Synthetic Zero-offset VSP Including Attenuation

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Abstract

The zero-offset synthetic VSP seismograms were created on a horizontally layered medium with constant-Q attenuation by a 1-D, two-way wavefield extrapolation approach. The amplitude variation of the downgoing waves is verified by the comparison of the input Q and estimated Q. The travel distance, amplitude and polarity of the deconvolved upgoing waves are consistent with the variation in the impedance estimated from log data. The corridor stacking over the deconvolved upgoing waves is close to Well-log synthetic seismogram. The result shows that the synthetic VSP seismogram is accurate.

Principle of 1-D, two-way wavefield extrapolation

Considering a plane, compressional wave normally incident in a horizontally layered anelastic medium, the Fourier component of the wavefront at depth z can be expressed as

$$\hat{s}(z,\omega) = D(\omega)exp\left(-\frac{\omega z}{2Q(z)v(\omega)}\right)exp\left(-i\frac{\omega z}{v(\omega)}\right) + U(\omega)exp\left(\frac{\omega z}{2Q(z)v(\omega)}\right)exp\left(i\frac{\omega z}{v(\omega)}\right), \tag{1}$$

where $D(\omega)$ is the Fourier spectrum of the downgoing source signature and $U(\omega)$ is the Fourier spectrum of the upgoing source signature. Q and $v(\omega)$ are quality factor and phase velocity respectively. Equation (1) is similar to the equation given by Ganley (1981). Using 1-D wavefield extrapolation method, this equation is extended to generate zero-offset VSP synthetic seismograms for a many-layered model derived from a real sonic and density log.

If $D(z,\omega)$ is the Fourier spectrum of the downgoing wavelet at the depth z , then the downgoing wavelet at $z+\Delta z$ is given by

$$D(z+\Delta z,\omega) = D(z,\omega)exp\left(-\frac{\omega|\Delta z|}{2Q(z)v(z,\omega)}\right)exp\left(-i\frac{\omega\Delta z}{v(z,\omega)}\right), \tag{2}$$

where Δz is the depth step which should be much less than the minimum thickness of any layer in the model. In the same manner, the upgoing wavelet, $U(z+\Delta z,\omega)$, is expressed by

$$U(z+\Delta z,\omega) = U(z,\omega)exp\left(-\frac{\omega|\Delta z|}{2Q(z)v(z,\omega)}\right)exp\left(i\frac{\omega|\Delta z|}{v(z,\omega)}\right), \tag{3}$$

where $\Delta z > 0$ for the downgoing waves and $\Delta z < 0$ for the upgoing waves. Equation (2) is used to move the primary wavefield downward while equation (3) moves the reflected primary wavefield upward. Multiples are not modeled.

For the normal-incidence VSP in n layers over a half space, we can include reflections and transmissions in the zero-offset VSP seismogram in anelastic media as follows. First the lager depths of the model are all shifted slightly to fall exactly on a depth step. This causes minimal error if Δz is much smaller than the larger thickness. Then we use equations (2) and (3) to extrapolate the downgoing wavefield and the upgoing wavefield. If the wavefield is reaches the j^{th} interface, the downgoing and upgoing waves transmitted to the next layer is given by

$$\begin{bmatrix} D'(z=h_j,\omega) \\ U'(z=h_j,\omega) \end{bmatrix} = \begin{bmatrix} 1-R_j & 0 \\ \frac{-R_j}{1+R_j} & \frac{1}{1+R_j} \end{bmatrix} \begin{bmatrix} D(z=h_j,\omega) \\ U(z=h_j,\omega) \end{bmatrix}, \tag{4}$$

where D' and U' are the downgoing wavefield, the explicit "0" suppresses multiples, and the upgoing wavefield in the next layer. h_j is the depth of the j^{th} layer and R_j is the complex reflection coefficient at the j^{th} interface which is written as (Ganley, 1981)

$$R_j = \frac{\rho\left(h_{j+1}\right)v_c\left(h_{j+1},\omega\right) - \rho\left(j\right)v_c\left(h_j,\omega\right)}{\rho\left(j+1\right)v_c\left(h_{j+1},\omega\right) + \rho\left(j\right)v_c\left(h_j,\omega\right)}\,, \tag{5}$$

where ρ is density and v_C is the interval complex velocity expressed as (Aki and richards, 1980)

$$\frac{1}{v_C\left(h_j,\omega\right)} = \frac{1}{v\left(h_j,\omega\right)}\left(1 - \frac{i}{2Q\left(h_j\right)}\right). \tag{6}$$

