Introduction

In the oil rich Bohai area, the fault systems play an important role in hydrocarbon exploration and production. The strong velocity variation across the high dipping fault structures, serious shallow water multiple problem and low signal to noise ratio in the target zone prevent clear and accurate fault imaging from the conventional pre-stack time migration. Previous attempt using Kirchhoff PSDM also failed to improve the image quality without first solving the low signal to noise issue and creating an accurate anisotropic model.

With the recent development of PSDM technology including high resolution tomography (Han and Xu, 2011), TTI model building and High Fidelity Controlled Beam Migration, we have developed an effective PSDM workflow to improve the complex fault system imaging for the dataset in this area. In this paper, we will discuss our workflow, show the result and demonstrate its huge impact on the field development through a case study from the Luda field, offshore China.

Geological Setting

Luda field is located in the Liaodong Bay of Bohai Sea. As part of the Liaodong structural belt, this field is controlled by the Liaozhong No. 1 strike-slip fault as the main trapping mechanism and then partitioned into small parts from north to south by a complex secondary fault system as shown in Figure 1. The imaging quality and position of the strike-slip fault system are the key factors in the field development, which have direct impact on the reservoir size/economy of the oil discovery and further drilling plans. However, in the conventional PSTM sections (Fig 2), the main strike-slip fault and secondary fault were poorly imaged, the fault was not well defined and lots of conflicting events and migration swings were observed in the target area. All of these influence the mapping of the structure closure and imaging of the complex gas/water relationship in the reservoir zone.

To improve the fault imaging, three key components are required: good de-multiple in the pre-processing, an accurate anisotropic velocity model and a high accuracy prestack depth migration algorithm which can address the low signal-to-noise ratio issues in the input data. For the de-multiple part, a two-step surface related multiple attenuation approach (Hung et. al. 2010) was applied by targeting the short-period and long-period multiples separately using multichannel prediction filter and 3D SRME respectively. In this paper, we will focus on discussion of the model building and the new PSDM migration algorithm here.

TTI Velocity Model building

We start the model building with isotropic velocity update using a grid based tomography approach. A high-resolution tomography scheme (HRTOMO) is applied to resolve the rapid velocity change caused by the small faulting in the shallow layers. To achieve the best resolution, the inversion grid is non-uniform in the z direction which starts at 10m from the water bottom and linearly increases to around 100m at 8km. The lateral inversion grid is 50m in both x and y directions. The regularization
in the inversion is also depth dependent to preserve the resolution at shallow while avoiding the unwanted variation due to ill-conditioned inversion in the deep part. Figure 3 shows the velocity and PSDM gathers before and after HRTOMO update, the updated velocity field matched well with the shallow faulting structure; both the gather flatness and event focusing are significantly improved.

**Figure 3:** a: the initial velocity model; b: velocity model after HRTOMO; c: the CIGs from initial model; d: the CIGs from updated model.

After three iterations of HRTOMO, the gather’s flatness for flat and quasi-flat events are overall very good. However, the strong overcorrection for the boundary fault events and the conflicting residual curvature for the gathers in the highly tilted upfault block (Fig 4a) suggest that a further isotropic update won’t be able to solve these issues. Then anisotropy has to be taken into account, and the best approximation here is to honor the layering of the geological structure through TTI anisotropy. Traditional anisotropy analysis requires data with wide reflection angles and proper controls of well information as the anisotropic parameters can’t be derived solely from seismic data (Thomsen, 2002). In our case, with relatively shallow penetration of the wells (<2500m) and short cable length (<4500m), the traditional approach is only applicable for the shallow section. However, with some understanding of the regional rock property, it is possible to derive a reliable anisotropic field from the seismic data. The key here is the residual curvature analysis from the dipping events in the tomography update (Birdus and Li, 2010). To jointly invert $V_0$, $\varepsilon$ and $\delta$ in the TTI anisotropy model, some assumptions have to be made for the initial anisotropic model:

1. A $\varepsilon/\delta$ ratio constraint file is created as one of the input. The ratio was set to 1.2 for the most sandy Dongying formation (E3d) and was set to 1.6 for the more shaly Shahejie formation (E2S) based on the regional experience.
2. The initial dip angle $\theta$ and azimuth angle $\phi$ are interpreted based on the isotropic PSDM stack volume.
3. The short spread Moveout velocity for flat or quasi-flat events remains unchanged.

