

Challenges and Opportunities in Pre-Stack Depth Imaging of Legacy Seismic Data: an Overthrust Belt Case Study

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Summary

Over the past five years, the introduction of affordable 3-D pre-stack depth migration (PSDM) has changed industry perspective on how to approach seismic data in areas of complex geology. The ability to define an *accurate* interval velocity model and *economically* perform 3-D pre-stack imaging in depth provides the opportunity to more fully exploit the hydrocarbon potential of these difficult areas. Legacy or vintage data sets are also amenable to re-examination using these new pre-stack depth imaging tools. However, the PSDM method is more demanding of the data requirements than conventional time techniques to deliver the degree of velocity model accuracy required for optimal spatial positioning of target reflectors. This paper discusses a seismic reprocessing program intended to assess deep gas potential in a mature producing province with very complex overthrust geology using the PSDM method. It highlights the challenges presented by vintage seismic 3-D acquisition methodologies in an older rock/fast velocity regime and the opportunities from fully incorporating the wealth of available geologic knowledge into the model-building process. A well-constrained velocity model-building solution is presented that overcame the limited sensitivity of the available 3-D seismic data to velocity change due to acquisition geometry in this fast rock regime.

Introduction

The targeted area is a major gas field discovered in 1978 that has been producing large quantities of gas in the Overthrust Belt of Utah/Wyoming. In addition to providing an improved image of depth structure, the primary objective for this project was to aid in the economic assessment of deeper levels between 17000 and 19000ft in this complexly faulted overthrust regime. Before committing to an expensive deep well test, it was necessary to confirm the deep structural configuration and its dimensions. Several vintages of time and depth processing had not resolved the structure. Because the geology is characterized by significant structural distortion due to severe thrusting in the area as well as the presence of a variable thickness salt layer in the shallower section, a state-of-the-art Kirchhoff pre-stack depth migration and velocity model-building solution was selected for a 45 square mile area of 1998 vintage 3-D seismic data.

Tectonic movement in the Overthrust Belt of the Rocky Mountains of Utah/Wyoming has occurred over many

miles along the Absaroka Thrust creating major structural distortions of the Mesozoic and Paleozoic rocks below a Tertiary overburden. The area has produced around 1 TCFG with estimated ultimate recovery of 500 MMBOE (Powers, 1995) from the pre-Tertiary sedimentary section generally below 10000ft from surface. The main field is a combination structural-stratigraphic trap with the primary existing reservoirs in the Mississippian Mission Canyon formation, composed of interbedded dolomite, limestone and anhydrite running along the crest of an anticlinal closure. The rocks are typically well-consolidated sandstones and limestones with a Jurassic salt layer of variable thickness present above the producing layers. A representative geologic cross-section is shown as Figure 1. There is a good distribution of wells centered along the main porosity zone structure but very limited well presence to the east. Favorable industry gas pricing provided the motivation for identifying new deep gas reserves. The decision to apply a state-of-the-art PSDM solution was based on:

- Uncertain structural extent
- Complex geology
- Variable salt layer in overburden
- Presence of rapid lateral velocity variations.

Seismic Acquisition and Pre-processing

Because of its geologic complexity, the Overthrust trend was an early target for 3-D imaging beginning in 1979 (Johnson, 1983). The 3-D data volume for this project was acquired over 45 square miles in 1998 using dynamite as source. The area is typified by rough topography and elevations ranging from 6500 ft to 8200 ft ASL.

The 3-D acquisition provided a nominal 24 fold, 82.5 x 165ft data volume. Because of the acquisition geometry, the fold distribution exhibited zones of higher trace density. Offsets were available up to 17000ft but inspection of the offset distributions showed that there was frequently clustering of offsets and restricted offset ranges within bins (with implications for velocity sensitivity, to be discussed later).

Effective PSDM processing requires good quality pre-processed data. A robust noise-attenuating, bandwidth-preserving processing flow was developed with particular emphasis on resolving the highly variable travel times induced by the near-surface conditions in the area. A two-layer refractor-based 3-D tomography solution provided an

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effective result complemented by several iterations of 3-D residual reflection statics.

Model Building Process and Issues

Once the near-surface and careful pre-processing was satisfactorily completed, attention turned to defining an accurate velocity model for the Kirchhoff PSDM solution. An iterative tops-down workflow was adopted to progressively establish the upper layer velocities and horizon positions before moving deeper to define the next series of formations. The workflow included using the pre-stack time migrated velocity volume complemented by available well/geologic data as an initial model.

