THRUST FAULT AND SUB-THRUST IMAGING IN THE TARANAKI BASIN WITH LEAST-SQUARES TILTED ORTHORHOMBIC Q-RTM

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Summary

The Taranaki Basin is one of New Zealand’s largest basins. Initially forming as a Cretaceous rift basin, it has over 400 exploration and production wells. Early basin history is characterized by extensional fault blocks, and as basin evolution continued, thrusting and inversion associated with the convergent active margin set up trapping mechanisms for petroleum accumulations. Recent fault blocks within shallow Plio-Pleistocene sediments exhibit strong azimuthal anisotropy. Without considering this effect, seismic imaging in the area suffers structural discontinuity and fault misplacement. Below these fault blocks, it is challenging to image the thrust system and sub-thrust structures due to poor illumination from strong velocity variation around the thrust.

To overcome these challenges, we focused on two major aspects. First, we built a tilted orthorhombic (TORT) velocity model to handle the strong azimuthal anisotropy in the overburden. At the time, we only had access to narrow-azimuth (NAZ) data, thus we derived the TORT parameters through scanning based on stack and gather responses. Second, we applied least-squares (LS) TORT Q-RTM to honor azimuthal anisotropy and compensate for poor illumination from the complex velocity. We observed significant imaging uplifts compared with the vintage data that subsequently provided an improved geological interpretation.

Introduction

The Taranaki Basin, the only producing basin in New Zealand, is still considered to be under-explored compared with many other failed rift complex basins of its size. Rifting during the Late Cretaceous opened the basin before becoming tectonically quiescent during the Eocene. An active margin was then fully developed by Early Miocene times. The Taranaki Fault System (TFS) is a large crustal-scale thrust system that defines the eastern edge of the basin and extends over 400 km. It brings the pre-rift basement above younger strata. Deformation and associated movement of the Taranaki Fault during the Miocene compressional regime resulted in changes to fault dips and corrugations in the principal thrust surface, together with tilting and folding of sedimentary strata adjacent to the fault (Nicol et al., 2004). These complex structures pose significant challenges to subsurface imaging and introduce uncertainty to the petroleum exploration potential in the adjacent and sub-thrust regions.

The Kaheru 3D marine narrow-azimuth (NAZ) seismic survey was acquired in 2006 to explore this region. The survey, acquired from west to east, covers 150 km^2 of a full-fold area located at the south-eastern margin of the Taranaki Basin (Figure 1a). The data was first processed in 2006 with both Kirchhoff PSTM and PSDM and subsequently re-processed in 2008 and 2009 to improve the signal-to-noise ratio and extract AVO volumes. In 2010, isotropic reverse time migration (RTM) was used to further improve the sub-thrust structural definition and resolution. Despite the extensive effort, the final isotropic RTM image still suffers from various problems. In the shallow Plio-Pleistocene sediment, there are periodic migration swings observed on the depth slice (Figure 1b). These swings, which we found to be related to azimuthal anisotropy, exist in all vintage images. In the deeper area below the Plio-Pleistocene overburden, as migration swings (artefacts) cut through the target sub-thrust structure (blue arrow) and the TFS (orange arrow), the structures are difficult to delineate (Figure 1c). To resolve these imaging challenges, we applied an advanced seismic processing package with two key aims: resolving azimuthal anisotropy via tilted orthorhombic (TORT) migration and compensating unbalanced illumination via least-squares (LS) RTM.

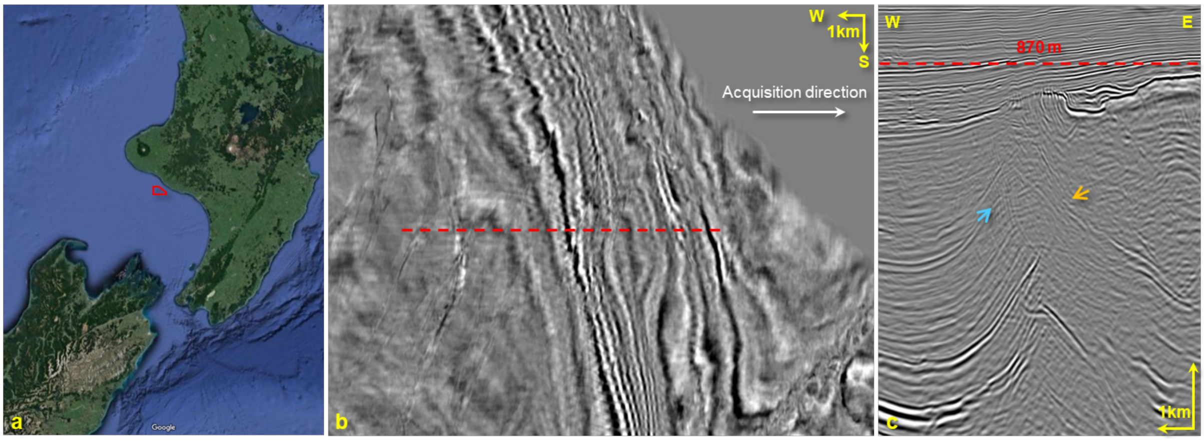

Figure 1 *a) Survey location (red outline); b) depth slice at 870 m from 2010 final RTM stack; c) transverse section (located at red dashed line in b) from 2010 final RTM stack.*

