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Attenuation, Velocity Dispersion and the Fate of the Vibroseis Signal

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Abstract

Small velocity dispersion caused by attenuation will have a detrimental effect on conventional Vibroseis correlation processes. In seismic survey areas with strong attenuation, uncorrelated Vibroseis data should be acquired and Q-dependent Vibroseis deconvolution should be applied prior to correlation. It should be noted, however, that velocity dispersion of the Vibroseis signal, once detected in VSP data, will provide new insights into fluid, fracture and porosity related attenuation processes.

Background

For seismic imaging, we cannot separate the effects of attenuation and velocity dispersion. Any anelastic process in the earth will lead to the dissipation of seismic energy. Dissipative effects demand frequency dependent modification of the elastic moduli (and consequently introduce frequency dependent velocities). For causal attenuation, this leads to pulse broadening. For given rheological models, enhanced attenuation occurs across a restricted range of seismic frequencies (Debey peaks). The sum of a large number of Debey peaks may produce a broad and flat absorption band over a wide range of frequencies (Cormier, 1989). In classical seismology, the spectral ratio method (Tonn, 1991) is often applied to obtain an estimate of attenuation coefficients due to fractional loss of energy per wavelength.

Whether we adopt a near constant attenuation model or focus on a specific dissipation process, we will have to deal with velocity dispersion. In general, larger attenuation is associated with larger velocity dispersion. Once a velocity dispersion relation is established for a wide range of frequencies, we can use the Kramers-Kronig relations to compute an attenuation model (Mavko et al., 1998). Often, velocities and attenuation are available for selected frequencies in the KHz or MHz range. For fluid-related velocity dispersion, for example, the characteristic frequency defines the range in which velocity changes most rapidly. It must be noted that characteristic frequency for patchy saturation, squirt flow and scattering mechanisms fall into the frequency band commonly used for exploration seismic studies (Mavko et al., 1998; Khan and Khan, 2005). Nevertheless, velocity changes as a function of frequency are expected to be relatively small for large Q values.

Methodology

An experiment utilizing broadband seismic data (within the exploration seismic bandwidth) must be designed to measure velocity dispersion or pulse broadening. Here we present results from a unique field experiment to measure velocity dispersion for seismic frequencies used in exploration.

First, we require a long, fixed baseline as velocity dispersion may be small over the estimated frequency range. Zero offset Vertical Seismic Profiling (VSP) surveys offer such data acquisition geometry. Secondly, we require a seismic source with a well-defined source function and a controlled frequency-phase relationship, ideally provided by a broadband uncorrelated Vibroseis signal. Thirdly, we decompose the recorded uncorrelated VSP signal into time-frequency maps based on multi-taper spectral analysis. Time-frequency displays are a classical quality control tool for monitoring the performance of Vibroseis sources. For example, these displays are useful to detect source generated harmonic distortions.

These time-frequency decomposition displays provide us with complete information regarding the frequency dependence of velocities. In particular, any mechanism with peaked attenuation (Debey peak) can be evaluated with the help of the Kramers-Kronig relation for linear visco-elastic materials. Once the method was established, it was applied to real VSP data collected at the Mallik 3L-38 gas hydrate research well in the Mackenzie delta in the Northwest Territories (Milkereit et al., 2005). This data set is ideal because of suitable survey parameters (uncorrelated Vibroseis data, long baseline up to 1200 m depth, 8-180Hz bandwidth within linear sweep) and geological setting (permafrost, gas hydrates and water-saturated sediments) which provides observable seismic attenuation with depth.

