Improved resolution in depth imaging through reflection static corrections derived from model-based moveout

Dennis K. Ellison, Kris Innanen

ABSTRACT

When seismic data are used to image the subsurface, assumptions and calculations are made about the near-surface to overcome the uncertainty of the velocities of the low velocity layer. A near-surface velocity model is generated to calculate a time shift that is used to correct for velocity anomalies in the near-surface for time migration.

Reflection statics are calculated because often the lack of detailed near-surface information leads to inaccuracies. A normal moveout (NMO) velocity field is picked and applied to stack the data in preparation for the reflection statics calculations. NMO is a two-term equation based on the assumption that the moveout can be approximated by a hyperbola. However, the accuracy of this assumption is valid when the moveout on data is near-hyperbolic and deviates when the moveout is more complicated than the two-term equation. A few scenarios of non-hyperbolic moveout are when the topography isn't flat, strong lateral heterogeneity of velocity is present, and when there are variations in the seismic weathering thickness and velocities.

Raytracing in depth migration has overcome many of the issues with the assumptions in time migration. Foothills datasets and other geologically complex environments compel us to look for ways to overcome these assumptions as they are violated. Using the depth migration velocity model we apply the zero-offset traveltimes as the moveout correction for reflection static calculations in depth imaging.

INTRODUCTION

Weathering and the near-surface

The term "weathering" differs to a small degree when speaking to geologists and geophysicists and should be instead *seismic weathering* and *geological weathering*. Sheriff (1991) defines seismic weathering as:

> "A near-surface, low-velocity layer, usually the portion where air rather than water fills the pore spaces of rocks and unconsolidated earth. Seismic weathering is usually different from geologic weathering (the result of rock decomposition). The term LVL (low-velocity layer) is often used for the seismic weathering. Frequently the base of the weathering is the water table. Sometimes the weathering velocity is gradational, sometimes it is sharply layered." — Sheriff (1991)

Sheriff's definition of seismic weathering the removes direct tie to geologic phenomena and is more of a characterization of the behaviour of seismic waves as they propagate down from and back up to the surface of the earth. As much as the velocity of this seismic weathering layer can vary, so can its thickness (Figure 1a).

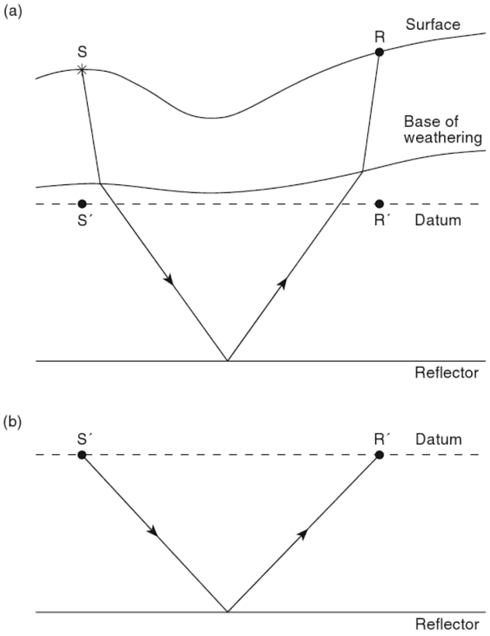

Fig. 1. Ray-path schematic from source to receiver and potential datum static correction. (a) Acquired source (S)-receiver (R) ray-path from surface. (b) Source (S)-receiver (R) ray-path corrected to datum, after Cox (1999).

Static corrections

Land seismic surveys commonly require statics corrections to reduce or remove the effects of the weathering layer by causing vertical time shifts on reflection data (Figure 1b). These shifts or corrections are often referred as just statics. Again using Sheriff (1991) for definition, statics are:

"Corrections applied to seismic data to compensate for the effects of variations in elevation, weathering thickness, weathering velocity, or reference datum." — Sheriff (1991)

Reflection statics

These statics are a calculated time shift that will compensate for the uncertainties of the seismic weathering layer. The assumption is that the near-surface model is underdetermined which causes small inaccuracies in the reflection data. Continuing from Sheriff's (1991) definition of static corrections:

"[Reflection statics] assume that patterns of irregularity that most events have in common result from near-surface variations and hence static-correction trace shifts should be such as to minimize such irregularities. Most automatic statics-determination programs employ statistical methods to achieve the minimization." — Sheriff (1991)

BACKGROUND

There are a number of potential geologic and technology related issues in acquiring seismic data that make it difficult to image the subsurface accurately. Near-surface modelling, seismic weathering corrections, and time delays are areas within seismic data processing that are constantly being tested, updated, and improved to increase the ability to image the subsurface of the earth. The assumptions made when modelling the frequent changes in the near-surface of the Earth are an attempt to quantify variations in weathering thickness and velocity with the intent to improve the quality of the final migrated image.

