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Velocity Dispersion in Field Seismic Data: Impact, Detection and Application

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Abstract

Seismic waves in a porous medium experience attenuation and velocity dispersion from various energy absorbing mechanisms. In conventional seismic data processing, velocity dispersion is neglected partially because of insufficient and inconclusive observations. However, recent theoretical and laboratory studies indicate that attenuation and velocity dispersion are "two sides of the same coin" and that in a medium of high attenuation (e.g. $Q<30$), velocity dispersion is a concern. Of special interest are Vibroseis profiles, in which the seismic data are cross-correlated with the source signal to get the correlation seismograms. Computer simulation shows that small velocity dispersion may introduce fatal distortion to the correlation seismograms.

In order to detect and measure velocity dispersion in the exploration seismic frequency band, uncorrelated broadband Vibroseis VSP data are utilized. The advantages of this type of data include the controllability of both the power and phase spectra of the source signal, which makes it possible to analyze frequency-dependent attenuation and velocity dispersion by means of seismic spectroscopy. Different approaches (cross-spectrum, time-frequency decomposition, and cross-correlation with moving window) have been investigated using simulated data to design a robust method of measuring velocity dispersion in Vibroseis data. Frequency-dependent velocity variations are observed in the borehole Vibroseis data from the Mallik gas hydrate research wells (Mackenzie Delta, NWT, Canada).

Velocity dispersion and frequency-dependent attenuation in field seismic data provide an important link between the seismic and the petrophysical parameters. By measuring them, we can improve the understanding of attenuation mechanisms in hydrocarbon reservoirs.

Introduction

Seismic waves in a porous medium experience attenuation and velocity dispersion from various energy absorbing mechanisms. The frequency dependence of attenuation and velocity dispersion varies with materials and their conditions, such as saturation, porosity, permeability and shape of the target. Theoretical studies indicate that a causal link exists between attenuation and velocity dispersion. For example, in a Q model independent of frequency, seismic velocities increase mildly with frequency at a constant rate. Generally, a smaller Q is associated with greater dispersion (Mavko et al., 1998). According to Molyneux and Schmitt (1999), velocity dispersion is not negligible in a medium with Q less than 30.

In conventional seismic data processing and interpretation, attenuation models that are independent of frequency are adopted, while velocity dispersion is neglected. This simplification can explain the phenomenon that the high-frequency components of a seismic wave are attenuated faster than the low-frequency components do, and is believed to yield satisfying results. However, there are insufficient observations directly verifying it, especially with respect to field seismic data. Most of the measurements are from theoretical studies or laboratories (e.g. Johnson, 2001; Fjær et al., 2005). On the other hand, if velocity dispersion does exist, the induced waveform distortion could be fatal in some circumstances. The two key questions are in exploration seismology, how do we detect seismic velocity dispersion convincingly for a broad band of frequencies; and once detected how to use it for data correction and interpretation.

Waveform Distortion due to Velocity Dispersion

Computer simulations were conducted to investigate the waveform distortion in Vibroseis data due to velocity dispersion. Ideally, correlation of the received and the pilot sweep produces a zero-phase wavelet at the arrival time of an event. However, the results revealed that the conventional correlation process could be detrimentally affected by small velocity dispersion. Two cases have been investigated. The first was linear velocity dispersion, i.e. seismic velocity increasing with frequency at a constant rate. This was simulated by "squeezing" the chirp for a minor amount. The correlated wavelet was rapidly distorted, as squeezing was a few milliseconds (Fig. 1). Another test simulated the effect of a single-Debye-peak Q model (Fig. 2a, from Toms et al., 2005). Fig. 2b shows the correlation wavelet being distorted as propagation distance changing. In both experiments, peaks of the correlation wavelets drifted away from the zero lags, where they were supposed to be, and were no longer symmetric. The input chirp in those tests was 14s long, with frequency increasing linearly from 8 to 180Hz.

