3D migration velocity analysis for common image gathers in the reflection angle domain

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Summary

We present a migration velocity analysis system for updating velocities based on common image gathers in the reflection angle domain. Such angle-domain common image gathers can be obtained from either wave equation-based or Kirchhoff integral-based prestack depth migration. Residual velocity associated with each subsurface image point is determined from semblance scans of common image gathers over a plausible range of values followed by automated picking. The extracted residuals can be tied to and smoothed along geologic horizons to improve an initial velocity model through vertical, normal-ray, or tomographic update. A marine data set and two synthetic examples are given to illustrate residual velocity analysis of common image gathers in the reflection angle domain.

Introduction

There is an increasing demand for advanced imaging techniques capable of providing improved knowledge of the subsurface detail in areas with complex geologic structure. Along with these advanced imaging methods, such as wave-equation migration, there are demands for complementary migration velocity analysis tools that can directly update the wave equation migration velocity model. In areas of complex structure and variable velocity distribution, conventional seismic imaging techniques may either incorrectly reconstruct the position of geological features or fail to create usable images at all. For example, in an area with the presence of gas cloud, conventional Kirchhoff integral technique may encounter the difficulty of treating caustics and multi-pathing events. DeHoop (1999) showed that the incorporation of Maslov integral and the formulation of the scattering integral with scattering angles can properly handle the adverse effects of caustics and multipathing. The output image gathers from these extended integral approaches are typically sorted with scattering/reflection angles. Additionally, several phase shift operator based techniques have been developed (Biondi, 1997; Prucha et al., 1999, Jin, et al., 2000) for accurate wavefield downward continuation in complex media. These wave equation based techniques have demonstrated the success in improving imaging of complex geologic structures such as subsalt or gas cloud zones. For all these improved imaging techniques, the output image gathers are sorted in reflection angle or ray parameter.

In addition to advanced migration techniques, obtaining high quality images of subsurface structures also requires a highly accurate velocity model. One way of constructing velocity models is Migration Velocity Analysis (MVA) based on Common Image Gathers (CIG). The CIGs contain redundant structural information which can be used to correct the initial velocity model. Several methods (Al-Yahya, 1989; Stork & Clayton, 1991; Liu, 1992; Stork, 1994; and Meng & Bleistein, 1999) are focused on using redundant structural information in the depth and offset domain to update initial velocity models. Ottolini and Claerbout (1984) derived residual velocity stacking trajectory in the angle domain. Clapp and Biondi (2000) presented reflection tomography from angle domain CIGs for migration velocity analysis. Jiao et al. (2000) extended MVA in the t-p domain to the plane-wave domain. In their approach, correct velocity is determined directly from a range of possible velocities through an iterative and interactive analysis process. We present a formulation of the relationship of residual migration moveout with RMS residual velocity without limitation on reflector dip, and show that the same MVA work flow for CIGs in the offset domain can be extended to the reflection angle domain (Liu et al., 2001). We also demonstrate the effects of steep dip on residual migration moveout with respect to non-zero residual velocities.

Angle-domain MVA

The exact work flow of residual analysis, picking and update for CIGs in the offset domain can be extended to the reflection angle domain. Given an initial velocity model and input seismic data, common image gathers at analysis subsurface locations are generated from a selected prestack depth migration capable of handling plane wave modes. Migrated events in the image gathers may exhibit curvatures due to incorrect migration velocities. Optionally, geologic horizons can be picked from the stacked volume using a graphic interface. To improve reliability, residuals can be tied to and smoothed along horizons prior to updating. Updates can be performed using an increasingly sophisticated portfolio of techniques, starting with a completely automatic approach for initial velocity models and simple structures, to horizon-based vertical updates, horizon-based normal ray updates, and tomography for the most challenging structures. The process is either iterated for all layers at once, or performed in a layer-stripping fashion until all events are aligned horizontally with ray parameter. In the following discussion, we focus on this approach of residual velocity analysis and velocity updating in the angle domain.

Common image gathers in the angle domain

Given a set of seismic data and an initial velocity model, a number of common image gathers are generated for the volume of interest. The CIGs in the reflection angle domain are preferably generated using a wave-equation migration method, but can in general be generated using other methods such as Kirchhoff migration. The upper left panel of Fig. 1 shows an Angle-domain Common Image Gather (ACIG) generated by common azimuth prestack depth migration (Biondi, 1997). In this figure, the vertical axis denotes the depth while the horizontal axis denotes an incident angle parameter *p*. The incident angle parameter, also termed the ray parameter, is indicative of the angle of incidence of plane waves at each subsurface image location. Each trace in the figure corresponds to a plane wave mode.

Computing residual velocity values

To extract residual velocity values from ACIGs, we consider the relationship of migration depth with migration velocity and residual velocity for each plane wave component (or equivalently, for each ray parameter). For a reflector embedded in a constant velocity medium, migration of the event with an erroneous velocity will misposition the image in depth. This mispositioning can be expressed in a ratio of migration depth and true depth as a function of migration velocity, residual velocity, dip angle and ray parameter. Additionally, the true depth can be represented in a form of migration depth for the zero ray-parameter component. Therefore, the dependence of residual migration moveout on residual velocity and dip angles renders itself as a scanning formula to find the best fit to ACIGs. In a varying velocity case, all velocity quantities in the residual velocity analysis are approximated by RMS values.

