Sensitivity Analysis of Seismic Depth Migrations: Canadian Structural Model

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Summary

Accurate velocity estimation is essential for successful seismic depth migration. There is a need to quantify methods for determining the effect of velocity on depth migration since velocity errors will ultimately lead to improper positioning and poor focusing of migrated reflection events. We describe relationships between inaccurate input velocities and depth positional errors on the migrated section. We perform sensitivity analysis for velocities derived from prestack depth migrations. As a final step, we examine the migration errors for a realistic Canadian Foothills model seismogram. Results demonstrate that systematic velocity errors, rather than random errors, are problematic, especially with prestack depth migration. Our results identify the need to quantify uncertainties in migrated images and an iterative and interpretive approach is needed in order to refine images of complex folds and faults in order to have success in hydrocarbon exploration and development.

Introduction

Depth migration is the processing step that can position seismic reflections in their proper spatial locations beneath the earth's surface. Accurate seismic imaging assists in structural interpretation and determination of optimum drilling locations. There are many migration algorithms to perform this depth-imaging step. Many of these algorithms and their applications to foothills data have been summarized by Lines et al. (1999). As pointed out by Parkes and Hatton (1987), most depth migration algorithms and seismic time measurements are quite accurate, but in order to improve migrations, greater emphasis needs to be placed on improving the accuracy of the input velocity field. Parkes and Hatton also state that depth migration uncertainty is primarily a result of the velocity field uncertainty used to map seismic data from time to space.

Migration Velocity Analysis Uncertainty

The depth migration of seismic data using the true velocity model will position and focus all the structural events correctly. However, the accurate determination of the velocity model is a difficult process when working in structurally complex areas, and the migration velocity analysis used to define the velocity model typically involves some uncertainty or error. The errors in positioning and focusing are a direct consequence of the velocity uncertainty. Therefore, the velocity estimation methods need to be improved to reduce the uncertainty in this process. In this study, systematic and random perturbations are applied to the exact velocity model prior to their use in several depth migrations. These migrated depth sections have been examined to gain insight on the sensitivity of input velocity to depth migrations.

The analysis of velocity perturbations allows us to examine the effects on the depth positioning of migrated seismic reflections. An extension of the "smiles and frowns" equation from Zhu et al. (1998) can help identify the change in migration depth with velocity perturbations. For constant velocity, the velocity errors are related to depth errors by:

$$\frac{\Delta v_m}{v} = \frac{\Delta z}{z}\frac{1}{\left(1+\frac{x^2}{z^2}\right)}$$

where z is depth, x is offset, v is true velocity, error in velocity is Δv_m and the depth positional error is Δz. The final relationship displays that fractional changes in velocity result in fractional changes in depth with the depth changes multiplied by an offset dependent term $(1+x^2/z^2)^{-1}$. This simple formula provides insight and basic understanding into the nature of migration velocity uncertainty and the corresponding positional error in the migrated domain. Even if the formula is only applicable in simple situations (constant velocity), it gives a good basis that the input migration velocity uncertainty should be quantified in migrated images. Like NMO analysis, it is seen that increasing the offset/depth ratio, x/z, can reduce velocity errors. While this equation gives a simple constant velocity relationship for depth and velocity errors, the analysis of more complicated situations are given by evaluating models.

Numerical Seismic Model

The velocity model in Figure 1 is derived from a numerical model on the geological structures of the Front Ranges of the Canadian Rockies from Kirtland Grech (2002). This model was used to test depth migrations with variations in the input velocity field. It is useful to study these models since these observed structures are analogous to Foothills petroleum traps just east of the Rockies. The model has a lateral extent of 33 km and a vertical extent of 16 km. The primary structures in Figure 1 are different geological layers and major thrusts of the Front Ranges of the Canadian Rockies. These include Heart Mountain Structure, Mount Yamnuska Structure, Panther River Culmination, and a footwall syncline (Kirtland Grech, 2002). The structural model of the Front Ranges of the Canadian Rocky Mountains was covered with lower Cretaceous and Jurassic clastic sediment to form a horizontal surface. Two other major faults that cut through this cross section are the Sulphur Mountain and Rundle thrusts. The flat datum used in this model does not require any static corrections usually associated with Rocky Mountain seismic processing. The migrations were done with the exact, 10% too fast, 10% too slow, and randomly perturbed velocity models. There were two algorithms used, specifically poststack reverse-time depth migration, and prestack Kirchhoff depth migration. These two algorithms were used to identify the sensitivity of the migration with variations in the velocity model.

