Anisotropic model building with wells and horizons: Gulf of Mexico case study comparing different approaches

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Summary

Anisotropic depth imaging with Vertical Transversely Isotropic (VTI) models has become dominant in the industry. However, anisotropic parameters for these models continue to be derived by very basic practices without use of tomography. Hanging a single profile of Thomsen parameters from the water bottom still remains the most common practice. In a simple structural setting, it is usually possible to focus the data and obtain a good image despite having a simple and unrealistic model for Thomsen parameters. However, depth positioning of such images is usually suboptimal. Better positioning requires more geologically plausible models. In addition, imaging in complex settings may require Tilted Transversely Isotropic (TTI) models. In this case study we construct several anisotropic models using approaches with increasing complexity and evaluate the model impact on image quality and ties to well data. We start with a "new default" model, where a single, smoothed, borehole-calibrated profile is hung from the water bottom, and then we progress to an "intermediate" model where a similar profile with more vertical details is propagated using major geological horizons. We finish with an "elaborate" model, where profiles from several wells are interpolated throughout the model using geologic horizons. We contrast all these models to an "old default" model derived without well calibration. We observe a generally steady improvement in well ties compared to the "old default" model, with the proportionally largest change coming from simple well calibration ("new default" model) and additional uplift coming from incorporating geologic horizons ("intermediate" model). Differences between "intermediate" and "elaborate" models are small, while switching to TTI models clearly helps resolve complex structures in dipping areas.

Introduction

It is well understood that seismic data do not constrain all parameters of an anisotropic velocity field. Therefore, Thomsen parameters are usually estimated from joint inversion of well and seismic data at borehole locations. Profiles derived at wells are extrapolated or interpolated throughout the volume and kept static; whereas, velocity is updated with tomography. It is a general expectation that more accurate and geologically plausible volumes of Thomsen parameters models may lead to better images and improved well ties. We apply different model building practices and quantify their impact on imaging and ties to well data.

Case study from Green Canyon, Gulf of Mexico

The area of interest is located in the northern part of the Green Canyon area, U.S. Gulf of Mexico. Seismic data consists of 100 outer continental shelf (OCS) blocks of wide-azimuth acquisition. Well data consists of checkshot and wireline log data for 18 wells. We consider five scenarios of deriving Thomsen parameters ε and δ:

1. "Old default VTI": single regional profile is hung from the water bottom, no well calibration.
2. "New default VTI": single, smoothed, borehole-calibrated profile is hung from the water bottom.
3. "Intermediate VTI": single, borehole-calibrated profile is interpolated using seven major horizons.
4. "Elaborate VTI": 18 profiles of ε and δ at wells are interpolated using seven major horizons.
5. "Elaborate TTI": same Thomsen parameters as "elaborate VTI", but symmetry axis is now perpendicular to bedding.

In the first scenario, profiles of Thomsen parameters plateau at ε=0.09 and δ=0.02; whereas in the second and third they plateau at ε=0.12 and δ=0.06 (Figure 1). At each of the 18 wells located in the areas of small geologic dip, we performed manual 1D layer-stripping inversion of seismic and checkshot data for Thomsen parameters ε and δ as described by Bakulin et al. (2010). The "intermediate" profile is obtained by averaging these 18 profiles without smoothing; whereas, the "new default" is obtained by averaging and smoothing (Figure 1). Smoothing removes high-frequency features that cannot be accurately propagated in the subsurface when only the water bottom

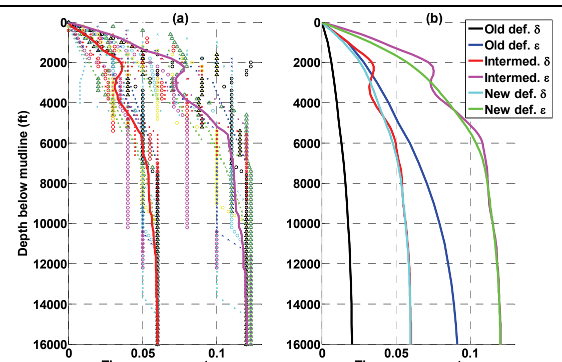

Figure 1: (a) Profiles of Thomsen parameters inverted at 18 well locations (various colors) together with their simple average (solid lines). (b) Profiles for scenarios 1-3: "old default" that uses no well calibration; "new default" is a slightly smoothed version of the average profiles from (a), whereas "intermediate" is a heavily smoothed version of the same profiles.

