Multicomponent Seismic Technology Assessment of Fluid-gas Expulsion Geology and Gas-hydrate Systems: Gulf of Mexico

B. A. Hardage, P. E. Murray, R. Remington, M. De Angelo, and D. Sava
Bureau of Economic Geology, Austin, Texas, U.S.A.

H. H. Roberts
Louisiana State University, Baton Rouge, Louisiana, U.S.A.

W. Shedd and J. Hunt Jr.
Minerals Management Service, New Orleans, Louisiana, U.S.A.

ABSTRACT

Four-component ocean-bottom-cable (4-C OBC) seismic data acquired in deep water across the Gulf of Mexico were used to study near-sea-floor geologic characteristics of fluid-gas expulsion systems. Although these 4-C OBC data were acquired to evaluate oil and gas prospects far below the sea floor, the data have great value for studying near-sea-floor geology. The research results summarized here stress the importance of the converted-shear-wave (P-SV) mode extracted from 4-C OBC data. In deep water, the P-SV mode creates an image of near-sea-floor strata that has a spatial resolution an order of magnitude better than the resolution of compressional wave (P-P) data regardless of whether the P-P data are acquired with OBC technology or with conventional towed-cable seismic technology. This increased resolution allows the P-SV mode to define seismic sequences, seismic facies, small-throw faults, and small-scale structures that cannot be detected with P-P seismic data.

INTRODUCTION

Seismic contractors have developed technology that allows four-component ocean-bottom-cable (4-C OBC) seismic data to be acquired in water depths as great as 2000 m (6562 ft). As a result, multicomponent seismic data are now available across several deep-water trends in the Gulf of Mexico that are appropriate for hydrate accumulations. Profiles of two-dimensional (2-D) 4-C OBC profiles that traverse two fluid-expulsion sites in
STUDY AREA
This study was confined to that part of the Green Canyon area of the northern Gulf of Mexico where WesternGeco offers long-offset 4-C OBC seismic data for multiclient sales (Figure 1). WesternGeco allowed access to selected 4-C seismic profiles from two deep-water OBC surveys they acquired across the Green Canyon lease area. These two surveys, Green Canyon north-central (GCNC) and Green Canyon northeast (GCNE), were acquired as grids of parallel north–south and parallel east–west seismic profiles extending to lengths of 50 mi (80 km) and spaced at intervals of 2 mi (3.2 km). Each survey area was large. The 770 line-mi (1230 km) of the GCNC program covered 675 mi$^2$ (1730 km$^2$), and the 1330 line-miles (2130 km) of the GCNE survey extended across 975 mi$^2$ (2500 km$^2$).

The study focused on two sites, Blocks GC237 and GC204, where deep-dive programs have confirmed the presence of sea-floor expulsion features typical of those associated with gas-hydrate systems across the Gulf of Mexico (Roberts, 2001). Each study area was a square lease block extending 3 mi (4.8 km) north–south and 3 mi (4.8 km) east–west. The water depths ranged from 525 to 825 m (1722 and 2707 ft) across the two study blocks. The positions of available 2-D 4-C OBC lines within the two lease blocks are illustrated in Figure 2. Two east–west OBC profiles (Line 288 and Line 284) traversed Block GC237, and one north–south OBC profile (Line 549) traversed Block GC204.

SEISMIC DATA ACQUISITION
The ocean-bottom cable used to acquire these multi-component seismic data deployed 4-C sensor stations at intervals of 25 m (82 ft). Each sensor package contained vertical, inline horizontal, and crossline horizontal geophones that acquired three-component, vector-based, particle-velocity data and a hydrophone that acquired scalar pressure data. The OBC cable was deployed along a straight, north–south or east–west profile on the sea floor to create a linear 2-D receiver line. A source boat towed a 3000-in.³ (46,161 cm$^3$) air gun array at a depth of 6 m (20 ft) directly inline with these sea-floor sensor stations to generate long-offset 2-D 4-C data. The air gun array fired at source intervals of 50 m (164 ft) as the source boat moved down each OBC profile. This acquisition geometry allowed image traces to be constructed at intervals of 12.5 m (41 ft) along the OBC line. The nominal fold of the data was 180 for deep reflectors. Continuous source-receiver offsets extending to 9000 m (29,527 ft) were used for deep-image data processing. Longer offsets were acquired for some shots, but field records were muted to maximum offsets of 9000 m (29,527 ft) for data processing. Record lengths were 20 s, so that deep converted-SV reflections would be recorded at all offsets.