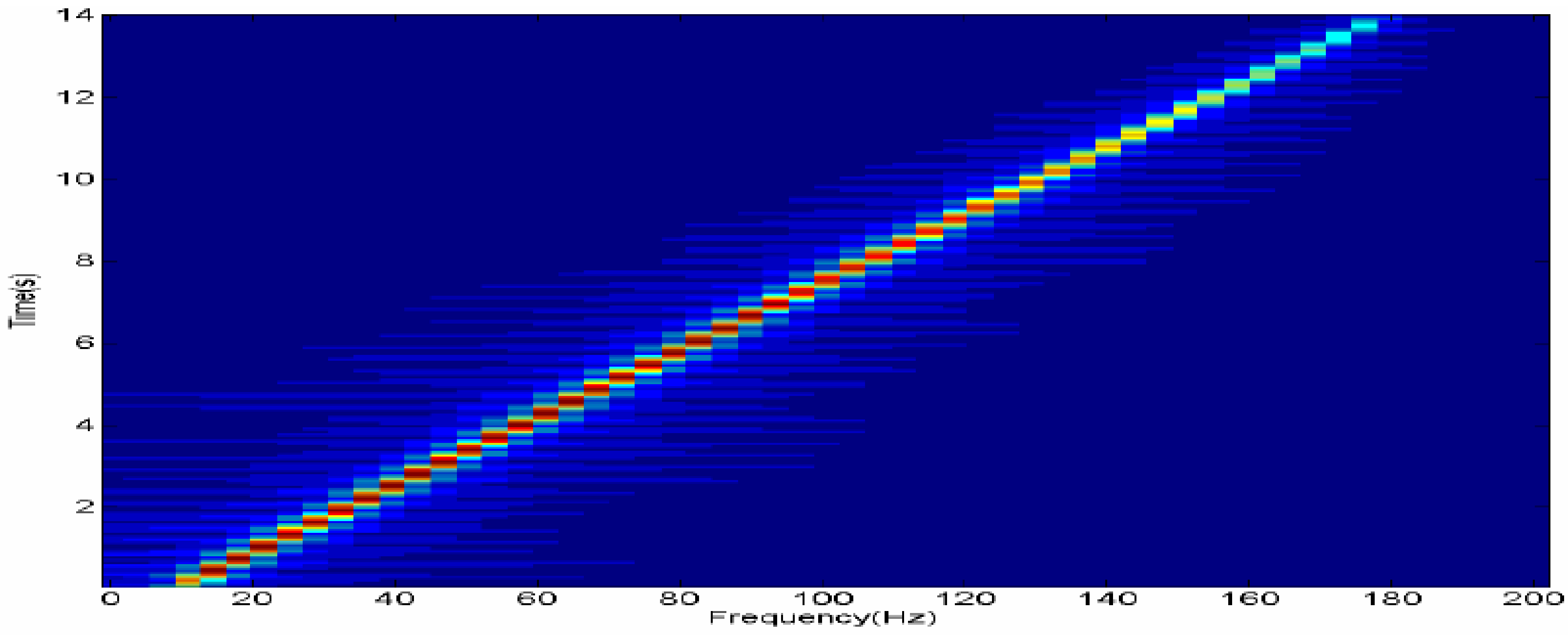

Figure 1. Time-Frequency decomposition of the 14 second long, 8-180Hz Vibroseis source signal.

