P-P and P-SV seismic imaging in the Triangle Zone, Canadian Rocky Mountain Foothills

Chakrit Sukaramongkol and Don C. Lawton

ABSTRACT

Seismic-reflection data were recorded over the Triangle zone near Sundre by Petrel Robertson in January 1990. The survey line was approximately 15 km. in length covering both the eastern and the western limbs of the Triangle zone structure.

The data were processed with an emphasis on the shallow parts of the data. Attempts were also made to enhance deeper horizons which are of exploration targets. Velocity variations, both laterally and vertically, were observed, specially between the Triangle Zone core, a duplex and its eastern limb. Detailed velocity functions followed by corresponding statics corrections were found to be important factors in improving the stack section's quality. Three migration techniques, i.e., F-K(Stolt) migration, Phaseshift migration and Finite difference(F-D) migration were tested on the stacked data. The resulting migrated sections from these three techniques are of comparable quality. Signal to noise ratio of the final section was enhanced considerably by the applications of a band-pass filter and KLSTAK (signal-to-noise ratio enhancement via the Karhunen-Love transform) method.

Using sonic logs of 3 wells from the area and derived synthetic seismograms, geological information was tied to the seismic data. An interpretation of the final section is shown in Figure 6, in which the upper and the lower detachments including the duplex are well defined. Also, a pop-up structure which formed by minor thrust faults associated with the advancement into the foreland basin of an intercutaneous wedge was found below the hanging wall of the upper detachment fault. The presence of the pop-up structure indicates that the Foothills deformation front is not stable but moving toward the foreland.

Modeling studies show that time-structural highs presented at the deep horizons, e.g., Mississippian, Devonian and Cambrian formations are partially attributed to the shallow-lateral velocity variations. Further analysis also indicates that these lateral velocity variations are mild to moderate, and do not produce significant amounts of ray bending as expected.

This study also demonstrates the application of converted-shear wave (P-SV) data in structural mapping.

INTRODUCTION

The term " Triangle Zone" was applied in an informal fashion to describe structures at the leading edge of the disturbed belt of the southern Canadian Foothills (Teal, 1983). It is characterized by an area where a southwest dipping sequence of thrusted rocks juxtapose against northeast dipping molasse of the mountain front monocline (Skuce et al., 1992) forming two sides of a triangle. In Alberta, the Triangle zone is underlain by relatively flat-lying autochthonous rocks of Mesozoic to Paleozoic ages.

The Triangle Zone in Alberta has formed at the eastern margin of the thrust and fold belt as a result of the movement of intercutaneous wedges towards the foreland basin. Each wedge tapered northeastward, and is bounded upward and downward by roof and sole thrusts (Charlesworth et al., 1987) which Jones (1982) defined as the upper and the lower detachments, respectively. The vergence of the sole thrust is foreland-directed, whereas that of the roof thrust is hinterland-directed (Lawton and Spratt, 1991). The foreland-dipping sediments of Cretaceous and Tertiary age in the hanging wall of the roof thrust form the west flank of the Alberta syncline (Jones, 1982), and he also indicated that the merging of the upper and the lower detachments beneath the axis of the Alberta syncline marks the eastern limit of foothills deformation.

A large number of seismic surveys have been conducted across the Triangle zone since they are the sites of significant accumulations of oil, gas and coal (Skuce et al., 1992). However, the Triangle zone structure which resides in the shallow parts of the section is often poorly imaged because most of the acquisition and processing have been focused on deep horizons of Mississippian carbonate reservoirs. Also, it is observed that in the zones below the Triangle zone core, the data quality of both shallow and deep horizons deteriorates considerably. This might be resulted from rough surface topography, near-surface velocity inversion, complicated-seismic ray path geometry through the Triangle zone core, or even improper techniques in acquiring and processing the seismic data from these structural features.

It is anticipated that a better understanding of the Triangle zone geometry will lead to improved data acquisition and processing techniques for the data collected from this structure. In this study we are also evaluating the application of the P-SV seismic method in structurally complex environments.

SEISMIC REFLECTION DATA

Seismic data presented in this paper were acquired by Petrel Robertson in January 1990. The survey line was approximately NE-SW across the Triangle zone near Sundre, northwest of Calgary. The total length is about 15 km and the northeastern half of the line is slightly crooked.

The data were shot using vibroseis as seismic sources with a sweep length of 12 s, 25-100 Hz sweep frequency, and were recorded with a split spread geometry. The recording instrument used in this survey was the 240-channel Sercel with 10 Hz geophones. Each geophone array consisted of 12 geophones spread over 35 m. The average group interval was 33 m. and offsets ranged from 66 to 3993 m. The shotpoint interval was 99 m. and the data were recorded to 3 s two-way time with 2 ms sampling rate. The nominal subsurface coverage was 40 fold, but the actual fold varied considerably because the line was crooked and also the station intervals were not constant. Table 1 gives a summary of the data acquisition parameters used in this survey.

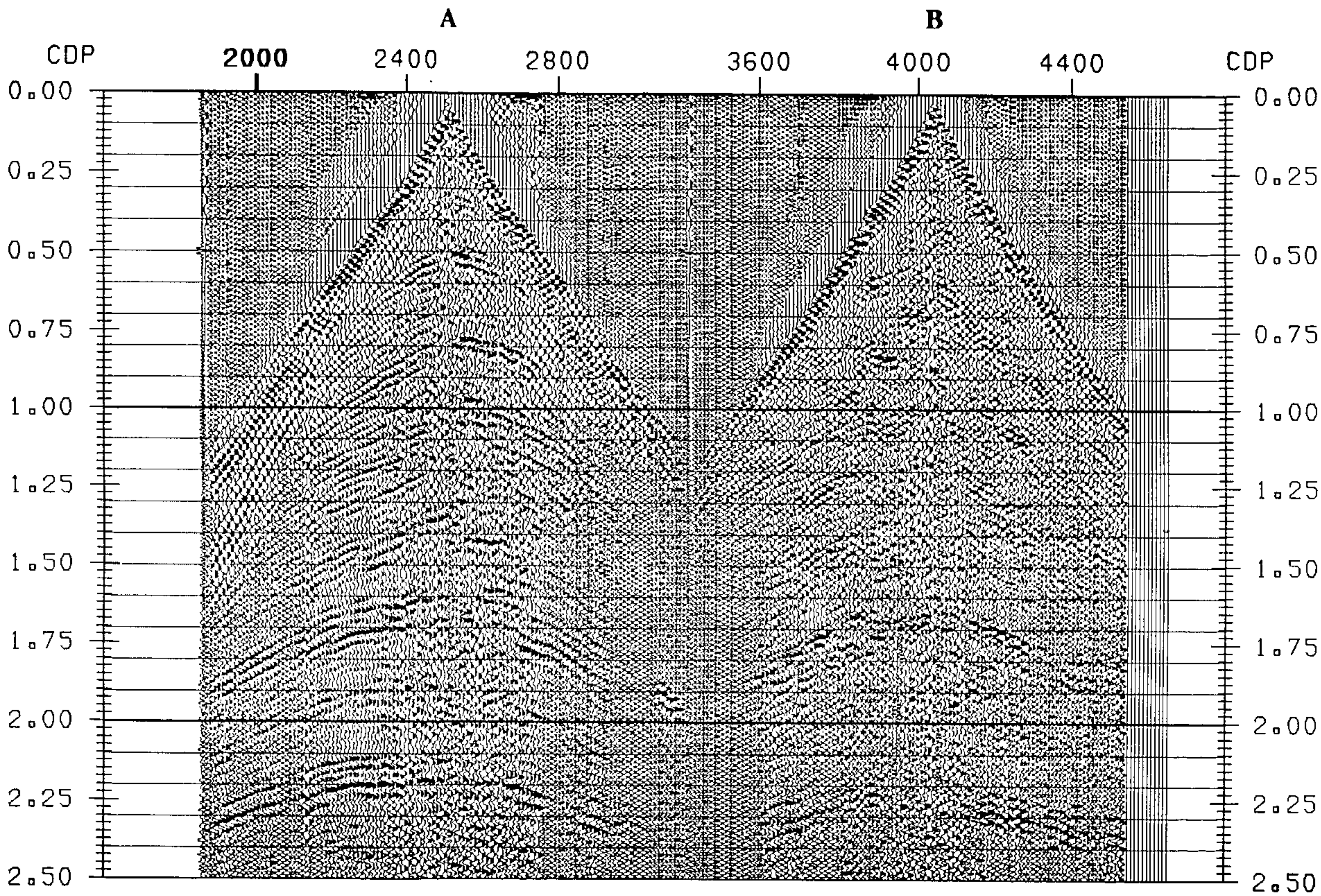


FIG. 1. Shot records from the eastern limb(A) and the core(B) of the Triangle Zone.
(Note the severe statics problems of the record B.)

Table 1. Field Acquisition Parameters

Spread	120 X 120, 3993-66-*-66-3993 m.Source
Interval	99 m.
Receiver Interval	33
Acquisition Fold	4000 %
Source	Vibroseis
Sweep	12 s, 12 sweeps, freq. 12-96 Hz.
Receivers	geo., 10 Hz., 12 inline over 33 m.
Instruments	Sercel/FPCS 240 trace
Tape Format	SEG D
Field Filters	out/178 Hz. , Notch : out
Sample Rate	2 ms.
Record Length	3 s.

SEISMIC DATA PROCESSING

The data were processed using the Inverse Theory Applications (ITA) processing system with the processing flow in Figure 2. Primary emphasis was placed on the shallow structures, i.e., the duplex, the upper and lower detachments, the pop-up structure and its associated faults planes. Also, it was attempted to improve reflection continuity of autochthonous reflections, in particular, Mississippian and Devonian formations which are of exploration interests.