SEISMIC DATA PROCESSING
Common midpoint (CMP) and common-conversion point (CCP) trace gathers created by WesternGeco were used for much of our analysis of near-sea-floor geology. These trace gathers were generated for purposes of deep imaging; thus, the mute patterns were not optimal for some analyses of near-sea-floor strata.
To emphasize some near-sea-floor stratigraphy and lithofacies features, short segments of 4-C OBC lines across the study blocks were processed using common-receiver trace gathers to make images that spanned only 25 m (82 ft) at each receiver station, and then these mini-images were combined to make a continuous image along the receiver line. This data-processing strategy differs fundamentally from techniques that use CMP and CCP trace gathers as explained by Backus et al. (2006). Both data-processing efforts (WesternGeco’s and ours) produced three distinct wave-mode images: a P-P image, a radial P-SV image, and a transverse P-SV image. Our data analysis procedure showed that a negligible reflection signal appeared on the transverse horizontal geophone for interfaces that were within 600 m (1968 ft) of the sea floor. P-SV reflections appeared on the transverse horizontal geophones only at deeper interfaces. Consequently, only radial P-SV data will be used in this article to analyze near-sea-floor geology. The qualifying adjective radial will be dropped, and the single term P-SV will be used to refer to all converted-S data that will be discussed.

WesternGeco’s data-processing procedure is summarized in Figure 3. Although the objective of the processing flow was to create optimal deep images, not optimal near-sea-floor images, this data-processing technique produced CMP and CCP trace-gather data that were valuable for interpreting near-sea-floor geology. Valuable P-P trace-gather data exist when the P-P data-processing procedure reaches step 10, and corresponding P-SV trace-gather data are created when the P-SV procedure reaches step 15. The P-P and P-SV near-sea-floor images that follow were constructed from WesternGeco trace gathers collected at these respective points in the two data-processing streams to illustrate that valuable near-sea-floor 4-C OBC

**Figure 1.** Long-offset four-component ocean-bottom-cable data coverage across the Green Canyon area of the Gulf of Mexico. The labels Green Canyon, Atwater Valley, and Mississippi Canyon are the names of lease block areas and do not indicate the positions of the sea-floor features having these names. This article illustrates data acquired across Green Canyon Blocks GC204 and GC237. GCNC = Green Canyon north-central; GCNE = Green Canyon northeast.
research data exist among seismic contractors that have processed the data for imaging much deeper geology. Gas hydrate researchers should be able to use any deep-water 4-C OBC data processed using equivalent procedures to study near-sea-floor geology in numerous deep-water gas-hydrate provinces.

ELASTIC WAVEFIELD STRATIGRAPHY

Traditional seismic stratigraphy is based on P-P seismic data. Few examples exist in the literature where S-wave data have been used in seismic stratigraphy interpretations. The 4-C OBC seismic data available in this study allowed seismic stratigraphy concepts to be expanded into the multicomponent seismic domain. Our analysis found that combinations of P-P and P-SV seismic data gave more insight into the depositional architecture and sedimentary fabric of sea-floor strata than what could be achieved with P-P seismic data alone. Much of the information in this article illustrates and emphasizes the advantages of elastic wavefield stratigraphy over conventional P-wave seismic stratigraphy.

FIGURE 2. Locations of seismic profiles across four-component ocean-bottom-cable shaded study areas A) GC237 and B) GC204. TD = total depth.
The P-P image along OBC line 288 that traverses Block GC237 is displayed as Figure 4. Several interpreted horizons that define seismic units immediately below the sea floor are shown. Horizon WB is the water bottom. Horizons 1 through 4 are successively deeper sequence boundaries. The seismic units defined by these boundaries are labeled A, B, C, and D. These horizons and units were selected arbitrarily to illustrate imaging similarities and imaging differences between P-P and P-SV data.

