Estimating the amount of hydrate and free gas from surface seismic

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SUMMARY

Marine seismic data and well log measurements at the Blake Ridge offshore South Carolina show that prominent seismic Bottom Simulating Reflectors (BSRs) are caused by sediment layers with gas hydrate overlying sediments with free gas. We apply a theoretical rock physics model to 2D Blake Ridge marine seismic data to determine gas hydrate and free gas saturation. High-porosity marine sediment is modeled as a granular system where the elastic wave velocities are linked to porosity; effective pressure; mineralogy; elastic properties of the pore-filling material; and water, gas and gas hydrate saturation of the pore space. To apply this model to seismic data, we first obtain interval velocity using stacking velocity analysis. Next, all input parameters to the rock physics model, except porosity and water, gas and gas hydrate saturation, are estimated from geological information. To estimate porosity and saturation from interval velocity, we first assume that the entire sediment does not contain gas hydrate or free gas. Then we use the rock physics model to directly calculate porosity from the interval velocity. Such porosity profiles appear to have anomalies where gas hydrate and free gas are present (as compared to typical profiles expected and obtained in sediment without gas hydrate or gas). Porosity is underestimated in the hydrate region and is overestimated in the free-gas region. We calculate the porosity residuals by subtracting a typical (without gas hydrate and gas) porosity profile from that with anomalies. Next we use the rock physics model to eliminate these anomalies by introducing gas hydrate or gas saturation. As a result, we obtain the desired 2D saturation map. The maximum gas hydrate saturation thus obtained is between 15% and 20% of the pore space (depending on the version of the model used). These saturation values are consistent with those measured in the Blake Ridge wells (away from the seismic line) which are about 12%. Free gas saturation varies between 1% and 2%. The saturation estimates are extremely sensitive to the input velocity values. Therefore, accurate velocity determination is crucial for correct reservoir characterization.

INTRODUCTION AND PROBLEM FORMULATION

Gas hydrate is an ice-like crystalline lattice of water molecules with gas molecules trapped inside. Given the favorable combination of pressure and temperature, and the availability of free methane and water, gas hydrates can form and remain stable (Sloan, 1990). Such conditions can exist in ocean-bottom sediments at water depths below 500 m (Kvenvolden, 1993). Seismic bottom simulating reflectors (BSRs) that parallel the seafloor at the sub-bottom depths of several hundred meters are presumably associated with the base of the hydrate stability zone. BSRs manifest the negative impedance contrast between the sediments with gas hydrates overlying sediments without hydrates and possibly with free gas.

Gas hydrates are increasingly recognized as a potential future energy resource, based on the vast amounts of methane trapped within them (Kvenvolden, 1993). Surface seismic is currently the most suitable technique for identifying BSRs and mapping gas hydrates in the ocean sediments. Once a BSR is identified, it is important to characterize the hydrate reservoir and estimate the amount of gas hydrates present.

Several recent analyses estimate the amount of hydrate directly from seismic velocities. Sholl and Hart (1993), Wood et al. (1994), and Korenaga et al. (1997) determine hydrate saturation in the pore space from Wyllie's et al. (1958) time average equation that relates acoustic velocity to porosity and saturation. Dillon et al. (1993) use a weighted mean of Wyllie's and Wood's (1941) equations.

Wyllie's equation has been obtained empirically for consolidated reservoir rocks and cannot be used for high-porosity unconsolidated sediments (Dvorkin and Nur, 1998). In order to apply this equation to high-porosity marine sediments, calibration is required based on extensive core measurement or well log data. The results are modified ”time-average-form” equations that do not carry any physical meaning. It is likely that such equations can indeed link velocity to porosity and gas hydrate content if they have been derived from an extensive experimental database. However, such equations lack generality and cannot be used for diagnosing sediments, i.e., inferring their internal structure from seismic.

In order to estimate hydrate saturation, Yuan et al. (1996) first derive a relation between velocity and porosity from core and well log data. Then they calculate a porosity profile from velocity at a BSR and subtract from it the ”normal” porosity profile (where a BSR is absent). The resulting relative porosity reduction above the BSR is attributed purely to the presence of gas hydrate in the pores, which directly translates into hydrate saturation.

