Localized anisotropic tomography with checkshot : Gulf of Mexico case study

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Summary

Borehole information must be used to build accurate anisotropic depth models. While various techniques exist, almost none of them is extendable to a general case of complex structure and deviated wells. Localized tomographic inversion is a flexible approach that can potentially be applied to most complex cases. It attempts to streamline and automate the estimation process by directly incorporating the available well data into conventional reflection tomography. We present a case study from Gulf of Mexico where we invert for local vertically transversely isotropic (VTI) model using a joint dataset consisting of seismic and checkshot data. Because this area has flat-layered structure, the results can be compared with more traditional manual 1D layer-stripping inversion. We invert for three VTI parameters and search for a smooth velocity field that both fits the checkshot traveltimes and flattens all seismic gathers. To regularize tomographic inversion, we apply smoothing operators that are oriented along geological dip and have large lateral extent. The anisotropic profiles derived by tomography and 1D inversion have similar trends, but differ in high-frequency details. Borehole data require careful conditioning before joint inversion because of potential difference in water velocity between seismic and well surveys. The workflow we present can be applied to calibrating anisotropic parameters in the more general case of 3D models with structural dip and borehole data from deviated wells.

Introduction

Estimation of anisotropic parameters remains the most challenging and ambiguous part of the modern velocity model building process. The available automated methods suffer from at least two serious restrictions. First, many of them rely on inverting seismic signatures that are not often extracted in practice, such as prestack traveltimes. Second, many of them only invert for certain types of models such as 1D, homogeneous layers, layers with gradients, and others. Manual trial-and-error inversion can be applied to more complex cases, but the lack of automation makes the process highly tedious and the final result subjective. As a result, none of the available methods is widely used in the oil and gas industry, where most of the velocity model building is performed with ray-based post-migration hybrid gridded tomography (Woodward et al., 2008). Standard industry tomography makes no assumptions about the model type and can generally handle both "hard" geology (with highly contrasting properties) as well as "soft" geology (compaction-driven velocity regimes). Therefore, it makes practical sense to adapt existing reflection tomography for anisotropic inversions with the appropriate well data. Such an approach was suggested by Bakulin et al. (2009a) and demonstrated on synthetic data. Here, we present a case study where we jointly invert checkshot and seismic data from the Gulf of Mexico.

Case study

The case study objective is to perform an anisotropic calibration near one of the existing wells that has a checkshot survey. In other words, we intend to revise existing velocity and anisotropic parameters in the model to simultaneously fit both seismic and well data. Prior to this study, an initial vertically transversely isotropic (VTI) model was built without well control from a wide-azimuth survey for a large portion of the Green Canyon area, Gulf of Mexico. We extract a subset of these data around a well of interest (Figure 1). We extract a 50,000- by 50,000- by 20,000-ft subvolume from the initial model that will be used for localized inversion (Figure 1). We select 1,700 common-image-point (CIP) gathers that fall in the 3,000- by 3,000-ft area centered at the well. The stacked image shows very little structural dip; however, we observe some lateral velocity variation in the initial model. The vertical velocity in the initial model is too fast, which is manifested by residuals of up to 60 ms between measured checkshot times and traveltimes computed by ray tracing in the initial model (Figure 2a). We embark on simultaneous inversion of three parameters: vertical velocity V_{P0} and Thomsen parameters ε and δ. To avoid nonuniqueness, we invert only for a smooth model. In addition, we steer all parameter updates along the horizontal layers using smoothing operators in reflection tomography (Woodward et al., 2008). In a nutshell, we acknowledge that independent inversion for three parameters at each grid cell is highly nonunique, and therefore, unfeasible. We apply pre-condi-

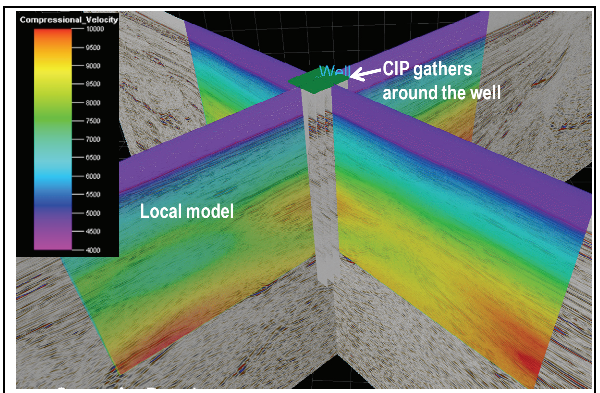

Figure 1: Local velocity model around a well used for joint inversion of seismic and checkshot data. The green box shows the extent of CIP gathers used for tomography.

