Characterizing Marine Gas-Hydrate Reservoirs and Determining Mechanical Properties of Marine Gas-Hydrate Strata with 4-Component Ocean-Bottom-Cable Seismic Data

ANNUAL PROGRESS REPORT

Period of Performance
September 29, 2000, through September 19, 2001

by
B. A. Hardage, M. M. Backus, M. V. DeAngelo,
R. J. Graebner, P. Murray, and L. J. Wood
assisted by K. Rogers

January 2002

Prepared for U.S. Department of Energy
Under Contract No. DE-FC26-00NT41024

DOE[®]

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ABSTRACT

The technical approach taken in this gas-hydrate research is unique because it is based on applying large-scale, 3-D, multi-component seismic surveys to improve the understanding of marine gas-hydrate systems. Other gas-hydrate research uses only single-component seismic technology. In those rare instances when multi-component seismic data have been acquired for gas-hydrate research, the data acquisition has involved only a few receiver stations and a few source stations, sometimes only three or four of each. In contrast, the four-component, 3-D, ocean-bottom-cable (4C3D OBC) data used in this study were acquired at thousands of receiver stations spaced 50 m apart over an area of approximately 1,000 km² using wavefields generated at thousands of source stations spaced 75 m apart over this same survey area.

The reason for focusing research attention on marine multi-component seismic data is that 4C3D OBC will provide a converted-SV image of gas-hydrate systems in addition to an improved P-wave image. Because P and SV reflectivities differ at some stratal surfaces, P and SV data provide two independent, and different, images of subsurface geology. The existence of these two independent seismic images and the availability of facies-sensitive SV seismic attributes, which can be combined with conventional facies-sensitive, P-wave seismic attributes, means that marine gas-hydrate systems should be better evaluated using multi-component seismic data than using conventional single-component seismic data.

Conventional seismic attributes, such as instantaneous reflection amplitude and reflection coherency, have been extracted from the P and SV data volumes created from

the 4C3D OBC data used in this research. Comparisons of these attributes and comparisons of P and SV time slices and vertical slices show that SV data provide a more reliable image of stratigraphy and structure associated with gas-invaded strata than do P-wave data. This finding confirms that multi-component seismic data will be more valuable than conventional P-wave seismic data for exploiting gas-hydrate reservoirs that cause gas invasion into surrounding strata.

Published laboratory studies have shown that the ratio of P-wave velocity (V_p) and SV velocity (V_s) is an important parameter for identifying lithofacies. (In this report, the subscript S that accompanies a parameter can be replaced with the subscript SV to more accurately define the type of shear wave data used in this study.) Seismic estimates of V_p/V_s can be made when multi-component seismic data are acquired. Seismic-based V_p/V_s ratios are being analyzed across the research study area to determine what types of shallow lithofacies can be distinguished by this velocity parameter. These research findings will be summarized in the final project report.

Two unique SV seismic attributes may show promise in evaluating gas-hydrate systems. The first attribute is the use of SV receiver statics to detect variations in shallow, marine lithofacies. Receiver statics are not calculated when conventional, towed-cable, marine P-wave data are acquired. The second attribute involves the comparison of converted-SV stacking velocities calculated in positive-offset and negative-offset directions. If the source-receiver offset range spans a single, shallow lithofacies, the converted-SV stacking velocity across this shallow interval is the same for positive offsets as it is for negative offsets. If the offset range spans two distinct shallow lithofacies, then positive-offset velocities and negative-offset velocities differ across this

heterogeneous interval when converted-SV stacking velocities are determined. This difference in positive-offset and negative-offset velocities can indicate lithofacies distributions across gas-hydrate prospects.

A key focus of this research is to determine the value of multi-component seismic data for estimating the shear strength of shallow strata that overlie gas-hydrate reservoirs. Seismic-based estimates of shear moduli of shallow strata can be calculated once accurate values of the V_p/V_s velocity ratio are determined over targeted stratigraphic intervals. This phase of the research is still in progress and will not be summarized until the final project report is issued.

An important research study that has been completed and is documented in this annual report is a numerical modeling of the responses exhibited by seafloor hydrophones and vertical geophones. This modeling was done to explain differences in the P-wave responses of the hydrophone and vertical-geophone data acquired in the 4C3D OBC survey being used for research. The modeling demonstrated that ghost events and water-column reverberations are amplified in seafloor hydrophone data but are attenuated in vertical-geophone data, which are the effects seen in the real seismic data.

The bulk of this interim report focuses on descriptions of the database amassed for the study and on establishing the basic physics of the processes and techniques that are involved in applying 4C3D OBC seismic data to shallow gas-hydrate systems.

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EXPERIMENTAL RESULTS AND DISCUSSION

INTRODUCTION

This research investigation is based on two concepts: (1) marine gas-hydrate reservoir systems can be better characterized using multi-component seismic data than using single-component seismic data and (2) the elastic constants, shear moduli, and mechanical stability of strata that surround and overlie marine gas-hydrate accumulations can be determined in a relative sense when multi-component seismic data are recorded across gas-hydrate targets, and perhaps even in an absolute sense if there is adequate subsurface control to establish firm correlations between petrophysical properties and seismic attributes.

The advantage of using multi-component seismic data for evaluating gas-hydrate systems is that gas-hydrate reservoirs and their surrounding environment can be imaged with both compressional (P) waves and shear (S) waves, whereas this same geology can be described only in terms of P-wave images if single-component seismic data are all that are available. The integration of P and S seismic attributes provides more information about sequence relationships, lithofacies distributions, and pore-filler material than does the use of P-wave attributes alone. In addition, the P-wave velocity (V_p) and S-wave velocity (V_s) associated with a sequence can be used to calculate key elastic constants of the material within that sequence and thereby infer the shear modulus and mechanical strength of targeted strata. A more detailed and informative characterization of marine gas-hydrate systems will thus result if gas-hydrate targets are described in terms of

integrated P and S seismic data rather than just P-wave seismic data, as is conventionally done in marine environments.

The principal barrier to overcome in imaging marine gas-hydrate systems using both P and S wavefields is that S waves do not propagate in fluids and marine gas hydrates are concentrated in sediment that is overlain by rather deep water. This S-wave illumination problem is now solved by the development of four-component ocean-bottom-cable (4-C OBC) seismic technology that positions three-component geophones on the seafloor. These seafloor sensors record reflected SV shear modes created by P-to-SV mode conversions at reflecting interfaces because the transducers are in physical contact with an elastic layer of the Earth and are not suspended in the water column as towed-cable hydrophones are. The important SH shear mode is not acquired using 4-C OBC technology.

The 4-C OBC seismic data used in this study were recorded in 50- to 100-m water depths at a location where there was adequate shallow subsurface control to verify P and converted-SV data interpretations over the first 500 ms of seismic image time, where gas hydrates would be positioned if they were present. If the P and converted-SV data processing and interpretation techniques developed in this study are encouraging, they can then be transferred to the analysis of deep-water, multi-component OBC data that span known gas-hydrate reservoirs. The study is being done over an area of about 1000 km² in the Gulf of Mexico where 4C3D OBC seismic data were acquired by a consortium of oil companies who agreed to allow the shallow part of these new seismic data, together with shallow geologic and engineering control, to be used in this research. These donated

seismic data allow the latest oil and gas marine seismic technology to be applied to gas-hydrate exploitation.

