Imaging complexity in the earth — Case studies with optimized ray tomography

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Abstract

When building velocity models for seismic depth imaging, a key tool used in the industry is ray-based tomography. In the past 10 years, the resolution of tomographic solutions has seen a continuous increase because of evolving sophistication in methodologies and technology. A vital issue in the data domain is accuracy and density of residual-moveout picks that are used to derive tomographic velocity-model updates. A new automated method allows for precise tracking of accurate residual moveout on prestack depth-migrated gathers and consequently the fast determination of dense, high-quality traveltime residuals for seismic tomography. Synthetic and real data examples from this method demonstrate the value that accurate information concerning local wave paths inherent in these picks brings to the problem of resolving small-scale velocity anomalies. The determination of such small-scale anomalies ultimately leads to flatter prestack depth-migrated gathers and consequently better-focused structural images.

Introduction

Ray-based migration velocity analysis is well established as a key component for estimating accurate P-wave velocity models for depth-imaging projects (Stork, 1992; Jones, 2003; Woodward et al., 2008). Since its adoption, the effectiveness of ray-based tomography has improved significantly as a result of both increasing computing power and innovative acquisition technology. On the data side, for example, dense volumetric picking has replaced the original horizon-based schemes, leading to a massive increase in ray illumination (Hardy, 2003; Woodward et al., 2008). The availability of wide-azimuth data in the past 10 years has further expanded model illumination in structurally complex regions, resulting in much more accurate models.

On the model side, TTI anisotropic tomography has become routine in areas of complex geology, and the recent introduction of orthorhombic anisotropy has been successful for explaining azimuthal residual-moveout (RMO) variations that are poorly reconciled with TTI models (Li et al., 2012). On the inversion side, a wealth of a priori information (e.g., well logs) can now be integrated readily into the scheme with the aim of reducing the model null space of the inversion and helping to produce more geologically compliant subsurface models (e.g., Clapp et al., 2004).

Interestingly, one area that inherently affects the resolving power of tomography but has received less attention is the representation and picking accuracy of RMO. The common practice is to use a one- or two-term parametric form of representation to describe residual-migration depths and to apply some sort of automated scanning to generate spatially dense sampling of those depths (e.g., Jones, 2003; Woodward et al., 2008). The advantage of this approach is that the RMO can be constructed easily along the offset direction to provide input data as dense as desired. It has been observed that dense offset sampling appears to improve ray illumination of the subsurface model and thus improves the conditioning of the whole inversion system.

However, the redundancy of RMO information in the offset direction does not necessarily translate into more accurate tomography results if this information misrepresents the actual physical reality (Jones, 2003; Brittan and Yuan, 2005). From a ray-migration point of view, residual-migration depth at each offset is tied closely to local migration-velocity perturbations experienced by the associated specular ray. Accurately characterizing the local velocity perturbations makes it possible to drive higher-resolution velocity estimation, especially when small-scale velocity anomalies are of primary interest.

Simple parametric forms of picking might reasonably characterize RMO when overburden migration-velocity errors have only weak or moderate lateral variations. However, when significant lateral variations occur within the ray bundle of a single subsurface point, RMO can become complex, and the use of a parametric representation will lead to erroneous input data. Although any ray-based method will struggle to resolve local perturbation to the velocity field if the perturbation is significantly smaller than the Fresnel zone, perturbations that are considerably larger will be resolved accurately only if the associated moveouts are characterized accurately.

Figure 1 shows a single low-velocity feature (of velocity 1800 m/s) embedded inside a constant background velocity (2000 m/s). PreSDM gathers (Figure 2a) are generated using the background velocity with the perturbation removed. Because of this localized migration-velocity error, a single reflector might be imaged correctly only at near offsets, only at intermediate and far offsets, only at near and far offsets, or at other combinations of offset ranges. The resulting RMO shows extremely discordant undulations among offsets. If parametric scanning is used to pick these complex shapes, it will feed spurious RMO data into tomography.

