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Well-constrained Anisotropic Tomography

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SUMMARY

We outline a concept of well-constrained interactive tomography and apply it to building anisotropic velocity models in depth. To reduce or eliminate non-uniqueness we supplement seismic data with the well information and we localize tomography to a near-well volume. Finally, we regularize tomography with smoothness or any reasonable a priori constraints. As a result we recover the anisotropic velocity field around the well. We present a synthetic data example of anisotropic tomography applied to a 1D VTI model when vertical velocity is constrained from a checkshot. Anisotropic tomography confidently recovers global profiles of Thomsen parameters along the entire well profile of 11 km. The accuracy of recovered parameters is equally good for either sequential or simultaneous inversion approaches. Well-constrained anisotropic tomography has multiple advantages over manual approaches and deserves a place in the portfolio of model-building tools.

Introduction

Anisotropic depth imaging continues to gain popularity and has become a default mode of operation. Vertical transverse isotropy (VTI) is abundantly used; while, tilted transverse isotropy (TTI) has started to replace VTI. At the same time more stringent requirements are placed on positioning errors. However, anisotropic parameter estimation has been proven to be a highly non-unique process, even for layered geological environments (Grechka et al., 2002). Many different depth models may flatten seismic gathers: however, only one of them gives the correct depth positioning. A practical solution to this problem is to inject well measurements and all possible a priori information to constrain the anisotropic models (Bear et al., 2005). In this study we introduce a notion of localized interactive tomography with well information and show that it may recover the correct field of anisotropic parameters around the well in a rather automated fashion.

Well-constrained tomography

Reflection tomography (Woodward et al., 2008) has become a workhorse of velocity-model building for depth imaging. Anisotropic extensions of tomography were reported for VTI and TTI media (Zhou et al., 2004; Woodward et al., 2008); however, non-uniqueness makes it difficult to use. Blind use of anisotropic tomography may lead to velocity/anisotropy fields that flatten the gathers and yet are geologically non-plausible. Well-constrained tomography jointly inverts seismic and well data locally around the borehole. The aim is to derive a localized anisotropic velocity model that is consistent with well and other data. Smoothness and other constraints are imposed to avoid artifacts, although more sophisticated geological constraints may also be incorporated. While one may intervene and edit the model at any step of the process, the aim of interactive tomography is to deliver a constrained solution in an automated fashion.

Synthetic example

Let us apply well-constrained anisotropic tomography to a simple deepwater model (Figure 1). The subsurface is represented by layered VTI sediment. The model has smooth vertical variation of velocity and anisotropy (Figure 1a, b). Several pronounced velocity inversions are present in the model. A cable length of 12 km is assumed. A prestack gather computed with

