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Dynamic-image Warping and Volumetric Vp/Vs Constraint for Nonlinear PP/PS Tomography

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SUMMARY

Serial processing of PP and PS waves leads to depth inconsistencies between the PP and PS migrated images. The link between the P- and S-velocity models is the Vp/Vs ratio, whose estimation is an important task in multicomponent analysis because of its applications to lithology and fluid discrimination. We show the advantages of using the Vp/Vs ratio estimated with dynamic image warping as a volumetric constraint for nonlinear slope tomography. Our approach does not require repeated shift estimation between PP and PS events during inversion and does not depend on picked horizons thus reducing human interaction and uncertainty associated with interpretation.

Introduction

The importance of converted waves in seismic exploration has long been recognized. Converted-(PS) waves can help image under low P-velocity anomalies (gas-clouds), delineate faults, estimate anisotropy parameters, discriminate lithology and fluid contents, and can play an important role in reservoir monitoring (Stewart et al, 2003). However, processing of converted waves is notoriously more time consuming and complex than P data processing and PS waves are relatively seldom used. The main reasons are the acquisition cost, the components separation/identification, and the different geometry that underlies converted wave propagation (e.g. the need to use conversion point and not common mid-point geometry) for the initial time-imaging processing. Another reason is the serial processing of PP and PS waves, where, especially for velocity model building purposes, P-waves are processed first and their output is then used to estimate the S-velocity model from converted waves.

However, PS waves also contain information about the P-velocity model since propagation from the shot point to the subsurface reflection point happens through P-waves. The link between the two models is the Vp/Vs ratio, which also contains information about the lithology of the subsurface, and thus its estimation is an important task in multicomponent seismic processing. The Vp/Vs ratio resolves the depth ambiguity between PP and PS events and can be used as a volumetric constraint to link P- and S-wave velocities, regularize joint PP/PS nonlinear slope tomography, and achieve automatic co-depthing of PP and PS images.

Dynamic image warping is a dynamic programming algorithm, which has been proven particularly effective for the problem of matching seismic images (Hale, 2013). Dynamic image warping finds the optimum solution to the problem of aligning two sequences and outputs the 1D shift field that warps the monitor signal to the baseline signal. Applications of dynamic image warping to the registration of PP and PS time images and Vp/Vs estimation give encouraging results (Compton and Hale, 2014). We propose to use the Vp/Vs ratio estimated directly from dynamic image warping as a model space volumetric constraint for tomography. Previous works on automatic co-depthing (e.g., Mathewson *et al.*, 2013) use floating constraints between PP and PS images by including the norm of the computed shifts between PP and PS events in the objective function. Our approach avoids assessing the quality of the estimated shifts at every tomographic iteration and reduces human interaction.

Method and Theory

The Vp/Vs ratio is derived directly from the shifts computed using dynamic warping with the following expression (Compton and Hale, 2014):

$$\frac{V_p}{V_s} = (2c - 1) + 2c\frac{du(t_{pp})}{dt_{pp}}, \tag{1}$$

where the factor c is a constant squeezing factor to perform a first match of the PP and PS time axis. The shifts $u(t_{pp})$ are defined with respect to the vertical PP time; we first depth-to-time convert the PP and PS images and then estimate the 1D shifts using dynamic warping. We use a low-frequency augmentation strategy (Baek *et al.*, 2014) to stabilize the shift estimation. The estimated Vp/Vs ratio is then converted from time to depth. The volumetric constraint is introduced in the tomography problem as a regularization term (*prior* information) by integrating the standard objective function for non-linear slope tomography (Guillaume *et al.*, 2001, Lambaré, 2008, Montel *et al*., 2009):

$$C(m) = \sum_{rmoevents} \alpha_i ||\delta RMO_i||^2 + \beta_j ||\gamma_j - \gamma_{j,prior}\ ||^2, \tag{2}$$

where $C(m)$ is the cost function, which depends on the model m, δRMO represents the residual moveout (RMO) slope of the migrated gathers, γ_{prior} the *prior* Vp/Vs ratio and γ the Vp/Vs ratio computed for the current models. The α_i and β_j scale the data and model norm of the objective function and depend on signal to noise ratio (SNR) and confidence in the *prior* information, respectively.