In this study we use a 2D seismic line at the Blake Ridge (where gas hydrate presence has been documented) to obtain interval velocity. In order to translate this velocity into hydrate and free gas saturation, we use a rock physics model that relates velocity to porosity; effective pressure; mineralogy; elastic properties of the pore-filling material; and water, gas and gas hydrate saturation of the pore space. This model is based on that of Dvorkin and Prasad (1998) for sediments without gas hydrate.

A fundamental issue of seismic interpretation here is how to obtain two unknown parameters, porosity and saturation, from a single velocity input. We solve this problem by assuming first that porosity is a monotonous function of depth as in sediments without hydrate and free gas. Next we obtain this porosity profile at the BSR by fitting a monotonous functional form to porosity values in the upper and lower parts of the depth section where it is known that hydrate and gas are absent. Finally, we calculate saturation from the known porosity and velocity. To verify this interpretation method, we apply it to estimating gas hydrate saturation from sonic velocity in two wells at the Blake Ridge where porosity was measured on cores. First we calculate the saturation using only the velocity. Then we recalculate it using both velocity and the porosity data. The two results are in reasonable agreement which validates our scheme of reservoir characterization from seismic. This work is an example of applying rock physics to seismic reservoir characterization.

SEISMIC DATA AND INTERVAL VELOCITIES

The data used in this study were recorded at the Blake Ridge, offshore Florida and Georgia. The part of the seismic line analyzed extends from the gas hydrate region into an area without hydrate. Processing of the data included spherical divergence correction, source wavelet deconvolution, amplitude calibration and prestack time migration. After migration, the data were stacked and converted to depth using a simple vertical stretch from time to depth. A migrated stack section of the seismic data is shown in Figure 1. The seafloor reflection, at more than 3 km water depth, is followed by a strong BSR between 25 and 52 km lateral distance. Among other authors, Ecker and Lumley (1994) have shown that the BSR in this region is caused by sediments with gas hydrate overlying sediments with free gas. In this interpretation, the flat reflector underneath the BSR is the base of the gas-saturated zone, marking the transition to the sediments fully saturated with brine. Since the geologic structure at the Blake Ridge is fairly simple, we used stacking velocity analysis on the prestack data to obtain RMS velocities. These velocities were then converted into a physical interval velocity model using Dix's equation. The resulting interval velocity field is displayed in Figure 2. Velocity increases from 1.5 km/s at the sea bottom to approximately 1.9 km/s above the BSR. A similar velocity increase is commonly observed in sediments containing gas hydrates (Minshull et al., 1994; Andreassen et al., 1995; Yuan et al., 1996). Beneath the BSR, velocity drops to approximately 1.6 - 1.7 km/s which indicates the presence of free gas. This velocity drop is consistent with the negative reflection polarity of the BSR. Between 0 and 25 km lateral distance, where no BSR exists, the velocity steadily increases with depth. No pronounced anomaly is present.

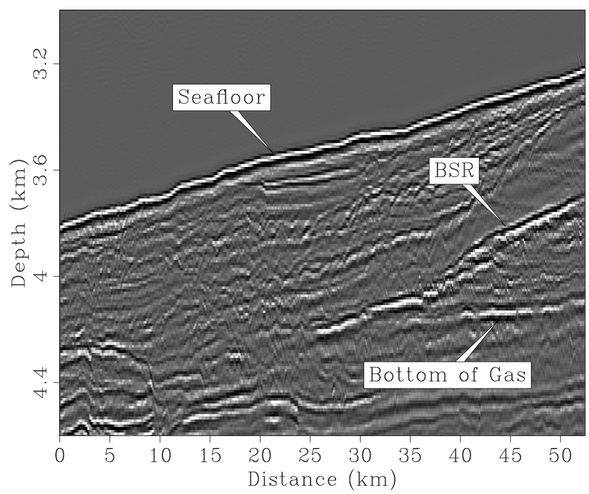

Figure 1: Stacked section after migration.