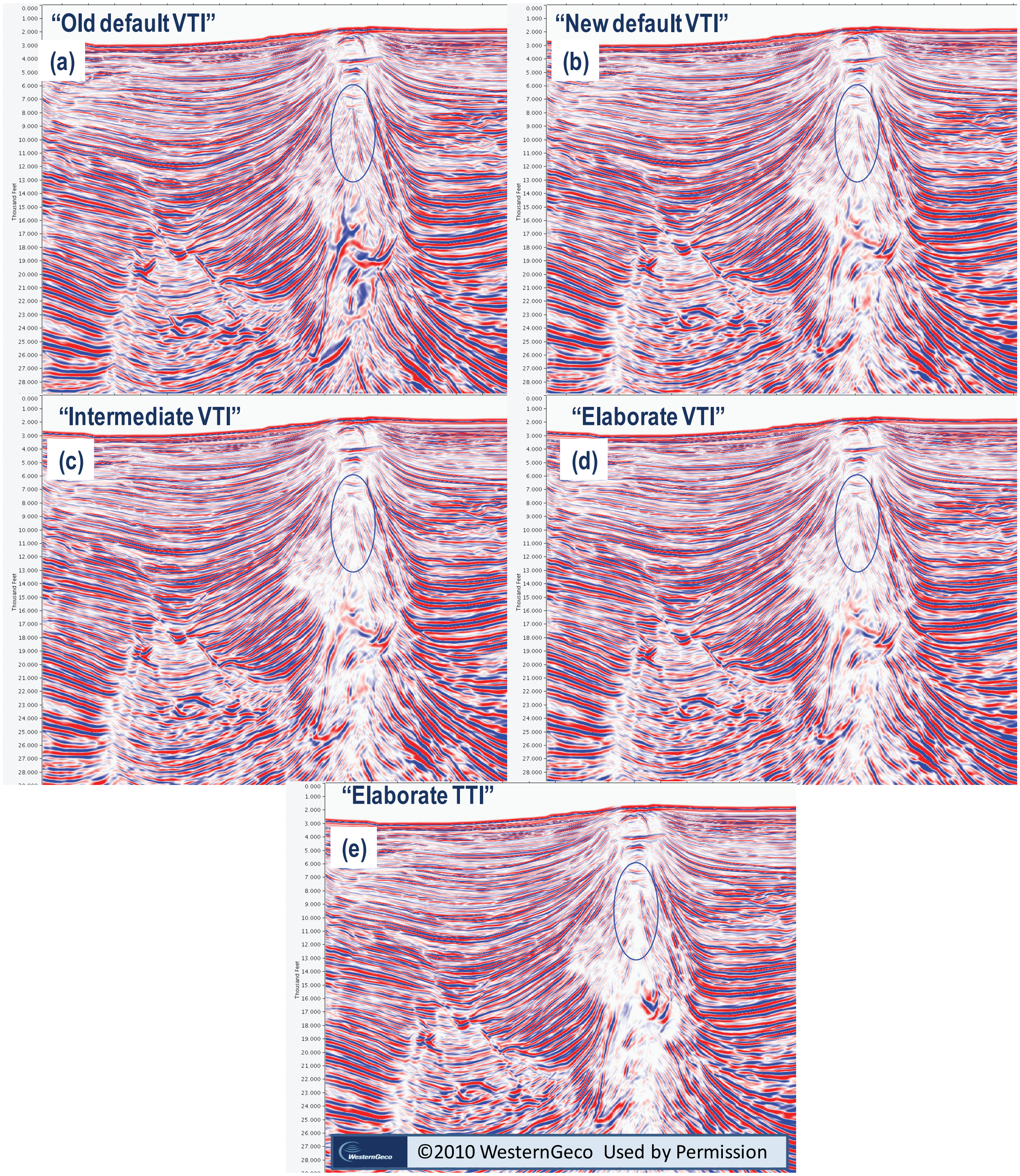

Figure 2: Images for each scenario after final tomography obtained by rapid beam migration: (a) "old default VTI", (b) "new default VTI"; (c) "intermediate VTI"; (d) "elaborate VTI"; (e) "elaborate TTI". (courtesy WesternGeco)

horizon is used for extrapolation. After generating the anisotropic volumes, anisotropic (VTI or TTI) tomography was run to update velocity along the symmetry axis (Woodward et al., 2008) and final images were produced.

Impact on imaging

Figure 2 compares images for each of the five scenarios after final tomography. All seismic events are shallower in Figure 2b-e compared to Figure 2a because of the slower velocities induced by larger values of Thomsen parameters. VTI scenarios 2-4 have similar focusing and mainly differ by vertical positioning. Larger horizontal shifts occur for the TTI scenario, thus making anticline-type structures wider. This leads to more realistic images in areas of high dip where VTI scenarios suggest geologically implausible crossing structures (Figure 2).

Well misties

To judge positioning accuracy of different models, we evaluate misties for 11 of the 18 wells used for calibration. Note that standard well-tie analysis is a highly interpretive process that relies on many assumptions that are often not satisfied