Examples

We first consider a finely layered VTI model with lateral heterogeneity in the shallow section. We simulate 80 shots with a spacing of 100m starting at x=250m; there are receivers at z=400m over the entire length of the model to simulate an OBC-like geometry. The data are generated with a fully-elastic finite-difference algorithm; the source function is a Ricker wavelet with dominant frequency 40Hz. The P-wave model is accurate and we restrict the inversion to the S-velocity model only. Inversion for anisotropy parameters is not done. Vertical particle velocity data are used for PP migration; the horizontal particle velocity converted to radial is used for PS migration. Beam Migration is used for imaging (Casasanta, 2013). Figure 1 shows the exact S-velocity model used to generate the data (a), and the estimated Vp/Vs ratio using dynamic image warping (b); the initial migration model is a vertical gradient of velocity. Panels (c) and (d) show the result of inversion using the RMO only and both RMO and estimated Vp/Vs ratio, respectively. The volumetric constraint not only changes the inversion result in the shallower part of the model but also affects the deeper part. The constrained solution better resembles the exact model.

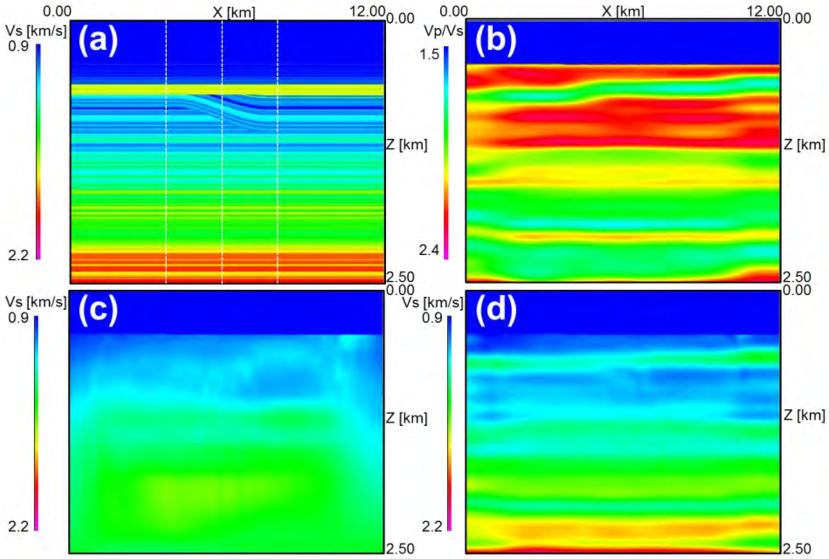

__Figure 1__ Simple synthetic test. Exact Vs model (a), the dashed lines indicate the position of the gathers in Figure 2; estimated Vp/Vs ratio (b), result of the inversion using RMO information only (c), and inversion with Vp/Vs volumetric constraint (d).

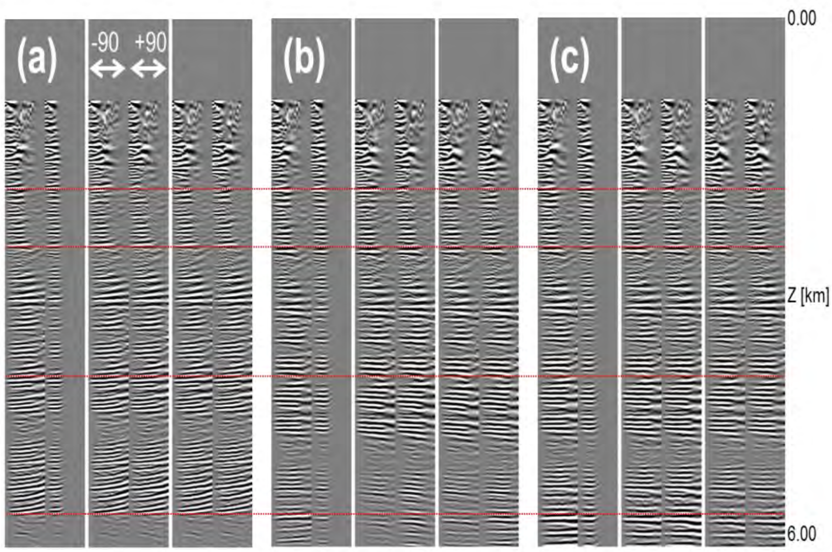

__Figure 2__ Three offset-domain common-image gathers of opposite azimuths (+/-90 degrees) computed on the initial model (a), the unconstrained inverted model (b), and the Vp/Vs constrained model (c). The maximum offset is 2050m. The shallow events have poor offset coverage and they are not able to fully constrain the inversion. The horizontal lines are inserted for visual aid.

