Extracting frequency dependent velocities from full waveform sonic data

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Summary

In porous, fluid-filled rock formations, compressional seismic wave velocities show a strong dependence on frequency. The potential linkage between P-wave velocity dispersion and permeability would make the use of broadband sonic waveform data suitable for determining reservoir parameters. Automatic velocity analysis of multi-channel sonic data can be tailored to detect and measure frequency dependent velocities. This seismic data processing strategy enables the creation of velocity dispersion logs for fluid-filled porous media.

Introduction

Permeability k is a very important parameter to investigate subsurface formations in groundwater and hydrocarbon exploration. Accurate k measurements give engineers, geologists and geophysicists a better understanding of the structure of the geological formations and its producibility. Currently there exist only a limited number of methods in determining k of formations. It has long been under research to obtain k measurements using seismic method, a cost-effective technique to study in-situ subsurface conditions without causing damage to the formation. Pride (2005) formulated the relationship between P-wave velocity (v_p) dispersion (or seismic attenuation, Q^{-1}) and k (or porosity, Φ) in poroelastic media with predicted dispersion and attenuation models as a function of frequency. Figure 1 shows the trend of the dispersion and attenuation models.

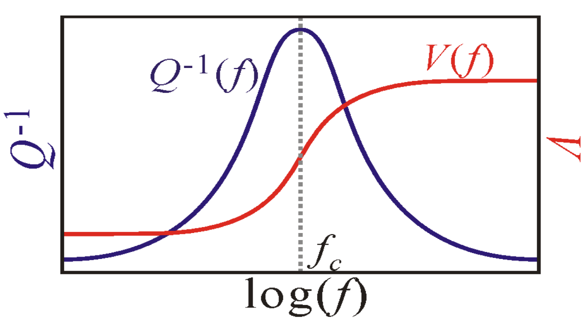


Figure 1: Attenuation (blue line) and P-wave velocity dispersion (red line) as a function of frequency. Peak attenuation occurs when the change of velocity is the greatest (Liu et al. 1976). These mechanisms depend on physical rock properties.

Pride (2005) showed that there is a potential to obtain k measurements from the slope of the attenuation model, which is linked to the dispersion model by the complex slowness. He stated that in the approach to peak attenuation, the slope of Q^{-1} as a function of frequency is inversely proportional to k. However, so far there exists no experimental data with a continuous frequency band large enough to evaluate Pride's predicted P-wave velocity dispersion and attenuation models.

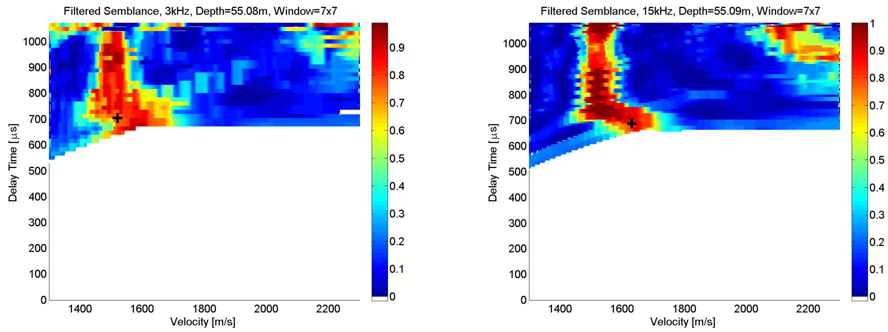
Two multi-channel seismic data sets are available for this research covering a frequency range of 1 kHz to 30 kHz. The first data set contains rerun sonic logs obtained from the Yarragadee Aquifer research well in Western Australia, and the second contains broadband sonic logs from the Mallik gas hydrate research well in Mackenzie Delta of the northwestern Canadian Arctic. In this project, velocity analysis of multi-channel seismic data is performed with the semblance technique and cross correlation method proposed by Pun et al. (2010). Two methods of extracting v_p dispersion information are presented. Downhole logs and v_p dispersion logs are plotted with full waveform data for identification of regions of interest for further reservoir studies.

Velocity Analysis

Seismic wave propagation in fluid-filled boreholes was shown in detail by Biot (1952). In the past, interpretation and analysis of full waveform sonic data focused on dispersive waveforms of shear, tube and Stoneley wave arrivals (Paillet and Cheng, 1991; Hornby and Pasternack, 2000; Milkereit and Ji, 2005). In addition, frequency dependent attenuation and velocity dispersion are important seismic attributes of broadband sonic data that relate to rock lithologies and reservoir parameters (Figure 1). In practice, reliable attenuation and velocity dispersion are difficult to measure over a wide range of frequencies (Sun et al. 2009). Sun et al. (2009) first observed P-wave velocity dispersion over the continuous seismic frequency band (5 Hz to 200 Hz) with vertical seismic profile data. In this project, velocity dispersion in the sonic frequency band (1 kHz to 30 kHz) is computed.

