To TTI or not to TTI?
Semi-Automated 3D Tomographic Velocity Analysis in the Canadian Foothills: A Case History

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Abstract

In this case study, we evaluate how velocity model building strategy affects imaging in the Canadian Foothills Thrust Belt. Two depth imaging processing techniques using different near-surface weathering static calculations and different velocity model building strategies are compared. In the first processing, we tackled the depth-imaging problem with the usual highly interpretive, "model driven" approach. We used an unconstrained diving-wave traveltime tomography to take into account the near surface effects. We then depth migrated the data from the topography, interpreted the seismic data to extract the main velocity boundaries and used a layer stripping approach (manual tomography) to build the anisotropic (TTI) velocity model. The differences between the pre-stack time migration image and the anisotropic pre-stack depth migration image were disappointingly small. With the second processing, we used a Tau-P refraction tomography, with constraints derived from up-hole times. The Tau-P model provided us with a more convincing near-surface velocity model that matched known geology and improved the resulting depth image. The data were depth migrated from the base of the weathering layer instead of the topography, decoupling the near surface effects from the depth imaging migration velocity analysis. Lastly, we used a "data driven" automated tomography velocity analysis to build the final velocity model. With this dataset, the isotropic "data driven" automated global tomography gave a superior image over the anisotropic "model driven" manual tomography. Using scanning to determine the anisotropic parameters has shown us that anisotropy varies spatially within the 3D volume. Defining variable anisotropic parameters via scanning is very difficult in

areas with significantly varying dip. A global approach that would integrate dip meter data, well formation tops and velocities would make the estimation of spatially varying TTI anisotropy easier.

Introduction

The Canadian foothills are the youngest and easternmost part of the Rocky Mountains. Their structural geology is composed of fold-thrust deformation sheets, tight folds and complex duplexes. Due to these steep-limbed geological structures, the large topographic relief, and the poorly resolved effects of the near surface, seismic imaging in the Canadian foothills requires depth imaging (Gray, 1997). Conventional seismic processing such as pre-stack time imaging (PSTM) does not work as well as depth imaging because many of the assumptions underlying time imaging are being violated in this geological setting. Unfortunately, our experience with most depth imaging projects has been that it is a slow and costly procedure with a poor benefit to effort ratio (Figure 1). PSTM remains the imaging workhorse despite its often poor performance, particularly for deeper formations. Since many wells in the Canadian foothills are drilled directionally, there is a strong need for clearly imaged, three dimensionally defined targets. The data set that we have used in this paper is a good illustration of such a situation.

In our first anisotropic depth imaging attempt, the velocity model building strategy used to derive the final velocity model was "model driven". The main velocity boundaries were interpreted on the prestack time-migrated volume and the upper part of the model was constrained by surface geology (bedrock) maps. The velocity model was then converted to depth and updated using a model building strategy defined in Murphy and Gray, 1999 or more recently Vestrum, 2004. Anisotropy parameters (TTI) were assigned to the Cretacous clastic formations on the basis of sandyness (ε=8%, δ=3%) or shalyness (ε=12-14%, δ=5%), to speed up the convergence of the depth imaging process. The velocities were adjusted to optimize the stacked image, and then adjusted so that the interpreted horizons tied the formation tops picked from well logs. The final anisotropic prestack depth migrated (PSDM) image reasonably tied the formation tops but is not well focused. The differences between the resulting anisotropic PSDM and the PSTM image were disappointingly small. These disappointing results are typical of what we have been experiencing with depth imaging in the Canadian Foothills independently of the contractor used to process the data. Perhaps, the problems are to do with the "model driven" velocity model building strategy used in depth imaging of the Canadian Foothills: do we necessarily need a highly interpretative approach for migration velocity analysis?

