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# MIGRATION FROM TOPOGRAPHY: EXPERIENCE WITH AN ALBERTA FOOTHILLS DATA SET

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## ABSTRACT

In imaging steeply dipping layers of a Foothills data set, it is apparent that thrust belt geology can violate the conventional assumptions of elevation datum corrections and CMP stacking. In order to circumvent these problems, we use "migration from topography" as introduced by Wiggins (1984) and advocated by Gray and Marfurt (1995), in which we perform prestack migration on the data using correct source and receiver elevations. Migration from topography produces enhanced images of steep shallow reflectors when compared to conventional processing.

## INTRODUCTION

Recent Canadian Foothills synthetic model studies by Gray and Marfurt (1995) have shown the effectiveness of migration from topography. We show results from a real data set that agree with these model results.

The data set is the Husky structural data set which was provided for the 1995 SEG Convention Workshop on Structural Imaging by Larry Mewhort of Husky Oil and by Christof Stork of Advance Geophysical. It is a data set intended for analyzing the current state of technology for imaging complex 2-D structures. The line is from the Benjamin Creek area of southern Alberta, and many of the preliminary results of the studies were compiled by Stork, Welsh and Skuce (1995). It is anticipated that this real data set will serve as a standard for many future processing tests, in the same way that the Marmousi data (Versteeg, 1994) has provided a means for testing seismic imaging algorithms on model data.

It is our intention to demostrate use of the "migration from topography" approach of Gray and Marfurt (1995) in processing the Husky data set. Thus far, we have processed this line using various depth migration algorithms including poststack reverse-time migration, Kirchhoff depth migration and prestack reverse-time migration. For the purposes of this discussion, we shall focus on the marked contrast between the quality of near-surface images for the poststack and prestack reverse-time migration algorithms. (Our prestack Kirchhoff depth migration results were similar to those obtained by prestack reverse-time migration.) As evidenced by the subsalt imaging results of Ratcliff et al. (1994), Kirchhoff prestack depth migrations also give improvements over poststack Kirchhoff migrations.

## METHODOLOGIES

Poststack reverse-time migration has proven to be a useful and general migration method for imaging both 2-D and 3-D data as evidenced by the many papers including those of McMechan (1983), Whitmore (1983), Baysal et al. (1983) and Mufti et al. (1994). Reverse-time methods have also been successfully used for prestack depth migration as exhibited by the research of Chang and McMechan (1986, 1990), Whitmore and Lines (1986) and Wu et al. (1995). Reverse-time migration is a general method which is able to successfully define complex structures such as overhanging salt domes and overthrust folded layers. We shall show a comparison between the poststack and prestack forms of reverse-time migration for steeply dipping beds and variable topography.

Major problems with the conventional seismic processing of Canadian Foothills data occur due to the wide variation in surface elevations and the complex geology of reverse faulting in steeply dipping sedimentary layers. Thrust belt geology can cause problems with conventional methods that attempt to apply statics corrections to a datum plane. Figure 1a illustrates the conventional elevation statics "correction" from the actual recording surface to the processing datum as described by Dobrin (1976). Although the raypaths as shown in Figure 1a are steep but not vertical, this "correction"

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assumes vertically travelling energy (raypaths) between the datum plane and the surface. (The correction is only slightly more complicated for a source at depth.) If the surface layer velocity is considerably less than the velocity of deeper layers and reflections from deeper layers are travelling in a near-vertical direction, then the vertical ray statics assumption is reasonably valid. This assumption is a good one for much of the Western Canadian Basin which is covered by a low-velocity unconsolidated glacial drift layer. However, this assumption is often violated in thrust belt environments where steeply dipping layers of high seismic velocity outcrop at the surface. In foothills geology, seismic reflection energy travels at oblique angles through steeply dipping surface layers.

Secondly, thrust belt geology often causes a violation of the common-reflection point (CRP) assumptions. As shown by the sketch in Figure 1b, source-receiver combinations having a common midpoint (CMP) will generally not share a common-reflection point for a steeply dipping event. Therefore, the sorting and stacking of common-midpoint traces will cause a smearing of reflection energy. This smearing effect will be particularly deleterious for shallow steeply dipping events which often occur in foothills geology. Due to the breakdown of these assumptions, it is not surprising that shallow steeply dipping events are not clearly imaged by conventional processing.

