Estimates of worldwide hydrate resources are large, but they are also uncertain because of inherent difficulties in determining the amount of gas hydrate present in ocean sediments. Estimates of gas-hydrate concentrations across a deepwater site can vary widely. For example, estimates of the volume of gas existing in gas hydrates and as free gas on Blake Ridge offshore South Carolina (USA) range from about 70 trillion m$^3$ over an area of 26 000 km$^2$ (Dickens et al., 1997) to about 80 trillion m$^3$ for a larger area of 100 000 km$^2$ (Holbrook et al., 1996). Discrepancies between some estimates of hydrate concentrations can partly be attributed to poor understanding of how gas hydrates are distributed in their host sediments. In particular, estimates based on seismic measurements, if not supported by reliable rock physics models and by in-situ observations, can be inaccurate.

**The need for rock physics.** The goal of our rock physics modeling of deepwater gas-hydrate systems is to develop a methodology by which gas-hydrate concentration can be inferred from seismic measurements. To achieve this goal, we define the elastic properties of deepwater gas-hydrate systems in terms of (1) elastic properties of the unconsolidated sediments that host the hydrates, (2) elastic properties of the embedded gas hydrates, (3) concentration of hydrates in the sediments, and (4) geometrical details of the distribution of hydrates within their host sediments.

**Theoretical models for unconsolidated deepwater sediments.** Most rock physics models for unconsolidated sediments are based on contact models, such as Hertz and Mindlin’s theory (see Mavko et al.) for describing the elastic properties of granular materials. The model we propose for unconsolidated sediments is based on an approach by Dvorkin and colleagues, with the distinction that the elastic properties of newly deposited deepwater sediments are described by Walton’s smooth model (see Mavko et al.), as opposed to the Hertz-Mindlin model. Walton’s theory is particularly appropriate for highly unconsolidated sediments at low effective pressure where grain rotation and slip along grain boundaries are likely to occur. Walton’s smooth model better explains the low shear strengths and high $V_P/V_S$ ratios observed in deepwater multicomponent seismic data and in lab measurements made on unconsolidated sediments.

We consider four rock physics models for deepwater gas-hydrate systems (Figure 1):

- **Model A** assumes gas hydrates are uniformly disseminated throughout the whole volume of sediment and act as a part of the load-bearing frame of the host sediments.
- **Model B** assumes gas hydrates are also disseminated throughout the whole volume of sediment, but they only fill the porous space and do not affect the dry mineral frame of their host sediments.
- **Model C** assumes an anisotropic, thin-layered medium having layers of pure gas hydrate intercalated with layers of unconsolidated sediments saturated with brine.
- **Model D** is also an anisotropic, thin-layered medium. However, in this model, gas hydrates are disseminated in thin layers of sediments, occupying 99% of the porous space of these layers, and act as part of the load-bearing frame. These hydrate-bearing beds are intercalated with layers of unconsolidated sediments saturated with brine.

The key input parameter in all of these models is gas-hydrate concentration. Our goal is to quantitatively relate gas-hydrate concentration to seismic observables such as P- and S-wave velocities and amplitude variation with angle of incidence (AVA). Detailed descriptions of the mathematics used to create each theoretical model have been submitted for publication and will not be presented here. We also will compare our theoretical predictions of velocity attributes in deepwater sediments with laboratory measurements made on synthetic hydrate-bearing sediments to illustrate the validity of the physics and mathematics used in constructing the models.

**Relations between P- and S-wave velocities and gas-hydrate concentration.** Figures 2, 3, and 4 present modeling results for P-wave velocity ($V_P$), S-wave velocity ($V_S$), and $V_P/V_S$ ratio, respectively, as a function of gas-hydrate concentration ($C_{gh}$) for the four rock physics models considered. In each model, the porosity of the host sediment is assumed to be 0.37, and the effective pressure is 0.01 MPa. For the two anisotropic layered models (C and D), we display two curves corresponding to waves polarized parallel to the layering (solid line) and waves polarized orthogonal to the layers (dotted line). From these figures we observe that relations between seismic velocities and gas-hydrate concentration depend on the geometrical details of how gas hydrates are distributed in their host sediments.