With this dataset, the complexity of the geological structures and the associated velocity field is such that it is unsuitable for a macro-model parameterization. This is because such a representation is over simplified and biased toward the interpreter's preconceived idea of the solution. We have therefore opted for a radically different approach to address the depth imaging problem: a "data driven" automated tomographic velocity analysis and a smooth representation of the velocity model (Woodward et al, 1999). This approach is routinely used to process data in the Gulf of Mexico for subsalt imaging (Albertin et al, 2001) but, to the best of our knowledge, has not been used for 3D anisotropic depth imaging in the Canadian Foothills.

Recent case histories (Stratton and Vermeulen, 2005 or Vestrum 2004) have demonstrated the impact of a specific type of anisotropy, namely tilted transverse isotropy (TTI), on the positioning of pre-drilling target locations. Sideslip and smearing are probably the most advertised effects of anisotropy, however the main difficulty with anisotropy lies in finding reliable estimation of the anisotropy parameters.

Can the Thomsen anisotropy parameters (Thomsen, 1986) be reliably assessed in the area of our survey? Will the anisotropic depth image really be an improvement over the isotropic depth image? In an attempt to answer these questions, we have taken a pragmatic but again data-driven approach.

We first generated an isotropic velocity model. Next, we analysed the misties with well data and used scanning around "regional values" to estimate average anisotropy parameters. As this approach was unsuccessful, for our next step, we plan to estimate the Thomsen parameters from well data and from a 2D line adjacent to the survey, with a simpler geological setting. This should generate a more accurate 3D anisotropic velocity model which should in turn produce a better image.

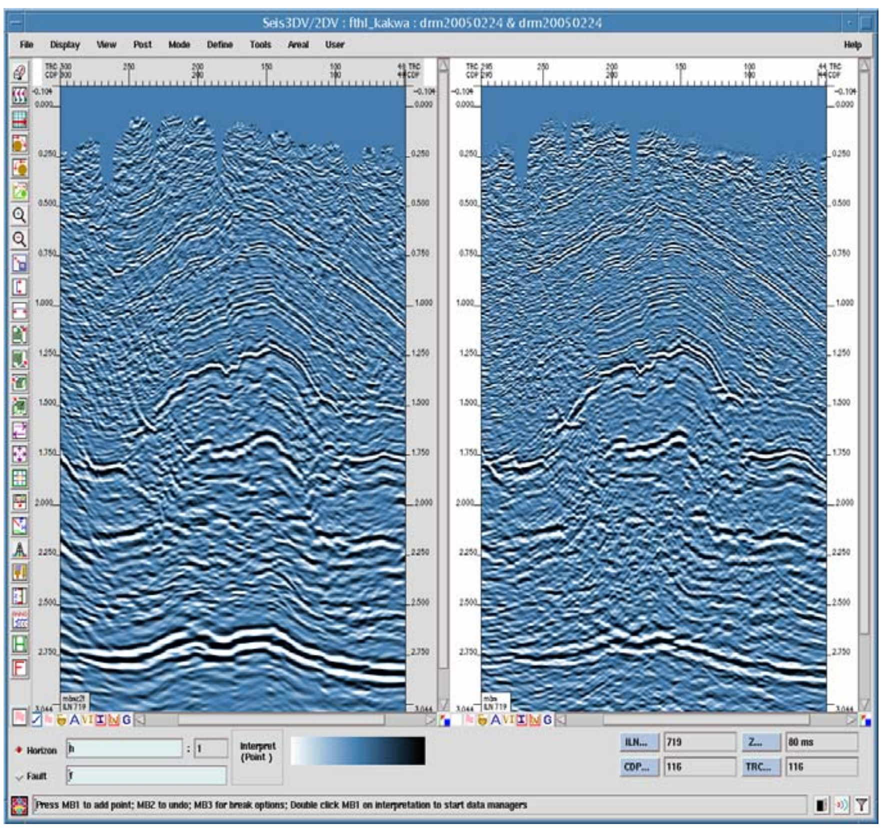

Figure 1. PSTM image on the right, Model driven Anisotropic PSDM on the left stretched back to time.