Azimuthal anisotropy and tilted orthorhombic (TORT) migration

Periodic stripes along the acquisition direction were first observed on the time slice from the pre-migration 3D stack (Figure 2a). These stripes correspond to the above-mentioned periodic migration swings. In the pre-migration common-midpoint (CMP) gathers, we also observed that event jitters perfectly correlated with the azimuth variations (Figure 2b). Both observations indicate the presence of azimuthal anisotropic velocity variations. The observed azimuthal anisotropy exists in the west side of the Kaheru 3D survey, where there is a clear shallow faulting system oriented ~45 degrees from the north. It is understood that fault movement induces maximum local stress along the fault direction, which explains the observed higher P-wave velocity (Nur and Simmons, 1969). A neighbouring wide-azimuth survey, Manutahi 3D, also observed strong azimuthal anisotropy (Taylor et al., 2013), which is consistent with our observation in this 3D NAZ survey.

To correct for this azimuthal anisotropy effect, considering the limited information available in this NAZ dataset, we first estimated the fast velocity azimuth and ellipticity via scanning based on stack and gather responses of normal moveout (NMO) corrected data (Sun et al., 2008). We found that an azimuth of 45 degrees from the north and a 12% ellipticity could best eliminate the jitters on the CMP gathers and the stripes on the 3D stack (Figures 2c, 2d). The fast velocity direction aligns with the dominant fault strike direction. In addition, the ellipticity is very close to the value in the nearby survey, which is around 10% (Taylor et al., 2013). We then built a TORT velocity and Q absorption model with these two parameters using TORT FWI (Xie et al., 2016), TORT tomography, and frequency-shift Q tomography (Xin et al., 2014). Compared with the TTI migration, the TORT migration not only eliminated the periodic migration swings in the shallow sediment layer, but also corrected the fault position (Figure 3), which helped validate the TORT model we built. From the transverse section comparison shown in Figure 3, the amplitude variation in the shallow section was balanced and event continuity was improved. The fault reflection planes moved towards the strata breaking points, allowing for more consistent fault interpretation. On the depth slice, we observed less migration swings, more focused faults and higher resolution shallow channel features.

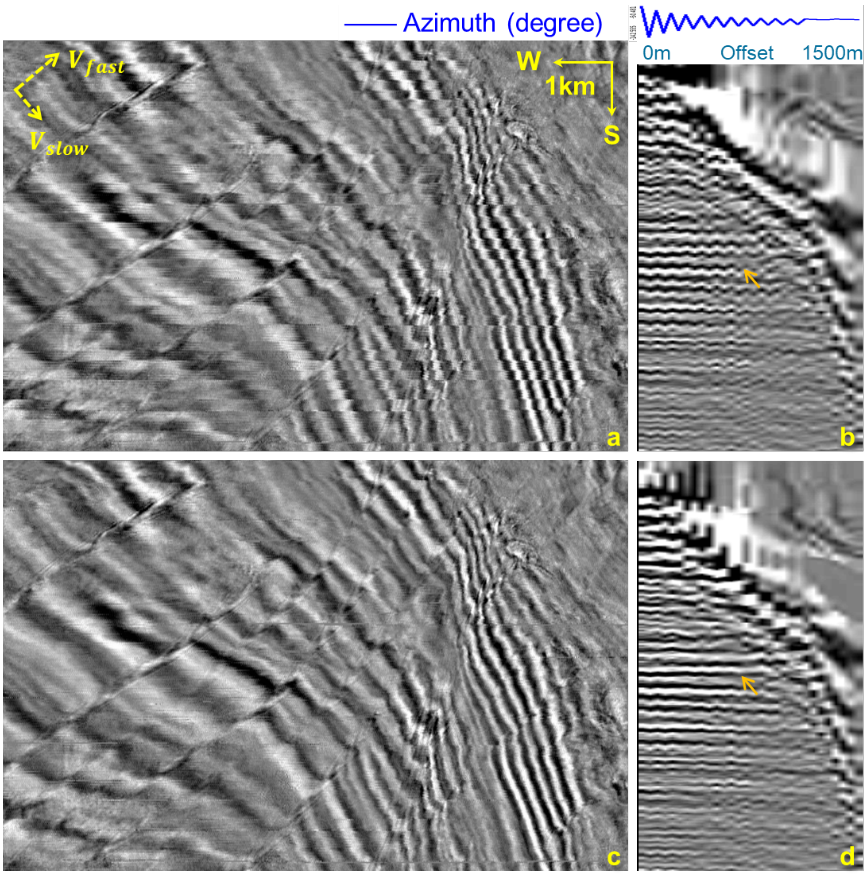

Figure 2 *3D stack time slice at 430 ms: a) before and c) after azimuthal NMO; Pre-migration NMO corrected gathers: b) before and d) after azimuthal NMO.*

