Simultaneous inversion of velocity and Q using wave-equation migration analysis

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ABSTRACT

I develop a method for simultaneous inversion of velocity and Q models. This method poses the simultaneous estimation problem as an optimization problem that seeks optimum velocity and Q models by minimizing user-defined image residuals. Its numerical tests with a modified SEAM model that has two gas clouds demonstrate the necessity of using such simultaneous inversion, when the existent velocity and Q models are inaccurate. The results show that this simultaneous inversion method is able to retrieve both velocity and Q models, and to correct and compensate the distorted migrated image caused by inaccurate velocities and Q models.

INTRODUCTION

Because strong attenuation and low-velocity anomalies are present in gas pockets or clouds, they present notoriously challenging problems for reservoir identification and interpretation (Billette and Brandsberg-Dahl, 2005). Attenuation degrades the seismic image quality by damping the image amplitude, lowering the image resolution, distorting the phase of events, and dispersing the velocity. A wrong velocity estimation for the low-velocity anomalies also results in image problems, such as mis-positioning the events and discontinuing the imaged structures. These problems impede accurate image interpretation for hydrocarbon production and well positioning. To mitigate the effects of such gas accumulations on the image and improve imaging of the subsurface, it is important to understand the properties of these gas pockets or clouds. Compressional velocity (V) and compressional quality factor (Q) play an important role in correcting and compensating for the gas-induced distortion in the image.

Shen et al. (2013, 2014) developed a method, wave-equation migration Q analysis (WEMQA), to produce a reliable Q model. This method analyzes attenuation effects from the image space, and uses wave-equation Q tomography to estimate Q models. However, this methods requires perfect velocities. An inaccurate velocity model used by WEMQA easily distorts the spectra of the migrated events and causes errors in spectral analysis for estimating the attenuation effects. Therefore, it is necessary to invert for both velocity and Q models if neither of these models is correct. Thus, such inversion mitigates the errors in Q estimation caused by inaccurate velocities.

In this paper, I first develop a method for simultaneous inversion of velocity and Q models based on the previous workflow of WEMQA (Shen et al., 2013, 2014). Then I applied this method to a synthetic dataset to demonstrate its necessity and effectiveness.

THEORY

I pose the simultaneous estimation problem as an optimization problem that seeks optimum velocity and Q models by minimizing user-defined image residuals:

$$J = J_v(v,Q) + \beta J_Q(v,Q), \tag{1}$$

where β is a weighting parameter that banlances two user-defined image residuals $J_v(v,Q)$ and $J_Q(v,Q)$, and it can be changed through iterations. The image residuals $J_v(v,Q)$ and $J_Q(v,Q)$ are the functions of the current velocity and Q models. However, $J_v(v,Q)$ emphasizes more on the kinematics change in an image caused by an inaccurate velocity model; while $J_Q(v,Q)$ emphasizes more on the amplitude spectral change in an image caused by an inaccurate Q model.

In this paper, I use the normalized differential semblance optimization (DSO) (Tang, 2011) as the criterion to mainly estimate the velocity. This objective function normalizes the square of the root-mean-squared (RMS) image amplitudes to reduce the influence of image amplitude variations due to attenuation and uneven illumination. The normalized DSO objective function is in the subsurface-offset $\mathbf{h}$ domain:

$$J_v = \frac{1}{2}\sum_{\mathbf{x}} \frac{\sum_{\mathbf{h}} |\mathbf{h}|^2 \left|m\left(\mathbf{x},\mathbf{h}\right)\right|^2}{\sum_{\mathbf{h}} \left|m\left(\mathbf{x},\mathbf{h}\right)\right|^2}, \tag{2}$$

where $m\left(\mathbf{x},\mathbf{h}\right)$ is the migrated image with the current velocity and Q models in the subsurface-offset domain. The physical interpretation of the subsurface-offset-domain DSO is that it optimizes the models by penalizing energy at non-zero subsurface offset, taking advantage of the fact that seismic events should focus at zero-subsurface offset if migrated using accurate models.