The P-SV image along this same profile is shown in Figure 5. P-SV units A, B, C, and D in Figure 5 are interpreted to be depth equivalent to P-P units A, B, C, and D shown in Figure 4. The unique geometry of unit C and the hummock-shaped reflection events within unit D define depth-equivalent geology that allows P-P image space to be depth-registered with P-SV image space. P-SV horizons occur at different image times than do the P-P horizons because of the difference in P and SV propagation velocities through the strata. Because near-sea-floor geology was not an imaging objective of the WesternGeco data-processing strategy (Figure 3), a mute pattern was applied to the P-SV trace gathers that eliminated the first several meters of subsea-floor strata. Our ongoing work uses a different data-processing strategy based on common-receiver trace gathers that eliminate the need to do wave-equation datuming (P-P step 5 and P-SV step 6, Figure 3), S-wave receiver statistics (P-SV step 4, Figure 3), and correction to sea level (P-P step 14 and P-SV step 19, Figure 3). This common-receiver trace-gather approach produces a P-SV image that starts immediately at the sea floor and is described in other articles (Backus et al., 2006). Because a water-bottom reflection is not included in the P-SV image, horizon WB from the P-P image was transferred onto the P-SV image. P-SV units A, B, C, and D were then interpreted as depth equivalents of P-P units A, B, C, and D.

The difference between the P-P and P-SV images is most pronounced for units A and B. The primary reason for the difference in the spatial resolution of P-P and P-SV data is that the Vp/Vs velocity ratio is unusually high for these near-sea-floor, deep-water sediments, as it should be for marine sediments that are highly unconsolidated and confined by low effective...
pressure. Our measurements showed that \( \frac{V_p}{V_s} \) within sequence A ranged from 10 to 15 along this part of Line 288, with a value of 12 being a reasonable average value. For each frequency component of the downgoing P wavefield that illuminates unit A, this \( \frac{V_p}{V_s} \) velocity condition means that the associated wavelength in the SV wavefield is 12 times shorter than the corresponding wavelength in the P wavefield. Shorter wavelengths produce better spatial resolution. The end result is the P-SV image of unit A has a spatial resolution that is an order of magnitude better than the spatial resolution of the P-P image.

The \( \frac{V_p}{V_s} \) velocity ratio decreases to about 8 in unit B, to about 6 in unit C, and then to about 4 in sequence D in the part of OBC Line 288 illustrated in Figures 4 and 5. As a result, the contrast between P-P and P-SV resolution diminishes as \( \frac{V_p}{V_s} \) decreases with depth below the sea floor. Spatial resolutions of P-P and P-SV images are equivalent not far below unit D.

A large difference between P-P and P-SV seismic amplitude facies along this profile is observed, particularly for units A and B. Almost no contrast between the P-P amplitude facies in unit A and the P-P amplitude facies in unit B is observed (Figure 4). In fact, there is no obvious reason to introduce unit boundary 1 into the P-P image if a seismic interpretation is restricted to only the P-P data. In contrast, a significant difference between the P-SV amplitude facies in unit A and the P-SV amplitude facies in unit B is observed (Figure 5). An interpreter is compelled to introduce a unit boundary (horizon 1) into the P-SV image to segregate P-SV facies A from P-SV facies B. Once this unit boundary is defined in P-SV image space, then its depth-equivalent horizon in P-P image space has to be interpreted, which results in horizon 1 shown in Figure 4. This mental exercise demonstrates that the use of elastic wavefield stratigraphy concepts in a seismic interpretation commonly causes more geological

---

**Figure 4.** Ocean-bottom-cable compressional wave image along Line 288, Block GC237. WB is the water bottom. Surfaces 1 through 4 are interpreted boundaries defining units A through D. CDP = common depth point.
information to become available than does the application of conventional P-wave seismic stratigraphy.

A major reason for using elastic-wavefield seismic stratigraphy instead of conventional P-P seismic stratigraphy to interpret near-sea-floor strata across this study area is that changes in high-resolution P-SV seismic facies and attributes in several units give insights into depositional processes and bedding architecture that would not be known if only lower resolution P-P seismic data were used. These observations suggest that 4-C seismic data should be used in deep-water, near-sea-floor studies in preference to single-component P-wave data whenever possible.

