PSGeologically Constrained Seismic Imaging in Andean Thrust Belts*

Rob Vestrum[1]

Search and Discovery Article #42530 (2020)**
Posted May 18, 2020

*Adapted from poster presentation given at 2019 International Conference and Exhibition, Buenos Aires, Argentina, August 27-30, 2019
DOI:10.1306/42530Vestrum2020

[1] Thrust Belt Imaging, Calgary, AB, Canada (rob@tbi.ca)

Abstract

Integration of geologic and geophysical data is essential to optimize seismic images in complex-structure areas. The seismic data in these areas have low data density, low signal quality, and complex geology. The conditions make it difficult to constrain the velocities needed to optimize the seismic imaging, so we rely on geological interpretation to guide and constrain the subsurface velocities for time and depth imaging. Seismic images from the Andes of Colombia and Peru show how geologic constraints improve the seismic imaging.

These data examples also show the trade-offs between accuracy and stability when we apply the different imaging algorithms: prestack time migration, Kirchhoff depth migration, and reverse-time migration (RTM). More accurate algorithms require a better understanding of the subsurface velocity structure, and are therefore more delicate and sensitive to velocity errors. Unfortunately, complex geology requires the higher fidelity algorithms to accurately image subsurface structures, and complex geology is where we have the most difficulty constraining the subsurface velocity model.

These thrust-belt data examples show how we apply the different algorithms to different geologic settings, and they illustrate the importance of geologic constraints to optimize the seismic image, regardless of the algorithm.

References Cited

Murphy, G.E., and S.H. Gray, 1999, Manual Seismic Reflection Tomography: Geophysics, v. 64, p. 1546-1552.

Vestrum, R.W., J. Vilca, and M. Di Guilo Colimberti, 2015, Creating a 3D Geologic Model for 2D Depth Migration in the Peruvian Andes: 77th EAGE Conference & Exhibition, IFEMA, Madrid, Spain, 1-4 June 2015, 5 p.

Geologically Constrained Seismic Imaging in Andean Thrust Belts

Rob Vestrum, PhD PGeo, Thrust Belt Imaging

Abstract

- **Seismic data in structured land areas have severe limitations**
- **Geologic interpretation and human collaboration can overcome these limitations**
- **Increased accuracy of an imaging algorithm also means increased sensitivity: PSTM → PSDM → RTM**
- **Examples from Colombia and Peru show how we resolve these issues through geoscience collaboration**

Introduction

Difficulties with land seismic data in structured areas:

- Low data density
- Low signal-to-noise ratios
- High geologic complexity

The subsurface velocity model is highly underconstrained by the seismic data, so automated methods for deriving the subsurface velocities required for seismic imaging are highly unstable. We use a workflow similar to Murphy and Gray's (1999) manual-tomography method to leverage the experience of the processor, interpreter, and geologist to overcome these limitations.

Geologic constraints are required to optimize the seismic image.

Once we have a geologically constrained velocity model, we have a variety of seismic-imaging algorithms, each with advantages and disadvantages. Generally, more advanced imaging technology requires more accuracy in the velocity model to optimize the seismic image. Simplifying assumptions and averaging the various velocity offers robustness in exchange for accuracy.

Velocities for PSTM

Since we do not know the subsurface velocities, we migrate the data across all possible subsurface velocities. We can then interactively scroll through the resulting seismic images in search of reflector continuity. Understanding the geology is key to identifying geologic shapes from seismic noise.

Model-building method for PSDM

Structural cross-section, regional lithology, and interpretation of the major velocity boundaries on the PSTM image are key inputs for the initial depth-migration velocity model.

Following the workflow in Figure 1, we migrate the gathers using the interpreted velocity model, and ask the tough questions:

- Have we optimized the seismic imaging?
- How does the image compare to the time migration?
- Do the depths of seismic reflectors tie the depths a the well?

Early in the process, the answers are mostly "no". We iterate until we can say "yes" to most or all of these questions. Resulting model examples are shown in Figures 2 & 5.

