Optimized use of 3D VSP data in anisotropic model building for depth imaging

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Abstract

Adding extra data and information in the anisotropic earth model building process is very important to reduce results uncertainty. 3D vertical seismic profile (VSP) surveys rarely exist in exploration areas but are quite common in development and production areas. In this case study, we discuss and show how 3D VSP data can be used in two different stages of modern anisotropic earth model building workflows and demonstrate the value of incorporating 3D VSP information with a real data example from the Green Canyon area of the Gulf of Mexico. We first use a large 3D VSP survey to assess, quantify and compare the global accuracy of two existing tilted transversely isotropic (TTI) models, built before the 3D VSP information became available. Then, we fine-tune the more accurate model further by using the 3D VSP transit times as a data constraint in a joint tomographic inversion scheme.

Introduction

In recent years, anisotropic depth imaging with transversely isotropic models has become the dominant industry practice. However, building such models is a complex and challenging task, highly dependent on the quality and geometry of the available surface seismic data, and on the availability of additional data and information (Zdraveva *et al.,* 2014). In anisotropic media, many earth models will fit a single surface-seismic data set. This ambiguity means that integrating any available borehole-seismic information (e.g., check shots and VSPs of various geometries) becomes an important element of modern anisotropic model building workflows. Such information can be used in three different ways: 1) local parameter derivation around well locations (Whitfield *et al.*, 2002; Bakulin *et al.*, 2010); 2) global parameter fine-tuning in later iterations of tomography (Esmersoy *et al*., 2011), and 3) model validation by comparing modelled and measured transit times (Li and Hewett 2014; Zdraveva *et al.*, 2012).

The process of model validation is an integral part of earth model building (EMB) and updating workflows. It is the quality control and assurance step in which we verify that the earth model we have at any given stage of the workflow actually fits all of the available data. We carry out this process after any modification of the model parameters, either in the initial model building phase or in the iterative tomography (or full-waveform inversion) model update loop (Zdraveva *et al.*, 2012). In cases with no well control, validation is carried out by evaluating the migrated seismic images and updated property fields. The main criteria used are the model's ability to produce: (1) well-focused seismic images with minimum residual curvature on gathers, (2) geologically plausible images, and (3) model property fields that are free of artifacts and consistent with rock physics and geomechanics. In cases with well control, we make certain that the model is consistent with well measurements, quantified through traveltime misfit graphs and maps, mis-tie analysis, examination of borehole seismic images and gathers, and simple visual comparisons of well logs and property fields.

In this case study, we demonstrate the use of 3D VSP information as an earth model validation asset, which allowed us to assess and quantify the global accuracy of two TTI models created in two different EMB exercises before the 3D VSP information became available. We also show the improvement to the chosen model resulting from an additional iteration of joint tomographic inversion with surface seismic and 3D VSP data.

The area and the data

The area of interest is located over the Deep Blue prospect in the Green Canyon area of the Gulf of Mexico (Figure 1) and is covered by two vintages of towed-streamer seismic data representing wide-azimuth (WAZ) and full-azimuth (FAZ) multivessel acquisition geometry.

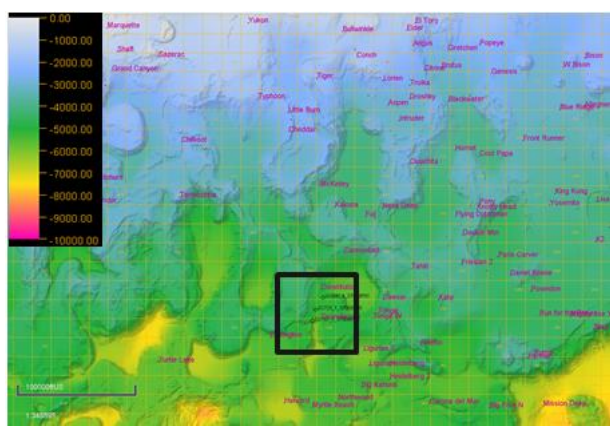

Figure 1 – *Base map of the main oilfield prospects located in the Green Canyon area of the Gulf of Mexico, shown on a background of water-bottom depth. The area of interest is marked with a black rectangle.*

The main well for analysis is GC723_1_ST00BP00 (marked in green on Figure 2 and 3), where several borehole seismic surveys exist.

