Target-oriented thin-bed prediction using spectral inversion

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Motivation

The thin layers with thickness below 1/8 of the predominant wavelength can't be resolved seismically (Widess, 1973), but they might be important flow units with reservoirs and sometimes be significant reservoirs. Thin-bed thickness is one of the most fundamental reservoir characteristics. Besides the tuning-thickness analysis method (Widess, 1973), the spectral decomposition provides another useful tool to estimate the thin-bed thickness (Partyka et al., 1999). Marfurt and Kirlin (2001) discussed the relationship between the thin-bed reflection impulse frequency response and the thickness. In Figure 1, we use an example of the peak frequency co-rendering with the coherence to illustrate their observations: the wider channels behave lower peak frequency, while the narrower ones behave higher peak frequency.

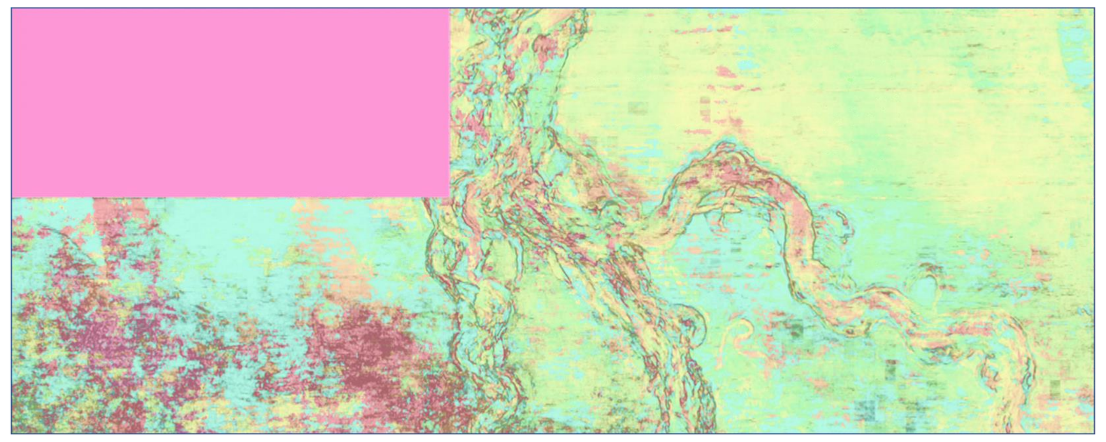

Figure 1. A time-slice multiattribute display of the peak frequency co-rendered with the coherence of a 3D survey, located in offshore Taranaki Basin, New Zealand. We can observe that the peak frequency is closely related with the thickness of the channels.

The simplest approach is to use the tuning (or peak) frequency after spectral decomposition to predict the thin-bed thickness. However, if the seismic bandwidth is insufficient for precise identification of the peak frequency, it is difficult to use these spectral decomposition methods to estimate the thin-bed thickness. A better approach is to use all the frequencies for the inversion of the thin-bed properties, which is known as spectral inversion (Portniaguine and Castagna, 2005; Puryear and Castagna, 2006, 2008; Chopra, 2006). The reflection coefficients and thickness are determined simultaneously, and the inversion of the thin-bed properties could be improved.

We first show the thin-bed spectral behaviors with different thickness and top/bottom reflectivity combinations. We also illustrate a spectral inversion method to predict the thin-bed thickness using a least-squares fitting algorithm. We further discuss the potential application of the method to interpolate the well properties.

Spectral behavior of thin-bed

Ormsby wavelet

Because seismic processors attempt to flatten the data spectrum, we use a 5-10-60-120 Hz Ormsby wavelet (Figure 2a) to study the spectral behavior of thin-bed.

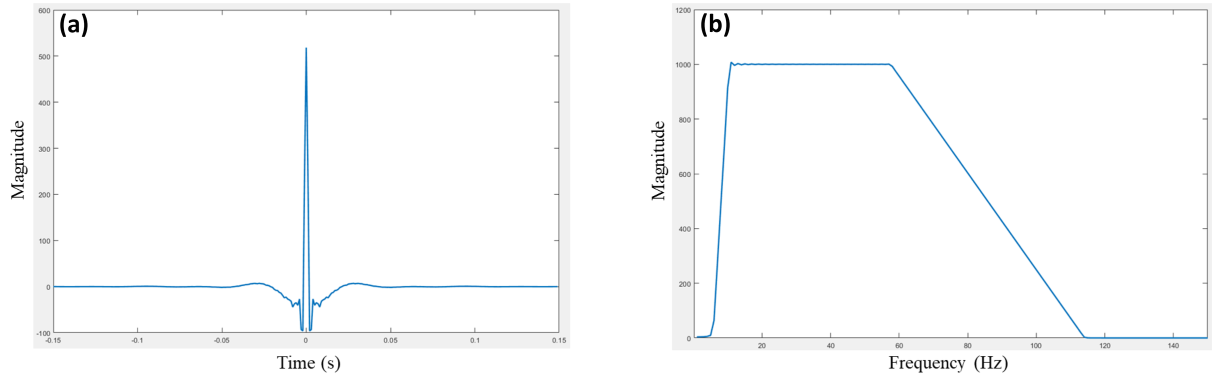

Figure 2. Ormsby wavelet (a) and the corresponding spectrum (b)