Figure 1c shows the tomographic result from parametric picks using a second-order formulation. The inversion using the parametric picking fails to recover the true location and velocity value of the perturbation. It should be noted that this inaccurate inversion result is likely to remain the same no matter how densely sampled an inversion grid is used and will persist even if the sampling in space and offset is also dense.

To identify small-scale velocity anomalies that are beyond the capability of parametric-based workflows, input RMO data must retain key information on migration-velocity error that is local to each individual offset. This demands that for an accurate representation of RMO, nonparametric shapes must be picked and used as tomographic inputs.

In general, reliable nonparametric picking is a tough problem because of the infinitely many shapes of curvature that are possible. Past efforts have indicated that a fair amount of manual effort was often needed to guide the picking process to obtain precise nonparametric picks (Brittan and Yuan, 2005). Woodward et al. (2008) describe an automated method that applies trace-by-trace crosscorrelation to parametric picks to boost the accuracy of nonparametric picks.

It is possible that in the case of very complex moveout, this technique might suffer from unavailability of the high-quality pilot traces that are required for its effective operation. In this article, we present a different methodology for nonparametric picking and show the resultant impact on tomographic velocity updates, with a focus on the resolution of localized velocity heterogeneities.

Method

To maximize the amount of data information that can be used to drive a tomographic velocity update, the new nonparametric picking method has been designed to maintain a capability for the automatic dense and volumetric picking of CIP gathers, a key advantage offered by the parametric methodology.

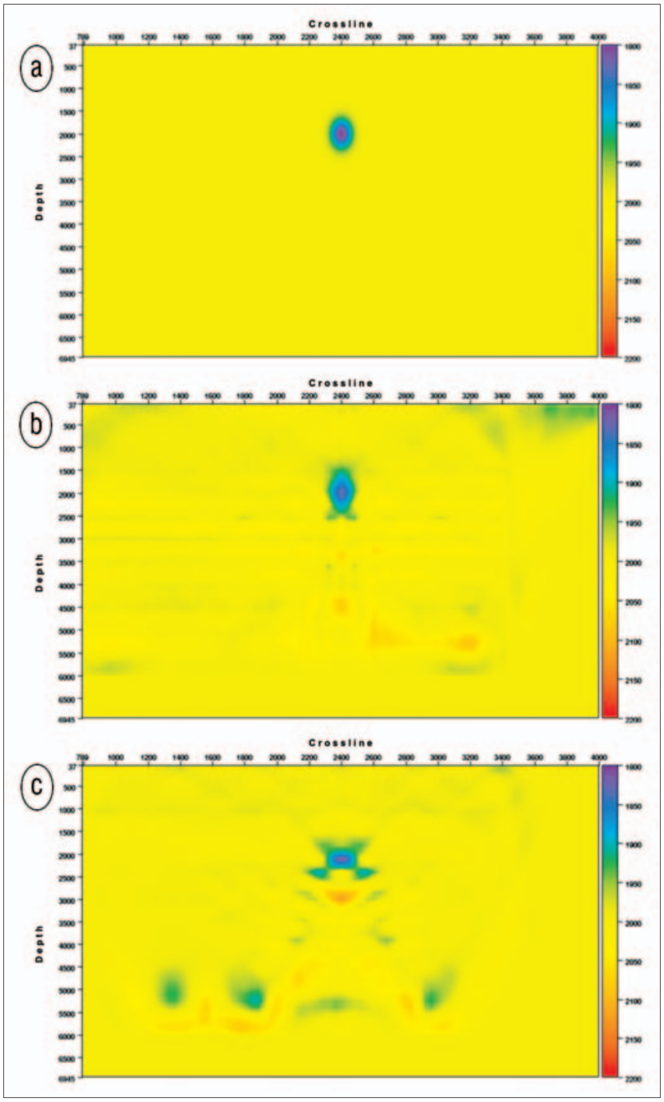

Figure 1. Constant-velocity model with an embedded low-velocity perturbation: (a) true model; (b) model inverted from nonparametric picks; (c) model inverted from single-parametric picks. Note that the result from tomography using nonparametric picks is considerably superior to that from parametric picks.