Near-surface and statics

"Knowledge of the near surface is essential in seismic reflection processing if deeper structures are to be imaged accurately." (Scales *et al*, 1990) Two very different methods were used to derive near surface static solutions. In the first case, diving-wave tomography was used (Zhu, 2001), and in the second, a Tau-P refraction tomography (Osypov, 2000). For the diving-wave tomography, source and receiver weathering statics were calculated from the surface to the 3600 m/s iso velocity layer (about 250 m below the surface). This choice was made on the basis of gather and stack continuity and shape of reflectors, compared to solutions from a GLI refraction method and a 400 metres iso-depth tomography solution. While all three sets of statics improved reflector imaging, the velocity depth models were not good physical matches to the expected Earth model. In the second processing, the Tau-P solution improved reflector imaging and the velocity depth model strongly correlated with surficial geology features, such as river valley fill, scree slopes, and bedrock outcrops (Figure 2). Source uphole times are generally considered to be unreliable, and so are often not included in the calculation of near-surface velocities. For this project, carefully edited uphole times were used to define the weathering velocity. Tau-P refraction tomography was run using first break picks for offsets 0 to 4500m. The output of the Tau-P tomography was a depth/velocity model of five layers, of which the first layer was the weathering layer with velocity defined from source uphole times. Only the first layer in the Tau-P tomography was used to calculate refraction statics. Deeper layers in the Tau-P tomography output depth/velocity model were included in the initial velocity model for depth imaging.

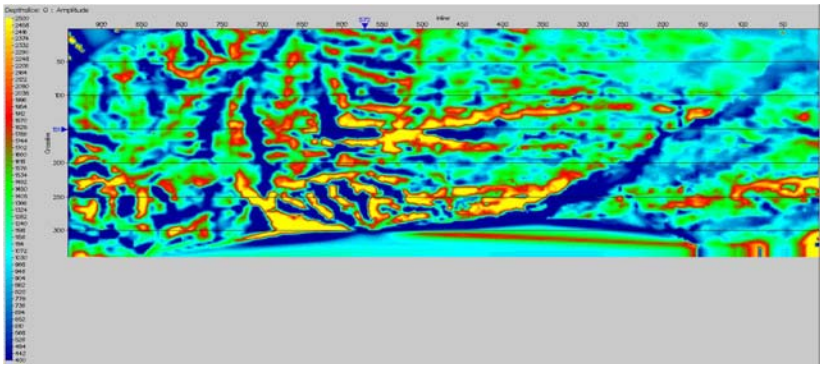

Figure 2. Weathering velocity model derived using the Tau-P tomography and up-hole times.

Migration from the base of the weathering layer

Near-surface velocity anomalies introduce both dynamic and kinematic distortions in seismic images. In time processing, the usual way to compensate for these distorsions is to apply surface-consistent static corrections. This is not a panacea. When a high velocity layer outcrops at the surface or for large offsets, the assumptions behind the static correction (vertical propagation within the near surface layer) are no longer valid. Gray and Marfurt, 1995 recommended that the data be processed directly from topography rather than from a flat or floating datum. This implies that one introduces the near surface velocity layer in the depth velocity model. In practice, the sharp velocity contrast that often exists between the weathering layer and the layer(s) immediately beneath it may cause instabilities in the ray tracing based traveltime table generation of the Kirchhoff migration. Smoothing of the velocity model is usually performed to reduce these instabilities but this may introduce an error on the original near surface velocity layer. Furthermore, in a global reflection tomography scheme, the near surface velocity layer needs to be constrained to avoid being altered at each nonlinear iteration. To avoid these issues, we applied a vertical correction to move sources and receivers to the base of the weathering layer and migrated the data from this new 'topographic' surface.