Both the statics correction problem and the CMP problem can be obviated by the use of prestack migration with sources and receivers at their correct elevation – provided we have an accurate velocity model. This concept is illustrated for synthetic examples by McMechan and Chen (1990). Figure 1c shows the basic model for prestack migration where the source and receiver positions are correctly located. This model follows the discussion of Liner and Lines (1994) who describe prestack migration in terms of aplanatic surfaces. For a particular traveltime, the aplanatic surface defines the locus of possible reflection points for particular locations of source and receiver. For a constant velocity medium, the aplanatic surfaces would be ellipses. For variable velocity media, the aplanatic surface is a distortion of an ellipse which can be computed by solutions to the eikonal equation or by solutions to the wave equation. The use of eikonal solvers to define aplanatic surfaces is used in Kirchhoff migration (Gray and May, 1994; Zhu and Lines, 1995), whereas reverse-time prestack migration methods can use eikonal solvers and finite-difference wave equation solutions to effectively define aplanatic surfaces (Chang and McMechan, 1986, 1990; Botelho and Stoffa, 1988). Seismic trace energy is spread over these aplanatic surfaces for a given trace. We then repeat this procedure for a multitude of traces and then sum the trace migrations to obtain the migrated image in depth.

Prestack migration from topography does not suffer from either the shortcomings of datum statics corrections or the assumptions that CMPs are the same as CRPs. As we shall demonstrate, these shortcomings are particularly problematic for Foothills data. The key ingredient for the success of prestack migration is the availability of an accurate velocity model. As pointed out by Lines et al. (1993), there are various methods for velocity analysis. Some of the most general (and useful) techniques for complicated geological structures involve the iterative use of prestack depth migration.

One prestack migration technique uses the criterion that the depth image at a CRP should be independent of offset. That is, the correct depth estimate of the reflector should not depend on the geometry of the seismic experiment. In order to test the validity of the migration result and the velocity model, we apply prestack depth migration to the data and for a CRP we examine the offset variation of the depth migrations. A variation in the depth estimates versus offset leads to velocity adjustment of the model in order to eliminate "smiles" or "frowns" as a function of offset for migrated CRP depth gathers. This approach is very similar to normal-moveout analysis of CMP data. As explained by Whitmore and Garing (1993), the same kind of analysis can be performed using plane-wave angles instead of source-receiver offset.