In contrast, however, the nonparametric method also is designed to track the actual shape of a reflection event without any a priori knowledge of its true moveout profile. With this method, a reflection event is defined as an ensemble of offset trace samples that corresponds to the seismic reflection from a single subsurface point. A sophisticated wavelet-tracking technique is used to calculate the depths of a reflection event of interest, working progressively from near to far offsets. Several constraints are introduced to enforce the searching process to follow the same reflection event (i.e., to prevent cycle skipping) and to prevent any remnant coherent noise (such as multiple energy) from being picked.

To ensure the quality of the picks, a metric of semblance also is introduced and computed along the tentative event trajectory as a basis for pick filtering. However, it should be noted that a picking algorithm using this methodology requires reflection events on migrated gathers to be cleaner and more continuous than methods using parametric-based algorithms. Data preconditioning thus is often needed to enhance the continuity of reflection events, and postpicking smoothing is also helpful for further enhancing the quality of the picks.

This technique requires no horizon or other a priori structural information and is fully automated in a top-down manner. In addition, it is efficient enough to allow large 3D or wide-azimuth data to be processed within a similar time frame to that normally needed for parametric picking. Picked nonparametric data, along with relevant semblance volume, are then supplied to the tomographic inversion, with the aim of deriving highly resolved velocity updates.

In addition to the use of nonparametric picks, geologic compliance of the resulting seismic-velocity model can be increased

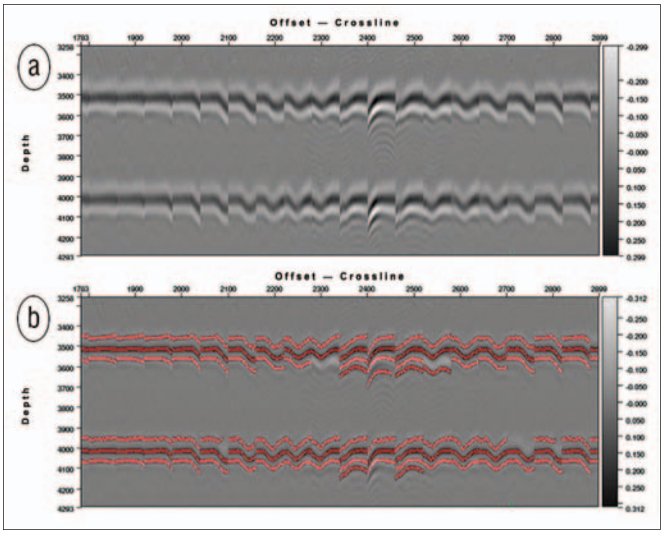

Figure 2. (a) PreSDM gathers show complex residual moveout because of the presence of a low-velocity perturbation that is not accounted for in the velocity model used for migration. In each gather, near offset is to the left and far offset to the right. The offset range is 100 to 8000 m in increments of 100 m. (b) The same gathers are overlaid with general moveout picks.