Residual moveout governed by the above method is performed on each ACIG for the region of interest with a suite of RMS residual velocities. A semblance distribution over RMS residual velocity is then generated. The peak semblance values correspond to the best-fit residuals that get the events of interest aligned horizontally.

Computing velocity updates

Once residual velocity is computed for ACIGs, several methods can be used to back project the residuals to the overburden medium and therefore update the initial velocity model.

The simplest method is vertical updating without horizon, which combines residual velocity picking and vertical updating. This is an automated process that does not require picking geologic horizons. Given a semblance spectrum of residual velocity, the method perturbs the initial velocity profile to search for a new velocity profile which typically follows peak semblance values at every depth. The output from this method is a residual semblance profile, a picked RMS residual velocities, and an updated interval velocity profile. Used alone, the method is best suited for preliminary velocity analysis in areas with slightly dipping layers.

The advantage of the automated vertical update lies in its efficiency of processing large volume of ACIGs without human intervention. The main drawback is limited noise discrimination and limited geological constraint. A better conditioned approach is to tie residuals to geologic horizons and perform horizon-based updates. Geologic horizons usually exhibit strong reflectivity and good lateral continuity and can be picked from stacked image volumes.

Combining vertical update and horizon constraints results in a horizon-based vertical update. In this method, the Dix inversion formula (Dix, 1955) is applied to RMS residual velocity for estimation of interval residual velocity. This algorithm is computationally efficient. A first step involves lateral smoothing of horizon-based residual velocities for each horizon. This is followed by a depth-to-time conversion of the horizons and associated residual values. RMS residual velocity is then converted to interval residual slowness. Based on the fact that linear smoothing of a slowness distribution keeps the kinematic fidelity of wave propagation, it is desirable to smooth residual slowness values before adding them to the background. The update velocity value is the sum of the background and the calculated residual velocity at the grid point of interest.

One major limitation of vertical update lies in its simplification of error back-projection methods. In the presence of steep dips, vertical back-projection can wrongfully misplace residual velocity values. With horizon-based normal-ray updating, however, perturbations occurring along a normal ray to the reflector are taken into account. A specular ray normal to the dipping reflection surface is used to approximate the wave propagation path. The improved accuracy of normal-ray backprojection comes with a slight increase in computation workload for ray tracing.

An even more accurate and yet computationally intensive method is horizon-based tomographic updating. In this method, a fan of rays with correct wave propagation trajectories is used to backproject residual velocities to the locations where the errors originated. Each tube of rays from an analysis ACIG point illuminates part of the overburden, and several overlapping ray tubes can be used to reconstruct the overburden velocity distribution in a tomographic manner. The method consists of two basic components: forward modeling and tomographic reconstruction. In the forward modeling, ray paths are determined through ray tracing from every analysis ACIG point and residual moveout as depth deviation in ACIGs is converted to residual traveltime. The influence of velocity errors on imaged reflector geometry is also taken into account. In the tomographic reconstruction part, ray paths, computed residual traveltimes, and the unknown residual slowness field comprise a linear optimization system, which is solved by the method of conjugate gradients.

Examples

In the first synthetic example, we compute residual velocity for a single flat reflector in a constant velocity medium. A synthetic CDP gather is generated by finite difference modeling. If the correct velocity is used for phase-shift-based common azimuth prestack depth migration, the reflection event would be aligned horizontally with ray parameter. In the first experiment, a 10% lower velocity was used for migration, and the migrated event deviates upward with increasing ray parameter, indicating too slow a migration velocity. Semblance scan and residual picking selected a peak value corresponding to the expected 10% velocity error. In the second experiment, a 10% higher velocity was used, and the migrated event deviates downward with increasing ray parameter, indicating too fast a migration velocity. Semblance scan and residual picking again recover the -10% expected residual.

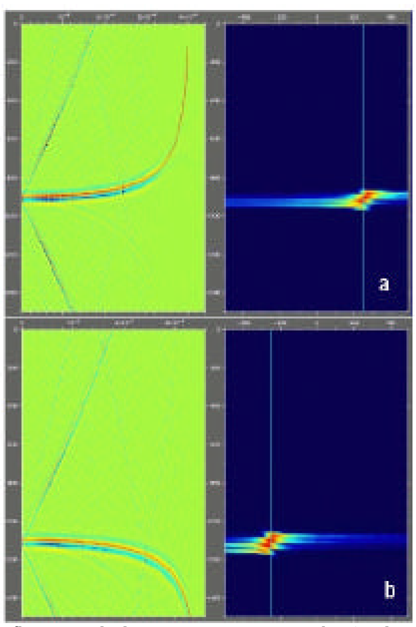

Fig. 1. Reflection angle domain common image gather (predicted moveout path marked by red line) and semblance scan over residual velocity (correct residual value marked by blue line) for the flat layer model. (a) migration velocity is 10% slow, (b) migration velocity is 10% fast.