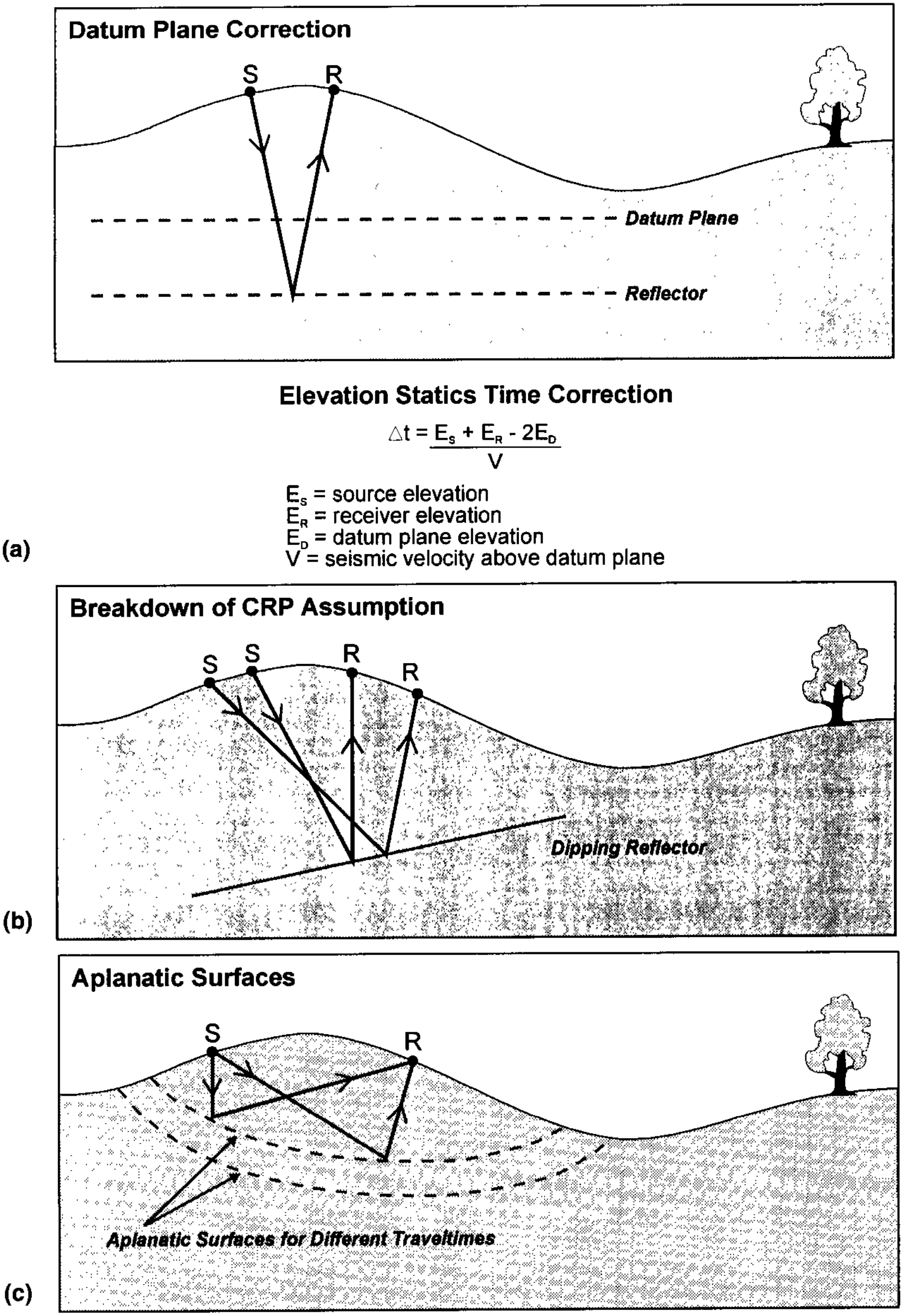
A second velocity analysis technique attempts to improve the focusing of the prestack migration by velocity adjustment. This interpretive method is similar to the focusing of a camera in that the correct velocity model is assumed to be the one which provides the most focused image. This form of migration velocity analysis is analogous to velocity analysis by CMP stacking.

Traveltime tomography represents yet another general method for velocity model estimation. This method can utilize prestack traveltimes from direct arrivals, refracted arrivals or reflected arrivals. Tomography sometimes experiences difficulties with complex geology since one has to be careful that the picked traveltimes are the traveltimes which one is modelling by ray tracing.

For the Husky data set, there is also additional information in the form of well logs and VSP data which can provide constraints on the velocity model. One of these constraint methods developed by Lines (1993) attempts to match depth migrations to formation tops. Although this was helpful for this study, it had the shortcoming that many layers in the model do not intersect the logged portions of the wells. Therefore, this migration/inversion method will not provide the entire velocity model picture in this case. Iterative prestack depth migration was the main tool in our development of a velocity model. Geological interpretation of the complex structural models by Jamie Jamison also provided a key part of the velocity model definition.

## RESULTS

The differences between conventional processing from a flat datum (including poststack depth migration) as opposed to prestack depth migration from topography are most pronounced on the shallow steeply dipping reflections. This can be seen in a comparison between the poststack migration with datum corrections in Figure 2 and a prestack migration



**Elevation Statics Time Correction**

$$\Delta t = \frac{E_S + E_R - 2E_D}{V}$$

$E_S$ = source elevation
$E_R$ = receiver elevation
$E_D$ = datum plane elevation
$V$ = seismic velocity above datum plane

**Fig. 1. (a)** The elevation statics "correction" is an approximation which assumes vertical raypaths between the datum plane and the surface, although, as shown here, the raypaths are often not quite vertical (Dobrin, 1976). **(b)** Raypaths for common midpoint (CMP) do not coincide with a common-reflection point (CRP) for dipping reflectors. **(c)** Aplanatic surfaces define isochrons of possible reflection points for arbitrary source-receiver elevations.

