Uncertainty in orthorhombic model building: Analysis, mitigation, and validation

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Abstract

As seismic processing technologies have advanced, model definitions have grown correspondingly more complex, progressing from isotropy, to transverse isotropy, to the much more general orthorhombic anisotropy. This growth, while supported partly by continued improvements in acquisition techniques and survey geometries, has progressed at such a rate that current projects require solutions to a much greater relative number of unknowns than those in the near past. This added complexity creates ill-posed problems with huge model spaces, leading to a high degree of uncertainty in the final solutions. This uncertainty can be greatly mitigated through pragmatic use of a priori knowledge and intelligent data leverage and model regularization. Orthorhombic anisotropy has been well characterized both microscopically and macroscopically. This understanding allows an unprecedented level of constraint and confirmation for the model-building process by validating the directionality and strength of azimuthal velocity variations. Information within the data itself can also lead to a much more well-determined model-building result. The observed structure can be used to precondition inversion results to ensure geologic plausibility, constraining similar updates to similar events. Concurrently, nonparameterized residual moveout picking allows for complete freedom in describing gather events, yielding results which best resolve the various anisotropic parameters by accurately fitting the gather data and generating a high-resolution model. By properly combining the various constraints available in a well-designed processing project, the myriad uncertainties that arise when moving to an orthorhombic model space can be simplified and reduced, allowing for geologically reasonable solutions that fit data, yield valuable structural information, and enhance interpretation possibilities.

Introduction

Modern seismic imaging relies on many advanced acquisition and processing techniques that seek to wring every possible detail from surveys. Processing improvement is often marked by new and novel methods that attempt to leverage similar data in creative ways to gain additional resolution, coherency, and interpretability. As the demands on processing have increased, acquisition has sought to keep pace largely by providing denser, more azimuthally complete data coverage at longer maximum offset. While additional data are almost always helpful in constraining imaging solutions, most advanced processing methods require assumptions and suppositions about their applicability to any given survey, which cannot always be offset by simply adding more data.

To add complexity to the issue, velocity and anisotropic models are becoming increasingly important as deliverable products themselves. In the past, models were treated as little more than processing parameters, the only purpose of which was to generate a focused and interpretable image by flattening gathers. Uncertainty then was assessed as it impacted the image itself, focusing on depth positioning and continuity. Conversely, modern processing depends on creating a suite of results, including both the model parameters and the image, which provides a greater variety of information together than separately. For this reason, a heavy emphasis has been placed on the generation of geologically plausible models, the features of which can be tied to physical properties. Particularly with the rise of unconventional oil and gas exploration, a desire to describe reservoir properties such as fracture orientation and density has led to the demand for interpretable velocity and anisotropic models and a need for a better understanding of model uncertainties.

Due to this increasingly difficult task of finding appropriate solutions to less well-determined imaging problems, the practice of quantifying, analyzing, and minimizing model uncertainty has become vitally important throughout the seismic industry.

We will examine the origins and complexity of uncertainty in the orthorhombic model-building process and discuss methods to analyze this uncertainty from a stochastic inversion point of view by constructing parameter-coupling matrices to describe the ambiguity of the orthorhombic model space. We will also look at methods to mitigate this uncertainty by including various forms of well seismic information or properly utilizing the full range of information provided by seismic reflection data by injecting a priori model information to regularize the derived model. Finally, we will discuss techniques to verify and validate the resulting model to ensure its geologic plausibility.

From isotropic to orthorhombic uncertainty

Seismic uncertainty can be introduced due to a number of unconstrained or poorly determined areas of the processing workflow (Wang and Braile, 1994). Uncertainties in the velocity and anisotropic parameter models arise during the model-building process, which usually relies on reflection-based tomographic model updates generated by inverting information from residual moveout (RMO) picks on common-image gathers to flatten events in gathers and therefore better focus events in the stacked image. This uncertainty in the tomographic process is largely based on the nonuniqueness of the solutions derived, as model parameters have overlapping sensitivities and often cannot be readily distinguished. For even a simple isotropic project, there is a complete set of solutions that will yield flat gathers and, therefore, focused images. However, not all of these results will image reflectors at the correct depth. Deep events have very low angular coverage, so their imaged depth is much more sensitive to velocity changes than their gather curvature. Without being able to provide more information to supplement RMO picks, there is no way to guarantee that final models are geologically

