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**SEISMIC CHARACTERIZATION OF A SHALLOW GAS-HYDRATE-BEARING
 RESERVOIR
 ON THE NORTH SLOPE OF ALASKA**

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Occurrence of gas hydrates on the North Slope of Alaska has been recognized for over three decades. Large-scale well-log studies over the entire North Slope, including detailed temperature profiling in the shallow subsurface, suggest widespread gas-hydrate occurrence, which is facilitated by the depressed geothermal gradient and thick permafrost (Collett et al., 1988). The Milne Point Unit (MPU) is one of several large, active oil fields on the North Slope of Alaska (Figure 1) characterized by a thick, near-surface gas-hydrate-stability zone (HSZ) as documented by many well-log-inferred gas-hydrate occurrences. These factors, along with moderate well coverage, a modern 3-D seismic survey and complex structure make MPU an ideal location for characterizing shallow, onshore gas-hydrate occurrence and distribution.

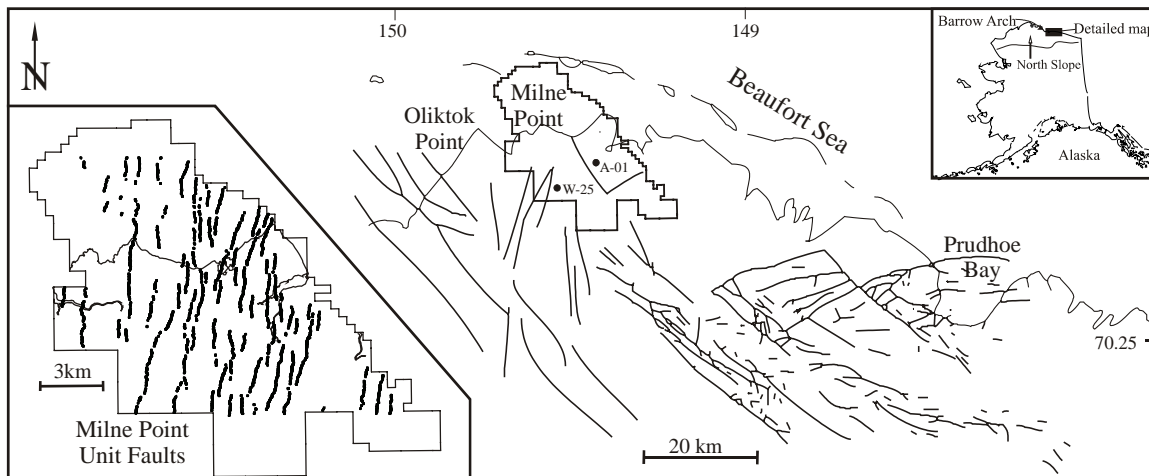


Figure 1. Regional map of structural trends at depth for current production areas; encompassing Prudhoe Bay, Kuparuk River (south of Oliktok Point), and Milne Point oilfields. Depths of these structures vary, but all are deeper than the zone of gas-hydrate stability, which is the focus of this study. Inset on the right shows location of the North Slope of Alaska, the trend of the Barrow Arch, as well as the location of the detailed structure map. Boundary for the Milne Point Unit indicates extent of 3-D seismic data utilized in this study. Location of wells WSak-25 and MPA-01 are identified in Milne Point. Inset on the left details normal faults within the HSZ interpreted from 3-D seismic data. Note NW-trending truncation of NE-trending faults in the center of the MPU. Modified from Collett et al. (1988).