in practice (Allouche et al., 2009). In addition, different water velocity conditions between checkshot and seismic surveys create unaccounted timeshifts manifested as poor well ties (Bakulin at el., 2010). For the majority of wells analyzed, we observe improved well ties as we progress to a more detailed subsurface model (Figure 3). The largest improvement occurs when the simplest form of borehole calibration is introduced, i.e., when moving from "old default VTI" to "new default VTI".

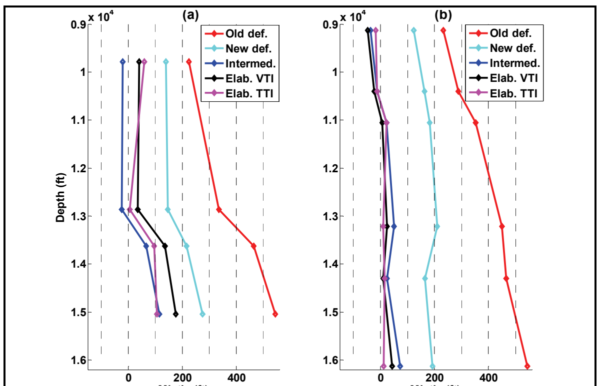

Figure 3: Well misties for various VTI and TTI model scenarios after final tomography for two representative boreholes in the Green Canyon area, Gulf of Mexico: (a) GC244, (b) GC197.

The second biggest improvement occurs when we propagate a single (but more detailed) profile according to subsurface horizons, i.e., when moving from "new default VTI" to "intermediate VTI". The "elaborate VTI" model is generally slightly more accurate than "intermediate VTI", but not uniformly so, and at places produces worse misties (Figure 3a). Figure 4 confirms that, with the exception of several outlier wells, we observe similar reduction in mistie for deepest horizon. Outlier wells suggest that low anisotropy values ("old default VTI") may be appropriate for the northern part of the area.