The source is considered to be buried within the first layer and the upgoing waves in the half apsce are assumed to be zero. Thus the downgoing wave in the half space and the upgoing wave in the first layer are linked by

$$\begin{bmatrix} D\left(h_n,\omega\right) \\ U\left(h_n,\omega\right) = 0 \end{bmatrix} = A_n \cdots A_j \cdots A_1 \begin{bmatrix} D\left(h_1,\omega\right) = w(\omega) - R_0 U\left(h_1,\omega\right) \\ U\left(h_1,\omega\right) \end{bmatrix}, \tag{7}$$

where $w(\omega)$ is the Fourier spectrum of the source signature and propagation matrix A_j is written as

$$A_j = \begin{bmatrix} \left(1-R_j\right) e^{-\frac{\omega\Delta h_j}{2Q\left(h_j\right)v\left(h_j,\omega\right)}} e^{-\frac{\omega\Delta h_j}{v\left(h_j,\omega\right)}} & 0 \\ \frac{-R_j}{1+R_j} e^{-\frac{\omega\Delta h_j}{2Q\left(h_j\right)v\left(h_j,\omega\right)}} & \frac{1}{1+R_j} e^{-\frac{\omega\Delta h_j}{2Q\left(h_j\right)v\left(h_j,\omega\right)}} e^{\frac{\omega\Delta h_j}{v\left(h_j,\omega\right)}} \end{bmatrix}, \tag{8}$$

where Δh_j is the thickness of the j^{th} layer.

An example and the result analysis

The source signature, shown in Figure 1, is a minimum-phase waveform with 50 Hz dominant frequency. The receivers are located in a vertical well at depths from 320 m to 1800 m with a receiver interval of 20 m. The model for synthetic data can be constructed from sonic and log data by making equal time layers (Goupillaud, 1961). The log data for the velocity and density calculations come from a well at Rosedale near Drumheller. Figure 2 shows the log data and impedance curve from the horizontal layers with equal traveltime of 0.002 second. Input Q for each layer is 50. Figure 3 shows the synthetic VSP data from the given model. This data consist of both the primary downgoing and the primary upgoing waves which are attenuated with increasing travel distance. Figure 4 shows the log spectral ratios and fitted straight lines. The estimated average Q from the downgoing waves by the specral ratio method is shown in Figure 5. The average Q estimates are very close to the given Q. Figure 6 shows the impedance of the given model and deconvolved upgoing waves. The deconvolution operators were designed from downgoing waves and applied to the upgoing waves recorded at the same level on trace-by-trace basis (Ross and Shah, 1987). The variation in impedance is consistent with the amplitude change in the upgoing waves where the peaks of the first arrivals are conincident with the increasement in the impedance. Figure 7 shows the corridor stack of the deconvolved upgoing waves and well-log synthetic seismograms with Ricker wavelet which has the same dominant frequency as the source signature shown in Figure 1. The corridor stacking over the deconvolved and flattened upgoing waves is siminal to the nonstationary deconvolution of the zero-offset seismic trace recorded on the surface. Our result shows that the corridor stack of the deconvolved VSP upgoing waves tied quite closely to the well-log synthetic trace. It also shows that the deconvolution procedure can not completely remove the effect of the attenuation since these two traces display different gain factors.

Conclusions

The synthetic VSP seismogram is verified by comparing Q estimates with given Q, impedance estimates with deconvolved upgoing waves, and corridor stack of the deconvolved upgoing waves with well-log synthetic seismogram. The result shows that the synthetic VSP seismogram is accurate for many horizontally layered media with a constatnt-Q attenuation.

Acknowledgements

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References

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Ross, W.S., and Shah, P.M., 1987, Vertical profile reflectivity: ups over downs: Geophysics, 52, 1149-1151.

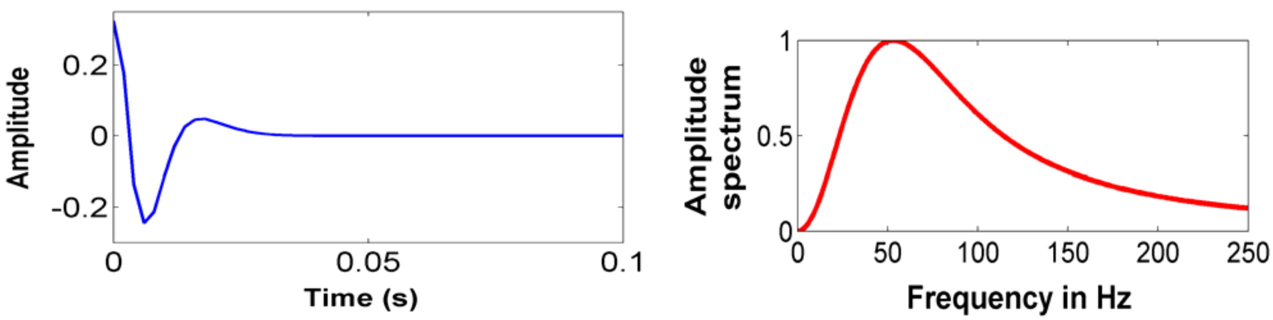

Figure 1 A minimum-phase source signature and its amplitude spectrum,.