In MPU, gas hydrates occur in highly faulted, fluvial, deltaic and shallow-marine sequences within and below permafrost, with a stability field ranging in depth from 600 to 3800 ft (180–

1160 m). Inferred well-log occurrences of gas hydrates in MPU (hydrate intervals C, D and E in Figure 2) indicate that they form in porous sand intervals and range in thickness from 5 to 25 ft (2–8 m). Despite numerous well penetrations, these shallow sands have not been systematically studied and borehole data is sparse. Free gas directly in contact with gas-hydrate-intervals C, D and E is not interpreted in well logs in MPU since these hydrate-bearing intervals do not intersect the base of the gas-hydrate-stability zone (BHSZ) in MPU. However, amplitude anomalies in deeper strata suggest free gas may be present in contact with gas hydrate at the BHSZ. Typical laterally continuous bottom-simulating reflections (BSRs) seen in seismic surveys of offshore gas hydrates, representing the velocity inversion of gas hydrate over free gas, are not obviously present in seismic data from MPU. Therefore, other means are employed in seismic interpretation to identify the occurrence of gas hydrates distributed within MPU strata.

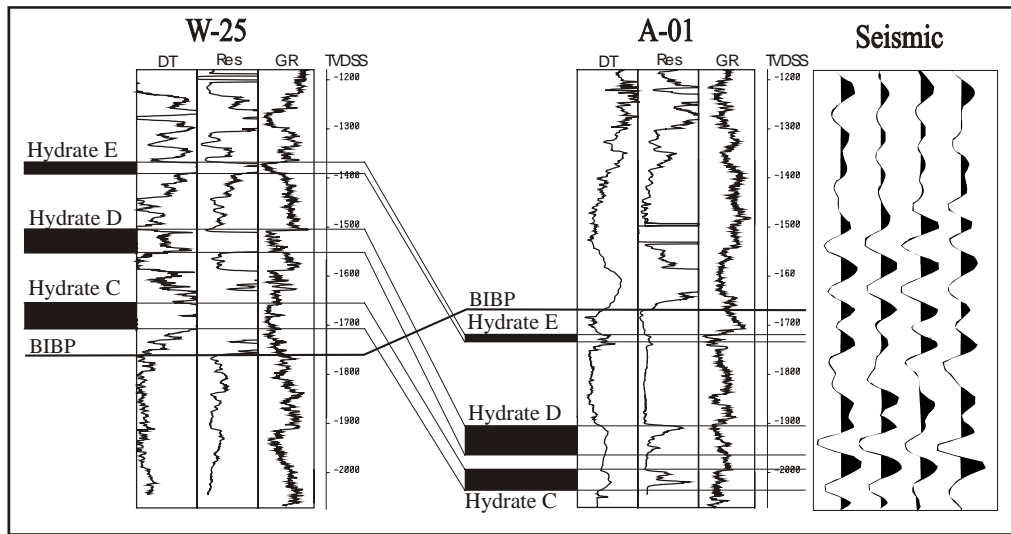


Figure 2. Well logs for wells WSak-25 and MPA-01 including sonic (DT), deep resistivity (Res) and gamma ray (GR); locations are shown in Figure 1. Gas-hydrate inferences for three correlative gas hydrate-bearing units, E, D and C (Collett, 1988), exhibit high velocities and high resistivities. Gamma-ray logs indicate that these gas hydrates occur in thin, sandy intervals. Note that the base of ice-bearing permafrost (BIBP) crosscuts stratigraphy and may interfere with seismic response to gas hydrate. WSak-25 BIBP may be up to 200 feet shallower than indicated and/or occur commingled with gas hydrates. Seismic traces shown on right are scaled to the well logs, taken near the well bore of MPA-01, to show the qualitative resolution of the data and the waveform response to gas-hydrate-bearing intervals.

Although originally collected to image deeper reservoirs, the 3-D seismic surveys used here are truncated below 950 ms. Post-stack processing of the MPU survey data includes predictive deconvolution to remove short-period multiples and wavelet deconvolution to enhance frequency content, which together significantly enhance data quality within the HSZ. Spectral analysis of the enhanced data reveals a dominant frequency of approximately 50 Hz; when calibrated to well logs as shown in Figure 2, this suggests an average tuning thickness for the survey ranging from 25 to 50 ft (8–15 m), which may compromise interpretation of thin (5–25 ft; 2–8 m) hydrate intervals and small-displacement faults. No direct gas-hydrate indicators, such as polarity reversals due to gas hydrate above free gas, are regionally evident in the MPU data, although some may locally occur. Nevertheless, finite-difference modeling of log-constrained gas-hydrate velocity fields suggests that both an amplitude and waveform response to gas-hydrate intervals

