Challenges in Seismic Imaging in Fold and Thrust Belts

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Thrust Belt Imaging

Summary

This presentation develops the themes presented in Chapter 2 of the AAPG publication, Andean Structural Styles: A Seismic Atlas, and presented at the AAPG ICE 2022, using data examples from the foothills of the Canadian Rockies.

Seismic data in areas like the Canadian foothills have unique challenges that break traditional seismic-imaging methods designed for offshore exploration. Reducing exploration risk in these basins requires a workflow tailored to the geologic setting. The under-constrained nature of the seismic data requires tight integration with the structural geologist.

Seismic imaging is a vital tool for mapping complex geologic structures. The method of imaging the Earth's subsurface with seismic waves is powerful, and it has certain limitations—especially when deployed in complex-structure land areas like the mountain ranges and high plains. Understanding the technologies involved and how they are applied to this specific geologic setting will improve our understanding of the risks and uncertainties involved in the interpretation of structures on seismic images.

Seismic data in thrust-belt environments are typically low data density and have low signal-to-noise ratios, all while attempting to image complex geologic structures. The data are acquired over rough topography with laterally varying velocities from the surface down. If the near surface is the lens through which we image the subsurface, our lens is bumpy and distorted. These are the challenges of seismic processing in fold thrust belts, and decades of technology development have gone into facing those challenges, from weathering corrections for the near-surface, to advance migration algorithms that can image below major thrust faults.

Understanding structural styles and other geologic constraints are key levers to overcome the limitations of seismic data under these difficult conditions.

Seismic imaging methods

Seismic migration moves the reflection energy into the position of the reflectors that created those reflections. The migrated section is the final interpretable image. The seismic image is dependent on the velocity that waves propagate in the subsurface. If we already knew the subsurface velocity structure, then we would have little need for the seismic image to define our subsurface structure. In some geologic settings, the redundancy of the seismic data is sufficient for automated algorithms to obtain the velocity structure that optimizes the seismic imaging with minimal human input. Unfortunately, in complex-structure land areas like the foothills of a major mountain range, the signal-to-noise ratios on the seismic data, the low data density in the near surface, and the geological complexity all combine to make automated velocity-estimation methods unstable and ineffective. The nonuniqueness of a numerical solution often results in erratic and nongeological artifacts in the inverted model. So, we rely on our geological understanding of the region, and we use a strategy of geoscience integration to use interpretive constraints on the subsurface velocity structure for time and depth imaging.

Prestack time migration (PSTM)

One way to address the problem of velocity uncertainty is with simplification. PSTM is the most common simplification to the subsurface imaging problem. PSTM assumes that we can approximate all velocity effects above our target reflector by an averaged velocity often referred to as root-mean-square (RMS) velocity. This assumption breaks down in the case of complex geologic structure, but, in practice, this simplification averages through imaging effects above each subsurface reflector. PSTM ignores seismic wave-propagation effects like refraction, which could result in errant reflector positions. On the positive side, PSTM is a robust method that allows the seismic imager to focus on optimizing individual reflectors without *a priori* knowledge of the subsurface velocity structure.

The redundancy in the seismic experiment gives us the ability to analyze the velocities on prestack, but low signal-to-noise on the prestack gathers and high geologic complexity often make traditional velocity-analysis methods difficult and automated velocity algorithms unstable. To overcome these limitations, the most common method for picking PSTM velocities in complex-structure uses the constant-velocity scanning method to pick RMS average velocities from the surface to each imaging point.

Figure 1 illustrates the process of picking velocities on constant-velocity scans on a 2D seismic dataset from the foothills of the Canadian Rockies (Skuce 1995). The seismic images in Figures 1a to 1c are constant-velocity PSTM images. The process is to run forty or more constant-velocity prestack migrations and interactively scan through the resulting seismic images, seeking the velocity that optimizes each seismic reflector. We may then pick the optimum velocity for each seismic reflector. In real-time, as each velocity is picked, the software creates and updates a composite image, combining a patchwork of the velocity panels at each pick location. Figure 1d shows the composite image of picks made on velocity panels. Note that the composite image of the velocity panels shows optimized imaging throughout the section, from the shallow reflectors that image at low velocity (Figure 1a) to the deeper reflectors optimized at higher velocity (Figure 1c), and the reflectors imaged at velocities in between (Figure 1b).

