Improving fractured basement imaging through WAZ OBC acquisition

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Summary

The oil-bearing fractured granite basement rocks form a very important and complicated hydrocarbon reservoir in the Cuu Long basin offshore Vietnam. However, the poor fractured basement imaging in conventional tow streamer data makes it hard for detailed interpretation and future well placement. To improve seismic imaging, the first 3D/4C OBC acquisition over the field was carried out. This provides better illumination, better elimination of multiples and a broader spectrum with a better signal to noise ratio. However, the presence of strong azimuthal anisotropy poses a serious challenge in imaging this OBC data with full azimuth (FAZ) coverage. The steeply dipping fracture imaging can be smeared if the subsurface orthorhombic (ORT) velocity model is not properly derived. In this paper, we present a new orthorhombic velocity model building workflow to estimate the azimuthal anisotropic velocity by incorporating shear wave splitting analysis, well formation microimager (FMI) information and 3D RTM subsurface angle gather based velocity sweeping inside the basement. Two geological layers with strong azimuthal anisotropy are identified and incorporated into the final ORT model which results in much sharper imaging not only in shallow clastic sediment layers but also in the fractured basement.

Introduction

The White Tiger OBC survey was acquired over VietsovPetro's Bach Ho field in 2015. The survey was designed to record data from all azimuths and offsets of up to 6km. The survey covered an area of 850 kmsq, large enough for imaging the entire basement structure. The acquisition layout is designed to have an orthogonal shooting geometry that allows the recording of full azimuth data. Trace density was 576 fold in the 0-5km offset range, significantly higher than the single azimuth 2009 towed streamer 3D data with a nominal fold of 50 and a maximum offset of 5km.

The fractured basement play in the Cuu Long basin is unusual in that oil migrated from younger shale source rocks to older fractured basement rocks as shown in Figure 1. Thus it is essential to understand the fracture development for identifying the most productive areas and further implementing a successful appraisal and drilling plan. Both PP and PS PSDM processing were conducted concurrently with the aim to achieve the best imaging on the primary (fractured basement) and secondary (clastic layer) targets.

In the PP PSDM processing, a Common Offset Vector (COV) based TTI tomographic velocity update was first conducted from the water bottom to the top of the basement. After four iterations of the TTI tomographic update, the azimuth dependent moveout jittering on common image gathers (CIG) can be clearly seen from the shallow to deep sections even though the background trend of the events is flat as shown in Figure 2. It is well known that there is strong azimuthal anisotropy inside the basement due to rich fracture systems in this area (Zhou et al., 2011). In addition to this, the data clearly manifest the existence of a strong azimuthal anisotropic layer in the shallow.

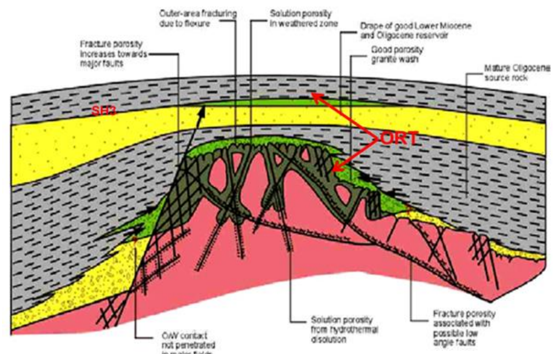

Figure 1: Cuu Long Fractured basement play (Nguyen & Hung, 2004)