Movement of top salt horizon between various scenarios

While quantifying well ties at selected well locations represents a good point check, a more complete picture on depth movements between various scenarios emerges when we examine displacement of entire horizons using map migration. Figure 5 quantifies movement of the top salt horizon between "old default VTI" and "elaborate VTI". Mean value of the upward movement is about 400 ft (Figure 5b). The upward movement increases with increasing depth of the horizon (Figure 5c); whereas, areas of high dip may exhibit anomalously large vertical displacement due to additional small lateral movements as explained in Figure 5d. If we quantify movement of top salt

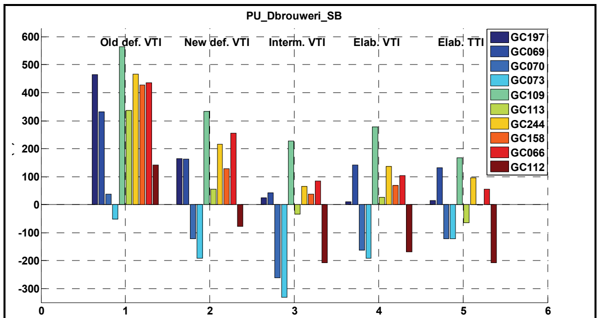

Figure 4: Mistie at deepest horizon evaluated in this study for a collection of eleven wells from Green Canyon, shown for all five VTI and TTI model scenarios. Observe an overall decrease in misties when moving to a more detailed subsurface model.

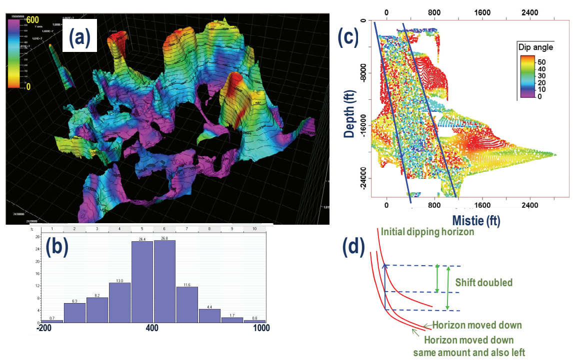

Figure 5: Difference (mistie) locations of top salt horizon in two images generated with "old default VTI" and "elaborate VTI" models after final tomography: (a) difference painted as an attribute on top of the salt horizon; (b) histogram of the difference; (c) difference as a function of depth color-coded by dip angle of the top salt horizon;(d) cartoon explaining why larger displacement is expected in ares of higher dip. Positive displacement corresponds to shallower depth of top salt in "elaborate VTI".

in other scenarios with respect to the "elaborate VTI", we generally observe significantly smaller displacements (Figure 6) as compared to Figure 5.

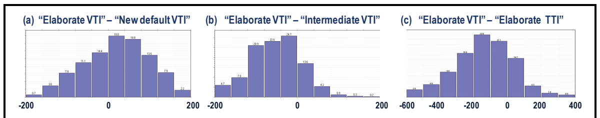

Figure 6: Histogram of the difference between locations of top salt horizon in "elaborate VTI" image and three other images obtained with different model scenarios. Positive number means that top salt in "elaborate VTI" case is shallower than in the other scenario of interest.

Validation with checkshots

Let us now validate constructed models using checkshot data. Figure 7 confirms that in wells used for calibration, the fit to checkshot data improves in more detailed models, although the progression of these improvements is slightly different than that observed for the misties for the same set of wells (Figure 3). More independent validation comes from wells in dipping areas that have not been used for calibration (Figure 8). Dip changes from 7º at 4,000 ft to 33° at 15,000 ft for the first well (Figure 8a); whereas, for the second, it is between 3° and 11º (Figure 8b). Again, however, we observe reductions in misfit when switching to borehole-calibrated models and adding horizons. The "elaborate VTI" seems a little worse than simpler models such as "intermediate VTI". The "elaborate TTI" is better than "elaborate VTI" for a well penetrating sediments with higher dip (Figure 8a), but slightly worse for a well with smaller dips (Figure 8b).

