Adventures in thrust-belt imaging

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Summary

We look at the evolution of seismic-imaging technology with a brief history of Foothills exploration, an overview of our current status, and we will take a peek into the future of thrust-belt seismic imaging. When imaging below interbedded clastic rocks, Kirchhoff anisotropic depth migration offers improved imaging and positioning of subsurface structures. When imaging below high-velocity carbonates in some complex-structure geometries, limited penetration of energy and weaknesses in Kirchhoff migration conspire to all but eliminate reflector continuity. If we wish to be as successful in imaging below high-velocity carbonates as we are in imaging below anisotropic clastics, we will need farther offsets to undershoot these high-velocity structures with more seismic energy and we will need a migration algorithm that will handle this velocity geometry as well as the irregular acquisition geometry and rough topography of Foothills data.

Introduction

As exploration continues in the Rocky Mountain thrust belt, new methods in seismic imaging are required to find new structures for resource exploration or to find untapped compartments for field development. Throughout the history of hydrocarbon exploration the discovery of new reserves has required the development of new technology and the development of new play types. In Foothills exploration, the continuous evolution of seismic imaging technology has been a key to opening up new play types and isolating fault blocks. Examples of technological innovations that have lead to new hydrocarbon discoveries range from multi-offset shooting to 3D depth migration. We look here at a snapshot of recent developments in seismic imaging in the Canadian Foothills, look into the near-future at emerging technologies, and consider what the future might hold in thrust-belt imaging.

The complex nature of subsurface–and near-surface–geology in the foothills makes seismic imaging a depth-migration problem. Theoretically, hyperbolic assumptions in time migration are completely invalid in an environment with such significant velocity variation. However incorrect time-migration assumptions are, throughout most of the 1990s time migration consistently offered better imaging over depth migration. Time migration is simply more robust. In areas where we have dramatic lateral-velocity variation, like carbonates coming to surface,

Unable to solve the imaging problems of imaging beneath carbonate thrust sheets, in the late 1990s, migration researchers moved further into the foreland and worked on the problem of imaging below dipping anisotropic strata (e.g., Ball, 1995; Vestrum and Muenzer, 1997; Di Nicola Carena, 1997; Leslie, et. al., 1997, Vestrum, et al., 1998; Leslie and Lawton, 1998; Ferguson and Margrave, 1998; Dai et al., 1998; Fei et al., 1998). In the last seven years, anisotropic depth migration has established itself in mainstream foothills exploration as a tool for reducing structural risk below interbedded sands and shales.

As we look back toward the hinterland, we see the same old imaging problems imaging beneath high-velocity carbonates. There are two major problems in these areas: (1) our current migration algorithms are not up to the task of imaging beneath these high-velocity features and (2) even if they were, we may not have enough signal to migrate.

In the following sections, we will look at the current status of 3D anisotropic model building and migration, the potential of Gaussian Beam migration, and using long-offset shooting in a thrust-belt environment.

Anisotropic depth migration

Thrust-belt land seismic data do not have the high multiplicity, prestack signal-to-noise ratio, or the limited-azimuth geometry of marine seismic data. Methodologies designed to automate velocity model building in offshore environments are typically unstable when applied in land environments. Velocity model building in a thrust-belt land environment then becomes an interpretation exercise (e.g., Murphy and Gray, 1999; Vestrum et al, 1998). The past several years of anisotropic depth migration research have focussed on improved strategies interpretation of the velocity model: visualization tools for 3D model interpretation, integration of geologic data such as well logs and dipmeter data into the workflow, and a velocity-model-building team that is tightly integrated with the interpreting geologist and geophysicist.

Taking the team approach to model interpretation, processors and interpreters meet on a regular basis to exchange ideas and evaluate all of the various constraints on the velocity model. Constraints include: flatness of events on the depth-migrated image gather, minimizing the difference between the depth of migrated events and correlated well depths, surface-geology constraints for horizon locations and dips, and structural-geology principles to constrain horizon and fault geometry. As we apply these various constraints to the re-interpretation of our velocity model, we need the interplay between all team members and their diverse specialties to optimize the velocity model.