STUDY AREA

The 4C3D OBC seismic data analyzed in this study cover the 455 mi² survey in the West Cameron Area of offshore Louisiana defined in Figure 1. The data were acquired by Seitel Data Inc. and WesternGeco as a “spec” survey that can be sold to operators who wish to use converted-SV data in conjunction with P-wave data to better exploit oil and gas prospects across the area.

The research focused on an 80-mi² portion of the survey. This study area was small enough to allow a comprehensive database of shallow subsurface control to be built, yet large enough to span a variety of shallow geologic conditions similar to what is expected to exist across gas-hydrate prospects. Digital copies of 4C3D OBC seismic field records were provided by Seitel Data and WesternGeco over this 80-mi² study area, not over the entire 455-mi² survey. But even this number of 4C3D seismic data (80-mi²) is an overwhelming database in terms of the massive disk storage required to maintain the data and the computational systems required to analyze the data.

Time-migrated P and converted-SV data volumes were analyzed over the total survey area (455 mi²). No P-wave data below one second (1 s) and no converted-SV data below two seconds (2 s) were utilized in these volume interpretations so that the technical value of the deep data spanning oil and gas targets would not be compromised and consequently jeopardize future sales of the data to oil and gas operators.

GEOLOGIC CHARACTER OF STUDY AREA

The shallow substrata of the study area (upper 500 ms of P-wave data) are characterized by lithologic, structural, and general architectural contrast. As will be shown in following sections, there is some difficulty in resolving the character of these shallow strata in the processed P-wave and SV-wave seismic data volumes constructed from the 4C3D OBC data donated to this study. It is therefore particularly important to build a reliable depositional model of shallow strata across the study area from nonseismic data. To develop the necessary understanding of the geologic character of the shallow substrate, we collected and analyzed data from industry and academe to map and understand the shallowest portions of the Gulf of Mexico shelf. These data provide an interpretive “baseline” by which the shallow imaging value of conventional 4-C OBC seismic data can be judged.

GEOLOGIC DATA

Data available to map and refine the stratigraphic and structural architecture of the shallowest strata across the study area include high-resolution sparker and air-gun seismic data, several lithologic and petrophysical descriptions of shallow boreholes, and one complete shallow core (Figure 2).

High-resolution seismic data collected by Texaco and made available from Rice University were acquired using a small 10-inch³ air-gun source. These data were filtered to restrict the frequency content to 150 and 1,000 Hz (almost 3 octaves) and produced P-wave penetration up to 700 ms, with a vertical resolution of 1 to 2 m. Other seismic lines were available using shallow-hazard surveys obtained from the Minerals Management Service for West Cameron Blocks 563, 572, and 595 inside the study area and Blocks

548 and 571 immediately outside the study area. These surveys included select seismic lines, bathymetric maps, mapped locations of hydrocarbon seeps and incised channels, and shallow structural maps. Data from these small-area maps were supplemented by Texaco high-resolution seismic data to interpolate between survey areas, the result being the composite map shown in Figure 2.

Borehole records from drill holes penetrating up to 377 ft below the mud line show lithology, shear strength of the sediment, and information on predicted rig-leg penetration depths. These borehole data were tied to seismic data using a time-to-depth conversion of 1550 m/s (Wellner and others, in press).

STRATIGRAPHY

Regional structural and seismic unit analysis of the northern Gulf of Mexico shelf by Berryhill and others (1987) used a database of several thousands of kilometers of seismic profiles (Figures 3 and 4). It is difficult to compare their dataset to the one used in this study area because so few of the Berryhill and others data have been published. The Berryhill group divided the shallow (500-ms P-wave time) section into four primary units: (1) pre-Wisconsinan, (2) early Wisconsinan, (3) middle Wisconsinan, and (4) late Wisconsinan to Holocene. These units were tied to our study area using the seismic line over the area published by Berryhill and others (1987), published studies by Coleman and Roberts (1990), and conversations with researchers at Rice University (personal communication, Julia Wellner, 2001; Wellner and others, in press).

Wellner and others (in press) used samples from two boreholes collected near our study area to age-date the stratigraphic study section involved in our research. Wellner's Stage 5e flooding surface is shown on the seismic line in Figure 5. This surface is

projected into our study area via Wellner's borehole cross section (Wellner and others, in press; their Figure 21) and found to occur between P-wave image times of approximately 180 and 190 ms. This flooding surface is documented in Borehole 349-B, located immediately to the southwest of the study area at a depth of 90 m and represents the initial, early-highstand, Stage 5e flooding event dated at 125,000 yr B.P. The only other key surface rigorously documented by Wellner was the Stage 2 lowstand sequence boundary (SB2), considered to be the late-Wisconsinan lowstand by Berryhill and others (1987). This surface is characterized by significant distributary and fluvial incision across the Gulf of Mexico shelf and represents the maximum lowstand of sea level during the last glacial maxima (Figure 4).

A series of incised valleys, up to 80 ms deep (62 m; 203 ft) in P-wave image time and over 4 km wide, characterize the SB2 lowstand surface (Figure 5). The study area falls within the axis of a major fluvial incision feeding a large, late-highstand, shelf-edge, deltaic complex centered immediately south of the study area; Delta C of Berryhill and others (1987) is shown in Figure 3. This fluvial incision is defined on high-resolution seismic data (Figure 5) and shows up to 80 ms of truncation into underlying Stages 3 and 4, subparallel, progradational, deltaic clinoforms of the late-highstand shelf delta.

Boreholes collected within the study area by Fugro-McClelland, Inc., and documented in Coleman and Roberts (1990) show the overlying valley fills to be composed of fine- to medium-grained sands incising into underlying gray clay and silty clay containing some shelly material (Figure 6). Seismic facies within these valleys are a complex-chaotic and prograding fill. Underlying clays are acoustically layered, continuous, wavy reflector packages in the high-resolution seismic profiles. The Stage 2 lowstand surface is dated

across the shelf as occurring between 22,000 and 17,000 years ago (Bard and others, 1990).

A series of flooding events have been interpreted within the study area and are associated with high-order, Stage 3, late-highstand flooding events. These events are identified in high-resolution seismic data by their continuous “railroad track” signatures across the study area and show up in core as carbonates interbedded with silts and clays (Coleman and Roberts, 1990). These carbonate depositional events show a sharp impedance contrast with overlying and underlying clays and sands (Figure 5) and allow detailed age-dating to be done across the stratigraphic section.

A deep, regional, downlap surface can be traced into the study area from the high-resolution seismic lines of Wellner and others (in press). This surface was tied outside the study area by these authors to its time-equivalent surface on the Texas-Louisiana shelf where it was dated by Thomas and Anderson (1994) as the Stage 5e flooding surface. This correlation makes the surface approximately 125,000 yr B.P. In West Cameron Block 586, this surface can be correlated to the Stage 5 condensed section of Coleman and Roberts (1990). However, the 5e maximum flooding surface (MFS) visible on seismic data in the northeast portion of the study area does not follow the Stage 5 condensed section of Coleman and Roberts (1990), which was determined using only platform borings. Results from Wellner and others (in press) indicate that much of the sand body mapped by Coleman and Roberts (1990), and identified by them as the Stage 6 delta (Fig. 11 of Wellner and others, in press), is actually the updip component of the Stage 5 delta. This makes the section much younger than previously claimed by Coleman and Roberts (1990). The borehole lithologies provided by the Coleman and Roberts

(1990) publication can nevertheless be correlated to seismic packages across the area. These boreholes thus provide lithologic understanding of the major seismic packages regardless of their questionable ages.

