Imaging permafrost with shallow P- and S-wave reflection

R.D. Miller, Kansas Geological Survey (KGS); J.A. Hunter, Geological Survey of Canada (GSC);*
W.E. Doll and B.J. Carr, Oak Ridge National Laboratory; R.A. Burns and R.L. Good (GSC); D.R. Laflen (KGS);
and M. Douma (GSC)

Summary

Shallow reflection events observed on coincident P- and S-wave data from within the permafrost zone possess sufficient coherency and resolution potential to compensate conventional 2- or 3-D data sets for structural artifacts related to lateral travel time variability. Reflections with dominant frequencies above 100 Hz on P-wave data and 40 Hz on S-wave data from within the permafrost have a very broad range of wavelet characteristics, which change vertically and laterally across the 1 km profiles. S-wave reflections appear much more continuous across the section when contrasted with the P-wave reflections. With the exception of the Iperk/MacKenzie reflection P-wave wavelet characteristics change quite dramatically across the almost 1km long shot gathers. Coincident interpretation of the P- and S-wave reflection data can address a variety of both engineering and petroleum exploration imaging problems.

Introduction

High velocity layers (HVL), such as permafrost, volcanics, and carbonates, represent a formidable obstacle for conventional seismic reflection surveying when present at the surface and within the near surface. Exploration within and below these HVL can be complicated by sizeable waveform and attribute distortion (Justice and Zuba, 1986), static irregularities (Palmore, 1984) and mode conversion (Gulati and Stewart, 1997) problems. Permafrost is a particularly complicated HVL due to the gradational yet extreme velocity contrast at its base (Dallimore et al., 1999).

Permafrost environments present challenges to the acquisition, processing, and interpretation of seismic reflection data. In particular, the effects of laterally variable permafrost thickness and material properties and the presence of free gas within the frozen sediments results in severe lateral velocity variations and adversely affects the transmission of seismic energy. Mapping the sediment layers and associated velocity field within this permanently frozen sediment can provide travel time corrections for improved seismic images of deeper structures and identification of free gas zones that might be present a hazard to drilling operations.

Shallow reflection has proven effective for resolving thin layers at shallow depths in a variety of near-surface settings. Compressional wave reflections surveys have shown promise for resolving static problems commonly observed on deeper conventional surveys (Steeples et al., 1990). Shear wave reflection surveying, when applied to engineering problems, has demonstrated value in permafrost regions investigating effects such as differential melting associated with surface structures (Skvortsov et al., 1992). Shallow P- and S-wave reflection profiles, when used coincidently could address a variety of issues including of mode conversion, free gas detection, and static irregularities on conventional data in permafrost regions.

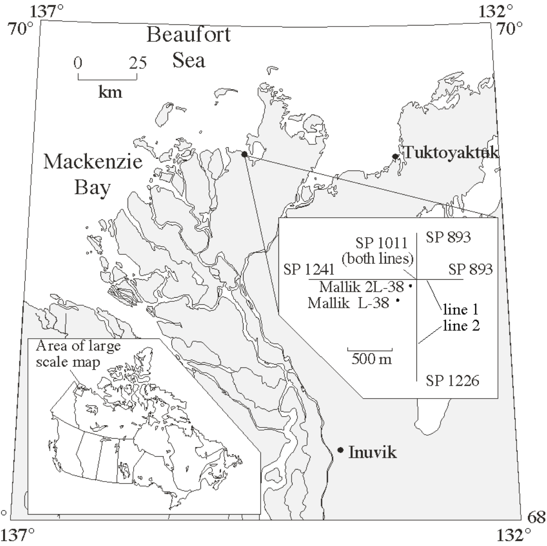

Figure 1. Location map showing relative locations of Mallik L-38 and Mallik 2L-38 as well as the two 1.2 km long seismic lines.

Developing accurate interval velocities for time-to-depth conversions and depth migration are critical to eliminating false structures on time sections in permafrost environments (Gonzalez et al., 1998). Traditionally, the velocity field has been determined using regional geologic information, stacking velocities derived from deeper reflection events, and/or tomographic methods requiring assumptions about the structural target or pilot reflections interpreted beneath the HVL. Shallow seismic reflection represents a method that requires only that acoustic impedance contrasts exist and it has the potential to resolve reflectors as thin as 5 to 10 m from within the permafrost. Defining the velocity field in areas with lateral variability in the permafrost would greatly reduce or possibly eliminate distortions in the stacked data from sub-permafrost targets.

