De-blending reverse-time migration

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SUMMARY

Reverse-time migration (RTM), based on the full two-way wave equation, has gained interest and become a popular imaging tool for complex structures in the last few years. The method is well-known for its ability to better image the steeply dipping and overturned structures than the migration methods based on the one-way wave equation extrapolation. However, the RTM image often contains low frequency and back-scattering noise, and the imaging quality is sensitive to the migration velocity. In order to improve the RTM imaging quality and make the RTM image less sensitive to the velocity model, we developed an RTM de-blending technique which separates upgoing and downgoing source and receiver wavefields, and then use them to construct final RTM images. Test results show that decomposed images obtained from only the downgoing source and receiver wavefields are less sensitive to velocity. It removes unwanted noise and migration artifacts from conventional RTM, and the imaging quality is greatly improved compared with a conventional RTM image.

INTRODUCTION

In subsurface areas with complex overturned structures and steeply dipping salt boundaries, migration methods based on one-way wave equation extrapolation have limitations in constructing an accurate image for steep reflectors. RTM, however, can overcome this limitation to create an accurate image in such complex areas.

Reverse-time migration was initially proposed by many authors Whitmore (1983); Baysal et al. (1983); McMechan (1983). Later on, other authors continued the RTM efforts to address various issues. Fei and Lerner (1995) developed a scheme to remove the numerical dispersion, Wu et al. (1996) studied high-order finite-difference scheme for RTM. In the last five years due to increasing computational capability, interest in RTM has been renewed. It is now becoming a powerful tool for accurate imaging in areas with complex structures. In recent years, many authors, Fletcher et al. (2006) and Liu et al. (2009), further studied migration noise that exists in RTM and proposed methods to remove the low-frequency, back-scattered noise and numerical dispersion. Fei et al. (2009) discussed velocity sensitivity for RTM, and concluded that high velocity contrast and velocity smoothing can create migration artifacts.

In order to remove the artifacts and noise from RTM and reduce the velocity sensitivity of the image, we propose to de-blend reverse-time migration images. The de-blending reverse-time migration technique decomposes the RTM image into four separate image panels via downgoing and upgoing wavefields separation, therefore separating the migration image, noise and velocity sensitive artifacts, and ultimately improving the RTM imaging quality.

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The concept of pre-stack RTM is simple and straightforward. It first propagates the source function based on the acoustic wave equation and stores the computed source wavefield $S(t, x, y, z)$. The recorded shot record, treated as a group of new sources, is then backward propagated to produce the receiver wavefield $R(t, x, y, z)$. The final image $I(x, y, z)$ is obtained by applying the conventional imaging condition

$$I(x, y, z) = \sum_t S(t, x, y, z) R(t, x, y, z), \quad (1)$$

or other similar imaging condition.

When the waves generated from the source and receiver propagate downward through the earth, they will reflect and propagate in all directions once encountered interfaces. In order to de-blend RTM image, we need to decompose the source and receiver wavefields into upgoing and downgoing wavefields as follows:

$$S(t, x, y, z) = S_d(t, x, y, z) + S_u(t, x, y, z), \quad (2)$$

$$R(t, x, y, z) = R_d(t, x, y, z) + R_u(t, x, y, z). \quad (3)$$

The imaging condition (equation 1) can then be re-written as

$$I(x, y, z) = I_{dd}(x, y, z) + I_{du}(x, y, z) + I_{ud}(x, y, z) + I_{uu}(x, y, z), \quad (4)$$

where, $I_{dd}(x, y, z)$ represents the image obtained using downgoing source and receiver wavefields, $I_{du}(x, y, z)$ represents the image obtained using downgoing source and upgoing receiver wavefields, $I_{ud}(x, y, z)$ represents the image obtained using upgoing source and downgoing receiver wavefields, and finally, $I_{uu}(x, y, z)$ represents the image obtained using upgoing source and receiver wavefields.

With a new image condition (equation 4), the original RTM image can be de-blended into four images, where the image constructed via $I_{dd}(x, y, z)$ is less velocity sensitive and free from back-scattering and other noise.

EXAMPLES

To investigate the velocity sensitivity of RTM and its de-blended migration image, we used a synthetic salt model with gently varying background velocity and scatters. Figure 1a shows the center portion of the velocity model used. As seen in the figure, the salt dome has a vertical flank and strong rugosity

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on the left side of the salt top and base. Underneath the left side of the salt, there is a low velocity target. The synthetic shot spacing is 40 meters and receiver spacing is 20 meters.

Because of the complexity of the true Earth model, velocity obtained via conventional migration velocity analysis will not be perfect; and therefore, certain errors or induced smoothness will always exist in the derived velocity model. Velocity errors can produce migration artifacts in RTM. Moreover, the high velocity contrasts on top of the salt and water bottom can generate noise due to the strong reflections at the interfaces.

