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Residual stereotomographic inversion

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ABSTRACT

Depth migration requires highly accurate knowledge of the subsurface velocity field. Different traveltime tomographic methods are used for this purpose. Stereotomography is a tomographic method that uses local dip estimates in addition to traveltimes for velocity model estimation. We present a new methodology for velocity model updating. It combines poststack stereotomography and residual moveout velocity inversion. The former is used for initial model construction and the latter for updating the velocity model. Residual inversion is a kind of stereotomographic inversion applied to common reflection point (CRP) gathers after model-based moveout correction. Velocity analysis can be made more efficient by preselecting the traces that contribute to a series of CRP gathers and using only these traces for inversion. The algorithm is defined in a two-step procedure. First, ray tracing from the reflection point for nonzero reflection offsets defines the source and receiver locations of the data traces in the CRS gather. Then these traces are moveout corrected according to the calculated traveltimes and residual moveout is estimated. The interval velocity model is updated by fitting the velocity that minimizes estimated residuals. Application of the proposed technique demonstrates its robustness and reliability for fast and automatic velocity model estimation.

INTRODUCTION

Prestack depth migration (PSDM) is widely used for obtaining accurate depth and geometry of subsurface structures in the presence of strong lateral velocity variations. Depth migration requires highly accurate knowledge of the subsurface velocity field. Different traveltime tomographic methods (e.g., Bishop et al., 1985; Stork, 1992; Lailly and Sinoquet, 1996) are proposed and used for this purpose. These methods use different types of input information. They may have different implementations or application domains, but eventually all of them use arrival traveltimes for primary reflection events to construct the velocity model.

In the last decade, numerous algorithms have been developed to determine a detailed velocity field directly from the output of PSDM (e.g., Al-Yahya, 1989; Lee and Zhang, 1992; Liu and Bleistein, 1995). These methods use a simple but fundamental fact that if the velocity field is correct, the reflected events in the common image gathers (CIG) in migrated prestack depth domain are flat. Analysis of the residual moveout of the CIG is used to update the velocity model. The tomographic principle is used to convert depth errors in migrated CIG to time errors and then to apply conventional traveltime tomography. Each method has its own advantages and weaknesses. However, most of them have one feature in common: multiple PSDMs must be run to obtain the final velocity model.

Stereotomography, proposed by Billette and Lambaré (1998), is a traveltime tomographic method that uses the idea of locally coherent events and local dip estimates to determine the subsurface velocity model. It is based on the principle of the controlled directional reception method (Riabinkin, 1957; Sword, 1987) and requires neither continuous reflectors nor a layered subsurface model. The locally coherent events are described by shot-receiver positions, two-way traveltime, and slopes at the shot and the receiver, which are estimated on common shot and common receiver gathers. These five parameters provide all the necessary information for velocity macromodel calculation.

Although several numerical implementations (e.g., Chauris et al., 2002; Billette et al., 2003; Lambaré et al., 2004) of the stereotomographic velocity inversion are illustrated in practical applications, automatic picking of locally coherent events in prestack time domain remains a critical point for stereotomography. Lavaud et al. (2004) proposed picking locally coherent events in poststack rather than in prestack domain. Poststack picking is a reliable procedure and widely used in seismic interpretation. The picked zero-offset traveltimes, together with associated kinematic parameters extracted from the prestack data (such as stacking velocity, radius of curvature, or emergence angle for reflection wavefront), can then be recal-

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culated into the information necessary to perform stereotomography.

Poststack stereotomography (POST) is a robust way for reliable macromodel estimation without using prestack traveltime picking or PSDM. Its one principal limitation is the hyperbolic assumption for CMP reflection traveltimes. In this sense, it is not very different from other stacking velocity tomographic inversion methods. To avoid hyperbolic assumption, we developed a procedure to update the velocity field using a stereotomographic inversion of the poststack picked, locally coherent reflected events in a common reflection point (CRP) gather which does not require PSDM. The purpose is to obtain a flatness of the picked reflection event in every CRP at the end of our procedure. In this paper, we present the methodology and applications to both synthetic and real data.

METHODOLOGY

The method uses map migration, CRP traveltime calculation, and stereotomographic algorithm in the prestack time domain to determine iteratively the global velocity model which can be followed by PSDM for a satisfactory seismic image in depth.