below the theoretical tuning thickness should be evident. Although studied amplitude anomalies do not at this time appear to directly correlate with gas-hydrate occurrence in MPU, lateral variations in the waveform may be correlative (Hagbo, 2003). Another complication for seismic interpretation of gas hydrates includes permafrost, which has similar acoustic properties to gas hydrate and is observed intermingling with gas-hydrate-bearing strata as depicted in Figure 2. Although difficult to remove from the data, the effect of permafrost is considered when making interpretations.

Structure in the MPU plays an important role in gas hydrate occurrence and reservoir delineation. Strata in this area dip gently to the NE due to their location on the northeastern limb of the East-plunging Barrow Arch antiform that dominates the region. Fault maps from current production depths indicate large NW- and NE-trending normal faults that control deep fluid contacts (Figure 1). Interpretation of the shallow MPU structure indicates dominate faults trending NE with normal offsets of up to 400 ft (120 m) and an average strike of N8°E (Figure 1). Throw on these NE-trending faults was calculated for several intervals and indicates that these faults were active during deposition. Plots of fault growth for different intervals indicate lateral and temporal variations that suggest a dynamic local stress regime. Isopach maps calculated from the depth-converted seismic volume for several intervals in the HSZ confirm NE-trending-fault-controlled deposition, which affects lateral variation of gas hydrate-bearing sands. Event-similarity-prediction (ESP) time slices and illumination of horizon surfaces assist with interpretation of subtle NW-trending structures. Although not evident as NE-trending offsets in the seismic data, broad NW-trending structures manifest as a zone of low displacement activity along NE-trending faults and may indicate a large structure at depth that accommodates this activity and contributes to control of gas-migration pathways and gas hydrate distribution (Figure 1).

The role that faults play in fluid distribution is revealed in calculations of fault-seal potential. Following the approach used by Yielding et al. (1997), clay-smear-potential (CSP) values were calculated for all shallow faults in the survey along gas hydrate-bearing horizons to compare the degree of shale smear throughout the survey. Log-determined shale ratios and seismically determined fault throws were utilized for CSP calculations. Results show significant lateral variation in relative sealing potential of faults within the survey area. Faults north of the NW-trending structural zone appear to have the greatest seal potential, while those faults within the NW-trending zone appear to have little to no seal potential.

As gas hydrates are not directly interpreted in the data at this time, classification of waveforms was utilized to examine waveform similarity within the survey area. Waveforms extracted from a window around gas hydrate-bearing horizons, like those seen in Figure 2, are classed based on their Manhattan Distance. Resultant maps of these classifications indicate systematic lateral variations in waveforms. Although it is difficult to quantify whether variations in waveform may respond to variations in lithologic facies, reservoir fluid, or both, the classes suggest a pattern of similar waveform occurrence. These variations are strongly controlled by NE-trending faults and, to a lesser extent, by NW-trending structures. Waveform classes generally consistent with gas hydrate-bearing wells may represent potential gas-hydrate-bearing reservoirs. When compared to maps of fault-seal potential, gas hydrate-consistent-waveform anomalies are separated from other waveform classes by faults with high sealing potential. This suggests that

gas hydrate occurrence is affected not only by fault geometries, but by fault-sealing efficiency as well. Ultimately, this supports a model for gas hydrate formation in which free gas migrated into sealed fault blocks containing reservoir sands and later formed gas hydrate with sufficient depression of the geothermal gradient.

Finally, in-place volumetric estimations of gas hydrate in MPU based on gas hydrate-similar waveform classes, fault-seal geometries, and interval thicknesses derived from well logs and depth-converted seismic horizons suggest that significant quantities of gas hydrate are present within the Milne Point Unit. Fault blocks with significant gas hydrate are of interest as targets for potential future delineation and/or production testing.

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