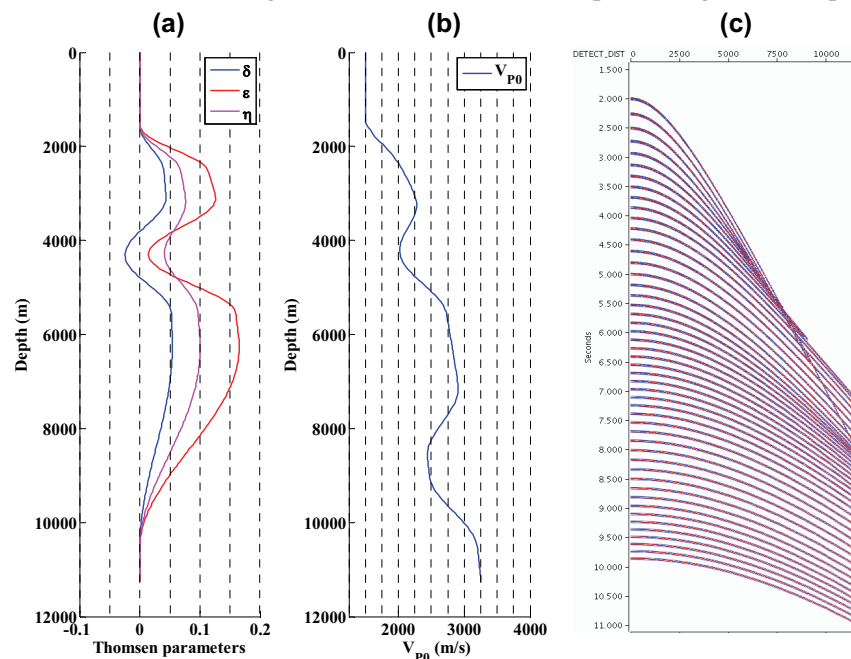


Figure 1. Deepwater 1D VTI model used for tomography: a) anisotropic parameters, b) vertical velocity, c) prestack gather. Water depth is at 1500 m.

anisotropic ray tracing is shown in Figure 1c. Reflected events from 49 interfaces of density contrast are located every 200 m.

Let us apply well-constrained tomography to this deepwater model. Here, we consider only the simplest scenario where complete profile of vertical velocity is known from a checkshot survey. Thus, the aim of the anisotropic tomography is to constrain vertical profiles of Thomsen's δ and ϵ . This goal can be achieved by different means. We examine and compare two approaches:

- Two-step approach, that starts with short-offset inversion for Thomsen's δ and then adds longer offsets to invert for ϵ ;
- One-step approach, that uses simultaneous inversion for Thomsen's δ and ϵ using all offsets.

We utilize Westerngeco reflection tomography described by Woodward et al (2008) and follow conventional workflow of reflection tomography applied to real data. In both cases, we assume a zero starting model for δ and ϵ .

Two-step inversion

In a two-step approach, we start by inverting short-offset data (less than 25 degrees) for Thomsen's δ . Figure 2 shows that the first iteration produces a reasonable estimate of δ that captures the main features of the actual profile and correctly predicting highs and lows. The standard deviation between actual and inverted δ is 0.015. The second iteration makes a little improvement. Then, we open up the offsets and angles to 50 degrees and invert for ϵ in iterations 3 and 4, while keeping δ fixed. Note that bottom part of the well (8-11 km) is only illuminated by angles of less than 40 degrees. Again, tomography recovers a reasonable global profile of ϵ with a standard deviation of 0.035. Two final iterations utilize all offsets and simultaneously update Thomsen's δ and ϵ . This helps to refine the estimate and remove unjustified artifacts introduced by a single-parameter inversion. For example, the high lobe in δ at ~ 8000 m gets reduced to a more appropriate value, while ϵ rises closer to the true values at the same depth (Figure 2). After the last iteration, the standard deviation of Thomsen's δ and ϵ from their true values are 0.006 and 0.011, respectively, across the entire well depth of 11 km.

One-step inversion

In a one-step approach, we perform simultaneous updates of δ and ϵ using all offsets from the start. To avoid small-scale artifacts and prevent any potential instabilities, we used a more conservative scheme for a smoothness constraints. At first two iterations we opted to recover smooth part of the anisotropy profile (Figure 3). Third and fourth iterations were allowed to alter the anisotropy profile at a finer scale and they promptly recovered actual highs and lows. After last iteration, the standard deviation of Thomsen's δ and ϵ from their true values are 0.006 and 0.011, respectively, across the entire well depth of 11 km.

Discussion

In general, for this simple case scenario of vertical velocity constrained by checkshots, both approaches rapidly recover good estimates of the entire global profile for Thomsen's δ and ϵ . The two-step approach took more iterations. The accuracy of the recovered profiles is similar and both solutions are likely to give an equally good estimate with flat gathers that can not be distinguished (Figure 4). Thus, the differences between them as well as between the estimates and the true answer represent a natural level of uncertainty for a noise-free data. The uncertainty level may be higher for real data where other events in addition to primaries can be present. In this example, we have homogeneous reflector coverage of good quality (every 200 m). Different reflector coverage may lead to a variable resolution of the anisotropy profiles. Possibly, a smaller-scale vertical variation than given in this example may be detected. For the case at hand, vertical variation was occurring at the scale of ~ 2000 m and

tomography with a smoothness constraints was able to deliver the desired profile with very few artifacts.