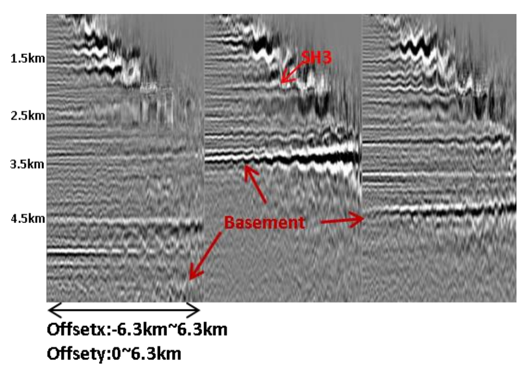

Figure 2: Kirchhoff PSDM snail gathers with TTI model

ORT model building in the shallow using shear wave splitting information

The conventional practice is to divide the WAZ/FAZ data into at least 4 azimuth sectors, build a TTI model for each individual azimuth sector and then elliptically fit the TTI velocity models from different azimuth sectors to derive the initial ORT model. After that, the tilted orthorhombic (TORT) tomography update can be applied using the COV gathers (Han and Xu, 2012). It is also a common practice to use a layer stripping method when a multi-layered ORT system exists.

Given the advantage of 3D/4C OBC data, the shallow azimuthal anisotropy effect can be effectively estimated by shear wave splitting analysis in PS processing, which reveals that the majority of the azimuthal anisotropy in the shallow is from the shale layer above SH3 in Figure 1. High resolution attributes of the fast velocity direction and the time delay between fast and slow velocity are generated from a shear wave splitting analysis as shown in Figure 3. After filtering out un-geological features, such as outlier and acquisition footprint, a smooth version of this attribute can be incorporated in the derivation of the initial shallow ORT model from the TTI models (layer above SH3).

To check the validity of this initial ORT model, Kirchhoff PSDM migration was conducted. It can be seen that the moveout discrepancy associated with azimuth anisotropy has been significantly mitigated by the orthorhombic velocity update in the shallow (Figures 4a and 4b). From the stack section, the faults are sharper and the events between faults are better focused (Figures 4c and 4d). The residual jittering above the basement can be further attenuated by one or two more iterations of ORT tomographic update using PP data.

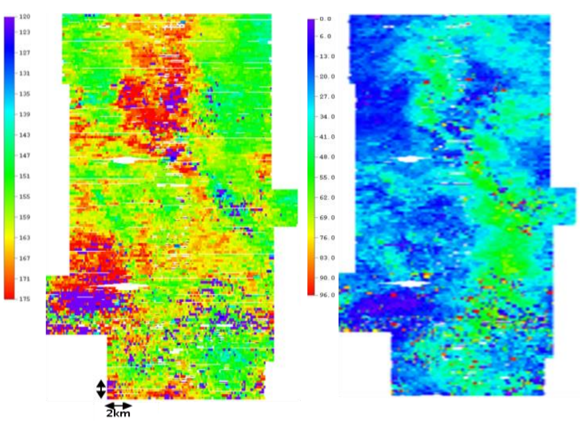

Figure 3: Fast velocity angles in degree from shear wave splitting on the left and the corresponding time delay in millisecond between fast and slow S waves on the right. The angle refers to real North.

