SEISMIC DETECTION AND QUANTIFICATION OF GAS HYDRATES IN NORTHERN GULF OF MEXICO

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ABSTRACT

In this paper, we present the results of our seismic characterization/quantification studies of gas hydrates in northern Gulf of Mexico, including examples from Alaminos Canyon Block 818 (AC818), Walker Ridge Block 313 (WR313), and Green Canyon 955 Block (GC955). Multiple large areas of high-concentration (over 80% of pore space) gas hydrate prospects were generated as a result of these sustained studies. Major gas hydrate discoveries were found in both WR313 and GC955 throughout the Gulf of Mexico Gas Hydrate Joint Industry Project (JIP) Leg-II drilling in the Spring of 2009. The drilling success denotes the first major discoveries of gas hydrate exploration in the Gulf of Mexico. It also confirmed that our seismic-based technology for gas hydrate detection is valid and effective. We will start with introducing the seismic-based gas hydrate detection technology, and present case histories of seismic exploration of gas hydrate in the Gulf of Mexico (GoM).

Keywords: gas hydrates, Gulf of Mexico

NOMENCLATURE

AVO: amplitude versus offset
GHSZ: gas hydrate stability zone
GOM: Gulf of Mexico
JIP: Gulf of Mexico Hydrate Joint Industry Project
PI: acoustic impedance or P-wave impedance
PR: Poisson’s ratio
PSWI: prestack waveform inversion
SI: shear impedance or S-wave impedance
V_p: P-wave or compressional velocity
V_S: S-wave or shear velocity
3D: three-dimensional

INTRODUCTION

Gas hydrates have been known to exist extensively in shallow sediments from the Arctic permafrost regions to the deepwater oceans of the Equator. The vast amount of naturally occurring hydrates is a large potential for an energy resource. While the world demand for fossil fuel is ever-increasing and the supply is dwindling, it is essential to have a methodology for reliable assessment of gas hydrates accumulation in worldwide deepwater basins. As a principle and matured technology for hydrocarbon exploration, the 3D reflection seismic method becomes a natural choice for detecting and characterizing gas hydrates.

Previously, we [1] have developed an integrated five-step workflow for seismic characterization of gas hydrates. Rock properties at shallow depth, within the gas hydrates stability zone (GHSZ), vary largely due to heterogeneity and strong influence of compaction. Because of the lack of good-quality well data in this zone, our seismic predictions use analogue models based on geologic interpretation, seismic inversion, and the...
basic principles of rock physics. We also calibrate our models with real data whenever available. Our method has been validated and improved through applications in GoM and elsewhere [2][3].

Recently, we have carried out detailed gas hydrates characterization studies in Alaminos Canyon OCS blocks 818 and 857 (AC818), Walker Ridge OCS block 313 (WR313), and Green Canyon OCS block 955 (GC955), using our five-step work flow. Figure 1 shows the locations of the study areas.

A special data processing scheme was applied for the purpose. The workflow has been modified to incorporate a robust simultaneous prestack inversion scheme for inversion of elastic impedances and density in addition to Prestack Full Waveform Inversion (PSWI) at selected locations. The final estimation of gas hydrates saturation was done using both a direct deterministic regression-based transform method and also from a Bayesian statistical inversion. Based on these inversion results, and integrating with the concept of gas-hydrate-system (source, charging, reserving, sealing, and preserving), a series of prospects were generated within these study areas.

Based on the study results, multiple wells were selected for JIP Leg II exploratory drilling in the spring of 2009. Three wells were drilled in GC955, two of which contains high-concentration gas hydrates as predicted. Two wells were drilled in WR313, both have discoveries of thick, high-concentration gas hydrate zones as predicted pre-drill. The successful drilling story reveals that the seismic method is valid and effective. We present these results in the paper.

**METHODOLOGY**

Our five-step workflow, discussed in details elsewhere [1][8], consists of (a) High-resolution seismic data reprocessing with special attention to the first 1s of data below the mudline, (b) Stratigraphic interpretation, highlighting various faults, hydrocarbon pathways, and fluid-flow conduits, (c) Attribute analysis, identifying anomalous zones for possible hydrates zones, (d) Rock physics modeling and elastic parameter inversion, and (e) Quantitative analysis to estimate hydrates saturation. A schematic of this workflow is shown in figure 2. In the present study we followed this general workflow, but substantially modified the details of data processing, prestack inversion procedure, rock model building, and the estimation algorithms. These are discussed in some detail below.

**Gas Hydrate Modeling & Analysis: The 5-step process**

**Seismic Data Processing**

Since seismic characterization of gas-hydrate involves PSWI and prestack elastic inversion, amplitude preserving 3D high-resolution processing with focus on the shallow 1 second section below seafloor is a prerequisite for the studies.