For example, the velocity of the near-surface weathering layer is much slower relative to the sub-weathering layer velocity, therefore according to Snell's law the energy traveling in the near-surface weathering layer is assumed to be vertical. This is a poor assumption when high velocity layers are at surface but is minimized when formations beneath are faster.

Reflection statics are calculated because often the lack of detailed near-surface information leads to inaccuracies (Cox, 1999). To pick reflection statics an NMO velocity field is picked and applied to stack the data in preparation for the reflection statics calculations. NMO velocity is approximated by a hyperbola and assumes lateral homogeneity (Figure 2). However, NMO deviates from the hyperbolic assumption when the topography isn't flat, strong lateral heterogeneity of velocity is present, and when there are variations in the seismic weathering thickness and velocities. (Marsden, 1993).

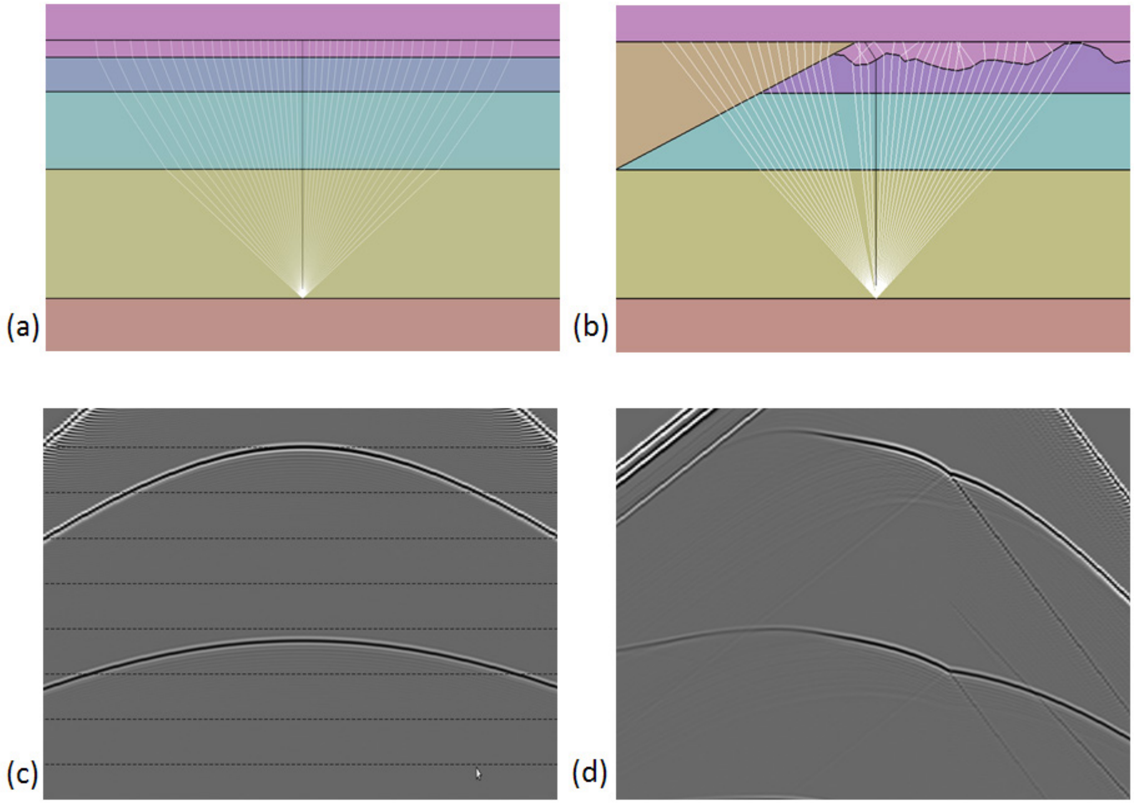

Fig. 2. Ray fan showing (a) near-vertical rays at the near-surface when velocities are slower in the near surface and when seismic weathering is flat, and (b) non-vertical rays in the near-surface when velocities are faster than the layer below and when seismic weathering is complicated, after Cameron (2016). (c) is the expected hyperbolic moveout for flat geometries, (d) is moveout that deviates from the hyperbolic assumption. — after G. Cameron (2016)

As we continue to incorporate better technology, and search for newer methodologies to mitigate the risk imposed by older assumptions, we gain greater ability to measure and calculate the subsurface of the Earth. Advances such as grid-based first-arrival tomography has many advantages over layer-based for seismic weathering corrections. First-arrival tomography has a greater potential for estimating strong lateral velocity variations and are calculated in greater detail (Zhu et al., 2000). By improving near-surface modelling methods, others have enhanced the data processing quality to ensure that they have correctly imaged deep structural layers. Particularly in foothills/structured data the weathering corrections can make or break the final image (Gray et al., 2002). As such a lot of effort has been put into conditioning of seismic data before processing to improve the final image (Baufo C. 2008; Liansheng L. et al, 2015; Zhu T. et al., 1999; Zhu T. et al., 2000).