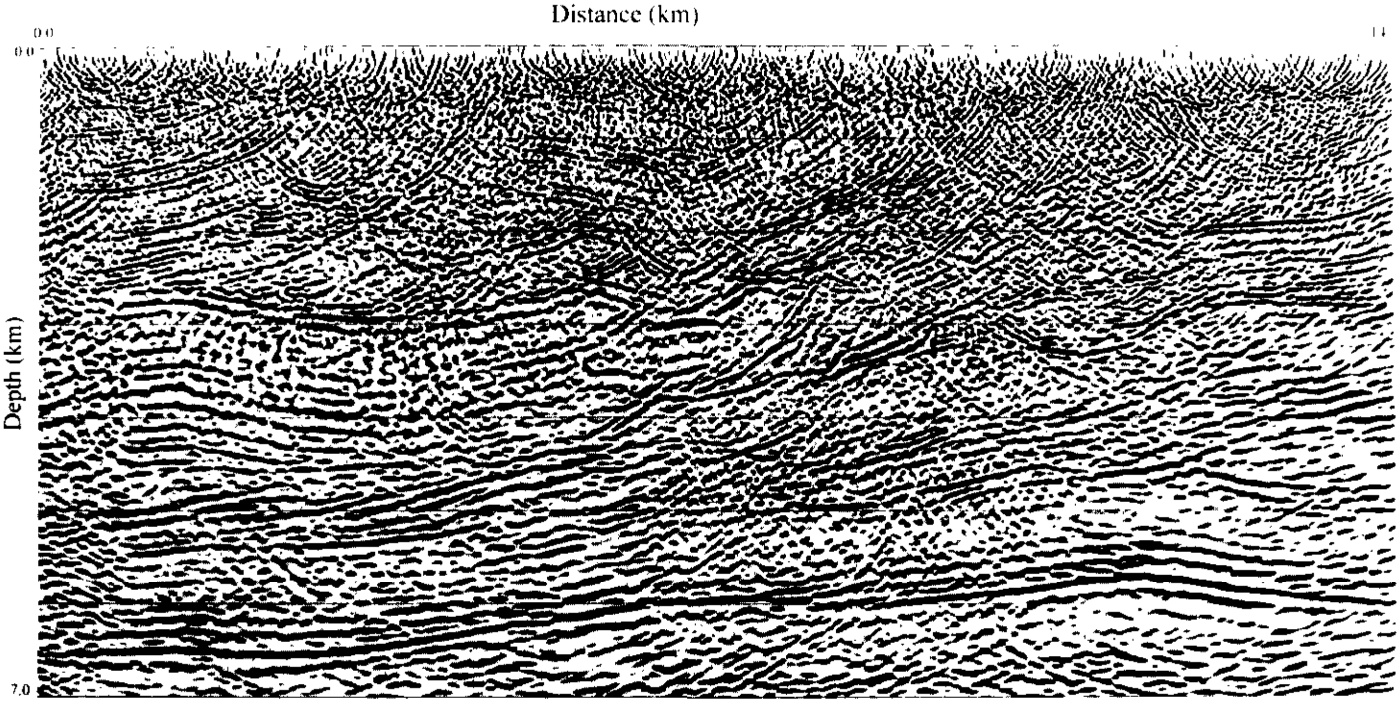


**Fig. 2.** Poststack migration of data with datum corrections. Section width = 14.7 km. Section depth = 7 km.

of the data in Figure 3 which uses the same velocity model. We see this difference very clearly in the upper left portion of the sections (upper 3 km and westmost 4.5 km of the section) where there is a syncline containing dipping beds of the Brazeau, Wapiabi, Cardium, Blackstone and Blairmore formations. An enlargement of this zone in Figures 4a and 4b shows a distinct difference between the poststack and prestack migrations. The poststack migration with elevation statics correction to a datum lacks near-surface coherent energy while the prestack migration from topography shows a clearer definition of near-surface reflections. In the middle of the section in Figure 4a, the poststack migration also shows some reflection energy with conflicting dips; these conflicting dips do not appear in Figure 4b. Trace density in Figure 4b is less than in Figure 4a due to trace interpolation used in the reverse-time algorithm.