STRUCTURE

Shallow structure across the study area is dominated by the gentle, southward, homoclinal dip of the Gulf of Mexico shelf, punctuated by a few large, down-to-the-south growth faults that rise to the seafloor (Figure 2). No obvious salt diapirs pierce the mud line in the immediate study area; however, diapirs do outcrop on the seafloor immediately west of the study area (Wellner and others, in press), and several deep diapirs were mapped around the area by Berryhill and others (1987). Deep diapirs beneath the study area uplift overlying strata, resulting in stratal onlap and thinning over the diapir crests. A significant deep diapir, whose southeast edge is located in the northwest corner of the study area, causes slight uplift of strata in that area. This topographic high was likely present during Wisconsinan time and confined the north edge of a large, late-Wisconsinan, Stage 2, lowstand incision across the study area (Fig. 4). Similar influence of diapirs on fluvial and distributary-channel development was documented by Wellner and others (in press).

The single largest normal fault across the study area trends west to east across the middle of the project area and appears to parallel the north edge of the large west- to east-trending incised channel (Figure 2). It is possible that the fault, which penetrates down several 100 ms into the P and converted-SV seismic images, also exerted a control on the orientation of this incised feature. Borehole data from within the study area show three to

four orders of magnitude variation in shear strength of sediments between the seafloor and about 400 ft below the mud line. Muds are firm, gray clay containing some silt stringers. Sands are fine grained, gray, and unconsolidated. Sands are generally confined to incised distributary channels.

MULTI-COMPONENT SEISMIC DATA ACQUISITION

Multi-component seismic data are acquired in marine environments using standard, towed air-gun arrays as the energy source and special 4-component (4-C) sensor packages deployed on the seafloor. The seismic sensors have to be on the seafloor to record S waves because S waves do not propagate in fluids. Marine S-wave data cannot therefore be acquired by towed hydrophone arrays as is done when conventional marine P-wave seismic data are recording.

The 4-C sensor that was used to record the seismic data used in this study is shown in Figure 7. This sensor package consists of a gimbaled 3-C geophone that is rotated by gravity always to position its moving-coil elements in the vertical, inline horizontal, and crossline horizontal directions regardless of the angle of repose of the sensor package on the seafloor. The fourth data sensor was the hydrophone labeled in the figure.

The particle-velocity wavefield recorded by the vertical geophone and the pressure wavefield recorded by the hydrophone can be combined to create P-wave data that have optimal attenuation of the water-column reverberations that plague P-wave data acquired by towed hydrophone arrays. The particle-velocity data recorded by the inline

and crossline horizontal geophones are used to create the upgoing, reflected SV wavefield arriving at the seafloor.

The source-receiver technology utilized in marine multi-component seismic data acquisition is illustrated in Figure 8. The energy source is a towed air-gun array, identical to the source used in conventional marine seismic programs. Each seafloor receiver station has a single 4-C sensor package like the one shown in Figure 7. These seafloor sensors are stationary as data are recorded; they are not towed as are conventional hydrophone arrays. A second, anchored boat is connected to the seafloor cable to record the 4-C seismic data as a source boat traverses a grid of source lines.

At nonnormal angles of incidence, the downgoing P wavefield creates both reflected P and reflected SV wavefields. The reflected P wavefield, recorded by the seafloor hydrophone and vertical geophone, can create significant responses on horizontal geophones at large offset distances. The P-wave responses on the horizontal geophones are ignored during data processing, and a P-wave image is built from a weighted combination of hydrophone and vertical-geophone data. Most of the reflected SV wavefield is recorded by the inline and crossline horizontal geophones. That portion of the SV data recorded on the vertical geophone is ignored in data processing. No SH shear data are acquired in 4-C marine seismic data.

SEISMIC ACQUISITION TEMPLATES

Two basic data-acquisition templates are used across the seismic industry to record marine multi-component seismic data. Option 1, shown in Figure 9, is swath shooting. Option 2 (Figure 10) is orthogonal recording. In both techniques, it is common

at this early stage of 4-C OBC technology to have only two receiver cables on the seafloor. In option 1 (swath shooting), the shooting boat follows source lines that parallel the OBC receiver stations. This geometry provides a complete range of source-receiver offsets in only that narrow azimuth corridor that aligns with the long axis (inline direction) of the template. In option 2 (orthogonal shooting), the shooting boat follows source lines that are orthogonal to the seafloor cables. This geometry allows trace offset analyses to be done in all azimuth directions if the length of the source lines is about the same as, or greater than, the depth to the target of interest. This type of azimuth-based analysis can be important when anisotropic targets such as fractured reservoirs are interpreted.

A swath geometry was used to record the multi-component seismic data used in this study. The specific source-receiver geometry is depicted in Figure 11. Two OBC receiver lines (labeled A and B) were deployed at a 400-m spacing. Each OBC line consisted of a series of 150-m segments (Figure 12) that were connected to make the desired receiver line length of 20 km. Each of these cable segments provided three 4-C sensor stations (labeled 1, 2, 3 in Figure 12.) The 4-C sensor stations were spaced at intervals of 50 m along each line. The basic acquisition template consisted of 10 source lines (labeled 1 through 10 in Figure 11) centered on these two OBC receiver lines. These source lines were spaced 100 m apart, and the source-station spacing was 75 m on each source line. Each source line extended 6 km beyond the ends of the receiver lines. A third parallel OBC receiver line was deployed at a 400-m spacing from line B as data were being recorded by the two-line template created by receiver lines A and B. When data from all of the shotpoints shown in Figure 11 were recorded, the acquisition template was

then *rolled* to include this new OBC line, which will be called line C. The receiver portion of the next data-acquisition template then consisted of line B and the new OBC line C. Source lines 5 through 10 were reshot to create the same source-receiver geometry for OBC lines B and C that was used to record data with lines A and B (Figure 11). As data were recorded by lines B and C, receiver line A was retrieved and deployed at a 400-m parallel offset from line C to create the next data-acquisition template.

NUMERICAL MODELING OF SEAFLOOR SEISMIC SENSOR RESPONSES

The basic appearance of seismic data differs according to whether they are recorded by seafloor hydrophones or seafloor geophones. Typical data differences are exhibited by the 4-C OBC field record in Figure 13. The horizontal geophones at a 4-C receiver station are affected more by reflected SV modes than by P modes; the vertical geophones and the hydrophone are affected more by reflected P than by SV. To illustrate the differences in OBC hydrophone and geophone responses, hydrophone data will therefore be compared with only vertical-geophone data, not with horizontal-geophone data, so that data differences expressed by hydrophones and geophones concentrate on only the P-wave mode.

Examination of Figure 13 shows that the response of an OBC hydrophone contains a large number of robust-amplitude events down to an arrival time of 2 s. In contrast, vertical OBC geophones (shown next to the hydrophone data) appear to record fewer events and to produce a lower amplitude wavefield. Numerical modeling demonstrates why these two basic seismic sensors (a hydrophone and a vertical geophone) produce P-wave records that have such fundamental differences.