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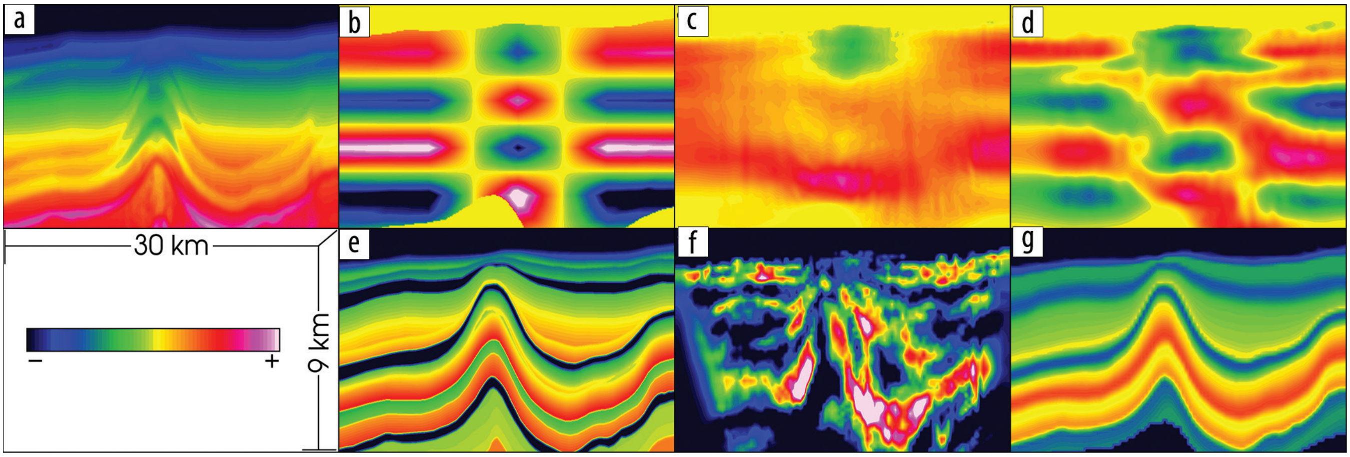

Figure 1. Results for a synthetic tomographic update test for (a) true velocity model. For (b) initial V_o and (e) δ perturbations, grid-based updates to (c) V_o and (f) δ offer much poorer solutions than the geologically constrained results in (d) and (g), respectively. ε is not shown as it follows the same pattern as δ. All color scales are consistent for their respective parameters.

plausible or accurate in depth. In practice, making reasonable assumptions regarding the shape and magnitude of velocity updates can mitigate much of this uncertainty. Initial images can provide useful information regarding structure, which can drive decisions on update resolution and smoothing, and yield more specific expectations through the a priori insight of interpreters, as well as rock- and reservoir-physics understanding. However, it is still not a simple task to accurately invert for a velocity model, even in this relatively straightforward situation.

With these problems inherent in isotropic projects, extension to anisotropy is a nontrivial process. The industry-standard tilted transversely isotropic (TTI) model assumes isotropic wave propagation within subsurface layers but slower effective velocities when moving across layering. This expands the list of unknown parameters from one to five: velocity along the symmetric axis V_o, azimuthal angle φ, dip angle θ, and δ and ε, the two parameters which describe the velocity distribution away from the symmetric axis. While this is daunting at first, it is a quick matter to reduce the uncertainty in the model space using some basic a priori knowledge. Consider the typical scenario in which the transversely isotropic plane is coplanar with the sedimentary bedding, and V_o is therefore the velocity in the direction normal to the bedding. This suggests that if an accurate measurement of layer dip can be obtained from the stacked image, this can constrain both φ and θ for most situations, leaving V_o, δ, and ε to be inverted for, and for most purposes collapsing the TTI parameter space to that of a vertical transversely isotropic (VTI) model in which layering is assumed to be horizontal. This is not always so simple, as there are other assumptions that may be made regarding a VTI model that are still not valid for TTI (Bakulin et al., 2010a), but it is useful to provide a starting point to expand to processing of data demonstrating orthorhombic anisotropy. This reduction of parameters for TTI inversion from five to three is helpful, but when isotropic seismic data cannot provide a unique solution for a single parameter, inverting for three at once can seem hopeless.