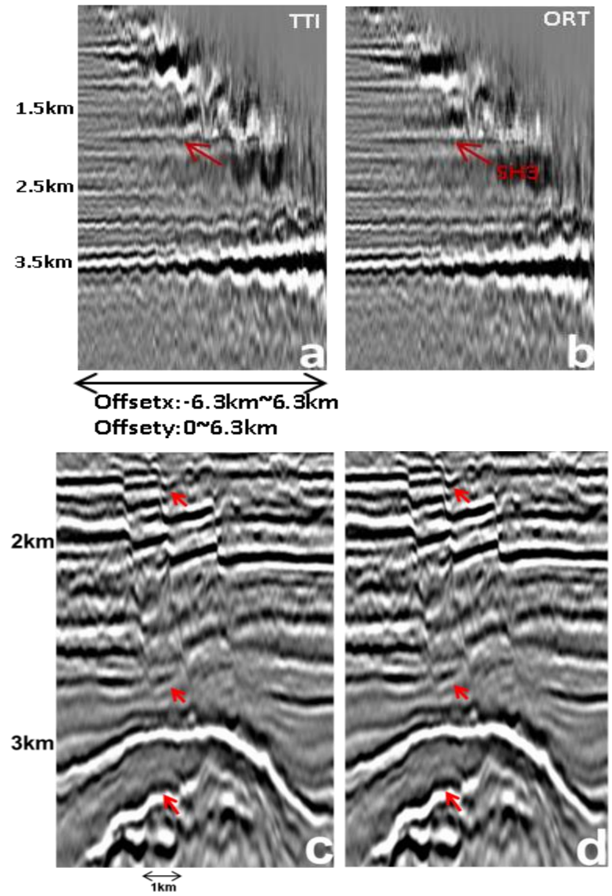

Figure 4: a): TTI snail CIG after 4 iteration of tomographic update from water bottom to top of basement, b): Initial ORT snail CIG, c): TTI stack section, d): Initial ORT stack section

Tilted orthorhombic model building inside basement

When moving to the basement level, the S/N ratio in the PS data is too poor for any meaningful shear wave splitting analysis due to strong absorption effects and the steeply dipping nature of the fracture events (above 70 degree). Dividing data into different azimuthal sectors for azimuth dependent velocity analysis fails because of the assumption that the surface azimuth is close to the subsurface azimuth of wave propagation. The best imaging velocity for each azimuth sector no longer represents the acoustic velocity of seismic waves propagating along that azimuth.

For NAZ data, a dual sweeping approach was proposed by Zhou et al in 2011 in which a Controlled Beam Migration (CBM) stack sweeping approach was used to firstly estimate the best imaging velocity inside the basement and then scan the slow velocity direction. However, with the full azimuth nature of OBC data and relatively low frequency content inside the basement, Reverse Time Migration (RTM) 3D subsurface angle gathers are the natural choice for efficient analysis of the subsurface azimuthal and opening angle dependent wave propagation. This also simplifies the ORT model building flow inside the basement. RTM 3D angle gathers with a 20Hz maximum frequency were generated with the different basement velocities as shown in Figure 5, then the stack imaging based velocity sweeping approach with reference to the flatness of angle gathers was used to derive the imaging velocity or horizontal velocity (ray is almost horizontal inside basement due to the steeply dipping nature of the fractures) along each azimuth inside basement. Combined with the vertical velocity information from the well sonic data, an elliptical fitting was carried out to derive the ORT model inside basement.

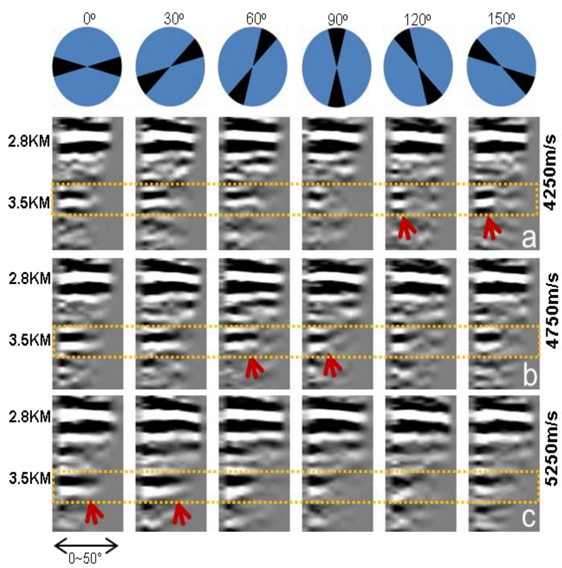

Figure 5: RTM subsurface angle gathers from 3 models, and the velocities inside the basement: a): 4250m/s, b): 4750m/s and c): 5250m/s. The top basement is at 2.8km depth. The six azimuths sectors are 0, 30, 60, 90, 120 and 150 degree from left to right referring to easting of survey. The yellow dash lines cover the angle gathers of the fractures for each azimuth. The red arrows show the velocities that best flatten RTM subsurface angle gathers within each azimuth from these three velocity models.

