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3D prestack depth migration with compensation for frequency dependent absorption and dispersion

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Summary

Spatial variations in the transmission properties of the overburden cause seismic amplitude attenuation, wavelet phase distortion and seismic resolution reduction on deeper horizons. This poses problems for the seismic interpretation, tying of migration images with well-log data and AVO analysis. We developed a prestack depth Q migration approach to compensate for the frequency dependent dissipation effects in the migration process. A 3D tomographic amplitude inversion approach may be used for the estimation of absorption model. Examples show that the method can mitigate these frequency dependent dissipation effects caused by transmission anomalies and should be considered as one of the processes for amplitude preserving processing that is important for AVO analysis when transmission anomalies are present.

Introduction

In the early days of seismic imaging, the main goal of migration was to get structural information about the subsurface geology. Now imaging the true reflectivity of the subsurface has attracted wide attention in the seismic exploration industry. This requires correct treatment of the factors affecting the amplitude of waves during the extrapolation and imaging steps of migration. Amplitude preserving migration methods account for geometrical spreading (e.g., Zhang *et al,* 2002). However, the factor of intrinsic absorption, such as gas within shallow sediments, is commonly neglected in conventional migration methods. Spatial variations in the transmission properties of the overburden cause seismic amplitude attenuation, wavelet phase distortion, and decrease of seismic resolution due to loss of high frequency component on deeper horizons. This induces anomalous amplitude decay and narrowed frequency bandwidth in zones beneath the gas anomaly, often making the identification and interpretation of deeper reflectors difficult. This, in turn, affects the ability to accurately predict reservoir properties. Thus, there is a need to compensate for the absorption effect caused by this kind of transmission anomalies.

Early attempts to treat dissipation were directed towards the elimination of its effects from the data by inverse *Q*-filters. Since the effects of dissipation increase with the length of wavepath, the filters are time-variant.

Rather than compensating for the effects of absorptions in a separate preprocessing step, it is more correct to do it during the migration itself (e.g., Causse 1999, Traynin 2008, Mittet 2007). Seismic energy is attenuated during the propagation in the earth, the frequency dependent loss must be compensated for according to the actual wavepath in the migration process to give a reflector with correct phase, magnitude and resolution.

How do we estimate the dissipation effect from seismic data? Xin *et al* (2008) have developed a generalized method for estimating transmission losses. The analysis is performed on the migrated data and based on the tomographic velocity updating algorithm described by Zhou *et al* (2003). The essence of the estimation approach is to obtain the amplitude variations in a represented model by back-projecting the amplitude variations from 3D prestack depth migrated data along the traced raypaths and then minimizing the amplitude discrepancies in CIGs. It involves 2 main steps: 1) picking events on the CIGs, measuring their amplitudes along the horizons for different offsets which will be used as the reference amplitudes for the inversion; 2) updating the amplitude perturbations in the model through tomographic inversion. With the estimated absorption coefficients, Xin *et al* use raytracing to calculate the cumulative amplitude factors from the estimated model and scale the prestack migrated data with the frequency independent factors accordingly.

Although this post migration approach works well for most cases, the more correct way is to apply the compensation during the migration. In the following part of this paper, we describe our approach for compensation of frequency dependent dissipation effects in prestack depth migration. We will discuss how to make use of the absorption model estimated from our 3D tomographic amplitude inversion for compensation of frequency dependent dissipation effects. We then apply this method on synthetic and real data to demonstrate its ability to compensate for the frequency dependent amplitude loss and dispersion caused by transmission anomalies.

Theory and method

Using the correspondence principle, wave propagation in a viscoacoustic medium can be treated as wave propagation through an acoustic medium with a complex velocity. The complex velocity is given in terms of the (real) acoustic velocity C_0 and the quality factor Q, representing the attenuation. If the attenuation is small ($1/Q<<1$), then an appropriate definition of the complex velocity is

$$C(x) = C_0(x)[1 + \frac{1}{2} iQ^{-1}(x) + \frac{1}{\pi} Q^{-1}(x)\ln(\omega/\omega_0)] \ , \quad (1)$$

where ω_0 is a reference frequency. The Q value is independent of frequency in this definition. The imaginary part of the velocity causes exponential attenuation along the raypath. The real part of the velocity contains a dispersive term, which ensures causality of solutions to the wave equation. If $1/Q<<1$, then, to the first order, the raypaths remain unchanged. Therefore, the attenuation only affects the waveform through the complex and frequency dependent traveltime, as shown by Keers (2001)