These improvements have focussed on corrections specific to the time migration image and relatively little research and resources have been allocated to the development, enhancement, and application of near-surface modelling and weathering corrections specific to the depth migration image. Generally, the static corrections from the time processing flow are applied to the input for depth migration.

Gray and Newrick have developed processes to test the advantage of a depth specific weathering corrections and have found this method to be beneficial if the model is accurate (Gray et al., 2002; Newrick et al, 2004). This method uses the near-surface model generated for static corrections, but instead of using the vertical time shifts they applied the model to the depth migration velocity model. This method does not assume the ray-paths to be vertical but in a specific direction determined by the near-surface model based on ray-bending through the near-surface velocity model. The process described by Newrick is rudimentary and can be improved because of the enhancement of technology over the past decade.

Typically, reflection statics created in time processing are applied to the input for depth imaging. These corrections are based on NMO velocities pick in time, assuming the moveout is near hyperbolic in shape. The weathering statics previously calculated and applied to force the NMO velocity correction to be more hyperbolic to fit the assumption. However in depth when the velocity field is not the same, and the vertical static corrections derived from the seismic weathering layer have little meaning to the depth migration process and begins to pull it way from being able to predict geologic features accurately.

This research focusses on the differences of the using the time-dependent reflection statics vs the seismic weathering corrections derived from the depth velocity model. A moveout velocity field is derived from the depth imaging velocity model, thus model-based moveout (MMO) statics.

METHODOLOGY

Synthetic Data

Two isotropic synthetic datasets were used for modelling and testing MMO. One we created, a wedge thrust model with multiple layers in the footwall (Figure 3) , the other model is an acoustics synthetic dataset which was created at Amoco in 1994 and has since been publicly released in 2008 (Figure 4). The SEG open data website has quoted that this ‘model is so detailed that with the noticeable exception of lacking ground roll (since it's acoustic) it looks very much like "real data"’.

The wedge thrust model is a 20x20 grid that is 10 km long with no statics and no elevation change. The intent was to determine the effectiveness of MMO on a common thrust environment where possible problems could be readily identified. The BP 94 model is a 5x5 60km line in total length. We focussed on the 20 km on the right end of the line as highlighted by the black rectangle in figure 4. This area is not only contains near-surface velocities characteristic of potential causes of statics issues but is also representative of a foothills environment.

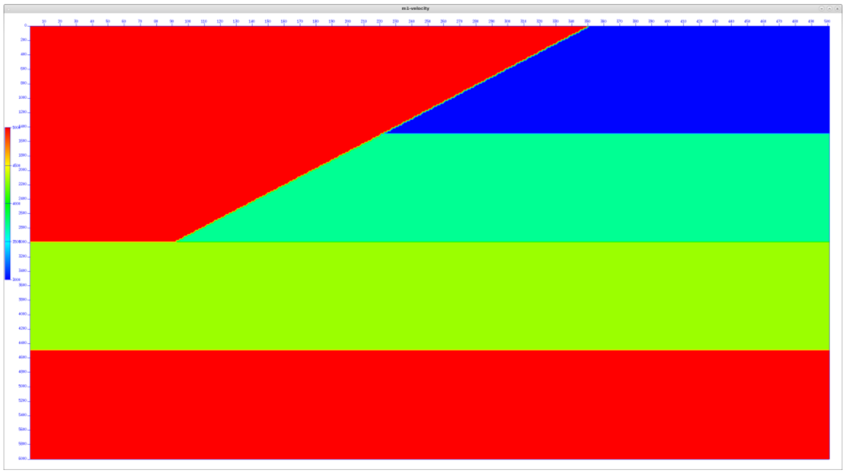

Fig. 3. Wedge thrust model.

