Feasibility of high resolution P- and S-wave seismic reflection to detect methane hydrate

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Summary

It is feasible to use high resolution seismic reflection techniques to image interfaces within the gas hydrate interval at this site on the northeastern edge of the Mackenzie Delta, NW Territories, Canada. Reflections were recorded with a high frequency vibrator to depths in excess of 1000 m. Resolution potential is well within the minimum for delineating individual hydrate zones within the nearly 300 m thick hydrate rich interval penetrated by two nearby boreholes. Several high amplitude, high frequency reflection events are interpretable within and immediately below the nearly 600 m thick permafrost.

Introduction

Natural gas hydrates can only form within specific pressure/temperature ranges and when optimal physical and chemical conditions exist. Gas hydrate deposits have been identified in a variety of marine and permafrost areas around the world. If methane hydrates can be economically produced, they have the potential to significantly impact global energy supplies. The allure of methane hydrates comes from their wide distribution throughout the continental margins (Kastner, 1996). Adding to the economic importance of methane hydrate is its potential impact on global climate change, its possible role as a catalyst for mass wasting on continental rises, and the hazard it represents to drilling (Minshull et al., 1995).

Gas hydrate in deep marine settings has been inferred from seismic data (Markl et al., 1970) and confirmed with drilling (Hollister et al., 1972). Free or dissolved gas collecting immediately below a hydrate layer produces a high amplitude reflecting event referred to as a "bottom simulating reflection" (BSR) (MacKay et al., 1994). BSRs generally mimic the sea floor relief and are coincident with the depth where temperature and pressure conditions are conducive for the formation and stable existence of gas hydrates. Questions such as: Can BSRs be universally associated with potentially economic quantities of gas hydrate? How do BSRs relate to thickness of hydrate? and What is the formation time of hydrate deposits, geometric distribution of deposits, and localized and regional variability of deposits (lateral, vertical, concentrations, etc.)? must be resolved to truly evaluate the significance of gas hydrates to the world energy supply.

An 1150 m deep gas hydrate research well (Mallik 2L-38) was completed during March 1998 at the northeastern edge of the Mackenzie Delta, Northwest Territories, Canada (Dallimore et al., 1998) (Figure 1). Research conducted at this well was

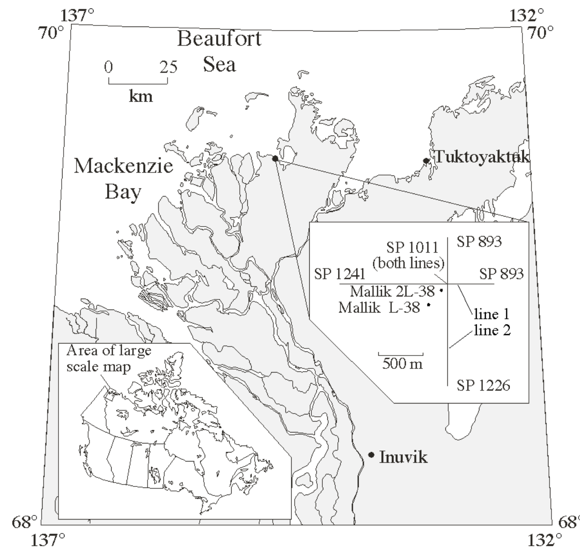

Figure 1. Location map showing relative locations of Mallik L-38 and Mallik 2L-38 as well as the two 1.2 km long seismic lines.

directed by the Japan National Oil Corporation and the Geological Survey of Canada. The research well was located less than 100 m from Imperial Oil's Mallik L-38, an industry exploration well drilled in 1972 that encountered several differentiated layers of gas hydrate. This site possessed the thickest known gas hydrate occurrences in the region.

A high resolution seismic reflection survey was conducted during March of 1999 along two intersecting profiles (Figure 1). This survey was designed to test the feasibility of high resolution seismic techniques to resolve hydrate layers identified by drilling at depths between 800 and 1200 m. Both P- and S-wave vibroseis data were acquired coincidently along line 1 and P-wave data only along line 2. Modeling and borehole logs allowed correlation of interpreted reflection arrivals with geologic interfaces. The east/west profile was acquired generally along a conventional exploration reflection survey, which was reprocessed in association with the Mallik 2L-38 research program.