High-resolution data were acquired at the northeastern edge of the Mackenzie delta, Northwest Territories, Canada along two

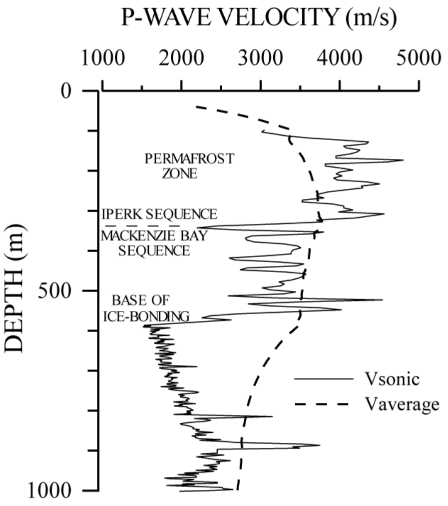

Figure 2. Interval and average velocity logs with lithologic units identified.

intersecting profiles (Figure 1; Hunter et al., 1999a, b). These data were designed primarily to evaluate the effectiveness of high-resolution seismic reflection methods in delineating gas hydrate deposits at depths from 0.8 to 1.2 km below ground surface. Secondarily, this research program attempted to determine the resolution potential, signal-to-noise levels, overall reflectivity of the permafrost zone, high-frequency reflection characteristics of the base of ice bonding, and correlation potential of P- and S-wave data at this site. Borehole data from this area penetrated over 600 m of permafrost which consisted of clastic Tertiary sediments of the Iperk and Mackenzie Bay sequences (Figure 2). Both P- and S-wave data were acquired coincidently along line 1 with an IVI Minivib.

Data Acquisition and Processing

Acquisition of high-resolution data in a permafrost environment presents unique source and receiver coupling challenges. Source and geophone types and configurations were tested to allow optimization of recording parameters and equipment. A shotgun source and an IVI Minivib (vibroseis) were recorded by a parallel deployment of five Mark Products L28A 30 Hz geophones and three Mark Products L28E 40 Hz geophones using several different Minivib sweep designs. Based on this test the P-wave data for the production portion of the survey were acquired with the five 30-Hz geophones grouped in a 1 m inline array. Shear wave data were also acquired with the IVI Minivib by rotating the mass into an orientation that polarized the direction of particle motion perpendicular to the survey line. Single 14 Hz GS-11S Geospace geophones, also oriented in an SH configuration, were deployed along the profile line.

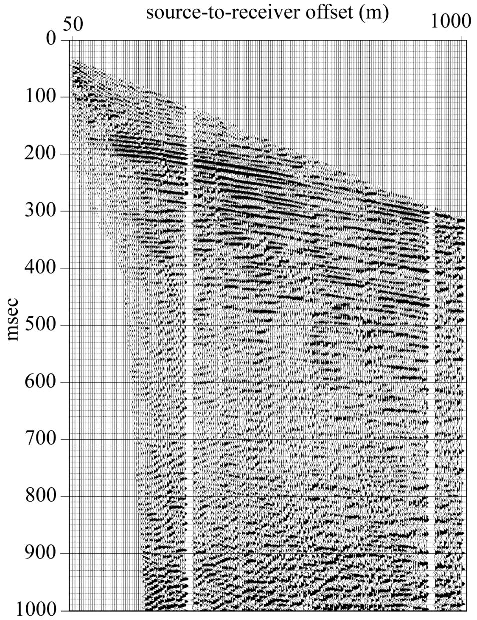

Figure 3. Fully edited and filtered P-wave shot gather.

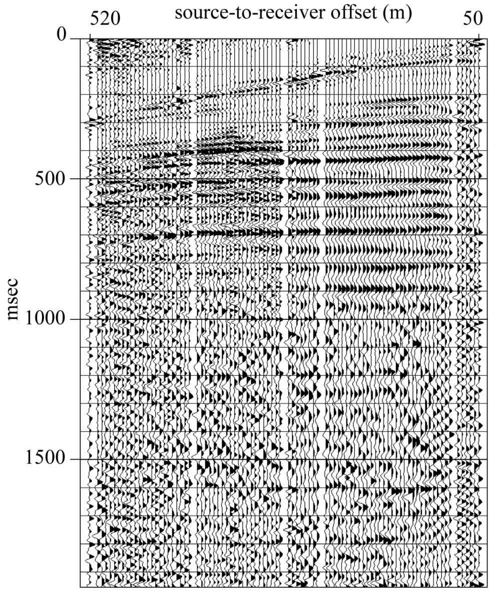

Figure 4. Filtered and scaled S-wave shot gather.

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 by up to 1 m of blowing snow, providing excellent ground coupling and 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.