<u>Manual Velocity Analysis</u>

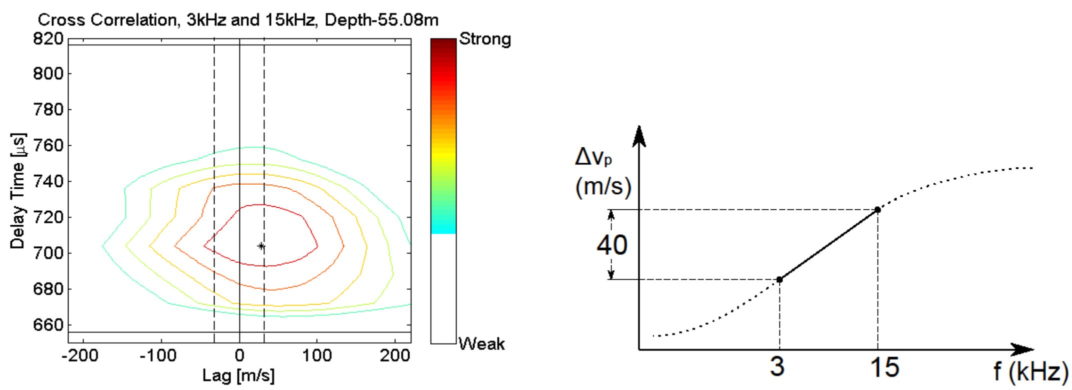
Visual inspection of waveform data is performed for preliminary velocity analysis. First-break energy for each channel is picked to estimate v_p. However, first-arrivals might be very weak and could be difficult to identify.



a) 3 kHz, 55.1 m depth

b) 15 kHz, 55.1 m depth

Figure 2: Semblance velocity analysis of multi-channel sonic waveform data. The plus sign "+" shows the manual velocity pick for the multi-channel data. Red and blue denote strong and weak coherency respectively. White regions contain coherency values of very weak signals.



a)

b)

Figure 3: a) Cross correlation of semblance plots in Figure 2a and 2b. Velocity lag of about 40 m/s is observed. Weak correlations are shown in white. The asterisk "*" indicates correlation value computed from the maximum correlation method. b) P-wave velocity dispersion graph obtained from a). Dotted line shows predicted trend by Pride (2005).

Moreover, borehole measurements were taken every 10 cm and 15 cm for the Yarragadee and Mallik data set respectively over a depth of hundreds of meters. Therefore an automatic process for velocity analysis is necessary for this project.

Semblance Analysis

Automatic semblance velocity analysis has been performed on the multi-channel data as proposed by Pun et al. (2010). This method is based on an automatic beamforming technique to produce velocity spectra. Figure 2 displays the semblance plots corresponding to 3 kHz and 15 kHz Yarragadee waveform data at 55.1 m depth. v_p dispersion is observed from the automatic method by a shift in the coherent events for the two frequencies.

Cross Correlation of Semblance Results

In order to find the velocity shift for both frequencies, a 2D cross correlation is applied to the two semblance velocity spectra. Figure 3a displays the cross correlation plot of the semblance analyses depicted in Figure 2. The gradient (Figure 3b) of 40 m/s over the two frequencies accounts for about 2.7% of the reference velocity, taken to be the velocity of water of 1500 m/s. This gradient is of the same range as that proposed by Pride (2005) for highly porous, fluid-filled media.

P-wave Velocity Dispersion Log

Two automatic processing methods of the cross correlation results have been developed to display v_p dispersion log: the maximum correlation method and the correlation ratio method.

Maximum Correlation Method

The maximum correlation method is performed such that the maximum correlation value is picked automatically from the cross correlation analysis (Figure 3a). The algorithm works by first finding the maximum correlation value at each delay time. The differences of the adjacent maximum values are computed. The algorithm looks for the first deviation that is negative (meaning that the correlation value at this time step is lower than the previous time step) and is greater than 8 % of the maximum allowable difference. These conditions ensure that the first strong contour region is captured. This method produces results that rely only on one correlation value for each depth. The quality of the pick might be affected significantly depending on data quality and the number of receivers on the borehole tool. Therefore, a less biased method would be preferable to display the log.

Correlation Ratio Method

The other method to display v_p dispersion is the correlation ratio method, an unbiased technique. Two boundaries are generated automatically to include the maximum correlation region corresponding to first-break arrival. The lower boundary is defined such that the correlation values start to reach 20 % of the maximum possible value. The upper boundary is 10 time steps higher than the lower boundary. The sum of the correlation values corresponding to positive and negative velocity lags within the boundaries are computed (Figure 3a). The ratio of the sums, positive lags to negative lags, are calculated to produce the v_p dispersion log. The result from this method is based on a number of cross correlation values and therefore does not vary greatly with data quality and the number of receivers available in the experiment. This method is therefore chosen for further analysis.

Examples

Yarragadee Aquifer Data

Figure 4 displays the single point resistance log, v_p dispersion log and 15 kHz full waveform data. The v_p dispersion data has been mean-filtered with a depth window of 70 cm. The highly porous groundwater reservoir is characterized by smooth downhole geophysical logs (gamma ray, spontaneous potential, single point resistance and sonic). The newly derived velocity dispersion log, however, identifies a number of zones of elevated P-wave velocity dispersion. An independent MRI-based permeability log is not available for this data set.