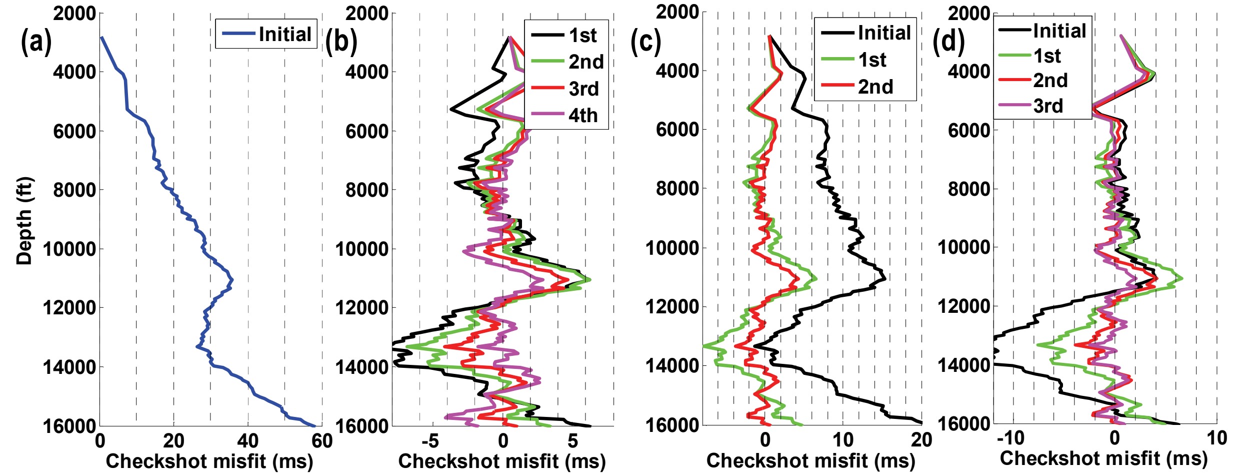

Figure 2: Misfit in checkshot traveltimes during the first tomographic scenario (Figure 3) shown for initial model (a) and all subsequent iterations (b). Misfit is computed as a difference between measured and predicted traveltimes. Likewise, misfit for the second (Figure 4) and third (Figure 5) tomographic scenarios are shown in (c) and (d) respectively.

tioning and smoothing that propagate well information (checkshot velocity) away from the well and prevents uncontrolled lateral variation of anisotropic parameters that would make the inverse problem highly unstable. The drawback to this approach is that we essentially restrict parameter updates to be laterally invariant; whereas, the initial model is laterally heterogeneous. Preliminary analysis showed that well data must be conditioned because the water velocity was different for the seismic and checkshot surveys (Carvill, 2009). We shift all checkshot traveltimes by 8 ms to make seismic and well data consistent before joint inversion. We proceed with three different tomography scenarios that use distinct initial models in terms of anisotropic parameters:

1) "Old" smooth regional trend;
2) "New" regional trend with larger anisotropy;
3) Initial model derived with 1D layer-stripping inversion that utilized the checkshot.

In all cases, we perform remigration with rapid beam migration instead of full-blown migration with a new model to obtain quick feedback on the local tomographic inversion and reduce turnaround time.

In the first scenario, we use the available seismic velocity with relatively low anisotropy values as an initial model. Because the seismic vertical velocity is too fast (Figure 2a), tomography slows down the velocity to fit the checkshot data (Figure 3a). At the same time, it increases Thomsen parameters (Figure 3b,c) to compensate for these velocity changes and preserve the flatness of the image gathers (Figure 6a,b). The first two iterations of tomography are performed with a large vertical smoothing scale of 8000 ft, thereby relocating velocity and anisotropy trends to a new position (Figure 3). The last two iterations are performed with a smaller vertical scale of 2000 ft; thus, allowing a better fit of checkshot traveltimes as well as revealing some finer details of anisotropy profiles. Because our checkshot data have no points in the first few thousand feet below water bottom, tomography tends to generate jumps in anisotropic parameters across the water bottom (Figure 3), which are not geologically plausible. To reduce these jumps, after a second iteration, we performed model editing by linearly tapering anisotropic parameters to zero near the water-bottom interface. However, two subsequent iterations still produced similar, but smaller in magnitude, jumps (Figure 3). This geologically implausible behavior can be reduced by either acquiring complete checkshots starting immediately from the water bottom, or by introducing additional rock physics constraints into the tomography.

