Evaluation of deepwater gas-hydrate systems

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The world’s offshore continental margins contain vast reserves of gas hydrate, a frozen form of natural gas that is embedded in cold, near-seafloor strata. Published estimates suggest that the energy represented by gas hydrate may exceed the energy available from conventional fossil fuel by a factor of 2 or more. Understanding marine hydrate systems has become critical for long-term worldwide energy planning. Groups in several nations are attempting to evaluate the resource and to define seafloor stability problems across hydrate accumulations.

Affordable, reliable, remotely based methodologies for evaluating deepwater gas-hydrate systems have been slow to develop. Four-component ocean-bottom-cable (4-C OBC) technology offers an option for remote, detailed evaluation of deepwater, near-seafloor geology. Increasing use of marine multicomponent seismic technology by oil and gas companies now allows marine gas-hydrate systems to be studied over areas of many square kilometers and the geomechanical properties of the strata that confine these hydrates to be analyzed.

Data acquisition and calibration. Marine multicomponent seismic data acquisition requires a surface-based air-gun source and long lines of ocean-bottom sensors that record three-dimensional vector motion of the seafloor. Using this combination of surface source and sea-

floor receivers, standard-frequency (roughly 10–100 Hz) compressional (P-P) and converted shear (P-SV) wavefields can be acquired that backscatter from near-seafloor strata. We used these wavefields to image seafloor strata over distances of several kilometers across the Green Canyon area of the Gulf of Mexico. For calibration purposes, high-frequency, chirp-sonar data were acquired along the same seafloor profiles using an autonomous underwater vehicle (AUV). This AUV system traveled at a height of 40 m above the seafloor and illuminated near-seafloor strata with a 2–8 kHz chirp-sonar signal. The backscattered, high-frequency, P-P data acquired with this system imaged geology to a depth of a few tens of meters below the seafloor.

Data examples and interpretations. A high-frequency chirp-

sonar image along one OBC line that traverses Green Canyon Block 204 about 300 km south of New Orleans, USA. The seafloor feature at the south end of the profiles is a fluid/gas expulsion chimney that serves as a methane source for gas-hydrate formation. WB = water bottom, which is not imaged by the backscattered SV data (c) because of the P-SV data-processing techniques that were used. HL = regional hemipelagic layer. TT = interval of thin regional turbidites. Numerous faults with vertical throws of 1 m or less can be seen on chirp-sonar images (a). Some of these faults are interpreted on the P-P and P-SV images (b and c) and shown as thin vertical lines. Water depth averages about 840 m along the profile.
Figure 2. Expanded views of (a) OBC P-P image and (b) P-SV image along profile 549, where the seismic line traverses a seafloor expulsion site in Green Canyon Block 204. Vertical lines on the images are interpreted faults. The deep expulsion chimney shown in Figure 1 is more obvious in these views. BU = air-gun bubble pulse, not a geologic interface. WB is the water bottom. A, B, and C are depth-equivalent units; a, b, and c are depth-equivalent horizons. The numbers labeled on the P-SV image (b) are representative $V_p/V_s$ velocity ratios across interval $X_3$. 
m are resolved; units thinner than 1 m are detected. In the data illustrated in this paper, we defined near-seafloor imaging depths by assuming compressional-wave propagation velocity ($V_p$) in these near-seafloor strata was a constant value of 1600 m/s. We find $V_p$ is as low as 1350 m/s in some unconsolidated near-seafloor sediments along various OBC lines we are studying, but an assumed value of 1600 m/s will be used in this data comparison. Using this velocity assumption at the line coordinate where the 30-ms vertical scale bar is positioned on the AUV chirp image (Figure 1a), the base of the scale bar is 40 m below the seafloor. The 40-m vertical scale bars then placed on the OBC images indicate the intervals in low-frequency P-P image space (Figure 1b) and P-SV image space (Figure 1c) that correspond to the interval imaged by the high-frequency chirp-sonar data. The $V_p/V_s$ velocity ratio measured from AUV and OBC data across the top 5–8 m of seafloor sediment ranged from 20 to 30 (and sometimes higher) along this profile, suggesting that shear-wave velocity $V_s$ is less than 100 m/s immediately below the seafloor in several locations. The 40-m scale bar drawn on the P-SV image in Figure 1c is based on an assumed $V_p/V_s$ ratio of 15 for the total interval. A hemipelagic layer 6–8 m thick has been defined by regional seafloor coring and is the first seafloor unit that drapes across this area. This hemipelagic layer is labeled HL on the chirp-sonar image (Figure 1a). In the AUV data, regional heterolithic turbidites that underlie this hemipelagic drape (again defined by seafloor coring) appear as the 10-ms-thick band of older reflections labeled TT that start about 10 ms below the seafloor. This thin turbidite interval cannot be seen in the OBC P-P image (Figure 1b) but appears as the first bold reflection below boundary WB in the P-SV image (Figure 1c).

