

Anisotropic model building with well control

Chaoguang Zhou*, Zijian Liu, N. D. Whitmore, and Samuel Brown, PGS

Summary

Anisotropic depth model building using surface seismic data alone is non-unique and one of the major reasons is that there is ambiguity among the anisotropy parameters. Additional well data can help reduce such ambiguity and thus yield a more accurate anisotropic model for depth imaging. In this paper, we present a tomographic model building approach that uses well data together with surface seismic data. It consists of four major steps: preparing data, estimating the local anisotropic parameters at the well locations, extrapolating the local parameters to generate a volumetric anisotropic model for further tomographic update, and finally tomographic updating with well control.

Introduction

Accurate depth imaging requires an anisotropic representation of the earth medium. Vertical transverse isotropy (VTI) and tilted transverse isotropy (TTI) are two commonly used representations. The multi-parameter joint tomography (Zhou et al., 2011) provides a way to build the anisotropic model by simultaneously inverting for velocity in the symmetry axis direction and Thomsen parameters ε and δ (Thomsen, 1986). However, ambiguity exists among the three parameters to be inverted and a tomographic approach using surface seismic data alone cannot solve such ambiguity. In areas where well data (sonic log, check shot, et al.) are available, the vertical velocity can be accurately determined at the well location. The accurate local velocity can help reduce the ambiguity during tomographic model updating and thus yield a more accurate anisotropic model.

A tomographic approach (Zhou et al., 2011; Bakulin et al., 2009) can be employed to estimate the anisotropy parameters at the well location but the process requires considerable quality control and human intervention. An automatic searching method is more appealing and we propose a simulated annealing (SA) method for inverting local Thomsen parameters ε and δ . In addition to the benefit of no human intervention, such methods are more likely to converge to global extrema than gradient descent methods. After the local anisotropic parameters are determined at a well location, they can be extrapolated to the whole working area to form volumes. The extrapolation can be performed with the guide of horizons (Bakulin et al., 2010). Alternatively, it can be guided by the dip field that is almost always available during the model building process, reducing the need to pick horizons. Each well yields an extrapolated volume for each anisotropy parameter and the individual volumes from all well profiles are weighted and

summed. The generated volumes then are updated simultaneously by multi-parameter joint tomography described in Zhou et al. (2011). This updating process follows the conventional reflection tomography flow that consists of iterative migration, residual picking and tomographic inversion. The local anisotropy parameters at well locations are accurate and we do not want them to be changed during reflection tomography. Nevertheless, it is not guaranteed because reflection tomography is a global updating method. Thus a well constraint is required to be added into the tomographic equation system.

The work flow for building an anisotropic model with well control is:

- Prepare data
- Automatically invert for Thomsen parameters ε and δ at well locations
- Extrapolate v_0 , ε and δ to generate volumes
- Tomographically update v_0 , ε and δ simultaneously using seismic data and the well constraints

Data preparation

For seismic data, basic preprocessing routines, such as de-ghosting and wave field separation in case of dual sensor streamers, should be performed. Multiple removal is ideal but not strictly necessary. An initial model, either isotropic or anisotropic, with correct water velocity is built and a full migration is conducted to generate a stack and common image gathers (CIG). Then the water bottom is picked and the dip field is scanned from the stack.

For well data, we need to obtain the vertical velocity profile at the well location. In the case of check shot data, the velocity can be calculated from the depths and travel times in the data. For sonic data, the velocity data are upsampled to seismic scale while maintaining travel times. Sometimes, the available well data may not span the entire well and work is needed to patch the gap, tying imaged seismic to well depths.

Automatic inversion for ε and δ at well location

The automatic inversion is based on the assumption of locally 1D VTI medium. At the well location, the vertical velocity v_0 can be accurately obtained either from sonic log or check shot data. The automatic inversion is employed to solve for Thomsen parameters ε and δ locally and the goal is to flatten the CIG at the well location. A non-gradient global optimization method is preferred and one of such global methods is SA. It is a powerful stochastic search algorithm that samples the model space randomly and then

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accepts the model that has a better objective function value at each iteration. To avoid local extrema some models that have worse objective function values are accepted according to a probability criterion. We choose a staged implementation of very fast simulated annealing (VFSA) (Ingber, 1989) to estimate Thomsen parameters.

