GEOPHYSICS, VOL. 73, NO. 5 (SEPTEMBER-OCTOBER 2008); P. VE1–VE3
10.1190/1.2969441

# Introduction to the supplement on velocity estimation for depth imaging

William S. Harlan[1], Robert T. Langan[2], and Tamas Nemeth[2]

## INTRODUCTION

In the last decade, much of 3D seismic signal processing has been replaced by the single imaging process called prestack depth migration. Rapid advances in resolution and illumination have changed the way we explore, delineate, and monitor reservoirs. We now see more attention turning to the velocity models that make such depth imaging possible. For this supplement to the September-October 2008 issue of GEOPHYSICS, we invited summaries of existing practices, descriptions of new approaches, and case studies that illustrate the practical aspects of building and updating velocity models.

Velocities are implicit in every imaging or moveout-sensitive processing step. Velocities still consume the most hours of human labor and interpretation during seismic processing. We cannot simply delegate the geologic implications of a velocity model to a later interpretive step. We need velocities for a seismic image, an image for interpretation, and interpretation velocities.

At the 2007 SEG annual meeting, the three of us encouraged one well-known researcher on imaging to submit a paper for this supplement. He had written a Ph.D. thesis on this very topic and had continued to work on it since, yet he had limited his publications in the last two decades largely to imaging algorithms. When we asked why he had not published more about velocities, he replied, “Because it never works!” Having seen his results, we knew otherwise, but he expressed a common feeling that velocity estimation never works as well as hoped.

Writing about velocity models always has been awkward. No one seems proud of all steps used to build any particular model. We hear more often about specific innovations confined to one part of a workflow. The industry never has been close to establishing a standard imaging-velocity workflow, even limited to one geologic regime. Students, take note: This is what a good research topic sounds like.

Seismic velocities appear in many forms. We like to imagine a physical property derivable from other rock properties, but we more often use a processing parameter with the appropriate units, somehow useful for depthing and imaging. Seismic methods have a legacy of pseudo-velocities that can be confusing to newcomers. One of the earliest uses in exploration was an “average-velocity” scale factor to convert reflection time maps to tie well depths. Simple scalar velocities also appeared in models of the near surface for refractions and static corrections with “replacement velocities.” Normal-moveout analysis is the most common parametric use of velocity, describing the hyperbolic curvature of reflection times with offset. Time migration requires differently averaged velocities that inconveniently never match the others. These traditional uses still appear in routine analysis because they are robust and well understood. As our data and computing power improve, however, we find that our velocities begin to look more like actual rock properties, including anisotropic and dispersive behaviors. Eventually, we might see velocities routinely handled as a complex tensor.

Migration velocity analysis has given us an impressive variety of approaches, most often optimizing some measurement of prestack coherence. Many methods that originated with tedious interactive procedures now have become heavily automated. Nevertheless, we want to appreciate the heuristics that made these procedures so effective.

Traveltime tomography has been adopted widely as the workhorse of velocity estimation for depth imaging. Originating in earthquake tomography, the method has been elaborated and refined for crosswell, VSP, reflection, and turning-ray geometries. A recent generation of geoscientists acquired optimization and regularization skills with traveltime tomography. Developments in this approach continue to have a big impact.

Waveform inversion attempts to fit the full seismograms directly rather than just simple kinematic attributes extracted from those data. Serious theoretical and numerical efforts have been under way since the early 1980s, but we now see computer resources making the method practical at the resolution and scope we desire. Full-waveform tomography, which recently became feasible on 2D field data sets, shows promising results in 3D applications. This approach promises finally to unify our imaging and velocity estimation, with comparable resolution for both.

Published online 1 October 2008.
[1]Landmark Graphics, Highlands Ranch, Colorado, U.S.A. E-mail: bharlan@lgc.com.
[2]Chevron, San Ramon, California, U.S.A. E-mail: bob.langan@chevron.com;tamas.nemeth@chevron.com.

Velocity estimation for depth imaging always has been more than just a computational and algorithmic exercise. Practical workflows and specialized model-building skills are essential. We need to document the details of what has been tried, what helped, what did not help, and the circumstances.

We have grouped the papers into five main categories: tomography, waveform inversion, velocity model building, case studies, and parametric velocity estimation. Each category has a core set of papers that clearly illustrates the current practices and results. Some manuscripts easily could fit multiple categories, which is as it should be.

We are particularly grateful to those who agreed to elaborate on their practical experiences in case studies. We hope this supplement to GEOPHYSICS encouraged some revelations that otherwise might not have been shared.

We believe this supplement will serve as a useful overview of the current theory and practice of velocity estimation.