**P-P AND P-SV IMAGES: OBC LINE 284, BLOCK GC237**

P-P and P-SV images along OBC Line 284, the northernmost OBC line across Block GC237, are displayed in Figures 6 and 7, respectively. Horizons WB, a, b, and c drawn across each image are interpreted to be depth-equivalent unit boundaries that create depth-equivalent units A, B, and C. As was the case along Line 288, P-SV data display a spatial resolution within these strata that is much better than the spatial resolution of P-P data because (1) the \( V_p/V_s \) velocity ratio is large in these sea-floor sediments and (2) P and SV wavefields have approximately the same frequency spectra for the first 100–200 m (328–656 ft) of P-wave penetration into the sea floor.

P-P units A through C (Figure 6) have individual geometries and spatial positions that are almost identical with the geometrical shapes and spatial pattern of P-SV units A through C (Figure 7), just as was observed for nearby OBC Line 288. Although P-P and P-SV seismic-unit architectures are similar, P-P and P-SV seismic amplitude facies are not. Important geologic insights into the depositional system result when P-P and P-SV seismic amplitude facies are compared. P-SV amplitude facies suggest a spatial distribution of

---

**FIGURE 5.** Ocean-bottom-cable converted shear wave image along Line 288, Block GC237. WB is the water bottom. Horizons WB, 1, 2, 3, and 4 and units A, B, C, and D are depth equivalent to the same labeled features in the compressional wave image (Figure 4). CDP = common depth point.
FIGURE 6. Uninterpreted (top) and interpreted (bottom) ocean-bottom-cable compressional wave image along Line 284, Block GC237. Labeled horizons a through c are interpreted lithostratigraphic boundaries. WB is the water bottom. Units A through C are interpreted lithostratigraphic units. Vertical lines are interpreted faults. BU is an air gun bubble pulse, not a geologic boundary. Compressional wave velocity ($V_p$), shear-wave velocity ($V_s$), and $V_p/V_s$ analyses were done across intervals $X_1$ and $X_2$. The sea-floor mound labeled trend of sea-floor expulsion identifies a structural feature that extends to a prominent sea-floor expulsion site approximately 800 m (2625 ft) south of this profile. This expulsion site area has been investigated by three of the coauthors in deep-dive programs. CDP = common depth point.
FIGURE 7. Uninterpreted (top) and interpreted (bottom) ocean-bottom-cable converted shear wave image along Line 284, Block GC237. Labeled horizons and units are interpreted to be depth equivalent to the same features labeled on the compressional wave image. Water-bottom horizon WB from the P-P image is transferred onto this image for reference. Numbers atop the interpreted data are seismic-based averages of compressional wave velocity/shear wave velocity ($V_p/V_s$) for each unit across intervals $X_1$ and $X_2$. CDP = common depth point.
lithofacies that differs from that implied by P-P amplitude facies. These facies differences will be reconsidered in a later section of this article.

A second difference between the P-P and P-SV images is their different depictions of small-throw faults that reach the sea floor. It is possible to find evidence of faults that traverse the shallowest sea-floor strata in both the P-P and P-SV images. However, several of the vertical alignments of reflector terminations that occur across units B and C in the P-SV image (Figure 7) are bolder, more prominent fault indicators than what is observed in the P-P image because more reflection terminations are involved along some of the fault trends in P-SV image space. Some of these fault-indicating features are identified with vertical solid lines in Figure 7. When analyzing these faults, it is important to keep in mind the large 1:25 vertical exaggeration of the display.

Sidescan-sonar, multibeam bathymetric, and high-frequency chirp-sonar data were acquired with an AUV along the track of OBC Line 284 in Block GC237. Only the chirp-sonar data will be discussed here. The AUV traveled directly above the coordinates of Line 284 at a height of approximately 50 m (164 ft) above the sea floor to acquire the P-wave chirp-sonar data that we studied. A high-frequency (2 to 8 kHz) chirp-sonar signal illuminated shallow sea-floor strata, and the P wave that then backscattered from sea-floor sediment interfaces was recorded by this same transducer acting in receiver mode. The resulting zero-offset, single-fold, P-P data were imaged to a depth of a few tens of meters (typically ~50 m, ~163 ft) below the sea floor.