Discussion and conclusions

We compared several approaches to build anisotropic VTI and TTI models. These approaches ranged from no well calibration, to using a single, borehole-calibrated profile, to multiple well profiles. To propagate anisotropic parameters into the volume, we used the water-bottom horizon in simple cases and seven geologic horizons in the most detailed cases. We observed that the incrementally largest improvement in ties to well data comes from using a smoothed, single-borehole calibrated profile even though it is still hung from the water bottom ("new default VTI"). Additional improvement occurs when subsurface horizons are used for propagation of Thomsen parameters throughout the volume ("intermediate VTI"). Even though the "intermediate" model is still based on a single, borehole-calibrated profile, albeit with additional vertical detail, it produces reduced well misties and provides a better fit to checkshot traveltimes compared to the "new default VTI" model. Interestingly, the most detailed "elaborate VTI" model, where 18 profiles are interpolated using horizons, does not result in consistent improvement in misties compared to the "intermediate VTI" model. The "elaborate TTI" scenario, on average, seems to have slightly better fit to well data compared to "Elaborate VTI", along with producing more geologically plausible images in steeply dipping anticline structures. Therefore, incorporating more well data into model generation seems to provide more returns in TTI scenarios. Finally, we note that even the best models do not guarantee achieving a certain predefined fit to well data. Further improvement in the fit to well data would require additional tomography that jointly inverts seismic and well data, and perturbs both velocity and Thomsen parameters. Alternatively, tomography with uncertainty (Bakulin et al., 2009) can be used to find nearby models from nullspace that provide a better fit to well data, while keeping seismic gathers flat.

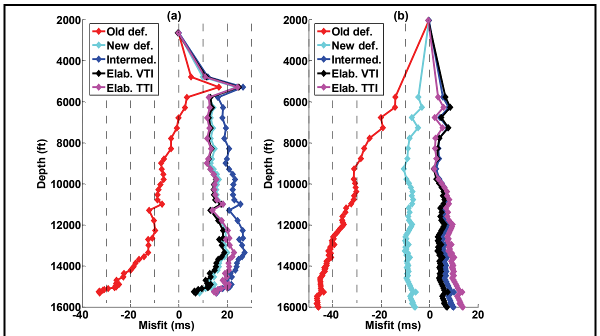

Figure 7: Checkshot misfit for various VTI and TTI model scenarios after final tomography shown for two vertical wells that have been used in calibration process: (a) GC244, (b) GC197. Misfit is a difference between ray traced in the model and experimental traveltimes.

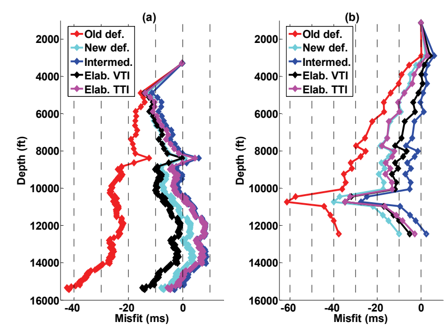

Figure 8: Same as Figure 7 but for two vertical wells in the dipping areas that have not been used for calibration: (a) GC248, (b) GC065.

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EDITED REFERENCES

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REFERENCES

Allouche, H., P. Thore, and T. Monnerie, 2009, Towards a better seismic to well tie in complex media: 79th Annual International Meeting, SEG, Expanded Abstracts, 1870-1874.

Bakulin, A., Y. Liu, and O. Zdraveva, 2010, Borehole-calibrated and Geologically Plausible Anisotropic Models Using Wells and Horizon-guided Interpolation: 72nd EAGE Conference and Exhibition, Extended Abstracts, C038.

Bakulin, A., M. Woodward, D. Nichols, K. Osypov, and O. Zdraveva, 2009, Anisotropic model building with uncertainty analysis: 79th Annual International Meeting, SEG, Expanded Abstracts, 3720-3724.

Woodward, M., D. Nichols, O. Zdraveva, P. Whitfield, and T. Johns, 2008, A decade of tomography: Geophysics, **73**, no. 5, VE5–VE11, doi:10.1190/1.2969907.