## TOMOGRAPHY

**Woodward et al.** review the evolution of depth-imaging tomography during the last decade as computer power and exploration requirements have grown. They give examples of the steady increase in model resolution, the shift from narrow- to wide-azimuth data sets, and a progression from isotropic to anisotropic models.

**Adler et al.** present a new formulation of nonlinear 3D reflection tomography using depth-migrated residual moveout rather than traveltimes as invariant observables in the objective function of the inverse problem. The method allows iterative solution of the nonlinear inverse problem without repeating expensive prestack depth migrations.

**Lambaré** describes the state of the art of stereotomography, a method proposed a decade ago for estimating velocity macromodels from seismic reflection data. The method now has fully demonstrated its robustness and applicability.

**Liu et al.** construct their inversion in a uniform grid domain but solve with a nonuniform grid by using matrix transformation. Thus, they can reduce ambiguity and improve stability over a strictly uniform approach.

**Costa et al.** propose a new reflection-angle-based smoothness constraint as regularization for slope tomography and compare the effects with those of three more conventional constraints. The smoothness constraint leads to models that are geologically more consistent, with a weaker effect on migrated data.

**Shen and Symes** describe an implementation of differential-semblance velocity analysis based on shot-profile migration and illustrate its ability to estimate complex, strongly refracting velocity fields.

**Singh et al.** develop a new automatic wave-equation migration velocity inversion using multiobjective evolutionary algorithms. The technique can cope with large velocity errors with a computational cost comparable to that of gradient methods.

**Koren et al.** use an interactive ray-based tool to update background anisotropic velocity parameters tomographically. Updated parameters correspond to residual-moveout curves that best fit migrated reflection events. The method splits the contribution to the computed residual moveout into two parts — from overburden residual parameters and from the actual picked residual parameter.

**Simmons** inverts turning-ray first-arrival times from a 2D shallow-marine data set to estimate the slowly varying components of the near-surface velocity model. A low-spatial-frequency model parameterization converges in a single iteration and produces a velocity model unbiased by anomalies from localized gas accumulations or shot statics.

## WAVEFORM INVERSION

**Ben-Hadj-Ali et al.** build a velocity model with a massively parallel 3D frequency-domain full-waveform inversion of wide-aperture seismic data. Synthetic studies show the potential and computational requirements of the method.

**Shin and Ha** compare various objective functions for acoustic waveform inversion in the frequency and Laplace domains. The Laplace domain appears to be robust for inaccurate initial velocity models.

**Vigh and Starr** describe a full-waveform inversion with multiple iterations of compute-intensive forward modeling and residual wavefield back propagation. A time-domain, plane-wave implementation proves to be computationally feasible.

**Sava and Vlad** present wave-equation migration velocity-analysis operators for zero-offset, survey-sinking, and shot-record migration configurations. The authors concentrate on the numerical implementation of these operators and discuss them algorithmically.

**Schleicher et al.** show that image-wave propagation in the common-image-gather domain can be combined with residual-moveout analysis for iterative migration velocity analysis. Gathers obtained by migration with an inhomogeneous macrovelocity model are continued from a constant reference velocity. A correction formula translates the residual flattening velocities into absolute time-migration velocities.

## VELOCITY MODEL BUILDING

**Wang et al.** describe a beam-based interactive imaging method to refine salt geometry. For subsalt velocity updates, either subsalt tomography or subsalt scan-based techniques can be used, depending on the quality of subsalt reflections.

**Jiao et al.** examine two approaches to build velocity models for subsalt imaging: a residual-moveout analysis in a layer-stripping mode and a wave-equation prestack-migration scanning technique. The authors use the former approach to approximate the subsalt velocity field and then use the latter to fine-tune velocity models below salt.

**Fliedner and Bevc** use waveform tomography to build a velocity model that is consistent with the wavefield migration operator, backprojecting traveltime residuals along wave paths instead of rays. A wave path is obtained by multiplying impulse responses of the wavefield propagator from a surface location and a reflection point.

**Cameron et al.** show that the theoretical relationship between the time-migration velocity and the true seismic velocity involves the geometric spreading of image rays and takes the form of a partial differential equation. The authors solve this equation numerically to estimate seismic velocities from time-migration velocities and to convert time-migrated images to depth.

**Buur and Kühnel** use a reverse-time migration directly inside the model-building process to help delineate complex (salt) structures. Application to a 2D West Africa seismic data set yields a dramatically improved velocity model and a compelling image of the subsurface.

**Cao et al.** parameterize a multiscale tomography with overlapping submodels of different grid sizes, thus minimizing artifacts in areas with poor ray coverage. A complex field data example with large shallow variations shows improvements in the migrated stack and common-image gathers.