Mallik Gas Hydrate Data

Figure 5 displays the MRI (Magnetic Resonance Imaging)-based permeability log, v_p dispersion log and broadband full waveform data. The v_p dispersion data has been mean-filtered with a depth window of 105 cm. A wide range of geophysical logs and petrophysical data are available for this borehole.

The shallow interval (880 – 910 m depth) exhibits elevated v_p dispersion data. This corresponds well with the MRI-based permeability log obtained by Kleinberg et al. (2005). Gas hydrate-rich interval (910 m depth and below) shows low v_p dispersion and low permeability estimates.

Conclusions

P-wave velocity dispersion is observed in both multi-channel full waveform sonic data sets from porous, fluid-filled formation. Higher frequency data corresponds to higher velocities. Two automatic processing methods for extracting P-wave velocity dispersion log are introduced: the maximum correlation method and the correlation ratio method. The latter technique is more desirable due to its unbiased nature. Our case histories indicate that P-wave velocity dispersion logs derived from broadband full waveform sonic data can be used to map relative permeability variation.

Acknowledgments

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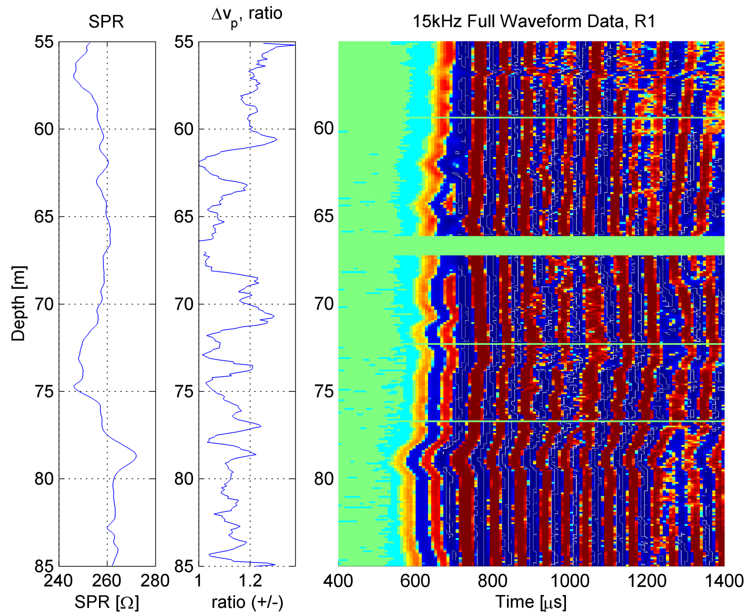

Figure 4: From left to right – single point resistance (SPR) log, P-wave velocity dispersion log computed with the correlation ratio method and the 15 kHz full waveform data recorded by receiver 1. Within the aquifer, the SPR log is smooth while the Δv_p ratios identify zones of high velocity dispersion within the groundwater reservoir.

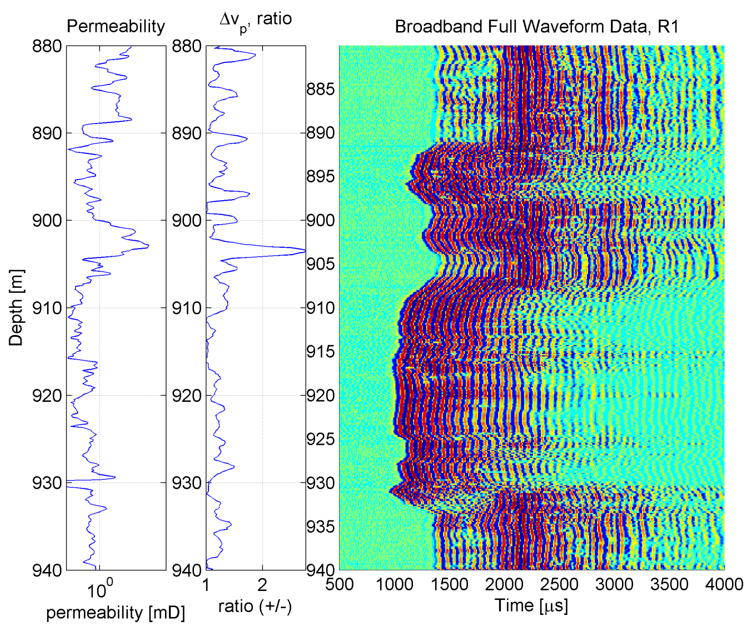

Figure 5: From left to right – MRI-derived permeability log, P-wave velocity dispersion log computed with the correlation ratio method and broadband full waveform data recorded by receiver 1. Fast (early) P-waves correspond to gas hydrate regions. The interval between 880 m and 910 m depth shows both elevated permeability and P-wave velocity dispersion data.

EDITED REFERENCES

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