High-resolution tomographic inversion with image-guided preconditioning and offset-dependent picking

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Summary

A high-resolution approach to tomographic velocity model updating is described, combining advanced techniques to avoid simplifications which conventional tomography relies on, in order to yield geologically plausible models with greater accuracy and no significant increase in cost for time or effort. First, offset-dependent picking is implemented to better track gather events than traditional curvature-based picking, especially in situations demonstrating high anisotropy and complicated geology. Matching complex moveout can yield updates which more quickly flatten gathers and bring out fine detail in velocity models. To complement this, structure-oriented inversion preconditioning is applied, enforcing adherence to a stacked image's geological features. This helps avoid the violation of faults and layering which may arise using conventional updates, as well as generating a higher-resolution update which requires less postprocessing. Together, these refinements fit into a current tomographic flow to generate high-resolution velocity models without sacrifices regarding computation time or accuracy.

Introduction

The assumptions and simplifications which traditional tomography relies on may extend the amount of time and number of tomographic iterations required to flatten gathers, and often yield geologically implausible velocity models. Our high-resolution tomographic method uses an offset-dependent residual moveout (RMO) picking technique, as well as preconditioning based on image-guided interpolation (IGI), in the inversion process, to flatten gathers more accurately and quickly than traditional methods, with more geologically plausible velocity models.

Woodward et al. (2008) note that typical methods to pick RMO fall into two categories. Polynomial-based schemes approximate moveout based on parabolic, hyperbolic, or higher order polynomial fits. Conversely, offset-dependent methods scan moveout along an event's entire offset range. This implementation can often lead to updates which flatten gathers in less time than polynomial-based techniques.

While conventional tomography may yield reasonable velocity updates, often these models do not follow a geologically consistent pattern. When attempting to resolve faults or layering, this is a problem which is not easily solved with traditional approaches. Previously, to generate the most resolute inversion results, the best option was to invert on the finest possible update grid. This was generally computationally impractical and still led to updates which required postprocessing smoothing to remove outlying values and unreasonable variations. When applied to seismic inversion, IGI (Hale, 2009a) helps avoid these issues by describing the update region as a sparse set of values which are interpolated along structures. Image-guided tomography (IGT) automatically enforces updates which honor layering and faults, to create more plausible subsurface models.

Combining offset-dependent picking and IGT generates higher resolution velocity models than traditional tomography. Increased complexity and variability in velocity updates follows directly from using offset-dependent picking to achieve greater gather flatness. IGT further increases these gains by allowing updates to converge to a final model more rapidly and avoiding postprocessing steps which may yield low-resolution updates, even when using very dense inversion grids.

Offset-dependent Picking

When CIGs display moveout which coincides with low order polynomial terms, polynomial-based RMO picking may effectively describe the smooth curvature. Industrial efforts have made great advancements in the use of this technique with real data (He and Cai, 2011; Bartana et al., 2011; Siliqi et al., 2007; Koren et al., 2008). However, in situations where the curvature is complex, the polynomial assumption may often be inaccurate (Liu et al., 2010). Complicated areas, such as those with high anisotropy, or showing heavy faulting, will often yield events with multiple turning points, which may actually be made worse by polynomial-based flattening. Offset-dependent techniques, such as the plane-wave destruction method described by Fomel (2002; Liu et al., 2010), offer an alternative to more simplistic methods, in areas which require higher resolution imaging. These schemes have become common in the past decade, as they enable an accurate fit to complex moveout, regardless of curvature properties.

Our novel offset-dependent RMO picking method considers each common-image-point gather as a two-dimensional plot. The RMO curves within a gather are viewed as paths of connected nodes with similar patterns. This turns picking into a path-finding problem, solved by a dynamic programming algorithm. Various geophysical factors, including event amplitude, displacement field, dip continuity, and flatness constraint, are utilized by an object

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function. This can be easily extended to include more factors to guide the event-finding process. Offset-dependent picking can pick RMO curves with multiple turning points, which is often problematic for polynomial-based methods. It has been tested with synthetic and real data, and has shown stable and accurate results.