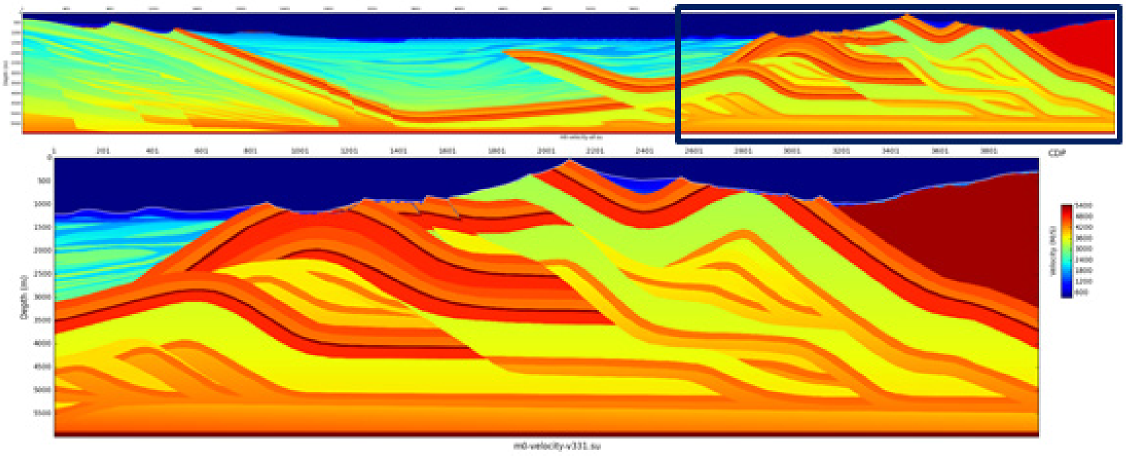

Fig. 4. 1994 BP statics benchmark model, created by O’Brien (1994). — Cameron (2016)

Using Acceleware's forward modelling program known as AxWave, we shot every fourth receiver station using a 25Hz source wavelet. The acquisition geometry for the BP 94 model was 40m source spacing and a 10 m receiver spacing producing a max fold of 126.

Model-based moveout

The wedge thrust model has no elevation change, therefore no previous statics were needed or applied. However, the BP 94 model has elevation changes and a smoothed elevation was used as the migration surface necessitating elevation statics to shift sources and receivers from topography to the migration surface.

The moveout applied to the pre-stack gathers is derived from the depth migration velocity model, hence model-based moveout. One advantage of depth imaging is the ability to capture the raypath as it moves through the subsurface; this is ignored when using NMO for reflection static corrections. By using the zero-aperture migration traveltimes, we are able to capture a more accurate shift associated with each source and receiver.

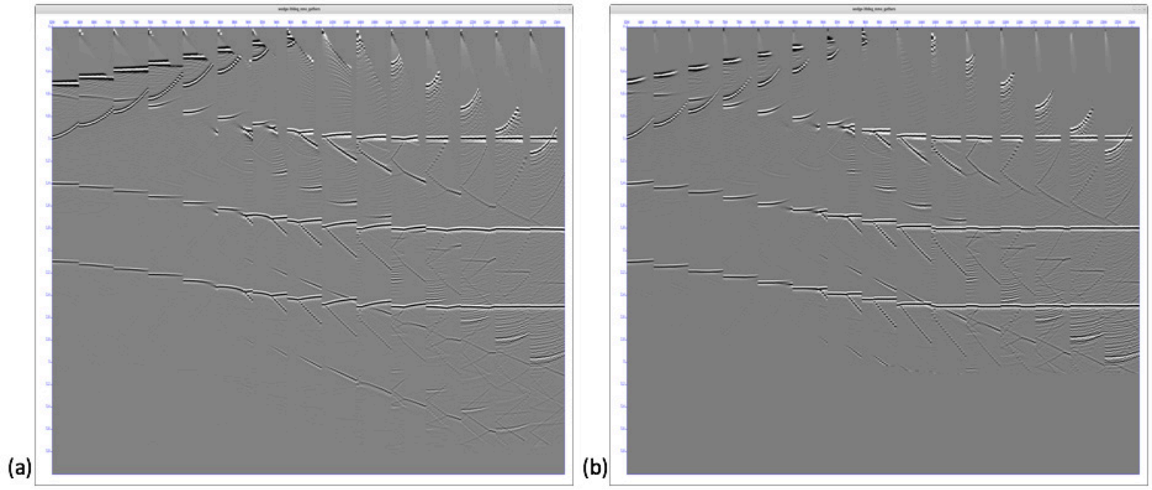

Fig. 5. (a) NMO gathers, the NMO assumption on flat reflectors below the high velocity dipping layer cannot flatten the gathers. (b) MMO gathers, MMO can compensate for the high velocity dipping layer.

When these traveltimes are applied to the depth input gathers, the gathers are converted to depth. The MMO corrected gathers are then converted back to time to limit variations associated with the correlation window and length and so that the static corrections are in time rather than depth. We used a smoothed version of the depth velocity model, so as not to reintroduce high-frequency velocity pull-up, and push-down structures. Once the reflection statics from the MMO stack were calculated they were applied to the pre-MMO conditioned depth input gathers and migrated with the same velocity field used to derive MMO. The MMO statics derived are unique to each velocity model and should be calculated whenever a new model is created (Newrick, 2005).