A key component of an optimization problem is the objective function. To avoid the cycle skipping problem, we pick a filtered semblance function that is similar to the partial stack-power-maximization objective function (Zhang and Shan, 2013):

$$\phi = - \frac{\sum_{j=0}^{M-1} \left(\sum_{k=0}^{N-1} (f(k) * I[j, k]) \right)^2}{N \sum_{j=0}^{M-1} \sum_{k=0}^{N-1} I[j, k]^2} \quad (1)$$

where $I[j, k]$ represents the CIG, $f(k)$ is the filter, and “*” denotes convolution. The negative sign makes the inversion a minimization problem. N is the number of offsets and M is the number of samples of the CIG.

In order to measure the objective function during each iteration, a pre-stack migration is needed to generate the CIG. Instead of a costly full migration, the fast local model-based moveout (MMO) algorithm (Liu et al., 2014) is employed as the re-migration/de-migration engine.

The automatic inversion includes following steps:

- Given a starting model do a migration of the data
- Apply the MMO “de-migration” to obtain the needed depth to time mapping of the specular image
- For each model iteration, apply MMO to re-migrate the specular reflection to new image depth positions
- Compute the objective function
- Accept or reject the model according to the defined criteria
- Repeat steps 3-5 until a satisfactory model has been generated

Extrapolating anisotropy parameters

After the anisotropy parameters are estimated at well locations, we want to generate volumes from them for further tomographic updating. It is natural to assume that the anisotropy conforms to the geologic sequences. Thus, generating anisotropy volumes in a geologically plausible fashion is preferred. Bakulin et al. (2010) described a method that uses picked major horizons to guide the interpolation. Here, we propose an alternative that uses the dip field to guide the extrapolation. In contrast to picking

horizons, the dip information is always available in tomography process and thus no extra cost is incurred. During reflection tomographic model building, the dip information is obtained and used for shooting specular rays in order to form tomographic equations. We often choose to use the dip field to describe the symmetry axes of the model and also may use the dip field to constrain the tomographic inversion (Zhou 2013).

The parameter field extrapolation consists of two steps: propagating and resampling. As depicted in Fig. 1, the extrapolating process starts from the well location where each depth grid point serves as an initiation point. First, the anisotropy values (v_0 , ϵ and δ) at all initiation points propagate to the neighboring CDP locations through the dip planes defined by local dips. For example, the values at point A propagate to point B and point C in Fig. 1. Then a resampling operation is performed to get the values onto the depth grid points. These points serves as new initiation points and the propagating and resampling process is repeated outwards to the edges of the volume. If there are multiple wells available, the individual volumes that are extrapolated from all well profiles are weighted and summed to form the final volume for each anisotropy parameter:

$$y = \sum_{i=1}^N w^i y^i, \quad (1)$$

where N is the number of wells available, y represents v_0 , ϵ or δ , and weight w^i is a function of the horizontal distance to well i .

Well constrained tomography

In reflection tomography, we normally have two goals: data fitting and model styling. The data fitting goal is to let the model flatten the CIG gathers and the model styling goal is usually measured as the smoothness along the coordinate axes or the local geologic axes. As mentioned in the introduction section, the anisotropy profiles estimated at well locations are accurate and we do not want them to be changed during the tomography process. Since the tomographic inversion is a global optimization, it does not guarantee that the anisotropy profile at a well location will not change considerably. Therefore, a constraint has to be explicitly added into the tomographic equation system:

$$\begin{aligned} \mathbf{A}\mathbf{S}\mathbf{x} &= \mathbf{b} \\ \boldsymbol{\tau}\mathbf{x} &= \mathbf{0} \\ \lambda\mathbf{C}\mathbf{x} &= \mathbf{0}, \end{aligned} \quad (2)$$

where \mathbf{A} is the tomography operator, \mathbf{S} is the model styling operator, \mathbf{b} is the data vector, \mathbf{x} is the model update vector, matrix $\boldsymbol{\tau}$ and scalar λ are trade-off factors, and \mathbf{C} is the added well constraint operator. The operator \mathbf{C} can be built

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in a similar way as operator **A** is built. The diagonal matrix τ allows different trade-off controls on the updates of v_0 , ϵ and δ .

The added constraint is “soft” and thus allows the model values to change slightly at well locations. This keeps the tomographic updating from producing a rough model. More importantly, when the anisotropy parameters are estimated at well locations, locally 1D VTI medium is assumed and this assumption may be inaccurate. This “soft” constraint allows such inaccuracy to be corrected in the tomographic inversion.