Complexity again increases when moving to an orthorhombic model space, which is necessary to describe azimuthal anisotropy within the subsurface, often assumed to arise due to aligned fractures or a dominant stress direction. This expands the TTI model to allow varying velocity distribution within the previously transversely isotropic layers. Specifically, there now are assumed to be two orthogonal planes of symmetry in the subsurface — one corresponding to a fast propagation direction and another to a slow direction, though both are usually assumed to still be faster than V_o. This means that to fully parameterize this model we need an additional angle α to describe the fast direction's rotation in the subsurface, and δ and ε for each symmetric plane.

In practice, we also add an extra δ parameter to describe the distribution of velocities between the fast and slow planes. This yields a total of nine parameters for the orthorhombic model space: V_o, φ, θ, α, δ_1, and ε_1 for the fast direction, δ_2 and ε_2 for the slow direction, and δ_3 for fine adjustment between the fast and slow planes. As with TTI modeling, we can use the layer dipping direction to define the two major angles φ and θ, and we can assume that the distribution of RMO by azimuth in a chosen subsurface plane will allow for a reasonable fit to α. However, this reduction still leaves us with six parameters to solve for, twice as many as for the TTI case, which already exceeds the capabilities of traditional tomographic constraints.

To account for the myriad uncertainties brought about by the move to an anisotropic model space, it is important to first understand and then consider methods to quantify the uncertainty.

Analyzing anisotropic uncertainty

The coupling of two parameters describes how those parameters change with respect to one another. When considering geologic anisotropy, it is useful to plot the coupling of the various model parameters against one another to visualize their interdependence. This can be used to evaluate various model setups to ensure the given information is being used optimally to generate a geologically consistent and mathematically reasonable model.

To demonstrate this process, we have conducted a simple synthetic TTI tomographic test, shown in Figure 1, with ε hidden as it follows the same trend as δ. This demonstrates results of attempts to update the velocity and anisotropic parameters together, first with generalized grid-based tomography, and second by applying structural constraints and dramatically reducing the number of unknowns. This was accomplished by dividing the model space along 13 sedimentary layers, picked from a stacked image. The velocity grid was also separated into eight lateral zones to retain an appropriate horizontal resolution. It is simple to observe that the additional constraints remove a great deal of uncertainty in the reproduced model, allowing a higher degree of accuracy.

For this synthetic situation, Figure 2 shows two coupling plots for V_o, δ, and ε. These plots are generated by multiplying the sensitivity matrix of the tomographic inversion for one parameter with another. The uniform 3 × 3 matrix on the left was derived from the initial naive grid-based approach for a model with 14,131 grid points. Matrix cells are labeled in their lower left corners in accordance with the parameter coupling depicted: "a" for V_o, "b" for δ, and "c" for ε. Therefore, the first cell, "aa," shows the coupling of velocity with itself. Comparing this to "bb" and "cc," the cells for the anisotropic parameters, there is a huge disparity in value. The off-diagonal cells show the coupling of parameters with each other. These are significant because the same pattern is reflected in all coupling plots, suggesting the parameters couple strongly in sensitivity.

The coupling plot on the right side of Figure 2 depicts the same cells for the sparse model space, which yielded the more accurate solution, on a corresponding color map. The velocity model space is separated into 13 layers and eight lateral zones, for a total of 104 model grid points, while the anisotropic parameters are only separated along the 13 layers. The overall pattern in each cell is similar to the pattern observed in the original grid-based coupling matrix, but the values are much more consistent between parameters, with the velocity cell lower in magnitude, closer to the values for the anisotropic parameters. By using structural knowledge to build a sparse model definition and improving the condition number of the matrix, we have reduced the uncertainty in the model as the data uncertainty is related to the model through the condition number, obtaining a better image while building a more geologically appropriate anisotropic description.

Since coupling matrices can be generated easily by reorganizing data used in the tomographic model-building process, they are frequently useful to analyze and quantify the relative uncertainty between different model spaces. This is the first step in understanding anisotropic model uncertainty, as it provides a simple tool to visualize this complicated idea and process.