The results presented in Figure 2 show that for all four
rock physics models considered, an increase in gas-hydrate concentration increases the P-wave velocity in the sediments. The smallest increase in P-wave velocity occurs for the thin-bedded model (C) having layers of pure gas hydrates, whereas the largest increase in P-wave velocity is obtained for the models having disseminated, load-bearing gas hydrates (A and D). The key point is that any value of $V_p$ measured across a hydrate-bearing interval can be related to hydrate concentration only if a specific hydrate-to-sediment morphology is assigned to that interval.

From Figure 3 we observe, as expected, that S-wave velocity does not vary with gas-hydrate concentration for model B in which hydrates fill the porous space of the sediments. However, a large, almost linear increase in S-wave velocity occurs when S-waves are polarized parallel to the layers of a medium having thin beds of disseminated, load-bearing gas hydrates (model D, solid line). The S-wave anisotropy in this model is large, as shown by the difference between S-wave velocities polarized parallel (solid line) and orthogonal (model D, dotted line) to layers of disseminated, load-bearing gas hydrates. S-wave anisotropy for a system of thin layers of pure gas hydrates (model C) is also large. If gas hydrates occur in thin layers within near-seafloor strata, we should thus expect significant S-wave anisotropy. This anisotropy can be used with other seismic information to aid in estimating gas-hydrate concentrations in layered seafloor strata. The concept emphasized by these calculations is that we must first define the correct geometrical distribution of hydrate within the host sediment before a measured value of $V_S$ can be interpreted in terms of hydrate concentration.

Figure 4 presents the $V_p/V_S$ ratio as a function of the volumetric fraction of gas hydrate in the sediment ($C_{gh}$) for four rock-physics models. Model A = load-bearing gas hydrates disseminated in the whole volume of sediments; model B = pore-filling gas hydrates disseminated in the whole volume of sediment; model C = layers of pure gas hydrates producing slow polarization (dotted line) and fast polarization (solid line); and model D = layers of disseminated, load-bearing gas hydrates producing slow polarization (dotted line) and fast polarization (solid line). Sediment porosity is assumed to be 0.37, and effective pressure is 0.01MPa.

Figure 5. Model assumed for base of hydrate-stability zone (BHSZ). $V_p$ measured across a hydrate-bearing interval can be related to hydrate concentration only if a specific hydrate-to-sediment morphology is assigned to that interval.

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**Figure 5.** Model assumed for base of hydrate-stability zone (BHSZ).
centration for all models except model B, which assumes pore-filling gas hydrates. This anomalous behavior occurs for model B because P-wave velocity increases with gas-hydrate concentration in that type of media (Figure 2), whereas S-wave velocity remains practically constant (Figure 3). For anisotropic models C and D, there is a significant decrease in $V_p/V_s$ ratio at low gas-hydrate concentrations for waves polarized parallel to the layers (fast direction). This modeling result suggests that for thin-layered gas-hydrate morphologies, we may be able to detect small gas-hydrate concentrations in sediments using $V_p/V_s$ ratios and anisotropy information. Again, we find there is a wide range in the functional dependence of $V_p/V_s$ on hydrate concentration, depending on how the hydrate is distributed throughout the host sediment.

**PP and PS AVA modeling—base of hydrate-stability zone.** To evaluate the potential value of amplitude-versus-angle (AVA) technology for studying gas-hydrate systems, we simulate the AVA response for PP and PS reflections from an interface between the base of the gas-hydrate stability zone and sediments immediately below that interface that contain free gas (Figure 5).

The gas-hydrate systems considered in this AVA modeling are represented by isotropic rock physics models A and B (Figure 1), which have gas hydrates disseminated in the host sediments.

Figure 6 presents the results for AVA modeling of PP (left panel) and PS (right panel) reflectivity as a function of incidence angle for the model of load-bearing gas hydrates (model A). Each curve corresponds to a different gas-hydrate concentration in the layer 1 of Figure 5. In this model, gas hydrates fill the porous space without changing the dry mineral frame of the host sediments.

As hydrate concentration increases beyond 0.7, the PP AVA behavior shifts from a class 3 to a class 4 reservoir response. This change occurs because at large hydrate concentration there is a significant increase in $V_s$ in the layer above the gas reservoir (layer 1, Figure 5). This $V_s$ behavior is required for a class 4 PP AVA response (Castagna et al., 1998). PP AVA response for angles of incidence greater than 20° is more sensitive to gas-hydrate concentration than is the PP AVA response. By using AVA information from converted PS waves we should be able to better predict hydrate concentration for media represented by model A.