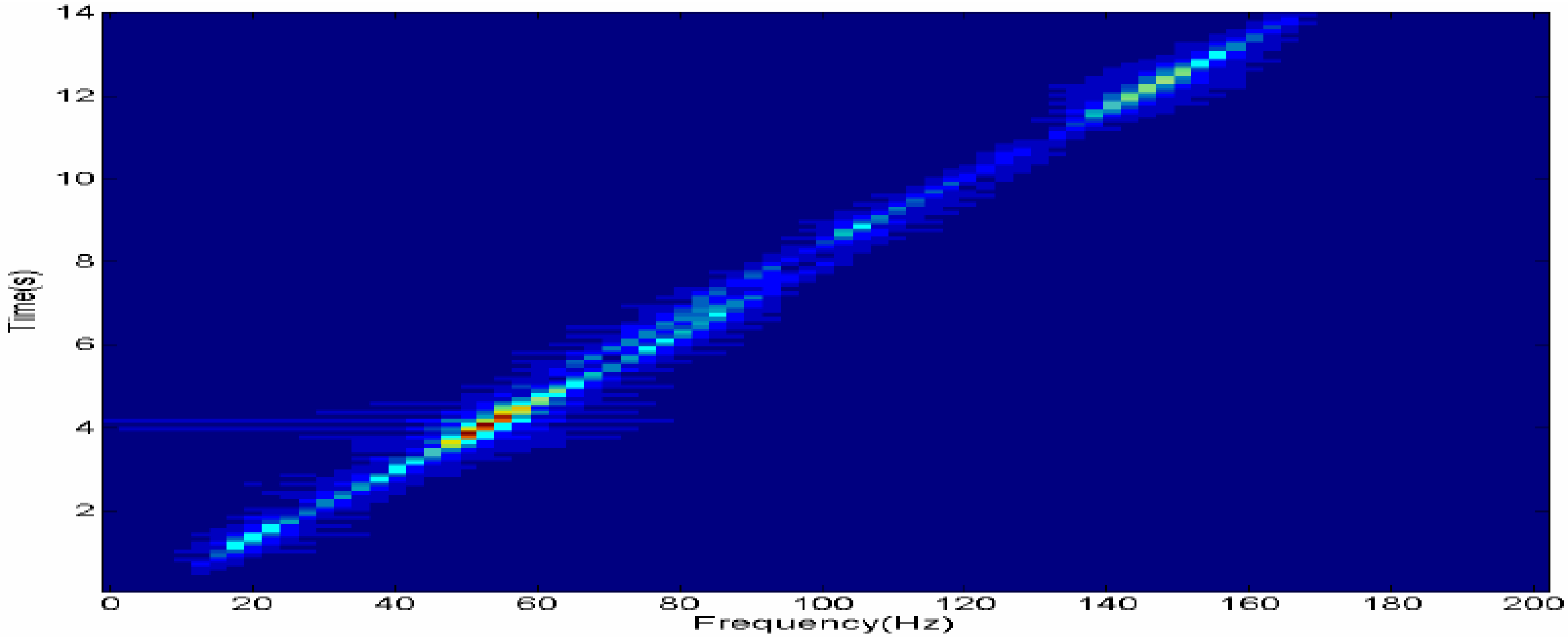

Figure 2. Time-Frequency decomposition of the 14 second long, 8-180Hz Vibroseis signal recorded at the depth of 1145 m in the Mallik 3L-38 well. The Vibroseis sweep traveled through 600 m of permafrost, 300 m of water-saturated sediments, and 200 m of gas hydrates.

Fig. 1 shows the time-frequency decomposition of the linear 14s Vibroseis sweep (8-180 Hz) with no distortion. Fig. 2 shows the distorted time-frequency decomposition of the uncorrelated Vibroseis signal recorded at 1145 m depth.

The Effect of Velocity Dispersion

A constant Q-model will give rise to a linear velocity increase with frequency (Cormier, 1989). To illustrate the effect of velocity dispersion on the Vibroseis correlation, we apply a linear time shift to the uncorrelated sweep (a simple stretch or compression of the sweep) prior to correlation. Figures 3 and 4 show that even minor travel time changes (in terms of ms) will alter the correlation process. The perfect zero-phase correlation wavelet only exists without velocity dispersion. Fig. 4 gives a 3-D presentation of the correlated data shown in Fig. 3 to highlight the rapid distortion (loss of peak amplitudes) of the correlated wavelet.