The Earth model used in the numerical analysis is shown in Figure 14. The top two panels show the raypaths associated with an upgoing reflection event that arrives at the seafloor and then reverberates in the water column. The one-way traveltime across the water column is Δt . The algebraic signs of the reflection coefficients for a pressure wavefield at the top and bottom of the water column are shown at the left; algebraic signs of the reflection coefficients associated with a particle-velocity wavefield are shown on the right. The reflection coefficients for these two wavefields (pressure and particle velocity) have opposite algebraic signs at each interface.

A wavefield recorded at the seafloor consists of two parts: an upgoing wavefield and a downgoing wavefield. The responses of a seafloor hydrophone and a vertical seafloor geophone were analyzed by our considering each of these component parts: first the upgoing wavefield observed at the seafloor and then the downgoing wavefield.

The sequence of upgoing events observed at the seafloor is labeled A, B, C, ... in the raypath diagrams of Figure 14. The reflectivity sequence at the bottom of the figure defines the upgoing wavefield that is created at the seafloor by either a pressure wavefield or a particle-velocity wavefield. The parameter R in this reflectivity sequence is the magnitude of the reflection coefficient at the seafloor; the magnitude of the reflection coefficient at the air-water interface is assumed to be 1.0. The principle demonstrated by this reflectivity series is that the upgoing wavefield recorded at the seafloor by a hydrophone (pressure wavefield) is identical to the upgoing wavefield recorded by a vertical geophone (particle-velocity wavefield).

Any distinctions in seafloor hydrophone and seafloor geophone data therefore have to be caused by differences in the downgoing wavefields that these sensors record.

The modeling is expanded to consider these downgoing wavefields in Figures 15 and 16. The sequence of upgoing events in both figures is the reflectivity series determined for upgoing pressure and particle-velocity wavefields in Figure 14. The downgoing wavefield seen by a vertical OBC geophone (Figure 15) is this upgoing particle-velocity wavefield delayed by $2\Delta t$ (the two-way time across the water column), and the polarities of the downgoing events are the same as the polarities of the upgoing events because the reflection coefficient at the top of the water column for an upgoing particle-velocity wavefield is positive (Figure 14). However, the downgoing wavefield seen by an OBC hydrophone is different (Figure 16). A hydrophone sees a downgoing wavefield that is also a time-delayed version of the upgoing pressure wavefield (a time delay of $2\Delta t$), but the polarity is opposite that seen by a geophone because the reflection coefficient for an upgoing pressure wavefield is negative at the top of the water column (Figure 14).

The total wavefield measured by an OBC hydrophone and by a vertical OBC geophone is the sum of the upgoing and downgoing wavefields that each sensor “sees” when on the seafloor. These sums are shown as the bottom displays in Figures 15 and 16. The resultant wavefields differ because the downgoing pressure wavefield enforces water-column reverberations, whereas the downgoing particle-velocity wavefield attenuates water-column reverberations.

Several numerical calculations are included in this section to demonstrate how this wave physics causes major differences in the P-wave responses measured by seafloor hydrophones and geophones. The first series of models assumes that the upgoing reflection (event A in Figure 14) is a simple, compact event. This simple wavelet is labeled *source* and shown as the top trace in Figures 17, 18, and 19. In these three

models, the seafloor reflectivity R increases from 0.2 to 0.4 to 0.7, showing the effect of a wide range of reverberation amplitudes.

The downgoing wavefield D in each figure is the downgoing wavefield seen by a vertical OBC geophone (not a hydrophone!). The total geophone response is the sum $U + D$, where U is the upgoing wavefield, but the total hydrophone response is the difference, $U - D$. The ghost event and all reverberations are amplified by a factor of $1 + R$ in the hydrophone response but are attenuated by a factor of $1 - R$ in the vertical-geophone response. These ghost and reverberation events are contaminations that make it more difficult to recognize and extract reflection signals. Even though data recorded with a seafloor vertical geophone may look inferior to hydrophone data (Figure 13), geophone data have less noise contamination.

A second series of models are included in Figures 20, 21, and 22 to illustrate the effect of a more realistic version of the upgoing reflection wavelet. A towed air-gun array cannot produce the simple source wavelet used in Figures 17, 18, and 19. Instead the source wavelet will contain water-column reverberations because it is positioned near the top of the water column as it is towed. For simplicity, the seafloor reflectivity and the traveltime across the water column at the source station will be assumed to be the same as they are at the OBC receiver station. The upgoing reflection A at the seafloor (defined in Figure 14) will then be the reverberating event labeled *source* in Figures 20, 21, and 22. The seafloor reflectivity R is varied from 0.3 to 0.5 to 0.7 in this sequence of figures. The ghost event and reverberations in the hydrophone response are now amplified by a factor of $1 + 2R$, but they are attenuated by a factor of $1 - 2R$ in the vertical-geophone response. These factors are twice the magnitudes of those associated with a nonreverberating

source wavelet (Figures 17, 18, and 19). A value $R=0.3$ (Figure 20) is typical across much of the seafloor of the Gulf of Mexico. The principle established by this modeling is that ghosts and reverberations are significantly attenuated in an OBC vertical-geophone response for the type of seafloor across our study area, but that these noise events will compose most OBC hydrophone data (Figure 13).

SEISMIC DATA PROCESSING ISSUES

The P-wave and converted-SV wavefields acquired in marine OBC programs are processed by two distinct types of imaging software that differ in fundamental ways. Some of these differences in P and SV data processing, as well as their effects on shallow gas-hydrate studies, are described in the following sections.

COMMON-MIDPOINT IMAGING

The P-wave part of OBC data is processed by common-midpoint (CMP) algorithms that have been used for decades in the seismic industry. The basic requirement for CMP imaging is that the velocity of the reflected, upgoing wavefield is the same as the velocity of the downgoing, illuminating wavefield. In P-wave imaging, downgoing and upgoing wavefields both travel at P velocity. Time-proven CMP software can thus be used to process OBC data to create P-wave images. The raypaths involved in CMP imaging are shown in Figure 23. Note that CMP reflection points from different stratal depths stack vertically above each other at CMP coordinate X_m in a flat-layered Earth. The reflection point trend labeled CCP is discussed in the next section.

COMMON-CONVERSION-POINT IMAGING

The reflected SV wavefield contained in 4-C OBC data is a series of upgoing SV reflection events that are created by P-to-SV mode conversions when a downgoing P wave arrives at reflecting stratal surfaces at nonnormal angles of incidence. In 4-C SV imaging, the downgoing wavefield is thus a P wavefield, and the upgoing wavefield is a SV wavefield. Because the downgoing wavefield has a faster velocity (P-wave) than does the upgoing wavefield (SV), the reflecting point does not occur at midpoint coordinate X_m but at a coordinate that is closer to the receiver station than to the source station. This reflection coordinate is called the *common conversion point* (CCP). The raypaths involved in CCP imaging are depicted in Figure 24. Note that CCP image points from different stratal depths do not stack vertically above each other as do CMP points but move closer to the receiver station as the depth to the reflecting point decreases.