The second synthetic example demonstrates the effect of dip angle on residual migration moveout. Synthetic shotgathers are generated by finite difference modeling and are sorted to CDP gathers in a constant velocity media with a 35 degree dipping layer. Migration velocity used is 10% lower than the actual value. In the first trial of residual velocity analysis, the 35 degree dip is neglected and peak semblance values suggest an exaggerated residual velocity value. In the second trial, the dip angle is considered in the residual scan, and the estimated residual velocity is close to the expected 10% error. This demonstrates that residual migration moveout depends on not only residual velocity

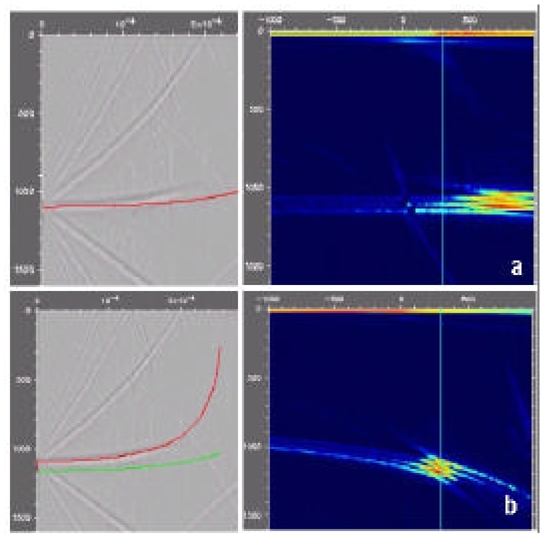

Fig. 2. Reflection angle domain common image gather (predicted moveout path marked by red line) and semblance scan over residual velocities (correct residual value marked by blue line) for the dipping layer model with a too slow migration velocity. (a) dip angle is neglected, (b) dip is factored in scanning formula.

but also on dip. In the presence of steep dips, this must be taken into account to insure maximum accuracy.

The third example is residual velocity analysis of a marine data set from the Gulf of Mexico. The 3-D survey covers an area approximately 21km long and 15km wide. The initial depth interval velocity is derived based on stacking velocity. Common azimuth (wave equation) prestack depth migration was applied to the data to generate CIGs (Fig. 3 left) in the angle domain with 32 ray parameters. Fig. 3 illustrates the semblance scan of residual velocity and automated picking. In the shallow part, most of the reflection events are aligned horizontally in the ACIGs. Therefore, peak semblance values are more or less aligned with zero residual in the semblance panel. Towards the bottom of the section, peak semblance values become less concentrated and reveal appreciable residuals. RMS residual velocities picked from semblance panels like this are used in vertical, normal-ray, or tomographic update depending on the level of complexity in the structures.

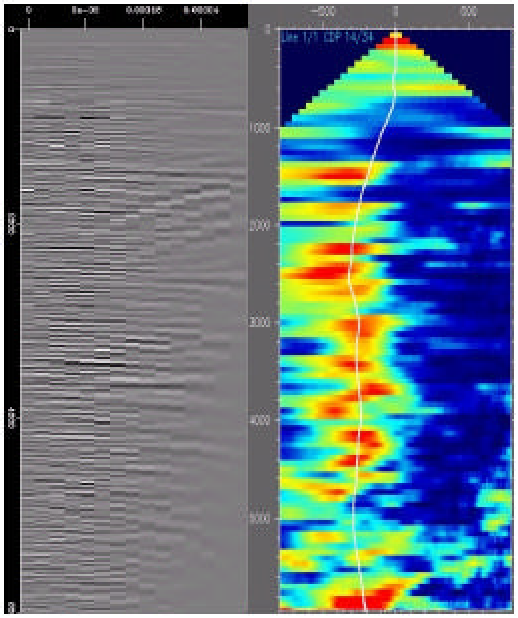

Fig. 3. Angle-domain common image gather of Seitel data (left) and corresponding semblance spectrum of a range of residual velocities (right). Automated picks of residual values along with the depth are marked by the white line.

Conclusions

We have derived a migration velocity analysis system for updating velocities based on common image gathers in the reflection angle domain. Such angle-domain common image gathers can be obtained from either wave equation-based or Kirchhoff integral-based prestack depth migration methods. RMS residual velocity associated with each subsurface image point is determined from semblance scan of common image gathers followed by automated and constrained picking. RMS residuals are further reduced to interval residuals, which are used in improving the initial velocity model through vertical, or normal-ray, or tomographic update. The synthetic test verifies the relationship of residual migration moveout with both residual velocity and dip angles. In the presence of steeply dipping layers, neglecting the dip angle term in residual moveout can result in over-correction of velocity models. The residual velocity analysis is also demonstrated on a marine data set from the Gulf of Mexico.

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Acknowledgments

The Gulf of Mexico data is courtesy of Seitel.