Image-guided Inversion Conditioning

In order to setup our IGT inversion, we must first define an array of zones covering the update region, which are tied to a grid of sparse control points. These zones' boundaries are defined by propagation time within the underlying image, to ensure that they follow image structures. This is enforced by calculating tensors which describe directionality and continuity of structures, based on image gradients. These tensors are used as a pseudovelocity in calculating structure-related propagation time, by solving the Eikonal equation around each control point. Propagation time is lower along coherent structures, such as clearly-defined layers, and propagation time is higher across coherent structures or at disruptions in the image, such as faults. Each control point is assigned to the zone of grid locations nearest it in propagation time. These zones will be anisotropic and extended along coherent structures, and will tend to be more isotropic in incoherent areas, or when interrupted by faults.

During tomographic inversion, a matrix of equations is inverted to find a velocity update which converges to a solution to minimize RMO. The basic relations governing this are

$$Am = d \text{ and } Lm = 0, \quad (1)$$

where A is the relation between the actual and current models, m is the actual model, d is the current model, and L is the Laplacian operator used to stabilize the update. The objective is to solve for an update to our model, given the RMO, which represents the inaccuracy in the current model.

IGI-conditioned inversion revises the first of the two relations in equation (1) to

$$Apx = d, \quad (2)$$

by replacing m with px. Here p is the preconditioning IGI matrix. This is applied in the inversion by averaging all values within each zone, and then performing structure-oriented smoothing (Hale, 2009b), using the previously-calculated structure tensors. This enforces the update's resemblance to the base image.

In order to make sure our technique is applied consistently, the priority-based selection method described by Cullison (2011) is applied to select optimal control point locations automatically, rather than based on constant or smoothly varying spacing. Fewer, more sparsely spaced control points are necessary along coherent structures, as major properties are expected to remain more consistent along their length, while control points should be more tightly spaced within incoherent areas. This adaptive method ranks locations by importance, based on a priority map of the image, which is built from its amplitude envelope, structural semblance, and local planarity represented by the degree of anisotropy in the structure tensors. From this priority map, control points are selected, while ensuring each is spaced appropriately from others.

Examples

Figure 1 demonstrates different RMO picking methods' capabilities. Polynomial-based fitting with a single parameter is unable to describe any but the events with the simplest curvature. Two-parameter fits are more effective with complex curvatures, especially when events display multiple turning points. However, offset-dependent picking is the only method which successfully fits every type of complex event, particularly in locations where events do not span the entire offset range.

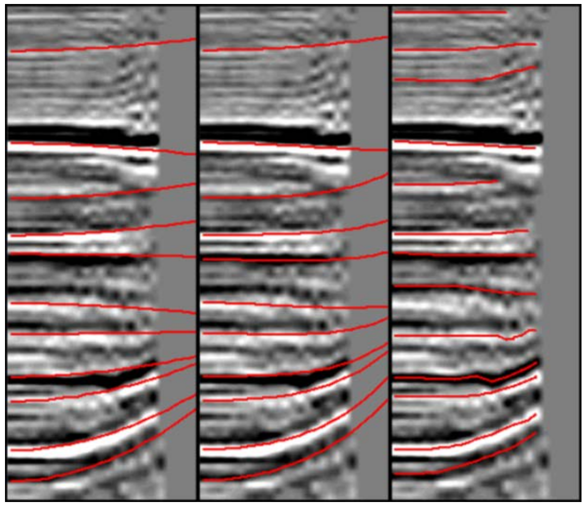

Figure 1 *Comparison of RMO picking methods: (left panel) one-parameter polynomial, (center panel) two-parameter polynomial, and (right panel) offset-dependent picking.*

Figure 2 shows results of our adaptive control point selection code. Each 'x' in the top panel shows the location of a control point selected by picking high priority map values in the bottom panel. The highest priority points tend to lie on strong, flat reflectors, and are usually spaced far apart along layers, while being closer in the direction across layered events. The zones this creates, shown in the central panel, are strongly anisotropic in layered locations and tend to stretch along layers. Control points in less coherent

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areas are assigned to smaller, more isotropic zones, and are more clustered and less patterned.