In comparing the poststack reverse-time migration of Figure 2 to the prestack reverse-time migration of Figure 3,

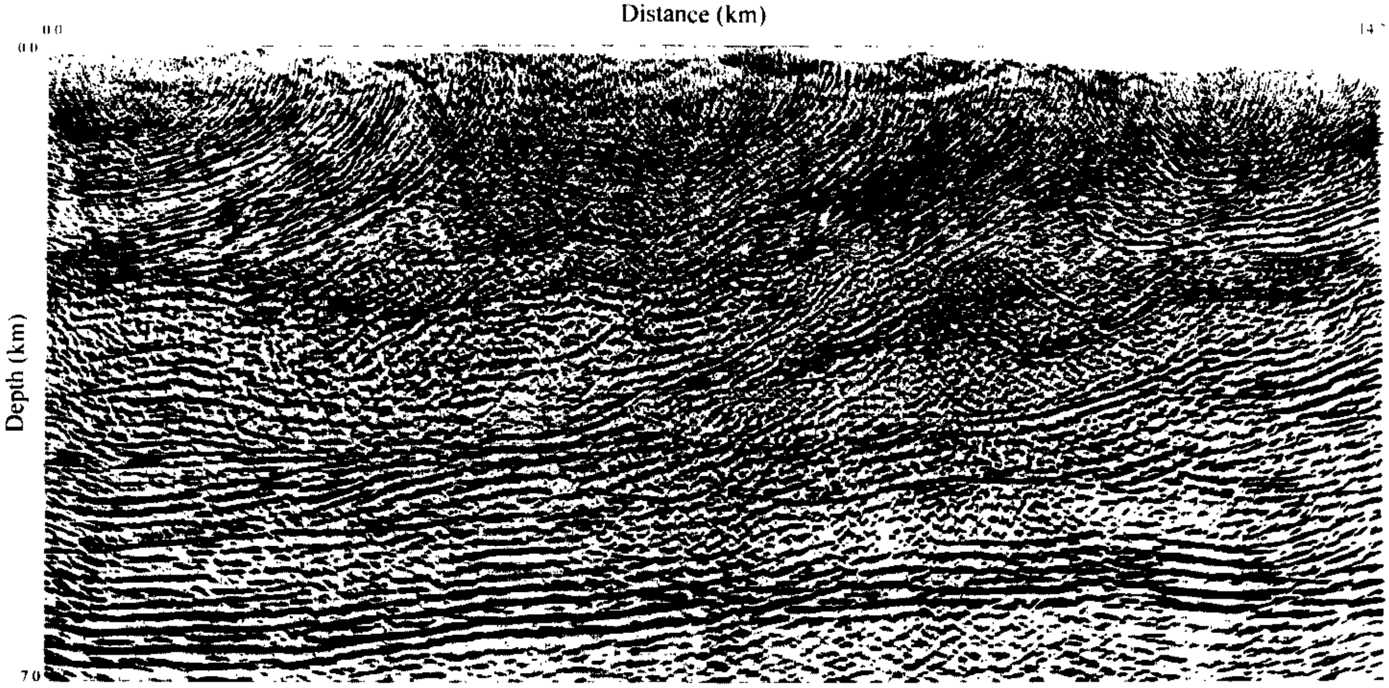


**Fig. 3.** Prestack migration from topography. Section width = 14.7 km. Section depth = 7 km.