Geology

Mallik L-38 was drilled to examine potential hydrocarbon targets below 1500 m depth associated with a broad faulted NW trending anticlinal Tertiary-Cretaceous structure. The upper part of the hole encountered clastic Tertiary-age sedi-

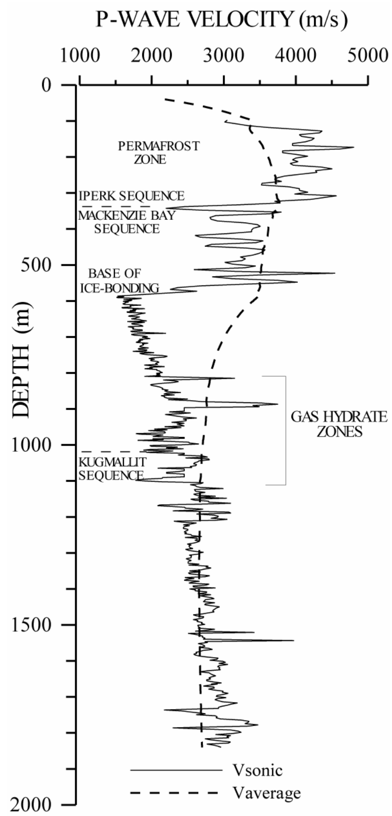

Figure 2. Interval and average velocity logs with key lithologic units identified.

ments known as the Iperk, Mackenzie Bay, and Kugmallit sequences (Figure 2). From well logs, a thick ice-bonded permafrost zone (> 600 m) has been identified. Beneath the base of permafrost, ten distinct gas hydrate bearing layers were interpreted between 820 and 1110 m of depth, with porosities in the range of 33-40% and estimated pore-space hydrate concentrations between 50 and 90%. Drilling and sampling of Mallik 2L-38, approximately 100 m NE of the first well, confirmed the existence of most of these zones (Ohara et al., 1999).

The composite smoothed sonic and the average velocity logs indicate high P-wave velocities associated with ice-bonded permafrost. Large velocity contrasts can be associated with the Iperk-Kugmallit Bay geological boundary as well as the base of ice bonding. Large velocity contrasts are also apparent within the zone of gas hydrate layering between 820 and 1110 meters depth.

Data Acquisition

Acquisition of high resolution data in a permafrost environment presents unique source and receiver coupling challenges. Different sources and receivers were tested to allow optimization of recording parameters and equipment. A 500-grain 8-gauge black powder load fired from a Buffalo Gun set 0.5 m below ground surface and an IVI minivib (vibroseis) were both recorded by a parallel deployment of five Mark Products L28A 30 Hz geophones and three Mark Products L28E 40 Hz geophones. Analysis of these test data suggested the minivib and 30 Hz geophones (P-wave) were optimum for this site. Shear wave data were also acquired with the IVI minivib. For shear wave generation the mass was rotated and oriented perpendicular to the survey line. Single 14 Hz GS-11S Geospace geophones also oriented in an SH configuration were deployed along the profile line.

To enhance coupling, snow was removed down to the ground surface (ice or frozen sediments). Geophones planted/frozen into holes drilled with power drills in the frozen ground were quickly covered with up to 1 m of blowing snow, providing excellent attenuation of wind noise. The area beneath the vibrator pad was cleared of all snow, allowing direct coupling of the pad to ice or frozen sediments. Pelton Advance II electronics were used to control the vibrator sweep and provide both ground force and the synthetic. A total of six sweeps were recorded for close offset data (approx. 50 to 500 m offsets) and eight sweeps were recorded for long offset data (approx. 500 to 1000 m). A 10-second 20 to 200 Hz upsweep was generated for the P-wave data and an 8-second 10 to 80 Hz upsweep was generated for the S-wave data.

Data were recorded on two 48-channel, R48 Geometrics StrataView seismographs networked for simultaneous 96-channel recording. Shot gathers were stored uncorrelated in SEG2 format. A 12-second record was recorded for both P- and S-wave surveys. Five 30Hz L28A Mark Products geophones were oriented in a 1 m long inline array. Receiver spacing was 5 m with source stations separated by 10 m along these 1.2 km long lines. Data were recorded to insure the optimum recording window was always maintained.

