Full Waveform Sonic Data From A Fast Formation

Jingping Ji and Bernd Milkereit, Department of Physics, University of Toronto, Toronto, Canada

2004 CSEG National Convention

Summary

We utilize the full bandwidth waveform of sonic array data to suppress source reverberations and enhance slow, low frequency tube wave arrivals in hard formations. As no prominent shear wave arrivals are observed in the sonic log data, the tube wave arrival places an important constraint on the range of shear wave velocities in a fast gas hydrates formation.

Introduction

Sonic logs determine the seismic velocities of formations traversed. Full waveform sonic logs can provide useful information about compressional, shear and tube wave velocities, in addition to allowing for attenuation estimates from waveform analysis. This study examines full waveform sonic log data through gas hydrate regions in the Mallik 2L-38 well, Mackenzie Delta, Northwest Territories, Canada (Collet and Dallimore, 2002).

Gas hydrates, crystalline solids formed from water and methane gas, have been of recent research interest due to their potential to be an energy source, and their impact on global climate change, continental margin slope stability, and conventional petroleum drilling. For better characterization of material properties in the gas hydrate zones, knowledge of shear wave velocities is highly desirable. Of gas hydrate physical properties, shear wave velocity is one of the least documented. Log data in the gas hydrate regions are characterized by fast arriving compressional waves and often an absence of shear waves. Consequently, we cannot determine the shear wave velocity directly and must rely upon indirect means, such as Stoneley wave characteristics from the log, to give us an indication of the shear wave velocity.

The data was collected with a monopole source, 8-station array (hydrophones, 9 ft between source and first hydrophone, 6 in between hydrophones) with a signal frequency of 2 to 40 kHz. A typical amplitude spectrum is shown in Figure 1. Source repeatability, bandwidth and dynamic range make this full waveform sonic dataset well suited for deconvolution signal processing. Deconvolution of waveform data assists picking of transit times (by helping avoid cycle skip in velocity picking) and attenuation of undesirable source-related reverberations.

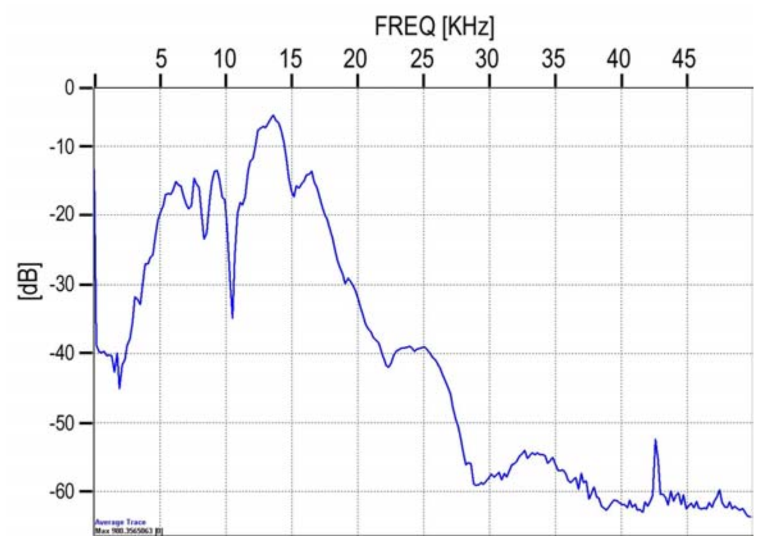

Fig. 1 Amplitude spectrum of full waveform sonic data from the Mallik 2L-38 well.

Full waveform data for the first array element are shown in Figure 2. Transit times for the first break compressional wave arrivals indicate slow and fast formations. As can be seen, the data set does not show prominent shear wave arrival between compressional wave and tube wave (Stoneley wave). For slow, soft formations we expect a fully trapped Stoneley wave with slight dispersion. This is observed in the data; however, for the fast formations (gas hydrates), we observe apparent gaps in the tube wave.