Figure 3 demonstrates results from traditional inversion methods and the newly presented IGT inversion technique. The panel on the top shows a stacked image overlaid with a velocity update calculated using traditional Laplacian regularization within the inversion process. The central panel introduces dip-guided Laplacian regularization, which more closely follows the stacked image's structure, especially in highly dipping locations, but does not substantially improve on the previous example's resolution. The bottom panel shows the velocity update with the same input data, but with the inversion conditioned by the constraints of IGT. This update is much more strongly tied to layering and geological structures observed in the stacked image. Furthermore, the resolution and distinct layering with IGT is vastly superior to traditional methods, particularly in shallow regions which tend to be very washed-out and low resolution without IGT. Figure 4 also depicts this IGT velocity update, in a three-dimensional comparison to the stacked image.

Conclusions

Offset-dependent RMO picking can accurately describe complex events to yield more accurate velocity updates without relying on ineffective polynomial-based curvature fitting. Gathers which display multiple turning points, or events which do not span the entire offset range, which would previously be incorrectly picked, are well-fit and appropriately flattened.

With traditional inversion algorithms, tomographic velocity updates may not follow geologic trends or resolve thin layers. Inversion using IGI as a preconditioner encourages updates to follow structure, which leads to geologically plausible and higher resolution velocity models which honor layering and faults automatically.

Our high-resolution tomography approach combines these methods into a new tomography flow, melding easily with earlier techniques. New results are a vast improvement over those obtained with conventional methods, yielding more accurate velocity models, and frequently saving time and effort.

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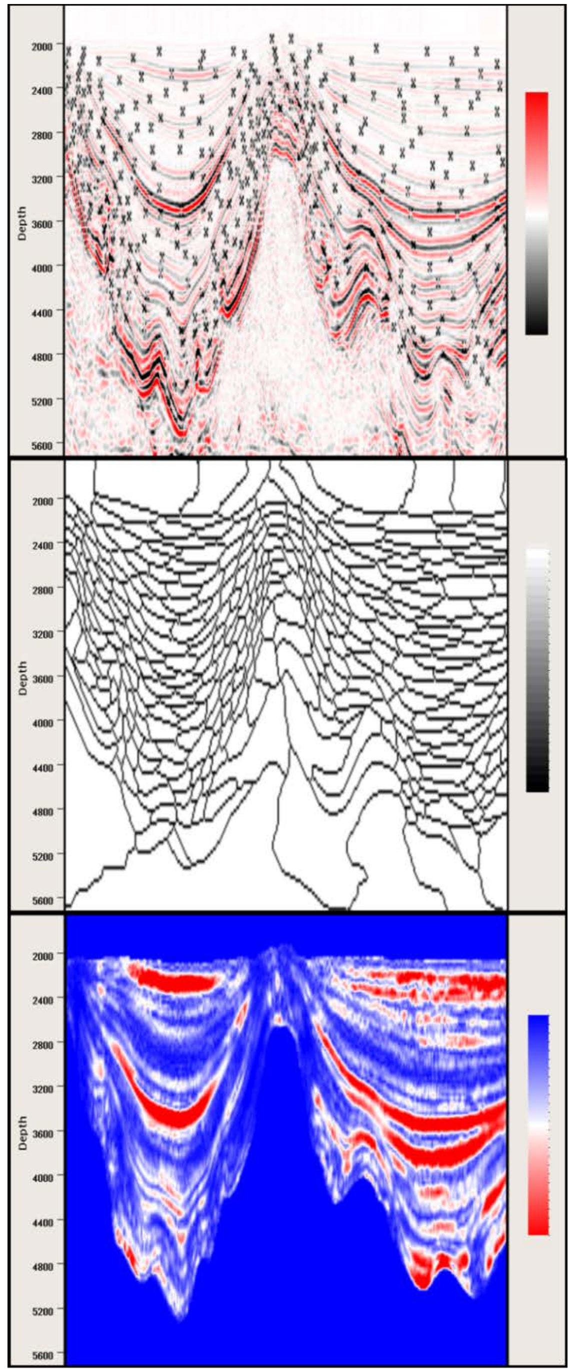

Figure 2 *(Top panel) Adaptively selected control points overlaid on the image used to guide interpolation in the update. (Center panel) The boundaries of the selected update zones. (Bottom panel) The priority map used to pick control points.*