LS TORT Q-RTM

To image the complex thrust system with high resolution and accurate fault positioning, we needed to consider multi-pathing, strong azimuthal anisotropy and Q absorption effects. To fully utilise the complex velocity (Figures 4d, 4h), we employed TORT Q-RTM, where we start from the linear visco-acoustic wave equation in a TORT anisotropic medium and use wavefields from both a conjugate medium and a lossless medium to compute the desired backward propagated receiver wavefield (Xie et al., 2015). This method resolved the instability issue associated with the frequency-dependent attenuation in time-reversal propagation and dealt with multi-pathing, as well as tilted orthorhombic anisotropy effects in this data.

LS migration can compensate for amplitude loss due to poor illumination and provide less migration artefacts/swings than standard migration. Our approach for LS migration was a single-iteration curvelet-domain Hessian filter (CHF) RTM (Wang et al., 2016), which was effective and efficient at resolving poor illumination under the thrust fault region. Analysis indicated that the Taranaki thrust fault and sub-thrust reflectors suffered from poor illumination due to the complex spatial velocity variation (Figures 4d, 4h) resulting from basement thrust activity. Figures 4b and 4f show a TORT Q-Kirchhoff image in which the thrust fault and deep target are dim due to poor illumination. LS TORT Q-RTM was able to provide better amplitude fidelity and gave clearer delineation of the thrust system (Figures 4c, 4g). Compared with the vintage isotropic RTM image (Figures 4a, 4e), our final LS TORT Q-RTM image shows that the thrust fault is much clearer and more focused, with more continuous sub-thrust reflectors. This provides evidence of rollover and truncation at the fault plane and thick source rock potential on the eastern side of the thrust, changing the interpretation of the area.

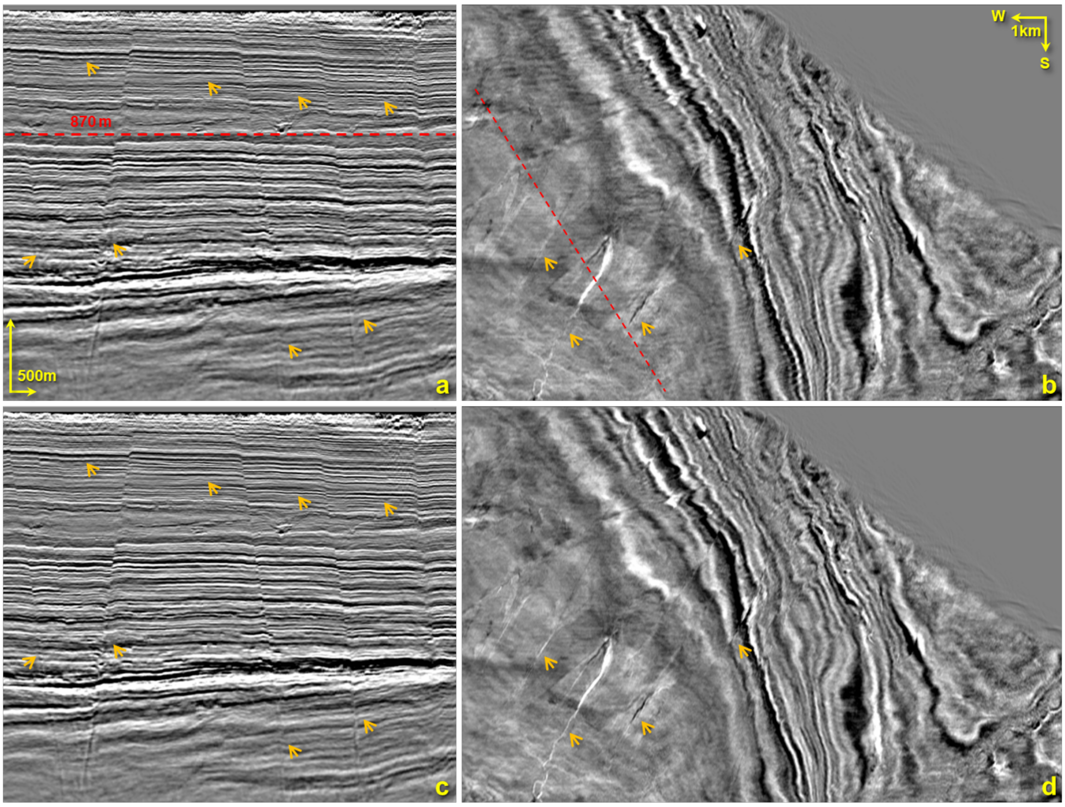

Figure 3 *TTI Kirchhoff PSDM: a) transverse section (located at red dashed line in b), and b) 870 m depth slice; TORT Kirchhoff PSDM: c) transverse section, and d) 870 m depth slice.*