In the second scenario, we start with an initial model that has a regional profile with larger magnitudes of anisotropy, albeit without any vertical details. This new initial model is derived from the original model using the following simplified workflow. First, we create new anisotropic volumes by hanging new anisotropy profiles from the water bottom. Second, we scale the original velocity down according to the simple 1D equation $V_{P0}^{new} = V_{P0}^{old}\sqrt{\frac{(1+2\delta^{old})}{(1+2\delta^{new})}}$ that preserves gather flatness. We expect such scaling to reduce the subsequent tomographic workload. In this case, the initial model has smaller checkshot misfits (Figure 2c) and we only need two iterations to arrive at a similar solution to the one that took four iterations in the previous scenario. Note that peaks and troughs as well as the magnitudes of anisotropic profiles

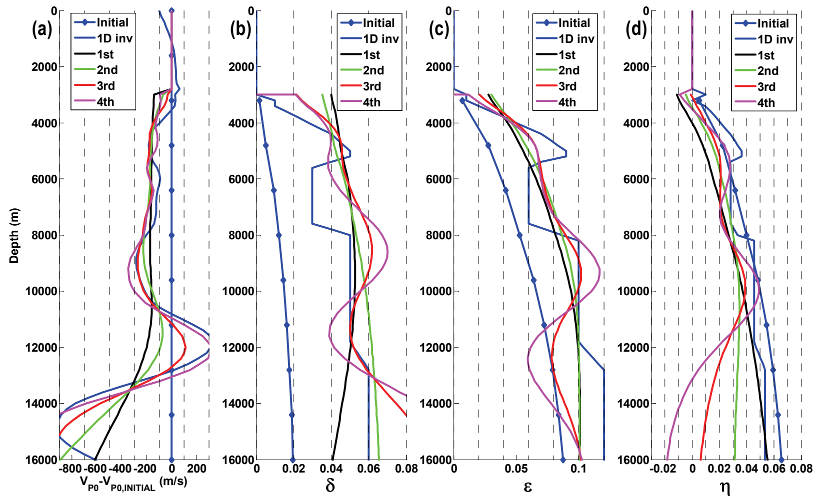

Figure 3: Profiles of model parameters along the vertical well after each iteration of a three-parameter (V_{P0}, ε, and δ) VTI tomographic inversion of joint seismic and checkshot data for the first scenario: (a) velocity; (b) δ; (c) ε; (d) η. Velocity is shown as a difference between the current velocity in each iteration and the initial velocity. Curves labeled "1D inv" refer to smoothed velocity estimated from checkshot traveltimes and an anisotropic parameters derived by manual 1D layer-stripping inversion of a single depth gather.

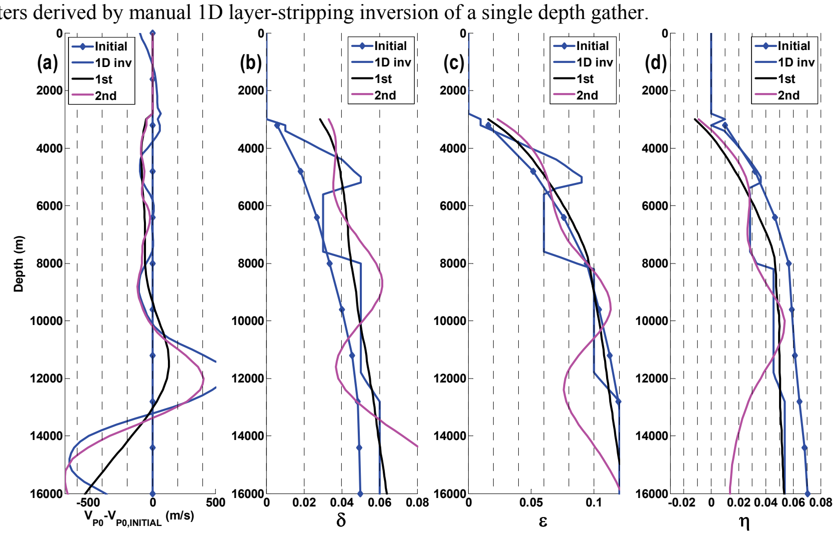

Figure 4: Same as Figure 3, but for the second tomographic scenario.

are in agreement between these two tomographic scenarios (Figures 3 and 4); therefore, validating the stability of local multiparameter tomography with well data. Note that there are a few shallow events around 4,000 ft that can only be completely flattened using a substantially finer vertical scale (Figure 6d).

