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**STUDY TITLE:** Multicomponent and Multifrequency Seismic for Assessment of Fluid-Gas Expulsion Geology and Gas Hydrate Deposits: Gulf of Mexico

**REPORT TITLE:** Multicomponent and Multifrequency Seismic for Assessment of Fluid-Gas Expulsion Geology and Gas-Hydrate Deposits: Gulf of Mexico Hydrates

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**BACKGROUND:** The northern Gulf of Mexico continental slope is a well-documented province where fluids and gases migrate to the modern seafloor at numerous sites. Many of these sites are accompanied by exposed gas hydrate deposits. Migration pathways and gas hydrates have been difficult to image because of the presence of bubble-phase gas and very complex geology (the product of a dynamic interaction between sedimentary loading and salt deformation). In the complex geology of the northern Gulf's hydrate stability zone there are very few reflection events that can be interpreted as bottom simulating reflectors (BSRs). These BSR's generally represent the phase change between gas hydrate and free gas at the base of the hydrate stability zone, but they are difficult to identify in existing p-wave seismic data sets from the northern Gulf. In simple geologic settings, BSRs clearly cut across subsurface stratigraphy. However, as the geologic complexity of the subsurface increases, BSRs become more difficult to identify and trace. Even though the entire continental slope is covered with high quality 3D-seismic, migration pathways for fluids and gases, as well as gas hydrates, are not well-imaged and details of these features have generally alluded geoscientists.

This study provides an unparalleled research opportunity to employ a new multicomponent seismic data set collected from across a large area of the northern Gulf of Mexico's upper continental slope (to a depth of 1000 m). These data were acquired to provide a new imaging capability. WesternGeco has collected the long offset multicomponent seismic data (four-component ocean bottom cable seismic, 4C-OBC) from which both shear wave and conventional compressional wave (p-wave) data can be derived. Not only will this long offset 4C-OBC data allow deeper imaging within the sediment column, but the c-wave data (up-going SV shear wave created by p-to-SV mode conversion) made possible with this acquisition strategy images through gas and image different stratal surfaces and boundaries, unlike standard p-wave data. In addition, lithofacies data, as well as shear moduli and bulk moduli, can be calculated from 4C-OBC data. We therefore consider this research to be a great opportunity to image migration pathways from the deep subsurface and to provide stratal information that can help define the base of the hydrate stability zone and properties of sediments invaded by gas hydrate. Analysis of 4C-OBC data also provides us with a means to assess c-wave data, with a focus on cross-over information that may be important for interpreting p-wave data of various frequency contents (8-100 Hz 3D-seismic to 2-8 kHz). Three test sites were established, based on relative fluid-gas expulsion rates: slow flux, intermediate flux, and rapid flux. These qualitative classes of flux rate are based on geologic response at the modern seafloor. The three study sites are located in the Green Canyon lease area in lease blocks 204, 237, and 240. Seismic profiles with three different frequency contents were collected along common track-lines across each experimental site. One of these three seismic types was 4C-OBC data. The others are standard exploration-scale 3D-seismic and much higher frequency "chirp sonar" subbottom data. The c-wave data from the 4C-OBC data provide valuable new insight critical for resource evaluation in the case of gas hydrates and imaging of fault systems necessary for constructing realistic numerical models of fluid and gas migration from the deep subsurface. In addition, critical geologic differences between slow flux to rapid flux settings may be revealed. Linking very high resolution images of the shallow subsurface using AUV and chirp technology with the 4C-OBC data is one goal of this investigation.

**OBJECTIVES:** The overall objective of the research project described in this report was to investigate the use of 4-C OBC data from our three study sites for identifying properties within the shallow stratigraphic section that relate to the presence and amount of gas hydrate.

**DESCRIPTION:** Assessment of gas hydrate within the shallow stratigraphic section of deep water areas has been a problem without having direct evidence provided by drilling and associated core samples. The use of four-component ocean-bottom-cable (4-C OBC) technology offers an alternative to standard surface-towed 3D-seismic technology for indirect and remotely sensed evaluation of the geologic configuration of the subsurface and for investigating the occurrence of gas hydrate that occurs in the shallow stratigraphic section. This technology involves a surface acoustic source (usually an air-gun) and long lines of ocean bottom sensors that are capable of recording three-dimensional vector motion of the seafloor with 3-component geophones, as well as scalar pressure variations with hydrophones. The advantage of the 4-C OBC data-collection is that standard compressional wave data (P-P), as well as converted shear wave data (P-SV), can be acquired simultaneously as backscatter from subsurface reflection horizons. These data are acquired in approximately the 10-200 Hz frequency range. From a regional grid of data acquired by WesternGeco in the northern Gulf of Mexico, outer-shelf to upper slope depth range, this study was given access to 4-C OBC data associated with three sites within the Green Canyon Lease Area: GC 204, GC 237, and GC 240. Direct observations from manned submersible dives confirm gas hydrate deposits as surface exposures at two of these sites, GC 204 and GC 237. Only the GC 240 site has no direct confirmation of gas hydrate at the modern seafloor.