By definition for J_Q, the image residual mainly coming from attenuation is the difference between the background image computed with the current background models and the attenuation-free image. In fact, instead of computing the difference between these two images, I calculate the spectral change of the images:

$$J_Q = \sum_{\mathbf{x}} \left|\rho\left(\mathbf{x}\right)\right|^2. \tag{3}$$

The change in the spectrum can be indicated by the steepness of the slope $\rho\left(\mathbf{x}\right)$ computed by the spectral ratio method (Tonn, 1991), between a number of selected, windowed events in the background image and those in the reference windows. These reference windows are carefully selected from the background image so that they are not contaminated by attenuation. All the windows in this method are large and the same size, hence the influence of the interfering reflectivies on the spectra are statistically the same over all windows. Based on the assumption that the amplitude spectra contain the same frequency content over the windows if the models for imaging is accurate, this method minimizes the spectral differences between the selected windows and the reference windows.

These user-defined residuals are mapped to the perturbations in the current velocity and Q models by the wave-equation velocity and Q tomography operators (Tang, 2011; Shen et al., 2013, 2014). I use the mapped perturbation as gradient directions to conduct a line-search in optimization schemes, to obtain both velocity and Q models.

NUMERICAL EXAMPLE

To demonstrate this methodology, I use a portion of the SEAM synthetic velocity, adding two gas clouds with lower velocity than the surrounding sediments, as shown in Figure 1(a). The Q model (in logarithmic scale) shown in Figure 1(b) also includes these two gas clouds with high attenuation. I generate a 2D synthetic data with 56 shots with 100 m spacing, 137 receivers with 40 m spacing, and a Ricker wavelet with 12 Hz central frequency.

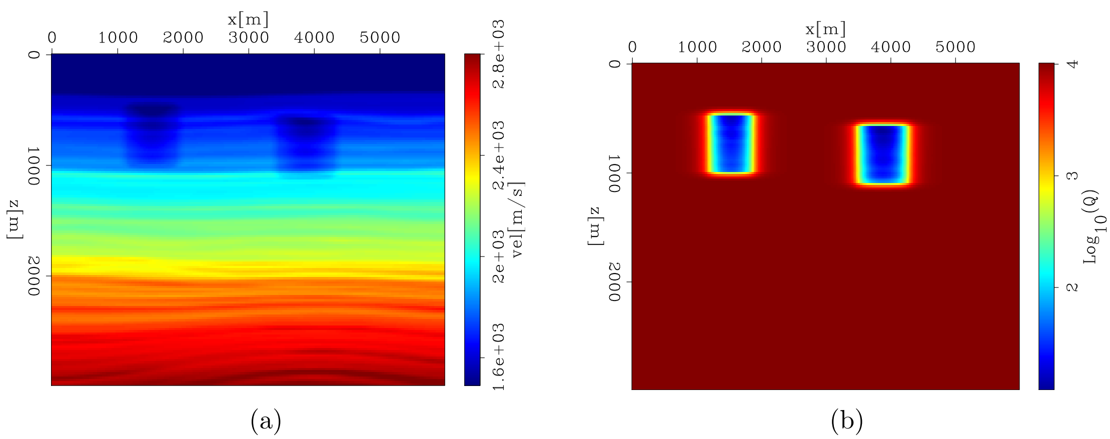
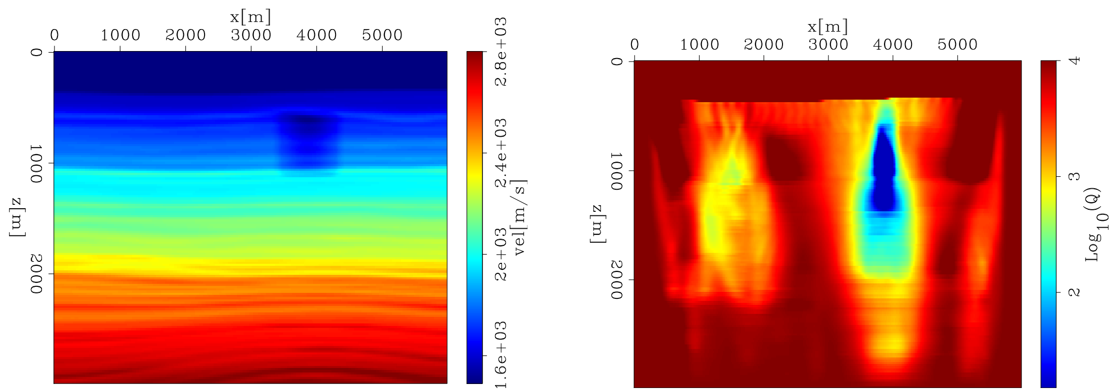


Figure 1: True models: (a) A part of a modified SEAM velocity model with two gas clouds; (b) Q model (in logarithmic scale) with two gas clouds. [**ER**]

The first test in this example is to invert for the Q model with an inaccurate velocity model shown in Figure 2(a). The inaccurate velocity in Figure 2(a) has the same background velocity as that in Figure 1(a). However, the velocity of the left gas in Figure 2(a) is slightly higher than the true velocity in Figure 1(a) and is set to be the same as the surrounding sediments; while the velocity of the right gas in Figure 2(a) remains unchanged from the true velocity in Figure 1(a).

