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CORRECTING FAULT SHADOWS – A CASE STUDY COMPARISON OF FAULT-CONSTRAINED TOMOGRAPHY AND TIME-LAG FULL-WAVEFORM INVERSION

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Summary

Solving fault shadow imaging problems has been a long-existing topic when extensive faults are present and the seismic imaging underneath is distorted. With full-waveform inversion (FWI), they are usually less of a concern when their depths are within diving wave penetration. However, beyond diving wave penetration, we have to rely on reflection energy, either by various tomographic methods or reflection FWI, both of which require special considerations in order to effectively resolve small-scale velocity anomalies associated with faults. In this paper, we present applications of fault-constrained tomography (FCT) and Time-lag FWI (TLFWI) with a weighted tomographic term for deep fault imaging using a streamer dataset with limited offsets from the South China Sea. Our learnings show FCT heavily hinges on high-quality common image gathers (CIGs) and fault picking. With a weighting factor to promote the tomographic term from reflection energies, the TLFWI workflow successfully corrected fault shadows and demonstrated advantages over FCT for resolving velocity anomalies in areas of complex faults.

Correcting Fault Shadows – A Case Study Comparison of Fault-Constrained Tomography and Time-lag Full-Waveform Inversion

Introduction

Fault shadows refer to the distorted and poorly imaged seismic zones in the vicinity of the fault, mainly arising from our failure to resolve the lateral velocity contrasts across the fault throw. The resulting spurious structural pull-ups and sags are well-known for bringing uncertainties to exploration targets associated with fault blocks as well as the heavily faulted overburden underneath. A high-resolution velocity model that correctly captures the rapid velocity variations across the faults is required to resolve these fault shadows.

Traditionally, ray-based reflection tomography with additional structural constraints has been the main approach to tackle fault shadow issues (Birdus, 2007; Guillaume et al., 2013; Xiao et al., 2018). These methods work well when the quality of the common image gathers (CIGs) is reliable for residual moveout (RMO) and structural dip picking. However, when there are large velocity errors in the initial model or unbalanced illumination in the subsurface, the RMO and structural dip picking can be challenging. Moreover, ray-based tomography relies on raytracing that is unstable in the presence of strong localised velocity contrasts, which are often present in fault zones. In recent years, full-waveform inversion (FWI) has become the main engine to derive high-resolution velocities. The largely horizontal propagation of diving waves is ideal for resolving the lateral contrasts; thus, fault shadows can be reasonably resolved by FWI when within diving wave penetration (Xie et al., 2016). However, they remain challenging in deeper sections where we must rely on reflections with limited angle coverage. Many studies have been carried out on how to utilize the tomographic and migration terms of the FWI gradient in order to improve effectiveness of correcting both high- and low-wavenumber kinematics using reflection data (Tang et al., 2013; Irabor and Warner, 2016; Gomes and Chazalnoel, 2017; Wang et al., 2018). Furthermore, kinematics-based cost functions have been established for robust inversion due to their ability to mitigate amplitude discrepancies between modelled data and real data. Time-lag FWI (TLFWI), proposed in Zhang et al. (2018), has shown impressive results in different geological settings. TLFWI uses the full wavefield including diving waves and reflections as the input data and therefore it can naturally infer velocity information from both diving waves and reflection energy. However, the velocity updates driven by the latter is often very weak compared with other terms in the FWI gradient. To better extract the benefits of reflection energy, we will explore TLFWI with a weighting factor used to promote the tomographic term from reflection energies (hereinafter, we call it tomo-promoted TLFWI) as an alternative approach to further improve updates related to fault shadows beyond diving waves.

The South China Sea is a typical area where high precision fault imaging is critical, as many exploration targets are associated with faults acting as the trap mechanism. Our study area in the South China Sea is covered by multiple vintage narrow-azimuth streamer datasets with little overlap between each other. The maximum offsets range from 3 to 6 km. Water depth in this area varies between 90 m and 130 m, with the main targets ranging from 2 – 5 km in depth. Extensive faults have developed in the zone of interest beyond diving wave penetration. Severe fault shadow effects are known obstacles for accurate structure mapping and trap definition. In the most recent re-imaging, we attempted both fault-constrained tomography (FCT) and tomo-promoted TLFWI to tackle the problems. In the following sections, we first present FCT to update the fault zone velocity when picking quality is reliable. We then demonstrate that tomo-promoted TLFWI outperforms FCT in the complex fault zone.