A field example

The proposed model building approach is applied to a 2D field dataset acquired in the Gulf of Mexico. The acquisition shot interval is 37.5 m and the receiver interval is 12.5 m with 960 channels per shot. The seismic data were recorded with dual-sensor streamers with maximum offset of 12 km. There is a vertical well drilled at cross line 2520 (Fig. 4), with sonic data available between depths 3270 m and 7272 m. The seismic data were pre-processed with wave field separation and de-ghosting. A scanning process is performed to obtain the accurate water velocity and the water bottom. Then a constant gradient velocity model is built for the initial migration followed by the MMO de-migration. The de-migrated gather at the well location is used as one of the inputs for the subsequent automatic inversion for ϵ and δ at the well location. The dip field is also scanned from the initial migration stack.

Since the sonic log does not provide a complete vertical velocity profile, we need to estimate the velocity above the top of the sonic log. Although reflection tomography can be employed to invert for the velocity between the water bottom and the top of the sonic log, we choose a simpler way to scan for velocity gradient by matching the imaged major reflectors at near offset with the sonic log. Then the sonic data are converted to seismic velocity and combined with the water layer and the velocity patch between the water bottom and the top of the sonic log as the vertical velocity profile (Fig. 3) at this well location. This velocity profile, together with the de-migrated gather, is supplied to the automatic inversion. The automatic inversion starts with $\epsilon = \delta = 0.005$ with search range [0.0, 0.2] and [0.0, 0.1] respectively for the earth below the water bottom. It flattens the gather (Fig. 2) after 10000 iterations and produces reasonable ϵ and δ (Fig. 3).

A 2D anisotropic model (Fig. 4) is then generated by extrapolating the anisotropy profiles at the well location with the guide of the dip field. This model serves as the starting model for the multi-parameter joint tomography with the well constraint and the geologic constraint for

further updating. Three iterations of tomography in angle domain flatten the gathers (Fig. 6) and produce a geologically plausible model (Fig. 5). The velocity at the well location is updated slightly while no visible changes are seen for ϵ and δ (Fig. 2) due to the well constraint.

Conclusions

We have proposed and demonstrated an anisotropic model building approach with well control. The automatic inversion for ϵ and δ at the well location requires no human intervention and produces globally optimal solutions. The cost-effective extrapolation guided by the dip field yields geologically plausible models. The well constrained tomography builds the desired model while maintaining the fidelity of the local anisotropic profiles at the well location.

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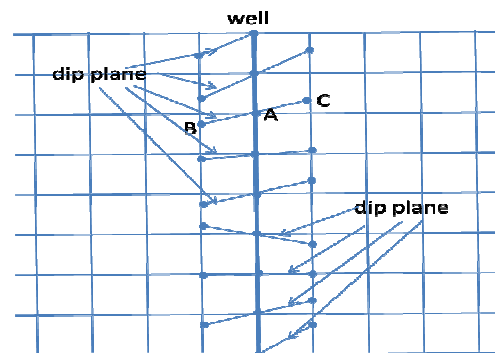


Figure 1: Generating a volume by extrapolating a well.

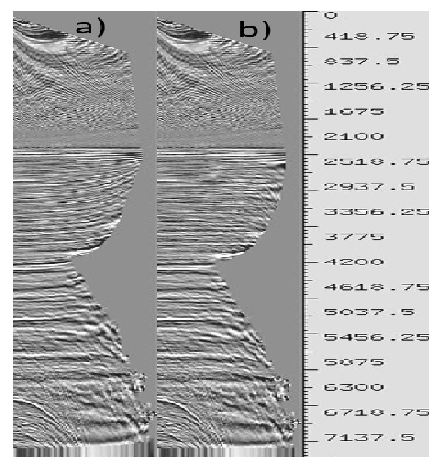


Figure 2: Offset gathers at the well location: a) before automatic inversion and b) after automatic inversion.

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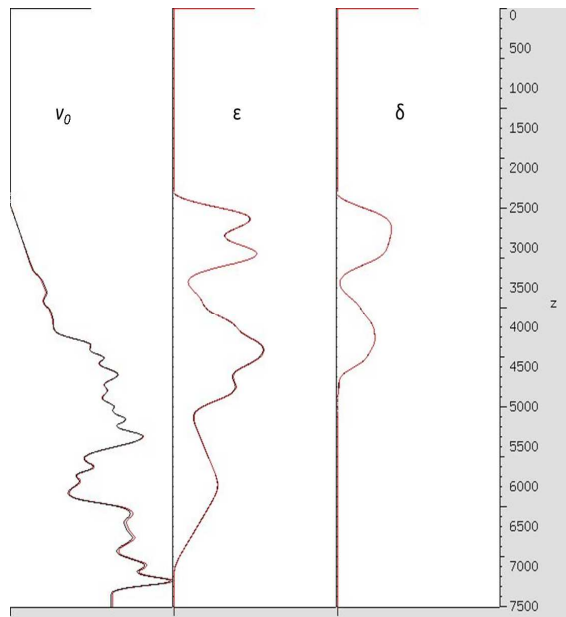


Figure 3: Anisotropy profiles at the well before (black) and after (red) tomographic updating. The velocity scale range is 1500-5500 and the scale range for ϵ and δ is 0:0.3.