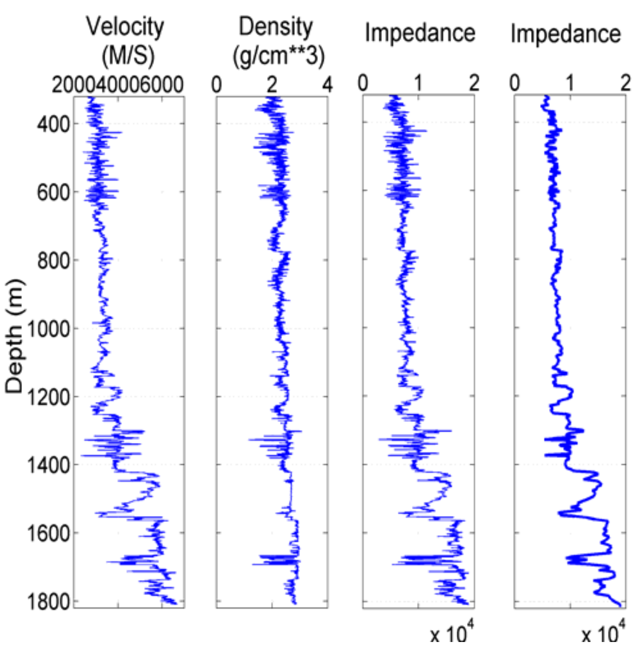

Figure 2 Velocity, density, impedance and impedance with equal interval traveltimes.

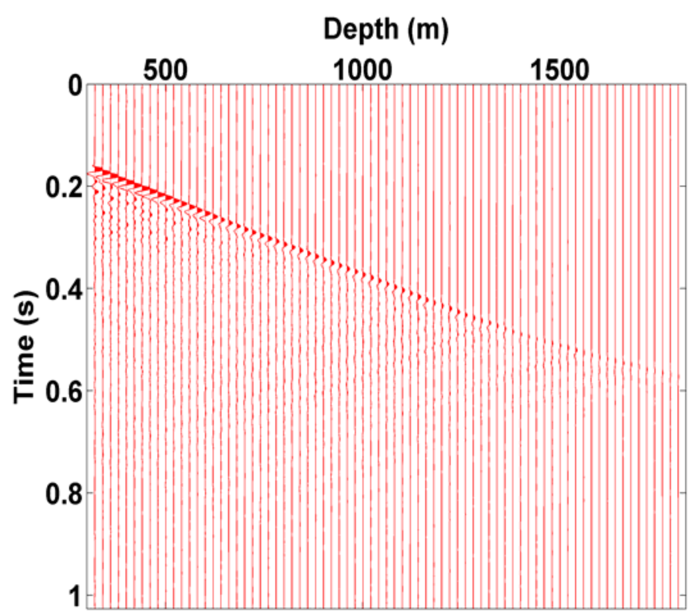

Figure 3 Synthetic VSP seismogram including attenuation.

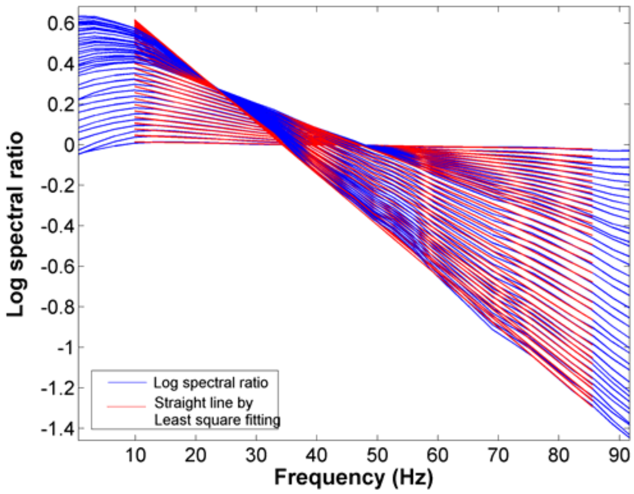

Figure 4 Log spectral ratios from the downgoing waves and straight lines by the least square fitting approach.