Figure 2 shows the initial PS gathers (a) and the inverted gathers using unconstrained (b), and Vp/Vs constrained inverted model (c) computed at the locations of the vertical dashed lines in Figure 1(a). The upswing of the initial gathers indicates a velocity error. The shallow events have limited offset coverage and they do not properly constrain the inversion of the shallow part of the model. Tomography adjusts the deeper events to compensate for the lack of information in the shallow with suboptimal results. The constrained inversion allows nonlinear slope tomography to avoid unwanted compensation effects and leads to higher quality results. The second test is a complex TTI model. The data are modelled using a visco-elastic modelling code. The data consists of 170 receiver gathers with 100m spacing on the water bottom. In Figure 3, the estimated Vp/Vs ratio using dynamic warping (left) is compared with the exact Vp/Vs model (right). Notice the agreement in the estimate especially close to the water bottom where the Vp/Vs ratio is rather high (>5). The estimate also conforms nicely to the structures; the PP image computed in the initial model is overlaid for comparison. The small scale blobs in the estimated model are due to noise in the estimated shifts; the computation of the Vp/Vs ratio requires the differentiation of the vertical shifts, which amplifies high-frequency (small-scale) noise.

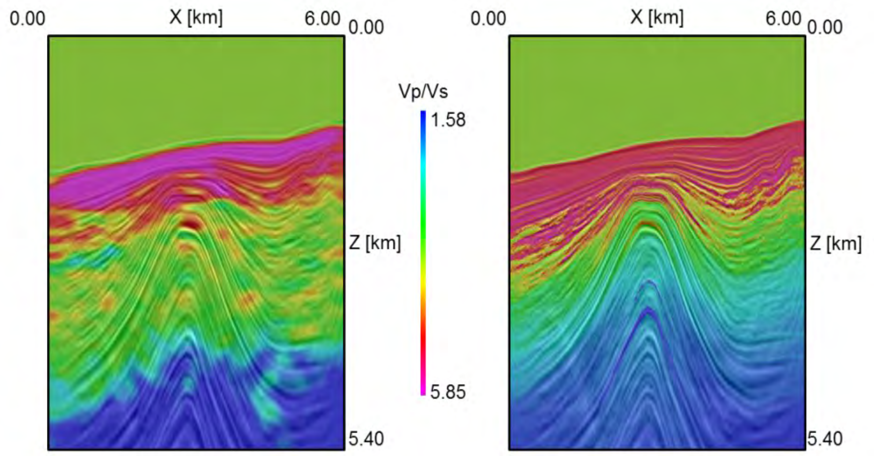

Figure 3 *Complex synthetic model. Vp/Vs ratio derived from the shifts computed using dynamic image warping (left) and actual Vp/Vs ratio computed from the exact Vp and Vs velocity models (right).*

Figure 4 shows the migrated PP (a,b,c) and PS (d,e,f) images using the initial model (a,d) and joint PP/PS tomography without (b,e) and with Vp/Vs volumetric constraint (c,f). The PP image is mildly affected by the constraint because of the high quality of the RMO picks (Figure 5). The PS image is more sensitive because the RMO picks are noisier and limited in offset. The PS image obtained from the Vp/Vs constrained inversion shows higher SNR, more focused and regularly imaged structures, especially at the hinge zone and on the limbs of the anticline.