$$T_c(x) = T(x) - \frac{1}{2} iT^*(x) - \frac{1}{\pi} T^*(x)\ln(\omega/\omega_0) \ , \quad (2)$$

where $T(\mathbf{x})$ is the travel time in the acoustic medium C_0, and

$$T^*(x) = \int_{ray} \frac{1}{Qv} ds = \int_{ray} \frac{2\alpha}{\omega} ds \ , \quad (3)$$

where the absorption coefficient, α , is related to the quality factor Q as follows (Mittet, 2007)

$$Q = \frac{\omega}{2\alpha v} \ . \quad (4)$$

Our assumption here is that the quality factor Q is independent of frequency. Under this assumption, the absorption coefficient, α , is linearly proportional to frequency ω, and higher frequencies suffer more attenuation than lower frequencies. Q can be derived from the absorption coefficients estimated from our 3D amplitude tomographic inversion according to equation (4).

Migration for a dissipative medium can be derived as

$$\beta(\bar{x}) \sim \frac{1}{8\pi^3} \int w(\bar{x},\bar{\xi}) \exp(i\omega T) D_a(\bar{x},\bar{x}_r,\bar{x}_s,\omega) \times u_s(\bar{x}_r,\bar{x}_s,\omega) i\omega d\omega d^2\bar{\xi} \quad (5)$$

where $w(\bar{x},\bar{\xi})$ is the migration weight $\vec{x}$ is the image location $\bar{x}_s(\bar{\xi})$ and $\bar{x}_r(\bar{\xi})$ are shot and receiver point respectively, $\bar{\xi} = (\xi_1, \xi_2)$ is the parameter labeling source and receiver points.

So the migration operator for a dissipative medium is in principle performed in the same way as in the conventional case, the difference being the new anti-dissipation function

$$D_a(\bar{x},\bar{x}_r,\bar{x}_s,\omega) = \exp[i\omega(-\frac{i}{2}T^* - \frac{1}{\pi}T^*\ln(\omega/\omega_0))] \ . \quad (6)$$

The anti-dissipation filter is a function of dissipation time, T^*, which is dependent on the velocity field, the quality factor field and the raypath. It is in general time-varying and laterally varying even for a constant Q medium. The traveltimes $T(x)$ can be computed by conventional travel time methods in an acoustic medium, the dissipation time, T^*, can be computed during conventional raytracing by integration of $1/(Qv)$ along the raypath. During the migration procedure, for a given subsurface point, with the computed dissipation time, T^*, and travel times corresponding to the specific image location contributed by a specific input trace, we can construct the migration operator for imaging with compensation for both amplitude attenuation and phase distortion honoring the actual raypaths. As our amplitude tomography can estimate the absorption anomaly in the background, our Q PSDM can compensate for Q effects relative to the background with the estimated absorption model.

A simple modification of the expression of the phase term of equation (6) allows separating off the effect of the time shift between seismic and sonic data due to velocity dispersion. For example, if we choose the reference frequency as ω_{ref} , the image will be

$$\beta_2(\bar{x}) \sim \frac{1}{8\pi^3}\int w(\bar{x},\bar{\xi}) \exp\left(i\omega\left(T - \frac{1}{\pi}T^* \ln\frac{\omega_0}{\omega_{ref}}\right)\right) \times \exp\left(\frac{\omega T^*}{2} - \frac{i\omega}{\pi}T^* \ln\frac{\omega}{\omega_0}\right) u_s(\bar{x}_r,\bar{x}_s,\omega)\, i\omega\, d\omega\, d^2\bar{\xi} \qquad .(7)$$

Therefore, the difference between image $\beta(x)$ and $\beta_2(x)$ is a pure shift. The shifted travel time is a function of the dissipative time, T^* and the shift amount is

$$\tau = -\frac{1}{\pi}T^* \ln\frac{\omega_0}{\omega_{ref}}.$$

Examples

The first example is composed of 5 flat reflectors in a medium with velocity v=2000m/s. The left half space (crossline 4000 to crossline 4500) is absorption free, the right half space has dissipation effect, with the quality factor Q=50, as shown in Fig. 1. Fig. 2 is the synthetic seismic section, the seismic source is 25Hz Ricker wavelet.