As the survey geometry was slightly crooked, it was necessary to rebin the data by means of CMP-rebinning. This was carried out to optimize subsurface coverage along the crooked line. A series of deconvolution parameters were tested, and a deconvolution operator length of 85 ms., along with prewhitining of 0.1 % were applied to the data. Consequently, initial velocity analysis was performed. Both lateral and vertical velocity variations were observed. This indicates that detailed velocity functions are necessary for processing of this seismic line. Based on these initial velocity functions, the CMP data were then NMO corrected followed by geometrical spreading and residual statics corrections. Finally, a brute stack section was generated and analyzed for further improvements. It should be noted that velocity analysis, geometrical spreading and residual statics corrections were performed iteratively until the optimum stack section (Figure 3) was achieved. Dip-moveout (DMO) and pre-stack depth migration are also being tested.The DMO corrected section is displayed in Figure 4 in which a small improvement of a fault plane on the eastern side of the pop-up structure is seen.

Three migration algorithms, namely, F-K(Stolt), Phaseshift and Finite Difference (F-D) were tested on the stack section. It was found that all of them yield comparable results in terms of events' repositioning. The F-K migration was then applied to the data followed by bandpass filtering (8/15 65/85) and KLSTAK (signal to noise ration enhancement) method. The final section is displayed in Figure 5 .

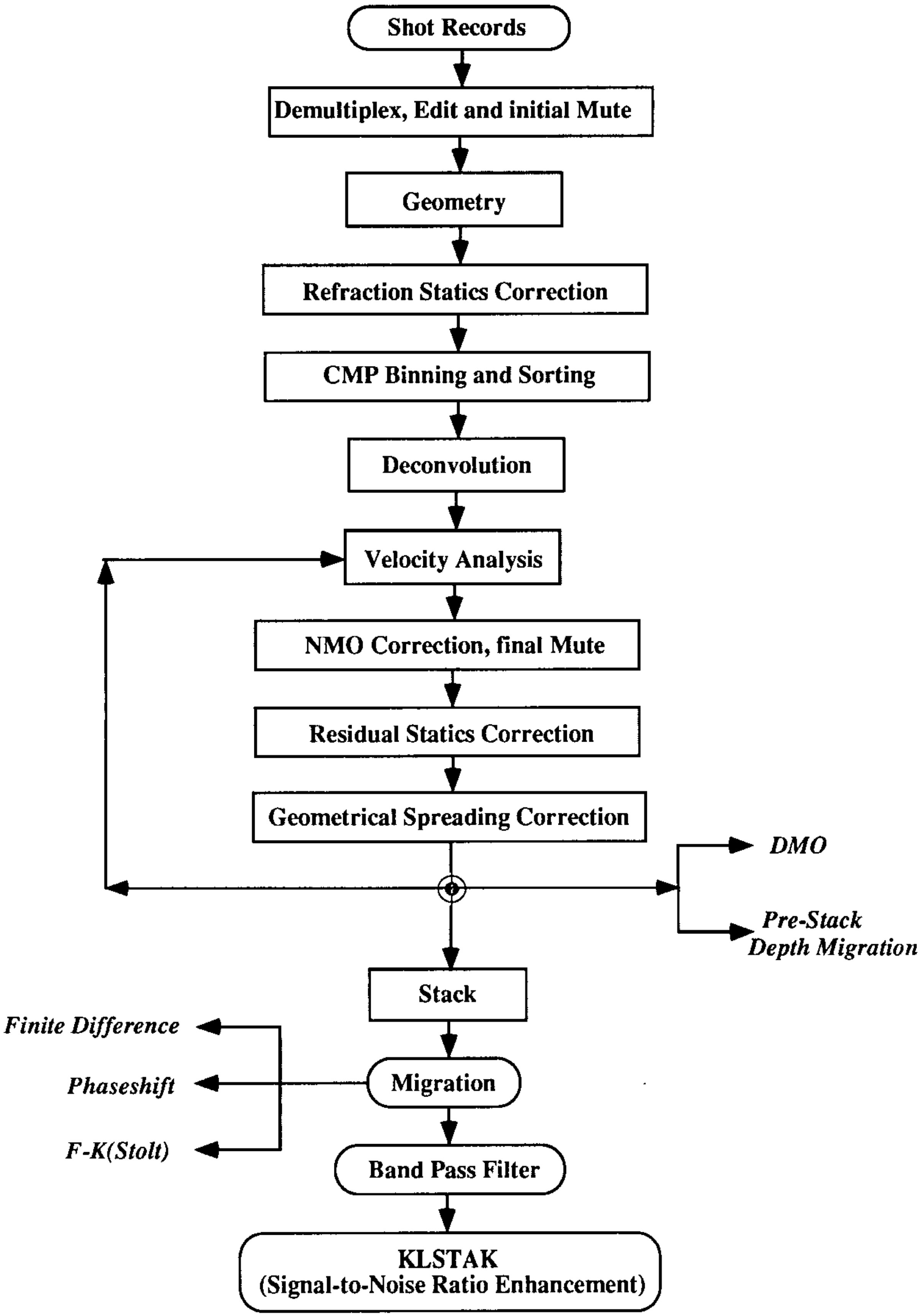


FIG. 2. Processing flow chart for the seismic line FTC-002B

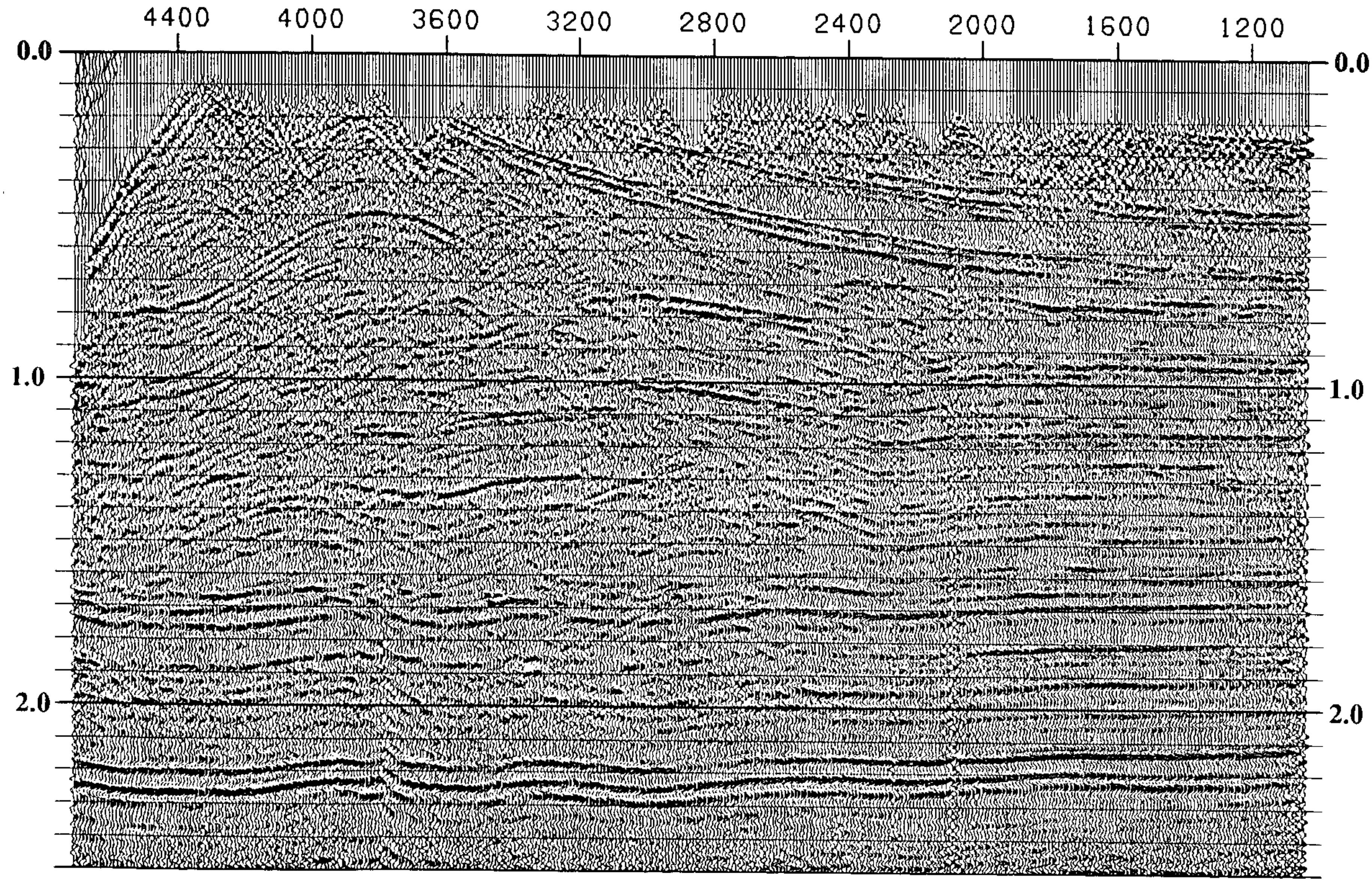


FIG. 3. A final stack section produced by the processing flow in Figure 2.