- A seismic-while-drilling survey with dense measurements (sample rate 100 ft.) and total depth up to 32,000 ft, equivalent to a zero-offset VSP (ZO-VSP) – used during building and updating one of the models included in this study;
- A 3D VSP survey – used in this study;
- Two walkaway (WA) VSP surveys – not used in this study.

The 3D VSP geometry follows a spiral source pattern centred at Well CG723_1_ST00BP00 (Figure 2). It represents 6456 shot points spaced every 150 ft along spiral arms separated by 1000 ft, with a maximum radius of 17400 ft. The receivers are part of a 40-level, three-component receiver array, with levels separated by 100 ft, spanning downhole depths ranging from 18270 to 22170 ft (highlighted in purple on Figure 3).

Two additional wells, C680_4_ST02BP01 and GC767_1_ST00BP00, with very short check shots (only 15000 ft deep) are located inside the zone of analysis and inside the illumination cone of the 3D VSP data. Their wellbore locations are marked in red on Figure 2 and 3. The two check shots were used during model building and updating for one of the models included in this study.

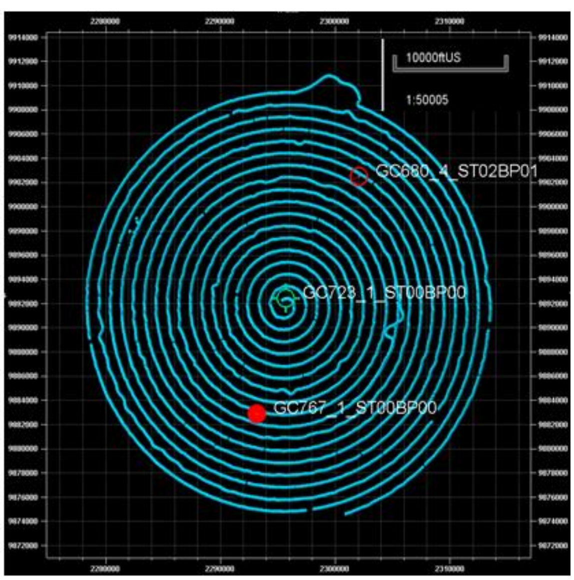

***Figure 2** – A map view of the location of the sources for the 3D VSP survey and the three wells in the area.*

The existing TTI models

Two models were available in the Deep Blue area. They were created for depth imaging at different times, utilizing surface seismic data of different vintages and geometry and covering much larger areas. The first (referred to as Model 1) was created in 2013 using only the FAZ surface seismic data, while the second (referred to as Model 2) used both WAZ and FAZ data sets during the model building and updating exercise in 2016. The model building strategy in both cases represents a variation of the anisotropic model building workflow described by Zdraveva *et al.* (2012) and involved multiple iterations of multiazimuth, multiscale common image point (CIP) tomography (Woodward *et al.*, 2008), with an additional full-waveform inversion step introduced between CIP tomography iterations.

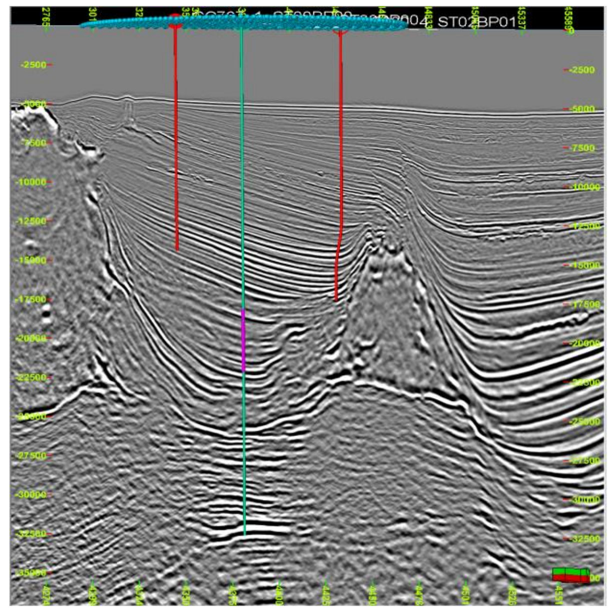

***Figure 3** – Seismic cross section through the three wells. The zone highlighted in purple is the depth interval where the 40-level tool was positioned.*

The main difference between the two EMB workflows is in the availability and use of well information, represented by ZO-VSPs, checkshots and well-marker mis-ties in the process. The Model 1 EMB exercise did not use any of the three wells in the area of interest. It updated only the compressional velocity along the symmetry axis (V_{P0}) during the extra-salt CIP tomography iterations, while keeping the anisotropic parameters δ and ε unchanged. In contrast, the Model 2 EMB exercise used all available ZO-VSP data during the initial model building phase. In addition, simultaneous V_{P0}, δ and ε updates were performed in a joint tomographic inversion scheme using surface seismic residual moveout, borehole-seismic transit times and well-marker depths.