The right hand section shows clearly the effect of absorption, with amplitude attenuated, phase distorted and resolution decreased. Fig. 3 is the conventional migration result without compensation of absorption. Migration corrects for the geometrical spreading effect, but not for the dissipation effect. Fig 4 shows the Q value derived from the absorption coefficients estimated from amplitude tomographic inversion. Fig. 5 is the result from our Q PSDM migration with both amplitude compensation and phase correction. The dissipation effects are removed. The corresponding spectra are compared in Fig. 6.

A real data set was then tested with our method. Fig 7 displays the section from conventional migration with four picked horizons. Amplitude dimming caused by gas in shallow region was observed. The amplitude loss makes it difficult for the reflectors to be identified and interpreted for AVO analysis. Using the amplitude tomographic inversion, we obtained the estimated transmission anomalies. Fig 8 shows the transmission anomalies extracted from one subline. The estimated transmission anomalies were then utilized in our 3D Q PSDM to mitigate the dissipation effects. Fig 9 depicts our Q PSDM result with frequency dependent compensation for both amplitude attenuation and phase distortion. The amplitudes are more balanced after the correction, and the resolution is also increased. Fig 10 compares the spectra, in dB, of the 2 migrated images. The PSDM with frequency dependent compensation balances the amplitudes and increases the high frequency component as well.

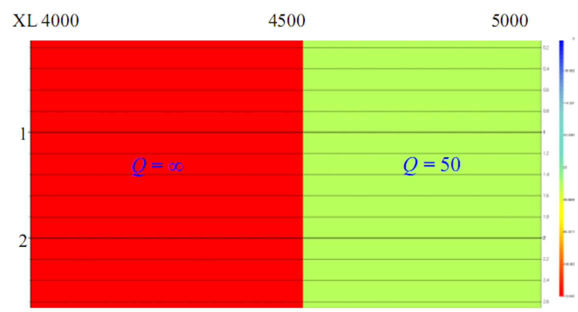

Fig 1 Quality factor Q model, with Q= ∞ at the left half space (red), Q=50 at the right half space (blue), Cooler color means lower Q

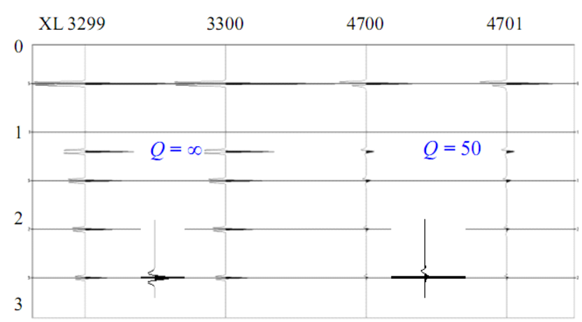

Fig 2 Synthetic seismic section in medium with Q shown in Fig 1, absorption causes attenuated amp, distorted phase, see zoom-in wavelets

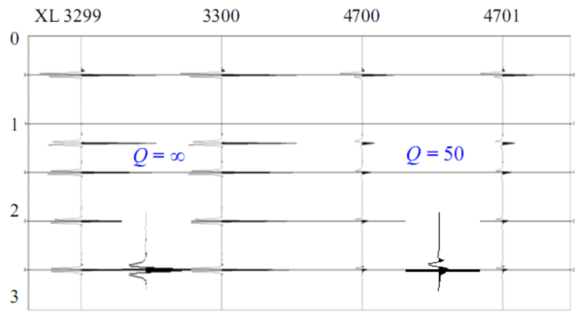

Fig 3 The conventional migration result, it recovers the geometrical spreading, but not the absorption effect.

Fig 4 Q model derived from Amplitude tomographic inversion.

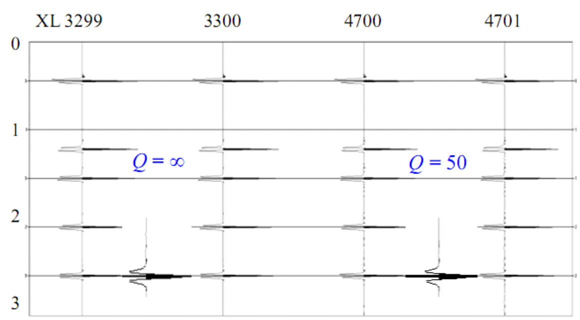

Fig 5 Migration with frequency dependent compensation for both amplitude and phase, the amplitude recovered and phase corrected, see the zoom-in wavelet