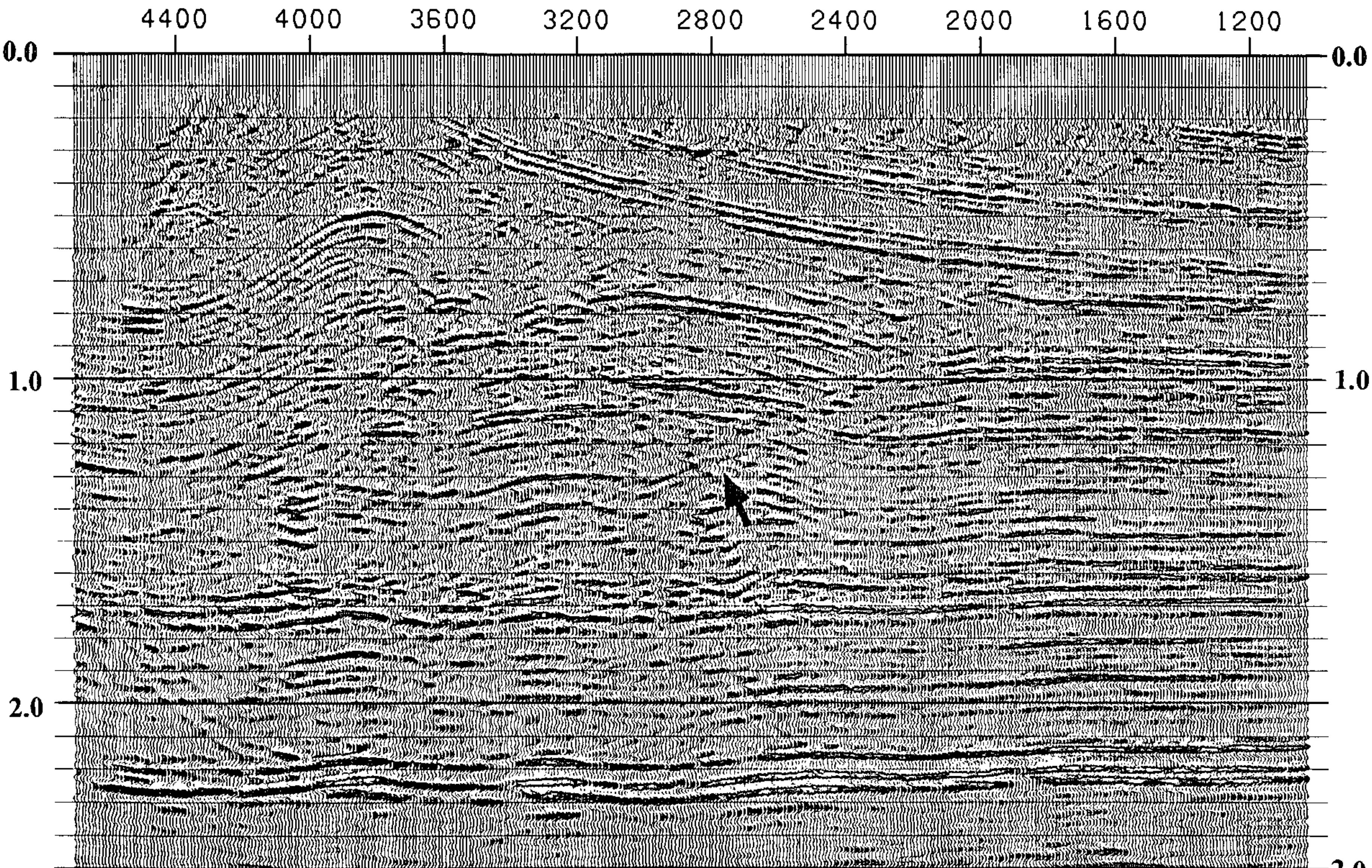


FIG. 4. A DMO corrected section after phaseshift migration, band pass filter and KLSTAK.
(Note a small improvement of the fault plane indicated by an arrow)

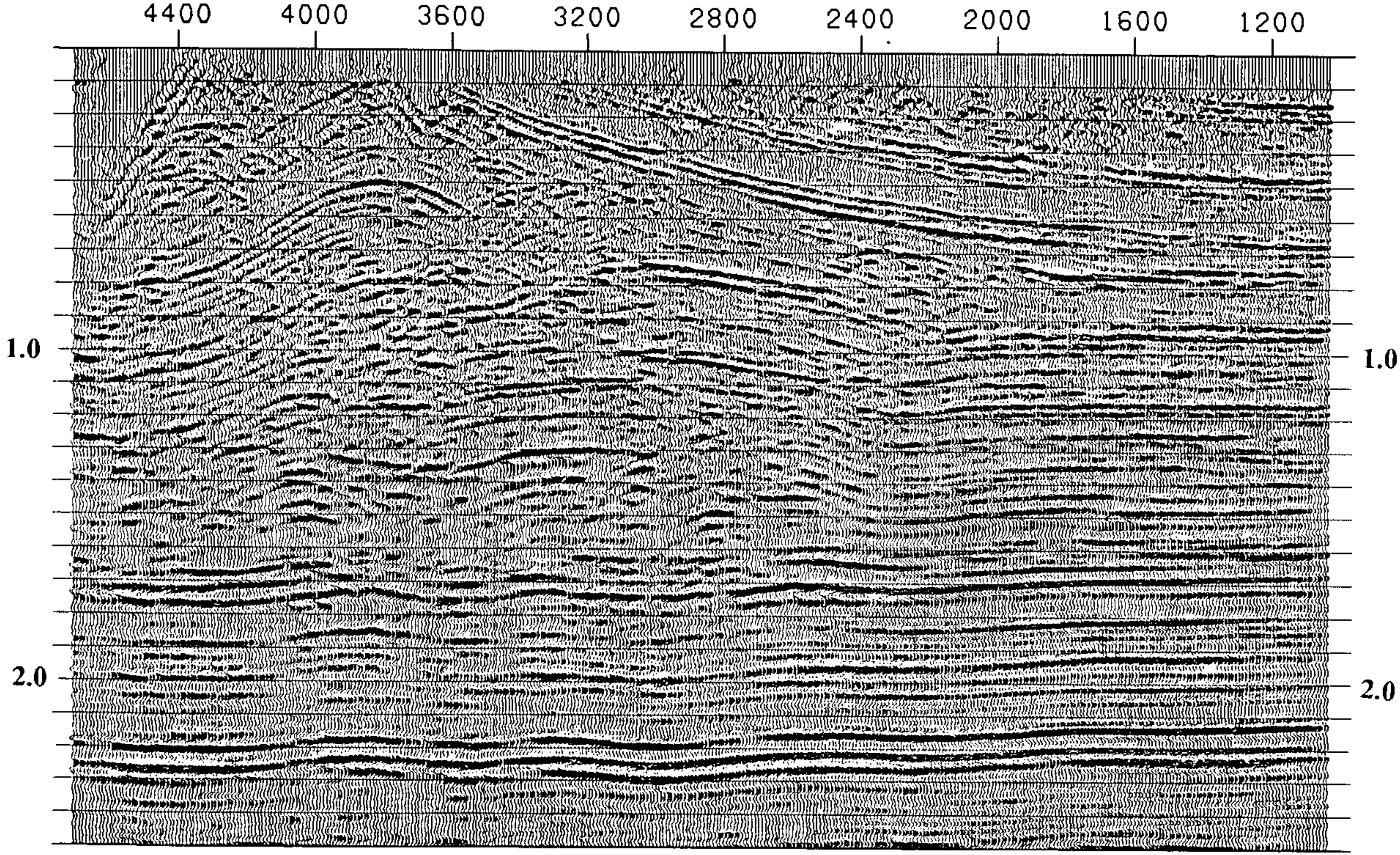


FIG. 5. The final section (DMO was not applied to this section).

SEISMIC INTERPRETATION

Synthetic seismograms were generated from wells located along the line, and were used to correlate the seismic data to the geological information. Interpretation of the seismic line FTC-002B is shown in Figure 6 in which the upper and the lower detachments, the duplex and the pop-up structure are indicated.

The upper detachment of the Triangle Zone in this region dips uniformly (approximately 15 degrees) towards the foreland and becomes folded over the duplex on the western limb of the Triangle Zone. The lower detachment exhibits a staircase geometry with a flat almost parallel to young strata in the northeastern half of the section. It is interpreted to be a blind thrust and merge with the upper detachment to the east. Note that almost no shortening was observed in the strata above the upper detachment while the strata below it have been severely deformed by the thrusting and folding processes. This indicates that strain must be accommodated by strata between the eastern tip of the duplex and the upper detachment. These strata might be transported from the west during foothills deformation.

In addition to the upper and lower detachments, the most prominent structural features in this seismic section are the duplex (which is composed of folded horses) and the pop-up structure. The folded horses were resulted from the movement of the intercutaneous wedge along the staircase-geometry lower detachment. As movement developed along a thrust, its staircase geometry produced bending folds in the overlying strata and older thrusts (Charlesworth and Gagnon, 1985). Charlesworth and Gagnon further indicate that, the most external or the lower most of these thrusts is relatively the youngest fault.

The pop-up structure was found below the hanging wall of the upper detachment. Slight shortening and thickening of the strata in this structural feature were observed. The pop-up structure was caused by a relatively young thrust fault below the upper and the lower detachment associated with a minor conjugate fault. Its detailed evolution mechanism is not well understood, but Its presence indicates that the foothills frontal deformation is not stable but migrates towards the foreland. The location of the pop-up structure can be interpreted as the approximate-eastern limit of the foothills deformation in this region.

SEISMIC MODELING

Following the previously described seismic interpretation, seismic modeling has been performed to confirm the interpreted Triangle Zone geometry and to examine the effects of velocity variations within the triangle Zone to seismic imaging beneath them. Geologic model and modeling parameters used in this experiment are showed in Figure 7. The studies have been undertaken on the Uniseis Ray -Tracing software.

Both zero-offset, vertical (P-P) and radial (P-SV) component synthetic reflection data have been acquired from this model. Zero-phase Ricker wavelets with center frequencies of 35 Hz. for the P-P and 25 Hz. for the P-SV case were used to convolve with the resulting coefficient series in this study.