Well information

The most practical approach to mitigating the uncertainties observed in orthorhombic model building is to consider methods to easily obtain data in a different regime than the time-offset recordings already available from a seismic survey. The hope is that by offering some constraint on velocity or reflector depth, the ambiguities of anisotropic model building can be reduced or eliminated. In practice, the measurements most often available to augment reflected seismic data are those taken from previously drilled wells in the vicinity.

There are a variety of methods used to extract information from wells that may be useful in constraining tomographic solutions. These may be loosely grouped into two sets based on their information yielded. Kinematic approaches provide direct information about the velocity in the well vicinity. Checkshots and sonic logs measure average and interval velocity, respectively, along the well path, while vertical seismic profiling (VSP) enables derivation of the seismic velocity at various offsets around the well. Conversely, marker information can give the depth of important reflectors directly, which enables mis-tie analysis when comparing with seismic depths.

All of these types of well data can be included in a tomographic solver for concurrent updates with the typical RMO information. Often this process uses ray tracing to simulate the traveltime errors suggested by well kinematics or depth information, which also allows for an easy combination with the typical tomographic scheme, with only weighting factors for each set of data needed to ensure rapid convergence. Bakulin et al. (2010b) studied anisotropic tomographic solutions to a VTI model for localized well locations through synthetic tests. They found, for this simple model of anisotropy, that any type of well information can enable a realistic reproduction of the true model, up to the resolution of the well information. Therefore, if given an accurate vertical velocity curve, from dense checkshots or sonic logging, the anisotropic parameters can be fit very closely throughout the well's depth range. Similarly, if provided well markers to incorporate into tomography, average velocity can be constrained at those depths, and a reasonable fit to the anisotropic parameters can be made down to the depth spacing of the markers.

The same research group studied the increased ambiguity of TTI models and whether these could be realistically constrained using the same methods as VTI (Bakulin et al., 2010a). Situations that allowed for unique solutions in VTI were not unambiguously constrained by the same well information used previously. Indeed, Cai et al. (2012) found that to

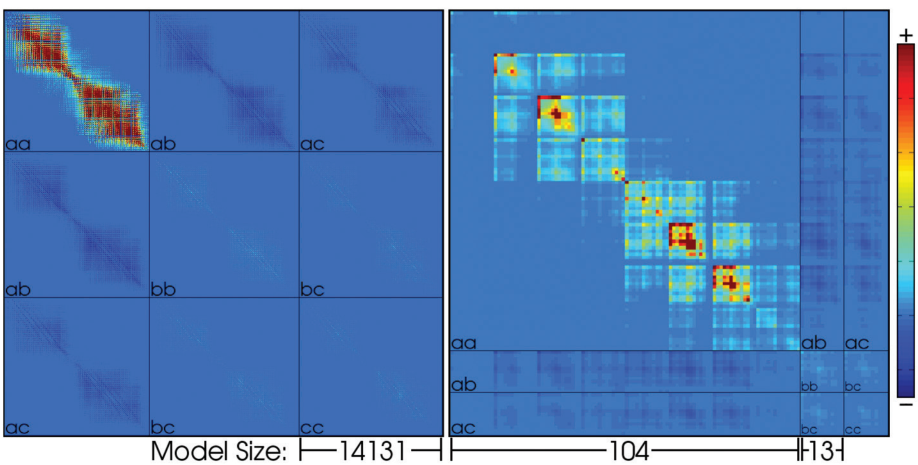

Figure 2. Parameter coupling matrices for the model spaces examined in Figure 1. The grid-based approach (left) shows much less consistent magnitudes between parameters than the sparse, geologic approach (right). Cells labeled with "a" represent V_o, "b" δ, and "c" ε. For instance, cells labeled "ac" show the coupling of V_o and ε.

obtain reasonable solutions for TTI models using tomographic solvers with RMO and well information, structural information also had to be included. In this case, observed structure was used to precondition the inversion results to encourage the update pattern to follow the expected underlying geology. By adding this additional constraint, good fits to all data were obtainable, and the synthetic anisotropic model was obtained.

Motivated by this idea, we will examine data-driven methods to further mitigate uncertainties to extend this well-constrained TTI model-building process to orthorhombic anisotropy, first considering an intelligent method of applying structural constraint to model conditioning.

