Paper 101

Detecting Heterogeneity Near a Borehole Using Vibrator VSP Data

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ABSTRACT

Heterogeneity of rocks, such as porosity, fractures, and fluids, causes attenuation and velocity dispersion of seismic waves, and induces waveform distortion. This distortion, once detected, offers an insight into the heterogeneous rock properties. In order to detect small velocity dispersion in the exploration seismic frequency band, a new signal processing method has been developed for uncorrelated vibrator sweeps. This method has been applied to the uncorrelated vibrator VSP data from a borehole in the MacArthur River uranium mine area. Extremely low Q values and significant velocity dispersion have been detected, which is a result of the fractures in the rock volume surrounding the borehole.

INTRODUCTION

Borehole geophysics, as a category of exploration methods, is capable of assessing heterogeneity in the media near a borehole. The standard methods include televiewer, which scans the borehole wall, sonic logging, which measures the sonic velocity with a penetrating distance of centimeter level, and multi-azimuth VSP (Cosma et al., 2003), which can map individual fractures near the borehole. In the seismic bandwidth, it is possible to assess the heterogeneity, such as porosity, fractures, and fluids, in a rock volume near the borehole as a bulk rock property. For example, Figure 1 shows the theoretical attenuation and velocity dispersion in a patchy-saturated porous medium (the single Debye peak model, after Johnson, 2001). In such heterogeneous rocks, seismic waves are distorted by attenuation and velocity dispersion, which are linked through the Kramers-Krönig relation (Bourbié et al., 1987). For a complex medium such as the earth, the quality factor Q is regarded as a constant in a wide frequency band (the constant Q model). Correspondingly, the velocity increases linearly with log frequency on this band (linear dispersion):

$$\frac{V(\omega)}{V(\omega_0)} = 1 + \frac{1}{\pi Q_{\mathrm{kk}}} \ln\frac{\omega}{\omega_0} \qquad (1)$$

where ω is angular frequency. Therefore, velocity dispersion provides an estimate of Q (Q_{kk}), comparing to the Q estimate (Q_{sr}) from the spectral ratio method (Tonn, 1991):

$$\ln\left(\frac{A_s}{A_r}\right) = \frac{\omega t}{2Q_{\mathrm{sr}}} \qquad (2)$$

where As and Ar are the amplitude spectra of the source and the received signals, respectively, and t is the travel time.

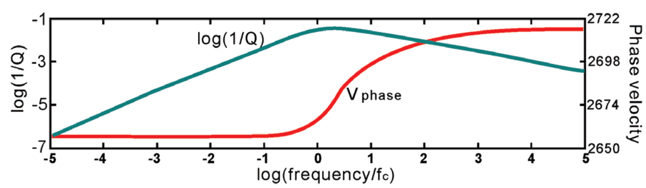

Figure 1: Attenuation and velocity dispersion in a patchy-saturated porous medium, after the theoretical calculation of Johnson (2001). The f_c is the critical frequency of the Debye peak at which the Q^{-1} is the maximum. The velocity dispersion in this model is 2%

Under the assumption of weak attenuation, conventional seismic processing often neglects the effect of velocity dispersion. However, measuring velocity dispersion will provide a better insight of the rock properties. In addition, in strong heterogeneous rocks with Q<30, the velocity dispersion is not negligible in the seismic frequency band (Molyneux and Schmitt, 1999). Thus, it is necessary to develop a robust method to measure attenuation and velocity dispersion in exploration seismic data. It is known that attenuation alters the power spectrum, while velocity dispersion changes the phase spectrum. Raw (uncorrelated) vibrator sweeps are therefore appropriate to accomplish this purpose. Broadband, long-baseline data are desirable to optimize measurements of the small velocity dispersion. The VSP data are preferred because transmission seismograms are easier to analyze than reflective seismograms.

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In Figure 2 the time-frequency (t-f) spectra of an uncorrelated vibrator VSP trace is compared with that of the source sweep using t-f decomposition (Castagna and Sun, 2006). The data was from the borehole 3L-38 gas hydrate research well in

Mallik, Mackenzie Delta, NWT, Canada (Sun and Milkereit, 2006). The wave had traveled through 600m of permafrost, 300m of water-saturated sediments, and 100m of gas hydrates. In the t-f spectrum of the received trace, the bright diagonal stripe is the direct wave. The reflections arrive later and are generally parallel to the direct wave. The events earlier than the direct wave are source-generated harmonics. The stationary noise appears as a vertical stripe at a certain frequency, and random noise is in the background. The effect of velocity dispersion in uncorrelated vibrator sweeps is similar to the Doppler Effect in marine vibrator surveys (Dragoset, 1988). Without velocity dispersion, the t-f relation of the received sweep is parallel to that of the source sweep. With velocity dispersion, the received t-f relation deviates from that of the source sweep.

