Comparison of Isotropic, VTI and TTI Reverse Time Migration: An Experiment on an Anisotropic Benchmark Dataset from BP

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Introduction

Reverse time migration (RTM) has been successfully applied to production imaging processing in recent years. It propagates a source wavefield forward in time and a receiver wavefield backward in time to create an image of a subsurface reflector (Baykal et al., 1983; McMechan, 1983). By using the two-way acoustic wave equation, RTM has no dip limitation. Also, it naturally takes into account both down-going and up-going waves and thus enables imaging of turning waves and prism waves, enhancing the image of steep salt flanks or other steeply dipping events.

Seismic anisotropy, the variation of the propagation speed of seismic waves as a function of traveling direction, widely exists in sediments in many areas, such as the Gulf of Mexico, West Africa and the North Sea. Transverse isotropy (TI) is the most common type of anisotropy currently being addressed in seismic imaging (Thomsen, 1986). Conventional isotropic RTM results in erroneous images and misposition of dipping events in TI media. Instead of developing an accurate and very computationally expensive anisotropic elastic RTM, Alkhalifah (1998) started from the dispersion relation and proposed a pseudo-acoustic approximation in TI media by setting the shear wave velocity along the symmetry axis to zero. Based on Alkhalifah’s pseudo-acoustic approximation, we have developed an RTM algorithm to account for vertical TI (VTI) media (Zhou et al., 2006a). Assuming the symmetry axis is normal to bedding and tilting the symmetry axis accordingly, extensions from VTI to RTM in tilted TI media (TTI) have also been developed (Zhou et al., 2006b; Fletcher et al., 2009). Alternatively, Duvencek et al. (2008) derived a pseudo-acoustic VTI wave equation by setting the vertical shear velocity as zero based on Hooke’s law and the equation of motion. These formulations are related and equivalent if Thomsen’s anisotropic parameter δ is constant. Figure 1 illustrates wave propagation in isotropic, VTI, and TTI media with a constant velocity model. Duvencek et al.’s approach physically interprets the horizontal and vertical stress components. However, even if we satisfy the stability condition required by the explicit finite-difference (FD) scheme, applying the pseudo-acoustic equation and simply setting the shear wave velocity along the tilted symmetry axis to zero can cause numerical computation instability in TTI media that have strong lateral variations of tilted dip angle. Attempts have been made to stabilize the TTI equation and reduce shear wave artifacts (Fletcher et al., 2009; Zhang and Zhang, 2009).

Figure 1. Wave propagation in (a) isotropic, (b) VTI, and (c) TTI media. In (b) and (c), anisotropic parameter ε=δ=0.2, the tilted dip angle is set to 60° in (c).

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Nonetheless, computational cost prevents the use of TTI RTM in imaging large production datasets. In this paper, we will discuss several practical issues concerning migration noise and artifacts. Comparison of isotropic, VTI, and TTI RTM on the BP 2007 TTI anisotropic benchmark dataset will be demonstrated.

Noises and Artifacts

Conventional RTM imaging conditions produce strong low frequency background noise. Laplacian filters (Yoon and Zhou, 2001) are one of the most effective solutions to attenuate this kind of noise (Figure 2). These artifacts are produced by unwanted cross-correlation of head waves, diving waves, and back-scattered waves in the imaging step. In anelliptic media ($\varepsilon=\delta$), due to the pseudo-acoustic approximation on the elastic wavefield for VTI and TTI RTM, diamond-shape artifacts caused by triplications in the SV wavefront impact the imaging results. Strong variations of dip angle and azimuth in the tilted axis of symmetry can cause TTI RTM to be unstable (Fletcher et al., 2009; Zhang and Zhang, 2009). SV wavefront triplications need to be removed to make the numerical computation stable. Adding shear wave velocities helps stabilize wave propagation. The imaging condition will prevent contamination of the image by the added shear waves. Figure 3 demonstrates that TTI RTM generates strong artifacts where there are strong variations of tilted dip, and produces stable images after the special handling of shear wave propagation.

Experiment on the BP Anisotropic Benchmark Dataset

We performed isotropic, VTI, and TTI RTM on the BP 2007 TTI anisotropic benchmark dataset created by an elastic finite difference modeling code. Although synthetic, the model is detailed so that it looks very much like "real data", with the noticeable exception of the lack of surface multiples (quoted from the release notes of the dataset).

Figure 4 shows the velocity in the symmetry-axis direction, tilted dipping angle of anisotropy, and Thomas's $\varepsilon$ and $\delta$ models. Strong lateral variations of anisotropic properties exist on the model. Rapid variations of tilted dip angle occur in three areas (highlighted in Figure 4d). These areas present challenges to TTI RTM.

Figure 5 shows the comparison of images in area 1 of Figure 4d containing a steep salt flank. As expected, the steep salt flank image is mispositioned on isotropic RTM (Figure 5a) because the presence of anisotropy affects the positioning of dipping events. The VTI RTM produces a superior image of the steep salt flank, but some sediment events cross the salt boundary and penetrate into the salt body (Figure 5b). On the TTI RTM image (Figure 5c), the sediment events have nice terminations. The missing salt boundary may be caused by the limited acquisition aperture. Figure 6 shows the comparison of images in area 2 that contain anticline structures. Amplitude variations are evident on the isotropic RTM image (Figure 6a). Discontinuities are clearly present and the deep

![Figure 2: (a) RTM result before Laplacian filtering, (b) RTM result after Laplacian filtering.](image-url)
anticline structures are distorted on the VTI RTM image (Figure 6b). The TTI RTM image perfectly matches the geological structure of the model (Figure 6c). Figure 7 illustrates the comparison of images in area 3 with steeply dipping faults. On isotropic and VTI RTM images (Figure 7a and 7b), the faults are mispositioned and the image is poor between faults. In contrast, the faults on the TTI RTM image are sharp and correctly positioned. Also, the detailed structures in this section are well reconstructed (Figure 7c).

Figure 4. BP TTI anisotropic model. (a) Velocity model; (b) Thomsen's ϵ model; (c) Thomsen's δ model; (d) Tilted dip angle along the tilted symmetry-axis.
Figure 5. Comparison of isotropic RTM (a), VTI RTM (b) and TTI RTM (c) in area 1 of Figure 4(d).

Figure 6. Comparison of isotropic RTM (a), VTI RTM (b) and TTI RTM (c) in area 2 of Figure 4(d).

Figure 7. Comparison of isotropic RTM (a), VTI RTM (b) and TTI RTM (c) in area 3 of Figure 4(d).
Conclusions

The TTI RTM produces a superior image over isotropic and VTI RTM on the BP TTI anisotropic benchmark dataset, especially in those areas with strong variations of dip angle along the tilted symmetry axis. On the TTI RTM image result, the sediment events nicely terminate on the salt flank. Steeply-dipping faults are sharp and correctly positioned. Amplitudes along the anticline structure are well preserved. Ignoring the tilted dip angle in anisotropic RTM will misposition subsurface structures and degrade image quality in the TTI anisotropic medium. The pseudo-acoustic approximation of the elastic wavefield generates diamond-shaped artifacts of quasi-shear wave triplications that could contaminate the final image. Adding a small shear wave velocity component can effectively remove the shear-wave triplications and help stabilize wave propagation in the presence of large variations of tilted dip angle.

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References