Since the azimuthal anisotropy is caused by the background fracture system, the slow velocity direction should be roughly perpendicular to the dominant fracture orientation. The well formation microimager (FMI) data was used as a QC and also a constraint in the elliptical fitting process. Figure 6 compares the inverted fracture strike angle map from the RTM 3D angle gather based velocity sweeping and the dominant fractures orientation from FMI analysis, which show a good match. The resultant ORT model greatly improved the imaging inside the basement compared to the starting TTI model as shown in Figure 7, the fractures and flank of the top basement are much better focused with the ORT model.

Compared to the 2009 towed streamer PSDM data (Figure 8), a step change in imaging quality can be observed in the OBC PP ORT PSDM imaging: broader bandwidth, much higher S/N ratio and higher resolution from shallow to deep, faults are better focused and most importantly, the fractures inside the basement are much better delineated both in vertical section and depth slice. These uplifts are attributed to the FAZ and high fold coverage nature of OBC acquisition along with the orthorhombic velocity model. Orthorhombic model building and PSDM are of critical importance for the fracture imaging inside the basement, which enable constructive stacking of the image formed by data propagating along different azimuthal directions.

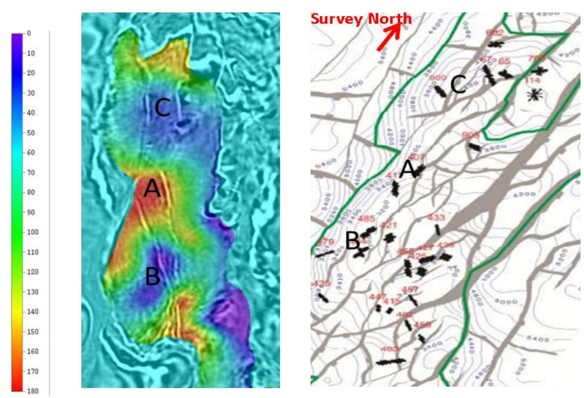

Figure 6: Slow direction of fractures inverted from RTM angle gathers at depth 3500m at left and fracture orientation analysis from FMI data at right. The north section of the survey shows as a red arrow which is 90 degrees from the east section of the survey. It shows that A is 180 degrees, B is 0 degree and C is 30 degrees, which is in agreement to FMI data in general.

Conclusions

We have presented a new orthorhombic velocity model building flow to estimate the complex azimuthal anisotropic system in the Cuu Long basin offshore Vietnam. By taking full advantage of the 3D/4C OBC data, we estimate the shallow azimuthal anisotropy through shear wave splitting analysis to derive the initial ORT model at shallow, and RTM 3D angle gather based velocity sweeping and FMI data for deriving the ORT model inside the basement. The resultant ORT model greatly improves the focusing of the fault/fracture imaging which is critical for this survey.

It is worth mentioning that the actual earth model is much more complex than TORT, for example, multi-phase tectonic movements will create fracture systems with different azimuthal orientation on top of each other. Nevertheless, our TORT imaging approach here enables a much better estimation of the acoustic wave propagation than the conventional TTI approach and provides an effective solution to improve the fractured basement imaging in the Cuu Long Basin using WAZ OBC data.