CONTRAST BETWEEN CMP AND CCP VELOCITY ANALYSES

The stacking and migration velocities needed for CMP and CCP imaging have to be determined by different analytic procedures. These differences can be explained by considering the simple Earth model in Figure 25. In this model, there is a change in rock facies along the imaging raypaths. The P and SV velocities in Facies 1 are assumed to be significantly different from the P and SV velocities in Facies 2.

The offset between source and receiver has to be defined now in terms of the direction of the offset from the source. Offsets measured to the right of the source will be defined as positive; offsets to the left of the source will be negative. In CMP imaging (Figure 25), the same raypath velocity occurs for both positive and negative offsets. The

lengths of the travelpaths in Facies 1 and Facies 2 are the same when B is the source and A is the receiver (negative offsets) as they are when A is the source and B is the receiver (positive offsets). The same CMP stacking and migration velocities are therefore calculated in positive and negative offset directions in CMP data processing.

However, a different conclusion is reached in CCP velocity analysis. The raypaths involved in CCP imaging are shown in Figure 26. If A is the source station and B is the receiver station (positive offsets), the velocity of the downgoing P wave is controlled by Facies 1, the upgoing SV velocity is controlled by Facies 2, and the reflection point is at coordinate CCP_A . For negative offsets (B is the source and A is the receiver), most of the P-wave velocity behavior is controlled by Facies 2, all of the upgoing SV travelpath is now in Facies 1, and the reflection point is coordinate CCP_B . Assuming that velocities in Facies 1 differ from the velocities in Facies 2, CCP stacking/migration velocities calculated for positive and negative offsets are not the same. CCP velocity behavior, where different velocities can be observed in opposite offset directions, is thus fundamentally different from CMP velocity behavior.

Increases (decreases) in the difference between CCP stacking (and migration) velocities in positive- and negative-offset directions indicate increases (decreases) in lithofacies contrast across the space spanned by the offsets. This fact can be used to advantage to evaluate lithofacies assemblages associated with gas-hydrate systems. To date, there are no published examples or evidence that interpreters have used differences in positive-offset and negative-offset CCP velocities to map lithofacies distributions spanned by 4-C OBC surveys. One objective of our research is to determine whether differences in CCP velocities in positive-offset and negative-offset directions can help

identify shallow lithofacies contrasts that are at subbottom depths comparable to the depths of typical gas-hydrate reservoirs, and then to demonstrate the applications and limitations of this unique velocity attribute. This research of converted-SV velocities is not complete and will be summarized in the final project report.

It should be emphasized that this new velocity parameter, the difference in positive-offset and negative-offset velocities, is available only with marine 4-C seismic data. This new attribute is only one of several provided by 4-C OBC data that should allow more detailed interpretations of marine gas-hydrate systems than can be done using single-component marine seismic data.

CONTRAST BETWEEN CMP AND CCP STACKING

For a seismic image to be created, the image space between a seismic source and a seismic receiver is segregated into small subareas called stacking bins. During data processing, data traces are positioned across this image space by calculating the bin locations where reflection points occur. In CMP imaging in a flat-layer Earth, reflection points occur at the midpoint between source and receiver stations regardless of the depth of the reflection (Figure 23). A CMP trace is thus shifted in time (source-static correction, receiver-static correction, other static corrections, and normal-moveout correction), and then the entire data trace is positioned vertically at the common midpoint for the source-receiver pair that produced that trace. This type of CMP imaging is depicted in Figure 27 by the vertical data trace in stacking-bin column A, which is at the common midpoint for the indicated source and receiver. This type of stacking, or image building, has been practiced for decades in the seismic industry. Robust CMP stacking algorithms are

widespread, and all seismic data-processing shops have extensive experience in CMP processing.

The curved wiggle trace in Figure 27 shows where this same data trace would have to be positioned across the image space if the data were acquired and processed according to the CCP technology. In this case, the downgoing raypath is a P wave, and the upgoing raypath is SV. The static and normal-movement time adjustments made to a CCP trace now affect several columns of stacking bins. Segments from several CCP traces have to be patched together to create a vertically stacked trace in each column of stacking bins. For example, three adjacent CCP-processed data traces are shown in Figure 28. That part of trace A between points 1 and 2 has to be combined with data window 2 to 3 of trace B and with data window 3 to 4 of trace C to create a vertical wiggle trace extending from point 1 to point 4 in the shaded column of stacking bins. CCP stacking is thus fundamentally different from CMP stacking. Much CCP stacking and imaging software is still in development across the seismic industry.

The parameter that controls the curvature of a CCP trace in CCP-image space is the V_p/V_s velocity ratio of the propagation medium. A model that illustrates this fact for small incidence angles is presented in Figure 29. This simple, straight-raypath model shows that the CCP coordinate is defined by the offsets X_p and X_{sv} from the source and receiver stations and that these offsets are proportional to the V_p/V_{sv} velocity ratio in the raypath medium. The top equation listed in this model is Snell's law of reflection; the middle equation is a statement of the raypath geometry shown in the model; and the bottom equation is valid when the incident and reflected angles are small enough that $\sin(\theta)$ is the same as $\tan(\theta)$. For larger angles of incidence and reflection in a layered Earth,

the relationship between the CCP reflection coordinates and V_p/V_s is more complicated than the simple equation in Figure 29, but the velocity ratio V_p/V_{sv} in the Earth layers still controls where the image point is located in CCP image space.

The construction of CCP images concentrates on a determination of accurate values of V_p/V_s over the total image space. In practice, seismic data processors take shortcuts. One shortcut is to do *asymptotic binning*. In asymptotic binning, the CCP coordinate for the deep part of an image trace, which is almost vertical, is calculated, and then the entire CCP trace is assumed to be vertically aligned at that coordinate. This approximation would cause all of the curved trace in Figure 27 to be positioned in stacking bin 7, the asymptotic bin for that trace. The result is that the deep part of the CCP image will be correct, but the upper part incorrect. The amount of error in the shallowest part of an image, where gas hydrates would be, can be enormous when asymptotic binning is used.

Most seismic data-processing shops have abandoned asymptotic binning and replaced that technique with procedures that calculate time-dependent and space-dependent estimates of V_p/V_s over the total CCP image space. In so doing, however, they still take some shortcuts. The major shortcut is that little attention is given to determining accurate values of V_p/V_s in the shallowest seismic data windows if there is no exploration interest in shallow strata. Data processing is focused on determining accurate V_p/V_s values only at those depths where accurate images are needed for oil and gas applications. This philosophy is a practical one in the low-margin business of seismic data processing. There is no financial reward for work done to make the shallowest parts of a CCP image correct if no one is interested in shallow geology.

The contractor-provided SV data volume interpreted in this gas-hydrate research was created by our calculating V_p/V_s velocity ratios over the total time-space coordinate range spanned by the 4C3D OBC survey. This CCP data processing represents state-of-the-art technology by a leading seismic contractor. However, the data-processing team did not devote much time or effort toward improving the accuracy of V_p/V_s evaluations for the geology above the shallowest stratum of interest to oil and gas operators. This limited attention to the shallow part of the SV image space was not a technical deficiency by the contractor; it was a shortcut taken as a matter of good business practice. If an operator wants to pay for improved SV image quality over shallow strata, all contractors would not only adjust their acquisition programs to achieve better SV stacking fold across these strata, but they would also concentrate on calculating accurate V_p/V_s values in shallow data windows.