These data examples show that in deepwater seafloor strata where the $V_p/V_s$ velocity ratio is high (15 to 20), P-SV data acquired with OBC seismic technology using surface-positioned, low-frequency (10–100 Hz) air guns can image small-throw seafloor faults, meter-scale layering, and subtle near-seafloor stratigraphy almost as well as do high-frequency, kilohertz-range, chirp-sonar data collected using deep-running AUV systems.

**Identifying gas-hydrate strata.** Laboratory measurements have shown that $V_p$, $V_s$, and the $V_p/V_s$ velocity ratio are petrophysical properties that help to discriminate lithofacies and rock types. In our work, these velocity attributes are applied to gas-hydrate systems. We analyzed P-P and P-SV data along OBC line 549 where the profile crossed a seafloor fluid/sediment expulsion chimney to determine seismic-based estimates of $V_p$, $V_s$, and $V_p/V_s$ in units that seismic images is challenging because, as a result of the differences in $V_p/V_s$ velocity ratios from unit to unit, there are ($x$, $y$, $z$)-dependent disparities between P-P and P-SV travel times to specified depth coordinates. An interpretation of a travelt ime disparity to a common depth coordinate is the difference in P-P and P-SV image times spanned by the 40-m scale bar in Figure 1.

To define depth-equivalent geology in P-P and P-SV images, we searched for reflection patterns confirming that P-P and P-SV wavefields were imaging identical geologic conditions. An example of P-P and P-SV data imaging depth-equivalent geology is the series of low-frequency P-P and P-SV reflections that downlap onto and prograde across horizon c interpreted at the base of unit C (Figure 2). Once a depth registration such as this is defined, additional depth registrations above and below that point (such as the boundaries of units A and B) are made by considering vertical transitions in P-P and P-SV reflection patterns (P-P and P-SV seismic facies), using interval velocities to estimate unit thicknesses and, perhaps most importantly, using iterative ray tracing to adjust thicknesses of layered models of $V_p$ and $V_s$ velocities until ray trace arrival times of P-P and P-SV events match arrival times of real P-P and P-SV events in local common-receiver gatherers. Numbers labeled on the P-SV image are the average $V_p/V_s$ velocity ratio for each unit across interval $X_3$ (marked in Figure 2).

Typical depth-profiles of interval values of $V_s$, $V_p$, and $V_p/V_s$ observed along this OBC profile are illustrated in Figure 3. Subseafloor depths in this graph were estimated using seismic velocities and are accurate to probably ±20%. The shallowest unit (A) is about 15 m thick and has a high $V_p/V_s$ ratio (24 and higher). By comparison, massive nodular gas hydrate has a $V_p/V_s$ ratio of 1.9 to 2.0. We conclude unit A contains no gas hydrate. Although unit A is within the pressure-temperature regime for gas-hydrate stability, several reasons are plausible for a disparity between the top of the gas-hydrate stability zone in the sediment (i.e., the seafloor) and the top of the actual zone of gas-hydrate occurrence. First, methane hydrate can form only if the concentration of methane dissolved in pore fluid exceeds methane solubility in seawater and the methane flux exceeds a critical value representing the rate of methane transport by diffusion. These conditions may not exist in unit A. Second, it is possible that vertical advection of gas into unit A may be prevented by capillary sealing. Third, excess pore-water salinities and intrusions of warm loop currents and eddies across the seafloor of the Gulf of Mexico may dissociate gas hydrate in the shallowest seafloor sediments. Fourth, sulfate migrating downward from seawater reacts with upward-migrating methane to create hydrogen sulphide,
water, and HCO₃. This chemical reaction prevents the formation of gas hydrate to a depth below the seafloor that is determined by the volume flux of the upward-migrating methane. The volume flux of methane at this study location is not known, thus the depth to which gas-hydrate formation is prohibited is unknown.

Below unit A, \( V_p \) and \( V_s \) increase and the \( V_p/V_s \) ratio decreases successively in units B and C, indicating increasing sediment rigidity with depth (Figure 3). We believe the increased rigidity in unit C is caused partially by concentrations of gas hydrate that are distributed throughout the unit as disseminated clathrates that partly fill pore spaces and either bear a part of the overburden weight or float freely in the pore space, or as alternating thin layers of hydrate-free sediment and hydrate-bearing sediment. Rock physics models for each of these morphological possibilities are summarized in the paper by Sava and Hardage in this issue.

Core samples are needed to define how gas hydrate is distributed throughout its host sediment at this study site.