The initial model for Q inversion is a model without attenuation. Figure 2(b) shows the inversion results (in logarithmic scale) using WEMQA (Shen et al., 2013, 2014). The results show that this Q inversion method with adequate accurate velocity information of the right part of the model, as shown in Figure 2(a), well recovers the location and value of the right gas, as shown in Figure 2(b). However, this method with inaccurate velocity in the left part of the model, as shown in Figure 2(a), fails in retrieving the left gas. The main reason for such failure is the inaccurate velocity that distorts the kinematics of the migrated structures, and that hence degrades the accuracy of the spectra analysis for Q inversion. Therefore, simultaneous inversion of both velocity and Q models is needed to obtain a reasonable inversion results, if neither information of these model is accurately available.



(a) (b)

Figure 2: (a) Inaccurate velocity model for Q inversion; (b) Inverted Q model using inaccurate velocity model in Figure 2(a). [**ER**]

To simultaneously invert for velocity and Q models, the initial velocity model has the same background velocity and the same velocity of the right gas, as shown in Figure 1(a), but without the velocity drops in the left gas. The initial Q model is a model without attenuation. Figure 3(a) is the inverted velocity model and Figure 3(b) is the inverted Q model. Simultaneous inversion well retrieves the locations and values of both gas clouds in velocity and Q models, as shown in Figure 3.

Figure 4(a) is the migrated image using the initial velocity and Q models. The initial velocity has larger velocity in the left gas, which causes the events below being pushed downward and discontinued. Attenuation caused by these two gas clouds degrades the quality of the imaged structures below in Figure 4(a), in terms of dimming the amplitudes, making the events incoherent, and stretching the wavelets. Figure 4(b) is the migrated image using the inverted models in Figure 3. Migration with the improved velocity model in Figure 3(a) moves the downward events below the left gas upward and makes the events there more coherent. Also compensation with the inverted Q model shown in Figure 3(b) makes the events sharper and more balanced in both phase and amplitudes, as shown in Figure 4(b).

Figure 5(a) and Figure 5(b) are the angle domain common image gathers(ADCIG)