Conclusions

We have presented a case study from the Taranaki Basin in which we encountered many imaging challenges, including steep dips, strong azimuthal anisotropy and horizontal velocity complexity. We estimated azimuthal anisotropy parameters through scanning, based on pre-migration CMP gather and stack responses. With this estimation, we built a TORT velocity model and corrected the azimuthal effect via TORT migration, which led to more accurate fault positioning. To reduce migration swings/artefacts and to balance the sub-thrust amplitude, we applied single-iteration CHF LS TORT Q-RTM. The new result shows significant imaging improvement and a more confident interpretation. We believe our approach provides a viable tool for NAZ data that requires complex fault imaging and suffers from strong azimuthal anisotropy.

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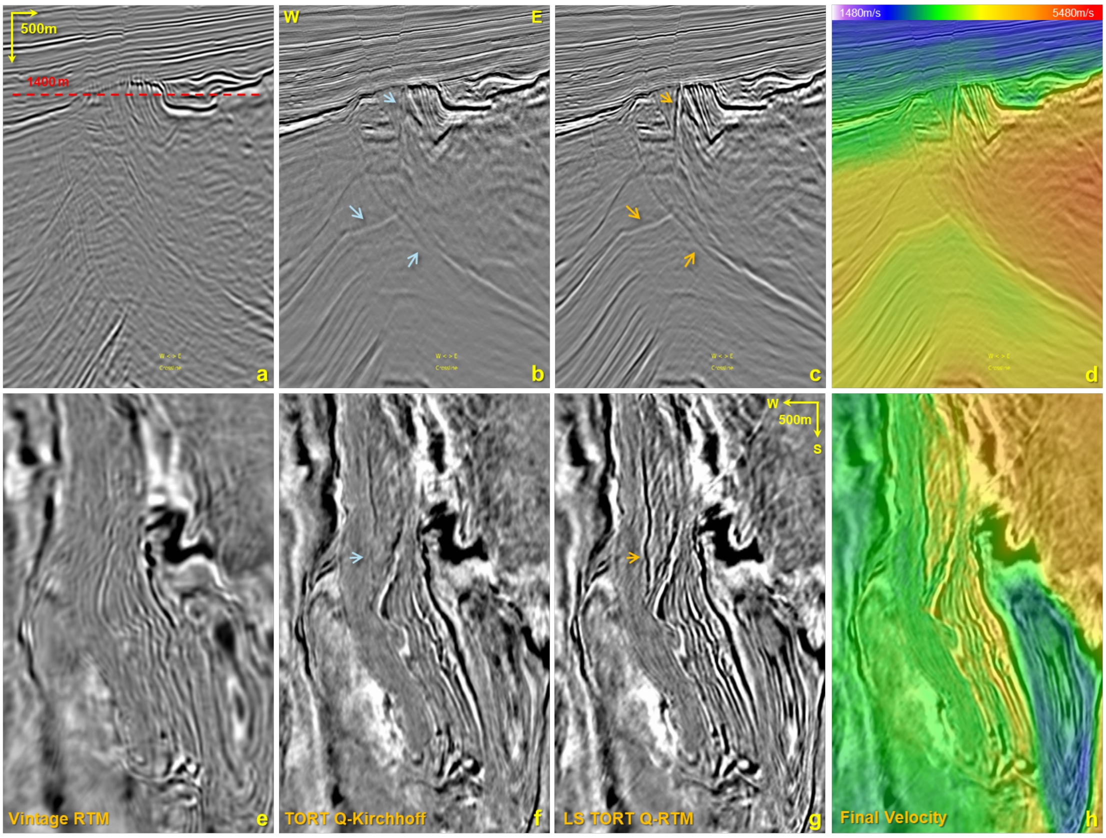

Figure 4 *Final image comparison of transverse section (upper panels) and depth slice at 1400 m (lower panels): a) and e) 2010 vintage isotropic RTM; b) and f) 2019 final TORT Q-Kirchhoff; c) and g) 2019 final LS TORT Q-RTM; d) and h) 2019 final migration velocity model.*

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