The result of current industrywide CCP data-processing philosophy is that converted-SV images available from 4C3D OBC surveys that have been acquired for oil and gas objectives are incorrect, to varying degrees, for shallow strata. The amount of image error over the shallow stratigraphy controls what applications can be developed from commercial oil and gas 4C3D OBC surveys for gas-hydrate interpretations.

Our research objective is to determine what gas-hydrate applications are valid, and what pitfalls exist, for the shallow parts of the 4C3D OBC data provided for this study. Some research findings are documented in this report; other findings will be added for the final report.

USING STATIC CORRECTIONS TO MAP SEDIMENTARY FACIES ASSOCIATED WITH GAS HYDRATES

During seismic data processing, seismic field data are time-shifted to represent data that are recorded with source and receiver stations distributed across a hypothetical, fixed, horizontal datum plane that forms the top boundary of a constant-velocity, near-surface layer. These time shifts are called *static corrections*. The principal objective of static corrections is to remove variations in reflection arrival times that are caused by elevation differences in sources and receivers and by lateral and vertical changes in the thickness and internal velocity of the weathering layer that underlies source and receiver stations.

Geophysicists use the term *weathering layer* to refer to the heterogeneous, low-velocity layer that begins at the Earth's surface and extends down to variable depths. This geophysical layer is thicker than the geologic weathering layer associated with in situ decomposition of rocks.

Elevation statics account for differences in the topographic elevations of source and receiver stations. *Source statics* and *receiver statics* account for lateral variations in seismic propagation velocity in the near-surface layer immediately below source and receiver stations. *Trim statics* (or *residual statics*) do final, small-scale time adjustments of data traces before stacking the data. The emphasis here is to determine whether source and receiver statics can be used to infer lateral variations in shallow sedimentary facies that lie above, and perhaps include, gas-hydrate deposits.

SOURCE STATICS

Source statics are rarely applied to marine seismic data, including OBC data, because all source stations of a marine survey are positioned on a fixed datum plane (a fixed towed depth for the air gun) during acquisition, and all source stations are located in a constant-velocity medium (seawater). A source-related time shift (similar to an elevation static) may be applied to marine data if the depth of the air-gun array varies owing to wave action or towing procedures. Source statics have to be considered only when the Earth layer in contact with the source exhibits velocity variations from one source station to another source station. A marine seismic source will encounter changes in water velocity only in instances where a survey spans areas of variable salinity (for example, a delta area where there is large fresh-water outflow mixing with seawater) or waters of variable temperature (for example, when a survey spans a large period of calendar time). No source statics were applied to the 4-C OBC data used in this study.

RECEIVER STATICS

Receiver statics are rarely needed for marine seismic data that are recorded using towed hydrophone cables because, as described in the preceding section, all receiver stations are maintained on a fixed horizontal plane during data acquisition and all receivers record data inside a medium (seawater) in which there is no lateral variation in seismic propagation velocity. Receiver statics are needed for conventional, towed-cable marine data only when a survey involves waters of differing salinity or temperature. However, receiver statics have to be calculated when seismic sensors are placed on the seafloor. A seafloor model that illustrates factors that affect ocean-bottom receiver statics

is shown in Figure 30. In this model, ocean-bottom sensors (OBS) can be at different elevations, and the P-wave and S-wave velocities in the heterogeneous, low-velocity layer immediately below the seafloor (and the thickness of that layer) can change significantly between receiver stations. All of these conditions adversely influence reflection arrival times at seafloor receiver stations and require that receiver statics be calculated and then applied to OBC field traces.

An example of the effects of ocean-bottom receiver statics on stacked, mode-converted, OBC data is shown in Figures 31 and 32. The image in Figure 31 was made without calculating or applying receiver statics. Receiver statics were used to make the revised image in Figure 32. Even though there is evidence in this latter image that at least one more iteration of receiver statics calculations should be done, the image quality is improved. Specific improvements occur at all receiver stations between 220 and 240, between 280 and 310, and at numerous other receiver stations. The result is that the lateral continuity and structural configuration of all reflections are better, as can be observed for the robust event between 0.5 and 0.6 s. Comparison of such “with statics” and “without statics” images demonstrates that it is essential to calculate and apply receiver statics to OBC data.

A map of contractor-generated receiver statics across the project study area is presented in Figure 33. One research objective is to use available subsurface geological control to create maps showing areal distributions of seafloor sedimentary facies and depositional regimes. One such map example is shown in Figure 2. We will then compare these geological maps with maps of receiver statics to determine whether areal patterns and trends in receiver statics infer geological processes that have occurred in shallow

seafloor strata. For example, the area of large positive (red color) receiver statics in the southwest quadrant of the study area lies atop the large incised channel trend shown in Figure 2, showing that receiver statics distinguish between sandy facies (channel fill) and shale facies. This use of receiver statics is unique for marine studies and may lead to a new technique for evaluating gas-hydrate reservoirs and seafloor stability. These receiver-static analyses will be included in the final technical report.

GEOPHYSICAL DATA QUALITY

The 3-D, ocean-bottom, multi-component (4-C) seismic data analyzed in this study were acquired in shallow water (< 200 to 275 ft), offshore Louisiana, West Cameron Area, over an area of approximately 455 mi² (Figure 1). The primary objectives of this seismic survey were to improve P-wave reflection quality at deep oil/gas reservoirs by combining hydrophone and vertical-geophone data, allow structural interpretations beneath gas clouds by using converted-SV data, and provide new seismic attributes such as V_p/V_s velocity ratios for stratigraphic, petrophysical, and reservoir studies of deep exploration targets. WesternGeco acquired the data from April through May 2000 and subsequently processed the data into two separate volumes, P and converted-SV. The study area of approximately 80 mi², where applications of these data for gas-hydrate applications was done, covered the southwest part of this 4C3D OBC seismic survey. These 4C3D OBC seismic data are a new “spec” survey that is still being marketed to interested oil and gas operators. The oil and gas targets of interest to these operators are deeper than 5,000 ft. The owners of the seismic data, Seitel Data Inc. and WesternGeco, graciously allowed the shallow parts of the P and SV data above these

deep oil and gas targets to be used to develop this new gas-hydrates seismic technology. The P-wave data provided for this gas-hydrate research extend to only 1 s, and the converted SV data extend to only 2 s.

Preliminary analysis of the P and SV data volumes reveals that the frequency content of the P-wave data is reasonably broad band in nature, from 10 to 70 Hz (almost 3 octaves), but that the signal spectrum is only 10 to 30 Hz (1.5 octaves) for the converted-SV data. Shallow data are dominated by processing artifacts (trace muting and incorrect V_p/V_s applications), making interpretation at levels above 0.5 s of the P volume and above 1 s in the converted-SV volume difficult. So many shallow data were muted during data processing that the shallow image has to be interpreted as a series of 2-D lines, making any type of areal attribute analysis across shallow intervals a risky proposition. Many shallow imaging problems are caused by the design of the acquisition survey and by subsequent data processing, particularly V_p/V_s calculations, because deeper hydrocarbon reservoirs, not shallow strata, were targeted by this Seitel and WesternGeco seismic program. Basically the converted-SV image is reliable for deep targets, but it becomes less accurate as reflector depth decreases. Surveys designed to optimize the imaging of shallower targets would go a long way toward improving the quality of shallow seismic data used in future gas-hydrate studies.