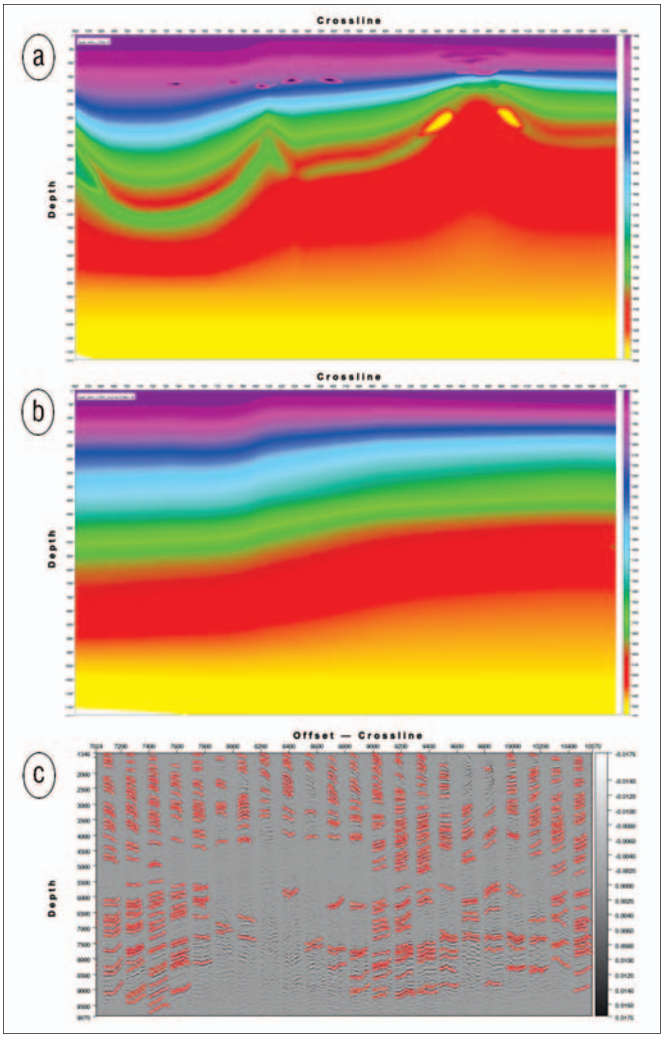

Figure 3. Complex synthetic EAGE workshop model: (a) true velocity model; (b) initial migration velocity; (c) preSDM gathers showing complex residual moveout. On the gathers, near offsets are to the left and far offsets to the right. The offset range is 0 to 8000 m in increments of 200 m.

by the use of a priori constraints during the inversion itself. In particular, we use a regularization operator such that the model itself will vary as little as possible along predefined geologic dips.

Examples

Our first synthetic example of nonparametric tomography is the single perturbation model introduced earlier in this article. RMO picks made using the new method are shown in Figure 2b. It is clear that localized nonhyperbolic moveouts are picked precisely along the offset axis, and thus, offset-dependent velocity information will be retained within those picks. In fact, tomographic inversion of the picks produces a much improved velocity model in comparison with that of conventional parametric tomography (Figure 1b versus Figure 1c, respectively). The recovered perturbation is close (in magnitude, location, and shape) to that of the true model, proving the effectiveness of the technique in resolving highly localized velocity heterogeneities.

Next we apply nonparametric tomography to the complex 2D EAGE synthetic model (Billette and Brandsberg-Dahl, 2005; Brittan and Yuan, 2005). This model is interesting in that it contains numerous small gas pockets in its shallow section and two structural high-velocity inclusions in the basement (Figure 3a). The initial migration velocity is generated by the removal of all local velocity features and heavy smoothing of the remnant model (Figure 3b). This is analogous to a velocity model that might be obtained from a prestack time migration. Figure 3c shows part of the preSDM gathers with nonparametric picks overlaid.