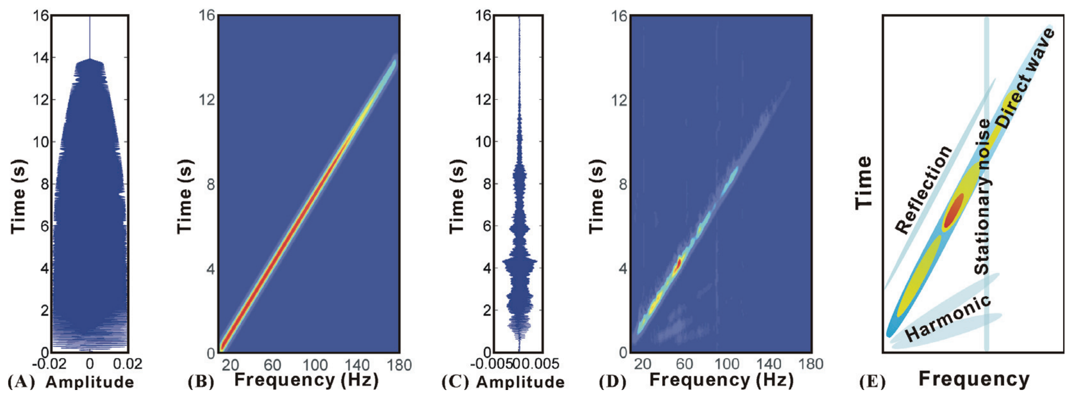

Figure 2: The t-f decomposition of the Mallik vibrator VSP data. (A) The source sweep. (B) The t-f spectrum of the source sweep. (C) The raw received sweep. (D) The t-f spectrum of the received sweep. (E) A sketch of the events in (D). The gray scale in (B) and (D) is amplitude.

In the following section, the method to detect velocity dispersion in uncorrelated vibrator sweeps will be briefly introduced. Then the raw vibrator VSP data from MacArthur River uranium mine MAC218 well, Athabasca Basin, SK, Canada (White et al., 2005; Figure 3), will be analyzed and discussed.

Figure 3: The approximate location of MacArthur River mines within Canada, as indicated by the red arrow.

METHODOLOGY

The key idea of detecting velocity dispersion in uncorrelated vibrator sweeps is to precisely determine the t-f relation of the received sweep. If noise exists, the frequency-domain methods do not produce results of sufficient precision and stability. Thus a time-domain method, the so-called crosscorrelation with a moving window (CCMW) method has been developed (Sun and Milkereit, 2006). In this method the t-f relation is obtained by crosscorrelating the received sweep with a portion of the source sweep, tapered with a time window which centers at a known frequency. In this way the arrival time of an event at this frequency can be determined. As the window moves along the source sweep, the t-f relation is obtained. This method is more robust with noise than the frequency-domain methods, e.g. the cross-spectrum method (Donald and Butt, 2004), thus is more suitable for raw field data without pre-processing.

AN EXAMPLE: MCARTHUR RIVER VIBRATOR VSP DATA

This vibrator VSP dataset was acquired in the borehole MAC218 of MacArthur River mines, Athabasca Basin as a part of EXTECH IV for uranium exploration (White et al., 2005). The area is highly fractured. For the 27m source-borehole offset, the three-component sensors were at depth levels 50–437.5m, with 2.5m interval. The source signal was 12s long, 20–300Hz, or 8s long, 20–200Hz. The sampling rate was 0.5ms. Figure 4 shows the vertical component of the correlated traces. Processing applied to the VSP data shown in Figure 4 includes front muting, 20–300Hz bandpass filter, and 60Hz notch filter. The velocity of the down-going P-wave from first break picking is shown in the right panel of Figure 4. The seismic wavelength ranges from 10m to 200m, which enables the study of the rock properties in a volume near the borehole. The wavefield was highly disturbed in 50–120m and 150–270m zones. This is possibly due to the tube / Stonely waves caused by the fractures.