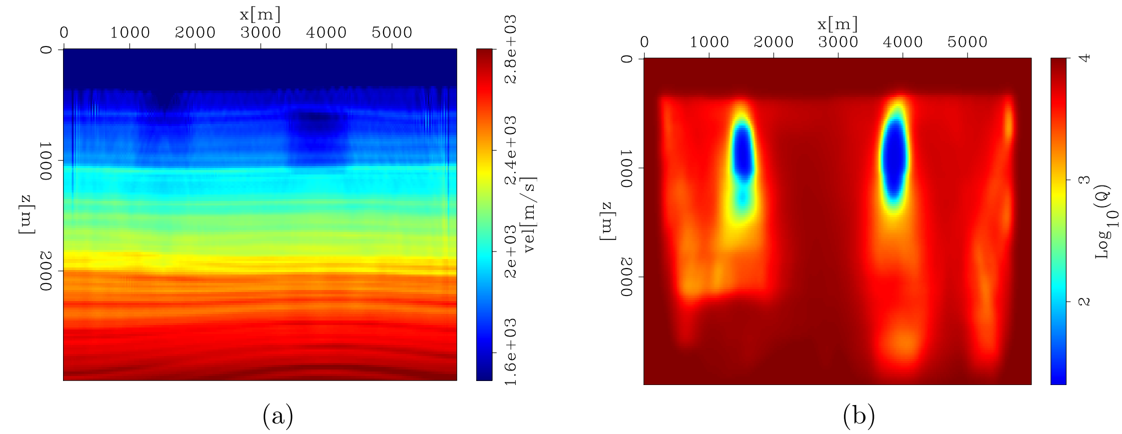


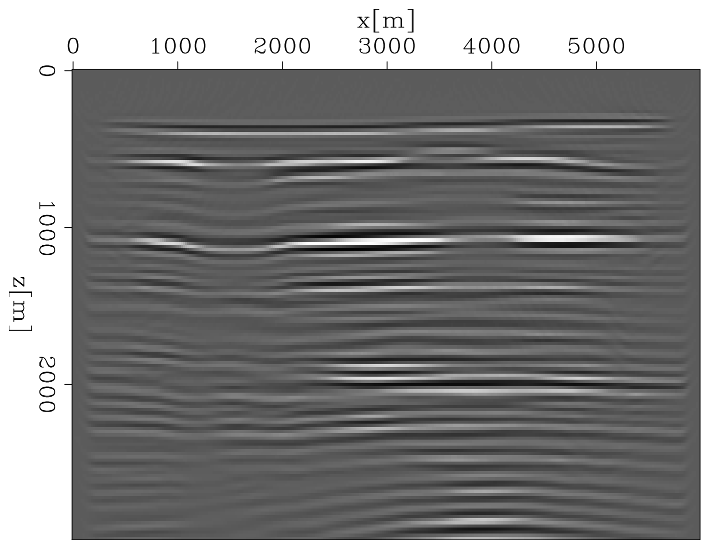
Figure 3: Simultaneous inversion results: (a) The inverted velocity model; (b) The inverted Q model. [**ER**]

extracted from the left gas location (x= 1500 m) and obtained with the initial models and the inverted models in Figure 3, respectively. The inaccurate large velocity causes the unflateness of the events shown in Figure 5(a). The inverted velocity model shown in Figure 3(a) corrects such kinematics error caused by such wrong velocity and flattens the events in Figure 5(b). In addition, migration with the inverted Q model in Figure 3(b) compensates the energy loss that appears especially strong at the near angle as shown in Figure 5(a), and hence makes the amplitude of the events more balanced in Figure 5(b).

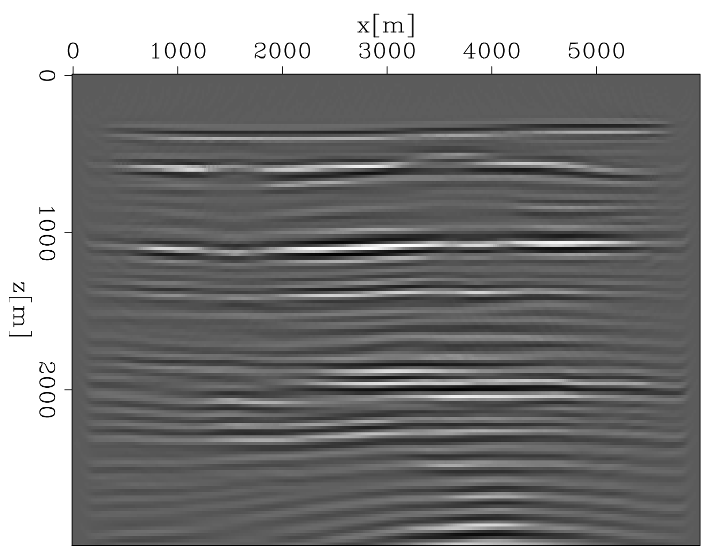
Figure 6(a) and Figure 6(b) are the angle domain common image gathers(ADCIG) extracted from the right gas location (x= 3800 m) and obtained with the initial models and the inverted models in Figure 3, respectively. The near angles in Figure 6(a) have low amplitudes, stretched wavelets and unflattend events caused by attenuation, although the velocity used in this region is correct. Compensation with the inverted Q model in Figure 3(b) compensates the high frequency loss caused by attenuation, therefore, it recovers the amplitudes and sharpens the events at the near angles in Figure 6(b). In addition, such compensation corrects the phase distortion and velocity dispersion caused by attenuation, hence, the events in Figure 6(b) becomes more flattened and more coherent than those in Figure 6(a).

CONCLUSION

I develop a method for simultaneous inversion of velocity and Q models. This method poses the simultaneous estimation problem as an optimization problem that seeks optimum velocity and Q models by minimizing user-defined image residuals. Its numerical tests with a modified SEAM model that has two gas clouds demonstrate the necessity of using such simultaneous inversion, when the existent velocity and Q models are inaccurate. The results show that this simultaneous inversion method



(a)



(b)

Figure 4: (a) The migrated image using the initial velocity and Q models; (b)The migrated image using the inverted models in Figure 3. [**ER**]