Fault-Constrained Tomography

To build an accurate high-resolution velocity model using tomographic approaches like FCT, there are a few critical requirements: 1) high-quality dense RMO and structural dip picking, which accurately preserve non-hyperbolic moveouts and small-scale image distortions caused by fault-related velocity errors; 2) dense tomographic inversion grid; and 3) preferably geological constraints like interpreted fault planes. Figure 1a shows RMO picking overlaid on CIGs in this area. The non-hyperbolic RMO is accurately picked. Figures 1b and 1c demonstrate that FCT can effectively update the velocity to correct the non-hyperbolic moveout. Figure 1d shows the velocity model before FCT overlaid on the corresponding PSDM image. Erroneous structures highlighted by the yellow arrows indicate that the model did not resolve the velocity contrasts across the faults. Figure 1e shows the FCT-updated velocity overlaid on its PSDM image. Image distortions are clearly corrected through the FCT-derived velocity changes within the fault blocks. In our FCT workflow we used fault constraining masks (Figure 1f) created through a machine learning process (Wu et al., 2019) to avoid smoothing across faults in the inversion. Nevertheless, such an application of FCT is not always sufficient. If imaging quality is less reliable for picking due to complexities such as: large velocity errors, more complicated structures, or strong multiple contamination (especially in a shallow water environment), ray-based tomography will be inadequate, as we will illustrate in a later example.

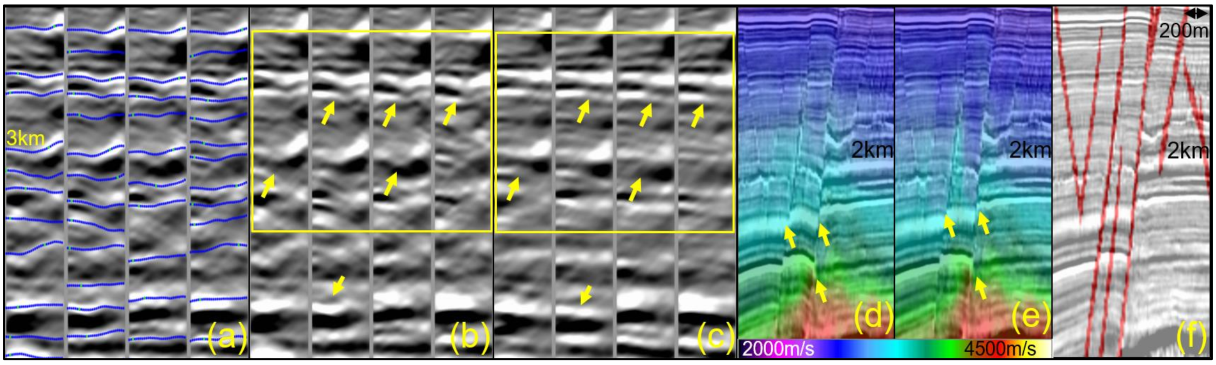

Figure 1 *(a) RMO picking overlaid on CIGs with non-hyperbolic moveout; CIGs and velocity model overlaid on PSDM; (b),(d) before FCT; (c),(e) after FCT; (f) machine learning picked fault constraints.*