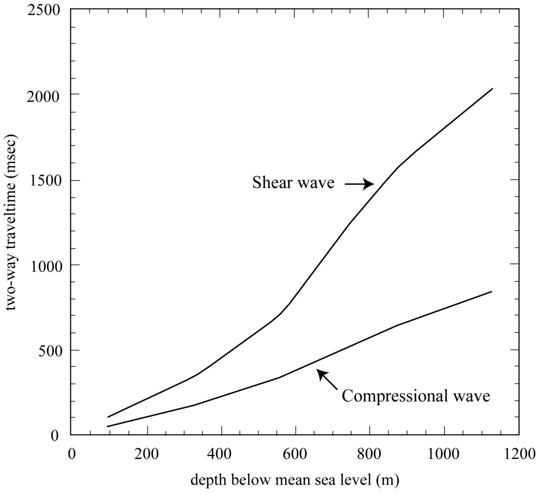

Figure 5. Two-way traveltimes for P- and S-waves from VSP (from Sakai, 1999).

Pelton Advance II electronics were used to control the vibrator and provided both ground force and the synthetic sweeps. Decoupling from the icy surface was a problem for shear wave data acquisition and carefully monitored throughout the survey. 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 linear upsweep was generated for the P-wave data and an 8-second 10 to 80 Hz linear 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. Channels 1 and 49 were used to save the synthetic and ground force pilots, respectively. Shot gathers were stored uncorrelated in SEG-2 format. A 12-second record was recorded for both P- and S-wave surveys. Receiver spacing was 5 m with source stations separated by 10 m along the 1.2 km line. Data were recorded to insure that the optimum recording window was always maintained.

Data were processed using routine shallow CMP processing algorithms and approaches (Steeples and Miller, 1990). Correlation of the synthetic with the uncorrelated data produced the highest quality shot gathers. Only the near-offset traces (<500m) are used in generating these stacked sections. Only the Iperk reflector appears continuous across the entire shot gather, so velocity analysis was challenging even with trace separations of 5 m. Detailed velocity analysis was undertaken using semblance, constant velocity stacks, and CMP curve fitting. Improved coherency of reflection events will primarily be accomplished with more accurate and higher density velocity functions.

Discussion

Reflection events with extremely high amplitude and frequency are evident from within the permafrost portion of the compressional wave shot gather (Figure 3). 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. An extreme velocity inversion is evident on the velocity log at the base of ice-bonding (Figure 2). This dramatic drop in velocity alters the raypaths sufficiently that a routine second-order NMO correction was not sufficient for reflections directly beneath the permafrost, demonstrating the need for the NMO equation being defined to at least the third order. Below the base of the permafrost (350 m), the dominant frequency of the reflections begins to decrease. At longer offsets weak reflection events are observed to depths in excess of 750 msec on this shot gather.

Shear wave reflection arrivals have different characteristics than equivalent compressional wave reflections (Figure 4), based on NMO velocity analysis and the VSP-determined velocity function (Figure 5). The relatively high amplitude reflection at about 400 msec is the top of the Mackenzie Bay Sequence. Unlike the compressional wave data, the Mackenzie Bay reflection on the S-wave gather is not the only high amplitude, laterally coherent event interpreted within the permafrost. Surprisingly, a relatively high amplitude coherent event is present at about 700 msec, which is the time-depth expected for the base of ice bonding. Compressional wave data showed no evidence of a continuous reflector present at that depth. Reflections from below that 700 msec event are difficult to identify with confidence but some hint of reflections as deep as 1500 msec are observed.

An important characteristic of these reflection data is their resolution potential, horizontal as well as vertical. Using the ¼-wavelength axiom (Widess, 1973), and concentrating on the reflection interpreted to be from the Iperk/Mackenzie Bay contact, vertical bed resolution of the 200 msec reflection on the P-wave data is around 7 m while for the equivalent S-wave reflection (400 msec) the potential vertical bed resolution is about 9 m. Provided the radius of the first Fresnel zone is a reasonable indicator of horizontal bed resolution, the reflection characteristics at 200 msec on the compressional wave data would relate to a radius of about 70 m, compared to a radius of about 90 m for the shear wave reflection at 400 msec.

Sources and receivers occupied the same locations during acquisition of both components. CMP profiles (1 km) provide added insight into the way these two different components of the wave field interact with the permafrost zone (Figure 6). A detailed velocity field calculated during the CMP processing of shallow, high-resolution P- and S-wave data could be used as a map for compensating structural artifacts on conventional exploration reflection sections that are related to variability in

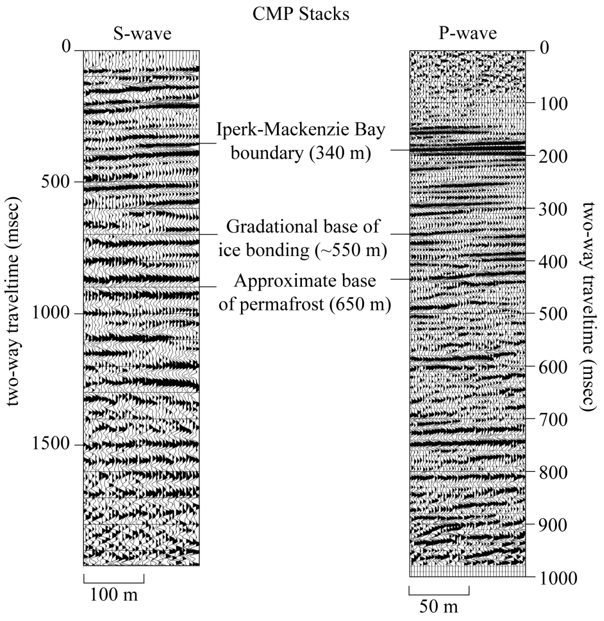

Figure 6. Snippets of the S- and P-wave CMP stacked sections. These two sections are comparable, but not from the same locations along the survey line