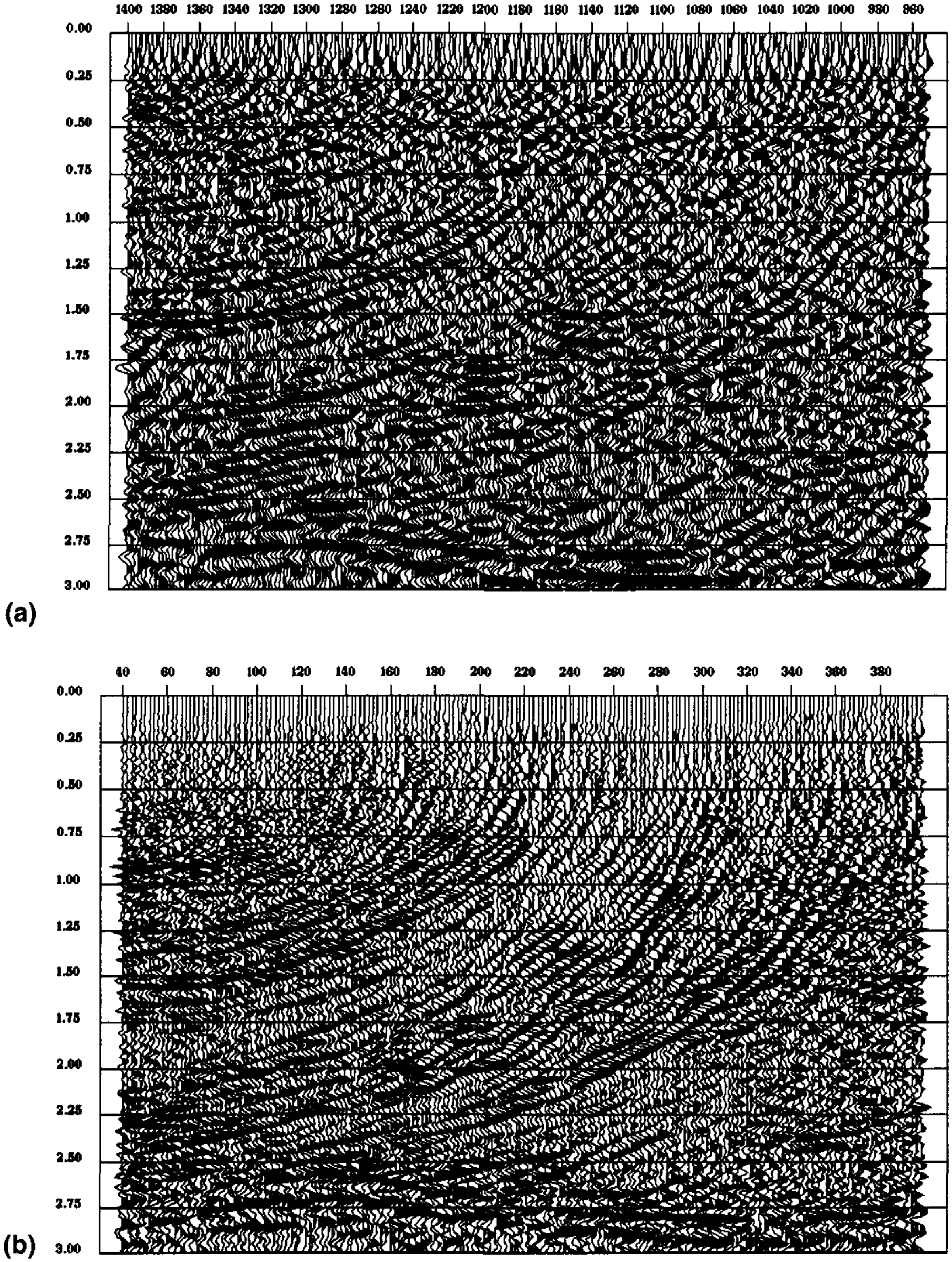


**Fig. 4. (a)** Enlarged portion of poststack reverse-time migration. **(b)** Enlarged portion of prestack reverse-time migration. Section width = 4.5 km. Section depth = 3 km.