Acknowledgements

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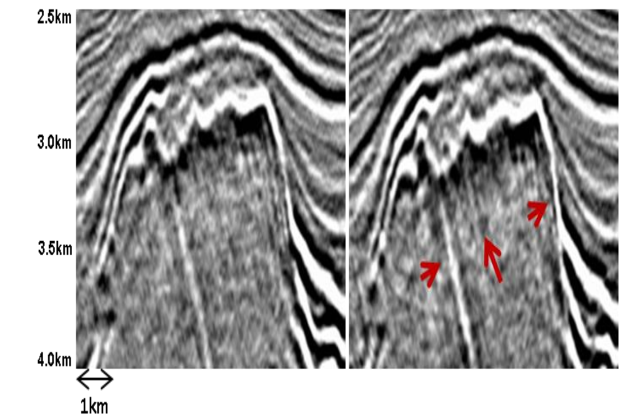
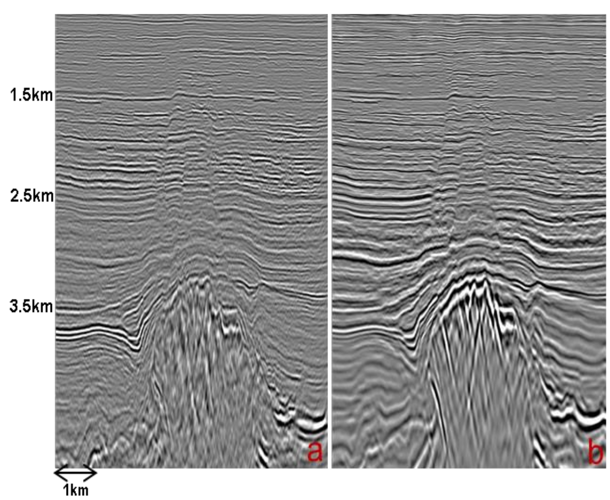


Figure 7: Kirchhoff isotropic PSDM at left and Kirchhoff ORT PSDM at right



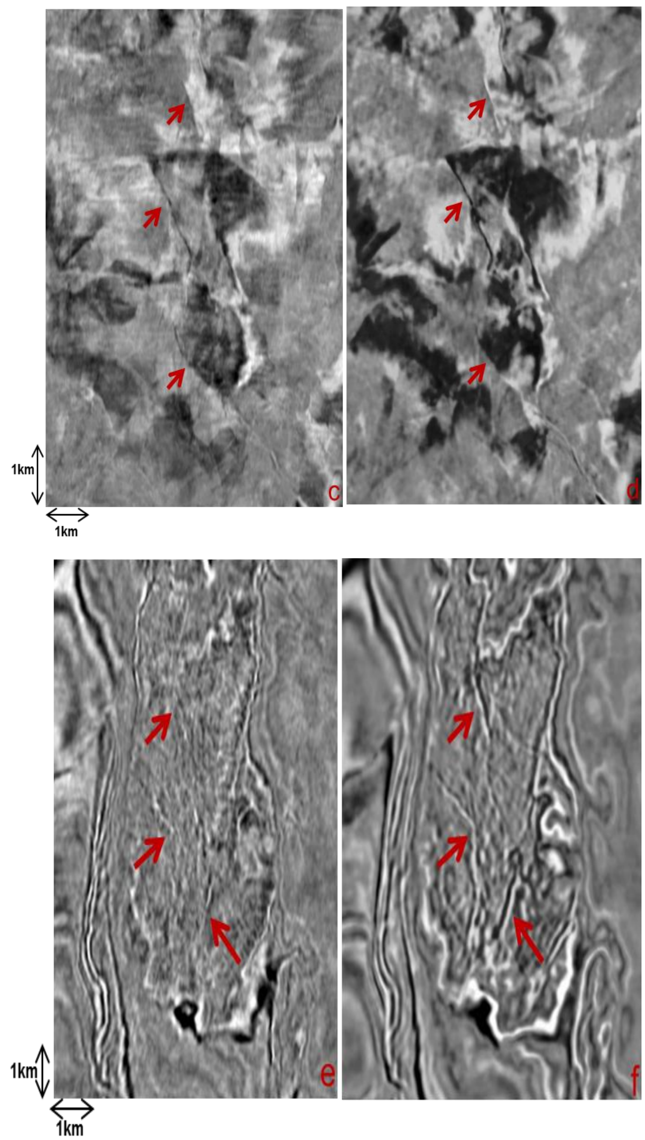


Figure 8: Towed streamer legacy PSDM vs 2016 ORT, a): 2009 PSDM stack section, b) 2016 OBC PP ORT stack section, c): 2009 PSDM depth slice of 1.5km, d) 2016 OBC PP ORT depth slice of 1.5km, e) 2009 PSDM stack slice of 3.5km and f): 2016 OBC PP ORT depth slice of 3.5km.