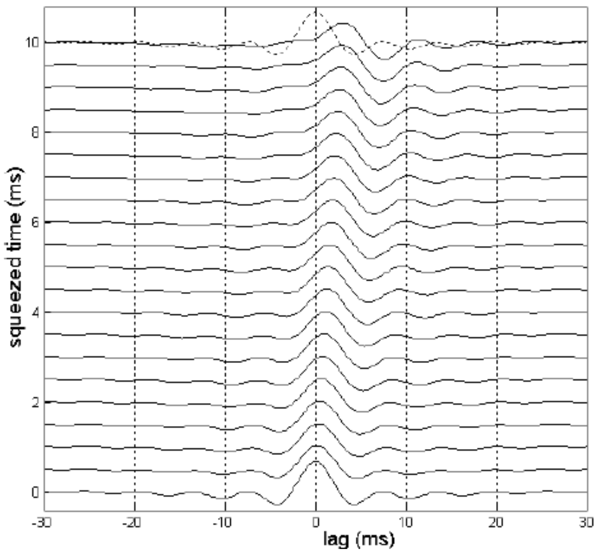


Figure 1. Distorted correlation wavelet versus "squeezing" time of the Vibroseis chirp, to simulate the effect of linear velocity dispersion. Waveform of the dashed line at the top trace is the same as that at the bottom, for comparison. The input chirp was 14s long, with frequency increasing linearly from 8 to 180Hz, attenuation not considered.

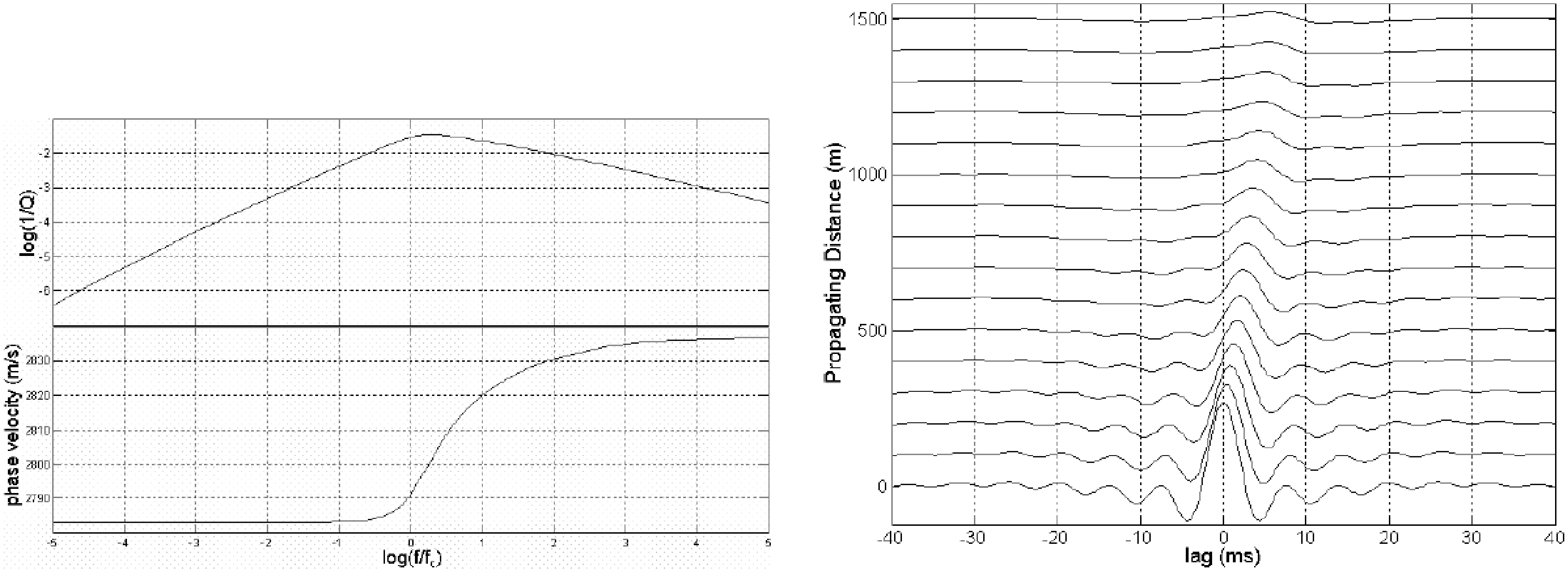


Figure 2. Left: the single-Debye-peak Q and phase velocity models (from Toms et al., 2005). Right: Distorted correlation wavelet versus propagation distance. The input chirp was the same as that in Fig. 1, f_c=20Hz.

Another observation from computer simulations was that velocity dispersion was more obvious if f_c was in the Vibroseis frequency band, e.g. 20Hz. This was because the phase velocity in a single-Debye-peak Q model changed rapidly in a narrow frequency band around f_c, whereas it was nearly constant elsewhere. Since the exploration seismic frequency band may be within the range of f_c of the attenuation mechanism of patchy saturation, which exists extensively in oil and gas reservoirs, the phenomenon of velocity dispersion should exist in seismic data, especially from the areas where Q is low, regardless of source type (Vibroseis, dynamite, etc).