Data Analysis

Many spectral balanced and scaled P-wave shot gathers recorded as part of the two CMP profiles possess reflection arrivals from about 250 to over 1200 m of depth (Figure 3). The extremely high velocity nature of the permafrost is evident from the velocity log (Figure 2). A purely elastic model of a shot gather with velocity and depth values determined directly from borehole logs correlates extremely well with reflection arrivals interpretable on shot gathers (Figure 4). Events arriving after ground roll and from below the base of the permafrost are a bit more difficult to confidently separate from noise, but with careful examination, key geologic interfaces appear to have produced reflections interpretable on these data. Superimposing the model reflection events (determined solely from log data) onto the real shot gather improves trace-to-trace correlation of reflection arrivals (Figure 5).

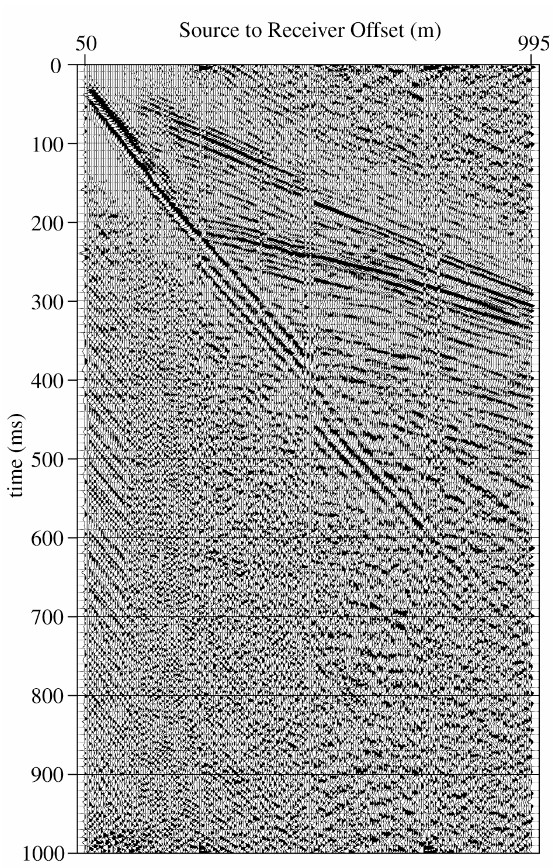

Figure 3. Shot gather combining two individually recorded 96 channel records. The almost 1000 m of spread captured the optimum window of most reflections of interest. These data were spectral balanced 20 to 200 Hz with a 100 msec AGC scale.

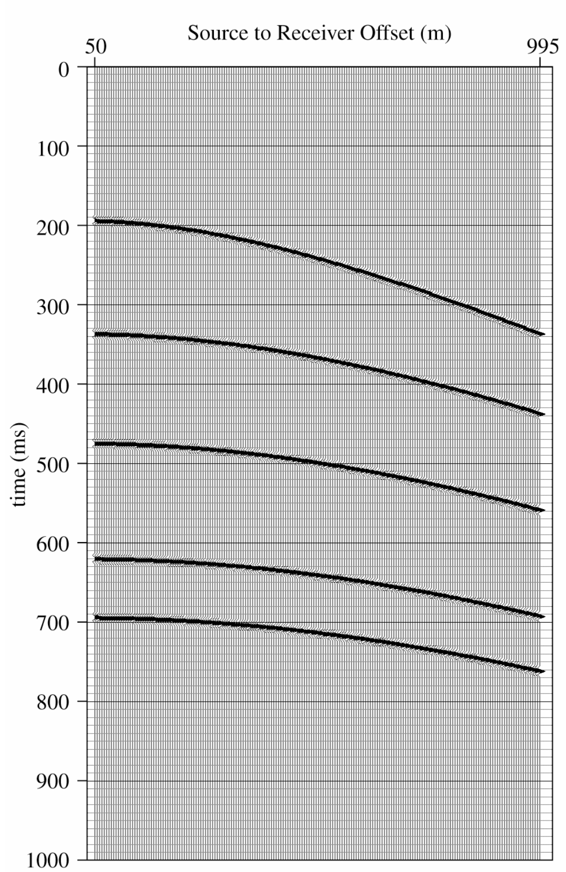

Figure 4. Elastic model of compressional wave arrivals only for the key lithologic interfaces. The velocity and depth information for this model were derived from borehole data. The five reflections are based on reflectors at 350 m, 600 m, 800 m, 1000 m and 1100 m with average velocity of 3600 m/s, 3500 m/s, 2900 m/s, 2750 m/s, and 2700 m/s, respectively

