Integrated Well Log and Reflection Seismic Analysis of Gas Hydrate Accumulations, Mackenzie River Delta, Canada

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ABSTRACT

The presentation, associated with this abstract, will focus on the geologic and geophysical evaluation of gas hydrates in Arctic permafrost environments. Within this presentation, we will assess the distribution and size of several gas hydrate and associated free-gas accumulations in the Mackenzie River Delta of Canada through the analysis and integration of downhole well logs and reflection seismic data. This presentation will conclude with a description of a proposed gas hydrate hydrocarbon play model that can be used to explore for the occurrence of gas hydrates throughout the Arctic.

QUANTITATIVE WELL-LOG ANALYSIS OF GAS HYDRATES

Gas volumes that may be attributed to a gas hydrate accumulation within a given geologic setting are dependent on a number of reservoir parameters, two of which, sediment porosity and gas-hydrate saturation, can be assessed with data obtained from downhole well logging devices (Collett, 1993). The well-logging devices that yield the most accurate gas hydrate reservoir porosities include the gamma-gamma density and neutron porosity logs. The electrical resistivity, acoustic transit-time, and neutron spectroscopic logs also yield highly accurate gas-hydrate saturations. In the well log response-modeling portion this presentation we will review the known and modeled well log responses attributed to the presence of gas hydrate. The well log response modeling phase of this presentation will also include the assessment of existing and the development of new gas hydrate well-log evaluation techniques used to characterize sediment porosities and gas-hydrate saturations in gas-hydrate-bearing reservoirs. In the field verification phase of this presentation, proposed gas hydrate well log evaluation techniques will be tested and used to calculate reservoir porosities and gas-hydrate saturations with the downhole log data from the Mackenzie River Delta. The well log investigation portion of this presentation will also contain detailed estimates of the volume of gas associated with each of the gas-hydrate accumulations assessed in this study.

In the field verification portion of this presentation, it will be demonstrated that the quality of the available downhole log data is one of the most significant factors controlling the accurate assessment of sediment porosities and gas-hydrate saturations. Within relatively high quality (in-gauge) boreholes, conventional downhole density logs, with appropriate corrections for the presence of gas hydrates and shales, yield the most accurate downhole measured porosities in gas-hydrate-bearing sediments. It has also been determined that the "standard" Archie (electrical resistivity log data) and the Lee (compressional-wave acoustic log data) relations yield the most accurate gas-hydrate saturations in well log assessed gas hydrate accumulations.

The downhole log derived sediment porosities within the assessed gas-hydrate-bearing reservoirs on Richards Island, discussed in the field verification phase of this presentation, are relatively high ranging from about 29 to 39 percent (Collett et al., 1999). The permafrost-associated gas hydrate accumulations on Richards Island where characterized by relatively high gas-hydrate saturations, ranging from an average value of about 33 to 61 percent (Collett et al., 1999). Well log sensitivity analysis discussed in the field verification portion of this presentation also demonstrate the relative importance of selecting appropriate values for the reservoir constants in the porosity and gas-hydrate saturation equations used to assess gas hydrates.

SEISMIC DETECTION AND EVALUATION OF GAS HYDRATES AND FREE-GAS

In studies of deep marine gas hydrate accumulations, reflection seismic surveys are often used to identify, map, and quantify the occurrence of gas hydrates (reviewed by Collett and Ladd, 2000). Gas hydrate has a very strong effect on acoustic seismic reflections because it is characterized by very high acoustic velocities (about 3.35 km/sec), and thus gas-hydrate-bearing sediments are characterized by high acoustic velocities. In comparison, sediments below the zone of predicted gas hydrate stability, if water saturated, have lower acoustic velocities (acoustic velocity of water is about 1.5 km/sec), and if gas is trapped below the gas hydrates, the velocity is much lower even if just a few percent of gas are present. Because of the strong acoustic impedance difference between gas-hydrate-bearing sediments and underlying free-gas-bearing sediments, the base of the gas-hydrate-bearing zone produces a strong seismic reflection. In marine environments this strong reflector at the base of gas-hydrate-bearing sediments has become known as the bottom-simulating reflector or BSR. An additional feature of a gas-hydrate-bearing sediment is caused by the abrupt acoustic velocity decrease at the BSR which is caused by moving from gas-hydrate-bearing sediments above to commonly free-gas-bearing sediments below. This downward velocity decrease, known as an "inversion", can cause an amplitude phase reversal, which can be detected on reflection seismic profiles. The high amplitude nature of a BSR is often compared to bright spots in petroleum exploration, which can be characterized by a phase shift (reversal), velocity pull-down, and strong intrinsic attenuation. It should also be noted, that gas-bearing sediments even in the absence of overlying gas hydrates, often appear as high amplitude anomalies and can be identified on seismic profiles from both marine and terrestrial environments.