A crucial interpreted volume required for correcting anisotropic effects on thrust-belt seismic data is the dip orientation of the clastic strata. 3D anisotropic depth migration then requires a full gridded volume of the dip and dip azimuth of any anisotropic strata. To accelerate the process of interpreting a dip volume, we generate inline and crossline apparent-dip attributes based on the dip of the horizons. For each velocity body, have three options for dip calculations: (1) conform to the dip of the horizon below, (2) conform to the horizon above, or (3) interpolate dips between horizons above and below the body. These options cover most dip scenarios, but there are some structural geometries where these options are insufficient. In these cases, we have the option to manually pick apparent dips in the inline and crossline directions. Once we have apparent dips, we then calculate the true dip and dip azimuth required for the depth migration.

To illustrate the effectiveness of the model-building strategy, a case history presented here follows the process of interpreting a 3D anisotropic velocity model with tilted transversely isotropic (TTI) strata above the target, constraining the velocity-model interpretation with geologic data, and finally interpreting and mapping the target horizon for planning a horizontal natural-gas development well. Comparisons between data volumes and resulting map interpretations from prestack time migration and anisotropic depth migration illustrated the improvements in imaging and lateral position of subsurface structures when we correct for anisotropic effects in the overburden. We will then look at the final well results to assess how much we have reduced the structural uncertainty of the final migrated volume using this strategy.

Gaussian Beam

Wave-equation migration does not handle the rough topography or irregular shooting geometries that define foothills seismic data. Kirchoff migration handles rough topography and irregular geometries beautifully, but its raytracing stability and handling of multi-arrival raypaths are weak.

Gaussian beam migration (Hill, 1990, 2001) is an elegant, accurate, and efficient depth migration method. It has the ability to image complicated geologic structures with fidelity exceeding that of single-arrival Kirchhoff migration and approaching that of wave-equation migration. In fact, its accuracy can exceed that of most wave-equation migrations in imaging very steep dips, especially in three dimensions and especially in the presence of anisotropy.

The success of Gaussian beam migration has sparked interest in beam migrations, some based on Gaussian beams, others not. Some variations of beam migration have as their sole purpose the speedup of Kirchhoff migration (Sun et al., 2000); others use wavefield extrapolation to build migration Green's functions (Brandsberg-Dahl, 2003); still others use wavelet decomposition of seismic wavefields to emulate the simultaneous space/wavenumber localization property of Gaussian beam migration (Wu et al., 2002). Our objectives are to explain Gaussian beam migration as an improved version of the more familiar Kirchhoff migration and to show field-data examples of imaging improvements when Gaussian beam migration is applied to thrust-belt seismic data.

Long-offset shooting

A migration algorithm designed to more effectively manage high velocity contrasts will improve imaging below carbonate thrust sheets. An improved algorithm will not, however, give us more signal below high-velocity carbonates than we recorded in the field. The lack of a considerable velocity gradient in the Canadian foothills means we should be able to shoot very long offsets without opening our reflection angles past critical, giving us the potential to undershoot high-velocity structures in a thrust-belt environment.

Italian researchers are leading the charge toward using very long offsets, or "global offsets", to undershoot difficult imaging areas in a thrust-belt (Dell'Aversana et al, 2000; Colombo et al, 2003; Dell'Aversana et al, 2003, etc.). Whereas in the Canadian thrust belt, we typically see a maximum offset in the 4km to 6km range, which gives us an offset/depth ratio of less than 2.0 for deep-gas targets beyond 3 km of depth, some studies (Colombo et al., 2003; Lin and Zhou, 2003) show that, in a thrust-belt environment, it is possible to acquire useful seismic data with offsets far enough to yield offset/depth ratios in the range of 2.6 to 2.8.

As we learn how to accurately process the additional offsets, long-offset shooting in the foothills will potentially reveal structures previously not imaged by short-offset seismic data.

Conclusions

Anisotropic depth migration in a thrust-belt environment has matured through anisotropy research and the development of visualization tools essential to thrust-belt velocity-model interpretation. We see 2D and 3D anisotropic depth migration becoming a standard exploration tool in triangle-zone areas and other environments where we have shale-dominated clastics in the overburden.