Reflection statics calculations

The correlation gate for reflection statics calculations is 1850-2700ms (Figure 6), with a correlation length of 100ms.

A common practice in depth imaging is to apply a smoothing factor to the velocity model before the traveltimes are calculated and the image migrated. This allows for a reduction potential erroneous traveltimes created by breaking the traveltime algorithm due to rapid and large changes in the velocity model. This is also another source of uncertainty with the depth migration process. While it may be more geological in some cases in others it is not.

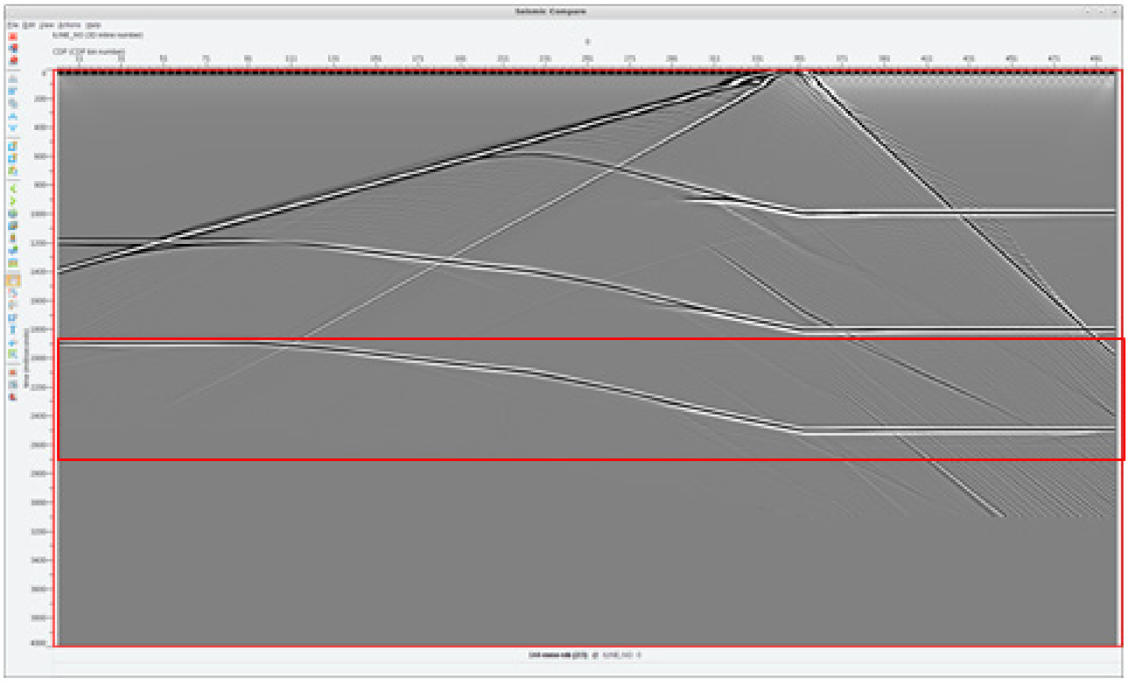

Fig. 6. Stacked gathers in time with MMO applied. The correlation gate is in red.

RESULTS

The reflection static corrections perform as expected for the time NMO stack in improving reflection continuity within the correlation gate (Figure 7). For the time MMO stack, there is a negligible difference before and after static corrections (Figure 8). The quality of the reflector continuity on the time NMO stack (Figure 7a) versus the MMO stack (Figure 8a) prior to the reflection statics calculation is predicative of the required shifts to make a more coherent stack. Regardless of the coherency of the respective input stack, the quality of the output stacks is comparable in the correlation window (Figures 7b and 8b).

We applied these reflection static corrections to the depth input gathers for migration, one with the NMO statics (Figures 9c and 10c) and another with MMO statics (Figures 9b and 10b). The results from this test show that the MMO statics have increased reflector coherency. Although, the benefit seems negligible on the wedge thrust model results when compared to the depth image without any statics applied. The reflection NMO statics have made the depth image reflections less continuous than when no statics when applied to the input gathers (Figure 9c). There is a notable difference in the magnitude of reflection NMO statics required relative to MMO statics to make a more coherent stacked image, leads us to infer that these reflection NMO statics while effective for time processing, are unfavourable to the final depth image.