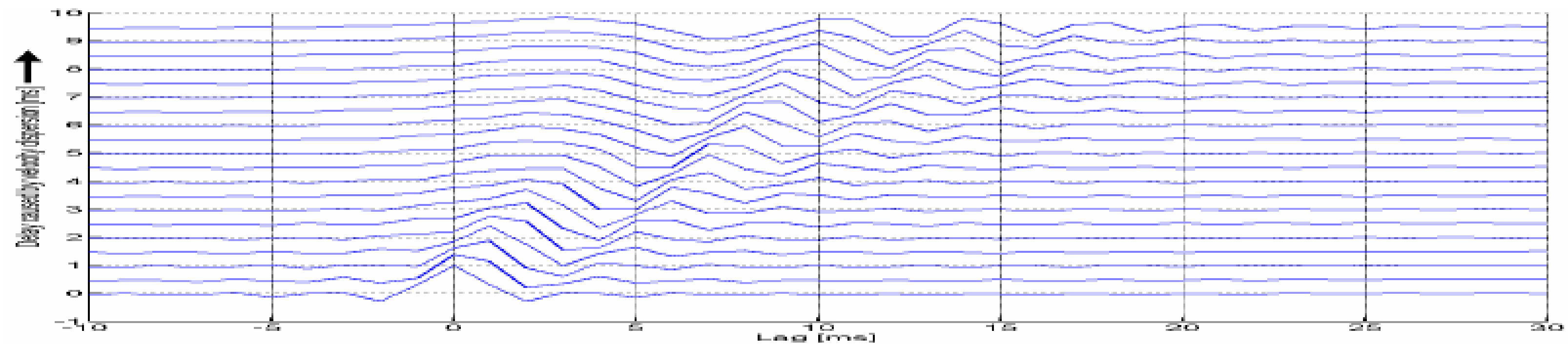

Figure 3. Change in Cross-Correlations with increase in linear delay caused by velocity dispersion. Note the rapid distortion of the correlation wavelet for small delays.

Consequences

As seismic attenuation is linked to velocity dispersion, we have to deal with a number of issues concerning correlation-based seismic data acquisition techniques.

1. Velocity dispersion as low as 0.25% can be observed in uncorrelated VSP data. Such minor velocity changes may severely distort the Vibroseis signal recorded at depth and the subsequent Vibroseis correlation process.
2. In survey areas where seismic attenuation is a problem, uncorrelated Vibroseis data should be acquired.
3. The time-frequency decomposition of uncorrelated Vibroseis VSP data can be used for velocity dispersion and Q estimation. This kind of velocity dispersion analysis can provide the basis for new seismic transmission spectroscopy applications in exploration seismology.
4. The potential distortion of seismic source functions is not limited to conventional land-based Vibroseis recordings, but may be interpreted for all seismic field and lab-based techniques using chirps such as borehole-to-borehole tomography systems, DTAGS and marine Vibroseis systems.

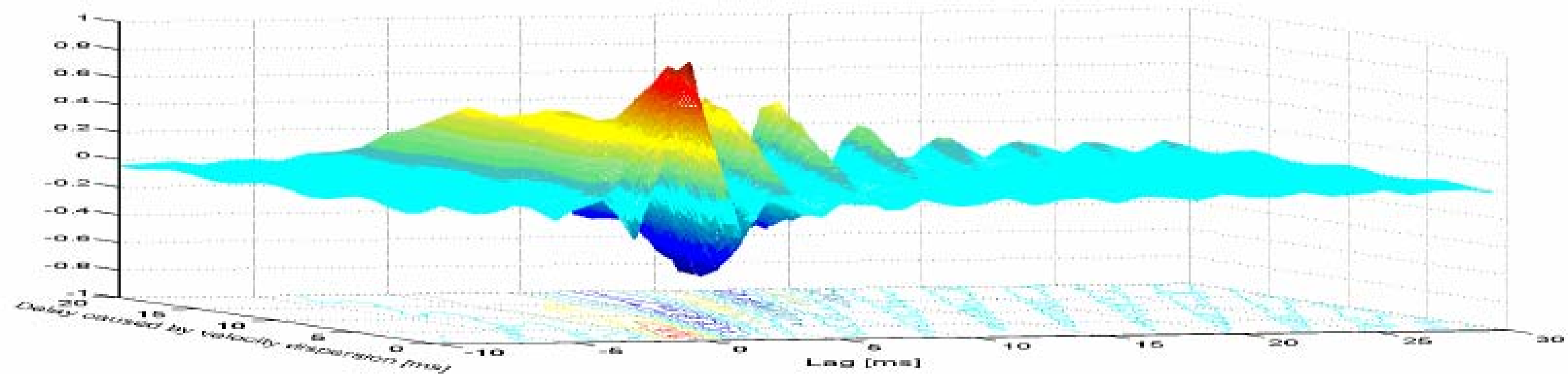

Figure 4. 3D representation of change in cross-correlations with increase in delay caused by linear velocity dispersion. Note the rapid decay of peak amplitude for small delays.

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