First, we perform POST. Let us briefly recall stereotomographic principles (Lavaud et al., 2004). A stereotomographic data set consists of N picked locally coherent events $d^{\text{data}} = (d_i^{\text{data}})_{i=1}^{N}$ with $d_i^{\text{data}} = (\mathbf{s},\mathbf{r},p_s,p_r,t_{sr})_i$, where $\mathbf{s} = (s_x,s_z)$ and $\mathbf{r} = (r_x,r_z)$ are the source and receiver locations, t_{sr} is the two-way traveltime, and p_s and p_r are the horizontal components of the local slopes at source and receiver, respectively, estimated on common shot and common receiver gathers. These slopes correspond to the horizontal components of the slowness vectors emerging at the source and receiver. The model $\mathbf{m}$ is described as N pairs of ray segments and a smooth velocity field C, $\mathbf{m} = [(\mathbf{X},\beta_s,\beta_r,t_s,t_r)_i]_{i=1}^{N}, \; [C_j]_{j=1}^{M}$ where a reflection or diffraction point describes each pair of ray segments $\mathbf{X}$, two emergence angles β_s, β_r towards the source and the receiver, and two one-way traveltimes t_s, t_r from the point $\mathbf{X}$ toward the source and receiver. In this approach, the cost function is defined as a misfit for all components of input data d_i^{data}; the pairs of ray segments and the velocity model are estimated jointly by a local optimization technique based on a conjugate gradient-type algorithm.

The main advantage of this approach is the fact that picked events do not need to be interpreted in terms of reflection on any particular interface. In POST, we pick locally coherent events in poststack time domain on the common reflection surface (CRS) stack. Picking performed on a stacked section provides reliable information on zero-offset reflection or diffraction arrival times. CRS stack is also used to extract kinematic reflection wavefront parameters such as angle of emergence of the zero-offset ray and radius of curvature of the so-called normal incident point (NIP) wave from the prestack data. We use the picked zero-offset times and the corresponding kinematic parameters to calculate the prestack traveltimes and the slope information required for stereotomography. The resulting velocity model serves as an initial model for the following residual inversion.

Now we position the picked locally coherent events at their depth locations by a ray migration procedure using the zero-offset times, angles of emergence of the zero-offset times, and the obtained velocity model. For each reflection segment obtained by this positioning, we calculate CRP traveltimes by tracing rays through the model and apply model base moveout (MMO) to CRP gathers corresponding to each picked reflection event. If the velocity model obtained after POST is correct, the MMO corrected CRP gathers are flat. If the velocity is wrong, the reflected events in the CRP gathers arrive at different times for different offsets. If we use a velocity value higher than the real velocity, the reflected event appears deeper (later) versus offset. If the velocity is lower, the reflected event appears shallower versus offset. There is a full analogy with CIG alignment used for velocity verification after PSDM.

The next step is to estimate the residual moveout on the MMO corrected CRP gathers. We perform it by assuming a parabolic trend of the residual moveout in each CRP with a semblance maximization approach. Following determination of the residual times on the CRS gathers, we can start the stereotomographic inversion procedure. First we calculate a new stereotomographic data set consisting of a new locally coherent event $d^{\text{new}} = (d^{\text{new}})_{i=1}^{N}$ with $d^{\text{new}} = (\mathbf{s},\mathbf{r},p_s,p_r,t_{sr})_i$, where $\mathbf{s} = (s_x,s_z)$ and $\mathbf{r} = (r_x,r_z)$ are the new source and receiver locations, t_{sr} is the new two-way traveltime, and p_s and p_r are the new local slopes at source and receiver, respectively.

The new two-way traveltime t_{sr} is equal to a sum of the traveltime calculated for arbitrary source-receiver location by tracing rays in the initial velocity model and the residual time δT at the correspondent trace, estimated by the semblance optimization procedure. To calculate the horizontal components of the local slopes p_s^{data} *and* p_r^{data} at the source and receiver positions, we use the following equations:

$$p_s^{\text{data}} = p_s^{\text{ray}} + \frac{1}{2}\frac{\partial(\delta T)}{\partial h}$$

and

$$p_r^{\text{data}} = p_r^{\text{ray}} - \frac{1}{2}\frac{\partial(\delta T)}{\partial h},$$

where p_s^{ray} and p_r^{ray} are the slopes at source and receiver positions (calculated by ray tracing in the initial model), and h is the offset. Note that the expressions for calculating the horizontal components of the local slopes p_s^{data} and p_r^{data} are similar to those proposed in Chauris et al. (2002) for calculating local slopes in the postmigrated depth domain. Derivative $\partial(\delta T)/\partial h$ is estimated using the parabolic assumption for the residual CRP moveout:

$$(\delta T) = t_0 + \alpha h^2,$$

$$\frac{\partial(\delta T)}{\partial h} = 2\alpha h,$$

where t_0 is the picked zero-offset time and α is the curvature of the best fitted residual parabola.