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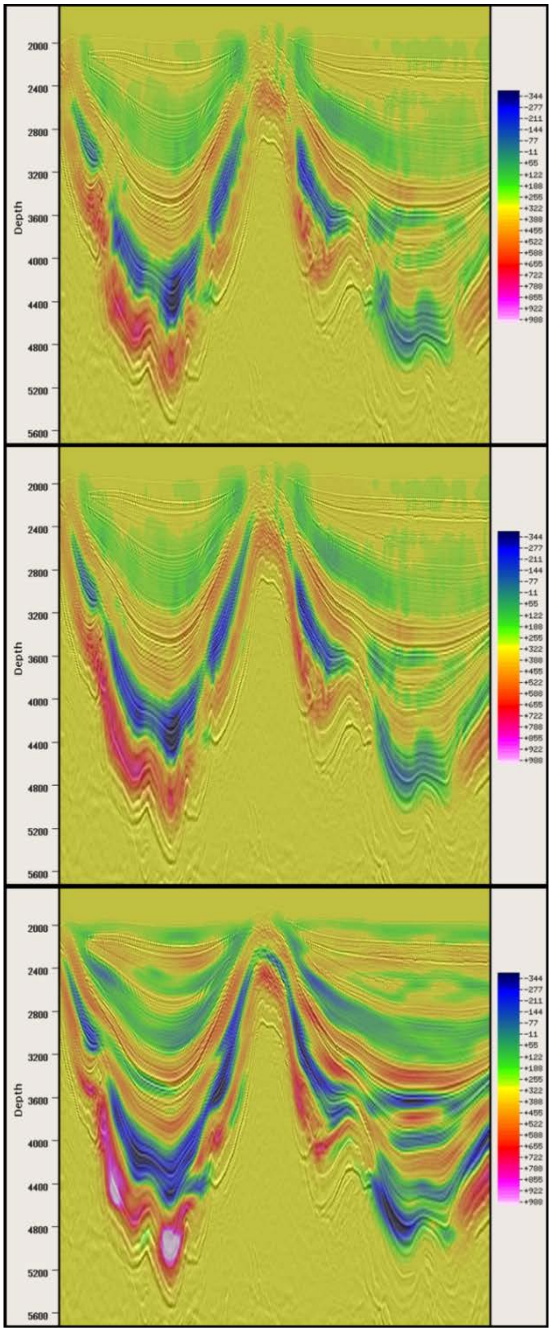

Figure 3 Velocity update following inversion, overlaid on a migrated image, for: (top panel) traditional tomography methods with normal Laplacian regularization, (center panel) with dip-oriented Laplacian regularization, and (bottom panel) using IGI to precondition the inversion matrix.

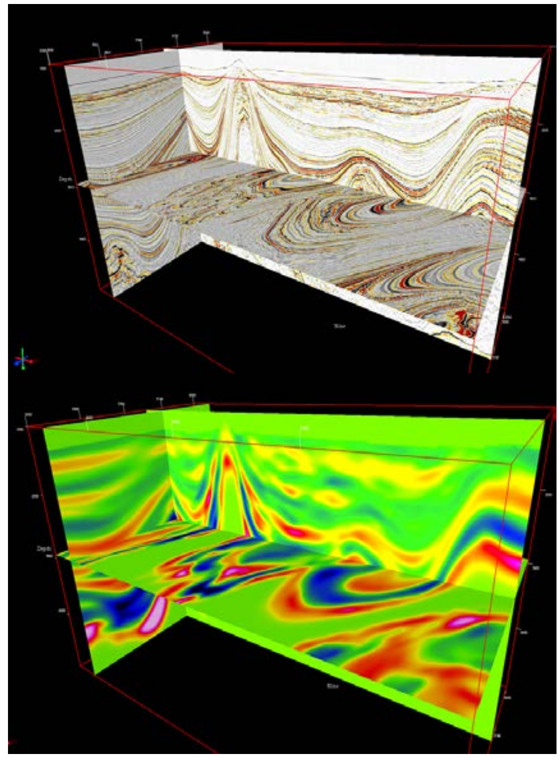

Figure 4 Three-dimensional view of stacked image (top panel) compared to IGT velocity update (bottom panel).

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EDITED REFERENCES

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