The two models were independently validated and they both produced reasonably flat gathers for all azimuths, with plausible property fields. Figure 4 compares final images produced with the two models and corresponding seismic data sets in the neighbouring Tahiti-Tonga area (just east of the area of interest). It is evident that the image corresponding to Model 2 (Figure 4b) shows improved event continuity, especially at the deeper Wilcox and Top Cretaceous levels, and better definition of the deep thrust fault at the core of the fold. Another indication that Model 2 is better for imaging is that it yields a better tie to the well markers and a clearer picture of the overall shape of the structural closure at Tahiti, which will have implications for volumetric calculations and scenarios.

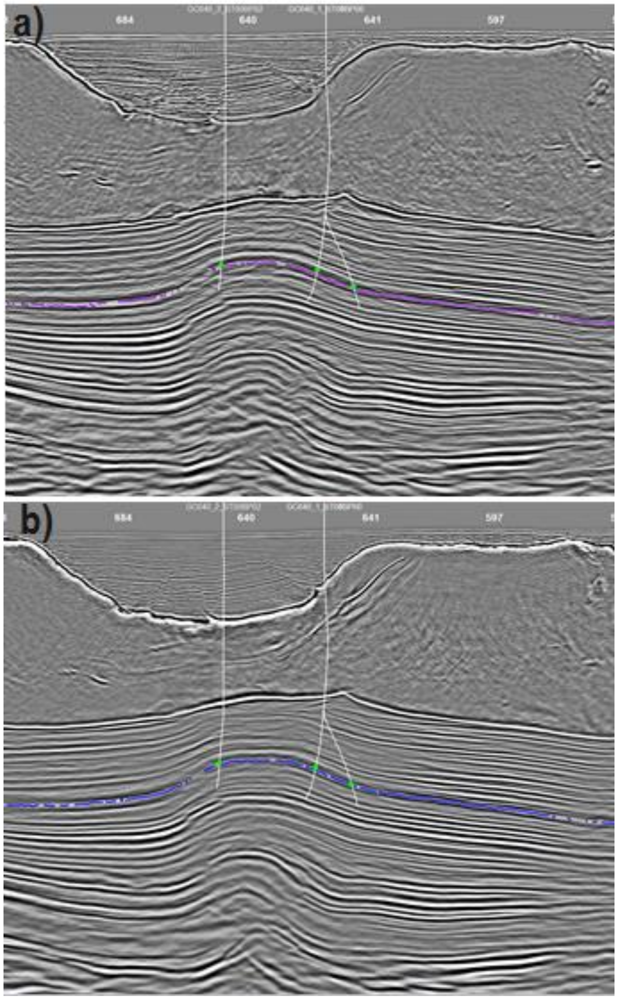

Figure 4 *– Final images with intra-Miocene horizon interpretation and two wells overlaid for: a) Model 1, and b) Model 2. Green dots indicate well markers.*

Model validation with 3D VSP data

To validate a model, we first simulate the source-to-receiver transit times (TT) corresponding to the actual VSP geometry, using a high-accuracy 3D TTI two-point ray tracer. Next, we compare the simulated TT to the TT picked from the real borehole seismic data, creating a difference measurement, called the TT misfit. This measurement quantifies the model accuracy, enabling the validation, because the TT misfit will be zero if the model is sufficiently accurate. The same procedure is used for ZO-VSPs, WA VSPs and 3D VSPs.

In this study, if the TT misfit values are larger than zero, velocity from the model is slower than the velocity in the real earth (or effective anisotropy is too high), and vice versa. For the 3D VSP TT calculations, we used a 6-ft tolerance for the source locations and rejected all rays passing through salt, keeping only those travelling through the sediment zone alone.