**Chitu et al.** use common-focus-point analysis to obtain an ensemble of models that fit input traveltimes within the same predetermined misfit. The authors extract statistics from this ensemble to assess overall accuracy.

## CASE STUDIES

**Fruehn et al.** describe an effective combination of hybrid gridded tomography and detailed manual picking to build a velocity model for prestack depth migration. Their deepwater data from offshore India suffers from severe imaging problems because of gas hydrates and seabed channels with low velocity fill.

**Zhu et al.** show recent applications of turning-ray tomography to a crooked-line survey from the Canadian Foothills, a 3D narrow-azimuth survey from offshore China, and a 3D wide-azimuth survey from the Surmont mining property in Alberta, Canada. The authors demonstrate that near-surface velocities are important for time and depth imaging. An azimuthal study suggests that near-surface heterogeneity can masquerade as anisotropy.

**Isaac and Lawton** build velocity models for 2D seismic data from mountainous terrain by integrating the mapped surface geology and dips, well-formation tops, and geologic cross sections with seismic velocity information. The resulting prestack depth-migrated sections show more geologically realistic and better focused reflectors at depth than those available from time processing or from only flattening offset gathers.

**Charles et al.** evaluate how velocity and anisotropy model-building strategies affect seismic imaging in the Canadian Foothills Thrust Belt. The authors compare the results of a model-driven approach with a semiautomated data-driven approach. The latter achieved better imaging and better well ties.

**Jaiswal and Zelt** show a novel method of imaging land multichannel seismic data by combining wide-aperture traveltime inversion and prestack depth migration. They apply this “unified imaging” to a 2D seismic line from the Naga Thrust and Fold Belt and assess it with a well-log comparison.

**Kabir et al.** build a velocity model by combining refraction, reflection, and wave-equation-based tomography. Wave-equation tomography resolves a gas-sag problem with a detailed update of the shallow velocity field.

**Dümmong et al.** compare two approaches of grid tomography: prestack stereotomography and NIP-wave tomography. They apply both techniques to a marine data set from the Levantine Basin in the eastern Mediterranean and analyze the impact of the different traveltime approximations and different input data domains.

**Pruessmann et al.** show that initial model building for depth imaging can be based on common-reflection-surface attributes, thus incorporating the structural dip that is absent from Dix inversion of stacking velocities. The authors show that in the Gulf of Mexico, both the tomographic model-building approach and the depth-imaging applications directly benefit from these attributes.

**Foss et al.** describe a workflow of integrating geologic and other geophysical information in seismic velocity model building. They illustrate the workflow through an offshore Brazil example in a highly complex salt setting.

## PARAMETRIC VELOCITY ESTIMATION

**Bube and Langan** show that reflection traveltimes for selected reflectors can improve the resolution of slownesses obtainable from crosswell transmission traveltimes alone, with the drawback of additional unknown reflector positions. The authors show theoretically and computationally, with resolution matrices, that the reflectors are determined very well and that reflection traveltimes do improve resolution.

**Bube and Langan** illustrate that in most geometries in which seismic traveltime tomography is applied, determining the slowness field from traveltimes alone is not a well-conditioned problem, thus requiring regularization of the problem, often by adding smoothing penalty terms. The authors present a continuation approach for selecting penalty weights, decreasing them step by step, with guidelines to improve accuracy over fixed weights.

**Reshef** presents the advantages of performing interval velocity analysis in the dip-angle domain. He discusses in detail the practical aspects of working in this domain and sensitivity to migration velocity errors.

**Schneider** suggests a method to estimate residual-moveout corrections from prestack depth migrations with inaccurate velocity models. These estimated residual moveouts not only improve the signal-to-noise ratio of the migrated data, they also help to determine the parameters of well-known formation-dependent velocity laws away from borehole positions.

**Stovas** shows that different velocity distributions or kinematically equivalent velocity distributions can result in the same traveltime parameters. An inversion for traveltime parameters is strongly nonunique even if these parameters are estimated accurately. To evaluate the accuracy of the velocity model, one can choose the phase of a two-way propagator.

**Bube and Washbourne,** in Part 1 of a two-part article, present a new method, called wave tracing, that is at least as computationally efficient as ray tracing and provides propagation paths and times more consistent with finite-frequency seismic data and more robust with respect to small changes in the medium velocity. They retain the structure of ray tracing but include a penalty term that encourages raypaths to be more direct while still staying within the Fresnel zone for frequencies of the seismic data.

**Washbourne et al.**, in Part 2 of a two-part article, present synthetic and field data examples of applying wave tracing to traveltime tomography and depth imaging. They demonstrate improved robustness of the algorithm when compared with standard ray tracing, with improved velocity and depth images.