The chirp-sonar sea-floor image along Line 284 is illustrated in Figure 8, together with P-P and P-SV images constructed from OBC data acquired along the same profile. The chirp-sonar data provide impressive definitions of near-sea-floor strata. Units 1 m (3 ft) thick are resolved. Thinner beds are detected but not resolved. The base of the chirp-sonar image is labeled BCS and is marked on all three images to emphasize (1) the difference in OBC P-P and P-SV resolutions of near-sea-floor geology and (2) the approximate equivalence of the resolutions of low-frequency (10–100 Hz) OBC P-SV data and high-frequency (2–8 kHz) AUV data.

The high-frequency chirp-sonar data show numerous small-throw faults that reach the sea floor. Essentially all of the faults imaged by the chirp-sonar data can be seen in the OBC P-SV data (Figure 8). In fact, several of these subtle faults are the most eye-catching features on the P-SV image. In contrast, some of the chirp-sonar-imaged faults are difficult to see in the OBC P-P data even if the chirp-sonar image is available for comparison. These image comparisons lead to the conclusion that, in deep-water, near-sea-floor strata where the Vp/Vs velocity ratio is high, P-SV data acquired with OBC technology intended for deep oil and gas exploration can image small-throw faults and subtle subsea-floor stratigraphy almost as well as high-frequency AUV chirp-sonar data. Repeated comparisons of AUV chirp-sonar and OBC P-SV images along OBC Lines 284 and 549 (Figure 3) built considerable confidence in the validity and value of P-SV data for studying near-sea-floor geology in deep-water environments.

**TOWED-CABLE SEISMIC DATA: BLOCK GC204**

The oil and gas industry has acquired numerous three-dimensional (3-D) and 2-D surveys of towed-cable P-P seismic data across the Green Canyon area. The sea-floor image across Block GC204 extracted from one conventional 3-D P-P survey by interpreters at Minerals Management Service (MMS) is shown in Figure 9. An interpretation of the sea-floor P-P reflectivity pattern is labeled on the figure to show expulsion sites and flow paths of methane-bearing and sulfate-bearing fluidized sediment away from these expulsion features. Unpublished deep-dive programs by MMS and Louisiana State University (data from H. H. Roberts, W. Shedd, J. Hunt Jr.) have confirmed that the labeled features are expulsion sites. Tracks of expelled methane-rich sediment were observed to radiate away from the expulsion chimneys and arc downslope following favorable sea-floor gradients, similar to the pattern shown in Figure 9. Numerous methane-consuming and sulfate-consuming organisms were found to be...
congregated on this expelled material. The dense concentration of clam shells (sometimes 1 m [3 ft] in thickness), bacterial mats, and other fauna atop the methane-laden sediment is thought to be the principal reason the P-P reflection coefficient of the sea floor is greater along the sediment ejecta tracks than it is across adjacent soft-sediment sea-floor areas that have no methane and have not attracted methane- and sulfate-dependent organisms. Also shown in Figure 9 is the location of east–west profile XX’ where a vertical slice through the proprietary MMS 3-D seismic volume is used to illustrate the expulsion system in section view. The near-sea-floor part of this seismic profile is displayed in Figure 10. Higher amplitude sea-floor reflectivities associated with areas of methane-laden sediment are indicated in red. The two vertical zones where there are obvious losses of P-P reflection signal and continuity are interpreted to be fluid-sediment expulsion chimneys. A robust reflection event labeled BSR (?) has been interpreted by MMS as an excellent candidate for a bottom-simulating reflector (BSR) that marks the base of a local hydrate stability zone (BHSZ). A question mark is used in labeling this event because in this view, the reflection does not exhibit the classic crosscutting of strata that is typical of many other BSR events. Away from this expulsion chimney, event BSR is conformable to the sea floor. As the event approaches the expulsion chimney, it climbs toward the sea floor. This behavior is expected because deep-source thermogenic gases that migrate upward through expulsion systems cause warmer isotherms to move closer to the sea floor inside fluid-flow chimneys. A BHSZ horizon would thus rise toward the sea floor as it approaches an expulsion system in response to the warmer sediment it has to traverse.