Model building strategy

There have been so many case histories demonstrating the impact of anisotropy that it can no longer be ignored in data processing (Isaac and Lawton 2004). Ignoring the anisotropy in the velocity field can potentially introduce errors of the same order of magnitudes as velocity heterogeneities (Wu, 1999). In the area of our dataset, the shallow part of the overburden is composed of dipping shale-dominated clastics which exhibit weak tilted transverse isotropy or TTI (Leslie et al, 1997). Weak anisotropic effects on the traveltimes can be modeled by a perturbation of the isotropy case (Chapman and Pratt, 1992). It should be noted that the effects of weak anisotropy on the traveltimes has a higher-order effect on the seismic velocities.

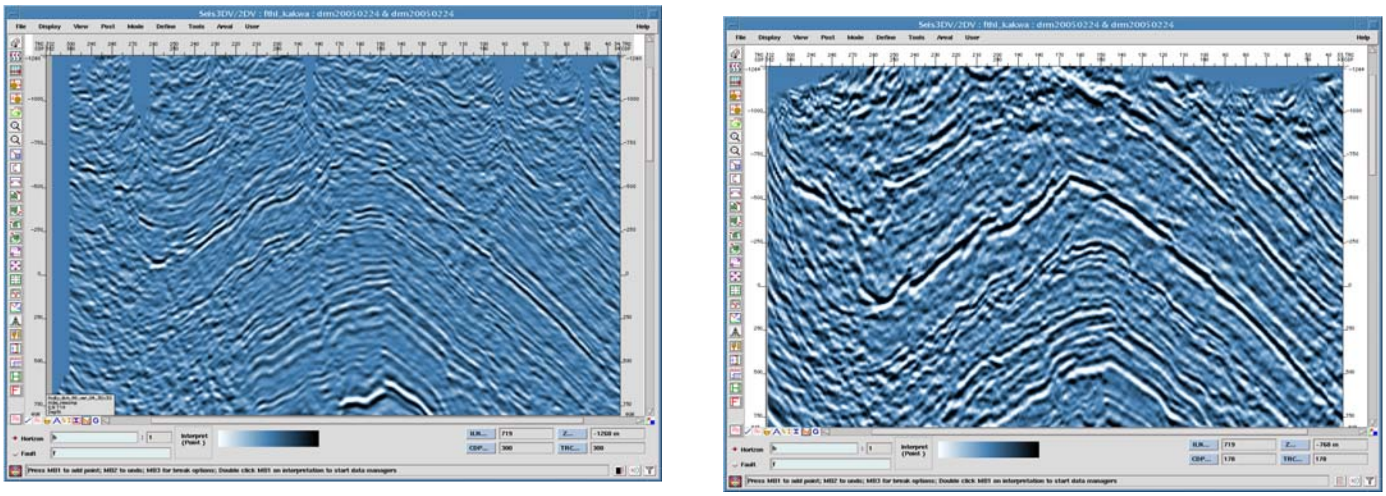

Figure 3. Zoom of the upper part of the same dip line. Left: "Model Driven" Anisotropic PSDM, Right: "Data Driven" Isotropic PSDM. Note the Isotropic PSDM much more clearly resolves the structure and faults, which are barely present on the Anisotropic PSDM.

This yields subtle changes in residual moveout that are difficult (if not impossible) to dissociate from residual velocity heterogeneity errors. Even though the isotropic depth image may be distorted, it is far superior to the PSTM image, reducing our exploration risks and satisfiying some of our operation needs. For the above reasons, to build our anisotropic velocity model, we will first recover the isotropic part of the velocity model that best focuses the depth image, and then tackle the anisotropy estimation as a perturbation of the isotropic case. This means that the isotropic velocity model will be slightly biased as the tomography will try to compensate for the unmodelled anisotropy effects (Pratt, 1993). We built the isotropic PSDM velocity model using a pure automated global tomography approach (Woodward, 1999), in which the length scales of the velocity updates are progressively reduced for stability and convergence. Due to the inherent limitations of the inversion, we applied a rather conservative velocity updating approach and did not allow the tomography to change the starting velocity field each time by more than 10-15%. Inversion velocity anomalies (mainly edge effects) were edited as soon as they appeared in the process, also helping to stabilize the inversion. For the deeper part, as this 3D dataset is too short in the dip direction, the tomography did not have enough data to adequately recover the velocity parameters. To overcome this problem, we flooded the velocity model beneath the Nordegg horizon (top of the carbonate) with a constant value of 5800m/s. A total of 8 non-linear inversions were performed to derive the final isotropic PSDM velocity model which is better than anisotropic depth imaging using layer-based velocity modeling in this situation (Figure 3).