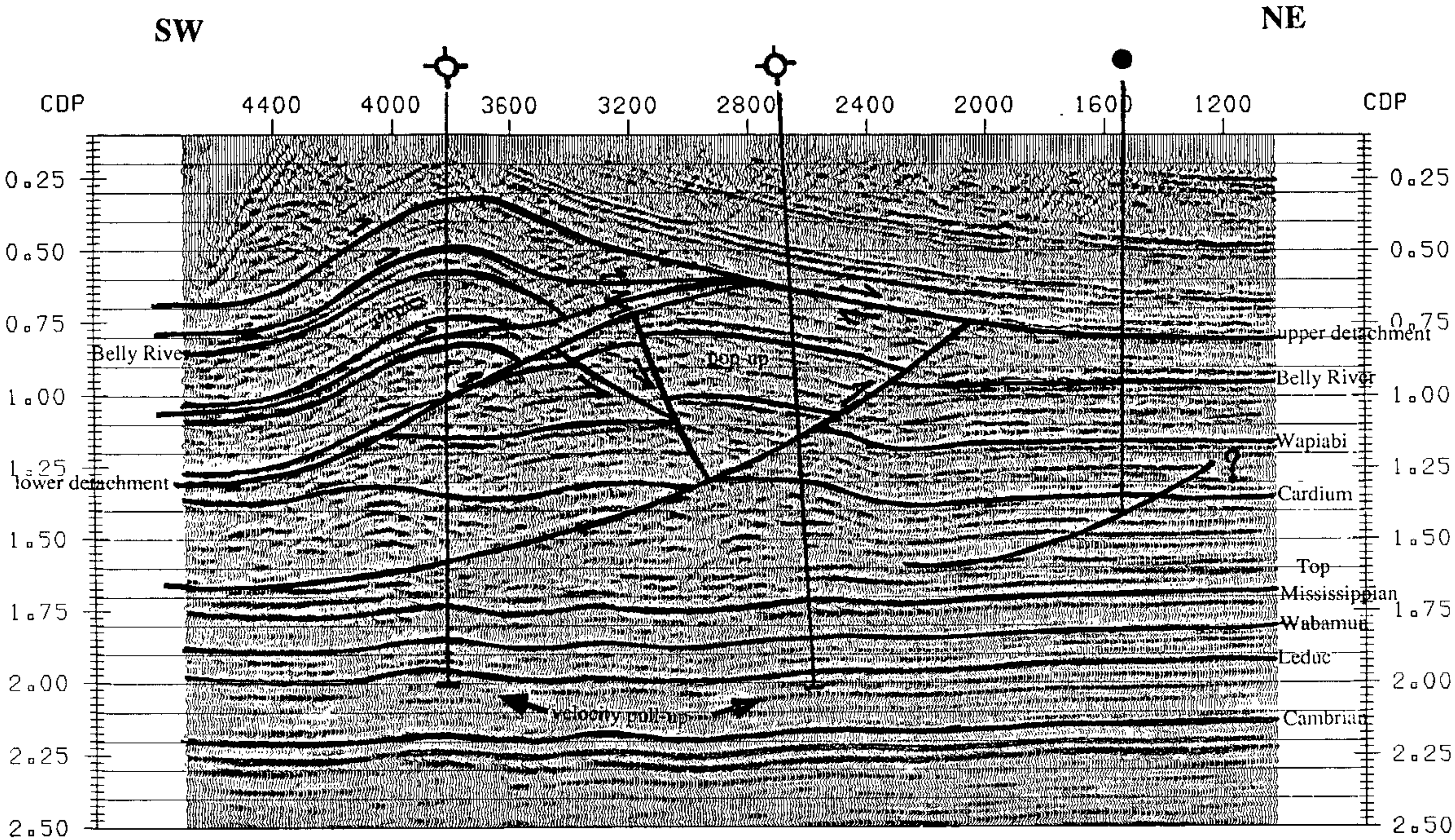
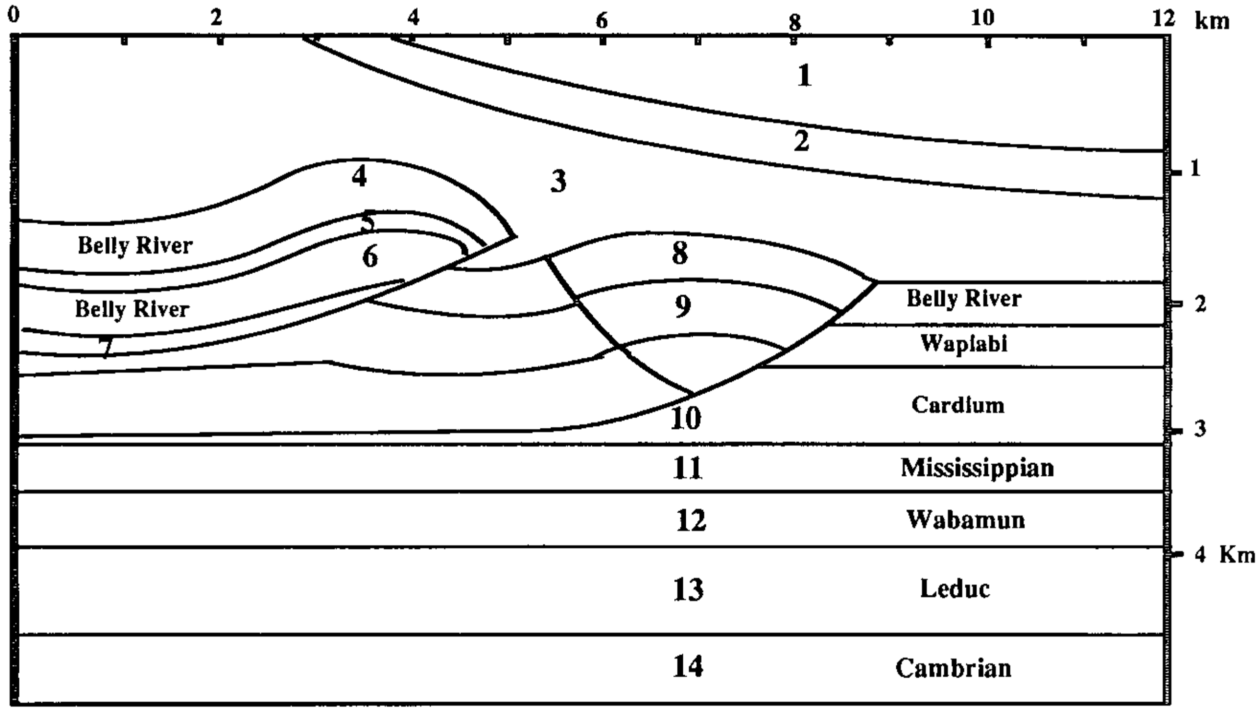


FIG. 6. An interpretation of the final section.



FORMATION	Vp (m/s)	Vs (m/s)
1	3350	1675
2	3480	1740
3	3520	1760
4	3760	1880
5	3592	1796
6	3975	1987
7	3896	1948
8	3831	1915
9	3930	1965
10	4049	2024
11	5880	2940
12	6050	3025
13	5900	2950
14	6200	3100

FIG. 7. Schematic model and physical parameters of the Triangle Zone

Acquisition parameters and spread geometry were derived from the field parameters of the presented seismic line. However, since surface topography was not incorporated into the geologic model, modeling acquisition parameters were slightly modified from the field parameters for simplicity and consistency of subsurface coverage.

Vertical Component (P-P) Modeling

Zero-offset data were first recorded with a trace spacing of 16.5 m. Three post-stack depth migration techniques as applied to the field stack section were tested on this zero-offset data. The results from these tests are shown in Figures 9, 10 and 11 respectively. It is apparent that ray bending, which was believed to be a major cause of deteriorated reflection beneath the Triangle Zone core is actually not too severe since all of these three migration methods give comparatively reasonable results in terms of seismic events' repositioning and amplitude characteristics preservations (Theoretically, the F-K and Phaseshift algorithms used in this experiment are not able to handle strong velocity changes, in particular lateral variations (ITA Insight/1, 1991)).

This study shows that if a reasonable zero-offset section can be achieved, any kinds of these three post-stack depth migration should be sufficient to image the Triangle Zone structure properly.

The juxtaposition of the duplex against the shallower formations also causes velocity pull-up on the underlying horizons. The amount of velocity pull up is approximately 70 ms. and can be seen on the Mississippian, Wabamun, Leduc and near Cambrian reflections. This strongly reflects a difficulty in identifying reservoir property of the Leduc and Wabamun formations beneath the Triangle Zone core based on P-P data solely.

Following the migration tests, offset data (P-P) were acquired and processed to confirm the results from zero-offset modeling and to assess whether the zero-offset section as in Figure 8 can be obtained provided that velocity and statics solutions are known. The data will also be used for DMO and pre-stack depth migration tests. The processing flow in Figure 12 was used to generate the P-P synthetic-stack section in Figure 14.

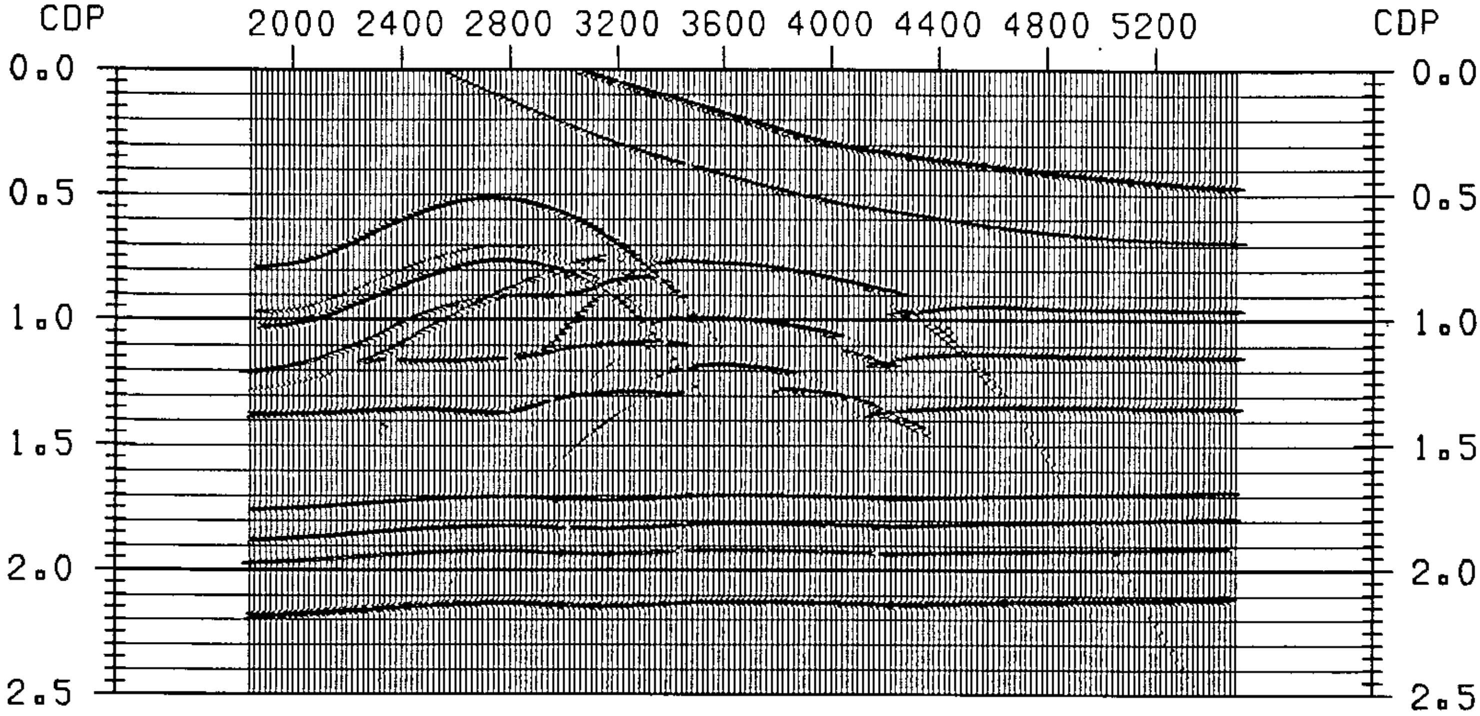


FIG. 8. A zero-offset synthetic seismic section from the model in Figure 7.