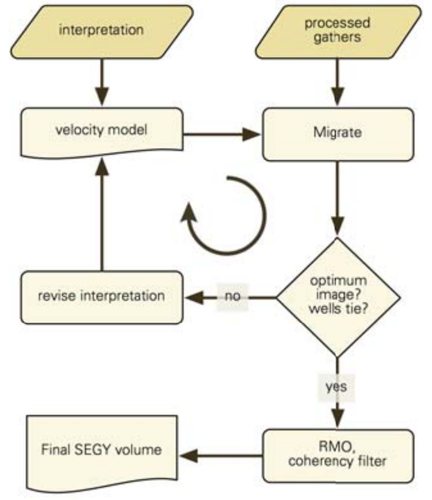
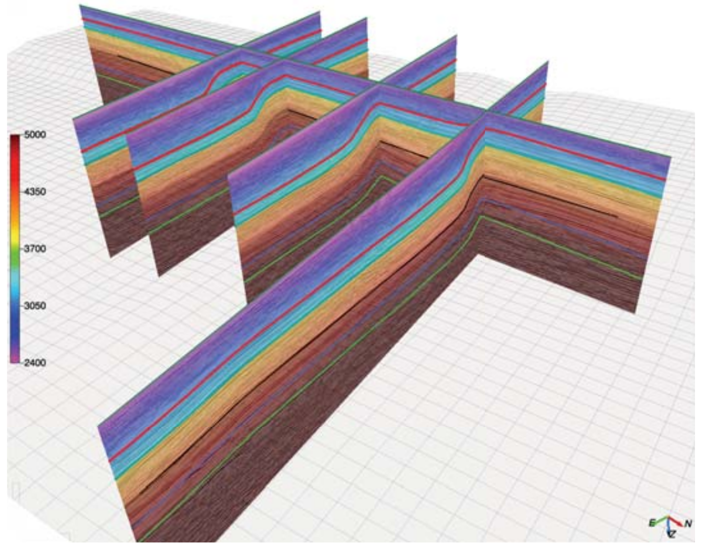


Figure 1: Workflow for PSDM velocity model building. Inputs are the structural interpretation and the processed seismic shot gathers. Iteration around the re-interpretation circle results in optimized image

3D model building for 2D data

In searching for additional model constraints, we built 3D models for 2D seismic-imaging projects to have more consistent velocities across a block and further constrain the model. Figure 2 shows an interactive display of 3D model-building software used to build the mononclinal velocity model for a 2D seismic-imaging project in the Ucayali Basin of Peru (Vestrum et al, 2015).

Figure 2: Velocity model using a 3D velocity model to migrate 2D lines



With the unconstrained nature of 2D land seismic data, there is a certain amount of ambiguity or non-uniqueness in the velocity-model-building process. The velocity model was constrained by two wells at either end of the exploration block. Constraining the velocity model in 3D further reduced ambiguity, and the resulting prospect maps were more consistent across the block. The interpretation team was more confident in the relative highs and lows of the structure from 2D line to 2D line, knowing the velocity variability was minimized.

Results

How much is pull-up, how much is structure?

The images to the right show the time (Figure 3) and depth (Figure 4) images from a line on the block. The dashed line indicates the regional trend of a deep reflector on the low side of the monocline. On the time section (Figure 3), the lateral velocity variation across the outcrop of the monocline resulted in a velocity pull-up on the deep reflector. The structural trend is amplified by the velocity pull-up.

Correcting for the lateral velocity variation across the monocline in the depth image (Figure 4) resulted in minimizing the effect of the pull-up. The resulting depth migration imaged more detail beneath the monocline and above the dashed line.