Inversion preconditioning with structural guidance

As observed, well information added to RMO data cannot adequately constrain even a TTI model, but there are a variety of methods to leverage an existing data set to limit or reduce uncertainty in the final results. It is possible to use the derived images to ensure that updates are geologically plausible, reducing the possibility of anomalous, unconstrained, and unrealistic updates.

For many years, the most advanced approaches to intelligent interpolation and smoothing of model updates during inversion were simplistic filters, the primary responsibility of which was to enforce a particular level of smoothness on the solution to encourage stability. Often, these filters contain some level of dip guidance, such as steering filters, or dipping Gaussian filters, and they may be applied either as a regularization term or as a preconditioner to the inversion process. There are drawbacks to these basic approaches, however. In the complicated regions where we expect to have orthorhombic influence, applying a simple dip-guided filter will often result in updates which are smeared across events whose typical curvature is shorter than the filter-smoothing lengths required for convergence. These types of filters also do not allow for automated methods of fault detection and edge preservation, both of which are vital for the heavily fractured areas expected to be home to strong anisotropy. Without the ability to resolve these geologic features in the velocity model, we cannot ensure that the anisotropic model accurately reflects the earth, adding to the uncertainty of the orthorhombic solution.

However, newer algorithms allow for unprecedented control of resolution, structural adherence, and edge preservation during inversion for model parameters. The image-guided tomography (IGT) method is a structure-oriented solution to interpolation and smoothing of update grids, applied as a preconditioner during the inversion process, which can automatically detect faults and image features (Hale, 2009; Hilburn et al., 2014). The most recent stacked image is scanned for directional coherency and structural semblance, which are used to construct the preconditioner, the directionality and strength of which take into account the continuity of events, disruption of coherent layers by faults, and the local curvature at each model cell. This ensures that geology is taken into account appropriately in situations where the model is lithologically tied, while allowing the freedom to resolve compaction-driven parameterization where the data suggests it is necessary.

A simple example of the IGT process is shown in Figure 3. The stacked image is used to generate a set of structural tensors (Hale, 2009), including structure-oriented semblance cubes. These volumes, and particularly the semblances, are useful as additional information to constrain the inversion result. Figure 3b shows semblance overlaid on the stack to highlight the faulted, fractured, and incoherent features in the image. This information then is used to guide the update shown in Figure 3c to encourage high-resolution layering, edge detection and fault adherence, and a geologically conformed velocity-model update. This provides the best possibility to rapidly converge on the solution while generating a velocity model that may be considered as an interpretable volume, containing as much useful information in some cases as the stack itself.

Nonparameterized residual moveout picking

In addition to appropriate use of image features, ensuring that gather information is properly determined and used is vital to orthorhombic model building. Traditional tomographic RMO picking uses parameterized low-order polynomial fits to gather events, usually by testing the semblance of each of a wide range of possible fits and choosing the optimal solution. These picks are often described by hyperbolic curves, perhaps with a second-order correction applied to allow some flexibility. However, true hyperbolic events are expected only for the simplest of cases, such as in isotropic horizontal layered geology without velocity inhomogeneities.

In any situation where we would expect to find orthorhombic anisotropy, we can be reasonably sure that gather events will frequently be complex and problematic to fit with a one- or