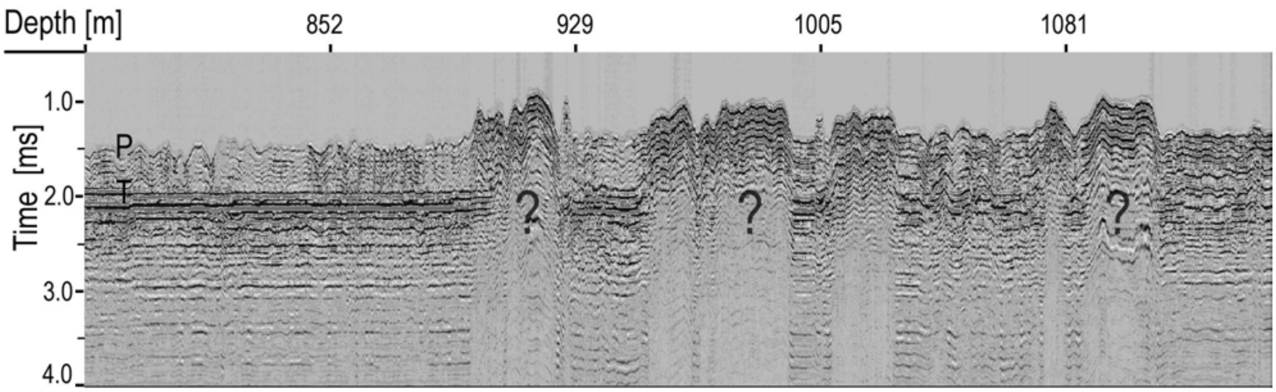

Fig. 2 Display of full waveform data (channel 1, trace normalized amplitudes) with clear first break compressional wave arrivals (P). Small transit times mark fast formations. Strong tube waves are observed in the soft, slow formation (T). Question marks indicate tube wave data gaps in the fast formation.

Methodology

Two different regions were selected out of the logs for analysis: a low velocity region (soft sediments) and a high velocity region (gas hydrate). The compressional wave and tube wave velocities of the different regions are picked using a simple manual method, by following a peak or trough of a wave through the eight receivers. The picked times are plotted and a linear regression applied; the slope is taken to be the velocity.

In the gas hydrate zones, the P wave is readily identifiable; however, aside from the apparent lack of a shear wave, the tube wave also appears absent. Through stacking adjacent shots of the same receiver, a slow arriving, low frequency tube wave can be identified within the gas hydrate zones. The clarity of the discovered tube wave in the gas hydrate zones is greatly improved by spiking deconvolution. Predictive deconvolution and spiking deconvolution with different parameters were also evaluated. First the data is deconvolved, then adjacent shots are stacked to reduce noise, and finally velocity picking is performed on the resulting trace. Figure 3a shows the array recording with strong P-wave and tube wave arrival for a slow formation. Spiking deconvolution helps to shape the waveform and enables better phase correlation and first break picking (Fig. 3b). The slow formation has an approximate compressional wave velocity of 2190 m/s and a tube wave velocity of 1560 m/s. The tube wave velocity is nearly constant in the slow formation.

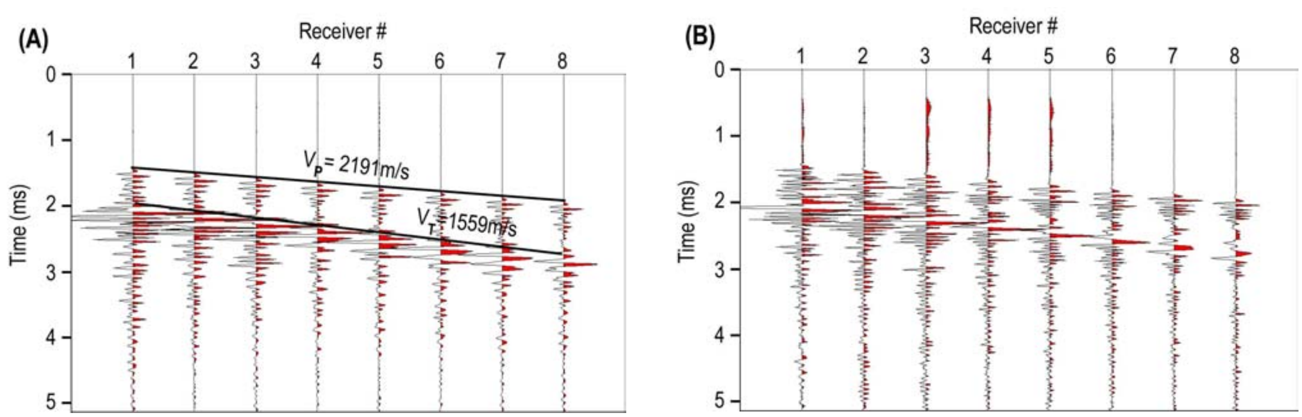

Fig. 3 Array waveform data from the soft slow formation (V_P: compressional wave velocity; V_T: tube wave velocity). Left panel (A) shows the raw data. Right panel (B) shows data after spiking deconvolution (1% pre whitening).

Two array recordings for the fast formation are shown in Figure 4. The P-wave arrival is "ringing" and clear tube wave arrivals are missing. Deconvolution attenuates ringing of the P-wave arrival and enhances the low frequency, low velocity tube wave arrival. Approximate mode velocity of the tube wave arrival is 1100 m/s. The detection of a low frequency, low velocity mode in a hard and fast formation comes as a surprise.