The next step of the inversion consists of determining the updated velocity model using a stereotomographic scheme. Figure 1 shows a flow chart of the proposed inversion procedure.

SYNTHETIC DATA EXAMPLE

To illustrate the proposed methodology for velocity model updating, we use a model with complex structure and strong lateral velocity variations. Figure 2a displays the correct smoothed velocity model and Figure 2b shows the prestack depth migrated image using this model. Synthetic data have been computed using a Kirchhoff method, where only primary events were calculated.

First we performed POST inversion to estimate an initial velocity model. We calculated the CRS stacked section and estimated the CRS parameters. Zero-offset times for 1548 locally coherent events were picked automatically on the stacked section. Then we used the estimated CRS parameters to calculate the prestack traveltimes and the slopes required for stereotomographic velocity inversion. The resulting velocity model is displayed in Figure 3a. The velocity model obtained by POST reconstructs the main features of the actual velocity, but it does not recover many important details and cannot be considered a satisfactory one. The migrated image (Figure 3b) shows that the subsurface has incorrect structural positioning, especially in the deeper part of the section.

In the next step, all picked events were localized in depth, using both ray migration and the obtained velocity model. Then the model-based moveout correction was applied according to the CRP arrival traveltimes calculated for corresponding source-receiver pairs. Figure 4 shows the MMO corrected time windows for three different locally coherent events picked on the stacked section. Incorrect velocity obtained after the POST inversion led to residual moveout in the corrected CRP gathers. We measured this residual moveout by parabolic approximation and semblance optimization. Then we recalculated two-way traveltimes and the slopes at source and receiver positions, and repeated the stereotomographic inversion. Figure 4b shows improved alignment of the same gathers after the residual inversion.

Figure 5 illustrates the updated velocity model (a) and the final PSDM section (b). Although in this example we applied only one iteration of the residual inversion (the residual traveltimes were calculated once), the resulting velocity model looks very different (and better) than the initial model (Figure 3a). We did not apply any constraints or additional smoothing. Comparison to the "correct" image (Figure 2b) shows the effectiveness of the residual inversion procedure: Velocity accurately represents high velocity anomalies; target events at depth of about 2200–2300 m look practically horizontal. This is also confirmed by analyzing CIGs which became flatter after the residual inversion process (Figure 6). Note that reflected events

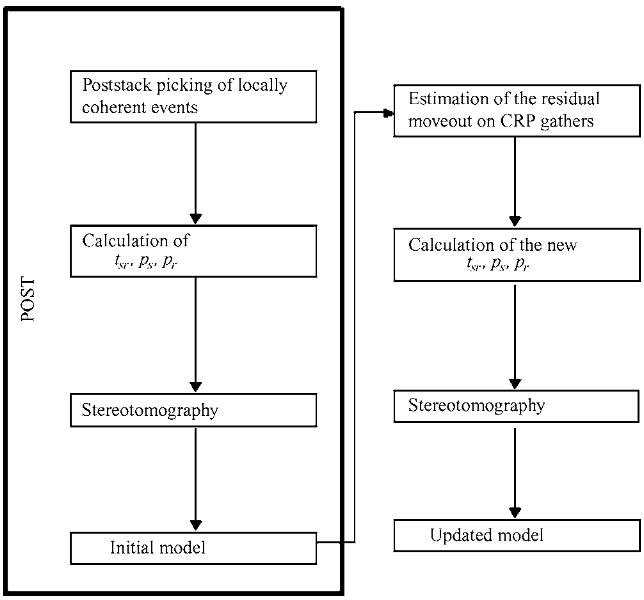

Figure 1. Flowchart of the velocity inversion procedure.