Figure 3: PSTM seismic image showing velocity pull-up below monocline

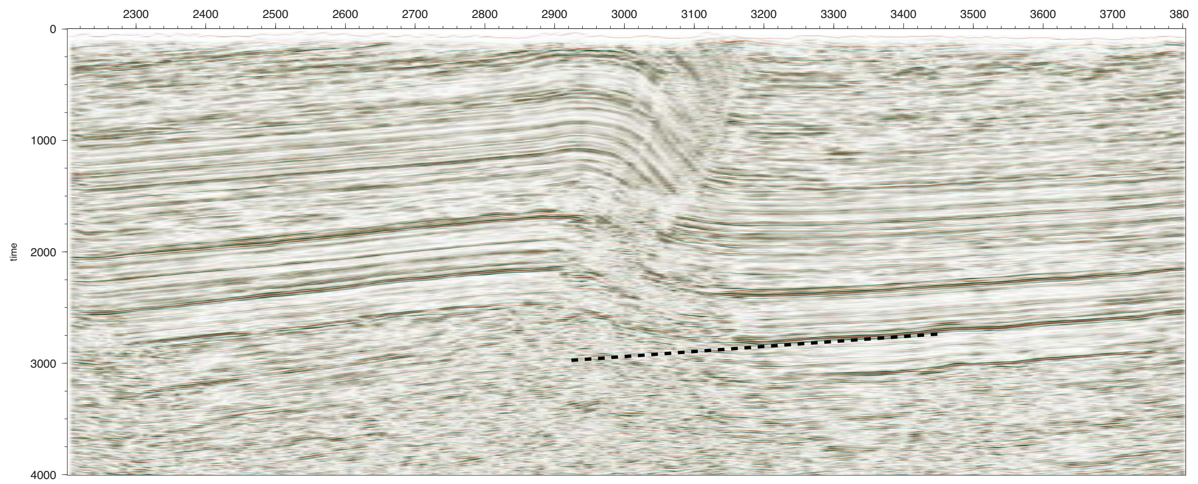


Figure 4: PSDM image. Minimized pull-up shows remaining structure above dashed line

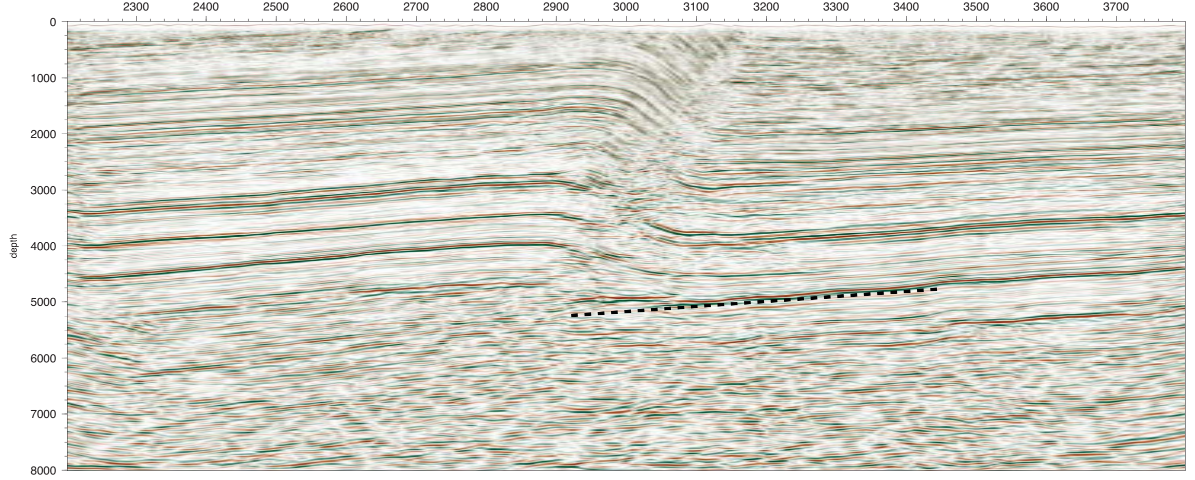
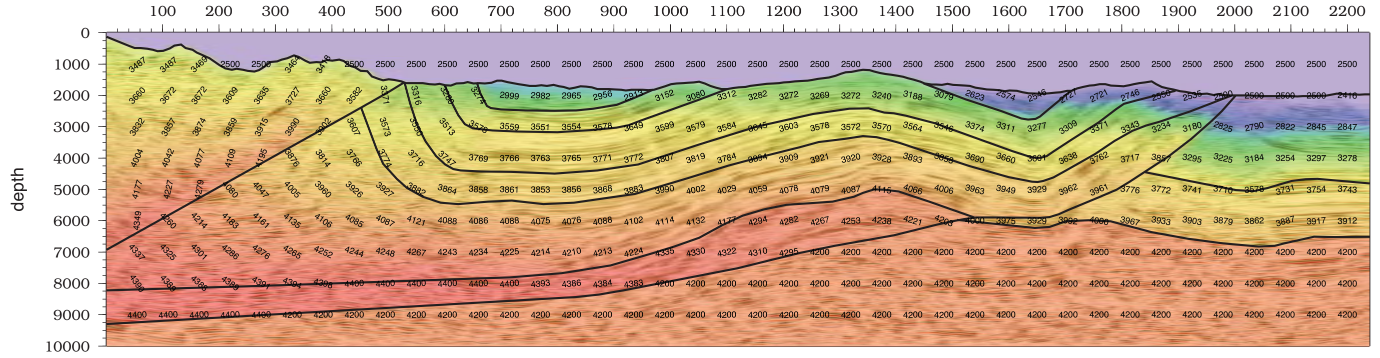