We now demonstrate RTM de-blending technique and compare the results with the wave equation extrapolation method using phase-shift-plus-interpolation (PSPI). We performed four migration tests for our model: (1) RTM using the true velocity model, (2) PSPI migration using the true velocity, (3) RTM using a smoothed velocity, and (4) PSPI using the same smoothed velocity. Using the true velocity model, the salt body and vertical salt flank are well imaged by RTM (red arrows in Figure 1b), whereas PSPI one-way extrapolation failed to image the vertical salt flank (red arrows in Figure 1c). Even though conventional RTM creates a better image for steeply dipping reflectors, it introduces unwanted noise at the water bottom, on the top of the salt, and underneath the salt with strong rugosity (yellow oval in Figure 1b). Using the smoothed velocity (Figure 1d), the result shows that all the noise still exists in RTM, and the noise level is getting worse underneath the salt with strong rugosity (yellow oval in Figure 1e). Moreover, the velocity smoothing creates a transition layer with strong velocity gradient around the salt, hence, generates additional noise on top of the salt (yellow arrows in Figure 1e). However, the smoothness of the velocity has minimal effect on PSPI migration (Figure 1f). After applying the de-blending technique, Figures 2a and 2d show that the quality of RTM images is greatly enhanced (using either the true or the smoothed velocities) when only downgoing wavefields are used for the source and receiver. From the figures, one can also notice that the vertical portion of the salt flanks has been unfortunately removed. However, the vertical salt flanks appear in Figures 2b and 2e (red arrows), which are generated using downgoing source and upgoing receiver wavefields. The zoomed images within the yellow boxes of Figures 2b and 2e are shown in Figures 2c and 2f. This example also demonstrates that most of the migration noise in RTM are generated when using downgoing source and upgoing receiver wavefields (seen in Figures 2b and 2e), upgoing source and downgoing receiver wavefields, and upgoing source and receiver wavefields to construct the RTM images (figures not shown in here).

A 2D marine dataset was also used to test the de-blended RTM. Figure 3a shows a smoothed migration velocity model generated from tomography. As indicated by the red arrow, a strong velocity gradient exists in the model. This velocity gradient causes the migration artifact in conventional RTM (red arrow in Figure 3b), but PSPI image does not have this artifact (Figure 3c). In order to remove the migration artifact from RTM, we applied upgoing and downgoing wavefield separation for the source and receiver. The RTM image using downgoing source and receiver wavefields shows the clean

image with the removal of the migration artifact and other noise up shallow (Figure 3d). The migration artifact due to the velocity gradient and other noise can be seen in Figure 3e which is generated using downgoing source and upgoing receiver wavefields. More noise can be seen in Figure 3f, the de-blended RTM image using upgoing source and downgoing receiver wavefields. For the earth model with salt (Figure 4a), conventional RTM produces a better image for the steep salt flank and faulted structures compares to the PSPI migration image (Figures 4b and 4c, red arrows). After de-blending the conventional RTM image and using only the downgoing source and receiver wavefields to construct the image, the quality of the RTM image has been greatly enhanced (Figure 4d), and the migration noise and artifacts have been filtered out (Figures 4e and 4f).

CONCLUSIONS

A de-blending RTM algorithm has been tested and compared with conventional RTM and PSPI one-way extrapolation methods on both synthetic and marine datasets. Test results demonstrate that the de-blended RTM is less velocity-sensitive compare to conventional RTM. It also removes most of the migration noise from conventional RTM. The de-blending RTM provides high fidelity images for complex salt structures without artifacts while preserving steeply dipping reflectors and overturned structures where one-way wave equation extrapolation methods may become inadequate. Therefore, the improved method of de-blended RTM is recommended to use for subsalt imaging to better handle the challenging velocity model.

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Figure 1: (a) Velocity model of a salt dome with a vertical flank. (b) Conventional RTM using the correct velocity. (c) PSPI migration using the correct velocity. (d) Smoothed velocity model of a salt dome with a vertical flank. (e) Conventional RTM using the smoothed velocity. (f) PSPI migration using the smoothed velocity. Red arrows highlight the changes of the vertical salt flanks, yellow arrows highlight migration artifacts due to velocity smoothing, and yellow ovals highlight the migration noise underneath the salt.

Figure 2: De-blended reverse-time migration using the correct and smoothed velocity models. (a) RTM image using downgoing source and receiver wavefields. (b) RTM image using downgoing source wavefields and upgoing receiver wavefields. (c) Zoomed image of yellow box in Figure 2b. (d) RTM image using downgoing source and receiver wavefields. (e) RTM image using downgoing source wavefields and upgoing receiver wavefields. (f) Zoomed image of yellow box in Figure 2e. Red arrows highlight the vertical salt flanks and yellow boxes indicate the zoomed area.

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Figure 3: Velocity model and migration images for marine dataset. (a) Smoothed velocity model with strong velocity gradient. (b) Conventional RTM image using all the wavefields. (c) PSPI migration image. (d) RTM image using downgoing wavefields from the sources and receivers. (e) RTM image using downgoing wavefields from the sources and upgoing wavefields from the receivers. (f) RTM image using upgoing wavefields from the sources and downgoing wavefields from the receivers. Red arrows highlight the strong gradient in velocity model and the migration artifacts due to the velocity gradient.

Figure 4: Velocity model and migration images for marine dataset. (a) Salt velocity model. (b) Conventional RTM image using all the wavefields. (c) PSPI migration image. (d) RTM image using downgoing wavefields from the sources and receivers. (e) RTM image using downgoing wavefields from the sources and upgoing wavefields from the receivers. (f) RTM image using upgoing wavefields from the sources and downgoing wavefields from the receivers. Red arrows highlight the steep salt boundary.

EDITED REFERENCES

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