Detecting Heterogeneity Near a Borehole Using Vibrator VSP Data

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Introduction

Borehole geophysics is capable of assessing heterogeneity in the media near a borehole. For example,

* Televiewer scans the borehole wall.
* Sonic logging measures the sonic velocity with a penetrating distance of centimeter level.
* Multi-azimuth VSP can map individual fractures near the borehole (Cosma et al., 2003).
* In the seismic bandwidth, it is possible to assess the heterogeneity in a rock volume near the borehole as a bulk rock property, because the wavelength of seismic waves ranges from a few meters to a few hundred meters.

In heterogeneous rocks, seismic waves are distorted by attenuation and velocity dispersion due to fractures, pore fluids, etc (Figure 1). We use a quality factor Q to describe seismic attenuation: $1/Q = \Delta E/2\pi E$, where ΔE is the energy lost in one cycle, and E is the peak energy in the cycle.

Attenuation and velocity dispersion depend on heterogeneity and are linked through the Kramers-Kronig relation (Bourbie et al., 1987). For example, patchy-saturation leads to single Debye peak attenuation (Figure 2). The critical frequency, at which the 1/Q is the greatest, depends on the mechanism of attenuation (Figure 3). The Q in a complex media can be regarded as a constant on a broad frequency band, and correspondingly, the phase velocity increases approximately linearly with log frequency (Figure 4). Using the Kramers-Kronig relation, the Q can be estimated from velocity dispersion (Figure 5).

Figure 1: Rock samples with heterogeneity and fractures. These features will cause attenuation and velocity dispersion for seismic energy.

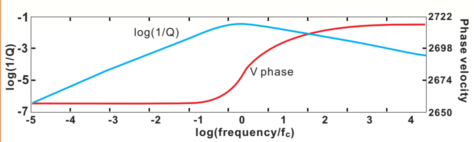


Figure 2: Single Debye peak model of attenuation and velocity dispersion for a patchy-saturated porous medium, after Johnson (2001). The total velocity dispersion is 2%. The f_c stands for critical frequency.

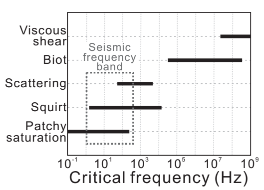


Figure 3: The critical frequency of Debye peaks depends on the mechanism of attenuation.

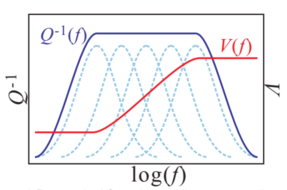


Figure 4: The constant Q model, and the corresponding linear velocity dispersion (i.e., the phase velocity increases with log frequency.

Summary Heterogeneity of rocks, as well as porosity, fractures, and fluids, cause 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.

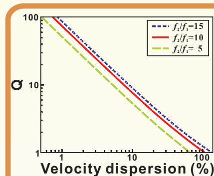


Figure 5: For a constant Q on a frequency band f_1 to f_2, the Q can be calculated from velocity dispersion.

An example: 4% velocity dispersion in 20-200 Hz band is corresponding to Q=20.

The Problem

How to measure attenuation and velocity dispersion convincingly in seismic frequency band?

Methodology

We analyze attenuation and velocity dispersion in transmission seismic waves, i.e., the vertical seismic profiles (VSP). The data acquisition geometry is shown in Figure 6.

Uncorrelated vibrator sweep data are used to measure attenuation and velocity dispersion in the exploration seismic frequency band.

* Both the power and the phase spectra of the vibrator source signal are controllable.
* By comparing the time-frequency (t-f) spectrum of an uncorrelated vibrator VSP sweep with that of the source sweep, the travel time at different frequencies can be determined (Figurew 7 and 8).

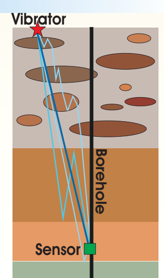


Figure 6: The acquisition geometry of vibrator VSP data used to analyze frequency-dependent attenuation and velocity dispersion.

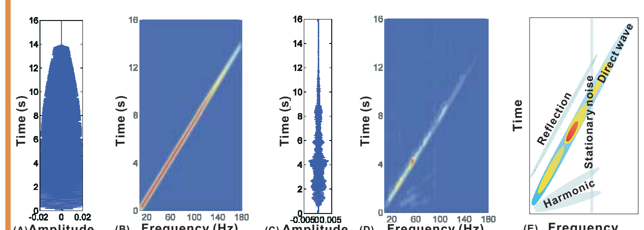


Figure 7: The t-f decomposition of the raw vibrator VSP data. (A) The source sweep. (B) The t-f spectrum of the source sweep. (C) The received sweep. (D) The t-f spectrum of the received sweep. (E) A sketch of the events in (D). The gray scale in (B) and (D) represents amplitude. The data was from a gas hydrate research well in Mackenzie Delta, NWT, Canada (Dallimore et al, 2005). The received wave had traveled through 600 m of permafrost, 300 m of water-saturated sediments, and 100 m of gas hydrates.