When exploring further west into the hinterland, high-velocity carbonates carried to surface or to the near-surface on major thrust sheets can reduce the effectiveness of Kirchhoff migration to image structures below. Gaussian Beam migration is a promising solution to improved imaging in these areas, with its ability to handle multiple-arrival travelpaths, more realistic finite-frequency assumption, and its inherent ability to handle land acquisition geometries.

As our migration algorighms evolve to handle more complex raypaths, we will be well poised to handle future trends in thrust-belt acquisiton. Long-offset shooting may prove to be highly beneficial in imaging below certain complex velocity structures. Further work in understanding the geologic settings that will benefit most from long offsets, what acquisition geometries will optimize signal improvements, and how our processing methodologies can optimize the final imaging will reveal the true potential of long-offset foothills acquisition.

References

Ball, G., 1995, Estimation of anisotropy and anisotropic 3-D prestack depth migration, offshore Zaire, Geophysics **60**, 1495-1513.

Brandsberg-Dahl, S., 2003, Beam-wave imaging: 73 rd Ann. Internat. Mtg., Soc. Expl. Geophys., 977-980.

Dai, N., Cheadle, S., and Isaac, J.H., 1998, Prestack depth migration in TI media: examples with numerical and physical model data, GEOTRIAD '98, Joint meeting of CSEG, CSPG, and CWLS.

Dell'Aversana, P., Ceragioli, E. and Morandi, S., 2000, A simultaneous acquisition test of high density 'global offset' seismic in complex geological settings: First Break, **18**, no. 03, 87-96.

Dell'Aversana, P., Colombo, D., Buia, M. and Morandi, S., 2003, Velocity/interface model building in a thrust belt by tomographic inversion of global offset seismic data: Geophys. Prosp., Eur. Assn. Geosci. Eng., **51**, 23-35.

Di Nicola-Carena, E., 1997, Solving lateral shift due to anisotropy: SEG 67th Ann. Mtg., Expanded Abstracts, 1525-1528.

Colombo, D., Wilkes, M., Villani, L. and Mantovani, M., 2003, Feasibility study for long offset seismic acquisition in a thrust-belt, 73rd Ann. Internat. Mtg.: Soc. of Expl. Geophys., 51-54.

Fei, T., Dellinger, J., Murphy, G.E., Hensley, J.L., and Gray, S.H., 1998, Anisotropic true-amplitude depth migration, GEOTRIAD '98, Joint meeting of CSEG, CSPG, and CWLS.

Ferguson, R.J., and Margrave, G.F., 1998, Depth migration in transversely isotropic media by nonstationary phase shift, GEOTRIAD '98, Joint meeting of CSEG, CSPG, and CWLS.

Hill, N. R., Gaussian beam migration: Geophysics, 55, 1416-1428.

Hill, N. R., Prestack Gaussian-beam depth migration: Geophysics, 66, 1240-1250.

Leslie, J.M., Lawton, D.C., Cunningham, J.D., 1997, A refraction seismic field method to determine the anisotropic parameters of Wapiabi shales, CSEG 1997 National Mtg.

Leslie, J.M., and Lawton, D.C., 1998, Depth migration of anisotropic physical model data, GEOTRIAD '98, Joint meeting of CSEG, CSPG, and CWLS.

Lin, Q., and Zhou, H, 2003, A study of long-offset seismic imaging, 73rd Ann. Internat. Mtg.: Soc. of Expl. Geophys., 1154-1157.

Murphy, G. E. and Gray, S. H., 1999, Manual seismic reflection tomography: Geophysics, Soc. of Expl. Geophys., **64**, 1546-1552.

Sun, Y., Qin, F., Checkles, S., and Leveille, J. P., 2000, 3-D prestack Kirchhoff beam migration for depth imaging: Geophysics, 65, 1592-1603.

Vestrum, R.W., and Muenzer, K., 1997, Anisotropic depth imaging below dipping shales, CSEG 1997 National Mtg.

Vestrum, R. W., Schmid, R. and Lawton, D. C., 1998, Determining parameters for seismic imaging in dipping anisotropic strata, 68th Ann. Internat. Mtg: Soc. of Expl. Geophys., 1289-1292.

Wu, R-S., Chen, L., and Wang, Y., 2002, Synthetic beam-sources and plane-sources for prestack beamlet migration: 72 nd Ann. Internat. Mtg., Soc. Expl. Geophys., 1336-1339.