**P-P IMAGE: OBC LINE 549, BLOCK GC204**

A P-P image created along OBC Line 549 that traverses Block GC204 is displayed as Figure 11. The interpreted surfaces in this image are labeled in the same manner...
as the surfaces shown in previous interpreted images across Block GC237 (Figures 6, 7). Water-bottom WB and horizons a through c are interpreted unit boundaries. The image along Line 549 differs from the P-P image across Block GC237 in that a prominent P-wave wipeout chimney between common depth point (CDP) 13,700 and 13,800 exists. No P-wave wipeout chimney was observed along the OBC lines analyzed across Block 237. The position of Line 549 atop the sea-floor expulsion chimney is shown in Figure 9.

Across the northern Gulf of Mexico, the loss of P-wave reflection signal within these types of vertical chimneys has been found to be geographically and genetically related to areas that are known to have sea-floor exposures of gas hydrate (Roberts et al., 1998). These P-wave no-signal chimneys are assumed to be caused by the vertical migration of deep thermo-genic gas, a key element in the formation of gas hydrate in the Gulf of Mexico. This upward-migrating gas deteriorates P-wave reflectivity along its migration path and contributes to hydrate clathrates as it approaches the sea floor and encounters temperature, pressure, and geochemical conditions that allow hydrate formation. In the Gulf of Mexico, the result is a genetic link between deep-water P-wave wipeout chimneys and numerous gas-hydrate accumulations. The topography of sea-floor surface WB atop this particular wipeout chimney suggests that prominent mounds exist on the sea floor at the chimney location. Mounded sea-floor features near expulsion sites are additional indirect indicators that gas hydrate may be found at or near the sea floor.

**P-SV IMAGE: OBC LINE 549, BLOCK GC204**

The P-SV image produced from the 4-C OBC data along OBC Line 549 is displayed in Figure 12. Surfaces a through c extending across P-SV image space are interpreted to be depth equivalent to the same labeled surfaces in P-P image space (Figure 11). Water-bottom surface WB is identical with surface WB in Figure 11. The P-SV images of the shallowest sequences have properties that are similar to those of the P-SV images studied across Block GC237. These P-SV data in Block GC204 again provide a significant increase in spatial resolution, particularly in the top two sequences, A and B, compared with the resolution of the companion P-P data.
P-SV WIPEOUT CHIMNEY

An intriguing feature of this P-SV image that was not observed in the data across Block GC237 is the presence of a P-SV wipeout chimney. One of the attractions of 4-C OBC seismic data acquisition in the Gulf of Mexico is that the P-SV data provided by this technology have excellent signal-to-noise properties within...
gas-invaded zones and provide high-quality images of structure and stratigraphy inside the numerous P-wave wipeout chimneys that occur across the northern Gulf (Hardage et al., 2002; DeAngelo et al., 2003). Thus, the P-SV wipeout chimney in this P-SV image (Figure 12) is an atypical P-SV response inside a P-P wipeout chimney. Some researchers speculate that the loss of P-SV reflection signal in this particular vertical column of strata is caused by something other than free gas, which is the common cause of P-wave...
wipeout chimneys. Roberts et al. (1998), for example, suggested from research in Block 161 of the Garden Banks lease area that sediments in an expulsion chimney located in that block are completely remolded and have lost acoustic impedance contrasts that define reflection horizons. The exact geologic significance of P-SV wipeout chimneys is yet to be answered.

**Vp/Vs BEHAVIOR**

Previous investigators such as Pickett (1963) and Domenico (1984) have shown that the Vp/Vs velocity ratio is a petrophysical property that can discriminate among many lithofacies and rock types. Dvorkin et al. (2003) and Chand et al. (2004) expanded Vp/Vs rock physics behavior to gas-hydrate systems. The P-P and P-SV data across Blocks GC237 and GC204 were analyzed to determine seismic-based estimates of Vp/Vs across the fluid-gas expulsion systems in these lease blocks. Interval values of Vp and Vs were also determined and used to supplement geological conclusions instead of relying on Vp/Vs velocity ratio information only. The interpretations that were imposed on the P-P and P-SV images along OBC Line 284, Block GC237, are shown in Figures 6 and 7 and have already been discussed. Interpretations along OBC Line 549, Block GC204, are illustrated in Figures 11 and 12.