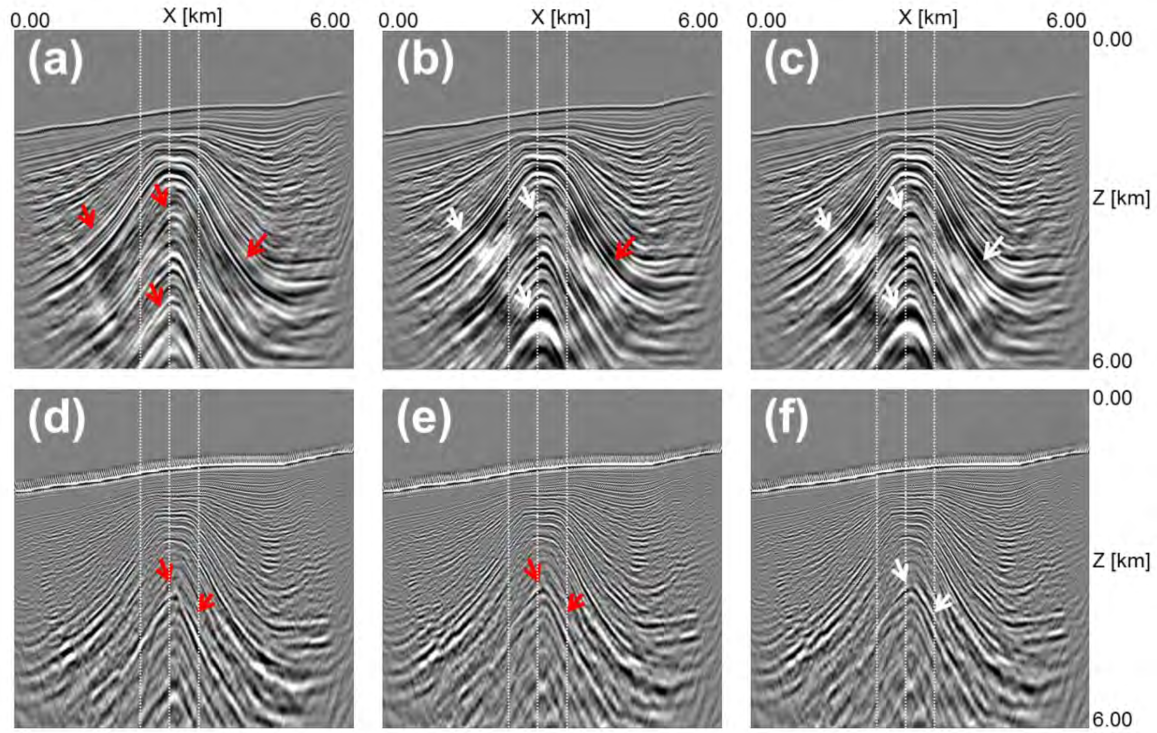

Figure 4 *PP and PS images with the initial model (a,d), without Vp/Vs constraint (b,e), and with Vp/Vs constraint (c,f). The PP image is mildly affected by the Vp/Vs constraint. All images are displayed on the same scale. The PS images shows improved focusing of the anticline structure. Red arrows point at poorly imaged features, white arrow point at imaging improvements.*

Conclusions

The Vp/Vs ratio derived using dynamic image warping represents an additional piece of *prior* information that can be used to regularize joint PP/PS nonlinear slope tomography. Our approach does not rely on interpreted horizons and is not subject to their associated uncertainty; it does not require displacement estimation after every iteration and thus reduces the need for human interaction.

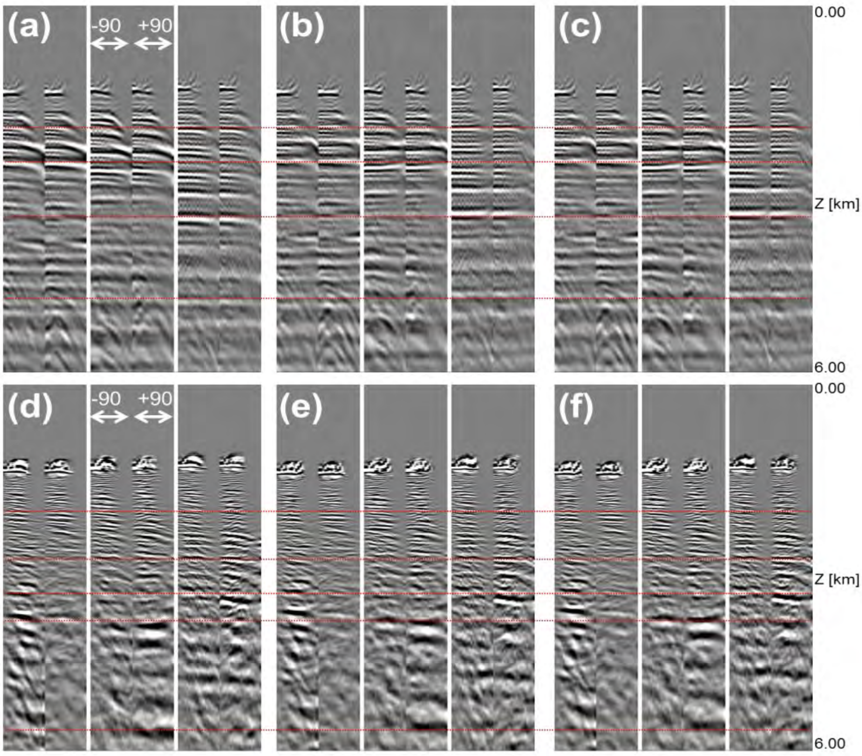

Figure 5 *Offset-domain CIGs at the selected locations indicated by the vertical dashed lines in Figure 4. Maximum offset is 4000m. PP and PS gathers using the initial model (a,d), the unconstrained (b,e) and constrained inverted model (c,f). The Vp/Vs constraint returns flatter and more focused CIGs. The horizontal dashed red lines are displayed for visual aid.*

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