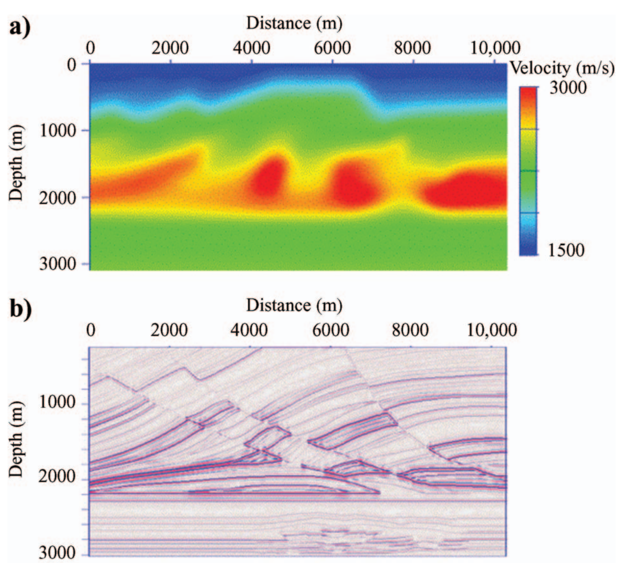

Figure 2. Synthetic example: (a) correct velocity model and (b) corresponding PSDM section.

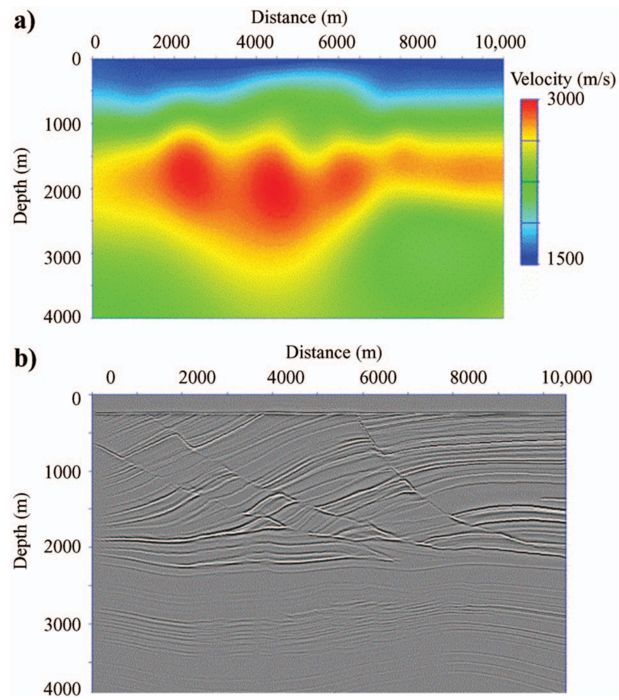

Figure 3. Synthetic example: (a) velocity model estimated by POST and (b) corresponding PSDM section.

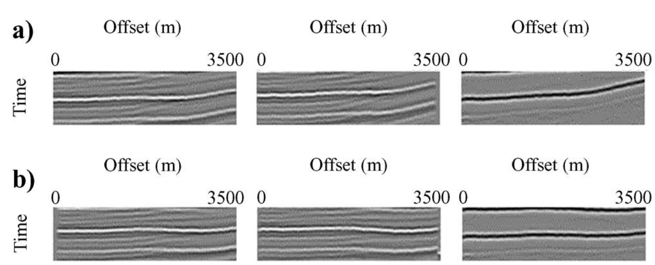

Figure 4. Synthetic example: three adjacent model-based moveout corrected CRP gathers, corresponding to three locally coherent events picked on stacked section: (a) before residual inversion and (b) after residual inversion. Time window of 50 ms is centered around the picked events.