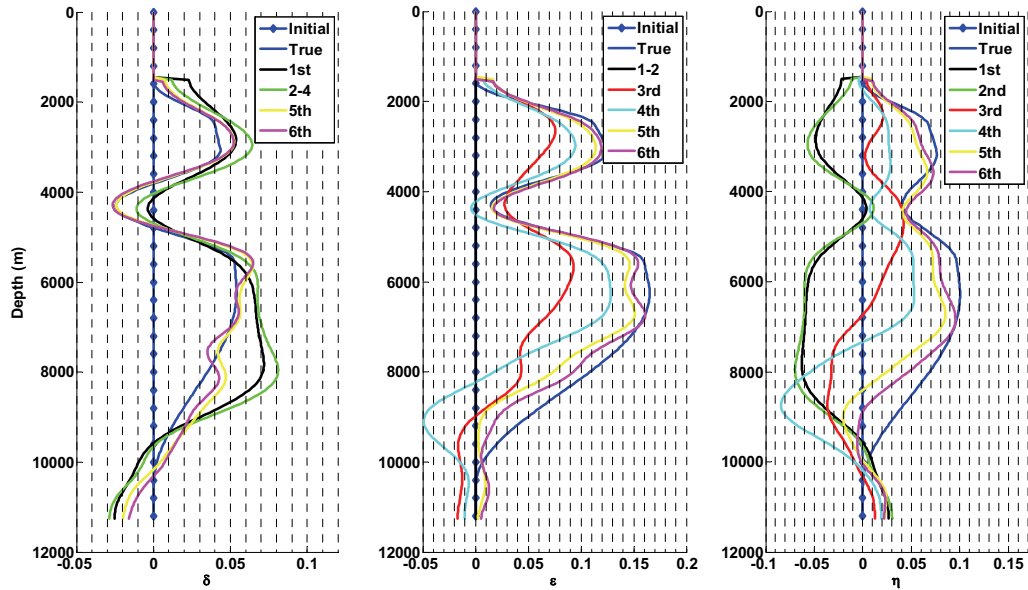


Figure 2: Convergence of well-constrained anisotropic tomography for two-step approach. Anisotropy profiles after each iteration are shown together with initial (zero) and true models.

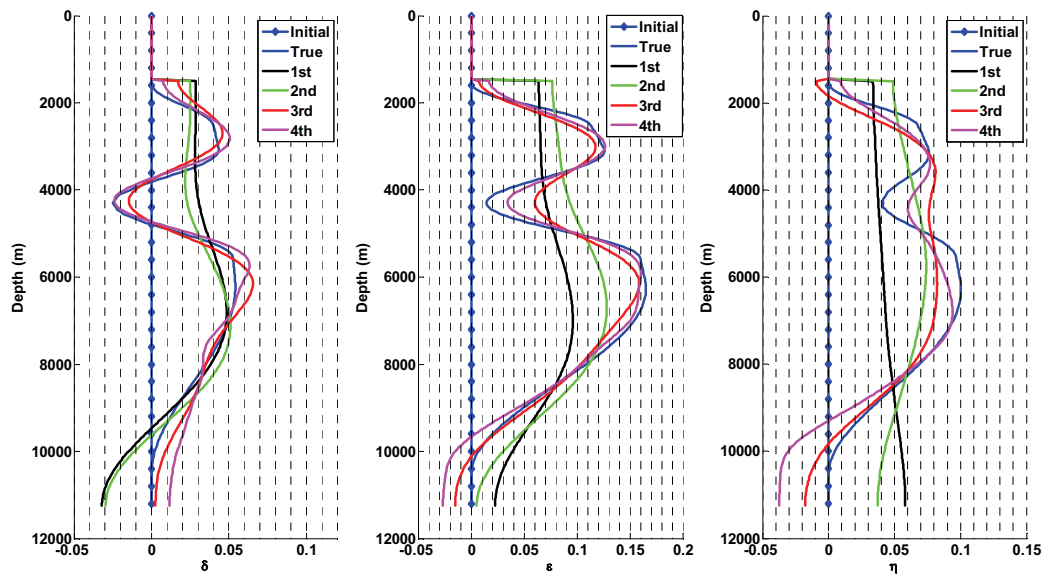


Figure 3: Same as Figure 2 but in the case of one-step approach.