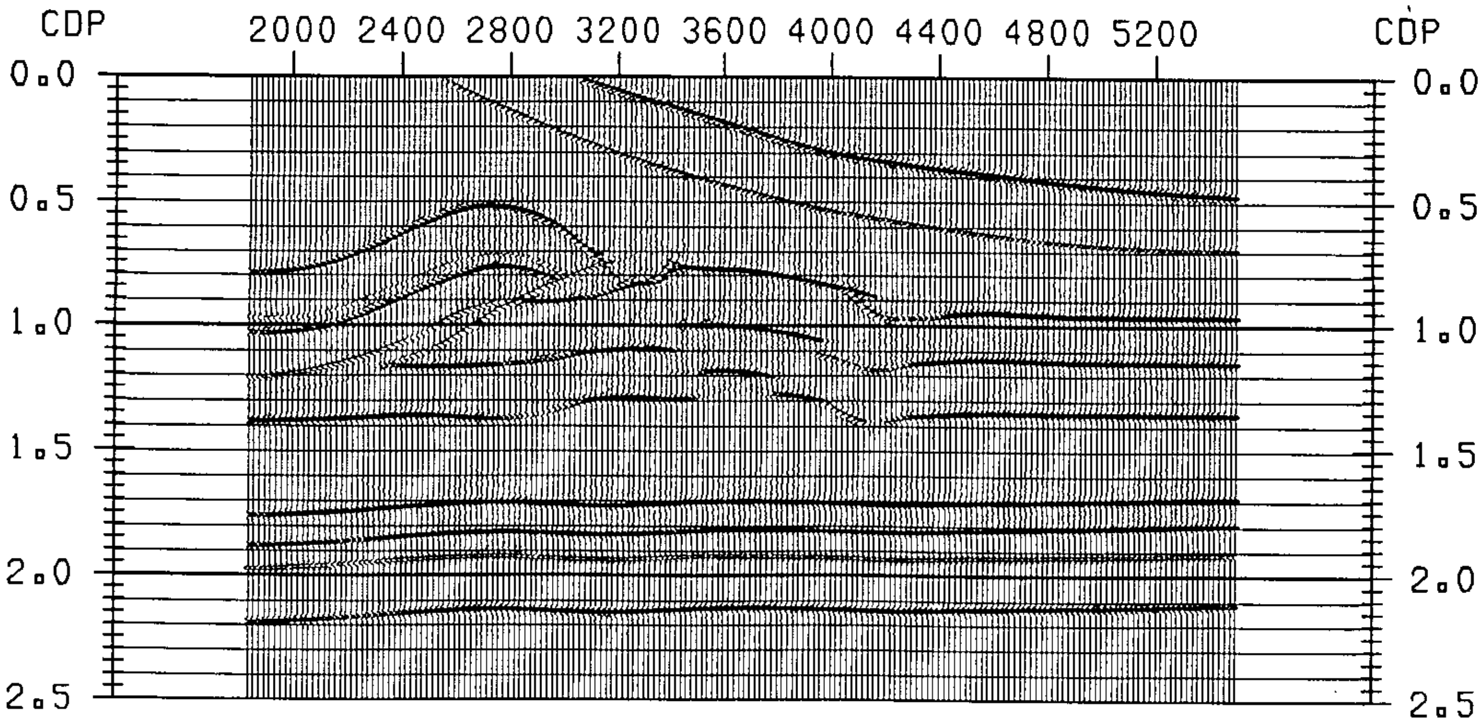


FIG. 9. A F-K migrated section of the zero-offset synthetic seismic section.

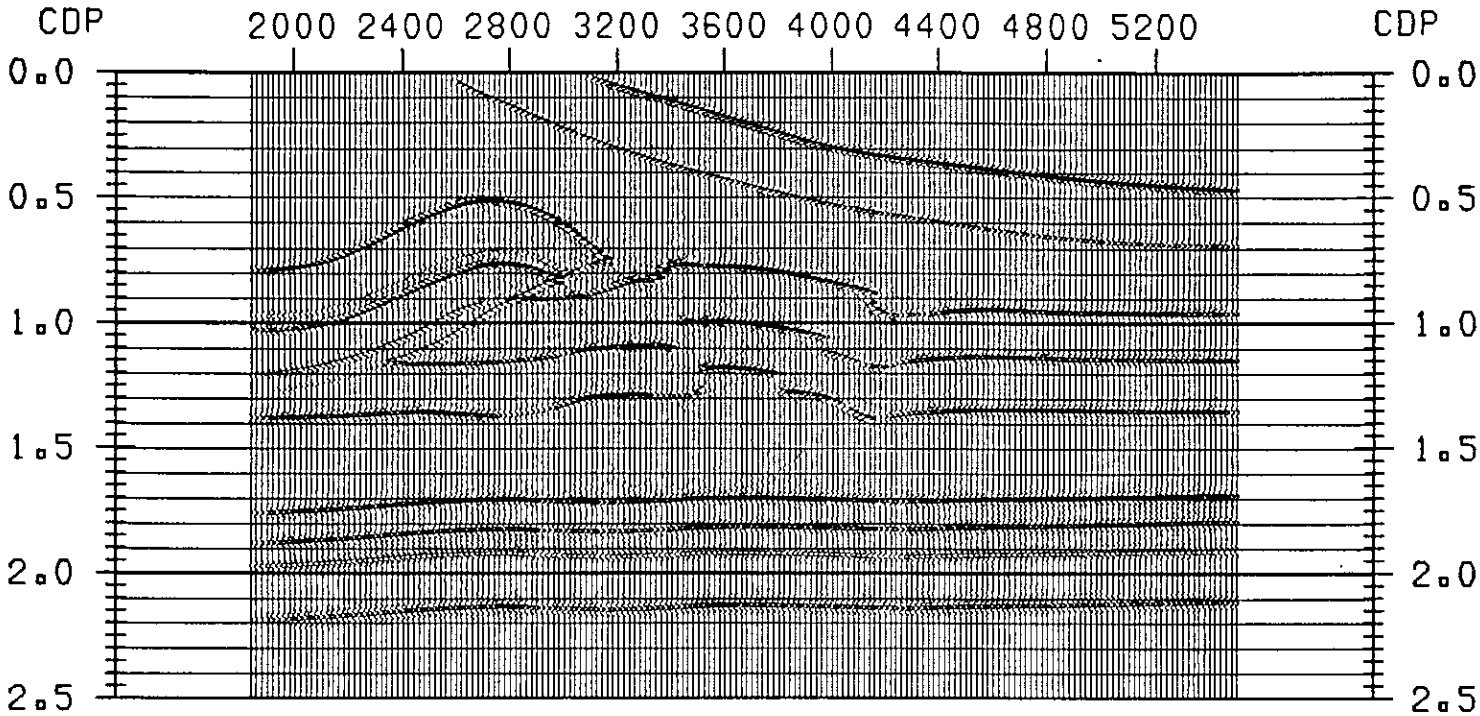


FIG. 10. A F-D migrated section of the zero-offset synthetic seismic section.

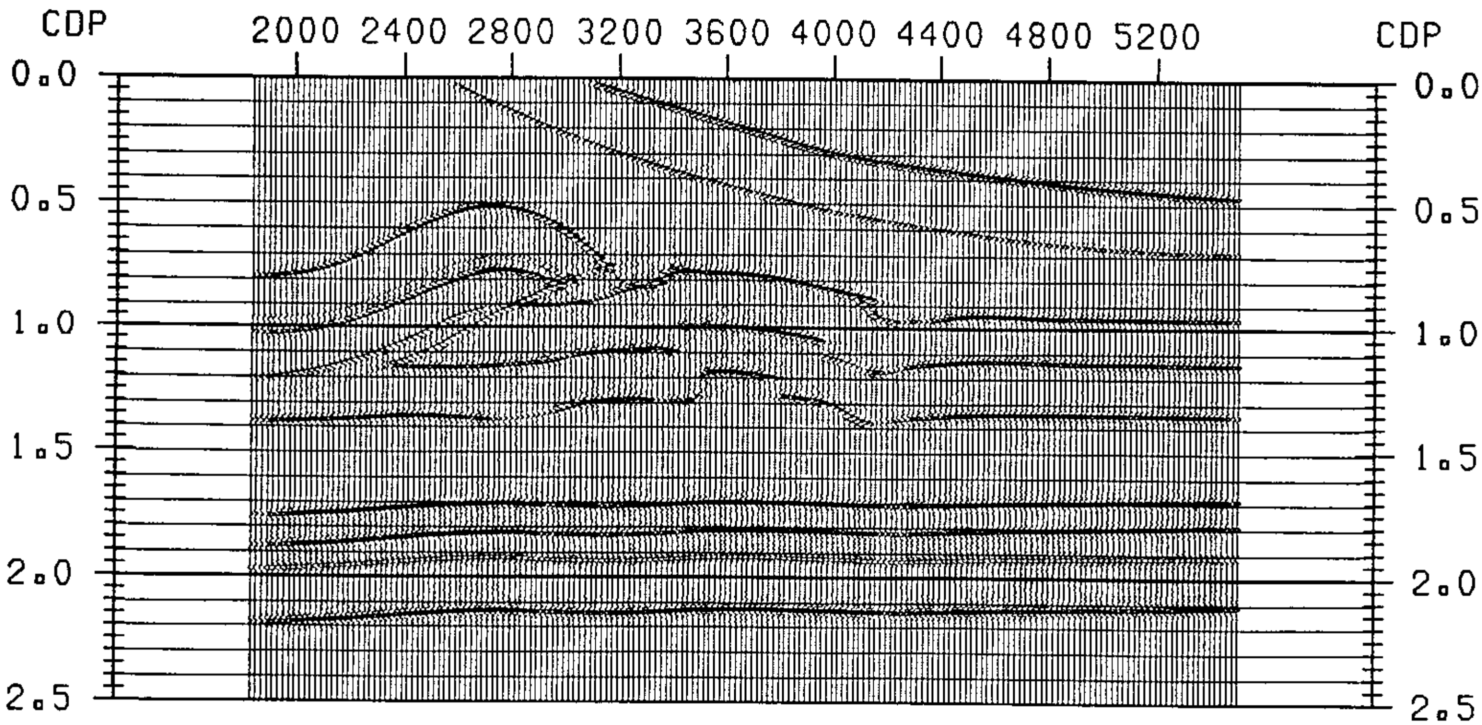


FIG. 11. A phaseshift migrated section of the zero-offset synthetic seismic section.