An estimate of Q can be calculated from velocity dispersion using Kramers-Kronig Relation.

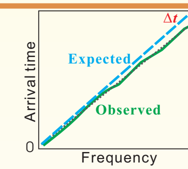


Figure 8: The arrival time difference (Δt) between the expected and the observed arrival times in the t-f relation of an uncorrelated vibrator sweep provides an estimate of velocity dispersion.

The Δt is small. An example: Q=20, i.e. 4% velocity dispersion in 20-200Hz band, source-receiver distance 1000m, average velocity 2500m/s, then the maximum Δt = 15ms.

Examples

1. Athabasca Basin - very low Q

The vibrator VSP data were acquired in Borehole MAC218 in Athabasca Basin (Figure 9) as a part of EXTECH IV for uranium exploration (White et al., 2005). The area is highly fractured metamorphic sediments, which can be observed in the VSP data (Figure 10). For the vibrator survey, the sensor were at depths from 50 to 437.5 m at 2.5 m intervals. The source signal was 20-300 Hz or 20-200 Hz.

Figure 9: Location of Borehole MAC218 in Athabasca Basin (indicated by the red arrow.

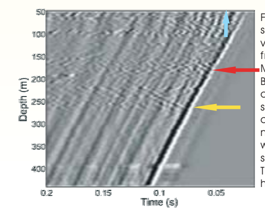
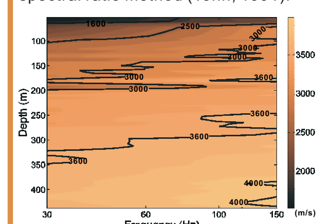


Figure 10: The first 0.2 s of the correlated vibrator VSP traces from Borehole MAC218 in Athabasca Basin, vertical component. The gray scale is normalized amplitude. The arrows mark the depths where strong scattering occurs. Those parts should be highly fractured.

Figure 11 shows the velocity dispersion in the vibrator data. Figure 12 gives the Q estimates calculated from velocity dispersion shown in Figure 11 and the spectral ratio method (Tonn, 1991).



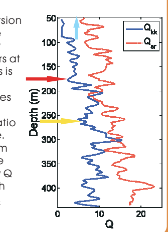


Figure 11 (left): Velocity dispersion of the down-going P-wave. The color scale is average velocity from the source to the receivers at depth. Note the frequency axis is in log scale.

Figure 12 (right): The Q estimates calculated from velocity dispersion (Q_{kk}) and spectral ratio (Q_{sr}) of the down-going P-wave. They are average Q values from the source to the receivers. The arrows indicate where very low Q values appear, comparing with the arrow in Figure 10. Note Q_{kk} and Q_{sr} were calculated on different frequency band.

2. Outokumpu, Finland - crystalline rocks and moderate Q

For comparison, the uncorrelated vibrator data from the ICDP borehole in Outokumpu, Finland (Figure 13) were analyzed. The source sweep was 20-120 Hz. The sensors were at depths between100 m and 2300 m with100 m interval. The velocity dispersion is shown in Figure 15. Correspondingly, The Q increases from about 10 at the top to over 50 at the bottom.

Figure 13: Location of Outokumpu, Finland (the red star).

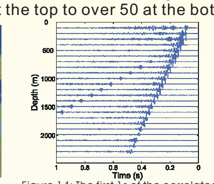


Figure 14: The first 1s of the correlated vibrator VSP traces from Outokumpu, Finland, vertical component.

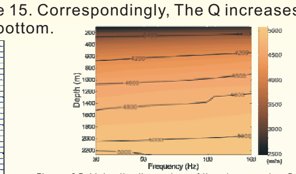


Figure 15: Velocity dispersion of the down-going P-wave. The color scale is average velocity from the source to the receivers at depth. The velocity dispersion on 30-160 Hz reduces from about 5% in the upper part to <1% in the bottom.

Conclusion and Outlook

Using the uncorrelated vibrator data, extremely high attenuation and significant velocity dispersion have been observed in the Athabasca Basin data. This indicates that the rock volume in the vicinity of the borehole is highly heterogeneous. On the contrary, velocity dispersion is much weaker in the Outokumpu data, which were from crystalline rocks. We can see, 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 boreholes will be studied to determine the relation between the mechanical rock properties and the observed velocity dispersion and attenuation. More 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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