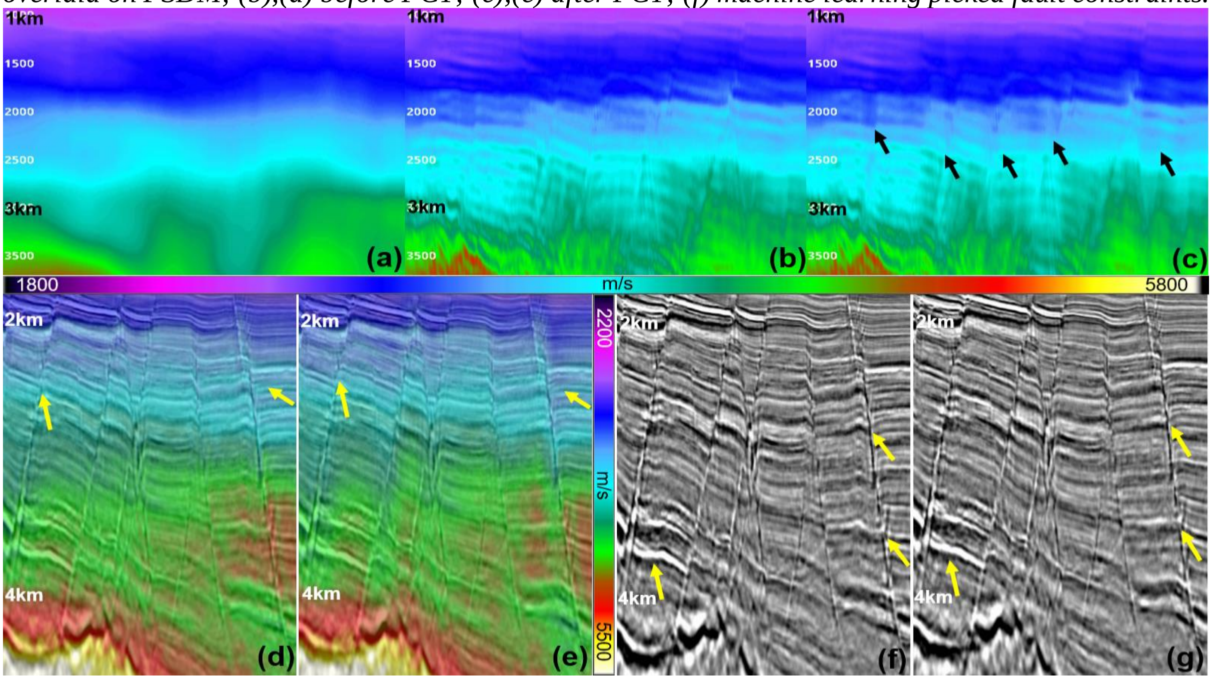

Figure 2 *(a) Initial velocity model; (b) conventional TLFWI velocity with reflection energies; (c) tomo-promoted TLFWI velocity with stronger vertical imprints as pointed by black arrows; (d) initial model overlaid on the PSDM stack; (e) tomo-promoted TLFWI velocity with weighted tomographic term overlaid on the PSDM stack with updates highlighted by yellow arrows; PSDM stacks from (f) initial model and (g) tomo-promoted TLFWI model with footwall reflectors' undulations effectively corrected.*

Tomo-promoted Time-lag FWI

FWI for fault shadows has benefits over tomographic approaches because: (1) as a full wave-equation based method, FWI can better handle the complex wave path; (2) data domain fitting can avoid difficulties in RMO picking caused by poor illumination and/or coherent noise like residual multiples;

and (3) FWI does not require a priori fault constraints. In practice, however, the tomographic terms associated with reflection energies are usually an order of magnitude weaker than the corresponding migration terms. As a result, conventional FWI inversion is dominated by short-wavenumber migration terms and often fails to derive the mid- to long-wavenumber updates that are needed to correct the fault-related velocity errors. TLFWI with a kinematic-based cost function is also desirable, as amplitude discrepancies are common in faulted sections due to factors such as fluid trapping, pressure changes, and illumination variations. Therefore, we extended the TLFWI framework with an additional weighting applied to the tomographic term for more effective kinematics correction. Figure 2b shows the conventional TLFWI update from the initial model in Figure 2a, while Figure 2c shows the TLFWI update with the weighted tomographic term showing stronger vertical imprints in the model as highlighted by the black arrows. The intrinsic low vertical resolution of the updates from the weighted tomographic term in the TLFWI framework is observed, which is similar to earlier documented observations from tomographic only based Reflection FWI (RFWI) (Gomes and Chazalnoel, 2017; Wang et al., 2018). Fortunately, for solving fault shadow issues, correctly resolving fine scale lateral velocity contrasts plays a more essential role. We demonstrate that the fault shadows are effectively corrected on this data when using the tomo-promoted TLFWI approach. Figure 2e shows the tomo-promoted TLFWI velocity updated from the initial model in Figure 2d. Figures 2f-g show the image improvements after the update, with effective correction of the footwall reflectors' undulations (yellow arrows). These uplifts will help exploration decisions as faults usually act as a good seal for potential reservoir layers beneath them.