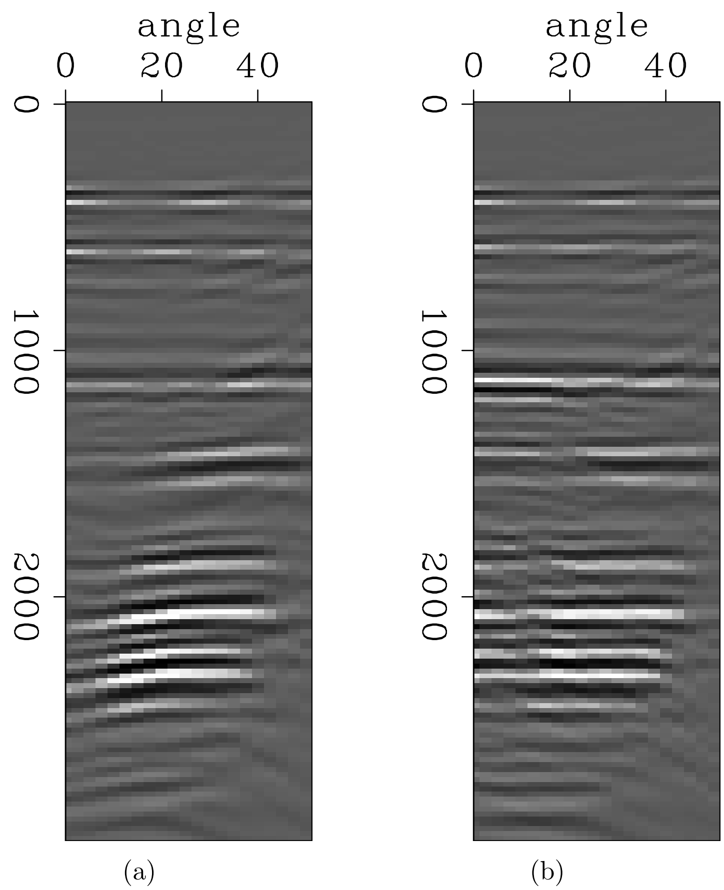
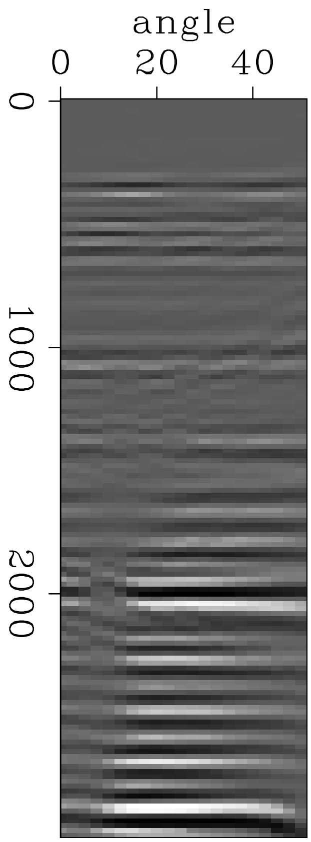
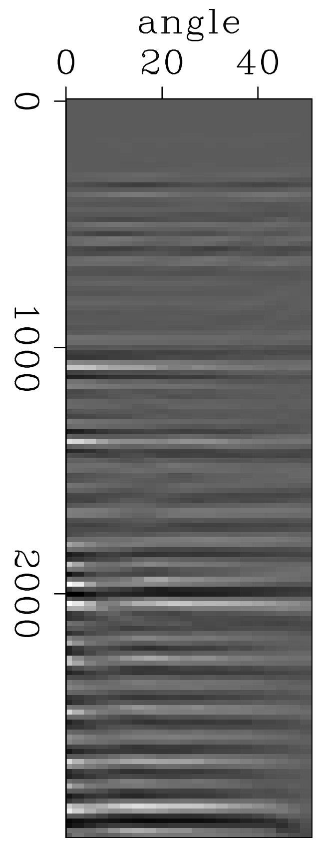


Figure 5: (a)The angle domain common image gathers(ADCIG) extracted from the left gas location (x= 1500 m) and obtained with the initial models; (b) The angle domain common image gather(ADCIG) extracted from the left gas location (x= 1500 m) and obtained with the inverted models shown in Figure 3. [**ER**]



(a)



(b)

Figure 6: (a)The angle domain common image gathers(ADCIG) extracted from the right gas location (x= 3800 m) and obtained with the initial models; (b) The angle domain common image gather(ADCIG) extracted from the right gas location (x= 3800 m) and obtained with the inverted models in Figure 3. [**ER**]

is able to retrieve both velocity and Q models, and to correct and compensate the distorted migrated image caused by inaccurate velocity and Q models.

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