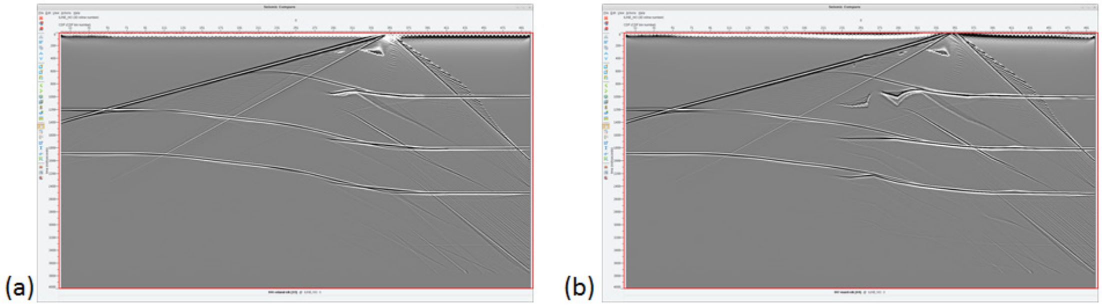

Fig. 7. Wedge NMO stack in time (a) before and (b) after reflection statics

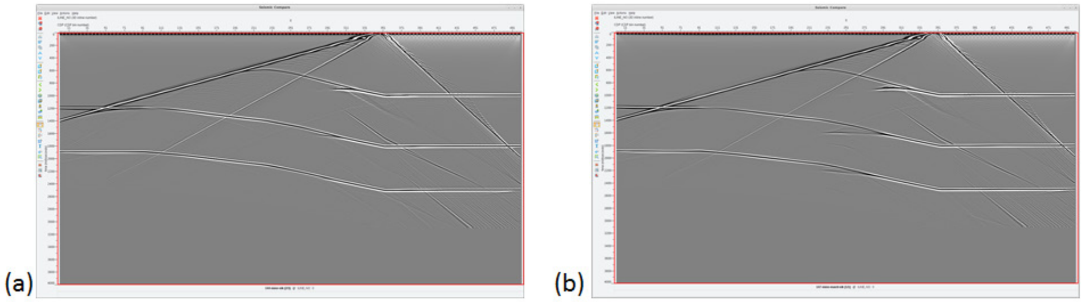

Fig. 8. Wedge MMO stack in time (a) before and (b) after reflection statics

Granted the wedge thrust model is helpful in understanding the impact of reflection NMO and MMO statics, the BP 94 results are more compelling due to its increased complexity and because of its likeness to real data. The BP 94 model results have a stronger contrast in the data quality between each output.