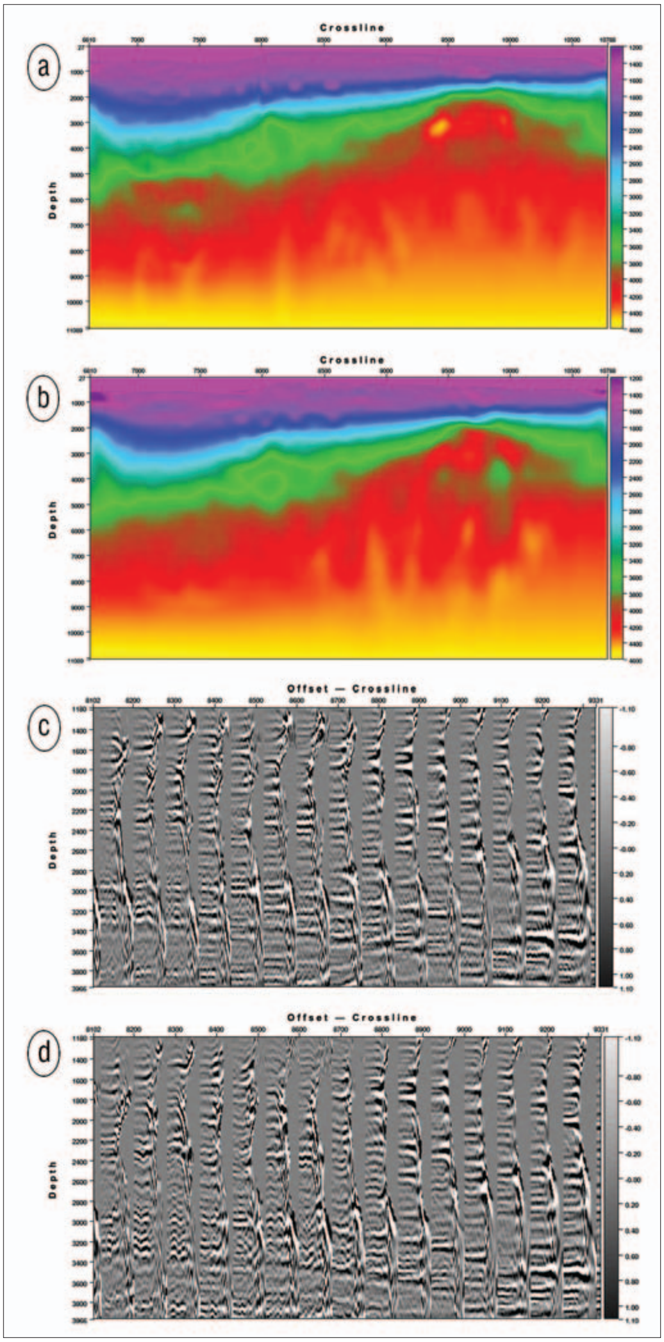

Figure 4. Comparison of tomographic results using (a) nonparametric picks and (b) single-parametric picks (b). Gas pockets are defined better in the nonparametric inverted model. When the gathers are remigrated with (c) nonparametric velocity, they are significantly flatter than those from (d) single-parametric picks. On the gathers, near offset is to the left and far offset to the right. The offset range is 0 to 8000 m in increments of 200 m.

Although these are noise-free synthetic data, it can be seen from the gathers that they exhibit extremely complex moveout curvatures tied to strong lateral variations in overburden migration velocity. It can be seen that the nonparametric picker does an excellent job in following these complicated moveouts, even for this tough data set.

The nonparametric picks are then input into the tomography inversion, and six iterations of model update are performed. Figure 4 shows the comparison between nonparametric and conventional tomography results. It can be seen that the model from nonparametric picks represents the actual velocity model better than that from parametric picks. Furthermore, the footprints of the small gas pockets and high-velocity inclusions are clearer with nonparametric tomography. This results in much flatter and more continuous reflectors in the remigrated preSDM gathers (Figure 4b) than the velocity model from parametric-based picks (Figure 4d).