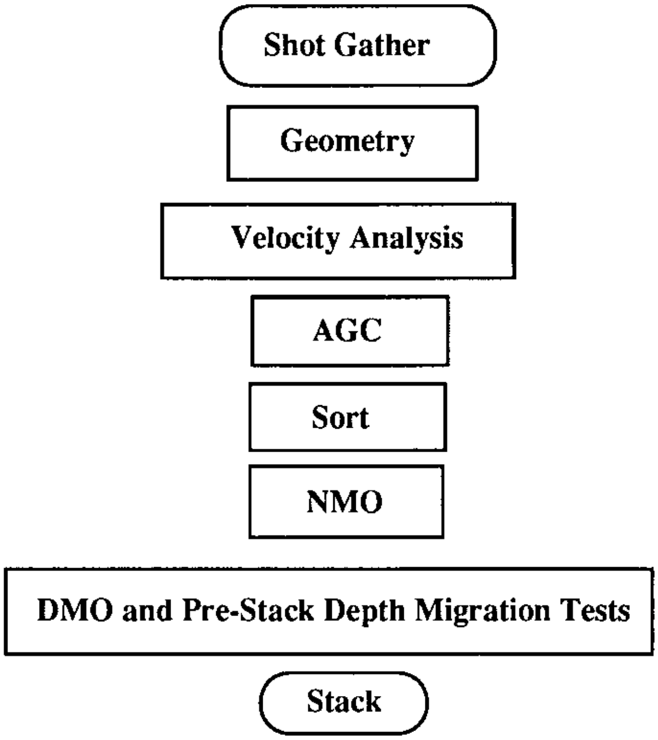


FIG. 12. Processing Flow Chart for the synthetic P-P data

Eighty-five shot gathers, each comprising 240 traces were collected using a split-spread geometry, 33 m. group interval and 99 m. shot interval. Examples of synthetic shot gathers from the core and the eastern flank of the Triangle zone are displayed in Figure 13A and B respectively. At present, DMO and pre-stack depth migration have not been completely finished yet. However, analysis and comparison between the offset-stack section (Figure 14) and the zero-offset section (Figure 8) demonstrate that the conventional processing flow is sufficient to image the Triangle zone in this region if good statics and velocity functions are achieved.

It is therefore anticipated that the key factors that affect imaging beneath the Triangle zone might be the statics and velocity problems since the Triangle Zone cores are usually associated with rugged topography and near surface velocity variations. Also, conflicting dips within the Triangle Zone core lead to difficulties in picking velocity functions. These problems can be reduced by proper data acquisitions, high-fold seismic data and detailed velocity analysis. Also, seismic modeling should be performed along with the processing and interpretation.

Radial Component (P-SV) Modeling

Ninety P-SV synthetic shot gathers were acquired over the model each comprising 120 traces-split spread, 99 m . shot spacing and 33 m. receiver spacing. This spread geometry yields a maximum fold of 20 over the duplex and the Triangle Zone core. Examples of the P-SV shot gathers are displayed in Figure 16, in which polarity reversal on one side of the spread is apparent. These shot gathers underwent

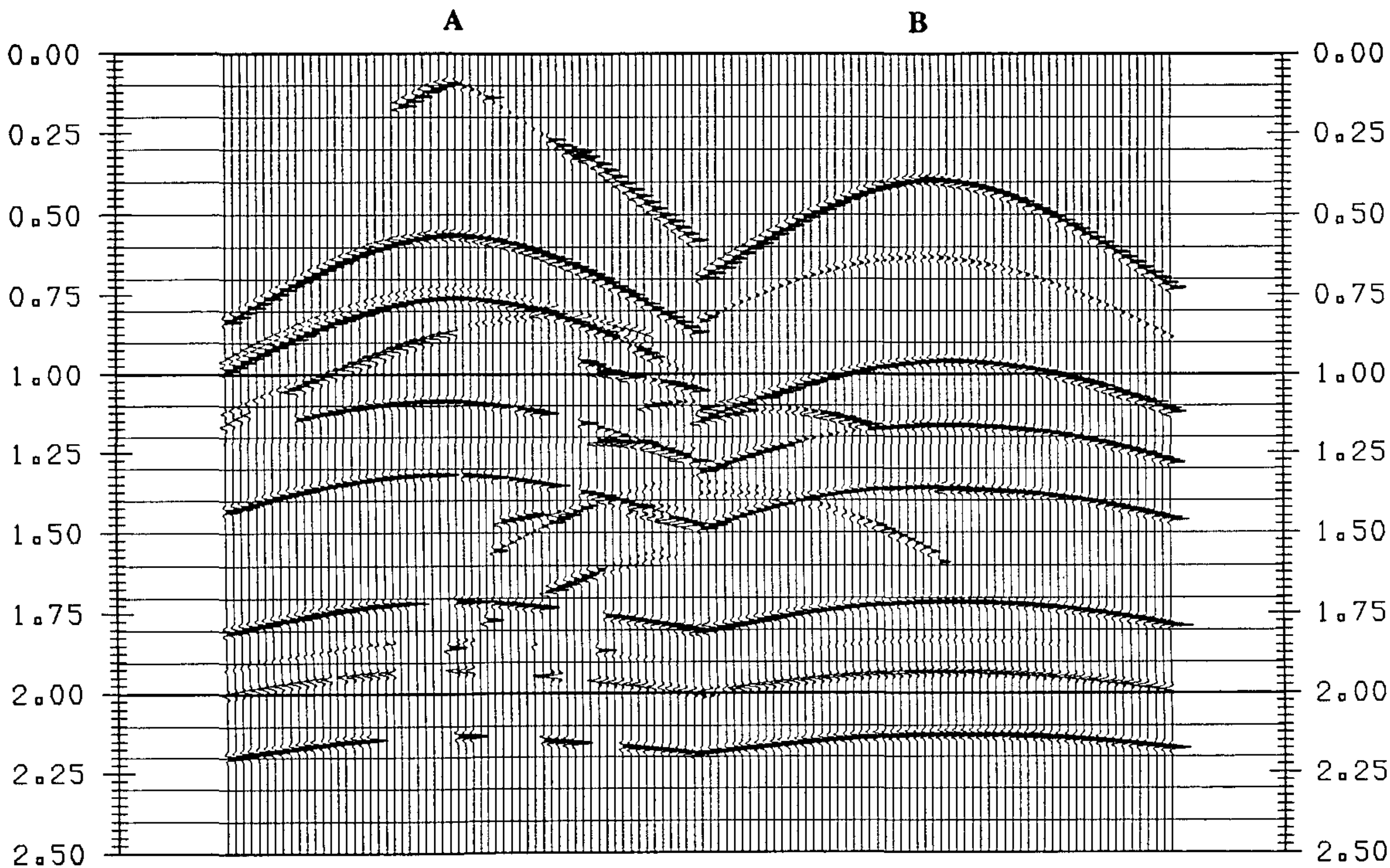


FIG. 13. Sample synthetic P-P shot records from the western(A) and the eastern(B) limbs of the the Triangle Zone model in Figure 7.