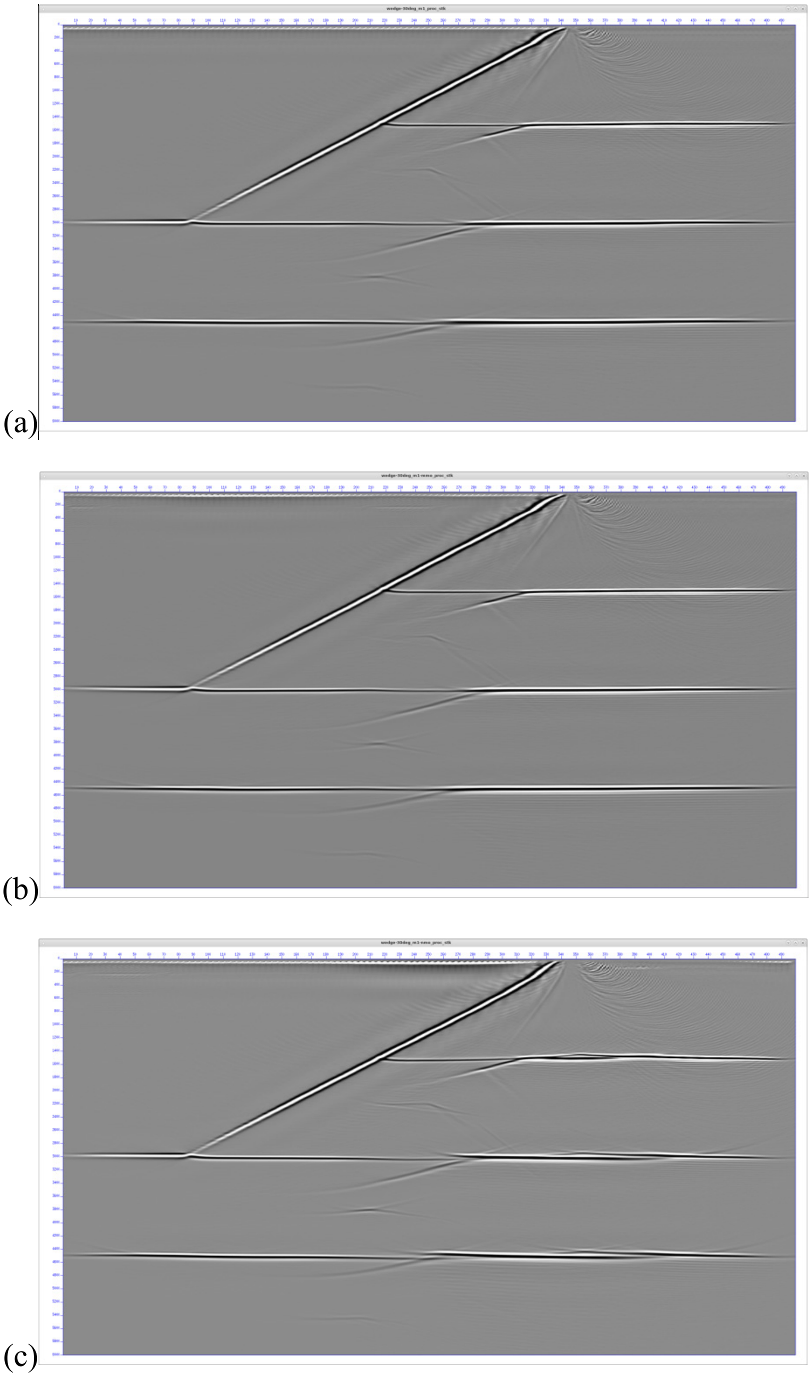

Fig. 9. Wedge reflection statics comparison (a) no statics, (b) MMO statics, (c) reflection NMO statics. Note the decreased coherency caused by the reflection NMO statics.

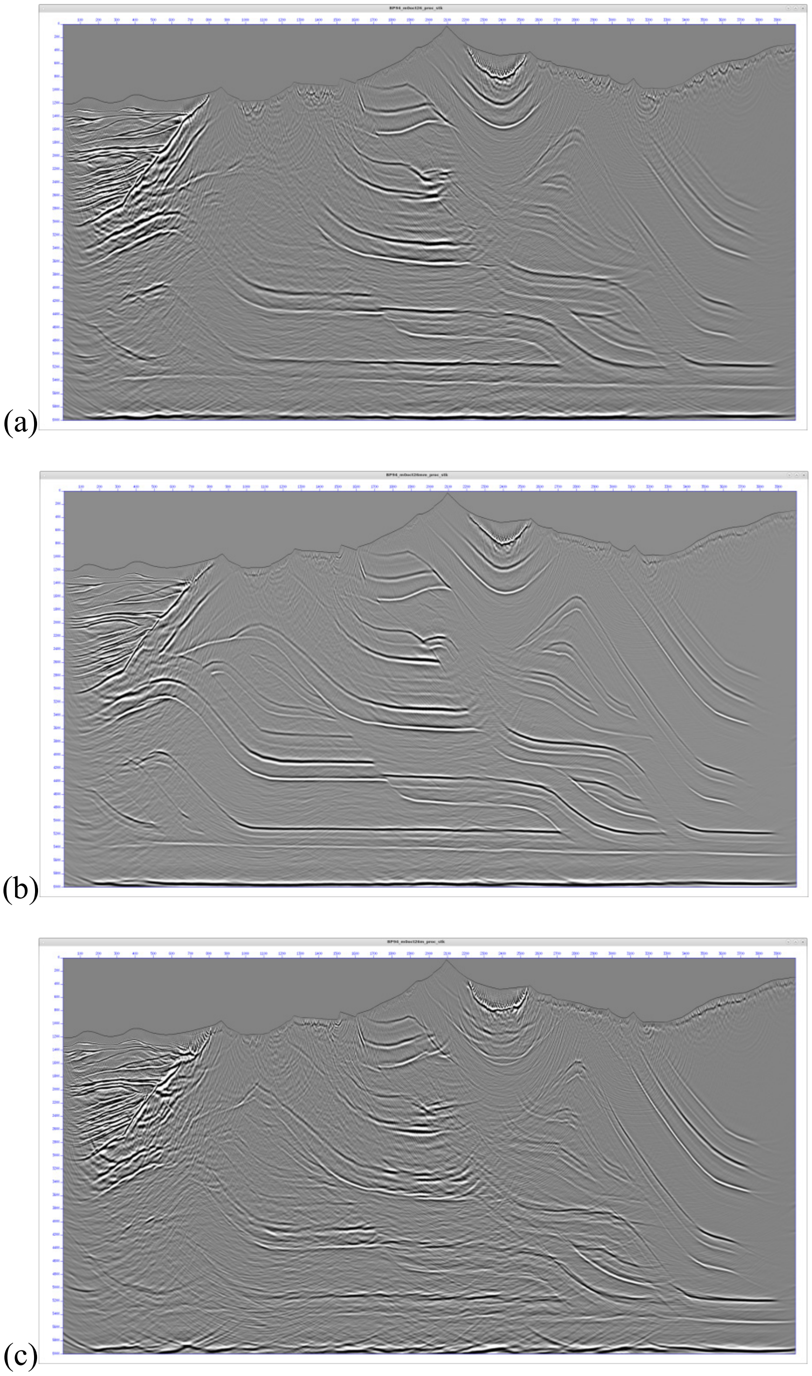

Fig. 10. BP 94 reflection statics comparison (a) no reflection statics, (b) MMO statics, (c) reflection NMO statics. Note the decreased coherency caused by the reflection NMO statics. — Courtesy of G. Cameron

DISCUSSION

MMO statics provide a better image as a part of the depth processing workflow than using the reflection NMO statics from time processing. There is increased reflector coherency which allows for more confident interpretations of foothills datasets. The wedge thrust model shows little benefit from using MMO statics compared to no statics, but it does show decreased reflector coherency when the NMO statics are applied to the depth input gathers.