Until recent studies in the Mackenzie Delta region of northern Canada (Collett et al., 1999), BSR's or other acoustic seismic anomalies associated with the occurrence of gas hydrates in onshore settings had never been reported in the literature. The lack of reported acoustic seismic anomalies associated with onshore gas-hydrate accumulations is probably due to the geologically complex nature of most terrestrial gas hydrate accumulations. In general, the geology of onshore gas-hydrate accumulations are relatively more complex than the geology of most marine gas-hydrate accumulations. Marine gas-hydrate accumulations, such as those on the Blake Ridge off the eastern coast of North America, occur within a thick uniform stratigraphic section of mostly silt and clay. However, terrestrial gas hydrates, such as those in the Mackenzie River Delta, occur within complexly interbedded sandstone and shale sequences with the gas hydrate concentrated in the high-porosity reservoir-quality sandstone units. Therefore, a reflection seismic profile across a known terrestrial gas-hydrate accumulation will not exhibit a classical marine type BSR. Instead, the interbedded gas-hydrate-bearing sandstone layers and non-gas-hydrate-bearing shale layers appear as a series of interbedded high and low amplitude reflectors and in some cases at the base of the gas hydrate stability zone along a given seismic reflector a distinct phase reversal may be detected.

INTEGRATION OF WELL LOG AND SEISMIC DATA – MACKENZIE DELTA CASE STUDY

This portion of the presentation will focus on the integrated geologic and geophysical assessment of the gas hydrate and associated free-gas accumulations on Richards Island in the Mackenzie River Delta of northern Canada. Open-hole conventional well log data for this study came from 11 industry exploratory wells (including the JNOC/JAPEX/GSC Mallik 2L-38 gas hydrate research well; Dallimore et al., 1999) located on Richards Island. With the exception of the Mallik 2L-38 well, all of the wells examined in this study were drilled in the early 1970's as industry exploration wells designed to test the more deeply buried conventional hydrocarbon accumulations. Therefore, the open-hole log data from the shallow, potential gas-hydrate-bearing, portion of the wells are often of inferior quality due to poor borehole conditions and in many cases certain types of well logs required to completely assess potential gas hydrate occurrences in the near-surface sedimentary section (<1,500 m) were never obtained. However, the available open-hole logs from the wells examined in this study were sufficient to evaluate the occurrence of gas hydrate and free-gas in the log and seismic inferred gas hydrate accumulations in the Ivik-Mallik-Taglu area of Richards Island.

Digital files for thirteen reflection seismic profiles, totaling about 240 km of data, were obtained from Imperial Oil Limited (IOL) for a portion of Richards Island within the outer Mackenzie Delta. This seismic data was acquired for conventional oil and gas exploration purposes in 1984 and 1985, so the field parameters were not optimum for the evaluation of shallow gas hydrate related features. However, specialized reprocessing provided the information needed to understand the distribution of gas hydrate and associated free-gas accumulations. The reprocessed seismic data also provided valuable insight to the sedimentologic and structural features controlling the distribution of the gas hydrate accumulations on Richards Island.

In this study (Collett et al., 1999), gas hydrates were inferred to occur in nine Richards Island exploratory wells on the basis of well-log responses calibrated to the response of the logs within the cored gas-hydrate-bearing intervals of the Mallik 2L-38 well. The integration of the available well log data with more than 240 km of industry acquired reflection seismic data have allowed us to map the occurrence of four significant gas hydrate and associated free-gas accumulations on Richards Island: those being the (1) Mallik, (2) Ivik C-52, (3) North Ivik, and (4) Taglu gas hydrate accumulations. Combined seismic and well log data analysis indicate that the known and inferred gas hydrate accumulations on Richards Island may contain as much as $187,178 \times 10^6$ cubic meters of gas (in-place).

For the most part, the seismic and well log inferred gas hydrate accumulations on Richards Island are restricted to the crest of large anticlines where the base of the gas hydrate stability zone intercepts the crest of these structural features. The distribution of these four distinct gas hydrate accumulations appear to be controlled in part by the presence of anticlines that may have acted as conventional hydrocarbon traps. Considering that the gas hydrate accumulations on Richards Island are restricted to conventional hydrocarbon traps and the gas associated with the sampled gas hydrate accumulations in the Mallik 2L-38 well probably migrated from a more deeply buried thermogenic source (Lorenson et al., 1999): It is likely that some portion of the Richards Island gas hydrate accumulations originated from migrated thermogenic gas that was first concentrated in shallow traps as conventional free-gas fields that were later converted to gas hydrate fields in response to climate cooling or changes in surface conditions. The occurrence of gas hydrates in conventional hydrocarbon traps provides us with an exploration model and play concept that may be used to predict the occurrence of gas hydrates in unexplored arctic regions.

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