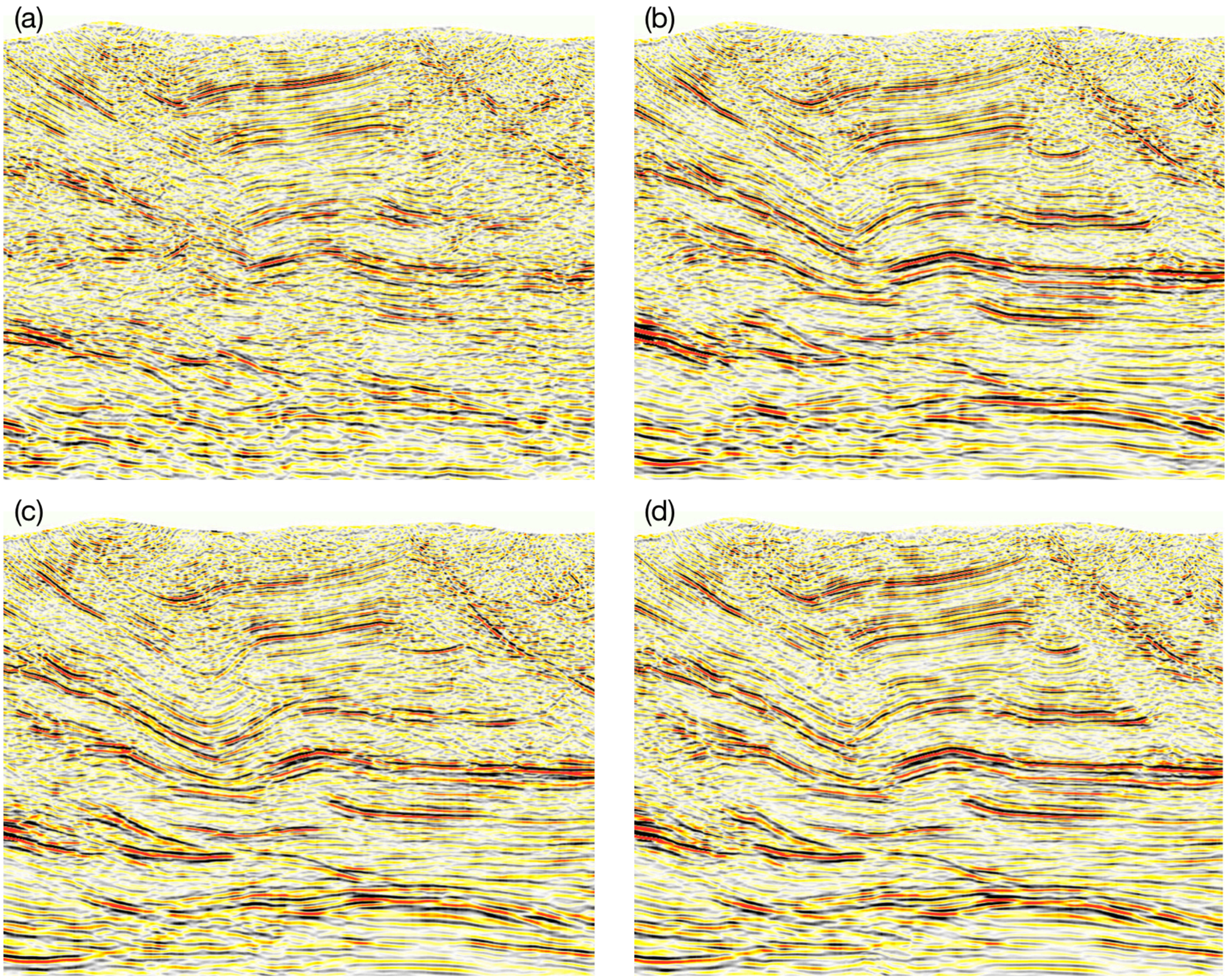

Figure 1 Constant-velocity PSTM images with (a) velocity of 3400 m/s, (b) 4300 m/s and (c) 4800 m/s. The composite image of velocity panels from each pick is shown in (d).

With this interactive approach to seismic imaging, understanding the structural style we expect to image is a key reality check for picking the optimum seismic image.

Prestack depth migration (PSDM)

The fundamental difference between time and depth imaging—PSTM vs PSDM—is in the simplification of subsurface velocity structure. As described above, the simplifying assumptions in PSTM average through overburden velocity effects. The velocities may not make geologic sense, but they are simply imaging parameters used to optimize the subsurface image. In contrast, PSDM works to correct for the wave-propagation effects that are averaged and simplified by PSTM. Instead of finding an averaged velocity at each imaging point, the PSDM calculates traveltimes through an Earth model, correcting for refraction and anisotropy effects from the surface down to each reflector position. Instead of a non-geological averaged velocity, PSDM requires a geological velocity model.

Instead of robustness, PSDM is delicate and highly sensitive to velocity errors. The delicate nature of PSDM is unfortunate because it is more difficult to optimize the velocity model for PSDM than it is to find optimum imaging velocities for PSTM, but the delicate nature of depth imaging helps us constrain the structural model for velocities, which can help with subsurface interpretation. Testing different model scenarios to observe the resulting PSDM image quality can be an effective tool to constrain the subsurface interpretation (Schultz and Canales, 1997; Vestrum et al, 2009; Ibáñez-Poveda et al, 2017).