Why is there spectral notch?

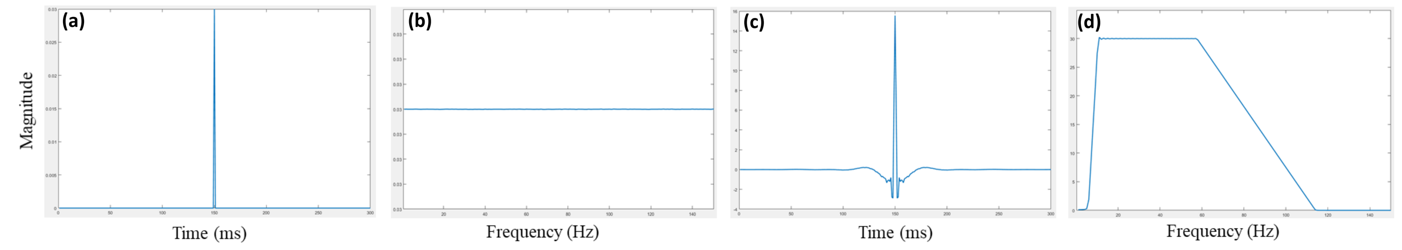

Figure 3. Spectral behavior of a single reflector: (a) the reflector model and (b) the corresponding spectrum, (c) the convolution with Ormsby wavelet and (d) the spectral behavior

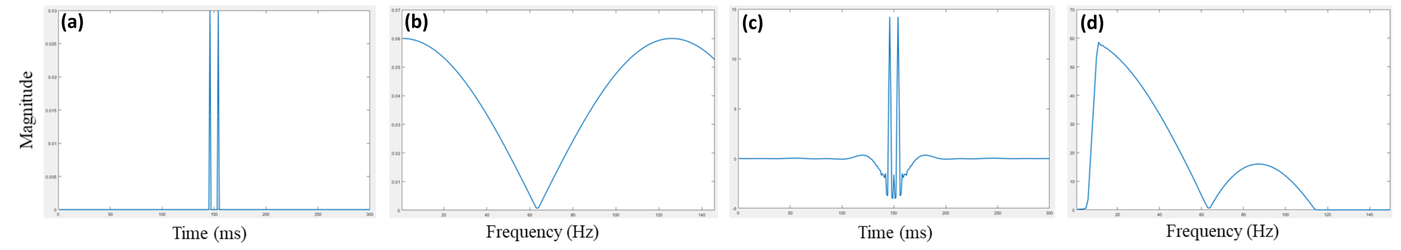

Figure 4. Spectral behavior of a thin-bed: (a) the thin-bed model and (b) its spectrum, (c) the convolution result and (d) the spectral behavior. Note the spectral notch at 65Hz.

Influence of thin-bed thickness

Thicker bed have lower-frequency notches. Higher-frequency notches may also fall within seismic spectrum to produce more notches.

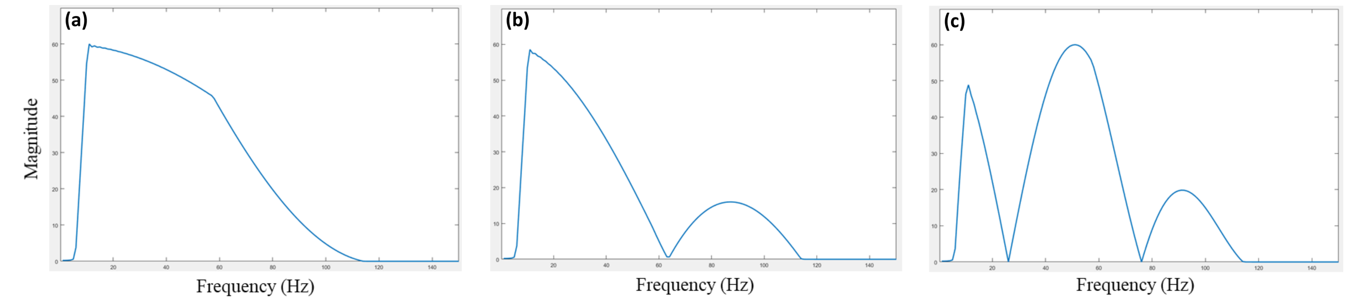

Figure 5. Spectra of the synthetic seismic traces with different thin-bed thickness: (a) 4ms, (b) 8ms, and (c) 20ms.