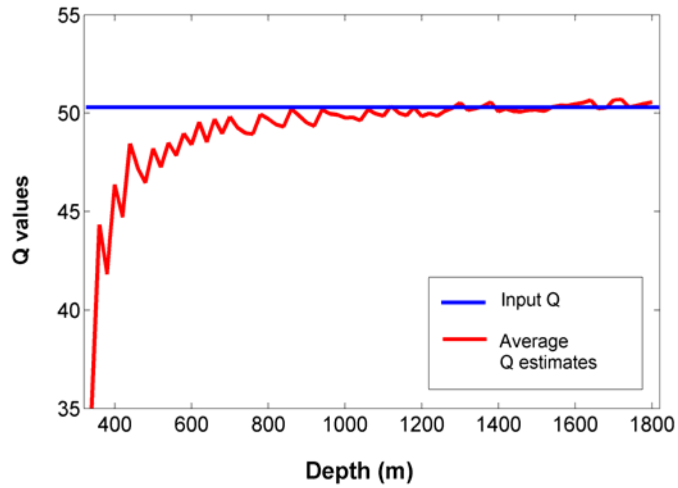

Figure 5 input Q and the average Q estimates by the spectral ratio method.

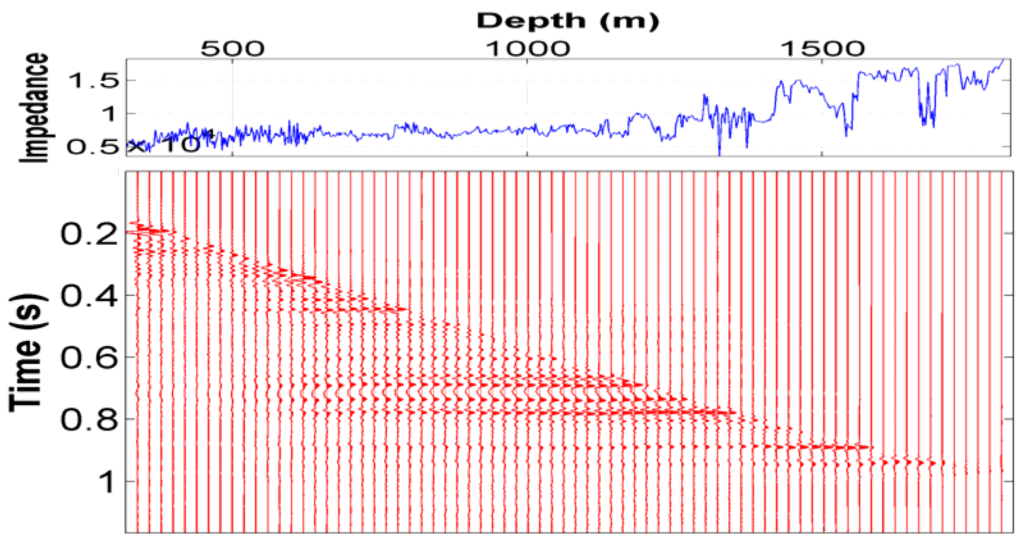

Figure 6 Impedance model and the deconvolved VSP upgoing waves. Major reflection events are consistent with variation in the impedance.

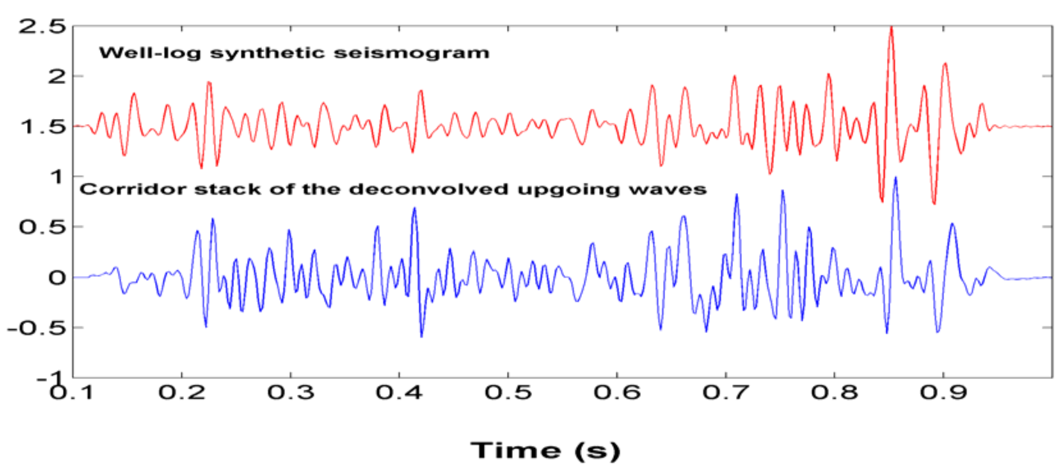

Figure 7 Well-log synthetic seismogram with Ricker wavelet and corridor stack of the deconvolved upgoing waves.