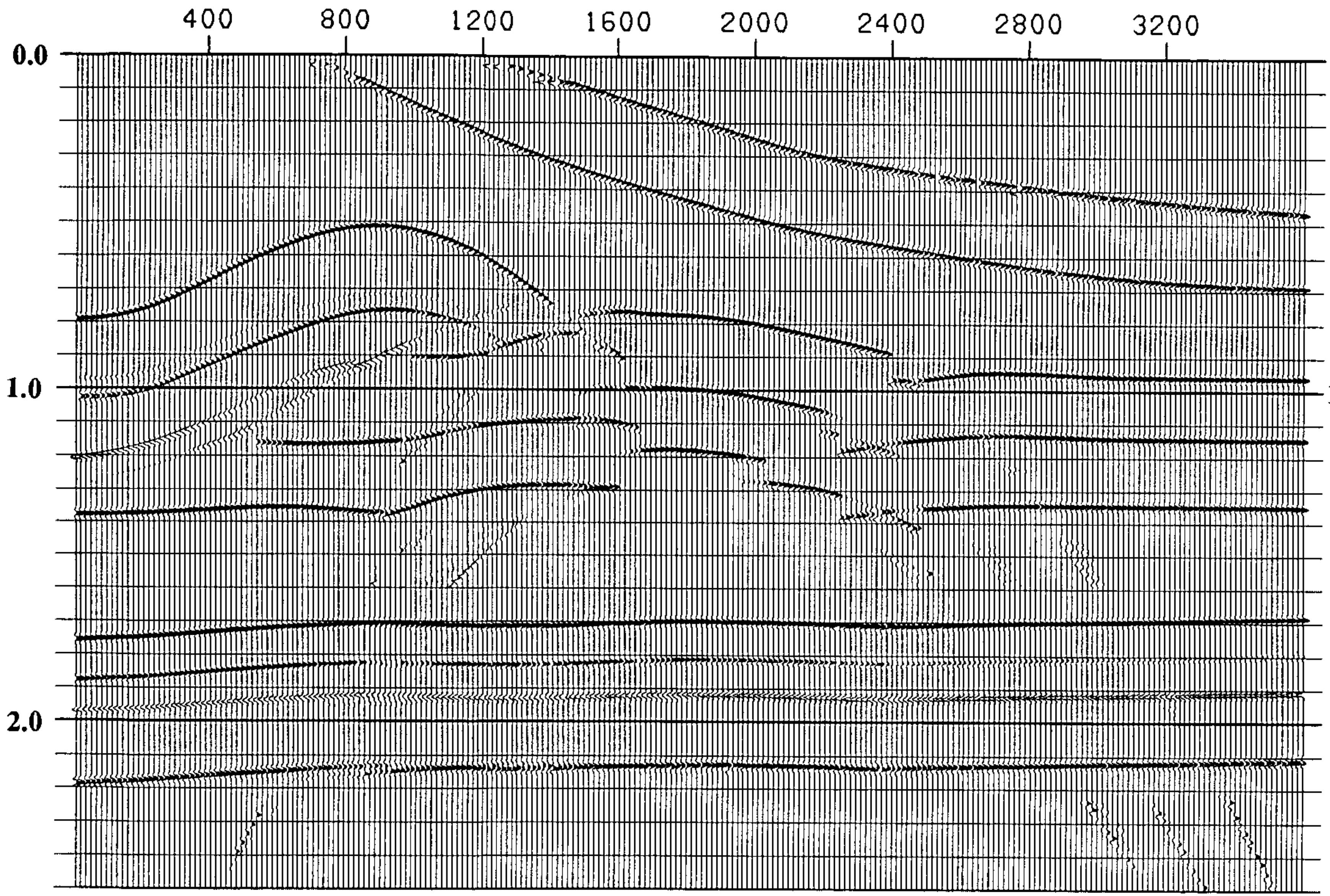


FIG. 14. A P-P stack section generated with the processing flow in Figure 12.

processing steps summarized in Figure 15. Note that a few additional steps were included in the processing flow, i.e., polarity reversal, mute and common conversion point rebinning.

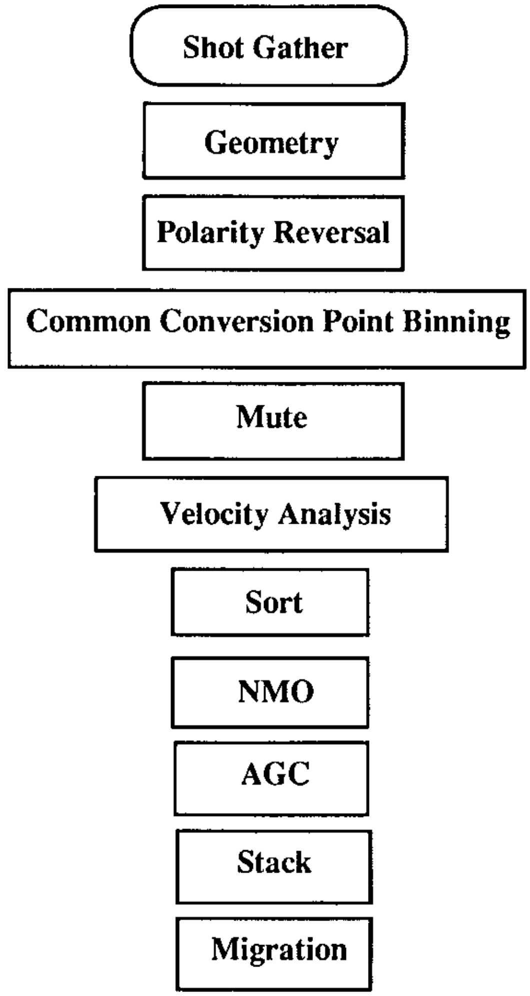


FIG. 15. Processing flow chart for the synthetic P-SV data

The P-SV stacked and migrated sections are showed in Figures 17 and 18. respectively. All the major components of the Triangle Zone and its associated structures, i.e., the upper and lower detachments, the pop-up structure and the duplex are clearly depicted. The result from this experiment is very encouraging in that, in terms of structural response, the P-SV data exhibits the same characteristics as the P-P data. This means an integrated P-P and P-SV data can be a very useful tool in delineating the Triangle Zone geometry and its associated structures. In addition, lithology and stratigraphy of the formations beneath the Triangle Zone which are of exploration interests can also be depicted by analyzing the variation of Vp/Vs ratio between these seismic horizons.

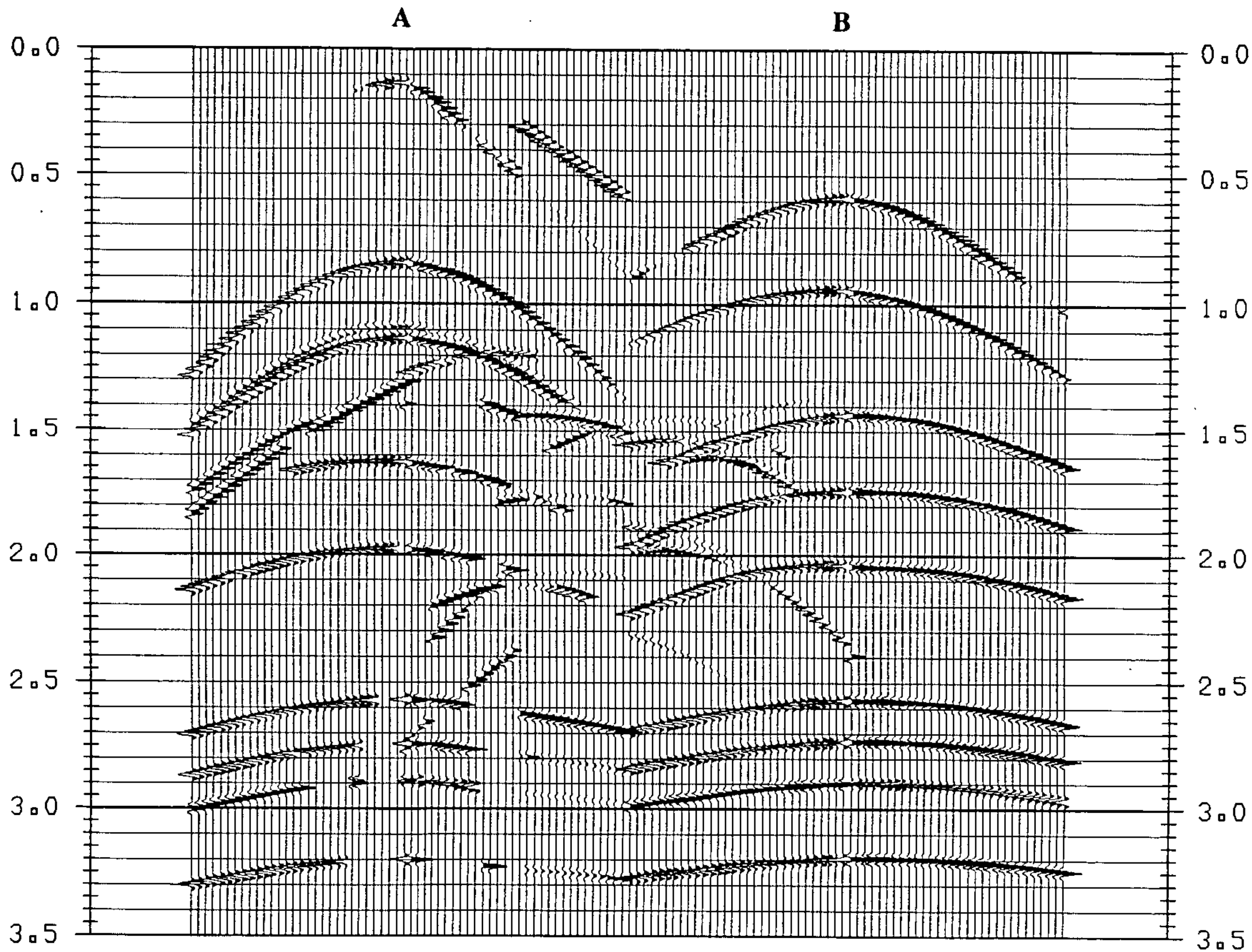


FIG. 16. Examples of the P-SV shot records from the western(A) and the eastern(B) limbs of the Triangle Zone model. Note polarity reversal on one side of the spread.