Velocity dispersion has been studied using the uncorrelated data. As an example, Figure 5 shows the pseudo t-f spectrum of the uncorrelated trace at 347.5m (as marked in Figure 4). The pseudo t-f spectrum is similar to the t-f spectrum in Figure 2, but the color scale is the correlation coefficient obtained from the CCMW method, other than the amplitude from short-window Fourier transform. Different events are well separated in the pseudo spectrum. The arrival time of the down-going P-wave has been picked at different frequencies. The arrival time was not picked for frequencies higher than 150Hz because of low sign-to-noise ratio. Figure 6 shows the velocity dispersion of the down-going P-wave detected from Figure 5. The velocity curve has a trend which is linear to log frequency, and with superposed perturbations. The linear trend is due to the background Q, while the perturbations are possibly due to the single-Debye-peak attenuation, scattering, or interference. The velocity dispersion is as large as 10% in the 30–150Hz band. By fitting Equation 1, the Qkk was calculated as 8 on the 30–150Hz band, compared to the Qsr of 15 on the 90–290Hz band. The spectral ratio of the first break of this trace is shown in Figure 7.

Figure 8 shows the velocity dispersion of the down-going P-wave in all the uncorrelated traces of 27m offset. The velocity estimates in Figure 8 are the average velocities from the source to the receivers. The velocity increases with frequency, and velocity dispersion is more significant above 200m than below. At 100m and 210m, the velocity increases obviously. Figure 9 shows the average Q_{kk} and Q_{sr} profiles. Both Q-estimation methods gave extremely low Q values. In general, the Q is higher at depths >200m, and is the lowest at depths <100m, although there are differences in the Q_{kk} and Q_{sr}. The difference may come from ignoring the non-linear features when conducting linear fitting of the velocity and spectral ratio. The strong velocity dispersion and the low Q values indicate that the surrounding rocks of the borehole are highly heterogeneous.

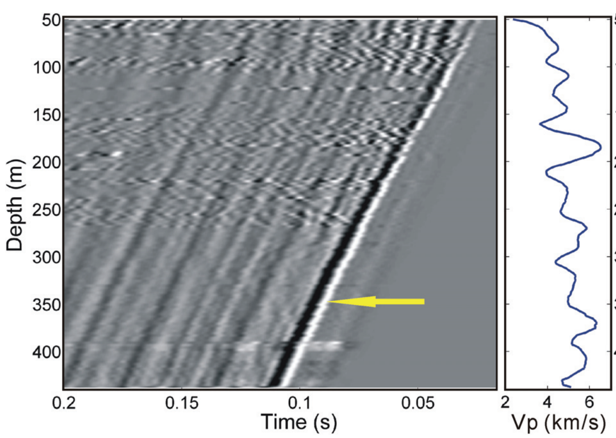

Figure 4: Left panel: The first 0.2s of the correlated vibrator VSP data, filtered and muted, vertical component. From borehole MAC-218 of McArthur River mine, 27m offset. The gray scale is normalized amplitude. The yellow arrow marks the trace at 347.5m. Right panel: The layer velocity of the down-going P-wave from the first break picking.

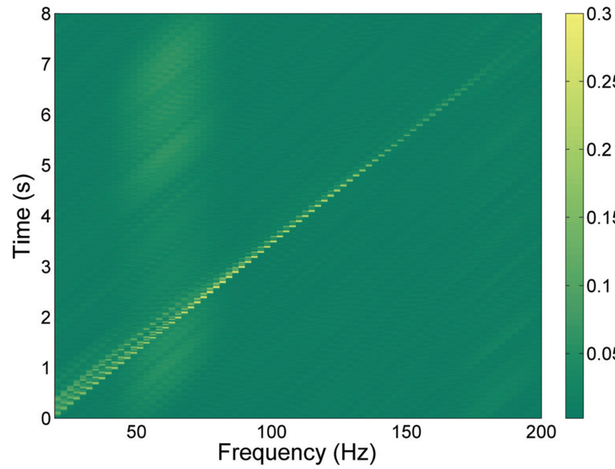

Figure 5: The pseudo t-f spectrum of the uncorrelated vibrator sweep at 347.5m from the CCMW method. The color scale is correlation coefficient.