Ramirez *et al.* 2016 compared in detail ZO-VSP TT misfits and velocities at Well CG723_1_ST00BP00 for Model 1 and Model 2. Not surprisingly, Model 2 explains the borehole data much better than Model 1, because the Z0-VSP was used explicitly in the Model 2 EMB exercise. 3D VSP data, however, were not used during the model building process for either of the models, making the analysis of the 3D VSP TT misfits much more interesting. Figure 5 compares the 3D VSP TT misfit graphs from Model 1 (in red) and Model 2 (in gold), generated as a function of the distance (Figure 5a) and the azimuth (Figure 5b) from the wellbore to the source location. These types of displays emphasize the azimuthal component of the velocity errors.

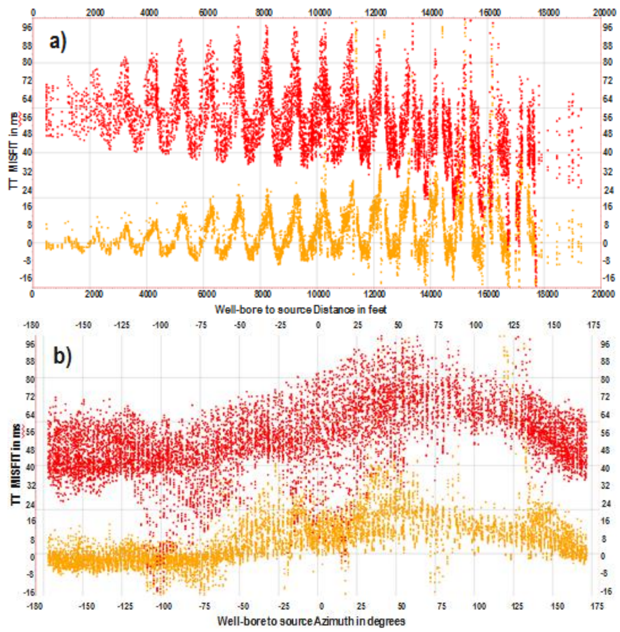

Figure 5 – *3D VSP TT misfit for Model 1 (in red) and Model 2 (in gold) as a function of: a) distance, and b) azimuth from the wellbore to the source location.*

The magnitude of the TT misfits indicates smaller velocity errors in Model 2: close to zero for near offsets and gradually growing to a range of -10 to 30 ms for offsets greater than 3000 m. In contrast, we observe a systematic bias of slower velocities (or too-high anisotropy) in Model 1, with TT misfit values centred around ~50 ms and ranging from <10 to >90 ms. In addition, it is evident that the magnitude of the azimuthal variation of the TT misfit is significantly reduced for Model 2. The two models show a consistent apparent slow velocity direction between 40º and 60º.

To finalize the process of validation, we migrated the pre-processed 3D VSP upgoing wavefield with reverse time migration (RTM) and created images and receiver gathers for the two models. As with our criteria for surface seismic data, we judge the model correctness based on the focusing of the images and the flatness of the gathers.

Figure 6 compares a group of three RTM receiver gathers migrated with the two models. We observe that Model 2 produced much better-focused images and flatter receiver gathers (Figure 6b) than Model 1 (Figure 6a).

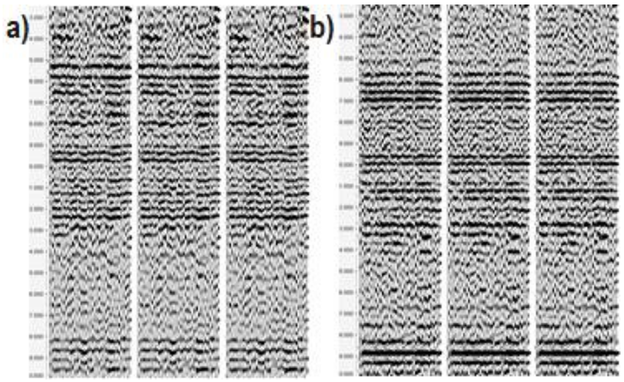

Figure 6 – *A group of three neighbouring 3D VSP RTM receiver gathers created with: a) Model 1, and b) Model 2.*

All types of the borehole seismic data analysis indicate that the velocity errors of Model 2 are smaller than those of Model 1; hence, Model 2 is more accurate for imaging over the Deep Blue area than Model 1. However, the 3D VSP TT misfit analysis suggests that Model 2 still has room for further improvement.

