The Blackfoot high-resolution 3-C seismic survey: design and initial results

Robert R. Stewart, Brian Hoffe, Henry C. Bland, Gary Margrave, Eric V. Gallant, Malcolm B. Bertram

SUMMARY

During November 1997, the CREWES Project at the University of Calgary acquired a high-resolution seismic survey at the Blackfoot field located southwest of Calgary. The 3 km 3C-2D survey consisted of recording dynamite shots into "conventional" (20 metre), high-resolution (2 m) and buried (6, 12 and 18 m) receiver arrays. A walk-away AVO VSP was also acquired by simultaneously recording the shots at four different depths in a well adjacent to the seismic profile.

Shot gathers of both vertical and radial components show good reflection data with a high signal-to-noise ratio. The transverse component data appears to contain very little reflection energy. Examination of receiver gathers of the same station at differing geophone depths show that the geophone depth has an effect on frequency content. Structural and migrated P-P and P-S stacks of the "conventional" (20 m shot spacing, 20 m receiver spacing) portion of the survey also posses a high S/N ratio. A cursory examination of these sections (available only one day before publication) show that they adequately image the target area. The analysis of the data from all the different portions of the survey remains as future work.

INTRODUCTION

On November 1 - 2, 1997 the CREWES Project at the University of Calgary with assistance from Boyd PetroSearch Consultants Ltd. and PanCanadian Petroleum Ltd. recorded a unique, high-resolution 3C-2D seismic survey at the PanCanadian-owned Blackfoot field. The Blackfoot field is located some 10 - 15 km southeast of the town of Strathmore, Alberta (see Figure 1). The producing formation within the Blackfoot area is a Lower Cretaceous cemented glauconitic sand which was deposited as incised channel-fill sediment immediately above the Mississippian carbonates (Wood and Hopkins, 1992). The Glauconitic sandstone lies at depth of about 1,500 m below surface and is up to 45 m thick. The average porosity in this producing sandstone is near 18% and the cumulative production from it throughout southern Alberta exceeds 200 MMbbls oil and 400 BCF gas (Miller *et al*., 1995).

The survey involved the acquisition of a 3 km 3C-2D reflection profile which consisted of a combination of “conventional” and high-resolution receiver intervals. The shot interval employed for the entire 2D profile was 20 m shot on the half-station. However, the receiver interval changed from 20 m to 2 m in the central 1.0 km of the profile. The survey also involved the simultaneous recording into 21×3 buried 3-C geophones situated in 6, 12 and 18 m holes drilled every 50 m along the central km of the profile. In addition to these buried geophones, a 48-channel vertical hydrophone cable with a 2 m receiver interval was deployed in a 100 m cased hole