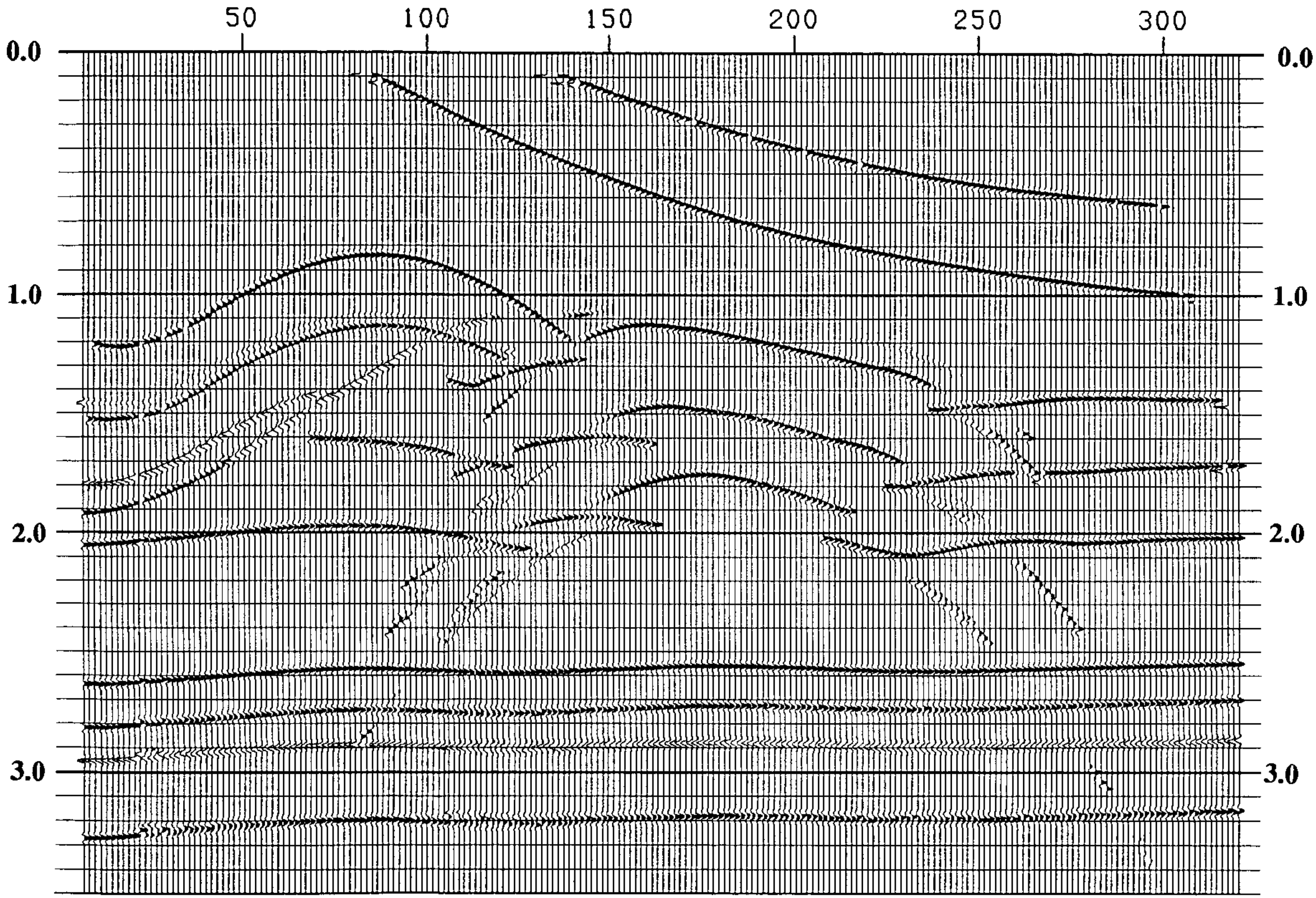


FIG. 17. A P-SV stack section using the processing flow in Figure 15.

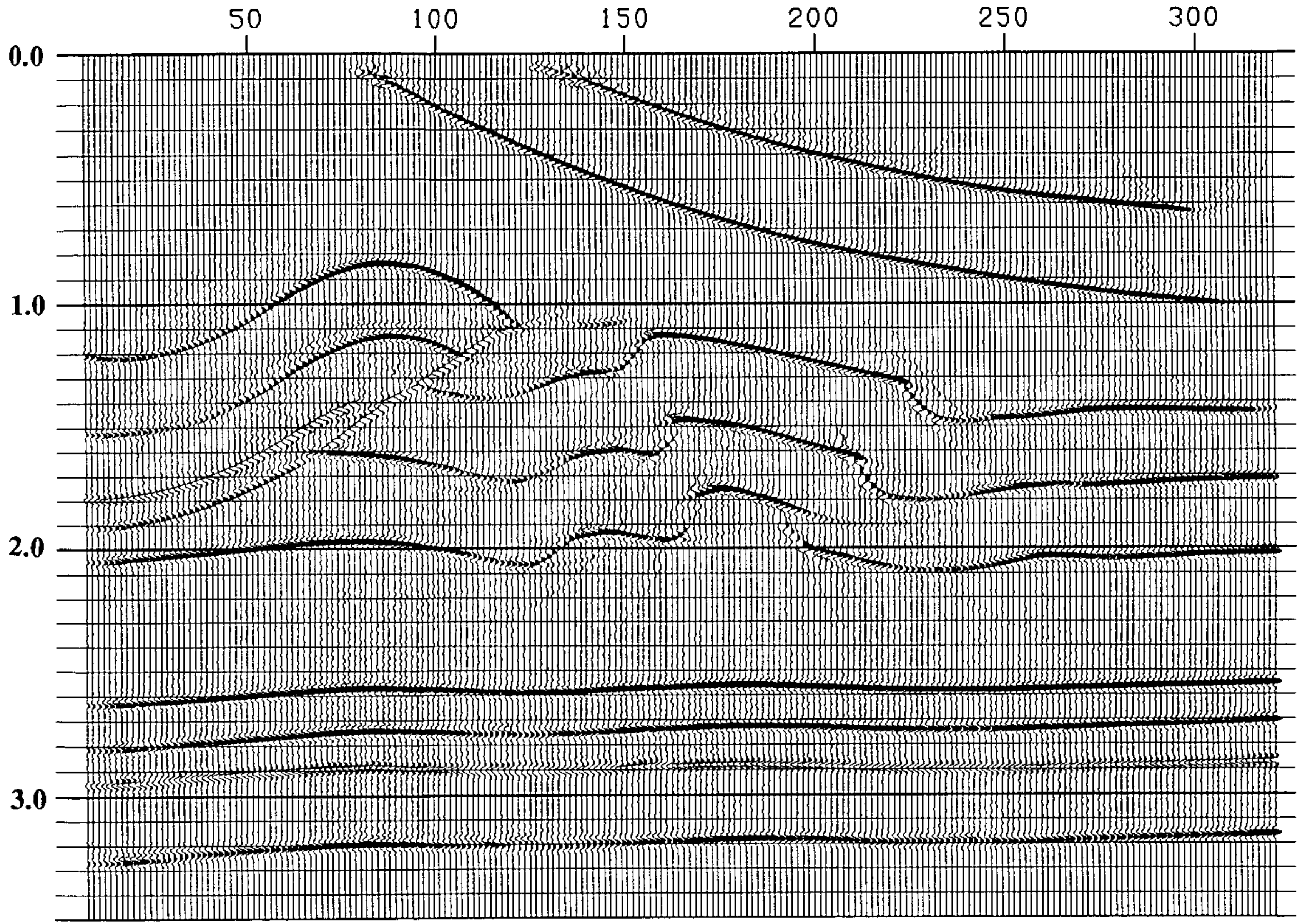


FIG. 18. A P-SV migrated section using phaseshift method.

CONCLUSIONS

The Triangle Zone geometry and its associated structure in this region are well delineated. The upper detachment does not expose to the surface but folded back over the duplex on the western half of the section. The lower detachment exhibits a staircase geometry and merges with the upper detachment. The pop-up structure was caused by a relatively young-west dipping thrust associated with its conjugate-east dipping thrust. The west dipping thrust is also interpreted to join the upper and lower detachments. Detailed deformation mechanism of the pop-up structure is not discussed in this paper. However, its presence indicates the advancement to the foreland of the foothills frontal deformation.

Additional comments on processing and modeling studies are made as follows :

1. The Triangle Zone and its associated structure do not produce a significant amount of ray bending which can affect many processing steps, i.e., migration, DMO, NMO and velocity analysis.

2. It was observed that statics of the shot records acquired over the Triangle Zone core are severe, also signal to noise ration of the corresponding records is relatively low. This might be because the Triangle Zone structures are usually associated with rough topography and near-surface velocity inversion which lead to severe statics in this region. Modeling results indicate that velocity variations are moderate and hence, are not the major cause of deteriorated reflections beneath the Triangle Zone.

3. Time-structural high found on the deep reflections of Mississippian, Devonian and Cambrian formations were resulted from the shallow velocity variations.

4. This study shows that in addition to lithologic and stratigraphic interpretations, the P-SV data are also applicable in structural mapping. However, some problems, i.e., P-SV statics and velocity which may be found to be crucial factors affecting the P-P reflections in the Triangle Zone are not discussed in this paper.

FUTURE WORKS

Physical modeling studies of the Triangle Zone will be undertaken. Both P-P and P-SV physical modeling data will be processed and compared with the numerical modeling results. It is also proposed to include a high velocity layer in the duplex to assess the effects of this layer to seismic imaging beneath it.

ACKNOWLEDGEMENTS

The authors would like to thank Petrel Robertson for donating the seismic line FTC 002B. The first author gratefully acknowledges a study grant from the Canadian International Developement Agency (CIDA).

REFERENCES

Charlesworth, H.A.K., and Gagnon, L.G., 1985, Intercutaneous wedges, the triangle zone, and structural thickening of the Mynheer coal seam at Coal Valley in the Rocky Mountain Foothills of central Alberta: Bull. Can. Petr. Geol., 33, 22-30.

__________, Johnston, S.T., and Gagnon, L.G., 1987, Evolution of the triangle zone in the Rocky Mountain Foothills of central Alberta: Can. Jour. Earth Sc., 24, 1668-1678.

Hale, D., 1984, Dip-Moveout By Fourier Transform; Geophysics, 49, 741-757.

ITA Inverse Theory and Applications Inc., 1991, Insight/1 : Prestack and Poststack reference guide

Jones, P.B., 1982, Oil and Gas beneath east-dipping under thrust faults in the Alberta foothills: in Powers, R.B.(Editor), Geological studies of the Cordilleran thrust belt: Rocky Mtn. Assoc. Geol. Bull., 1, 31-38.

Lawton, D.C., and Spratt, D.A., 1991, Geophysical and Geological aspects of the triangle zone, Rocky Mountains Foothills, a field guide for CSEG continuing education field trip, 33p.

Price, R.A., 1986, The southern Canadian Cordillera: thrust faulting, tectonic wedging, and delamination of the lithosphere: Jour. Struct. Geol., 8, 239-254.

Skuce, A.G., Gordy, N.P., and Maloney, J., 1992, Passive-roof duplex under the Rocky Mountain foreland basin, Alberta: AAPG Bulletin, 76, 67-80.

Teal, P.R., 1983, The triangle zone at Cabin Creek, Alberta: in Bally, A.W., ed., Seismic expression of structural styles: Am. Assoc. Petr. Geol. Studies in Geology, Series 15, 3, 3.4.1-48 - 3.4.1.-53.

Yilmaz, O., 1987, Seismic Data Processing; Soc. Expl. Geophys.