Lithostratigraphic units interpreted along OBC Lines 284 and 549 for this Vp/Vs analysis are labeled A, B, and C on Figures 6, 7, 11, and 12. Units A, B, and C along Line 284 should not be equated with units A, B, and C along Line 549. Each suite of layered units is unique to the seismic profile where the units are defined. Numbers labeled on each P-SV image (Figures 7, 12) are average Vp/Vs velocity ratios across each system layer in the vicinity of the line coordinate where the numbers are positioned.

A consistency in the Vp/Vs behavior across these two expulsion sites is observed, although the study locations are 50 km (31 mi) apart (Figure 1). This consistency is better seen with the Vp/Vs data displayed as a depth profile, as in Figure 13. Subsea-floor depth coordinates in this plot were estimated using contractor-generated seismic velocities and may be accurate to only (+/-) 20% near the sea floor, because when WesternGeco processed these 4-C OBC data, their objective was to image deep oil and gas targets, not near-sea-floor geology. Consequently, they did not concentrate on determining accurate near-sea-floor velocities in thin layers. Our procedure for processing common-receiver trace gathers has been improved to yield an accuracy of ±1% in interval velocities (Backus et al., 2006, their figure 24).

At both expulsion sites studied here, the shallowest unit, A, is about 15 m (49 ft) thick and has a high Vp/Vs.
value of 22 or greater. Below unit A, the Vp/Vs ratio decreases successively in units B and C, indicating increasing sediment rigidity with depth. This increased rigidity could be caused by any process that enhances the lithification of the sediment. Because of proximity to a gas expulsion chimney, one possible contribution to increased sediment rigidity is gas hydrate distributed throughout the sediment as disseminated clathrates, ultra-small nodules, or perhaps thin layers. Each of these morphological possibilities requires a different rock-physics model to relate seismic attributes to hydrate concentration. Core samples are needed for more insight into the physical phases and morphological character of any gas hydrate that may be present.

**FACIES ARCHITECTURE OF FLUID-GAS EXPULSION SYSTEMS**

Seismic facies architecture within the expulsion system of Block GC237 is similar to the facies architecture across the expulsion feature in Block GC204, 50 km (31 mi) away. The system-unit terminology and images presented in Figures 6, 7, 11, and 12 will be used in this discussion of facies architecture observed within the layered units associated with these expulsion systems. This description will start at the sea floor and work downward. The shallowest unit, A, had the highest Vp/Vs velocity ratio (greater than 20), robust and continuous P-P reflections, and weak and chaotic P-SV reflections. The next system, unit B, always had a lower Vp/Vs value (commonly 6 to 8) and was bounded at its top and base by prominent, reasonable-quality P-P and P-SV reflections. Its internal fabric consisted of continuous, conformable, and commonly robust P-SV reflections but weak, chaotic, and discontinuous P-P reflections.

In the next unit, C, Vp/Vs decreases further to values between 4 and 6, and the unit had an internal fabric of robust and conformable P-SV reflections combined with mostly weak and chaotic P-P reflections. The upper and lower bounds of unit C coincided with prominent breaks in P-SV reflection character and with isolated, rather robust P-P reflection events.

The geological meaning of this vertical succession of Vp/Vs ratios and P-SV and P-P reflection-amplitude facies needs further study. The fact that this vertical succession was reasonably consistent near expulsion sites separated by 50 km (31 mi) is intriguing. The distance that this vertical succession extended laterally away from each expulsion site was affected by local faults along the profiles that were studied. We do not know how these relationships vary across the 50-km (31-mi) distance separating our two study sites.

An analysis of P-P and P-SV seismic facies suggests that the common practice of using only P-P seismic data to infer the internal fabric and layering of deep-water near-sea-floor strata can be misleading. If P-P data across some part of a gas-hydrate interval exhibit an opaque, chaotic, or weak reflection pattern, a natural tendency is to conclude that the interval is homogeneous or has no significant variation in P-wave impedance. If P-SV data are available to accompany the P-P data, the P-SV data commonly reveal a conformable and layered reflection pattern across the same interval, suggesting a much different rock fabric and depositional process must be considered. In these instances, the shear modulus apparently varies among the many thin layers that form the interval and causes conformable P-SV reflections to be generated by short-wavelength P-SV data, whereas the bulk modulus changes little across the interval and produces weak and/or chaotic long-wavelength P-P reflections.