In addition, large spatial regularization (2000–3000m) along each geological formation is needed to get a stable solution from the joint inversion. Figure 4 shows the CIGs and stacks comparison between the isotropic model and the first TTI model, the conflicting residual curvature for the dipping events are greatly reduced after the first TTI model update.

In the following tomography update, the $\varepsilon$ field was further refined with $V_0$ and $\delta$ kept unchanged. After that, the vertical velocity was updated by a couple of more iterations of tomography update until the CIG gathers are flat. The dip and azimuth angle field were re-picked after each iteration based on the updated depth volume. The model building was concluded with a CBM velocity sweeping inside basement. The final TTI velocity model produced much better depth image with clear boundary fault imaging, good secondary fault truncation and no fault shadows. The reliability of this TTI model was confirmed by the further drilling results which show that most of the depth errors are under 1%.
High Fidelity Controlled Beam Migration

As a specialized version of beam migration, Controlled Beam Migration (CBM) enhances signal-to-noise ratio of image and particularly can reveal steep dips. It is a powerful imaging tool which can deliver clear, easy-to-interpret structural images in complex areas (Gray et. 2009). As a local slant stack migration, CBM operates in both localized space and localized angle; hence it can handle multi-pathing naturally. By adding multi-pathing, CBM can produce better images than single-arrival Kirchhoff migration in complex geology, reducing artifacts such as migration swing which can contaminate image of complex geology in conventional Kirchhoff migration. In the meanwhile, CBM keeps all the advantages of Kirchhoff migration such as steep dip imaging, efficient incorporation of anisotropy, including TTI which plays an important role in the fault imaging for the Luda field. However, earlier version of CBM falls short for AVO analysis and the inversion process. The new development of High Fidelity Controlled Beam Migration (HFCBM) further reduces the migration artifacts, enhances the signal-to-noise ratio and preserves the relative amplitudes. It benefits both model building and final imaging in this case.

In Figure 5, we compare images between HFCBM and Kirchhoff for the shallow strike-slip structures. The same input and TTI velocity model were used for both migrations. The truncation of the fault structures is important to identify shallow oil and gas target (<2000m). It is very hard to interpret the shallow faults in the Kirchhoff section while the image quality and signal noise ratio is greatly improved in HFCBM result.

Results and Impact on exploration

Ever since the first discovery in 2004, the development of Luda field was impeded by the lack of clear and accurate fault image. The data was reprocessed and re-interpret for multiple times without solving the uncertainty in the reservoirs area until the latest reprocessing with TTI model building and HFCBM technology. In Figure 6, we compare the previous PSTM and the current HFCBM section: great improvement can be observed on S/N ratio, fault imaging and fracture imaging inside basement;
most importantly, we can see the step change in the boundary fault imaging: the main and secondary boundary faults are clearly imaged compared to the original fuzzy fault zone in the PSTM session.

Based on the new interpretation result from the depth migration volume, four new wells (A4, A5, A6 and A7) were drilled in 2012. Commercial discovery was made on all four wells with an average 81m of net pay from the sand layers in the Donger formation (E3d2L). A5 well produced the best result with 163m of net pay in 33 layers of high quality sand reservoir. In Figure 7, we show the new interpretation for the T3m surface which is the base for the Donger formation. The drilling location for A2 and A3 was designed based on the structure high from the legacy PSTM volume. But based on the new interpretation, they are actually outside the main reservoir area which also explains the unfavorable performance of these two wells. The total proven and controlled oil reserves for the Luda field increased from 54 MMboe to 336 MMboe and the Luda field has revived from a marginal field status.

**Conclusion**

We have demonstrated the advantage and importance of the TTI model building flow and HFCBM technology through the Luda case study. The step change in the imaging quality for the complex fault system provides the key contribution to unlock the full potential in the filed development. Combined with SWD technique (Hung et al. 2010), this work flow provides an effective solution for the imaging issues in this complex fault system and also the middle to deep low S/N zone in the Bohai area.

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**References**


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