An important characteristic of these reflection data is their resolution potential: horizontal and vertical. Using the 1/4 wavelength axiom, vertical bed resolution of the 200 msec reflection is around 7 m and at 700 msec vertical bed resolution potential is about 11 m. Provided the radius of the first Fresnel zone is an indicator of horizontal bed resolution, the reflection waveforms at 200 msec would relate to a radius of about 70 m, and for the 700 msec reflection the radius is about 144 m. Spectral properties and signal-to-noise ratio of the reflection arrivals will improve when processing parameters are applied which are specifically designed to optimize bandwidth as a function of time. High frequency noise evident after the ground roll arrivals is related to the application of broadband spectral balancing. All frequencies swept were amplitude balanced on the displayed shot gathers.

Reflection events with extremely high amplitude and frequency are evident from within the permafrost portion of the shot gather. The 200 msec reflection (interpreted to be from the top of the MacKenzie Bay Sequence) can be traced from 50 m source-to-receiver offset to almost 1000 m. Evident on the velocity log is an extreme velocity inversion at the base of ice-bonding. This dramatic drop in velocity will provide a significant challenge during the CMP processing of these data. Below the base of the permafrost (350 m), the dominant frequency of the reflections begins to decrease. At longer offsets reflection events can still be suggested down to depths in excess of 750 msec on this shot gather.

The two (1.2 km) CMP profiles will provide added insight into the potential of high resolution data at this site. Each profile will have slightly more than 200 m of full fold (24) stacked traces with the full suite of source offsets present. The remaining 1 km of the CMP stacked section will possess predominantly long offset data at the start of the profiles and close offset data at the end of the lines.

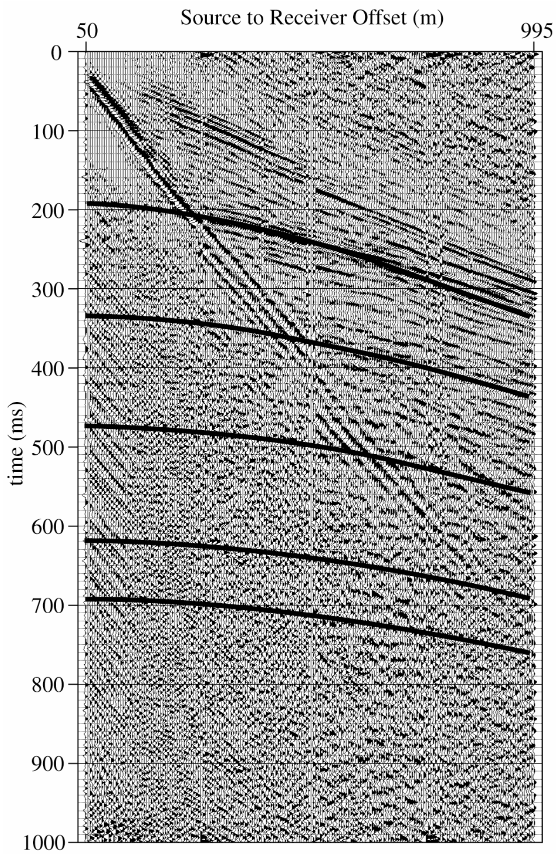

Figure 5. Superimposed reflection model onto shot gather to demonstrate the correlation between the model and real data and to aid in the identification of reflections arriving after the ground roll.

Conclusions

This first attempt at acquiring high resolution reflection data targeting gas hydrate deposits at 800 to 1000 m in this permafrost environment was successful. Resolution potential and penetration depths were consistent with our expectations. More data were acquired during the 6 days of acquisition than expected. It is very likely that several unique reflection arrivals will be interpretable on stacked section within the hydrate depth zone. Two hydrate layers (810 m and 900 m) identified in core and log data are separated by more than two wavelengths and are well within both the theoretical and practical resolution limits of this survey. If these two events can be uniquely delineated, it may be possible to observe on CMP stacked sections the geometries responsible for the presence of the 810 m gas hydrate in Mallik L-38 and its absence in Mallik 2L-38.

Acknowledgments

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