The same inversion for anisotropy profiles at the well can be performed using a manual layer-stripping approach, for example using a SeisCal tool (Morice et al., 2002). Such an approach involves manual subdivision into layers and then sequential scanning for epsilon and delta in each layer using anisotropic ray tracing. While giving the model builder more control at each step, this process is subjective and inherently limited by the top-down nature of layer stripping. Being a layer-stripping, it also suffers from an increased accumulation of errors with depth; whereas, tomography offers a global solution that accounts for all depths at once. To derive smooth anisotropy profile with the manual inversion, the model builder also needs to explicitly impose smoothness constraints. If one is guided only by gather flatness without smoothness constraints, then a blocky model with large oscillations is recovered.

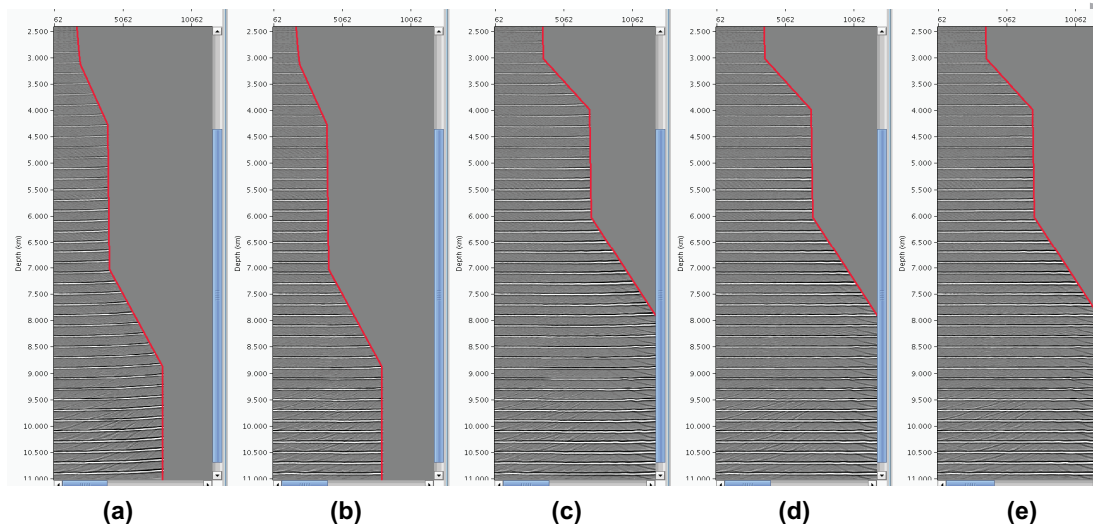


Figure 4: Common image point gathers at the well location for a two-step inversion process: a) initial isotropic model (short offsets, 25 degree mute); b) after 2nd iteration performing δ only update using short offsets; c) after 4th iteration performing ϵ only inversion using large offsets (50 degree mute); d) after 6th iteration performing simultaneous update of Thomsen's δ and ϵ ; e) true model.

Conclusions

We presented a concept of well-constrained interactive anisotropic tomography. We have demonstrated that by localizing the tomography to the volume near the well and introducing proper constraints from the well, we can recover a good estimate of Thomsen parameters around the well. Using short and then all offsets, or using all offsets from the start gave similar answers on a synthetic deepwater example. Well-constrained interactive tomography may replace the currently used anisotropic calibration approach that uses manual layer-stripping 1D inversion or it can be used as a good starting guess for a manual refinement. We anticipate that this approach of well-constrained tomography can be applied to inversion for anisotropy in 2D and 3D models and would allow anisotropic calibration with deviated wells.

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