Sensitivity Analysis of Depth Migrations

For tests of poststack migration, we used an idealized stacked section - an exploding reflector model. The data were migrated with a reverse-time depth migration code written by Phil Bording (and described in Lines et al., 1999). The structures as mentioned above are generally quite well imaged using poststack reverse-time depth migration with the exact velocity model (Figure 1). As shown by the migrated section of Figure 2, the steeply dipping Heart Mountain structure has both the hanging wall anticlines and footwall synclines imaged reasonably well. The fault bend fold of Mount Yamnuska is very well imaged including the McConnell thrust. Overall, the Panther Culmination is quite well imaged except at some locations along the faults where layers with the same velocity come in contact, resulting in zero impedance contrast. Also shown in Figure 2, the footwall syncline is clearly imaged right against the base of the Lac des Arcs thrust. The poststack reverse-time depth migration has imaged this structurally complex dataset reasonably well.

The main structures and a few other features will be used as a reference for comparison of the structures when the migration is run with a perturbed velocity model. Figure 2 shows the reference structures marked by red circles and labeled I, II, III, IV, V, and VI. These six reference structures occur at various distances and depths (x,z) as seen in Figure 2 and are described below with measurements in kilometers. Two features are located at distances of 8 km and they are: I located at (8.0,6.1) and V located at (8.0,14.3). There is one feature located at a 16 km distance and depth of 5.8 km (Figure 2); this is feature II-(16.0,5.8). Three features are coincident at a 24 km distance (Figure 2) and these are III-(24.0,4.7), IV-(24.0,9.0), and VI-(24.0,14.1). The migrations using the incorrect velocities have made these events experience a vertical displacement and they are measured to identify the relative movement due to velocity variations. These values will be used to calculate the resultant depth error Δz when the incorrect velocities are used for migration.

The migration velocities were adjusted by a systematic decrease of 10% and this was used for the next run of the poststack reverse-time depth migration. The 10% slow velocity model has affected the positioning of the imaged events primarily in the vertical direction. The velocity model perturbation affects the migration by undermigrating the data and leaving some events not fully focused. The poststack migration using the slow velocity model has shifted the structural features to a shallower depth, with the deeper events (V and VI) having the largest displacement. The next migration was the poststack reverse-time depth migration using a 10% fast velocity field (Figure 3). This migration has incorrectly positioned the events deeper in the section. The overmigration of the six features has positioned events I through IV to be displaced from 200 to 500 meters and structural features V and VI have been displaced 700 and 800 meters respectively deeper in the section compared to migration with the exact velocities. The 10% higher velocities have not affected the migration as much as the 10% slower velocity model. The randomly perturbed velocity model does not severely affect the poststack reverse-time depth migration. The positioning of the structural features is relatively close to the exact case, however the focusing of the events is not quite as sharp. The perturbed velocity models have change the imaging significantly.

We now examine the prestack Kirchhoff depth migrations for the first 8750 meters in distance and depth for a series of high frequency ray traced shot gathers. The section only looks at parts of the Sulphur Mountain and Rundle thrust sheets (Figure 4). The Kirchhoff migration using the true velocity model has imaged these two primarily carbonate sheets well. The prestack migration seems to image the complex model slightly better compared to the poststack migration.

The prestack migration using the exact velocity model will be used for reference once again to compare two features marked as I and II (Figure 4). I is located at (5000,3362) (using (x,z) for distance and depth respectively in meters) and represents the top of a limestone. Feature II is located at (7500,6224) and is the reflection from the base of the Banff shale. Although, there is lateral and vertical displacement when depth migrations are executed with incorrect velocity models, only the vertical displacement will be noted here. These two reference locations can now be used to analyze the sensitivity of the prestack migrations with variations to the velocity.

The two features (I & II) have been imaged higher in the section when migrated with a 10% systematic decrease in the velocity model. The deeper structure II has been displaced to a larger degree than I. The systematic increase in the velocity model by 10% has caused the migration to image all the events to a greater depth (Figure 4). The two structures (I & II) are slightly distorted and have shifted laterally and vertically in this migration. Only the vertical movement is considered here and the features are now located at I-(5000,3829) and II-(7500,7360) as seen in Figure 4. Comparison shows in the prestack case, the higher velocity model has affected the migration depth of the deeper event II more in terms of vertical displacement. The prestack Kirchhoff depth migration was run with a randomly perturbed velocity model. This model was obtained by using a random number generator from Press et al. (1992) where the random numbers have zero mean and a standard deviation of 750 m/s. The overall positioning of the structures has not been greatly affected, however the sharpness and clarity of the reflection events is lacking. Feature I is virtually located in the same position as with the exact velocity and feature II has moved slightly lower. Prestack migration has introduced some migration artifacts and blurred the reflection events when using the incorrect velocity model.