Top/bottom reflectivity combinations

If a thin-bed's top and bottom reflectivity have different signs, their spectra behave fewer notches, and the spectra with different absolute values behave smoother.

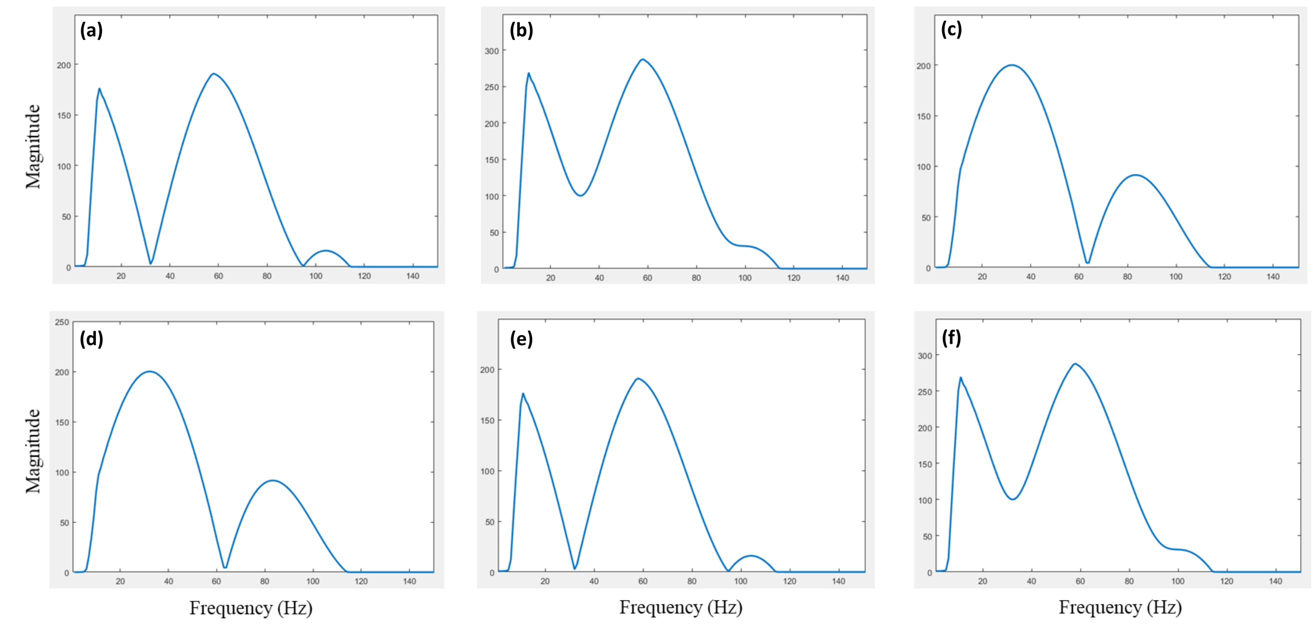

Figure 6. Spectra of the synthetic seismic traces with different top/bottom reflectivity combinations: (a) 0.1/0.1, (b) 0.1/0.2, (c) -0.1/0.1, (d) 0.1/-0.1, (e) -0.1/-0.1, and (f) -0.1/-0.2.

Spectral inversion theory

For a given two-layer model with top and bottom reflectivity r_1 and r_2, the Green function centered at time t of thickness Δt,

$$G(f,\Delta t)=r_1\exp\left[i2\pi f\left(t-\frac{\Delta t}{2}\right)\right]+r_2\exp\left[i2\pi f\left(t+\frac{\Delta t}{2}\right)\right]$$

The spectral magnitude is expressed by

$$a(f)=\left|r_1\exp\left[i2\pi f\left(t-\frac{\Delta t}{2}\right)\right]+r_2\exp\left[i2\pi f\left(t+\frac{\Delta t}{2}\right)\right]\right|$$