Method

To determine how severe the field seismic data are contaminated by velocity dispersion, a robust data analysis method must be developed to detect and quantify it. Noticing in frequency domain, attenuation mechanisms alter the amplitude spectrum, while velocity changes are equivalent to phase shifts, raw (uncorrelated) Vibroseis data are deemed to be appropriate to investigate the frequency dependence of attenuation and seismic velocities, because both the amplitude and phase spectra of the source signal are controllable. Thus, the attenuation and velocity dispersion can be calculated by comparing the spectra of the pilot and the received signals. Broadband, long baseline data are desirable to maximize the observability of the small velocity dispersion. As far as data acquisition geometry is concerned, vertical seismic profile (VSP) data are preferred because transmissive seismograms are easier to analyze. Three approaches have been investigated to detect phase velocity dispersion in Vibroseis data. The first is cross-spectrum method (Donald and Butt, 2004), in which the phase travel time is

$$t(f) = \Theta(f) / 2\pi f$$

where $\Theta(f)$ is the phase spectrum of the cross-spectrum of the source and received signals, smoothed if noise is present. The phase velocity is then

$$V_p(f) = l / t(f)$$

where l is the traveling distance. This approach is the most efficient one, giving out results of the highest resolution in all the three approaches on a sound theoretical basis, applicable for either Vibroseis or impulse-source data. Donald and Butt (2004) have successfully measured phase velocity dispersion with this method in their rock experiments. Unfortunately, it dose not work satisfyingly for field seismic data. A fatal problem appears when there are multiple events in the seismic data, which happens frequently in field seismic data. Spectra representing different events superpose each other and cannot be separated. In addition, it is sensitive to noises. Fig. 3 is an example of this method. The Vibroseis trace is from the Mallik 3L-38 VSP gas hydrate research well in Mackenzie Delta, NWT, Canada (Dallimore et al., 2005). The source signal was an 8-180Hz linear sweep of 14s long, offset 137m, sensor depth 1025m. The received trace was stacked, containing a single event. The travel time curve was smoothed with a 100-point window. It came out that the calculation was not stable at the low and high frequencies, where signal-to-noise ratio was low.

Another approach is time-frequency decomposition (Milkereit et al., 2005). It is to extract part of a Vibroseis trace (the source and the received, separately) with a narrow window moving along this trace, apply Fourier transform to each part of the waveform, pick the time points with maximum amplitudes for each frequency component on the direct event as the arrival times, and to subtract the arrival times of the source sweep from those of the received trace to get the travel times. Longer window length gives higher resolution of frequency, but smears the time-frequency relation of the trace, and requires longer computing time. Fig. 4 is an example of this method, using the same Vibroseis trace as that in Fig. 3. For the apparent reasonableness, this method is actually not practical, because it handles noises poorly. The advantage of this method is that it can be used to analyze frequency-dependent attenuation using spectral ratio method as described in Tonn (1991).

The third approach is cross-correlation with a moving window. This is to extract part of the source signal with a narrow moving window, cross-correlate each part of source signal with the received trace, and then find the maximum cross-correlation coefficients on the direct event for each window position. The central frequency of that part of the source is taken as the component's frequency. Fig. 5 is a demonstration of this method, using the same Vibroseis data as above. Considering convolution in time domain is equivalent to multiplication in frequency domain, this method should be essentially equivalent to the cross-spectrum method. A fact is that the window length here is related to the number of points for smoothing in the cross-spectrum method; a longer window suppresses noises better but smears the result heavier. Fig. 6 compares the results using these two methods. They matched each other quite well in the frequency band where the signal-to-noise ratio was high enough for the cross-spectrum method to be stable.

