Evaluation and joint inversion of TTI velocity models with walk-away VSP
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Summary
Anisotropic model building is critical to the success of a prestack depth migration (PSDM) project. Well data are essential in developing the anisotropic models for these seismic PSDM projects. We presented a case study where a multitude of walk-away VSP (WVSP) data was used in evaluating the accuracy of the anisotropic velocity models. In particular, we integrated the WVSP travel times with the surface seismic PSDM residual moveout measured in migrated CIGs, in the joint inversion of the anisotropic model parameters. The resulting anisotropic model significantly reduces the mis-ties between the modeled and observed first arrivals in the various WVSP lines, in addition to much flattened CIGs and significant improvement in imaging.

Introduction
Seismic PSDM has proven to be the most effective geophysical imaging tool in delineating subsurface features in large scale. Its success is hinged on the accuracy of the velocity model. But it has been demonstrated that it has the capability to be used as the platform where the velocity model could be iteratively refined. As the PSDM imaging technology gets matured progressively, taking into account the anisotropic effects of the rocks are essential in imaging. This way, the seismic PSDM could potentially produce more accurate subsurface images which are geologically more consistent while tied to wells.

However, anisotropic parameters cannot be derived solely from the seismic data (Tsvankin, 2001). Some well data such as well markers, check shots and/or VSPs have to be used to determine the anisotropic parameters. There have been many studies on how the anisotropic parameters can be obtained from VSP data (Hsu et al, 1991, Grechka and Mateeva, 2007, and Bakulin et al, 2010). In particular, Bakulin et al (2010) extensively discussed how well information can be utilized in localized anisotropic tomography.

Here we present a case study in deep water Angola where we try to build a tilted transversely isotropic (TTI) model to enhance imaging of the subsurface structures and fault delineations, using a recently acquired longer streamer seismic survey. The TTI imaging work inherited a TTI model from a recently completed project where only short streamer seismic was used along with the integration of well data. The VSP data in the earlier project provided modest anisotropic values about 12% of delta and epsilon, but the seismic could not substantially help to enhance the anisotropic inversion due to its very limited offset range. During the model building period of this TTI imaging project, an extensive suite of VSP, including 4 WVSP lines were acquired in an appraisal well. Thus we were given the opportunity to evaluate the accuracy of the anisotropic parameters of the models in development. These new VSP data were quickly put in inversion to define the anisotropic parameters by the WVSP itself. We were also using the picked travel times from the WVSP lines, and quickly compared to the simulated one way travel times from the surface source to the subsurface receivers. Such comparisons gave us additional gauges as to the correctness of the models developed by then. We found there were modest to significant drifts or mis-ties between the modeled walk-away VSP travel times and the field observations. This was not surprising though as the PSDM gathers in surface show to be very flat. We were just given an additional dimension to gauge the velocity model. Noticing the existence of the significant drifts, we were able to jointly invert for anisotropic model parameters by incorporating the various WVSP travel time picks into the standard surface seismic residuals measured in migrated gathers.

WVSP travel times for anisotropic model evaluation
There are 2 wells with WVSP lines acquired which are used in this case study. Well H-2 has 2 WVSP lines with maximum surface distance 5000m between the surface source and borehole receiver, while the newly acquired H-3 well has 4 WVSP lines with sources offset by as much as 4400m in intervals of 25m. So there are a total of 6 WVSP lines which were incorporated into this anisotropic model evaluation and also for joint tomographic inversion.

First, we picked the one way first arrival travel times on the WVSPs. Figure 1 shows such an example. The red curve overlain on the WVSP profile is the picked first arrivals from the surface sources to the receiver in the wellbore. Plotting the various picked travel times together for a group of receiver levels as shown in Figure 2 can sometimes help us understand any local variations of the subsurface geology.