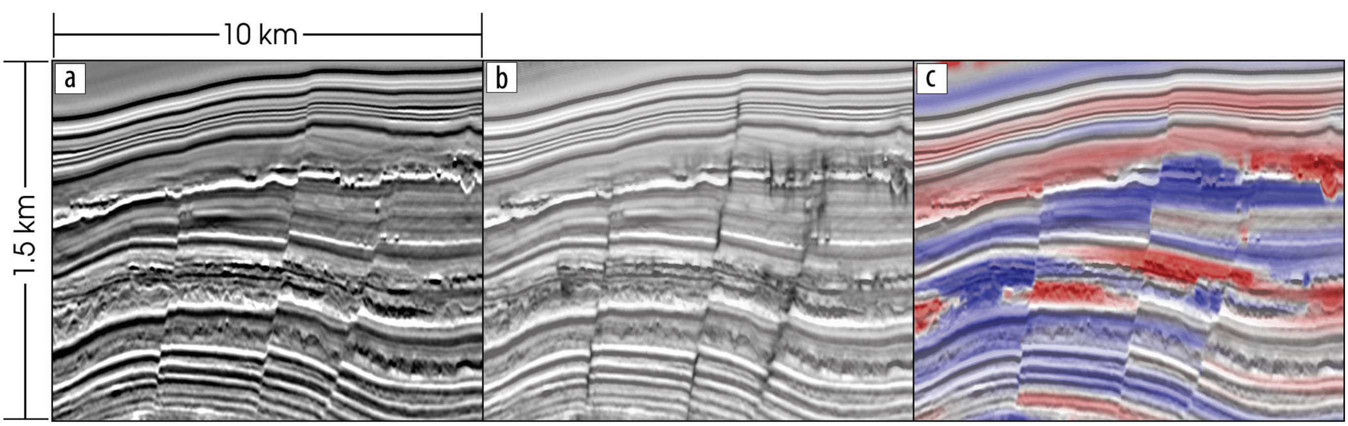

Figure 3. Image-guided tomography example. (a) A stack is used to generate structural tensors, including (b) structure-oriented semblances, which are used to guide (c) model updates that conform to the observed geology, including layering, faults, and other stack events.

two-parameter solution. This may be due to a variety of effects. Velocity heterogeneities can create very complex gathers, and since orthorhombic anisotropy is expected to be most important in areas with strong faulting, fracturing, and twisted sediments, the two are often correlated. Similarly, it is well known that velocity and the anisotropic parameters have different angular regimes of sensitivity. The overlap and interplay of these effects make it very unlikely that gathers in a strongly orthorhombic medium could be adequately described by a simple parameterized curve.

Instead, a nonparameterized approach to picking gathers is needed to accurately reflect the true complexity of the events. As demonstrated in Figure 4, offset-dependent RMO picking allows full freedom to pick gather events of any complexity to generate a high-resolution tomographic update, while also enabling appropriate constraints to ensure picking stability and reasonableness (Hilburn et al., 2014). This technique relies on the construction of a displacement field describing gather moveout at all offsets and depths, which may be processed as necessary to either enforce pick accuracy and resolution in areas of good signal or encourage smooth and consistent updates in regions of poor illumination or high noise.

Model validation and verification

Uncertainty in the model-building process can be reduced not only by acquiring additional well data and using geologically consistent processing techniques but also by applying a priori knowledge regarding anisotropic geology, rock physics, and geomechanical salt modeling (Rodriguez-Herrera et al., 2014) to constrain and validate model-building decisions. This is particularly important for orthorhombic processing as the model space is very large, but theory suggests quite specific requirements for the emergence of azimuthal anisotropy.

For many years, the geologic situation expected to be primarily responsible for transverse isotropy is one of ordered, layered sediments. This leads to a situation where propagation across layer boundaries is slower macroscopically than propagation within layers. This is easy to imagine expanded to a more general case in which there are one or multiple sets of aligned features, which may be sedimentary layers, faults or fractures, or other macroscopic or microscopic geologic imprints. In directions where propagation is uninterrupted by these features, effective velocity tends to be higher. As Tsvankin et al. (2010) note, arbitrarily oriented series of fractures are known by theoretical and numerical studies to yield approximately orthorhombic anisotropy. As major faulting is often associated with smaller-scale fracturing, a comparison of fault planes to a derived fast-velocity orientation in orthorhombic media should show a strong correlation and provide a valuable tool for selecting and confirming a model.

This supposition is demonstrated in Figure 5a with data from the Gulf of Mexico 3D orthogonal WAZ survey Declaration. The fast-velocity direction is fit by examining azimuthal variations in RMO for six angular bins, at each model grid point. Here it is overlaid as vectors on a structural semblance plot, intended to highlight faults and fractures. This is a useful large-scale validation for the α angle, and it is observed to match well the overall fault directionality, particularly away from the salt flanks, suggesting that the fast-direction fit is an appropriate one. Mismatch at this point of initial orthorhombic model building would lead to reinvestigation of azimuthal RMO distribution and a more appropriate way to characterize it. Instead, if α is consistent as in this case, uncertainty associated with the fast direction is better accounted for and effectively reduced.