The errors in the velocity model for prestack and poststack migration respond similarly. The depth measurements in these migrations are not precise due to the human errors in measurement, however they give a good representation of the error in positioning when the migrations are run with inaccurate velocity models. Both migration algorithms are depth dependent, i.e., the positional error increases with depth. The sensitivity seen in the depth migrations with variations in the velocity model can be somewhat related with the mathematical relation shown earlier. The overall effect of a systematic perturbation to the velocity model by +/-10% has imaged the structural features too deep and too shallow respectively. The migrations with the random velocity variations have primarily affected the focusing of the reflection events. This is an expected result since the depth migration is dependent on traveltime to a given depth. This result is shown by the fact that smoothed versions of velocity models can produce accurate depth migrations. For example, note the foothills data examples of Yan and Lines (2001). In these randomly perturbed velocity models, the random perturbations had zero mean, hence the positioning of reflectors is not adversely affected.

Conclusions

The uncertainty of the input velocity model for depth migration has unfavorable effects on the positioning and focusing of seismic reflections. In order to understand depth migration sensitivity, we extend a relationship for the depth and velocity errors in the constant velocity case. The mathematical relationship demonstrates that fractional errors in velocity will approximately result in fractional errors in depth migrations. Also, velocity estimation will be improved with increasing offset. In order to analyze more complicated velocity structures, we examined a Canadian Foothills model. The examples, which display the sensitivity of depth migrations to velocity perturbations, show that systematic velocity errors are more problematic than random errors. We also see that prestack depth migration is a "double edged sword". While the depth mispositioning of events on both prestack and poststack migrations is caused by velocity errors, prestack migration images are more sensitive to incorrect velocities. Therefore, prestack depth migration can be used as a velocity analysis tool. On the other hand, prestack depth migrations are more blurred by incorrect velocities than poststack migrations. Finally, it becomes clear from model studies (as well as our experience with real data), that an iterative and interpretive approach is needed in order to refine seismic images of complex structures. With improved estimation and sensitivity analysis techniques, higher success rates in hydrocarbon exploration can be achieved.

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Figures

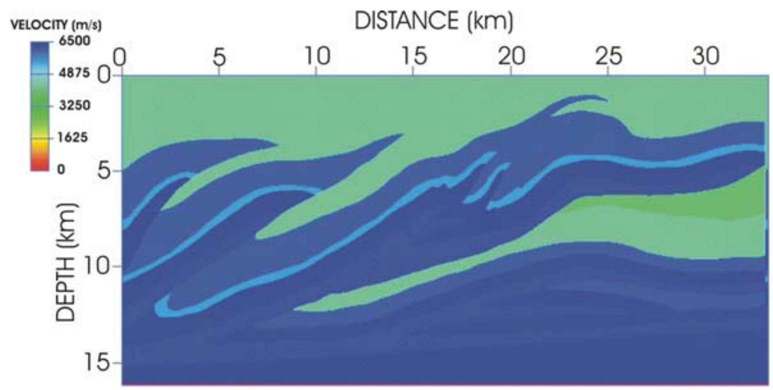

Figure 1 - This shows the true velocity model used for the various depth migrations. Numerous perturbations (10% too slow / fast and random) were applied to this model to test the sensitivity of the depth migrations.

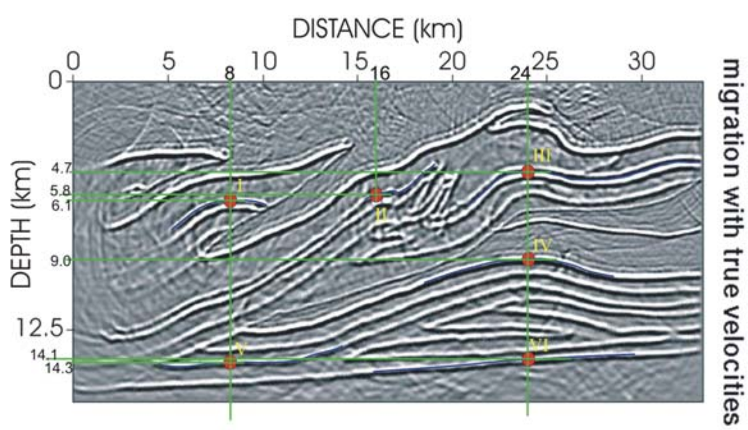

Figure 2 - This section displays a poststack reverse-time depth migration using the exact velocity model. The main structures are very well imaged. Six features are marked with a red circle and labeled (I, II, III, IV, V, and VI) and these will be used as a reference to compare the vertical displacement when migrations are performed with the incorrect velocity. The features are related to the horizons marked in blue and have their corresponding distance and depth marked on the respective axis at the end of the green lines.