To enhance shallow resolution and amplitude fidelity, a shallow gas-hydrate optimized, high-resolution seismic data processing, including iterative high-definition velocity model building, curved-ray Kirchhoff migration, followed by an advanced gather flattening technique was applied. The preprocessing includes: reformat, trace edits, despike, binning, sea level datum static, spreading
correction, diversity weighting, channel scalars, linear tau-p filter, designature filter, demultiple, shot scalars, residual de-bubble / de-ghost, 2D SRME, Radon filter, and Q-filter.

Several key preprocessing steps made a major difference in the quality of the final PSTM product. Crossline interpolation provided an improved method of regularizing 3D fold of coverage relative to the typical flex binning approach. The footprint removal process in which we adjusted the short period amplitude envelope to its local median value removed the acquisition foot-prints substantially. The effect of foot-print removal is shown in figures 3.

A proprietary curved ray Kirchhoff migration was applied for prestack time migration. The aperture radius was a time-variant function of the specified (75°) dip-limits. For each input trace and output sample, travel times were computed to determine the proper input sample to sum. Travel times were computed using an algorithm which took into account true 1-D ray bending at interfaces. Input sample values were scaled and filtered before summing. Anti-alias filters as a function of dip and midpoint distance were applied to the data during migration.

The migration was run on common offset volumes, and as migrated velocities were required, it was run in an iterative fashion, giving improved velocity control with each pass.

Non-rigid matching (NRM™), a newly developed proprietary method to time-align two cubes of data was applied for flattening events in the final image gathers. Final migration gathers and after NRM is shown in figure 4. The sinusoidal events at seafloor and below in the re-processed PSTM gathers were flattened after NRM.

The NRM procedure helps not only the image but also the AVO inversion. A comparison between the legacy image with the hydrate-optimized section is given in Figure 5. Higher resolution, signal to noise ratio, and more lateral continuity are manifest in the hydrate-optimized image (right panel of figure 5).
Fig. 5 Comparison between legacy stack (left) and the newly-processed stack (right). The spatial continuity and resolutions are much enhanced in the re-processed image.

**Rock Models of Gas Hydrates**

It is well known that the introduction of gas hydrates causes an increase in rock velocity. There are several rock physics models in the literature that attempted to quantify this effect. We used the model in which the hydrates grow in the interior of the porous frame and support the overburden together with the grains. This model has been found to describe the rock properties of hydrates in many regions such as gas hydrate wells in Mallik of the northern slope, GoM, Nankai Trough, etc.. We had previously used the same model in the GOM Keathley Canyon area with good results. Based on this model, we then estimated nomograms of acoustic and shear impedances as a function of depth or time for various saturations of gas hydrates using typical rock property of the working region. These steps were repeated with various combinations of rock model parameters until satisfactory results were obtained. The final rock model was used to transform inverted seismic impedances into probable hydrate saturation volumes.

**Seismic Inversion**

The inversion work was done by first performing PSWI at selected locations to help build the background model (0-8 Hz) and estimate wavelets for different angle stacks, then by implementing ISIS™, a 3D simultaneous inversion [5] to generate P-wave impedance (PI), S-wave impedance (SI), and density volumes.

PSWI was developed by Mallick [6][7]. It is a statistical optimization technique that operates much like biological evolution and derives P- and S-wave velocities and density profiles from a given CMP seismic gather.

An example of PSWI run at a key well location in AC818 was shown in Fig. 6. The left three curves on the left are inverted Vp, Poisson’s ratio (PR), and density respectively. The curves in green are the values of elastic properties and the yellow bands show the range of possible errors corresponding to the individual properties. The middle and right panels display the observed seismic angle gather and the synthetic angle gather after convergence during the iteration process. Note that the correlation coefficient between the two gathers is over 0.90, signifying a good match.

The local highs and lows in the derived Vp reflect possible lithology or fluid variations although there are uncertainties associated with noise accumulated during the inversion process due to the lack of full bandwidth frequencies in the input gather and the noise in the gather that corrupts the inversion results. The extreme high Vp event indicated by the red arrow reveals a very likely, high-concentration gas hydrate anomaly. This high Vp anomaly was later confirmed by the acoustic logging result at the actual well location.

The pseudo-logs generated from PSWI were used to generate low frequency models together with the seismic velocity and, constrained by seismic horizons. These pseudo-logs were also used to estimate the wavelets for different angle stacks. Simultaneous inversion (ISIS) was used to invert for the elastic impedances and density volumes.
ISIS inversion [5] is a seismic inversion method for simultaneous inversion of elastic parameters from prestack seismic data. Preconditioned seismic data are input as multiple angle stacks. Prior models for PI, SI (or PR), and density are the initial low frequency models of the elastic parameters that form a basis for the objective and the cost functions of the inversion. A simulated annealing method is used to generate and update model parameters. The forward modeling is done by convolving reflection coefficient series (linearized Zoeppritz equation-based) with wavelets. The wavelets may vary spatially and temporally for each angle stack in order to generate optimal results.