Figure 5: Velocity model for PSDM and RTM created from the geologic structural model and seismic diagnostics



Imaging algorithms

The seismic-imaging toolkit has a range of algorithms with strengths and weaknesses. This imaging project from the Llanos foothills of Colombia illustrates these trade-offs between imaging algorithms.

- Prestack time migration (PSTM)
  - Kirchhoff migration using RMS average velocity from surface
  - Averages through near-surface effects
  - Requires minimal *a priori* knowledge
  - Velocities are unconstrained and often do not correlate with geology
  - Robust method gives highest probability of creating image
- Prestack depth migration (PSDM)
  - Kirchhoff migration uses raytracing through geologic model
  - Corrects for near-surface effects
  - Requires *a priori* knowledge for structural velocity model
  - Velocities that correlate with geology
  - Delicate method useful for scenario testing and risk assessment
- Reverse time migration (RTM)
  - Depth migration uses wave propagation through geologic model
  - Corrects for more wave-propagation effects
  - More delicate than Kirchhoff, but performs better below large velocity inversions like sub-thrust imaging

The higher-fidelity algorithms that correct for more wave-propagation effects require higher accuracy in the subsurface velocity model.

Results

The second dataset, shown in Figures 5-9, is a 2D seismic line from the Colombian Andes.

Reprocessed PSTM (Figure 7) shows improvements in deeper structures that result from improved near-surface corrections, more detailed velocity analysis, and coherency enhancement.

PSDM image (Figure 9) resolves the imaging of the syncline in the hangingwall of the major thrust (CDP 1500-1900). There is also more structural detail in the footwall of the thrust, below the syncline.

RTM image (Figure 9) shows further imaging improvement in the imaging below the fault and below the syncline. In the area to the left end of the section, in CDP ranges 100-400, however, the velocity-model ambiguity resulted in a degraded image on the RTM as compared to the Kirchhoff PSDM in Figure 8.

Conclusions

No matter which imaging algorithm is used, the more geophysical, geological, and regional constraints we can apply to the subsurface velocity model, the more we may optimize the seismic imaging.

References

Murphy G.E. and Gray, S.H., 1999, Manual seismic reflection tomography, GEOPHYSICS 64: 1546-1552.

Vestrum, R.W., Vilca, J., Di Guilo Colimberti, M., 2015, Creating a 3D Geologic Model for 2D Depth Migration in the Peruvian Andes, 2015 EAGE Conf & Exhibition, Madrid, Spain.