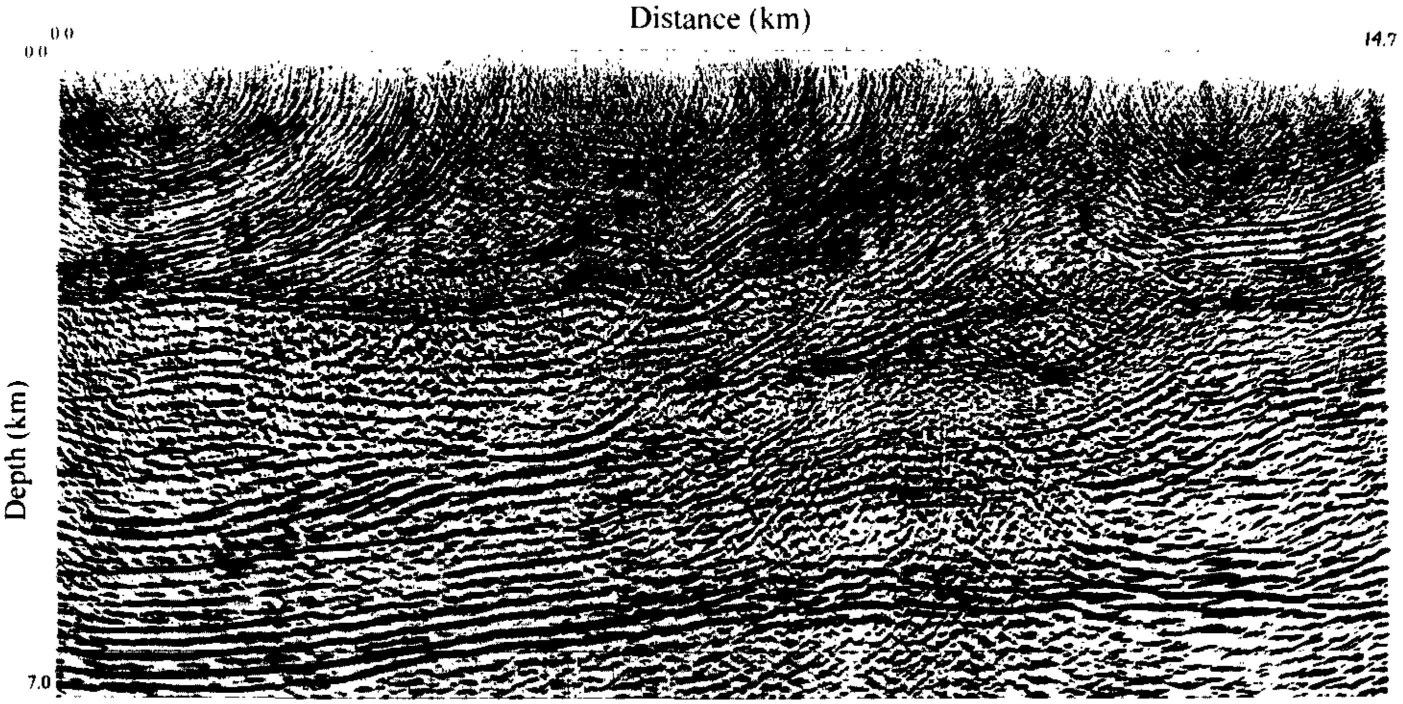


**Fig. 5.** Prestack migration from topography using improved velocity model. Section width = 14.7 km. Section depth = 7 km.

we note that the depth migration differences between the two sections becomes less obvious for deeper reflections. This is an expected result since as offset/reflection depths decrease, raypath differences between prestack and poststack models become less pronounced. In almost all cases, the prestack migration result is the same or better than the poststack migration. There are still improvements which can be made by adjustment of the velocity to produce the prestack depth migration result of Figure 5. (Further improvements could possibly be made by further adjustment of velocities on the eastern segment of the line.) According to Skuce (1995) velocity models should also take anisotropy into account, especially in shale layers. This appears to be a very difficult inversion problem for complicated structures unless rock property anisotropy measurements are available as constraints on the problem.