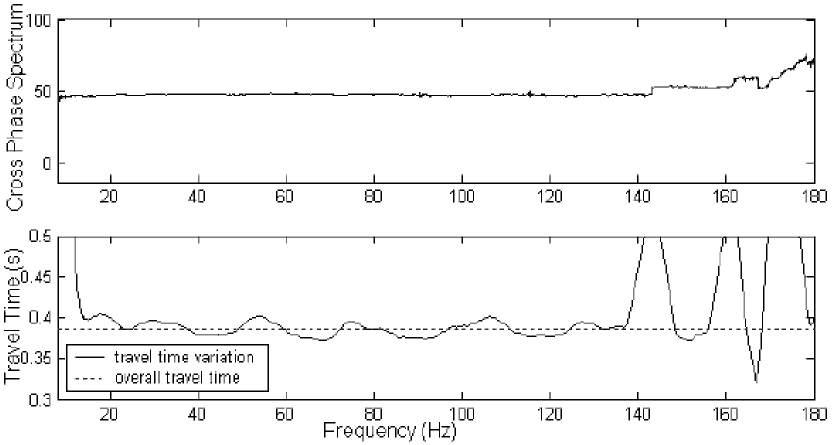
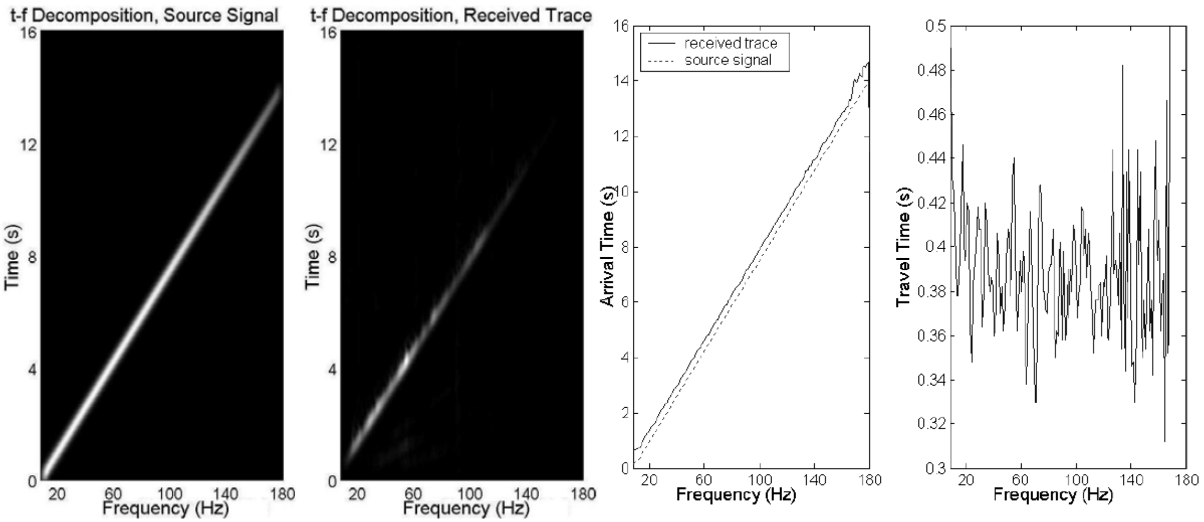


Figure 3. A demonstration of calculating travel time varying with frequency using cross-spectrum method. The Vibroseis trace is from the Mallik 3L-38 VSP gas hydrate research well, Mackenzie Delta, NWT, Canada, sensor depth 1025m, offset 137m, source signal 14s long, 8-180Hz linear sweep. The travel time curve was smoothed using 100 points. The calculation was not stable at the low and high frequencies, where signal-to-noise ratio is low.


t-f Decomposition, Source Signal

t-f Decomposition, Received Trace

Figure 4. A demonstration of calculating frequency-dependent travel time using time-frequency decomposition method, for the same Vibroseis trace as that in Fig. 3. Notice this method dose not produce robust travel time estimates (the most right diagram). The gray scale in the right two diagrams is amplitude.