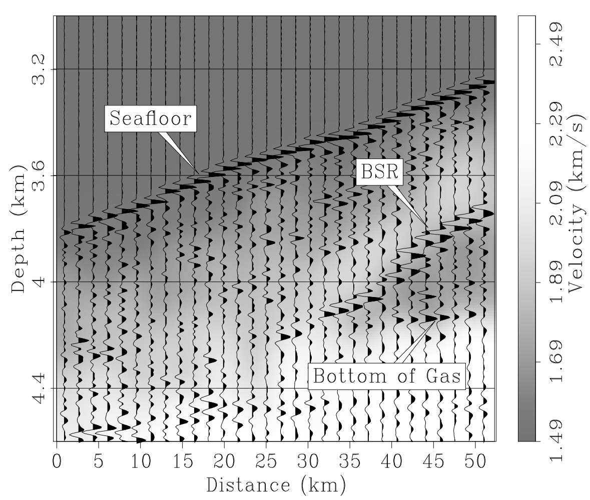

Figure 2: Interval velocity section.

ROCK-PHYSICS INTERPRETATION OF INTERVAL VELOCITIES

Rock-physics model and input parameters

In this model, we first relate the elastic moduli of the isotropic dry frame of the sediment to porosity (Dvorkin and Prasad, 1998). To do this, we assume that at the porosity of about 40%, which is that of a random pack of identical elastic spheres, the elastic moduli of the sediment can be calculated as the moduli of this pack. The grains of this pack have the elastic properties of the sediment's mineral phase. The moduli of the pack depend on the effective pressure defined as the difference between the overburden and hydrostatic stress. The elastic properties of a sphere pack at 40% porosity are treated as the low-porosity end member. The elastic moduli of the high-porosity end member at 100% porosity are zero. We connect these two end members (to calculate the moduli at an intermediate porosity) using an effective medium theory. As a result, we relate the elastic moduli of the dry frame to porosity, effective pressure, and mineralogy (the elastic properties of the grains). We use a similar model for porosities below 40% as given in Dvorkin and Nur (1996).

To calculate the elastic moduli of the sediment at full brine saturation, we use Gassmann's equation. The required compressibility (as well as density) of the brine can be calculated from salinity, pressure, and temperature (Batzle and Wang, 1992). If free gas is present, we use Gassmann's equation where the compressibility of the pore fluid is the isostress average of those of the brine and gas.

To estimate the effect of gas hydrate on the sediment's elastic moduli we use two models. In the first one (Model A) we assume that gas hydrate is part of the pore fluid and affects its compressibility. In the second one (Model B) we assume that gas hydrate is part of the solid frame and acts to reduce porosity and alter the elastic properties of the mineral phase.

We use our rock physics model in the inversion of the interval velocities for porosity and saturation. To do so, we separate the input parameters required by the model into two groups. In the first one are effective pressure, mineralogical composition of the sediment, and the elastic properties of the sea water, gas, and gas hydrate. We assume that the sediment's solid phase includes quartz, calcite, and clay (Matsumoto et al., 1996). In particular, we use 35% calcite, 5% quartz, and 60% clay. The bulk moduli and densities of methane and sea water are calculated (Batzle and Wang, 1992) at 36 MPa pore pressure and 15° C temperature (Matsumoto et al., 1996). For the minerals involved, we use standard moduli and density values (Carmichael, 1990). Pure hydrate properties are taken from Sloan (1990).

In the second group are porosity, and gas and gas hydrate saturation of the pore space. We assume that free gas and gas hydrate do not coexist at the same location. Then we can replace gas hydrate and gas saturation with a single parameter which is one minus water saturation. As a result, we have only two input parameters in the second group, which are porosity and water saturation. Our goal is to estimate these two parameters from a single measurable parameter: seismic interval velocity.