The GC 204 site is adjacent to Chevron's Genesis Field, and BHP-Billiton's Typhoon Field is adjacent to our GC 237 site. Both of these fields had well logs available for use in our study. Well log data were extremely important to this study for calibrating acoustic properties of the subsurface to rock properties. Most well log data spanned at least part of the gas hydrate stability interval and were therefore important calibration data used to make estimations of gas hydrate concentrations, especially the resistivity log measurements. Only the GC 240 site did not have supporting well log data from an adjacent oil and/or gas field.

A ray tracing method was used to adjust the thicknesses of equivalent stratigraphic intervals derived as separate P-P and P-SV images. Since representations of the subsurface are different using P-P as compared to P-SV data, the ray tracing method was employed to adjust layer thickness and interval velocities (Vp and Vs) so that other datasets such as those from resistivity logs could be compared to converted shear wave data (P-SV) images of the subsurface. The interval from the seafloor to the base of the hydrate stability zone was analyzed at each of our three study sites. Using this methodology, velocity layers or stratigraphic units were defined as a function of depth below the seafloor.

**SIGNIFICANT CONCLUSIONS:** Estimates of gas hydrate were made for calibration wells using primary data from resistivity logs and seismic velocity estimates (Vp and Vs) for given stratigraphic intervals defined from the ray tracing method. Depth dependent increases in Vp and Vs were incorporated and used in the gas hydrate assessment employing normal sediment compaction theory. Stratigraphic intervals within the gas hydrate stability zone where both interval velocities and resistivity values were greater than those expected with normal compaction were interpreted as zones of hydrate concentration. Using a probability function described in this report, the amount of pore space occupied by gas hydrate was calculated. At intervals of 10 receiver stations (250 m) along each OBC profile, velocity layering and estimated gas hydrate concentrations were calculated. Our results indicate: (1) gas hydrate was pervasive throughout the sites we studied in the Green Canyon lease area; (2) concentrations of gas hydrate ranged from zero to one-third of available pore space, but values of 10-20% of the pore volume were typical of most areas; (3) free-gas was found immediately underlying the base of the gas hydrate stability zone (not easily determined from resistivity logs alone); and, (4) the estimation of gas hydrate stability zone thickness from resistivity logs alone produced an overestimation of gas hydrate zone thickness and amount present.

**STUDY RESULTS:** A key to interpreting the presence of gas hydrate and perhaps bubble-phase gas in stratigraphic intervals defined by velocity data was the integration of several primary datasets: (1) resistivity (well log data), (2) interval velocity, and (3) seismic images (P-P and P-SV). However, the relationships between gas hydrate occurrence/concentration with resistivity data, as well as the relationships between seismic propagation velocity and gas hydrate occurrence/concentration, were found to be non-unique. Spatial variations in host sediment properties and the nature of gas hydrate (e.g., small crystals in pore spaces to massive layers) within the hydrate stability zone accounted for much of the uncertainty in interpretations. By combining gas hydrate-dependent geophysical data (e.g., velocity estimates and formation resistivity measurements), predictions of gas hydrate concentrations were constrained. A rock physics model that related seismic velocity to gas hydrate concentration was used (methodology described in Appendix C). This model accounted for the uncertainty of all parameters used in the calculation of gas hydrate concentration.

Applying our analysis methodologies to 4-C OBC data calibrated to well log data in Typhoon Field area (lease blocks surrounding GC 237) the following conclusions can be drawn:

1. Gas hydrate occurs in the shallow subsurface throughout the Typhoon Field area and it manifests itself at the seafloor in GC 237 where flux rates of gas and fluids toward the modern ocean bottom eliminate the sulfate reducing zone where gas hydrate does not form.
2. Depth of the hydrate-bearing stratigraphic interval beneath the Typhoon Field is approximately 460 m.
3. Resistivity relationships indicate that gas hydrate concentrations within the approximately 460 m thick zone of hydrate stability range from approximately 20-40 % of available pore space.

Our results from analyzing 4-C OBC seismic data and well logs from the Genesis Field (lease blocks surrounding GC 204) lead to the following conclusions:

1. Data suggest that the shallow subsurface associated with the Genesis Field supports more gas hydrate than the Typhoon Field area.
2. The gas hydrate stability zone ranges in thickness across the Genesis Field area from approximately 365 m to 760 m.
3. Within the variable zone of gas hydrate stability, we estimate that 20-40 % of the pore space is filled with gas hydrate.

Because no well logs were available for our third study site, GC 240, gas hydrate concentrations were interpreted from seismic interval velocities only. The following conclusions can be stated:

1. The gas hydrate stability zone is highly variable and ranges from less than 800 to nearly 1400 m.

2. Compression of the hydrate stability zone is related to a prominent expulsion center in the study area where fluid/gases and heat are transported toward the modern seafloor.  This process moves the base of the hydrate stability zone (BHSZ) stratigraphically upward.
3. Estimates of gas hydrate in the pore space of host sediments based on velocity data alone range from approximately 12 to 30% of the pore space.

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