**DEFINING DEPTH-EQUIVALENT P-P AND P-SV HORIZONS**

Most of the conclusions made in this article are based on the assumption that horizons shown on the P-P and P-SV images along each OBC line are depth-equivalent horizons. If for instance P-P and P-SV horizons b or P-P and P-SV horizons c interpreted along OBC Lines 284 and 549 are not depth equivalent, then the measured values of Vp, Vs, and Vp/Vs across unit C are incorrect, as would be any estimations of gas-hydrate concentration based on these velocity attributes. Of all the problems that have to be faced when applying multicomponent seismic data in a geologic interpretation, defining depth-equivalent P-P and P-SV horizons is the most challenging.

A rigorous option for defining depth-equivalent P-P and P-SV seismic reflections is to acquire a multicomponent vertical seismic profile (VSP) at an appropriate location on an OBC line. However, VSP data will rarely be acquired in most deep-water gas-hydrate studies. The depth registration technique that was used in this investigation was to search for equivalent stratigraphic features in companion P-P and P-SV images. Two examples of depth-equivalent stratigraphy are

1) the thinning wedge labeled C along OBC Line 288 (Figures 4, 5) and
2) the low-frequency events that downlap onto horizon c along OBC Line 549 (Figures 11, 12).

Most interpreters accept that these two features are depth-equivalent stratigraphy in P-P and P-SV image space. The greater difficulty is to select depth-equivalent P-P and P-SV horizons in uniformly layered intervals, such as occurred around unit B on Lines 284 and 549 (Figures 6, 7, 11, 12).

The depth equivalencies of some of the P-P and P-SV horizons that are shown here are interpretive judgment. New data-processing and data-interpretation methods are emerging whereby prestack common-receiver trace gathers of deep-water P-P and P-SV data are combined with iterative velocity-layer modeling to define depth-equivalent P-P and P-SV reflections (Backus et al., 2006). If this approach proves to be as successful as our early tests imply, its application to the OBC data discussed here may cause some depth-equivalent horizons to be adjusted at some locations.

CONCLUSIONS

This investigation demonstrated that 4-C OBC seismic data used for deep geological imaging can be invaluable for evaluating sea-floor fluid-sediment expulsion sites and their associated near-sea-floor geology in deep-water environments. The P-SV mode provided by 4-C OBC seismic technology is particularly important. A P-SV image of deep-water strata provides more information about near-sea-floor geology than does a P-P image because P-SV data have much shorter wavelengths in deep-water, near-sea-floor sediments, where the \( V_p/V_s \) velocity ratio is high and SV wavefields have the same frequency content as P wavefields. The increased spatial resolution provided by P-SV data identifies small-thrust faults, lithofacies patterns, and small-scale structural and stratigraphic features that cannot be seen with P-P data.

Interval values of \( V_p, V_s, \) and \( V_p/V_s \) velocity ratio determined from a unified interpretation of P-P and P-SV images can be valuable seismic attributes for modeling gas-hydrate distributions. These parameters were found to be consistent at two expulsion sites in the Green Canyon area of the Gulf of Mexico that were separated by a distance of 50 km (31 mi). Similar investigations need to be done at other deep-water sea-floor expulsion sites across the Gulf of Mexico to determine the velocity behavior across near-sea-floor strata where different mineralogies, effective pressures, and porosities from those at our two study sites are observed.

P-P and P-SV seismic facies architecture associated with the two fluid-expulsion features that were studied exhibited consistent vertical and lateral patterns. One finding of importance for gas-hydrate researchers is that P-SV seismic reflection facies commonly indicate that numerous conformable thin layers are present across intervals where reflection-free P-P seismic facies suggest that the intervals are homogeneous. Different internal architectures of deep-water gas-hydrate systems could be developed, depending on which facies morphology is adopted: a thick homogeneous unit (P-P reflection facies) or a unit of conformable thin layers (P-SV reflection facies).

ACKNOWLEDGMENTS

WesternGeco provided the 4-C OBC seismic data used in this research. Research funding was provided by the U.S. Department of Energy (DOE/NETL contract DE-FC26-05NT42667) and by the Minerals Management Service (contract MMS 0105CT39388).

REFERENCES CITED


Domenico, S. N., 1984, Rock lithology and porosity
Determination from shear and compressional wave velocity: Geophysics, v. 49, p. 1188–1195.