Inversion methodology

In order to obtain porosity and saturation from interval velocity, we first use our model to calculate a vertical porosity profile at every surface position by assuming that the sediment contains no gas hydrate or free gas in the entire depth section. In Figure 3 we give three porosity profiles (solid lines) at locations where (a) no BSR exists – 12.5 km lateral distance (see Figure 1); (b) the BSR begins – 34 km; and (c) the BSR is fully developed – 45 km. In the first case we observe an approximately monotonous decrease of porosity with depth. In the second and third cases, the departures of the calculated porosity from a monotonous curve occur at the depths where gas hydrate (reduced calculated porosity) and free gas (increased calculated porosity) are presumably present. Next, we assume that these departures (anomalies) are due to our initial assumption that the sediment is fully water saturated in the entire depth section. We also assume that the true porosity increases monotonously with depth and has the same functional porosity-depth form as in the region without BSR. An appropriate functional form is that of a second-order polynomial because it can adequately reproduce the calculated porosity-depth profiles outside the BSR zone (dashed line in Figure 3, 12.5 km lateral distance). Now we can use this functional form to calculate the ”true” porosity profile within the BSR zone. To do so, we assume that the sediment is fully water saturated (a) above the muted-reflection zone which overlies the BSR; and (b) below the flat reflector visible beneath the BSR which presumably marks the bottom of the free gas zone (Figure 1). In order to calculate the "true" porosity profile, we fit a second-order polynomial to these two parts of every vertical section (Figure 3, dashed lines). Finally, with "true" porosity identified in the entire interval, we are left with only one unknown – saturation – which can now be directly calculated from the interval velocity using the rock physics model. The resulting sections of gas hydrate and free gas saturation are given in Figure 4 for the two models of gas hydrate position in the pore space.

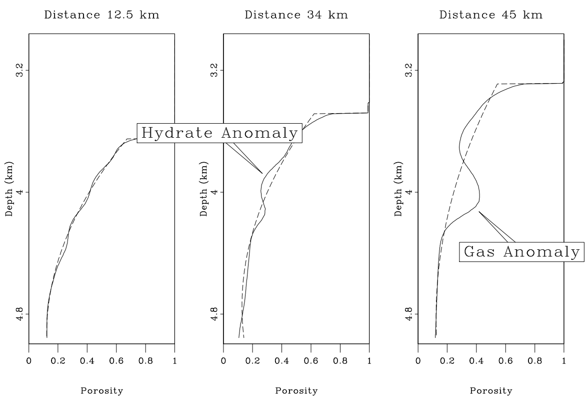

Figure 3: Vertical porosity profiles determined from interval velocity. Solid lines are for porosity under assumption that sediment is 100% water saturated. Dashed lines are for "true" porosity profiles.

As a result of our rock physics interpretation of the seismic data, we arrive at two pronounced patches with gas hydrates above the BSR: between 32 and 42 km, and 45 and 52 km lateral distance (Figure 4). These patches correspond to the two well-pronounced portions of the BSR (Figure 1). In the main (right-hand) patch, Model A, where gas hydrate is part of the pore fluid, gives maximum hydrate saturation of about 20%, whereas Model B, where gas hydrate is part of the solid frame, gives maximum saturation of about 15%. In the left-hand patch, maximum hydrate saturation is between 10 and 12% (depending on the model). We consider these two models as upper and lower bounds for gas hydrate saturation. Free gas saturation beneath the BSR is as low as 1 to 2%.

VERIFICATION OF RESULTS

In order to validate our technique of estimating gas hydrate and gas saturation from interval velocities, we use it with sonic velocities from wells 994 and 995 at the Blake Ridge. Porosity data in these wells are available from core measurements (Matsumoto et al., 1996). First we use the method with only velocities. Then we apply the rock physics model to calculating saturation with both velocity and porosity data. The results of these two calculations are compared in Figure 5 for Model B (gas hydrate is part of the solid frame). In the upper part of the gas hydrate zone, these results are very close for well 994, and deviate from each other by about 5% saturation in well 995. In the lower part the results of the two calculations differ noticeably. We attribute these differences to the lack of velocity data in the lower portions of the wells which affected the accuracy of porosity polynomial fitting. The convergence of the calculation results in the upper portions of the wells convinces us that the methodology offered is quantitatively accurate. The saturation values obtained here cannot be confirmed by direct measurements since no well exists in the direct vicinity of the seismic line. However, the hydrate saturation magnitudes obtained are consistent with those measured in the Blake Ridge wells which are about 12% (Matsumoto et al., 1996).