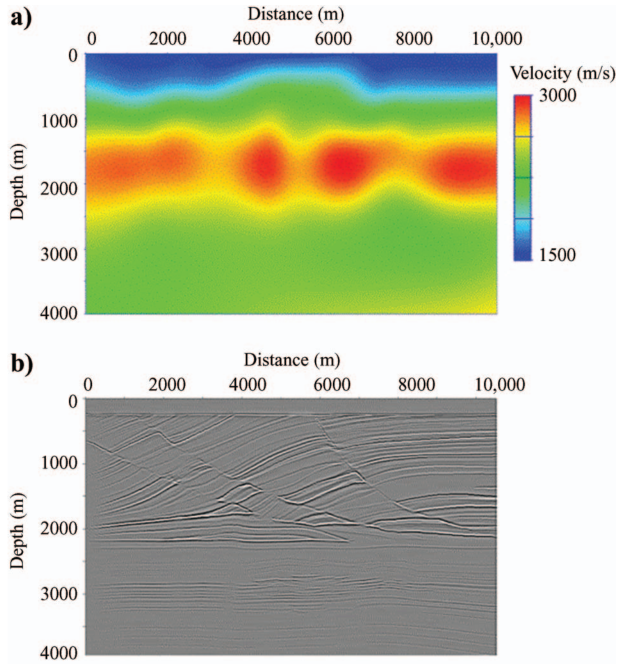

Figure 5. Results of the residual inversion for synthetic example: (a) velocity model and (b) corresponding PSDM section.

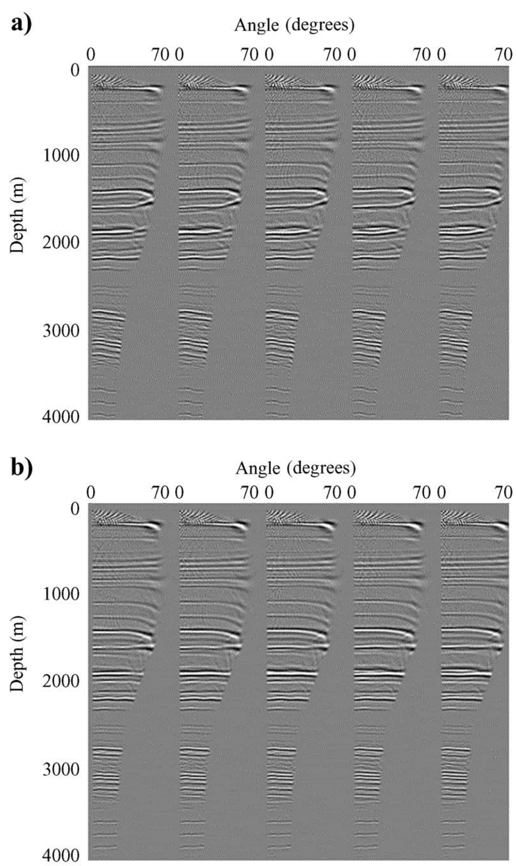

Figure 6. Synthetic example: (a) CIGs after POST inversion and (b) after residual inversion.

not only improve their alignment but also change their depth position (e.g. depth about 3000 m). Note that on these CIGs, the reflection events are not perfectly flat (e.g., around depth 1200 m), and there is a need for more iterations of residual inversion to get a further model update.

REAL DATA EXAMPLE

We applied the proposed velocity updating algorithm to a real 2D marine seismic line extracted from a 3D survey in the North Sea. Figure 7 illustrates a CRS stacked section. First, we calculated the CRS stacked section and estimated the CRS parameters. Then we used 1367 automatically picked zero-offset times and associated CRS parameters to estimate an initial velocity model using the POST inversion. The resulting velocity model is displayed in Figure 8a. The depth migrated image using the initial model is shown in Figure 8b.

In the next step, all picked events were localized in depth using zero-offset ray migration and the initial velocity model. We applied model-based moveout correction to the CRP gathers and calculated the residual moveout using semblance optimization. Then we performed stereotomographic inversion with the new input information

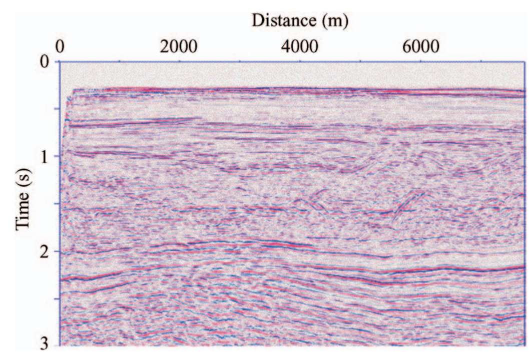

Figure 7. Real data example: CRS stacked section.