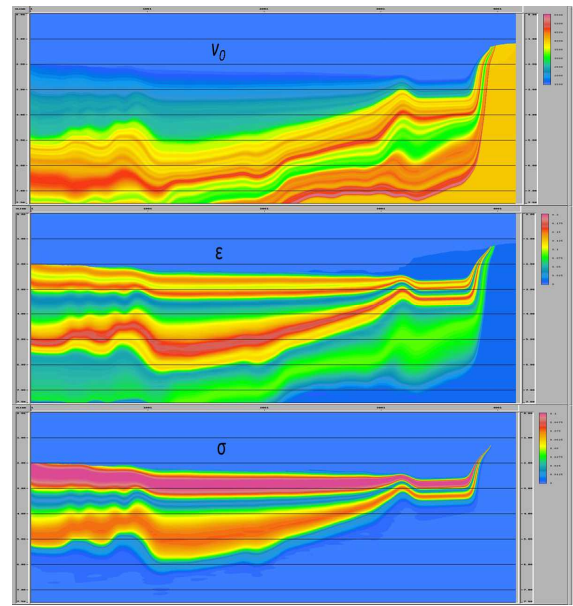


Figure 5: Anisotropic model after tomographic updating. The scale range is 1500 to 5500 m/s for velocity, 0 to 0.2 for ϵ and 0 to 0.1 for δ .

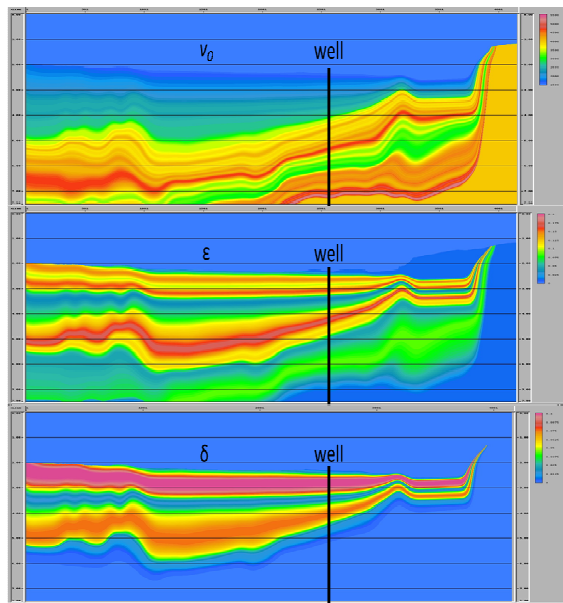


Figure 4: Anisotropic model extrapolated from the profiles at the well location. The scale ranges are 1500 to 5500 m/s for velocity, 0 to 0.2 for ϵ and 0 to 0.1 for δ .

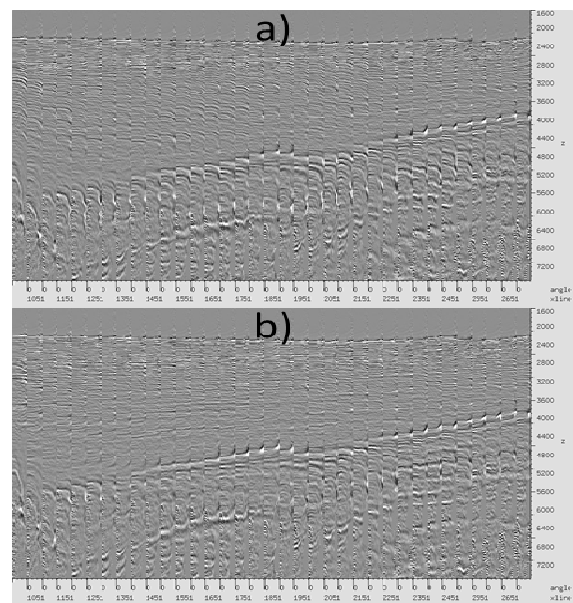


Figure 6: Raw angle gathers: a) before tomographic updating and b) after tomographic updating. Angles range from 0 to 70 degrees.

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EDITED REFERENCES

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