A series of key horizons were selected to define boundaries between iterations:

- Top Salt,
- Base Nugget
- Base Weber

This was augmented during PSDM stages, wherever possible, by:

- Stump
- Lodgepole
- Absaroka Thrust boundary.

The proposed workflow assumed that the initial velocity model would be high-graded using Kirchhoff PSDM image gather and semblance analyses. The residual curvature (velocity) estimates would be used in the model update process to tune the velocity model for each progressively increasing depth interval. The velocity model would be built up in increasing depth to the maximum depth of interest. At each stage available well data would be integrated for calibration as an indicator of the fidelity of the PSDM volume as an accurate spatial representation of the subsurface.

After several early iterations targeting the top 10000ft - 15000ft of the geologic section, several issues were identified that affected the stability of the imaging results.

- The interval velocity regime in this highly consolidated rock environment is “fast”, typically in the 16000ft/sec range or greater.
- In the shallower section, because of the field acquisition geometry, all offsets across the full range are not available to assist the velocity estimation process. Longer offsets out to 17000ft (often helpful to velocity resolution) do not contribute for the shallower depths.
- As a second order effect to the above, the 3-D acquisition geometry causes variable offset distributions across the available offset range within and between bins that results in varying sensitivity to velocity.

- The fast velocity regime results in low curvature across the offset range for large velocity variation (i.e. only small residual moveout error represents large velocity variation).

The net effect is that residual curvature estimates from image gathers are relatively insensitive to velocity change. This causes hypersensitivity in the velocity model updating process to minor variations and/or “noise” in the residual curvature estimates. Time-based processing is relatively insensitive to this situation as reasonable stack response is available across a wider range of velocity in a “fast environment”. Depth imaging, however, is highly sensitive to variations or noise in velocity as positions in space are directly linked to velocity. Additionally, since the situation exists in the shallow section it affects accurate positioning of reflection energy at all subsequent depths.

This dilemma is demonstrated by an example line extracted from the 3-D volume before and after a PSDM iteration update (Figure 2). The variability in the velocity field is evident as semblance/curvature analysis attempts to capture velocity variation. The PSDM images show similar stack response, but also very noticeable changes in the depth position of the major reflectors. Also, gathers before and after update suggest that the updating has had no stabilizing effect.

Following the identification of this particular geology and acquisition interaction, an alternative strategy for velocity modeling and updating was pursued. This approach was highly constrained by available geologic and well data with seismically-derived updating only included where it was *strongly* and *consistently* supported by the subsurface data. At each stage, a close tie to known formation tops would act as a primary criterion for velocity model accuracy

Available well data tended to be clustered in an approximately north-south trend along the crest of the major structure. For the subset of wells with both good quality check shot and formation top data available in the vicinity of the PSDM prospect area, interval velocities were derived between the major horizons of interest. With these interval velocity profiles, a “keep it simple” modeling approach was adopted with strong adherence to the well-derived interval velocity trends except where strongly and consistently contra-indicated by the seismic. This approach was especially helpful in reducing the high variability experienced in the early velocity models and providing guidance in areas of no/low well control e.g. to the east.

With this modeling strategy, interval velocities from wells were intersected with horizons interpreted from the seismic PSDM volumes at each stage. After each iteration, data were assessed for image quality, tie to formation top

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information, and curvature consistency with a horizon review/update of the model before the next iteration. With this strategy in place, the PSDM process proceeded rapidly through a series of iterations to produce the final PSDM volume. An early Base Tertiary iteration was followed by iterations to Twin Creek, Base Weber, and Absaroka with a final full iteration to maximum depth.

An interesting footnote was that the Salt layer above Twin Creek considered early to be important to an accurate depth solution was not included in the velocity model. It was carried as a horizon but, because its observed interval velocity of approximately 15500-16000ft/second was close to the slightly faster surrounding medium, it was believed that the depth fidelity improvement by including it was small (e.g. at an average thickness of around 500-700ft, the depth variation is only 50ft). It is possible that any inaccuracies in consistently tracking the Top Salt and Twin Creek horizons may, in fact, induce an equivalent or higher error in the final volume.

Results

The final volume based on the geology-constrained modeling approach exhibits good image quality. It closely tied key formation top data within this Overthrust Belt project area and exhibited good reflector continuity in the primary zones of interest. In addition to tying available well data, confidence in the accuracy of the volume was reinforced by the stability of the deeper section (Absaroka and below) where the reflection energy in the final depth volume closely matched the known regional attitudes of these beds (Figure 3). The stability and geologic plausibility in the final result is evident versus the implausible reflector topography seen in the early iterations. We believe that the final velocity model used in this project contains the essential information for an accurate subsurface image in depth across the project area.