## CONCLUSIONS

Useful depth migrations of Foothills data depend on accurate velocity models, general migration and velocity analysis algorithms, and detailed interpretation. The results of the Husky data set experiments for the 1995 SEG workshop will undoubtedly see future publications. Thus far, one of the largest improvements in processing that we have seen is due to the use of prestack migration from topography. In this sense, our results for the Husky data set basically agree with the synthetic model results of Gray and Marfurt (1995). Our conclusions are that for shallow, steeply dipping Foothills reflections, prestack migration from topography will provide a substantial improvement over the conventional processing flow of elevation datuming, CMP stacking and poststack migration.

## REFERENCES

Baysal, E., Kosloff, D.D. and Sherwood, J.W.C., 1983, Reverse time migration: Geophysics **48**, 1514-1524.

Botelho, M.A.B. and Stoffa, P.L., 1988, Velocity analysis using reverse-time migration: EOS **49**, 1326.

Chang, W.F. and McMechan, G.A., 1986, Reverse-time migration of offset vertical seismic profiling data using the excitation-time imaging condition: Geophysics **51**, 67- 84.

______ and ______, 1990, 3D acoustic prestack reverse-time migration: Geophys. Prosp. **38**, 737-755.

Dobrin, M., 1976, Introduction to geophysical prospecting: McGraw-Hill Book Co.

Gray, S.H. and Marfurt, K.J., 1995, Migration from topography: improving the near-surface image: Can. J. Expl. Geophys. **31**, 18-24.

______ and May, W.P., 1994, Kirchhoff migration using eikonal equation traveltimes: Geophysics **59**, 810-187.

Liner, C.L. and Lines, L.R., 1994, Simple prestack migration of crosswell seismic data: J. Seis. Expl. **3**, 101-112.

Lines, L.R., 1993, Optimization of seismic migration through use of well information: Can. J. Expl. Geophys. **29**, 419-428.

______, Rahimian, F. and Kelly, K.R., 1993, A model-based comparison of modern velocity analysis methods: The Leading Edge **12**, 750-754.

McMechan, G.A., 1983, Migration by extrapolation of time-dependent boundary values: Geophys. Prosp. **31**, 413-430.

______ and Chen, H.W., 1990, Implicit static corrections in prestack migration of common-source data: Geophysics **55**, 757-760.

Mufti, I.R., Pita, J.A. and Huntley, R.W., 1994, Finite-difference depth migration of exploration-scale 3-D seismic data: 64th Ann. Internat. Mtg., Soc. Expl. Geophys.

Ratcliff, D.W., Jacewitz, C.A. and Gray, S.H., 1994, Subsalt imaging via target-oriented 3-D prestack depth migration: The Leading Edge **13**, 163-172.

Skuce, A., 1995, Seismic imaging in the Canadian Rocky Mountain Foothills: Ann. Conv., Workshop #6, Soc. Expl. Geophys., Paper.

Stork, C., Welsh, C. and Skuce, A., 1995, Demonstration of processing and model building methods on a real complex structure data set: Ann. Conv., Workshop #6, Soc. Expl. Geophys., Proceedings.

Versteeg, R., 1994, The Marmousi experience: velocity model determination on a synthetic complex data set: The Leading Edge **13**, 927-936.

Wiggins, W., 1984, Extrapolation and migration of nonplanar data: Geophysics **49**, 1239-1248.

Whitmore, N.D., 1983, Iterative depth migration by backward time propagation: 1983 Mtg., Soc. Expl. Geophys., Exp. Abstr., 827-830.

______ and Garing, J.D., 1993, Interval velocity estimation using iterative prestack depth migration in the constant angle domain: The Leading Edge **12**, 757-762.

______ and Lines, L.R., 1986, Vertical seismic profiling depth migration of a salt dome flank: Geophysics **51**, 1087-1109.

Wu, W., Lines, L.R. and Lu, H., 1995, Reverse-time migration with finite-difference solutions of the acoustic wave equation: Ann. Mtg., Soc. Expl. Geophys., Exp. Abstr., 1149-1152, and accepted for publication in Geophysics.

Zhu, J. and Lines, L.R., 1995, Practical subsurface imaging by prestack depth migration and velocity anaylysis: Ann. Mtg., Can. Soc. Expl. Geophys., Exp. Abstr., 5-6.