velocity field from changes in thickness or composition of the permafrost. Most times this laterally variable permafrost material is shallower than conventional surveys would image. Minor modifications to conventional 2- and 3-D surveys could accommodate the kinds of detailed velocity analysis used here to define the velocity field from the ground surface to the base of ice bonding.

Conclusions

Shallow high-resolution reflection data can provide improved traveltime corrections for 2- and 3-D conventional reflection surveys in areas with a variable permafrost thickness or sediment sequence. P- and S-wave reflection surveys targeting the permafrost can provide not only valuable information about the velocity field, but can unravel problems separating mode converted from primary reflections within and immediately below the permafrost layer. Reflections observed here from within the permfrost were uninterpretable on conventional reflection data acquired less than a kilometer from these data. With modifications, conventional data could be acquired to allow the recording and analysis of permafrost reflections. Uniquely different reflection characteristics evident in a single reflector on coincident P- and S- wave are key to addressing problems on conventional data common in HVL environments.

Acknowledgements

Oak Ridge National Laboratory is managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

We would like to express a great deal of appreciation to Kathy Sheldon for the hours of working and late night conference calls getting equipment through U.S. Customs in and out of Canada. Thank also to Mary Brohammer for manuscript preparation and submission.

References

Dallimore, S.R., T. Uchida, and T.S. Collett, eds., 1999, Scientific results from JAPEX/JNOC/ GSC Mallik 2L-38 gas hydrate research well, Mackenzie Delta, NWT, Canada: Geological Survey of Canada Bulletin 544, 401 p, 4 plates.

Gonzalez-Serrano, A., A. Ramirez-Cuellar, J. Kapoor, D. Ince, T.P. Summers, and S.T. Michell, 1998, Refining 3-D velocity models for depth migration using tomography: Application to rapid permafrost variations in Alaska's North Slope transition zone province: Soc. Expl. Geophys., p. 1203-1206.

Gulati, J.S., and R.R. Stewart, 1997, Seismic exploration through high-velocity layers: Soc. Expl. Geophys., p. 1297-1300.

Hunter, J.A., R.D. Miller, W.E. Doll, B.J. Carr, R.A. Burns, R.L. Good, D.R. Laflen, M. Douma, and M. Riedel, 1999a, Feasibility of high resolution P- and S-wave seismic reflection to detect methane hydrate: Soc. Expl. Geophys., p. 445-448.

Hunter, J.A., R.D. Miller, W.E. Doll, B.J. Carr, R.A. Burns, R.L. Good, D.R. Laflen, and M. Douma, 1999b, Feasibility of high resolution P- and S-wave seismic reflection to detect methane hydrate, Geol. Survey of Canada Open File Report #3850, 45 p.

Justice, J.H., and C. Zuba, 1986, Transition zone reflections and permafrost analysis: Geophysics, v. 51, p. 1075-1086.

Palmore, D.R., 1984, Permafrost effects on geophysics exploration (special workshop): Soc. Expl. Geophys., p. 855.

Sakai, A., 1999, Velocity analysis of vertical seismic profile (VSP) survey at JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well, and related problems for estimating gas hydrate concentration: Geological Survey of Canada Bulletin 544, p. 326.

Skvortsov, A.G., J.A. Hunter, N.N. Goriainov, R.N. Burns, A.M. Tsarov, and S.E. Pullan, 1992, A high resolution shear wave reflection technique for permafrost engineering applications: New results from Siberia: 62nd Ann. Int'l Mtg., Soc. Explor. Geophys., Expanded Abstracts, p. 382-384.

Steeples, D.W., R.D. Miller, and R.A. Black, 1990, Static corrections from shallow-reflection surveys: Geophysics, v. 55, p. 769-775.

Steeples, D.W., and R.D. Miller, 1990, Seismic-reflection methods applied to engineering, environmental, and groundwater problems: Soc. Explor. Geophys. Investigations in Geophysics, Investigations in Geophysics no. 5, Stan H. Ward, ed., Volume 1: Review and Tutorial, p. 1-30.

Widess, M.B., 1973, How thin is a thin bed: Geophysics, v. 38, p. 1176-1254.