Reflection NMO statics are more closely tied to the time processing workflow and are helpful through to time migration. Weathering corrections in time processing effectively prepares data for reflection statics so the moveout velocity in near-hyperbolic and can be approximated by the stacking NMO velocity. However, these statics do not correct for the positioning issues in time processing of structured data and may add to them (Vestrum, 1999). These same static corrections derived in the time processing workflow are not valid for depth imaging. The NMO assumptions are largely invalid in the foothills data. Knowing that the only differences between Figures 9b & 9c and 10b & 10c are the MMO and NMO statics, only firms the thought of the negative effect of reflection NMO statics on the depth input gathers.

MMO provides more accurate traveltimes for the moveout velocity field and is independent of whether or not a moveout can be approximated by a hyperbola. The ray-tracing for the zero-aperture migration velocities provides a more accurate moveout velocity field than the time processing NMO velocity field and has a better tie to the depth processing workflow.

CONCLUSIONS

The assumption that the moveout is near hyperbolic enough in shape to be represented by the two-term NMO equation, breaks down when the topography isn't flat, strong lateral heterogeneity of velocity is present, and when there are variations in the seismic weathering thickness and velocities. It is important to note that the NMO velocity field did increase reflection continuity for the time pre-migration stack. Be that as it may, it did not improve for depth imaging and was more damaging when applied.

Depth migration has a more unique work flow from time migration. Initially with depth imaging the only difference is the migration algorithms. However, is seems that even the conditioning of the data prior to migration could be important step as well.

FUTURE WORK

To further improve depth resolution more work can be done on how to properly incorporate the near-surface model generated by refraction statics. Newrick (2005) and Gray (2002) have discussed and shown that if the near-surface refraction model is accurate enough it can improve the depth image. However, there is little documentation on the benefits and limits of applying such a technique.

ACKNOWLEDGEMENTS

I'd like to thank Greg Cameron, Marc Langlois, and Rob Vestrum from Thrust Belt Imaging for their technical guidance. Special thanks to the SEG and BP for the open synthetic data. I am very grateful for the CREWES sponsors and NSERC through grant CRDPJ 461179-13, who allow for seismology research, and I'd like to thank the CREWES staff, advisors, and students for their support. This work was supported by Mitacs through the Mitacs-Accelerate program.

REFERENCES

Baofu, C., 2008, First-arrival tomographic inversion and its application to identify thick near-surface structures, 2008 Society of Exploration Geophysicists., pg 3255-9

Cameron, G., 2016, TBI uses seismic forward modelling to refine seismic imaging workflow (webinar), Calgary, AB, http://tbi.ca/item/gregs-numerical-modelling-podcast

Cox, M., 1999, Static Corrections for Seismic Reflection Surveys: SEG, Tulsa, OK.

Gray et al. 2002, Using Advanced Seismic Imaging Tools to See the Invisible Beneath Foothills Structures, CSEG Recorder 27, no. 3

Liansheng L. et al. 2015, An integrated strategy: constrained tomography inversion of multi-type data for near surface velocity model building, CSEG Recorder 40, no. 4

Marsden, D., 1993, Static corrections-a review, part III: The Leading Edge, 12, 210-216

Newrick, R.T. and Lawton, D.C., 2005, Vεδθ Models for Pre-Stack Depth Migration, CSEG Recorder 30, no. 6

O'Brien, M., 1994, BP Statics Benchmark Model, Amoco Tulsa Research Lab, Tulsa, OK, http://wiki.seg.org/wiki/Open_data#2D_synthetic_seismic_data

Sheriff, R. E., 1991, Encyclopedic Dictionary of Exploration Geophysics: Society of Exploration Geophysicists.

Vestrum, R.W., Don C. Lawton, and Ron Schmid (1999) "Imaging structures below dipping TI media" GEOPHYSICS, 64(4), 1239- 1246.

Zhu, T., Cheadle, S., Petrella, A., and Gray, S., 2000, First-arrival tomography: Method and application, 70th Ann. Society of Exploration Geophysicists., 2028-2031.