Figure 6: Legacy PSTM seismic image

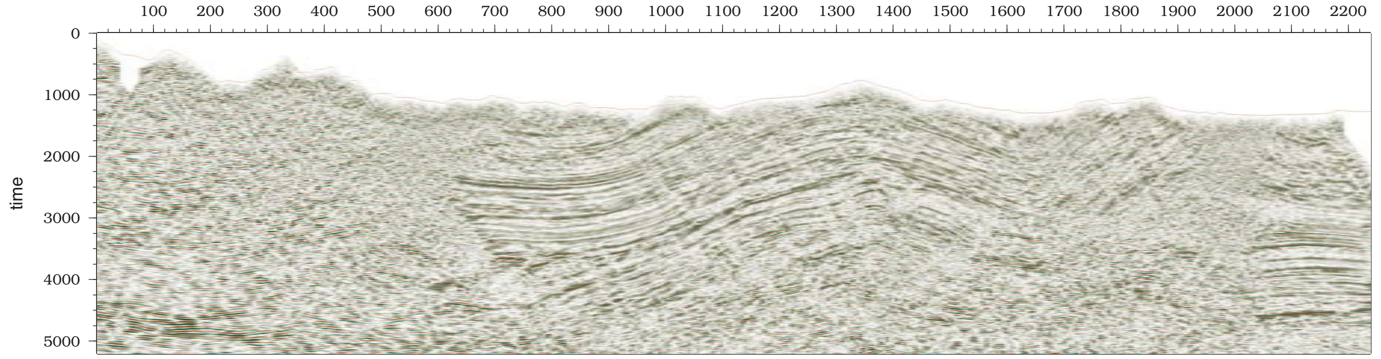


Figure 7: Reprocessed PSTM seismic image with focus on subthrust structures

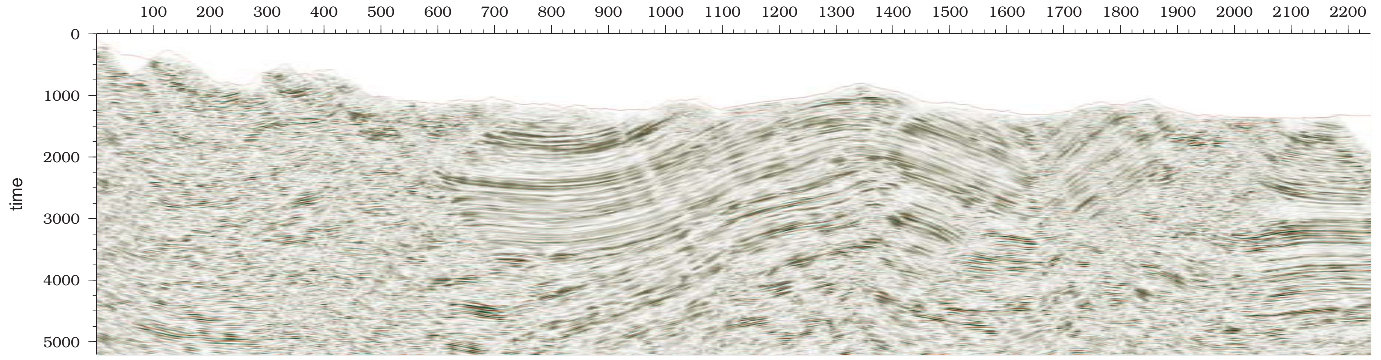


Figure 8: PSDM image using the velocity model in Figure 5. Resolves additional detail in the deep section

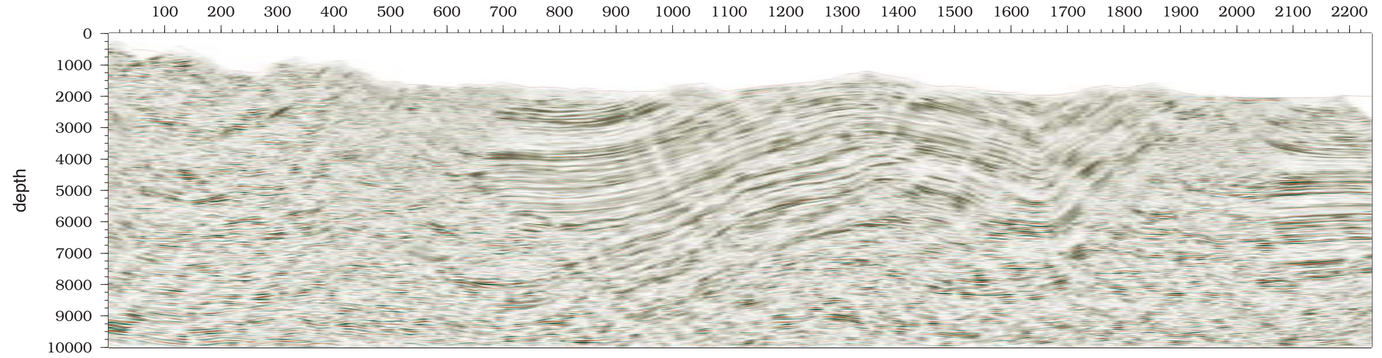


Figure 9: RTM image using the velocity model in Figure 5. Further improvements in the deep section, trade-offs on left side