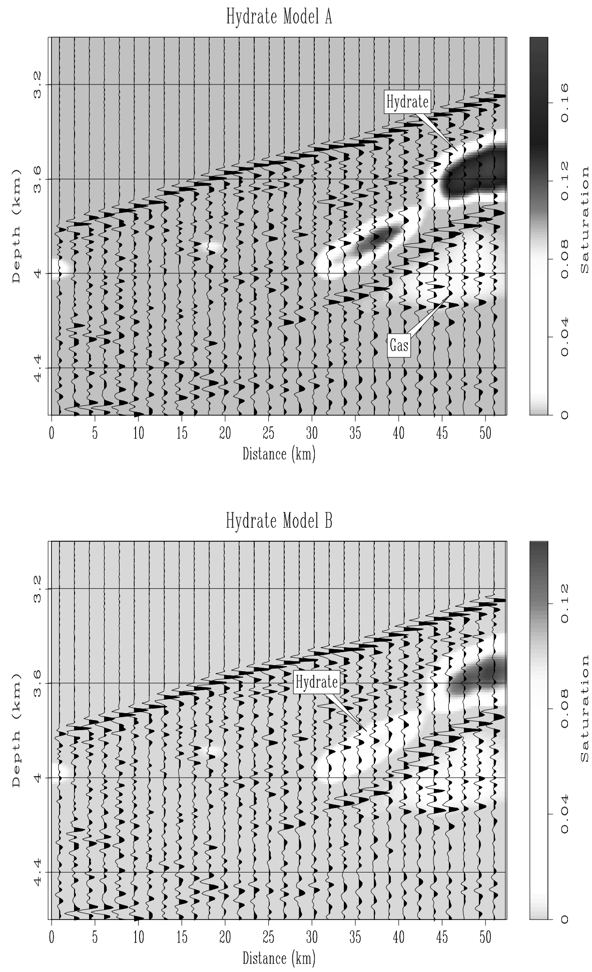

Figure 4: Gas hydrate and free gas saturation from Model A and B. Seismic traces are superimposed.

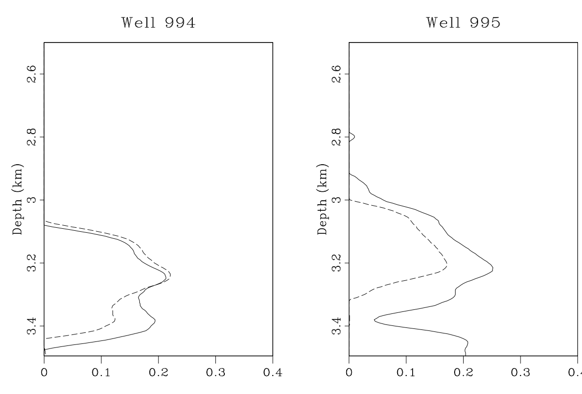

Figure 5: Hydrate saturation at wells 994 and 995 using velocity and porosity input (solid line) and velocity only input (dashed line).

SENSITIVITY ANALYSIS

In our seismic analysis, we determined that $\pm$ 10 m/s picking errors in the RMS velocity can cause as much as $\pm$ 200 m/s errors in the interval velocities. The interval velocity profiles at 46.5 km lateral distance, determined from the original RMS velocity as well as from RMS velocity with introduced errors, are given in Figure 6. The errors can either enhance the anomalous velocity zones in the hydrate and gas layer (dashed line) or suppress them (double dashed line). The resulting gas hydrate and free gas saturation estimates are given in Figure 7 where the solid and dashed lines correspond to those in Figure 6. For both models (A and B) errors in determining saturation are significant. Therefore, accurate velocity determination is crucial for correct reservoir characterization.

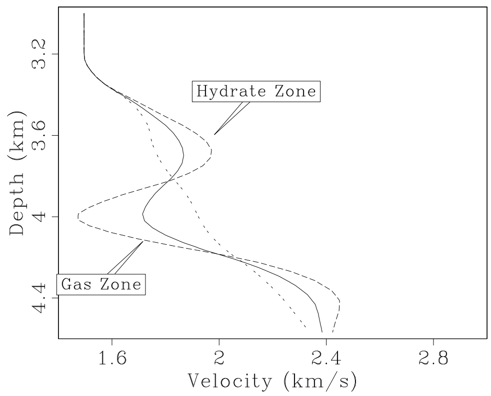

Figure 6: Possible errors in interval velocity. The solid line is for the velocity profile used, the dashed lines are for erroneous velocity.