**Figure 4.** Model calculations relating seismic estimates of \( V_p \), \( V_s \), and \( V_p/V_s \) to effective pressure and gas-hydrate concentration GHC for a sand-dominated facies. Model parameters are coordination number \( C \), critical porosity \( \Phi_c \), bulk modulus \( K \), shear modulus \( \mu \), and grain density \( \rho \). Subscripts Q and GH indicate quartz and gas hydrate, respectively. Rectangular outline shows ranges of calculated effective pressure and seismic-measured \( V_p \), \( V_s \), and \( V_p/V_s \) across unit C defined in Figure 2.

**Figure 5.** Model calculations relating seismic estimates of \( V_p \), \( V_s \), and \( V_p/V_s \) to effective pressure and gas-hydrate concentration GHC for a clay-dominated facies. Model parameters and meaning of the rectangular outline are defined in the caption for Figure 4, with the exception that subscript Q (quartz) is now replaced with subscript cl (clay).
Estimating gas-hydrate concentrations. Our study of deepwater gas-hydrate systems has required us to develop effective-medium models of near-seafloor sediments that allow gas-hydrate concentrations to be estimated using seismic-based determinations of $V_p$, $V_s$, and $V_p/V_s$. Key rock-physics model parameters that affect the prediction of these velocity attributes for near-seafloor strata are gas-hydrate concentration (GHC) within available pore space, grain type (quartz or clay) of the host medium, coordination number C (average number of neighboring grains contacted by each grain of the medium at critical porosity), porosity of the medium, and effective pressure.

One effective-medium model used in this study assumes that gas hydrate is uniformly distributed throughout the pore space of a targeted seabed unit and acts as a part of the load-bearing mechanism of the sedimentary column. Relationships between gas-hydrate concentration, effective pressure, $V_p$, $V_s$, and $V_p/V_s$ predicted by this model are illustrated in Figures 4 and 5. The curves in Figure 4 assume that the seismic propagation medium is sand-dominated and has a porosity of 60%. The curves in Figure 5 assume that the medium is clay-dominated and has a porosity of 60%. The curves labeled GHC = 0, 50%, and 99% define velocity conditions that occur when 0, 50%, and 99% of the available pore volume is occupied by gas hydrate. When GHC is less than 100%, the remaining pore space is occupied by water.

The rectangular outlines define the range of effective pressure across unit C (Figure 2) and the ranges of seismic-based estimates of $V_p$, $V_s$, and $V_p/V_s$ measured across that unit. Effective pressure was calculated by assuming a depth-dependent porosity behavior from the seafloor to the base of unit C and then assigning a grain density of 2.55 gm/cm$^3$ to the clay-dominated sediment deposited in this interval. The seismic-based velocity parameters ($V_p$, $V_s$, and $V_p/V_s$) measured across unit C implied the concentration of gas hydrate within the unit was commonly 10–20% if the interval was assumed to be sand-dominated (Figure 4). Occasionally the $V_p/V_s$ ratio implied the hydrate concentration increased to about 40%. The same velocity attributes led to the conclusion hydrate concentration was slightly higher if the interval was clay-dominated (Figure 5).

Several assumptions are embedded in the seismic-based predictions of gas-hydrate concentration that are illustrated here. For example, if the porosity of unit C is less than the assumed value of 60% used in Figures 4 and 5, then the calculated curves of gas-hydrate concentration are displaced in each crossplot space in a direction that reduces the percentage of concentration in the seafloor sediments. The combination of lower porosity and lower gas-hydrate saturation within that porosity significantly affects estimates of gas-hydrate reserves.

Our purpose is not to claim we have made accurate predictions of gas-hydrate concentrations across this particular study area. Rather, our purposes are to describe a new seismic-based, 4-C OBC approach to evaluating deepwater gas-hydrate systems, to illustrate the tremendous resolution of near-seafloor geology that is provided by the P-SV mode of deepwater 4-C OBC seismic data, and to demonstrate how the combination of a calibrated effective-medium model and multicomponent seismic data allows gas-hydrate concentrations to be estimated over large deepwater areas. We believe that with appropriate calibration data, this methodology can produce estimates of hydrate resources that are reasonably accurate.

**Technological impact.** The investigative approach we illustrate here needs to be refined and applied at other deepwater gas-hydrate sites. Marine multicomponent seismic technology seems to be invaluable as a robust and remotely sensed source of data that can provide great detail about the internal architecture of deepwater gas-hydrate systems, geomechanical properties of deepwater seafloors, and deepwater, near-seafloor geology. Also, gas-hydrate-sensitive parameters, such as $V_p$, $V_s$, and $V_p/V_s$, can be extracted from P-P and P-SV data derived from 4-C seismic data, integrated into calibrated effective-medium models, and used to estimate gas-hydrate concentrations over large deepwater areas. These estimates should lead to better assessments of hydrate volumes in critical energy-dependent regions of the world.


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