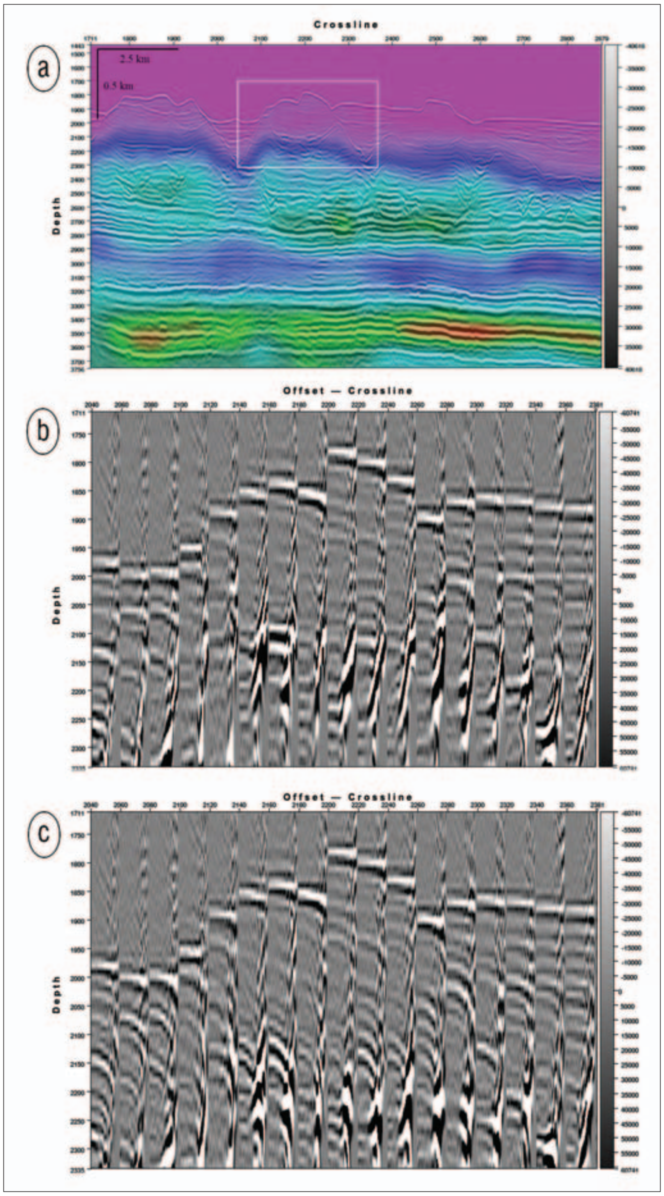

Figure 5. Example from marine data set. (a) PreSDM image with velocity overlay. The box shows the area in which gathers in part (b) and (c) are located. (b) PreSDM gathers derived from nonparametric tomography. The gathers range in offset from 300 to 5250 m in increments of 150 m. Near offset is on the left. (c) PreSDM gather from parametric tomography.

Finally, nonparametric tomography is applied to a real 3D marine data set. This data set is interesting because the water bottom in the area is characterized by strong topological variations that might serve as local velocity heterogeneities. Initial preSDM gathers, produced using a smooth layerlike starting model, display fairly large nonhyperbolic moveout stemming from the rugose water-bottom surface and other small-scale velocity anomalies. It is difficult to characterize moveout undulations using parametric picking, and this poses a challenging model-building task for parametric-based workflow.

We use both single-parametric and nonparametric schemes for RMO picking and model updates. Four iterations of isotropic tomography are performed with the same set of control parameters. Figure 5 shows preSDM gathers produced from the updated velocities. In both cases, seismic images show improved gather flatness, with only a few model-building iterations. The result from nonparametric tomography (Figure 5c), however, is obviously superior to that from conventional tomography, especially in the shallow section. It is easy to understand that high-quality nonparametric picks retain differentiating information that is required to undo the effects of localized lateral velocity variations caused partly by the highly varying water bottom and thus help to better resolve the velocity field in the shallow area.