To expand this validation of the directionality of orthorhombic anisotropy, we can also consider situations where we would expect strong degrees of azimuthally dependent velocity. Rodriguez-Herrera et al. (2014) show that, by conducting geomechanical modeling of a typical salt dome and its surrounding sediments, it is possible to construct an image of the preferentially directed stress field that is one of the known stimuli of orthorhombic anisotropy. For this well-studied case, azimuthal anisotropy will be oriented such that the fast direction of propagation will be radial from the salt dome, due to the compression of sediment

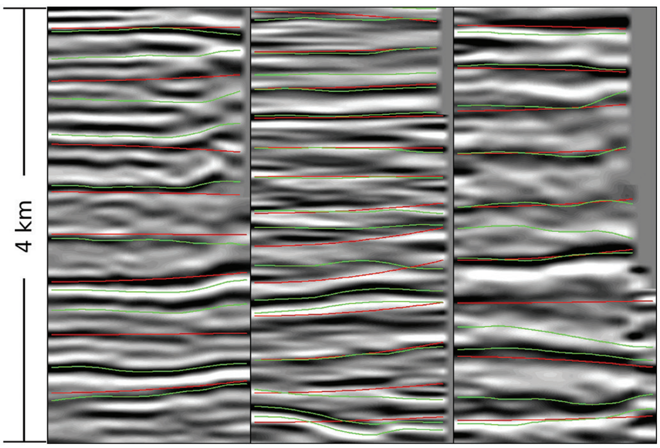

Figure 4. Example demonstrating parameterized hyperbolic curve fits to RMO (red curves) compared to nonparameterized offset-dependent RMO picking (green curves).

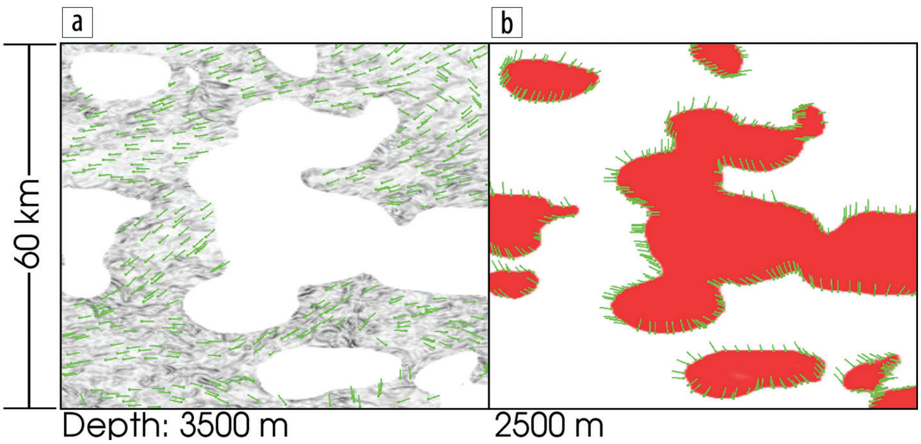

Figure 5. Vectors following the fast-velocity direction are overlaid on depth slices for Gulf of Mexico WAZ survey Declaration data. These vectors align well with faults and fractures highlighted in the structural semblance at (a) 3500 m, and they also correspond to geomechanical theory by radiating away from salt domes at (b) 2500 m.

during the intrusion of the salt. The amount of compression experienced by the nearby rocks will also relate to the amount of anisotropy. For these reasons, we expect to find high regions of orthorhombic anisotropy near salt features, with the fastest propagation directions oriented radially to salt domes.

This situation is confirmed by further examination of the Declaration project data. Figure 5b shows a shallower depth slice near the top of salt features, with the fast direction plotted as vectors near the edge of salt. Again, α directionality is as we expect, with the fast direction radiating from the salt features at their boundaries. To reinforce this, Figure 6 shows the differences in azimuthal RMO, with the strongest values found largely near salt flanks, which fits the geomechanical modeling results. The pattern of positive and negative RMO for each bin also suggests the same directionality as before, as negative RMO values show a faster velocity is needed, and these align with the azimuthal direction of each section as it is directed toward or away from the salt features.