Gas clouds (or gas chimneys) pervade much of the shallow part of the P-wave data volume (Figure 34), obscuring structural and stratigraphic features beneath the gas charged intervals. As expected, the converted-SV data (Figure 35) image through these gas-invaded zones and allow interpretation of previously obscured structural and stratigraphic features. The improved image of geologic conditions provided by SV data in

gas-charged strata could be critical in some gas-hydrate prospects. Preliminary analysis has determined that it would be prudent to interpret (1) P-wave data, (2) the converted-SV data volume to locate structural components (faults, topographical highs, etc.) hidden by gas effects in the P-wave data, and (3) the P-wave volume again to fine-tune the structural interpretation.

PRELIMINARY INTERPRETATIONS OF P AND SV DATA

Time-slices generated from the P-wave amplitude data (Figure 36) display bright spots attributed to gas-charged intervals. P-wave images immediately beneath these features are faint, distorted, and difficult to interpret because of severe attenuation of P-wave energy by the gas-invaded zone (Figure 34). Converted-SV time-slices (Figure 37) extracted from approximately the same chronostratigraphic interval do not show these intrusive P-wave bright spots because S waves propagate through the solid matrix of a rock and are not influenced (except in a minor way) by variations in pore fluid (Figure 35). For example, a prominent gas-cloud depression in the south of the study area (Figure 36) shows characteristic P-wave amplitude banding around the depression, which implies steeply dipping reflectors indicative of synclines or anticlines. In contrast, the same area in the converted-SV data (Figure 37) is imaged as a single reflection band, diagnostic of a gently sloping or flat reflector, which most likely represents the true subsurface topography of the gas-invaded strata. Coherency time-slices were also generated for both P-wave (Figure 38) and converted-SV (Figure 39) data. These images identify possible structural components not readily apparent from amplitude-attribute analysis and confirm that SV images associated with gas-charged strata are superior to P images. This principle

implies that multi-component seismic data will be more valuable for evaluating gas-hydrate systems than will single-component data whenever free gas has invaded strata around gas-hydrate deposits. Comparison of these coherency time slices shows that the P-wave data available for this study provide a better-quality image at shallow depths than do the converted-SV data. The north-south striations in the converted-SV coherency display (Figure 39) are caused by the acquisition geometry, which, as has been emphasized, was designed for deep targets, not for imaging shallow strata in which this time slice was made.

The dominant east-west fault across the central part of the greater seismic survey (Figures 38 and 39) coincides with an obvious anomaly in the receiver statics map, this being the blue-shaded trend at the same map coordinates in Figure 33. This fact is another indication that receiver statics have value for mapping contrasts in shallow structure and lithofacies where gas-hydrate deposits occur.

Evaluation of both P and converted-SV seismic data volumes via 3-D visualization software helped identify areas appropriate for P- to SV-event correlations. Identifiable structural components, such as antithetic faulting or intersecting faults, are good candidates for correlating P and converted-SV reflection events. Such structural features should be consistent in both the P-wave and converted-SV data volumes. Seismic events that correspond to these features can then be mapped throughout both P and converted-SV seismic volumes and be assumed to represent the same surface. One surface was mapped in the P-wave data to depict the subsurface topography (Figure 40) of one targeted interval. The same seismic event was then identified and mapped in the converted-SV data (Figure 41). Although the two mapped time-structures are similar,

they have a few important differences. First, the structural details (i.e., fault polygons) are more pronounced in the P-wave data, reinforcing the concept of using the P-wave data for fine-tuning the structural interpretation developed with converted-SV data. Second, the P-wave data show numerous synclines (velocity sags) that correspond to the gas clouds that pervade the area, but the corresponding converted-SV data show higher topography at these points and most likely represent the true structural setting. Finally, the P-wave seismic coverage is less (355 mi^2 vs. 455 mi^2) than the converted-SV seismic coverage because the P-wave data were muted at the edges of the survey to leave only full-fold data. Less muting was done to the SV data, and the converted-SV data volume was allowed to have low-fold edges.

Additional research is ongoing with these P and SV data to determine whether P-wave data image sequences and facies differently than do converted SV data and to determine which combinations of P and SV attributes best define areal distributions of different lithofacies. Developing new and efficient methodologies for evaluating P-wave and SV data acquired in shallow water will aid in the seamless transition of 4C OBC data to deep-water environments where large marine gas-hydrate deposits exist.

USING P AND SV SEISMIC DATA TO INFER LITHOFACIES

P-wave velocity (V_p) and S-wave velocity (V_s) change as P and SV waves travel through different rock types. In general, V_p and V_s are higher in carbonates than in siliciclastics and tend to be higher in sandstones than in shales. However, V_p values alone or V_s velocities used in isolation, may not be reliable indicators of rock type unless rock porosity is known because both V_p and V_s decrease as porosity increases. This velocity-

porosity relationship means that a porous sandstone may have V_p and V_s properties equivalent to those of a compacted shale. Neither wave velocity alone (V_p nor V_s) can distinguish such a conflicting lithofacies situation.

Previous researchers (Pickett, 1963; Domenico, 1984) have shown that the velocity ratio V_p/V_s can be used to define lithofacies regardless of variations in rock porosity. In essence, porosity dependence appears in both the numerator and denominator of this velocity ratio and divides out (approximately), making the ratio relatively insensitive to porosity while maintaining its sensitivity to lithology. Domenico's (1984) laboratory measurements of V_p/V_s ratios in different rock types are given in Table 1. These data provide one of the fundamental theses for this research: that in a siliciclastic system the V_p/V_s ratio increases as grain size decreases. (Compare sandstone and shale values in Table 1.) One research objective is to test this hypothesis for poorly consolidated siliciclastic sediment near the seafloor and to determine whether V_p/V_s ratio data can be used to distinguish sand-dominated sediment, mud-dominated sediment, and gas-charged sediment. These velocity analyses are not completed. Research findings will be included in the final report.

Table 1: Ranges of V_p/V_s in typical rocks (after Domenico, 1984).

Rock Type	V_p/V_s
Sandstone	1.59 – 1.76
Shale	1.70 – 3.00
Dolomite	1.78 – 1.84
Limestone	1.84 – 1.99

USING V_p AND V_s TO ESTIMATE MECHANICAL STABILITY OF SEDIMENT

Once V_p and V_s velocities are determined from seismic data, key elastic parameters within targeted sequences can be calculated using the following relationships:

$$K = \rho \left(V_p^2 - \frac{4}{3} V_s^2 \right), \quad (1)$$

$$\mu = \rho V_s^2, \quad (2)$$

$$E = 9K\mu / (3K + \mu), \text{ and} \quad (3)$$

$$\lambda = K - 2\mu/3, \quad (4)$$

where K = bulk modulus, μ = shear modulus, E = Young's modulus, λ = Lamé's constant, and ρ is the bulk density of the rock.

The mechanical stability of strata that overlie gas-hydrate accumulations is a critical concern to marine scientists. Areas of high shear moduli provide more secure sites for implementing gas-hydrate production tests because there will be less likelihood of seafloor movement that will result in sediment slumping and venting of methane into the atmosphere. The ability to predict areas of lower shear modulus will allow oil/gas operators and government agencies to define locations where sediment movement is most likely to be initiated.