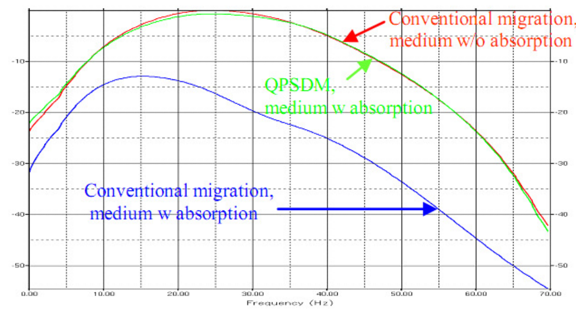

Fig 6 Comparison of the spectrum in attenuating medium by conventional migration, QPSDM, migration with amplitude compensation only and migration in medium without absorption.

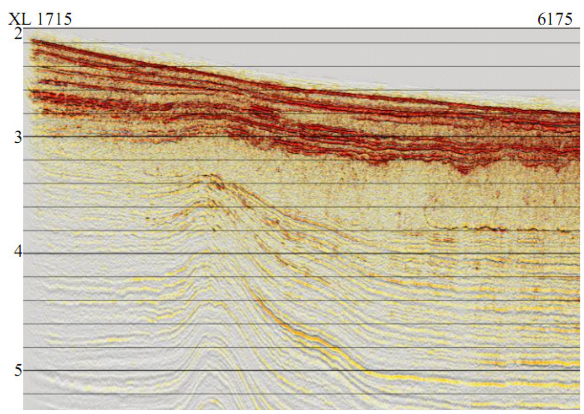

Fig 7 One migrated line from standard PSDM

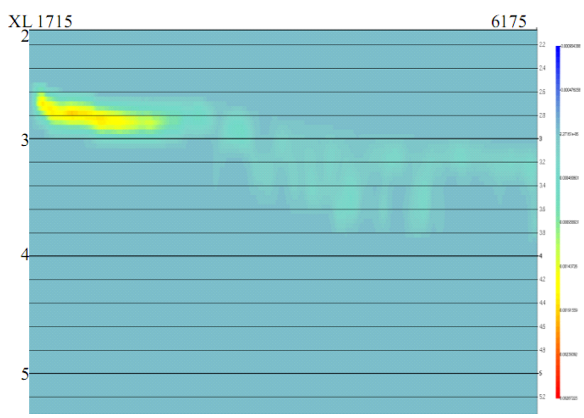

Fig 8 The corresponding absorption model from Amplitude Tomography

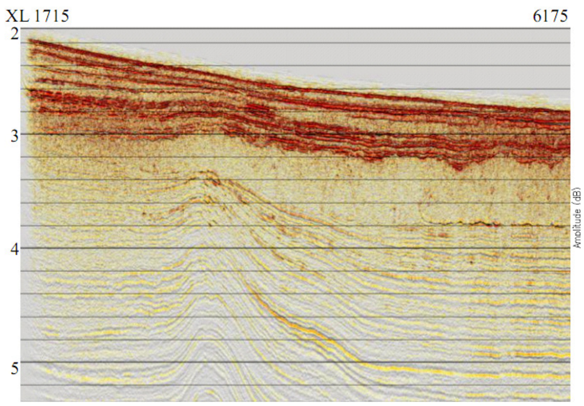

Fig 9 The same line migrated by Q PSDM with compensation for both amplitude and phase

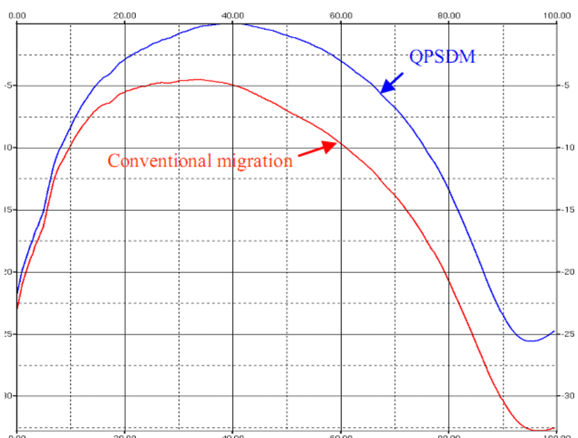

Fig 10 Comparison of spectrum of the section in Fig 7 by standard PSDM and the section in Fig 9 by QPSDM with compensation for both amplitude and phase

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