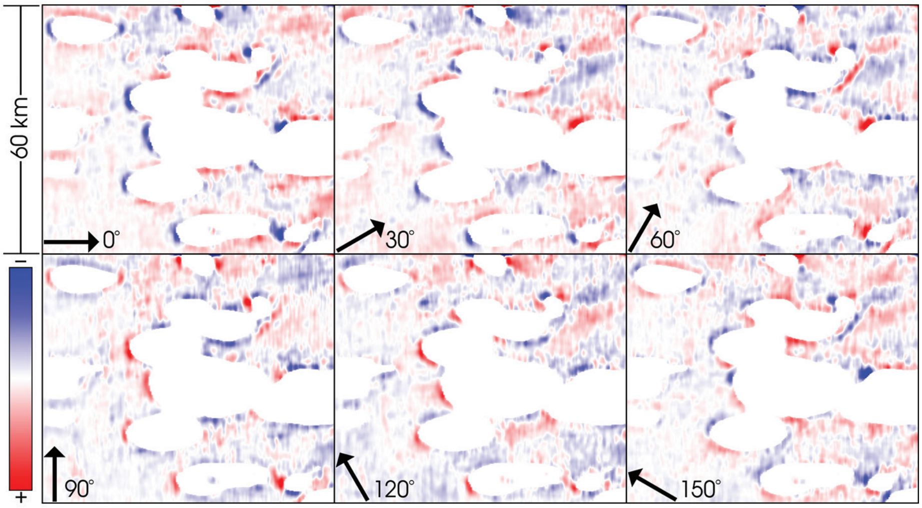

Figure 6. RMO is plotted for the six azimuthal bins used for processing the Declaration project. Azimuthal RMO differences are strongest near salt, as expected. For each azimuth, negative and positive moveout (corresponding to necessary positive and negative velocity updates, respectively) are also oriented to suggest that the fastest velocities are oriented radially from salt.

These types of checks, which relate data-driven parameterization or fits to observed and theorized effects, are invaluable for constraining uncertainties when processing orthorhombic data. The vast model space can be extremely ambiguous, but careful consideration of rock physics and geologic plausibility allows for decisions to be made between conflicting models, as well as providing verification of unconstrained results.

Conclusion

Orthorhombic models are required for many situations of current interest in the seismic community, such as salt vicinity model building and unconventional surveys for fracture detection and reservoir characterization. With the increasingly complicated model spaces required for more general anisotropic models, the uncertainty inherent in seismic model building multiplies rapidly. It is vital to be able to understand and constrain this uncertainty to create models that are valuable for their interpretability and that can be used to yield additional subsurface information, beyond typical imaging products.

Statistical measures of model interdependence and overlap, such as coupling matrices, yield important information regarding the model space and can help inform decisions regarding the use of a priori knowledge in generating a model. This knowledge can take several forms. Often, the most useful additional data for constraining anisotropic models can be obtained from current wells. Kinematic or marker well data, when combined with typical tomographic approaches, can constrain VTI models unambiguously. Complexity increases when moving to TTI, but these models again can be derived accurately by leveraging more a priori knowledge, in this case the structural information in stacked images and seismic attributes generated from this information. The IGT process is ideal for guiding interpolation and smoothing of model updates from the current stack, as it ensures their geologic plausibility and adherence to faults and observed structure. To most appropriately consider gather information, it is also useful to move to an advanced RMO picking process. This reduces the uncertainty in the model building by accurately describing all offset ranges without a dependence on curve parameterization, which may bias results. Finally, it is vital to compare theory and observations to model-building results to ensure their validity. The regimes in which orthorhombic anisotropy arises are well understood, and there are a variety of situations that can be analyzed to confirm that results match theory. The fast-velocity direction is frequently of use for this process, as it is known to follow preferential stress or fracture directions, and comparisons to geomechanical modeling results can help verify the reasonableness of the solutions.

By focusing on the trade-off in sensitivity between parameters, incorporating additional information from wells and geomechanical modeling, using image-guided preconditioning to reduce the inversion model space, and applying structural attributes to regularize and validate the derived model, we obtain a geologic structure-conformed model that is useful as an interpretable volume to supplement typical stack and gather seismic results. TLE

Acknowledgments

The authors would like to first thank TGS for permission to publish the data examples contained within. We also would like to acknowledge the efforts of Connie van Schuyver, Gary Rodriguez, Francis Sherrill, Dhananjay Tiwari, Zhiqiang Guo, Jean Ji, and Zhiming Li to help this paper become a reality, from initial discussion to final editing.

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