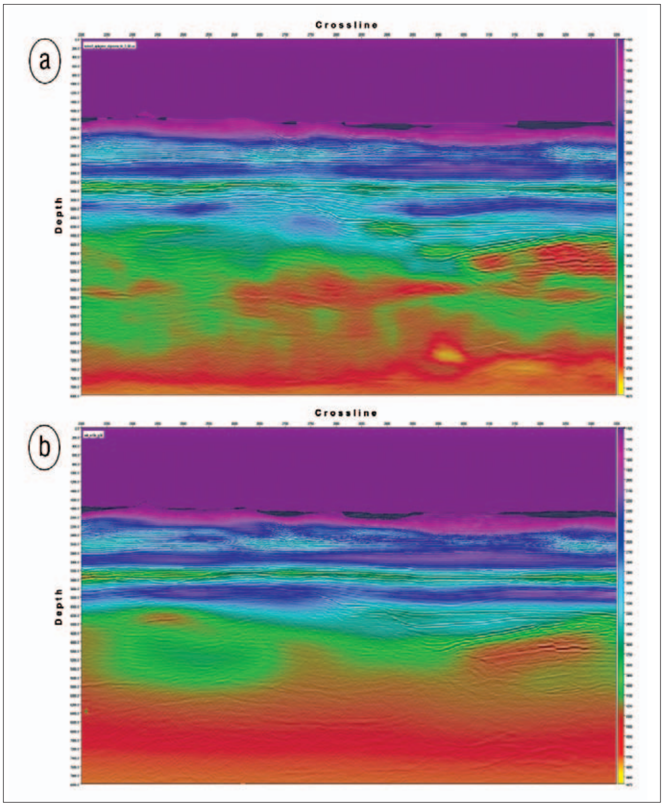

Figure 6. Example from marine data set. Comparison of tomography using (a) nonparametric picks and (b) parametric picks. It should be noted that the nonparametric result also used dip-based regularization in the inversion and was completed in five iterations, as opposed to the 15 iterations used for the parametric result.

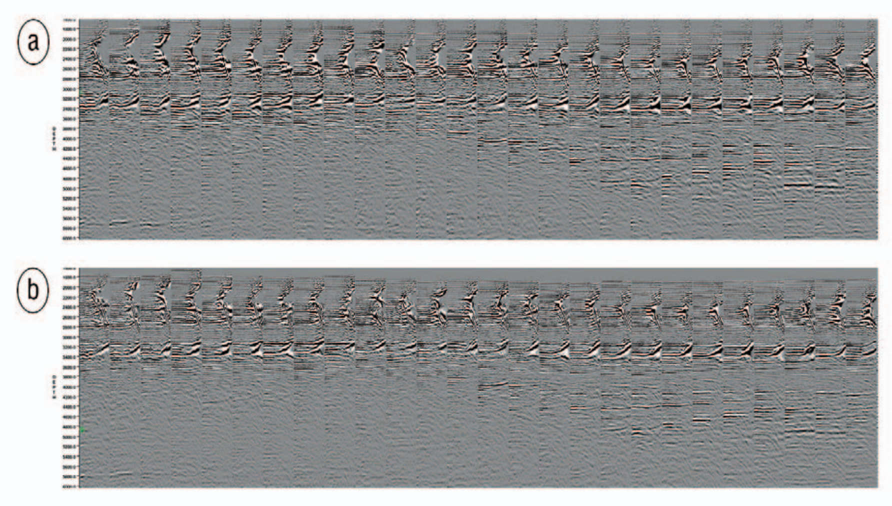

Figure 7. Example from marine data set. Comparison of preSDM common-image gathers migrated using (a) the velocity model derived using nonparametric picks and (b) the velocity model derived using parametric picks. As noted for Figure 6, the nonparametric result also used dip-based regularization in the inversion and was completed in five iterations, as opposed to the 15 iterations used for the parametric result. The gathers range in offset from 300 to 5250 m in increments of 150 m. Near offset is on the left.

In Figure 6, we compare the result of tomographic inversion using nonparametric picks with that using parametric picks. In contrast to the straight comparison in Figure 5, in this case, the nonparametric pick inversion has the additional application of a priori geologic information in terms of the dip-based regularization described above. What can be seen from examination of Figure 6 and Figure 7 is that by using nonparametric picks and a priori geologic information, a velocity model which is both geologically reasonable and provides flat and coherent gathers (and thus a high-quality structural image) can be obtained as quickly as possible. (The nonparametric result was obtained using five iterations of tomography, as opposed to the 15 iterations required for the result using parametric picking.)

Conclusions

We address the necessity of having accurate residual-moveout picks as input data for high-resolution reflection tomography. A new methodology is presented that allows reliable and efficient picking of complex residual moveouts in a fully automated manner. Tests of two synthetic data sets demonstrate the method's superior capability of recovering small-scale velocity anomalies compared with conventional parametric tomography. Applying this new method to a 3D marine data set shows that accurately characterizing RMO curvature helps to produce flatter reflection events in preSDM gathers.

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