Figure 7 shows the results for AVA modeling of PP (left panel) and PS (right panel) reflectivity as a function of incidence angle for the model of pore-filling gas hydrates (model B). In this case only PP reflectivity exhibits any sensitivity to gas-hydrate concentration. All PP AVA reflectivity curves in Figure 7 are class 3 responses. For this model, the shear strengths of the sediments containing gas hydrates do not change with gas-hydrate concentration. Moreover, shear velocities in sediments containing pore-filling gas hydrates and in sediments containing free gas are similar. Therefore, all PS reflections are weak and vary little as gas-hydrate concentration increases.

The modeling results presented in Figures 6 and 7 show that PP reflectivity cannot differentiate between the two hypotheses of gas-hydrate occurrence (models A and B). However, PS reflectivity is different for load-bearing gas hydrates (model A) and for pore-filling gas hydrates (model B). Therefore, multicomponent seismic technology—in par-
ticular, the use of PS-mode AVA behavior—can be a powerful tool to understand the way gas hydrates are distributed in relation to their host sediments (Figures 6 and 7). Using combinations of $V_p/V_s$ ratios and AVA analyses of P-waves and converted PS-waves should improve estimates of deepwater gas-hydrate concentrations.

**Comparing rock physics modeling results with laboratory measurements.** In Figures 8 and 9 we compare laboratory measurements made by Yun and colleagues from Georgia Institute of Technology (USA) of P- and S-wave velocities as a function of gas-hydrate concentration with our results for rock physics model A (load-bearing gas hydrates). The left panels in these figures show the lab measurements, and the right panels show our rock physics modeling results. The unconsolidated sediments in the rock physics model are represented by quartz grains at critical porosity, assumed to be 0.37, the same porosity as that of the sand samples used in the laboratory measurements. The effective pressure used in the model is 0.01 MPa, and the mean effective pressure in the lab is also approximately 0.01 MPa.

Figure 8 shows that P-wave velocity increases with gas-hydrate concentration for both lab measurements and the rock physics model of load-bearing gas hydrates. The increase in P-wave velocity is nonlinear and is larger when gas-hydrate concentrations in pores exceed 50%. For gas-hydrate concentration smaller than 50%, the increase in the P-wave velocity due to the presence of gas hydrates is small. We observe a rather good agreement between the laboratory measurements of P-wave velocity as a function of gas-hydrate concentration and our rock physics modeling results, which implies the mathematical structure and physical concepts used in the numerical modeling are sound.

Figure 9 shows that S-wave velocity increases with gas-hydrate concentration for both lab measurements and the rock physics model of load-bearing gas hydrates. The increase in S-wave velocity is again larger when gas-hydrate concentration in pores exceeds 50%. For gas-hydrate concentration smaller than 50%, the increase in S-wave velocity due to the presence of gas hydrates is very small. The agreement between these laboratory measurements of $V_s$ and our calculations indicates Walton's model is a good physical model for deepwater, unconsolidated, near-seafloor media.

**Conclusions.** Rock physics modeling results show that the elastic properties of gas-hydrate units depend on the geometrical details of gas-hydrate distribution within the sediments. If hydrates occur in thin beds, the effective elastic properties of stratified near-seafloor sediments containing gas hydrates are highly anisotropic, and the acquisition of fast and slow components of multicomponent seismic data has great value.

AVA modeling is a second indication that multicomponent seismic technology can be important for understanding the way gas hydrates are distributed in relation to their host sediments and for estimating gas-hydrate concentrations. Using combinations of PP and PS AVA reflectivity, P- and S-wave interval velocities, and $V_p/V_s$ ratios should improve our understanding of deepwater hydrate systems.

Comparing our rock physics models and laboratory measurements made at the Georgia Institute of Technology on synthetic gas hydrates in unconsolidated sands suggests that gas hydrates are disseminated throughout deepwater media as a part of the load-bearing frame of near-seafloor sediments. We find satisfactory agreement between our theoretical predictions for P- and S-wave velocities corresponding to this rock physics model (our model A) and laboratory measurements of $V_p$ and $V_s$ velocities.

We conclude that rock physics modeling is a critical tool for understanding gas-hydrate distributions in deepwater environments and for quantifying the amount of gas hydrate present in deepwater, near-seafloor sediments under different geologic scenarios.


**Acknowledgments:** Research support for this study is provided by the U.S. Department of Energy (Contract DE-PS26-05NT42405) and by the Minerals Management Service (MMS Contract 0105CT39388).

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