Estimation of spatially variant anisotropic parameters (TTI)

The estimation of anisotropy parameters is not a trivial problem (Tsvankin and Thomsen, 1995, Pratt, 1993). Isaac and Lawton, 2004 proposed estimate the Thomsen parameters (δ,ε by scanning. Earlier, Vestrum in 1998 proposed using movies with various values of the Thomsen's parameters to detect the optimum depth image. In both cases, the TTI parameters do not vary spatially i.e average anisotropy values for an area are used. For our dataset, scanning with an increment of a few percent about the "regional values" of δ and ε on selected dip lines have shown us that, "optimum" values on the West and East flank of the anticline structure differ. This finding is consistent with the structural geology i.e. thrusting has affected the fine layering of the upper shaly layers and has changed the amount of anisotropy. The "optimum" values also vary along the strike direction. Although the TTI anisotropy is likely to dominate in the direction of primary thrusting, there is also minor thrusting and deformation in other directions that alter this effect. In the worst case scenario, the assumption of TI symmetry is no longer valid. Imaging and mistie inconsistencies (better well ties but leaving events over/under migrated) that could not be resolved by subsequent non-linear iterations of tomography, indicated to us that a more accurate estimation of the anisotropy parameters in the upper layers was necessary. We therefore chose to use a high quality 2D line adjacent to the survey on the East side of the main anticline structure. The estimated Thomsen parameters will be used to populate the 3D anisotropic velocity model. As earlier, we will analyse the misties with existing wells and the focusing of the image to refine the values of δ and ε. We will show at the conference whether or not the imaging of the deeper part is improved as expected.

Stack enhancement

Even in a noise free isotropic case, a tomography inversion is inherently unstable and needs to be regularized. The regularization is mostly achieved by applying smoothness constraints to the objective function which in our case is the minimization of the residual moveout errors. There is therefore an inherent tradeoff between the resolution of the velocity model and the flattening of the gathers that can be achieved. Inevitably, unsolvable residual moveout errors will be left in the CIG gathers output by the final migration. This means that independently of any other considerations (lithology variations affecting the character of a seismic marker for instance) the seismic horizons will not tie in perfectly with the well formation tops, nor will the stack image resolution be optimum. Although it is less expensive to output a stack volume directly from the migration, we recommend not to do so as post-migration, pre-stack processing can drastically enhance the final depth image (Sherrill, 2005). Stack enhancements were applied post-migration to optimize the final seismic image.

Conclusions

- Tau-P Tomography using up-hole times to define the weathering velocities gave a coherent near-surface velocity model that matched known geology and resulted in an improved depth image.
- With this dataset, isotropic depth imaging using global 3D tomography gave a better result than anisotropic depth imaging using highly interpretive, layer-based, manual tomography.
- With adequate signal-to-noise ratio, use of global gridded 3D tomography can give greater efficiency and very reliable results.
- Defining variable anisotropic parameters via scanning is very difficult in areas with significantly varying dip. Parameters that tie the wells can give poor imaging; parameters

that give good imaging often do not tie wells. A global approach that would integrate dip meter data, well formation tops and velocities would make the estimation of spatially varying TTI anisotropy easier.

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