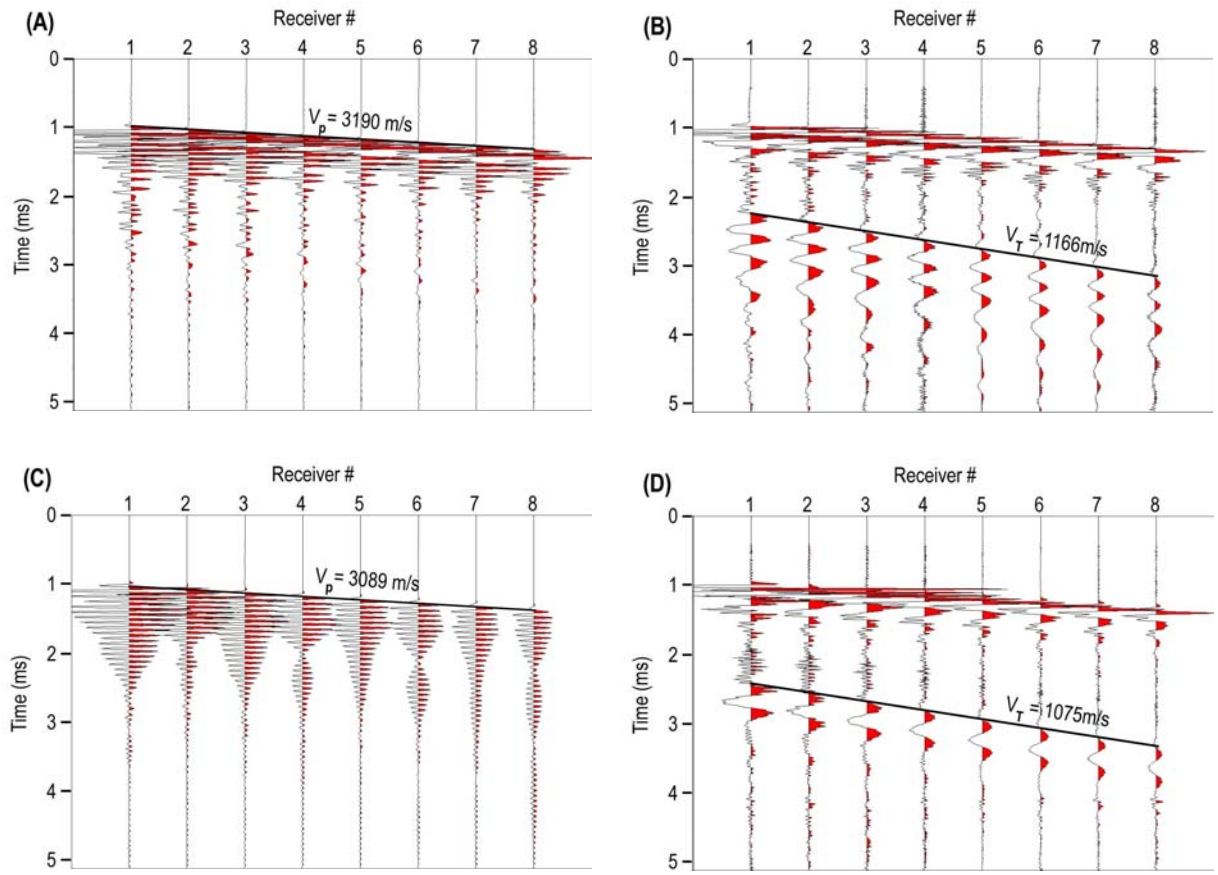

Fig. 4 Two array waveform data examples from the hard, fast formation. Panels on the left (A) and (C) show clear first break compressional wave arrivals. The P-wave signal is "ringing" and masks later, weak arrivals. The same data after spiking deconvolution (B) and (D) shows prominent low velocity, low frequency seismic events.

As discussed by Paillet and Cheng (1991), a wide variety of seismic wave modes are present over a wide frequency band. In a fluid-filled borehole, tube wave/Stoneley wave phase velocities maintain a finite value in the low frequency end. Our data processing results indicate that low velocity, low frequency modes can be extracted from broadband full waveform sonic data. Figure 5 is a display of data for the first array element after deconvolution.