By the time the newly acquired WVSP travel times are available, we have already developed several anisotropic velocity models during the iterative PSDM and model building process. So, we can immediately use the picked travel times to compare with the computed travel times for
WVSP for TTI model evaluation and joint inversion

the same WVSP configurations assuming different anisotropic velocity models. To do that, it is most effective to calculate the drift between the modeled and the picked travel times. Figure 3 shows the mis-ties for 4 different velocity models on the same receiver level on WVSP source line 1. Notice the sources spread over about 9km of length on the surface. What is most obvious is that all of the models show generally small mis-ties, within 15ms in the center of the source line with VSP source offset of about 2000m which is equivalent to about 4 km of surface seismic source-receiver offset. This means that the velocity models are reasonably good in the near offset sense. The model with 3 digits only is the inherited model from a previously completed project where a very limited short streamer 3D seismic data set was used for the TTI anisotropic PSDM work. Even though 7 wells have been incorporated in that earlier TTI project, there were only two WVSP lines acquired in H-2 well. The anisotropic inversion result from those WVSPs in H-2 well showed modest anisotropic parameters in the range of low teen percentages for both the delta and epsilon. We can also notice that as models progress (bigger 4 digit numbered models are more advanced), the mis-ties generally decreases, especially in the far offset ends. This is expected, but we would expect a more efficient convergence. This figure also shows that almost all of the models predict the modeled travel times too large vs. the observed which corresponds to positive mis-ties, especially in the far offset. This indicates we might not have come up with the ε large enough.

WVSP travel times as input to joint tomographic inversion for anisotropic model parameter

At this juncture, we know that there are still quite some mis-ties between the modeled WVSP travel times and the picked ones, even for the then most recent model, m0313, though it shows its superiority over other earlier versions of the anisotropic models. And this observation holds true to the other source line WVSPs and other wells. It is natural thus to move to the next step: to invoke all the picked WVSP first arrival travel times, and inject them into the tomography inversion process. This is essentially a joint inversion problem by integrating these WVSP travel time picks with the seismic residuals picked on the PSDM CIGs. Bakulin et al. (2010) has performed some local anisotropic tomography using check shot data together with surface seismic data in VTI sense for a GOM case. Our methodology nevertheless extends it into TTI scenario using WVSP travel times. We think our WVSP data are even better and more suitable for anisotropic inversions, as the WVSP provides significant larger angle propagation information over the check shot whose rays primarily travel near vertical. It is of course much more challenging to invert for TTI anisotropic model parameters, as it has 5 parameters: the symmetric axis velocity $v_0$, the Thomsen anisotropic coefficients $\delta$, $\epsilon$ (Thomsen, 1986), and the angles and azimuth of the tilted symmetric axis $\theta$, $\phi$. We have to exercise extreme caution to avoid instability of the tomographic inversion. Generally, we do not invert for update to the tilted axis azimuths and dips. Instead we found it better to leave them to be updated directly from the PSDM volume. We also generally prefer to invert for the axis velocity first and then invert the Thomsen parameters in a chain of processes.

Figure 4 shows the mis-ties of the WVSP for the same receiver level and source line in H-3 well. For complete comparison, we also include the same group of WVSP travel time mis-tie curves for the earlier models. It is obvious that the mis-ties are all within 10ms for the joint inversion model m0336, even for the very far source locations which will be equivalent to about 9 km of surface seismic source-receiver offset. This is really encouraging.

As mentioned earlier, we have noticed similar observations on other WVSP lines. Figure 5 is an additional example from a WVSP line in well H-2.

From both Figures 4 and 5 we can easily see that the joint inversion has significantly reduced the mis-ties from as large as 65ms at the far offset to within 10ms. Nevertheless, the reduction in the near offset is much modest as the earlier models are reasonable in the near offset measurement. The net effect is a huge improvement in subsurface imaging.

Conclusions

We presented a case study where WVSP travel times provide another way to measure the accuracy of velocity models built during the anisotropic PSDM process. Though the PSDM CIGs are flat, WVSP travel times can still prove the lack of accuracy of the related velocity model. We further demonstrated that joint inversion of WVSP travel times with surface seismic residual measurement from PSDM CIGs can be very effective in reducing the mis-ties otherwise existing but not observed if no WVSP data are used. The jointly inverted anisotropic model thus produces better and geologically more consistent subsurface imaging.

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Figure 1: A WVSP line from H-3. The overlaid red curve is the picked first arrivals.

Figure 2: First arrival travel time picks on 4 different receivers on a given line, from well H-3.

Figure 3: One way travel time drifts for various modeled WVSPs at level 1 along source line 1 in well H-3
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Figure 4: One way travel time drifts for various modeled WVSPs at level 1 along source line 1 in well H-3.

Figure 5: One way travel time drifts for various modeled WVSPs at level 3 along source line 2 in well H-2
References