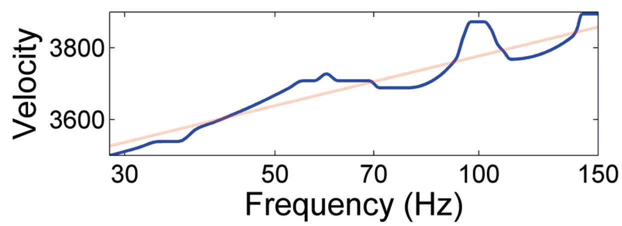

Figure 6: The velocity dispersion of the down-going P-wave in the uncorrelated trace at 347.5m, measured from the pseudo t-f spectrum of Figure 5. The dashed red line shows the linear fit of the velocity curve with respect to log frequency.

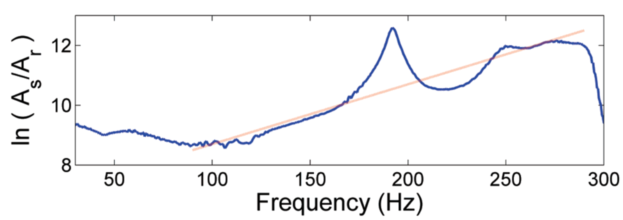

Figure 7: The spectral ratio of the down-going P-wave to the source signal in the trace at 347.5m. The dashed red line shows the linear fit of the ln spectral ratio with respect to frequency. A_s: amplitude of the source signal; A_r: amplitude of the received signal.

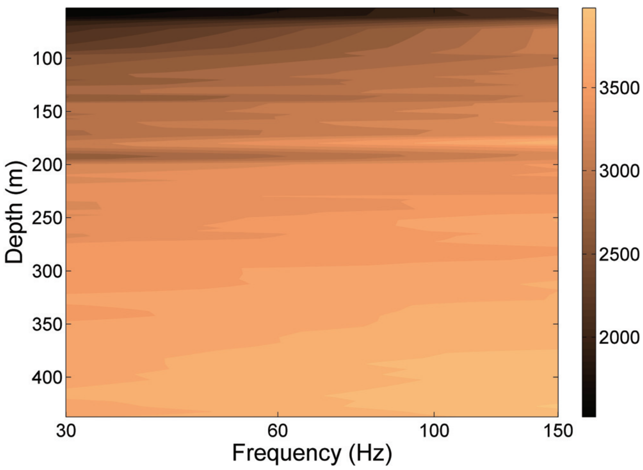

Figure 8: The velocity dispersion of the down-going P-wave with respect to log frequency, detected in the uncorrelated vibrator VSP data from MacArthur River borehole MAC218, 27m offset, vertical component. The color scale is average velocity measured from the source to the receiver.

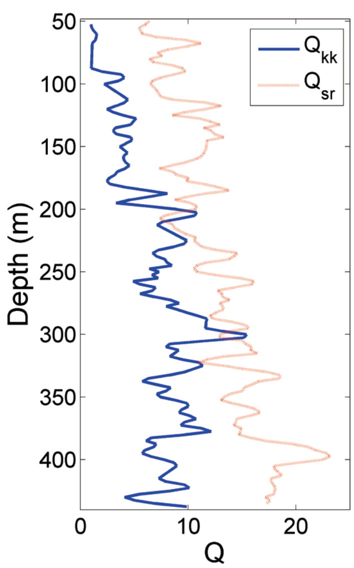

Figure 9: The profiles of the Q_{kk} and Q_{sr} of the down-going P-wave in the vibrator VSP data from MacArthur River borehole MAC218, 27m offset, vertical component. The Q_{kk} and Q_{sr} are from linear fitting as demonstrated in Figures 6 and 7, respectively. The Q_{kk} and Q_{sr} are average values measured from the source to the receiver.

CONCLUSION AND OUTLOOK

Using the uncorrelated vibrator data, extremely high attenuation and significant velocity dispersion have been observed in the MacArthur River borehole MAC218. This indicates that the rock volume in the vicinity of the borehole is highly heterogeneous. Attenuation and velocity dispersion measurements obtained from broadband vibrator VSP data provide new insight into fracture and porosity distribution in the rock volume surrounding an experiment borehole.

As the next stage of our research, the core logs from the borehole MAC218 will be studied to determine the relation between the mechanical rock properties and the observed velocity dispersion and attenuation. Various petrophysical models will be tested to invert the observed attenuation and velocity dispersion in terms of fracture distribution and fluid fill, and other rock properties.

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