In the third case, we create the initial model by deriving anisotropy profiles from manual 1D layer-stripping inversion that uses well velocity from checkshot. Then these profiles are hung them from the water-bottom surface. Vertical velocity volume was derived using the same scaling process as in the second case. Because the subsurface model is close to 1D around the well, we expect this initial model to be similar to a solution that may come out of 3D tomography. This expectation turns out to be true with some degree of uncertainty. As before, tomography is able to fit the checkshot with acceptable accuracy (Figure 2d). As for anisotropic profiles, they largely keep Thomsen parameter ε untouched (Figure 5c); whereas, modifications to Thomsen parameter δ are mild to moderate depending on depth. We emphasize that the high-anisotropy layer at ~ 5,000 ft depth as well as the anisotropy increase below 7,000 ft were largely preserved by tomography. Thus we cross-validate our local tomography and 1D layer stripping inversion.

Conclusions

We have presented a case study of local anisotropic tomography with checkshot data. We simultaneously fit checkshot traveltimes in the well and also flatten seismic image gathers. Any velocity update coming from checkshot data was propagated laterally into the entire volume by using smoothing operators elongated along the dip of seismic events. Likewise, laterally elongated updates of Thomsen parameters ensured that flattening of seismic gathers is achieved with the simplest possible model. Gradual reduction of the vertical height of the smoothing operator allowed recovery of finer vertical details of anisotropic profiles. We observed that tomography arrived at a similar solution when two different initial models of similar smoothness were used as a starting point. When fine vertical details were introduced into the third initial model by performing manual 1D layer-stripping inversion prior to tomography, we observed that inversion largely retained those features intact. All three derived models provide same degree of fit to seismic and checkshot data; therefore, they are likely to belong to a null-space of the joint inverse problem. We should be always aware of such ambiguities and may use tomography with uncertainty for more thorough quantification (Bakulin et al., 2009b). Despite ambiguities, local joint tomography is capable of recovering a reasonable estimate of local anisotropic parameters around the well. We believe that the workflow is also applicable to calibrate more general tilted transversely isotropic models using data from deviated wells.

Acknowledgements

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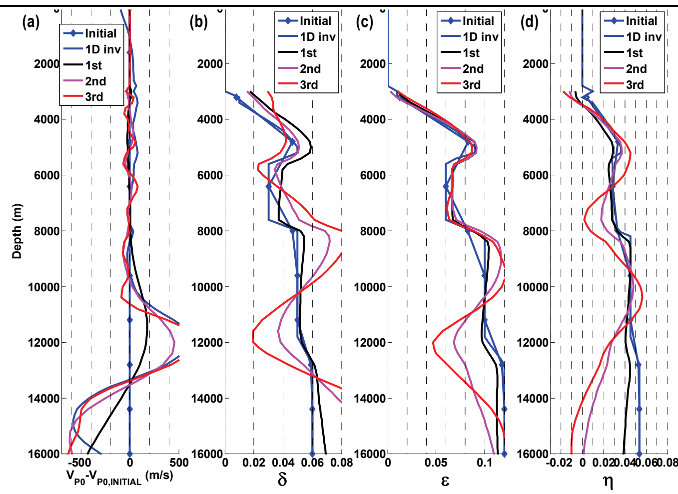

Figure 5: Same as Figure 3, but for the third tomographic scenario.

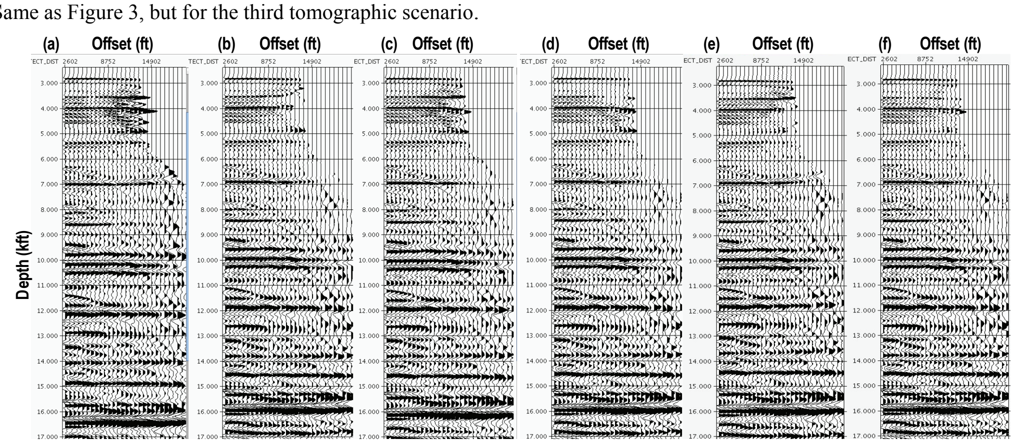

Figure 6: Common-image-point gather near the well obtained with a different model sceanrios: (a) initial model for first inversion; (b) final model after first inversion; (c) initial model for second inversion; (d) final model for second inversion; (e) initial model for third inversion; (f) final model for third inversion.

EDITED REFERENCES

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