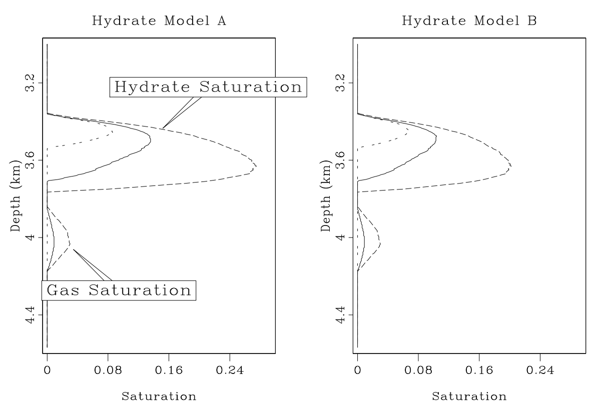

Figure 7: Errors in saturation estimates corresponding to those in interval velocity. The solid line is for the velocity profile used, the dashed lines are for erroneous velocity.

CONCLUSIONS

- This study is one of the first attempts to characterize a reservoir from surface seismic using rock physics.
- The resulting gas hydrate saturation values are consistent with those determined from well logs in this region.
- Saturation estimates are extremely sensitive to interval velocity values which requires precise velocity determination from seismic data.

REFERENCES

Andreassen, K., Hart, P. E., and Grantz, A., 1995, Seismic studies of a bottom simulating reflector related to gas hydrate beneath a continental margin of the Beaufort Sea: Jour. Geophys. Res., **100**, 12659–12673.

Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: Geophysics, **57**, 1396–1408.

Carmichael, R. S., 1990, Practical handbook of physical properties of rocks and minerals: CRS Press.

Dillon, W. P., Lee, M. W., Fehlhaber, K., and Coleman, D. F., 1993, Gas hydrates on the atlantic continental margin of the United States - controls on concentration: The Future of Energy Gases, USGS Professional Paper 1570.

Dvorkin, J., and Nur, A., 1996, Elasticity og High-Porosity Sandstones: Theory for Two North Sea Datasets: Geophysics, **61**, 1363–1370.

Dvorkin, J., and Nur, A., 1998, Time-average equation revisited: Geophysics, **63**, 1–5.

Dvorkin, J., and Prasad, M., 1998, Elasticity of marine sediments: GRL,submitted for publication.

Ecker, C., and Lumley, D. E., 1994, Seismic AVO analysis of methane hydrate structures: 64th Ann. Internat. Meeting, Soc. Expl. Geophys., Expanded Abstracts, 1100–1103.

Korenaga, J., Holbrook, W. S., Singh, S. C., and Minshull, T. A., 1997, Natural gas hydrates on the southeast U.S. margin: Constraints from full-waveform and travel time inversions of wide-angle seismic data: Jour. Geophys. Res., **102**, 15345–15365.

Kvenvolden, K., 1993, Gas hydrates – geological perspective and global change: Reviews of Geophysics, **31**, 173–187.

Matsumoto, R., Paull, C., Wallace, P., and the Leg 164 Scientific party, 1996, Gas hydrate sampling on the Blake Ridge and Carolina Rise: ODP, Leg 164 Preliminary Report.

Minshull, T. A., Singh, S. C., and Westbrook, G. K., 1994, Seismic velocity structure at a gas hydrate reflector, offshore western Columbia, from full waveform inversion: Journ. Geophys. Res., **99**, 4715–4734.

Sholl, D. W., and Hart, P. E., 1993, Velocity and amplitude structure on seismic-reflection profiles– possible massive gas-hydrate deposits and underlying gas accumulations in the Bering Sea: The Future of Energy Gases, U.S. Geo. Surv. Prof. paper 1570.

Sloan, E. D., 1990, Clathrate Hydrate of Natural Gases: Marcel Dekker, Inc.

Wood, W. T., Stoffa, P. L., and Shipley, T. H., 1994, Quantitative detection of methane hydrate through high-resolution seismic velocity analysis: J. Geophys. Res., **99**, 9681–9695.

Wood, A. B., 1941, A text book of sound: New York, MacMillan.

Wyllie, M. R. J., Gregory, A. R., and Gardner, G. H. F., 1958, An experimental investigation of factors affecting elastic wave velocities in porous media: Geophysics, **23**, 459–493.

Yuan, T., Hyndman, R. D., Spence, G. D., and Desmons, B., 1996, Seismic velocity increase and deep-sea hydrate concentration above a bottom-simulating reflector on the northern Cascadian slope: Jour. Geophys. res., **101**, 13655–13671.