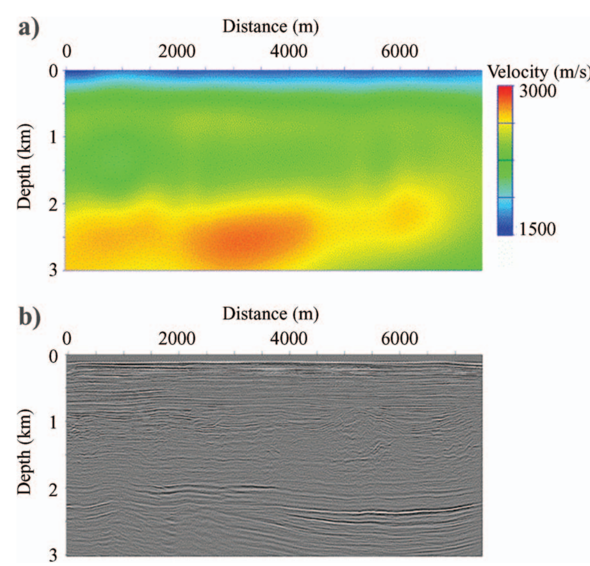

Figure 8. Real data example: (a) velocity model estimated by POST and (b) corresponding PSDM section.

(prestack traveltimes and local slopes). Figure 9a shows an updated velocity model and Figure 9b shows an associated depth migrated section. The improved velocity model better focuses the data, showing many structural elements that are difficult to see in the section obtained using the initial model. Analysis of CIGs obtained using the initial model (Figure 10a) and the updated model (Figure 10b) shows better alignment of reflection events within the shallower depth range.

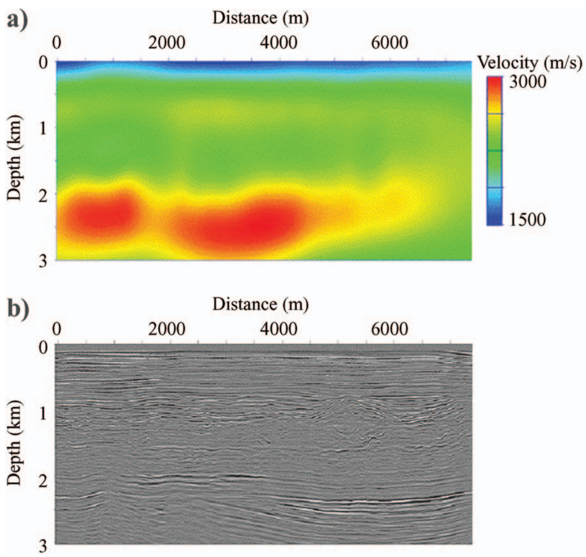

Figure 9. Real data example: (a) updated velocity model and (b) corresponding PSDM section.

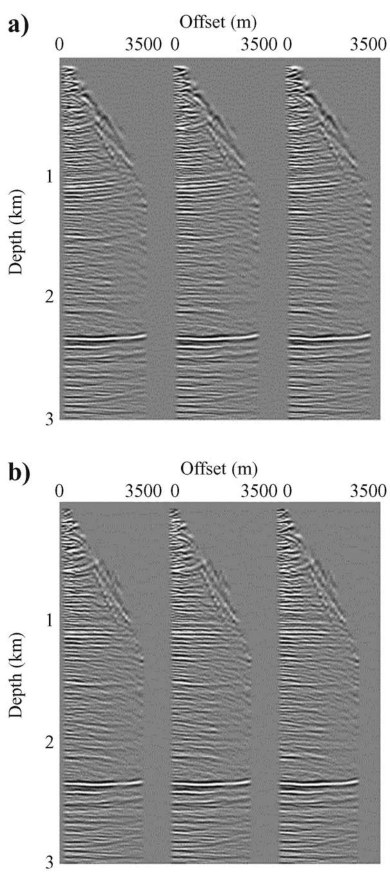

Figure 10. Real data example: (a) three adjacent CIGs after POST inversion and (b) after residual inversion.

CONCLUSIONS

We have presented a new methodology for velocity model building and updating. It consists of a two-step procedure: (1) initial model estimation by poststack stereotomographic inversion and (2) model updating using residual inversion based on traveltime residuals estimated on CRP gathers. The proposed scheme is robust and does not require any picking or tracking of reflected events on prestack data. Instead, it is based on a reliable procedure of picking locally coherent events on an unmigrated stacked section, while kinematic parameters of the wavefield are extracted from iteratively improved CRP gathers. The proposed method is data driven and computationally fast: it does not require performing PSDM during the iterations. Limitations of the proposed method are assumption of the hyperbolic traveltime approximation for poststack stereotomography to estimate an initial model, and the parabolic approximation for residual traveltimes in velocity updating. Iterative use of the proposed scheme can partially overcome these limitations.

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