Model parameter fine-tuning with 3D VSP data

VSP TT can be used jointly with surface seismic data in tomography to constrain anisotropic parameters at and around well locations. Bakulin *et al.,* 2010 used such updates for anisotropic parameter derivation in a local sense. The same approach for simultaneous update of multiple anisotropic parameters can be used in a global joint tomography scheme to fine-tune a model that is already reasonably accurate. Woodward *et al.,* 2014 outline how to set tomography equations to solve simultaneously for V_{P0}, δ and ε updates, fitting a combination of surface-seismic data depth errors and borehole-seismic data traveltime errors. In such updates, in addition to geologic-dip-based solution shaping, a prior covariance estimate (based on relative expected parameter update values) is imposed on the model update as a soft constraint, where it does not contradict the data.

We refined Model 2 with one extra iteration of joint tomography using both the ZO-VSPs and 3D VSP TT as data constraints. Figure 7 shows a comparison between TT misfit maps (and corresponding histograms) for the shallowest receiver for Model 1 (Figure 7a), Model 2 (Figure 7b) and the refined version of Model 2 (Figure 7c).

We can observe that the TT misfit was further reduced and the newly derived model fits the 3D VSP data much better for all offsets and with almost no observable azimuthal variation. In addition, the refined model yielded better focused 3D VSP and surface seismic images.

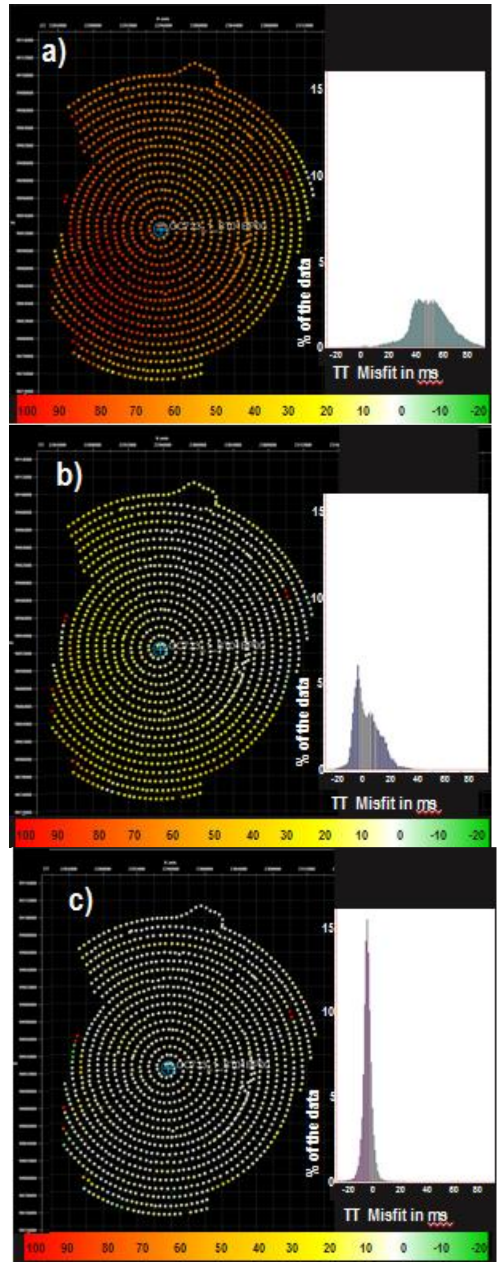

Figure 7 *– TT misfit maps for the shallowest receiver and corresponding histograms for a) Model 1, b) Model 2, and c) Model 2 updated with an extra iteration of joint tomography using 3D VSP TT.*

Conclusions

Use of 3D VSP allowed us to quantify and compare the velocity errors of two existing models. The Model 1 EMB workflow, without direct use of any of the ZO-VSP and checkshots, produced a model inconsistent with the 3D VSP. The Model 2 EMB workflow, making explicit use of the ZO-VSP and checkshot TT and well markers, yielded a model much more consistent with the 3D VSP. We demonstrated that model parameters for Model 2 can be fine-tuned and improved further in subsequent iterations of joint tomography, by adding the transit times from the 3D VSP as a constraint.

Incorporating 3D VSP data in EMB workflows for surface seismic imaging can significantly improve the model accuracy and quality of the final surface and borehole seismic images.

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