Whereas PSTM ignores the effects of seismic anisotropy and velocity heterogeneity for the sake of robustness in the face of uncertainty, PSDM attempts to correct for these effects to optimize the imaging and reduce position uncertainty of imaged reflectors. The only way we may correct for these wave-propagation effects is with a geologically accurate velocity model. Obtaining a geologically accurate velocity model is difficult in complex structure land areas, because the seismic data in these areas typically have low data density, low signal-to-noise ratios on the seismic records, and high geologic complexity. Our only hope to overcome these limitations and build an accurate subsurface velocity model is through geoscience integration and collaboration with structural geologists.

We take the interpretive, geologically constrained strategy for building velocity models because the more data-driven, automated methods like reflection tomography or full-waveform inversion become numerically unstable and often create erroneous velocity structures that neither match the geology nor optimize the seismic imaging. If there are areas with high data signal and low geologic complexity, automated methods may yield useful information about the velocity structure that may be incorporated into the geologic velocity model.

Figure 2 shows an interpretive model-building display from the 2D and 3D interpretation tool, opendTect. This level of detail in velocity structure is required to optimize the seismic imaging, but there is not enough information in the seismic data to constrain the velocity model. Geologic constraints on the structural model are essential for an optimum imaging result.

Conclusions

Seismic data in foothills areas is highly unconstrained and requires additional geologic input to optimize the subsurface imaging. Geologic principles and data constrain the seismic model, and the seismic diagnostics further constrain the geologic model. This process adds value over and above the primary objective of an optimized subsurface image.

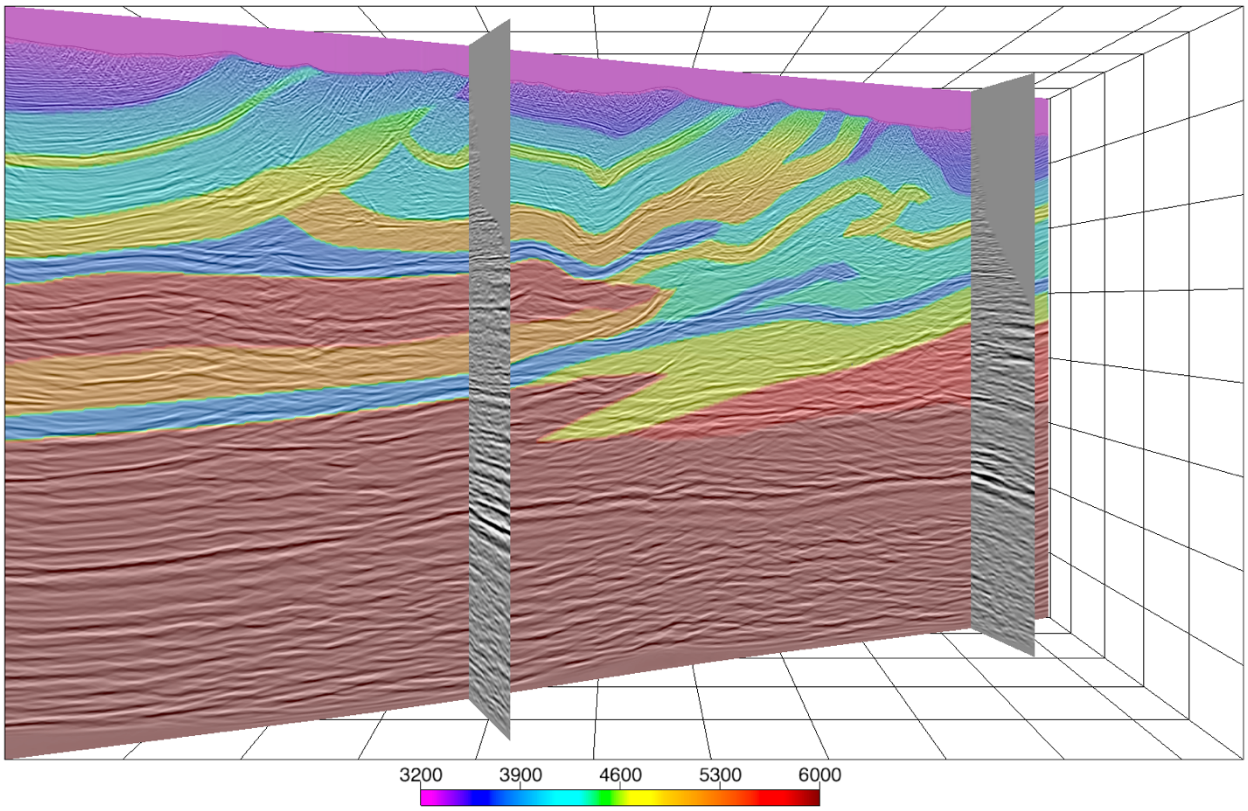

Figure 2 Interpretive display for PSDM velocity model building. The gray bars orthogonal to the seismic section show the prestack image gathers, with offset increasing in the direction away from the section. Events on these image gathers will be flat when we have optimum imaging velocities.

Acknowledgements

The authors wish to thank Husky and Talisman for offering the Benjamin Creek dataset into the public domain. This 2D foothills dataset has been important for technology development in seismic imaging of complex-structure land seismic data for over twenty-five years.

References

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