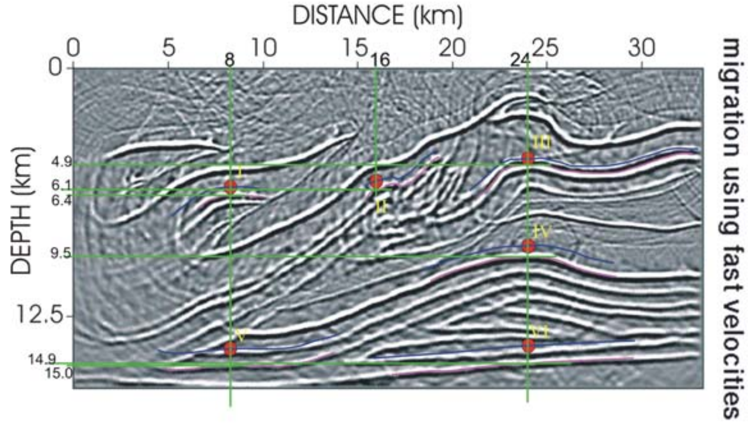

Figure 3 - This section displays a poststack reverse-time depth migration using a 10% fast velocity model. The six features (I, II, III, IV, V, and VI) are now imaged at deeper locations identified with pink horizons. The new depth coordinates are marked on the vertical axis (only noting the vertical displacement). The true features indicated with the red circles and horizons marked in blue have been superimposed on this section, which displays the original features I - VI.

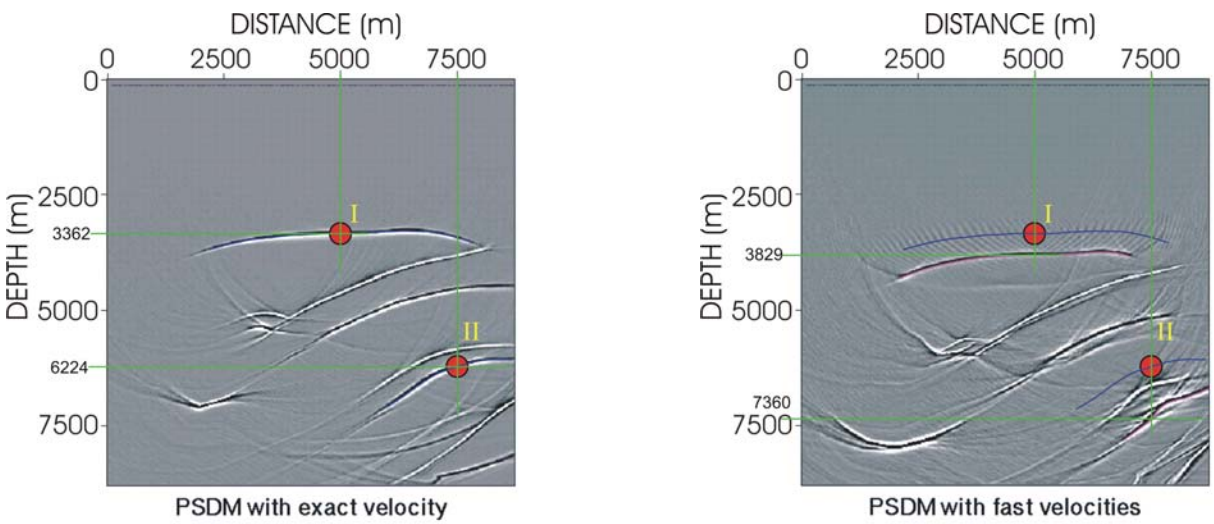

Figure 4 - The prestack depth migration using the exact velocity field (left) was used as the reference to note the changes in depth when various migrations were executed with inaccurate velocity models. The red circles and blue horizons are the events of interest and are labeled I and II. The structural feature I is located at an distance of 5000 m and 3362 m in depth as marked on the respective axes. Feature II has coordinates of 7500 m and 6224 m for distance and depth respectively (above, left). The prestack depth migration using the 10% fast velocity model is shown above (right). The new depths are represented by the horizons marked in pink; these new depths are the result of migrating with the incorrect velocity model. The red circles and blue horizons are the true event positions. The structural feature I located at distance of 5000 m has moved deeper to 3829 m. Feature II at 7500 m distance has a new depth of 7360 m.

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