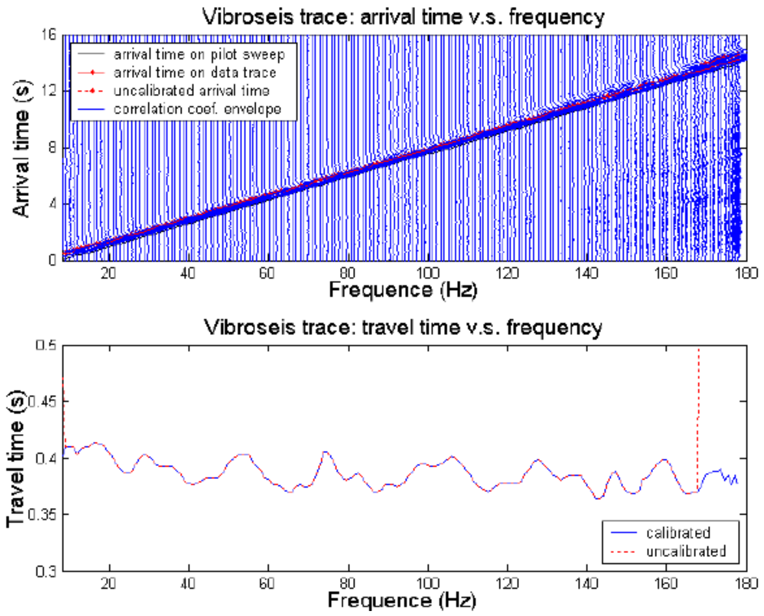


Figure 5. Cross-correlation with a moving window for frequency-dependent travel time, for the same Vibroseis data in Fig. 3. Calibration was to make sure the arrivals on the direct event were picked. Travel time deviation is 1.8% on average, 3.9% maximum.

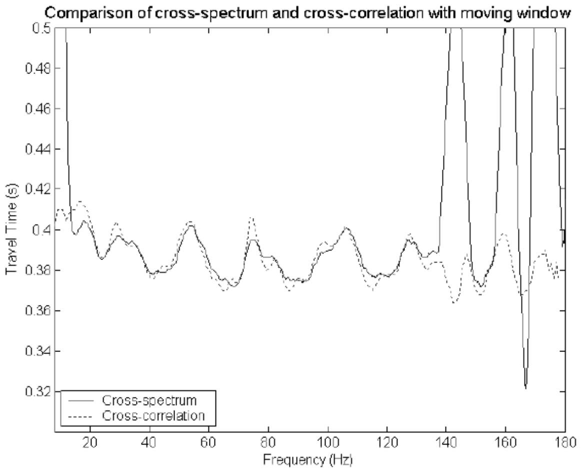
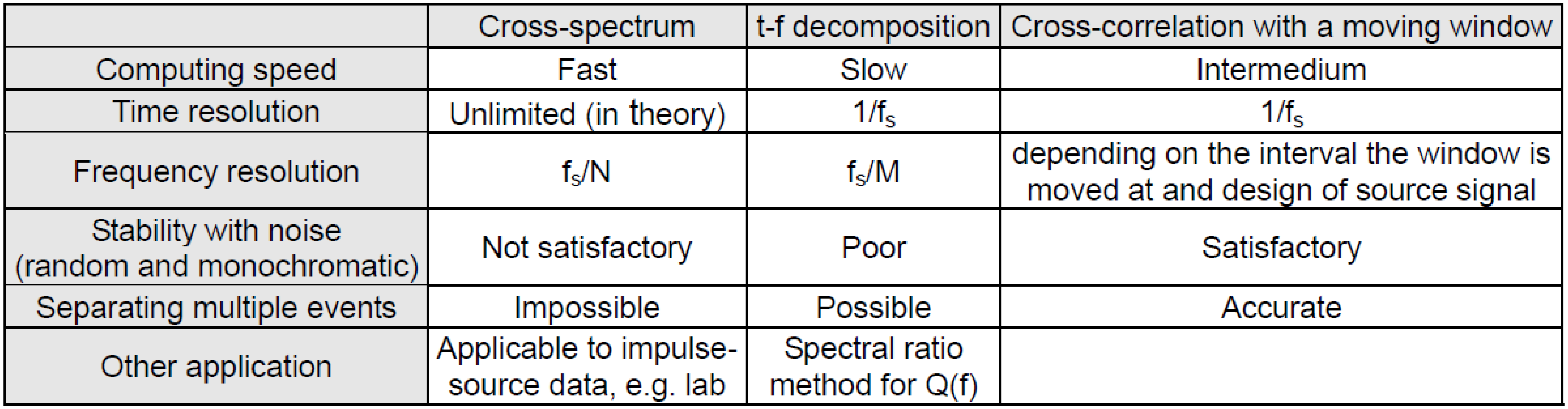


Figure 6. Comparison of the results from cross-spectrum (Fig. 3b) and cross-correlation (Fig. 5b) methods. They are consistent with each other in the frequency band of 20-130Hz, where the cross-spectrum method provides stable results.

Table 1 summarizes and compares the three methods. In general, the method of cross-correlation with a moving window is stable, and produces satisfying result. Systematic variations of travel time with frequency have been detected using this method in the Mallik Vibroseis data (Fig. 7). This indicates that result of this method is reproducible. The depths of the 15 sensors are from 1145m to 935m every 15m, offset -22m; the source signal was the same as above.