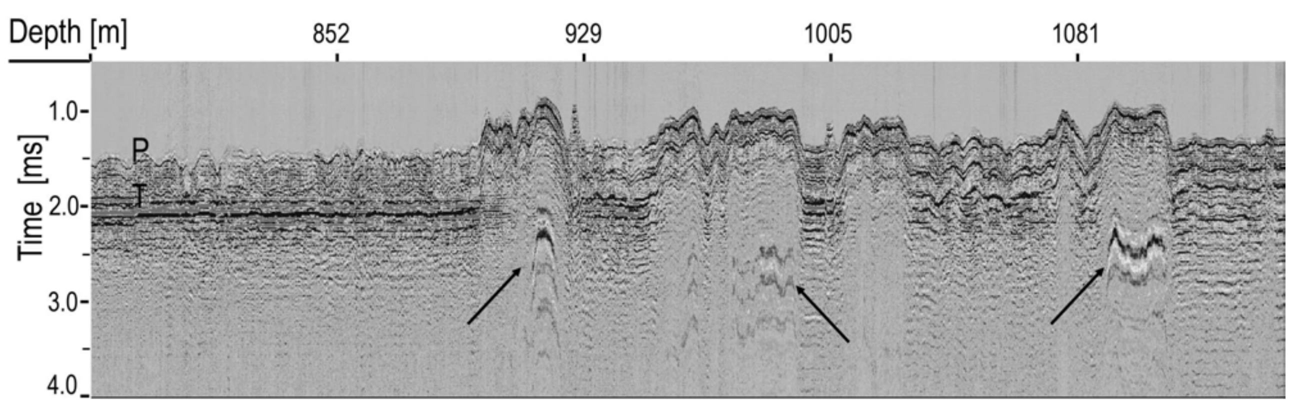

Fig. 5 Full waveform sonic data (channel 1, spiking deconvolution with 1% prewhitening applied). Compare with raw data shown in Fig. 2. This display confirms that slow, low frequency tube wave modes, noted by arrows, are characteristic for the fast formation (gas hydrates).

Interpretation

We will take the low frequency, late arriving tube waves in the fast gas hydrate regions to be Stoneley waves (and will hereon referred to them as such for simplicity). Shear wave velocity can be derived from the Stoneley wave (Stevens and Day, 1986). The formula relating Stoneley wave velocity to shear wave velocity is as follows (Hornby and Murphy, 1987):

$$\frac{1}{V_s} = \sqrt{\frac{\rho}{\rho_m}\left(\frac{1}{V_{st}^2} - \frac{1}{V_m^2}\right)}$$

Where V_s is the shear wave velocity, ρ is the bulk density of the formation, ρ_m is the fluid density, V_{st} is the Stoneley wave velocity, and V_m is the fluid velocity.

In our study, the velocities of the Stoneley waves range from 1075 to 1255 m/s, with a mean of 1152 m/s and a standard deviation of 83 m/s. Using the above formula and the Stoneley wave velocities from the sonic logs, shear wave velocities are derived for the gas hydrate regions. The estimated shear wave velocities range from 1638 to 2479 m/s, with a mean of 1977 m/s and a standard deviation of 385 m/s. There is a very large spread in the shear wave velocities derived, due to the spread in the Stoneley wave velocities. The spread could be caused by a variance of parameters, such as hydrate concentration, pore saturation, and overburdening pressure, in different hydrate zones. Another observation is that the derived shear wave velocities are in fact higher than the fluid velocity. This implies that there should have been critically refracted shear waves, and hence shear head waves in the data. However this was not the observed in the actual data.

There is still a crucial unanswered question: is the low velocity, late arriving wave in the gas hydrate zones indeed a low frequency Stoneley wave? Perhaps after answering this question, we can employ more involved methods of velocity picking and shear wave inversion to attain results of higher accuracy.

Conclusion

Conventional deconvolution processing applied to full waveform sonic data can be used to attenuate undesirable source related reverberations in hard formations. This processing strategy identified a prominent, late arriving, and low frequency wave in the fast gas hydrate formations. Under the assumption that this slow wave is a Stoneley wave, an estimate of shear wave velocity is arrived at using the relationship between Stoneley wave velocity and shear wave velocity.

Not much is known about the low frequency, low velocity event observed in the fast gas hydrate formation as detailed forward modeling studies in the past focused on source frequencies greater than 10 kHz. Further evidence will be necessary to establish conclusively that the late arriving, low frequency wave in the hydrate zones is indeed the Stoneley waves.

Acknowledgments
Schlumberger acquired the full waveform sonic logs for the 1999 Mallik Gas Hydrate Research Project. The SIS vista software was used for signal processing.

References

Collet, T.S. and Dallimore, S.R., 2002, Integrated well log and reflection seismic analysis of gas hydrate accumulations on the Richards Island in the Mackenzie Delta, N.W.T., Canada, CSEG Recorder, 27, No. 8, 28-40.

Hornby, E. B. and Murphy, W. F. 1987. V_p/V_s in unconsolidated oil sands: shear from Stoneley: Geophysics, v 52, n. 4, p. 502-513.

Paillet, F.L. and Cheng, C. H. Acoustic waves in boreholes. Boca Raton: CRC Press, 1991.

Stevens, J. L. and Day, S.M. 1986. Shear velocity logging in slow formations using the Stoneley wave: Geophysics, v. 51, n. 1, p. 137-147.