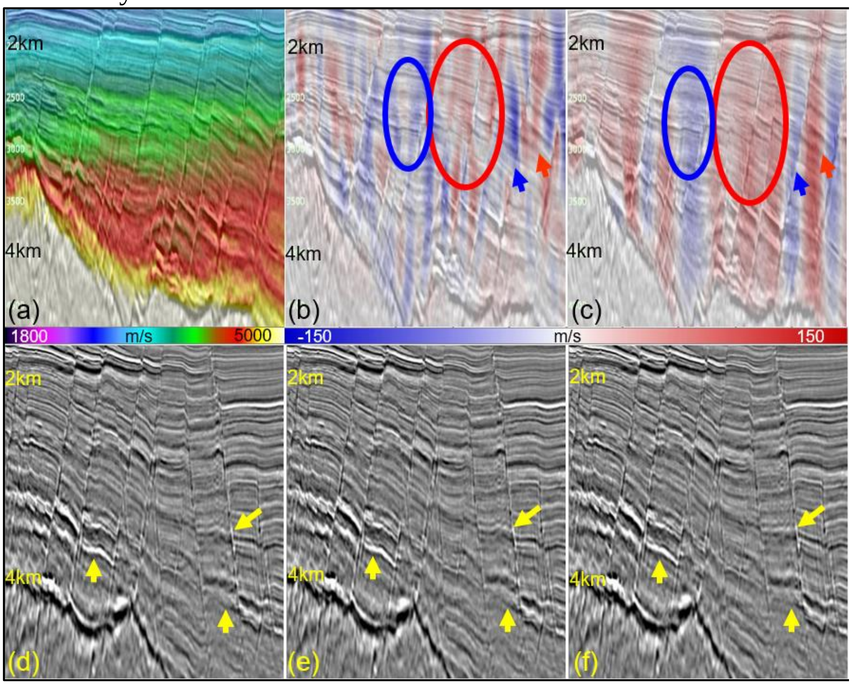

Figure 3 *(a) Initial velocity model; perturbation from (b) FCT; (c) tomo-promoted TLFWI; PSDM stacks from (d) initial model (e) FCT model with slight imaging improvement (f) tomo-promoted TLFWI model with improved imaging correction as pointed by yellow arrows.*

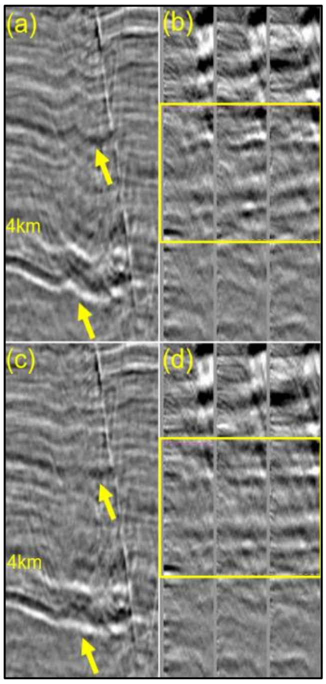

Figure 4 *Near stack and CIGs from (a),(b) the input model; (c),(d) the tomo-promoted TLFWI model.*

Discussions: FCT *vs* tomo-promoted TLFWI

We have discussed theoretical and practical aspects of using FCT and tomo-promoted TLFWI for fault shadows. It is interesting to compare the velocity updates from FCT with those from the tomographic term of TLFWI. A benchmark comparison starting from the same model is shown in Figure 3. The overall update direction is consistent between FCT and TLFWI, as shown in Figures 3b and 3c, with some local differences. Differences in the two solutions are understandable given the two methods are fundamentally different. In the meantime, it is a good confirmation that when proper conditions are met, both methods are effective at mitigating fault shadows to similar quality. In this case study, we identified areas where tomo-promoted TLFWI outperformed FCT. The RMO picking quality is poor in complex areas, such as those highlighted by the yellow arrows in Figure 3d, leading to less effective correction from FCT, as seen in Figure 3e. Figure 3f shows the effective imaging correction beneath the faults from tomo-promoted TLFWI. TLFWI obviously performs better than FCT in this case. Figures 4c-d show the image uplifts from tomo-promoted TLFWI on the near stack and CIGs over the initial model (Figures 4a-b). With less computational demand compared to FWI, FCT may continue as an effective application when geological settings and data conditions are favourable. However, the FWI-based method is likely to become the algorithm of choice to handle velocity updates in the presence of complex faults.

Conclusion

We discussed the benefits and limitations of FCT and tomo-promoted TLFWI for solving the fault shadow issues in a dataset with limited offsets. Traditional FCT worked reasonably well when data conditions allowed for reliable RMO picking and high-confidence fault constraints. TLFWI with additional weighting on the tomographic term further improved the velocity and fault imaging where FCT was suboptimal. As a data-driven algorithm that can start with field data, tomo-promoted TLFWI is the preferred algorithm to solve complex fault shadow issues. However, uncertainties still remain, as the robustness of TLFWI using reflections for velocity updates is bounded by incomplete angle illumination from the narrow-azimuth data with limited offsets. Extending the data dimension, e.g., with longer offsets for diving wave FWI, would help to further improve the velocity and reduce the imaging uncertainties as would of course acquiring wide azimuth data.

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