Figure 7 shows the PI and SI inversion results along the inline that passes the key well (pseudo-well) location. The vertical lines indicate the well position. Both PI and SI show a general increasing trend with time. They also reveal detailed variations both vertically and laterally, indicating possible subtle changes in litho-facies.

Fig. 7 Simultaneous inversion: PI (upper panel), SI (lower panel)

Anomalous high impedances were obtained at both sections at the level as indicated from PSWI result in Fig. 6, and in the vicinity of the key well (pseudo-well) location. Consistency between PSWI and ISIS inversions and with the actual acoustic measurement at the well location underscores the reliability and accuracy of the inversion results, which provides a solid basis for hydrate estimation.

Hydrate Saturation Estimation
Saturation of hydrates is estimated through the integration of seismic inversions and rock modeling of hydrate-bearing systems. The estimation involves both deterministic and statistical Bayesian-type Inversion with acoustic impedance (PI), shear impedance (SI), and combination of PI and SI as inputs.

For Bayesian inversion, the hydrate saturation will be determined following the maximum a posteriori (MAP) principle.

Hydrate saturations are mapped both deterministically and statistically, using P-wave and S-wave independently and jointly. Figure 8 shows the saturations estimated from PI and SI of the same inline as shown in Figure 7.

Fig. 8 Gas hydrate saturations from PI (upper panel), and from SI (lower panel). The red line shows the location of the pseudo-well.

Both sections show high-saturation anomalies (as high as 80% of the pore space) in the vicinity of the existing well location. Also a few anomalies of moderate-saturation are present at similar and/or shallower levels. We note that the saturation from SI is systematically lower than that from PI. The difference is thought to be caused by the errors in either seismic inversion or rock-physics modeling, or in both.
Gas Hydrate Anomaly in AC818

Figure 9 shows an areal view of the anomalous gas hydrates saturation ($S_{gh}$) throughout the inversion volume in AC818. Saturation values for gas hydrates in the pore space are between 0% and 100%. The map shows anomalous areas of continuous, high saturations. Anomalies “c” and “f” have continuous high values of $S_{gh}$ and occur in the porous Oligocene Frio sands. Anomaly “n” may also contain some Frio sands. The other anomalies occur in sediments younger than the Frio, most likely Pleistocene (or Pliocene) in age. As mentioned in the previous section, the seismic-based estimate of $S_{gh}$ is quite consistent with log-based estimate at the key well location near f. However, we find even higher saturation northeast of the key well location.

Fig. 9 Map of maximum saturation gas hydrates anomalies in AC818. Saturation for gas hydrates in the pore space values are between 0% and 100%.

Gas Hydrate Anomaly in GC955

A map view of accumulative gas hydrate distribution within GHSZ in GC955 is shown in Figure 10. The hot colors indicate high concentration of gas hydrate. The high gas hydrate saturation values mainly focus on a domed structure, southwest of the working area. Multiple gas hydrate layers were revealed in the section view of the structure (Figure 11). Two wells were drilled at this prospect by JIP Leg II in the spring of 2009. Both penetrated thick and high gas hydrate concentration zones at the target level, which confirms the pre-drill seismic prediction. More detailed comparison of the pre-drill seismic prediction with the actual drilling result is given by Shelander et al. (this issue).

Fig. 10 Map view of gas hydrate concentration in GC955.

Fig. 11 An estimated hydrate saturation section that runs through the domal structure shown in figure 10.

Gas Hydrate Anomaly in WR313

A map view of gas hydrate distribution in WR313 is shown in figure 12. A series of high gas hydrate concentration belts that lies northeast to southwest were defined as a result of the integrated study. A section view of these gas hydrate anomalies is given in figure 13, where high gas hydrate concentrations are calculated near the base of GHSZ (red line), and hydrate saturations decrease progressively updip. This is probably due to a combination of distance from the source of free gas below the GHSZ and reduction in permeability either due to the formation of gas hydrate or lithofacies change.
Two wells were also drilled at these high gas hydrate saturation belts by JIP in 2009 and both discovered high quality gas hydrates at the target level, which further confirms the pre-drill seismic prediction.

**CONCLUSION**

The integrated, five-step workflow proves effective for the seismic delineation of gas hydrate in GoM. It may play a major role in the exploration of gas hydrate in the near future.

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**REFERENCES**