Conclusions

The velocity model-building solution developed for this project using well-derived interval velocities between the major formation boundaries as a constraint to define a narrow range of velocities allowed this greatly reduced parameter space to be explored systematically with a small number of pre-stack depth migration iterations. The method successfully overcame the data insensitivity to velocity dilemma and provided good convergence on the best-fit model that met project objectives in this difficult subsurface imaging area.

Thus, with an awareness of key success factors, effective subsurface depth imaging using legacy data sets is a very practical option. These success factors include:

- Keen awareness of the capabilities and limitations inherent in legacy data sets
- Understanding the rocks
- Information access and integration leverage of all available well, geologic, and associated subsurface data
- Continuous interpreter involvement.

References

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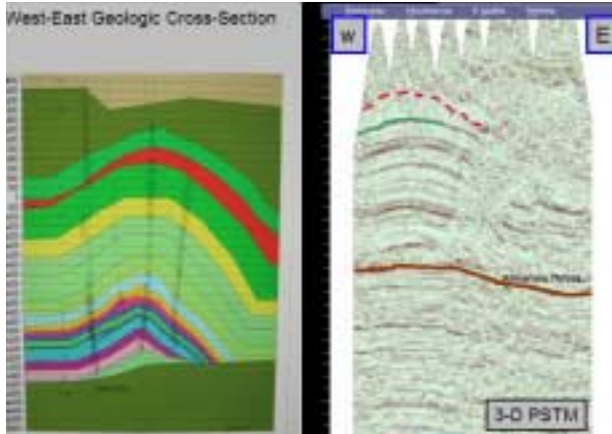


Figure 1: Geologic Setting

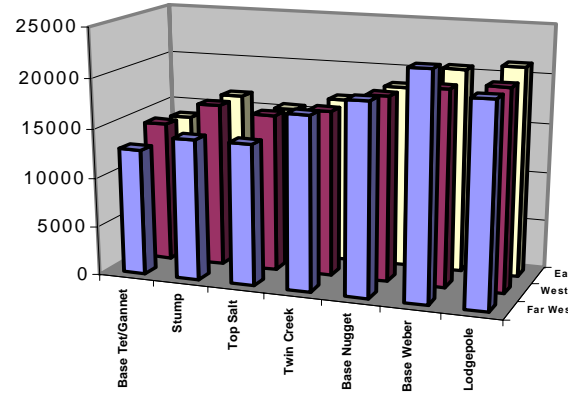


Figure 3: Well Interval Velocity Distribution

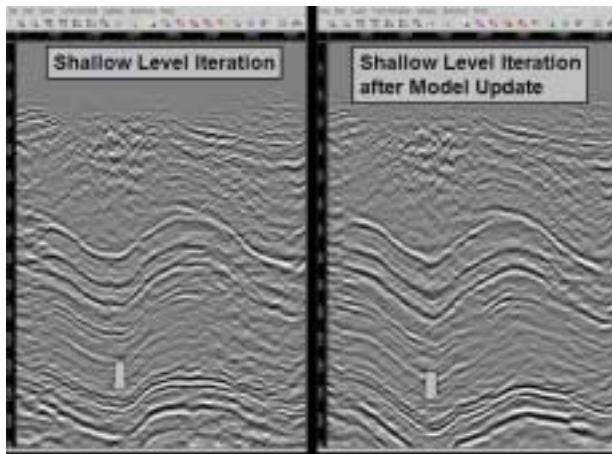


Figure 2: Velocity-induced Depth Variability (zoom)

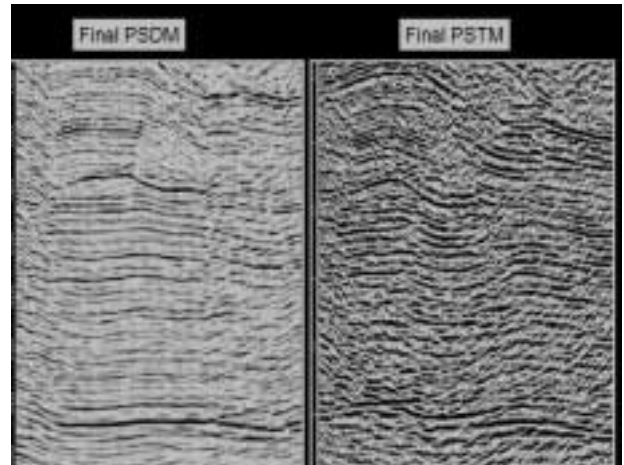


Figure 4: Final PSDM vs PSTM example (deep level - zoom)