Using the Euler's theorem,

$$\cos(\pi f\Delta t)=\frac{\exp(i\pi f\Delta t)+\exp(-i\pi f\Delta t)}{2}$$

$$\sin(\pi f\Delta t)=\frac{\exp(i\pi f\Delta t)-\exp(-i\pi f\Delta t)}{2i}$$

Puryear and Castagna (2008) define the even and odd coefficients,

$$\begin{pmatrix} r_{\text{even}} \\ r_{\text{odd}} \end{pmatrix}=\begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} \end{pmatrix}\begin{pmatrix} r_1 \\ r_2 \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}=\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}\begin{pmatrix} r_{\text{even}} \\ r_{\text{odd}} \end{pmatrix}$$

Then the Green function can be rewritten as

$$G(f,\Delta t)=2r_{\text{even}}\cos(\pi f\Delta t)+i2r_{\text{odd}}\sin(\pi f\Delta t)$$

A least-squares method is used to predict the thin-bed thickness, which try to minimize the difference between the observed and modeled spectra using the objective function

$$\min_{r_1,r_2} E^2(\Delta t)=\left\|U(f)-W(f)\left\{r_1\exp\left[i2\pi f\left(t-\frac{\Delta t}{2}\right)\right]+r_2\exp\left[i2\pi f\left(t+\frac{\Delta t}{2}\right)\right]\right\}\right\|^2$$

The solution of the reflectivity is given by

$$\begin{pmatrix} r_1 \\ r_2 \end{pmatrix}=\left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}\begin{pmatrix} U_1 \\ U_2 \\ \vdots \\ U_N \end{pmatrix}$$

The term $\left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1}\mathbf{A}^{\mathrm{T}}$ can be precomputed, where

$$\mathbf{A}=\begin{pmatrix} W(f_1)\exp(+i\pi f_1\Delta t) & W(f_1)\exp(-i\pi f_1\Delta t) \\ W(f_2)\exp(+i\pi f_2\Delta t) & W(f_2)\exp(-i\pi f_2\Delta t) \\ \vdots & \vdots \\ W(f_N)\exp(+i\pi f_N\Delta t) & W(f_N)\exp(-i\pi f_N\Delta t) \end{pmatrix}$$

The tuning thickness is provided by

$$\Delta t_{\text{tuning}}=\arg\left\{\min_{\Delta t}\left[E^2(\Delta t)\right]\right\}^2$$

The objective functions from cross-correlation analysis indicate effectiveness of the method.

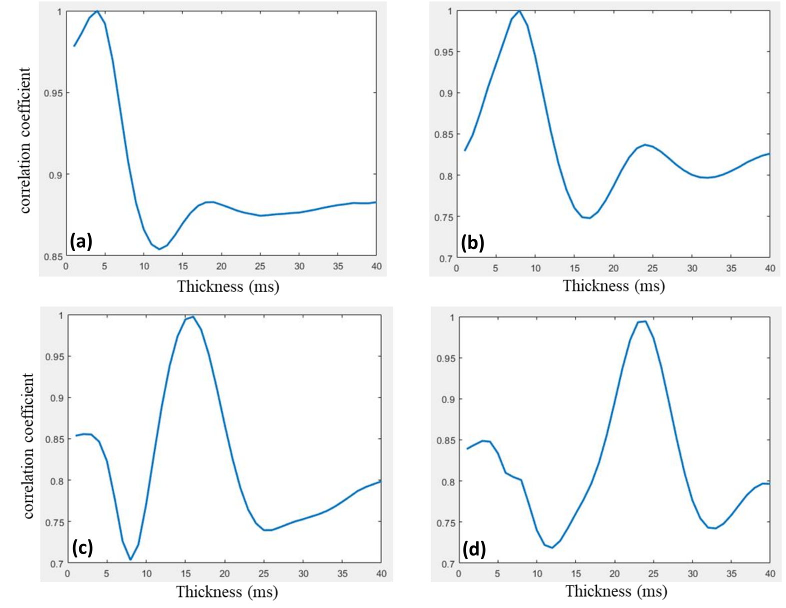

Figure 7. Objective function of synthetic thin-bed model with different thickness: (a) 4ms, (b) 8ms, (c) 16ms, and (d) 24ms.

2019 workplan

In 2019, we will extend this thin-bed spectral inversion method to the application of well property interpolation between nearby wells. A suite of reflectivity models could be generated using the method, followed by comparison to the measured spectra. The model whose spectra best fits the measured one is the "winner", and provides the output "inverted" results from a suite of possible input models. It could also be expanded to be more geostatistical if necessary.

Conclusions

To address the limitations of the thin-bed thickness estimation method using only peak frequency after spectral decomposition, we developed a spectral inversion method using a least-squares fitting algorithm, to yield more accurate and stable thickness determinations below tuning. Next, we will focus on extending this method to combine with the well-log data, to improve the vertical resolution, and apply it on well property interpolation and impedance inversion.

Acknowledgements

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