	Cross-spectrum	t-f decomposition	Cross-correlation with a moving window
Computing speed	Fast	Slow	Intermedium
Time resolution	Unlimited (in theory)	$1/f_S$	$1/f_S$
Frequency resolution	f_S/N	f_S/M	depending on the interval the window is moved at and design of source signal
Stability with noise (random and monochromatic)	Not satisfactory	Poor	Satisfactory
Separating multiple events	Impossible	Possible	Accurate
Other application	Applicable to impulse-source data, e.g. lab	Spectral ratio method for Q(f)	

Table 1. Comparison of the three methods to detect travel time variation with frequency. Above: f_s, sampling rate; N, number of points in the Vibroseis trace; M, number of points of the moving window.

Prospective Applications

The application of detecting velocity dispersion in exploration seismic data includes two aspects. First, if we can observe it convincingly, we can develop a method to correct the distortion induced to the seismic data. Ignoring velocity dispersion when processing Vibroseis data from low Q areas is likely to drop much of the intrinsic seismic character of the data and therefore will introduce artifacts. A better correction method should be able to adjust both Q(f) and velocity dispersion.

Second, to use the estimates of Q(f) and velocity dispersion for data interpretation. Those estimates should offer a bridge connecting seismic data and petrophysical features, and provide new insights into fluid, fracture, porosity, etc. If we can link the velocity dispersion observed in seismic data and the petrophysical features, it will be of great help for seismic data interpretation and inversion.

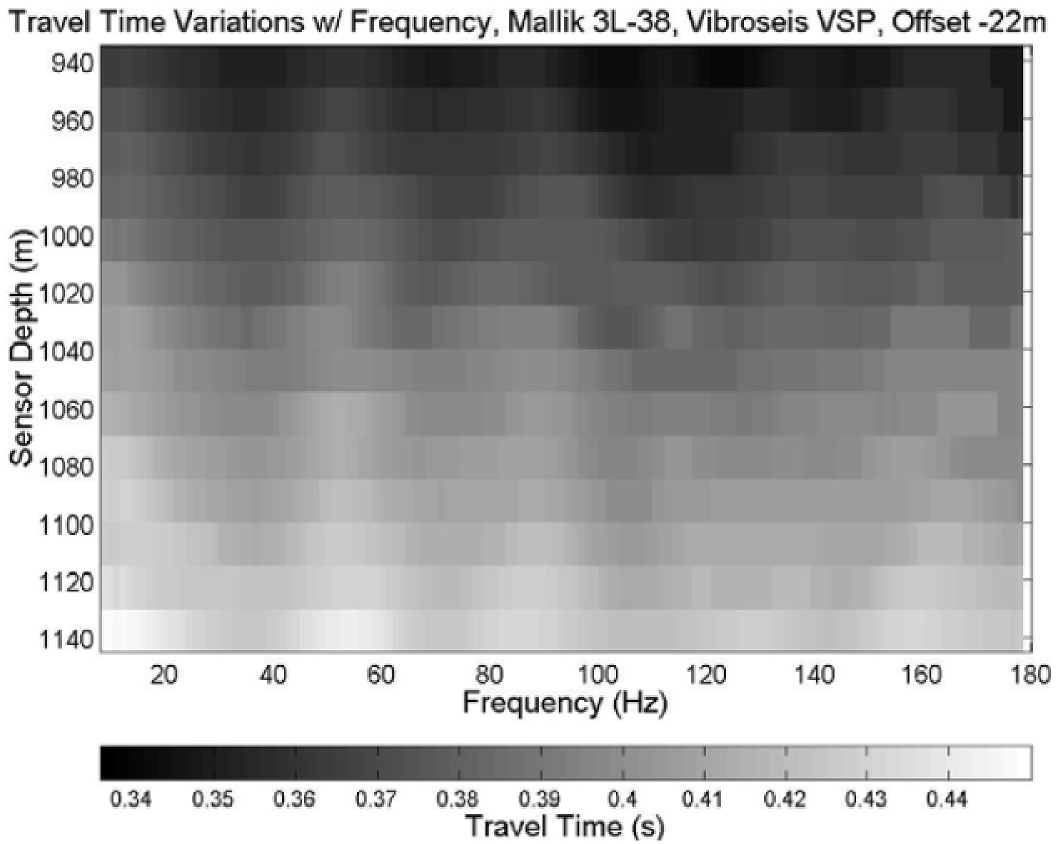


Figure 7. Travel time varying with frequency in Mallik 3L-38 VSP Vibroseis data. Sensor depth 1145m to 935m, every 15m, offset -22m. The travel time fluctuations are systematic for all these 15 depths.

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