A research objective of this study is to utilize V_p/V_s ratio behavior to predict elastic constants of strata that overlie gas-hydrate deposits so that improved field-operations safety can be applied to gas-hydrate exploitation. Equations 1 and 2 can be combined as

$$\frac{V_p}{V_s} = \sqrt{\frac{K}{\mu} + \frac{4}{3}}. \quad (5)$$

This relationship is important because it explains why the ratio V_p/V_s reduces to minimum values in gas-saturated rock. Gas is highly compressible compared with liquid, causing a gas-saturated rock to be more compressible than a water-saturated rock. Bulk modulus K is the inverse of compressibility, thus the value of K for a porous rock assumes minimum values when the pores are gas saturated. In contrast, the shear modulus μ is relatively unaffected by changes in pore fluid. This reduction in bulk modulus, coupled with little or no change in shear modulus, causes the velocity ratio V_p/V_s to have significant, and measurable, minimum values in gas-saturated zones. This behavior will be a key application of 4-C OBC seismic data for gas-hydrate exploitation.

CONCLUSIONS

This report is an Annual Report, prepared in January 2002, describing gas-hydrate research completed during the first 15 months of a 24-month study. Some of the research is completed and is documented in this interim report. Examples of completed work tasks are descriptions of the basic physics involved in 4C3D OBC data acquisition and processing, creation of a geologic database across the study area, documentation of the principle that converted-SV data provide more accurate geologic information across gas-invaded zones than do P-wave data, and numerical modeling of the P-wave responses of seafloor hydrophones and vertical geophones.

Most of the planned research is still in progress. This report documents the status of ongoing tasks that are evaluating the use of multi-component seismic data for

estimating shear strength of shallow strata and to improve the interpretation of stratigraphy, structure, and lithofacies distributions at depths commensurate with gas-hydrate reservoirs. Several of these investigations are encouraging and tentatively appear to support the premise that multi-component seismic data should be used to evaluate marine gas-hydrate deposits whenever possible. These findings will be documented in the final project report, which will be released in September 2002.

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Figure 1. Location of 4C3D OBC survey (shade area WCI). The final size and shape of the surveyed area were altered from what are shown in this early data-acquisition plan, as will be seen in subsequent figures.

Figure 2. Map of the study area showing seafloor bathymetry, large shallow faults, and locations of incised features within the study area. Texaco high-resolution seismic lines 6 through 10 and borehole locations are also shown.

Figure 3. Map showing early-Wisconsinan deltaic depocenters and fluvial systems, as well as significant salt diapirs that affect shallow stratigraphy. Distinct delta systems are labeled A through E. Modified from Berryhill (1987).

Figure 4. Map showing late-Wisconsinan deltaic depocenters and fluvial systems, as well as significant salt diapirs. By late-Wisconsinan time, the primary feeder system to the Mississippi paleo-delta was located well to the east of the study area. Modified from Berryhill (1987).

Figure 5. Portion of high-resolution seismic line (the heavy line interval of Line 10 shown in Figure 2) illustrating stratigraphic relationships between sand-filled, lowstand incisions and underlying clay-rich, silty, late-highstand, deltaic deposits.

Figure 6. Borehole cross section (location shown in Figure 2) showing major lithologic transitions within the shallow substrate of the study area. Several significant Stage 4 flooding events and the major Stage 2 lowstand sequence boundary are identified in the boreholes and on high-resolution seismic lines across the area.

Figure 7. Four-component ocean-bottom sensor (4-C OBS) package.

QA6139(b)c

Figure 8. Seismic data-acquisition concept. P denotes a compressional raypath, SV indicates a converted-SV raypath, and BSR is a bottom simulating reflector.

Figure 9. Swath geometry used to record 4C3D OBC seismic data.

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Figure 10. Orthogonal geometry used to record 4C3D OBC seismic data.

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Figure 11. Swath geometry used to record the 4C3D OBC seismic data used in this research.

Figure 12. Cable segment used to build an OBC receiver line having a length of 20 km or more.

Figure 13. 4-C OBC field record. A time-dependent gain has been applied to increase the amplitudes at late arrival times.

Figure 14. Earth model used to model the P-wave responses of seafloor. R is the reflectivity coefficient at the seafloor.

QAd309c

Figure 15. Reflectivity series seen by a vertical geophone positioned on the seafloor. The upgoing events (top trace) are defined in Figure 14. The downgoing events (center) are a time-delayed copy of the upgoing events. The resultant response (bottom) is the sum of the upgoing and downgoing reflectivity series.

QAd310c

Figure 16. Reflectivity series seen by a seafloor hydrophone. The upgoing events (top trace) are defined in Figure 14. The downgoing events (center) are an inverted and time-delayed copy of the upgoing events. The resultant response (bottom) is the sum of the upgoing and downgoing reflectivity series.

Figure 17. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.2. The source wavelet has no reverberations.

Figure 18. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.4. The source wavelet has no reverberations.

Figure 19. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.7. The source wavelet has no reverberations.

Figure 20. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.3. The source wavelet now has a reverberation period of $2t$ and a reverberation amplitude that is controlled by the seafloor reflectivity R .

QAd304c

Figure 21. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.5. The source wavelet now has a reverberation period of $2t$ and a reverberation amplitude that is controlled by the seafloor reflectivity R .

Figure 22. Calculated responses for seafloor hydrophones and vertical geophones when the seafloor reflectivity R is 0.7. The source wavelet now has a reverberation period of $2t$ and a reverberation amplitude that is controlled by the seafloor reflectivity R .

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Figure 23. Comparison between CMP imaging raypaths and CCP image points.

Figure 24. Comparison between CCP imaging raypaths and CMP image points.

Figure 25. Traveltimes for positive offsets are the same as travel times for negative offsets in common-midpoint-point imaging.

Figure 26. Traveltime for positive offsets are not the same as traveltimes for negative offsets in common-conversion-point imaging.

Figure 27. Comparison of CMP trace (vertical) and CCP trace (curved) positions in seismic image space.

Figure 28. Construction of a vertical binned trace (shaded column) in seismic image space from a suite of CCP traces.

Figure 29. Simple, straight-raypath model showing that the velocity ratio V_p/V_{sv} controls the position of a CCP image point.

Figure 30. Receiver static correction factors involved in seafloor data acquisition.

Figure 31. An OBC profile with no receiver statics applied to the data.

Figure 32. The same OBC profile (Figure 31) after one iteration of receiver static corrections.

Figure 33. A map of receiver static corrections applied to 4C3D OBC data across the study area.

Figure 34. A P-wave profile traversing a gas chimney (crossline coordinates 10050 through 10150). It is difficult (impossible?) to interpret stratigraphy and structure inside the gas-invaded interval.

Figure 35. A converted-SV profile, along with same inline coordinate as that shown in Figure 34. The converted-SV data provide an improved image of geologic conditions inside the gas-invaded chimney (crossline coordinates 10050 through 10150).

Figure 36. Time slice of P-wave reflection amplitudes.

Figure 37. Time slice of converted-SV reflection amplitudes.

Figure 38. Time slice of P-wave reflection coherency.

Figure 39. Time slice of converted-SV reflection coherency.

Figure 40. P-wave time-structure map.

Figure 41. Converted-SV time-structure map.