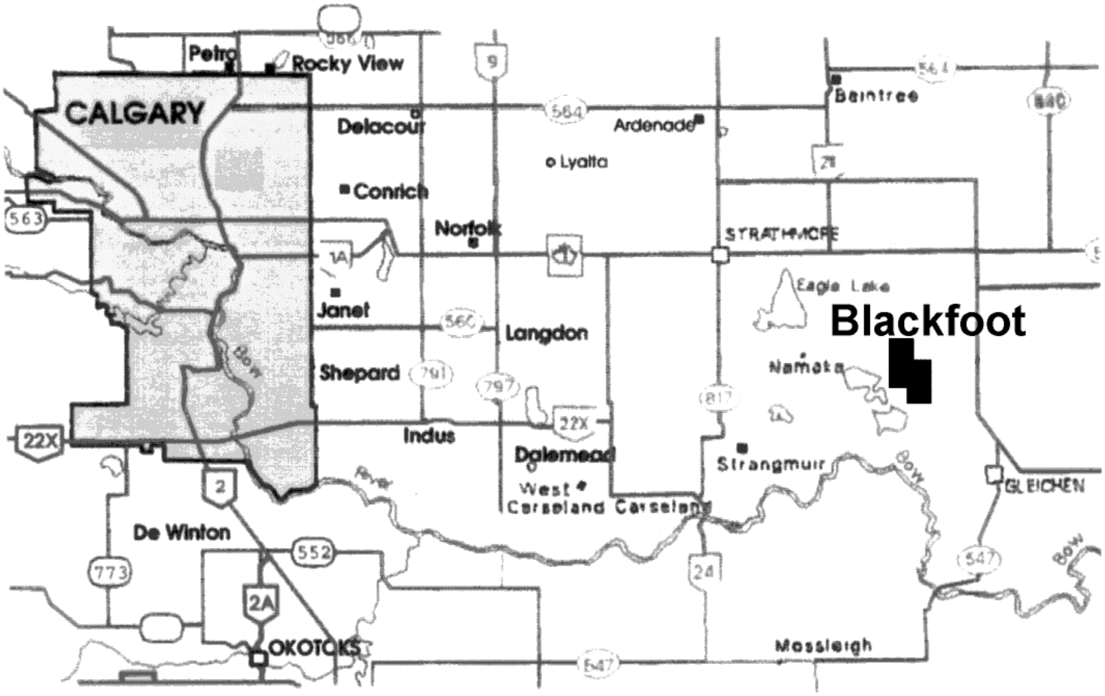

Figure 1. Map showing the location of the PanCanadian Blackfoot field.

located in the centre of the profile. Also, two 3-C accelerometers were deployed in the central km of the profile: one located at the vertical hydrophone cable location and the other at an adjacent downhole 3-C geophone location. A walk-away AVO VSP was also conducted in PanCanadian's 09-08 well by simultaneous recording subsets (every 4^{th}) of the surface seismic shots into a five-level 3-C ASI tool at four different well depths (1560, 1485, 385 and 310 m). An additional 15 shallower shots were recorded at a fifth depth (460 m).

The survey was designed to meet the following objectives: 1) to investigate the loss of P-S energy via monitoring of the surface geophones through the various buried geophones depths as well as the downhole VSP recordings, 2) to investigate the impact of VTI anisotropy in broadening or "skewing" of the V_p/V_s anomaly west of the known channel production and to establish accurate VSP-based TI measurements for the Blackfoot area, 3) to investigate whether vertical cable data can provide viable and decipherable seismic reflection information and 4) to provide new P-P and P-S images across the channel trend to aid in the interpretation of the Mississippian surface channel.

SURVEY DESIGN

To aid in the initial design of this high-resolution 3C-2D survey, it was important to investigate both the common midpoint (CMP) and common conversion point (CCP) folds expected at the proposed survey parameters for the "conventional", high-resolution and buried geophone components of the experiment. These fold calculations were performed via a relatively simple program that employs an asymptotic binning approach.

The expected CMP and CCP folds are displayed in Figures 2 (a, b and c) and 3 (a, b and c) respectively for the source and receiver parameters used for "conventional", high-resolution and buried components of the Blackfoot high-resolution survey. As is evident from these two figures, both the CMP and CCP fold calculated is certainly high enough in providing adequate S/N increase via CMP and CCP stacking to produce reasonable P-P and P-S stacks for all three acquisition components of the survey.

FIELD LOGISTICS

Recording Parameters

Veritas DGC Land was selected as the seismic contractor and used the I/O System II 24 bit seismograph to acquire the data. The preamp gain used for recording was 24 dB with low and high cut filters set at 3 Hz (12 dB slope) and 413 Hz (293 dB slope) respectively. The data were recorded in SEG-D IEEE format with a 6 s record length at a 1 ms sample rate. Because all 2,046 recording channels were live for each shot, 4 LIMs (Line Interface Module) were required to handle the volume of data due to recording at a 1 ms sample rate (≈ 500 channels per LIM).

Source Parameters

A schematic of the field layout for the high-resolution 3C-2D profile is illustrated in Figure 4. There were a total of 151 shot points which consisted of 4 kg charge size loaded in a single hole at 18 m depth. The shot interval was 20 m for the entire 3 km profile and were positioned on the half station. Also, to test the performance of an alternative source, 15 additional shot points were added in the center of the profile which consisted of 2 holes at 9 m depth each loaded with a 2 kg charge size. These additional 2 hole patterns were located at the same surface locations as the other single hole shots.

Receiver Parameters

(a) Surface Receivers

The type of surface 3-C geophone used for the survey was the Litton LRS-1033. The receiver interval for the 1st (east) and 3rd (west) km of the recording spread was 20 m (i.e. 50 3-C geophones for each km; see Figure 4). In the central, high-resolution km, the receiver interval changed to 2 m giving a total of 501 3-C geophones for the center km of the spread. Thus, a total of 601 3-C geophones were deployed along the 3 km profile. In order to eliminate wind noise, all surface geophones were buried at a depth of about 0.5 m in holes which were mechanically dug by a "Bobcat" equipped with a 8" soil auger.

(b) Buried Receivers

In addition to the 601 surface geophones, 63 OYO Geospace GS-20DM 3-C geophones where planted in drilled holes at depths of 6m, 12m and 18m. These 3 buried 3-C geophones at the 3 individual depths were situated in the central, high-

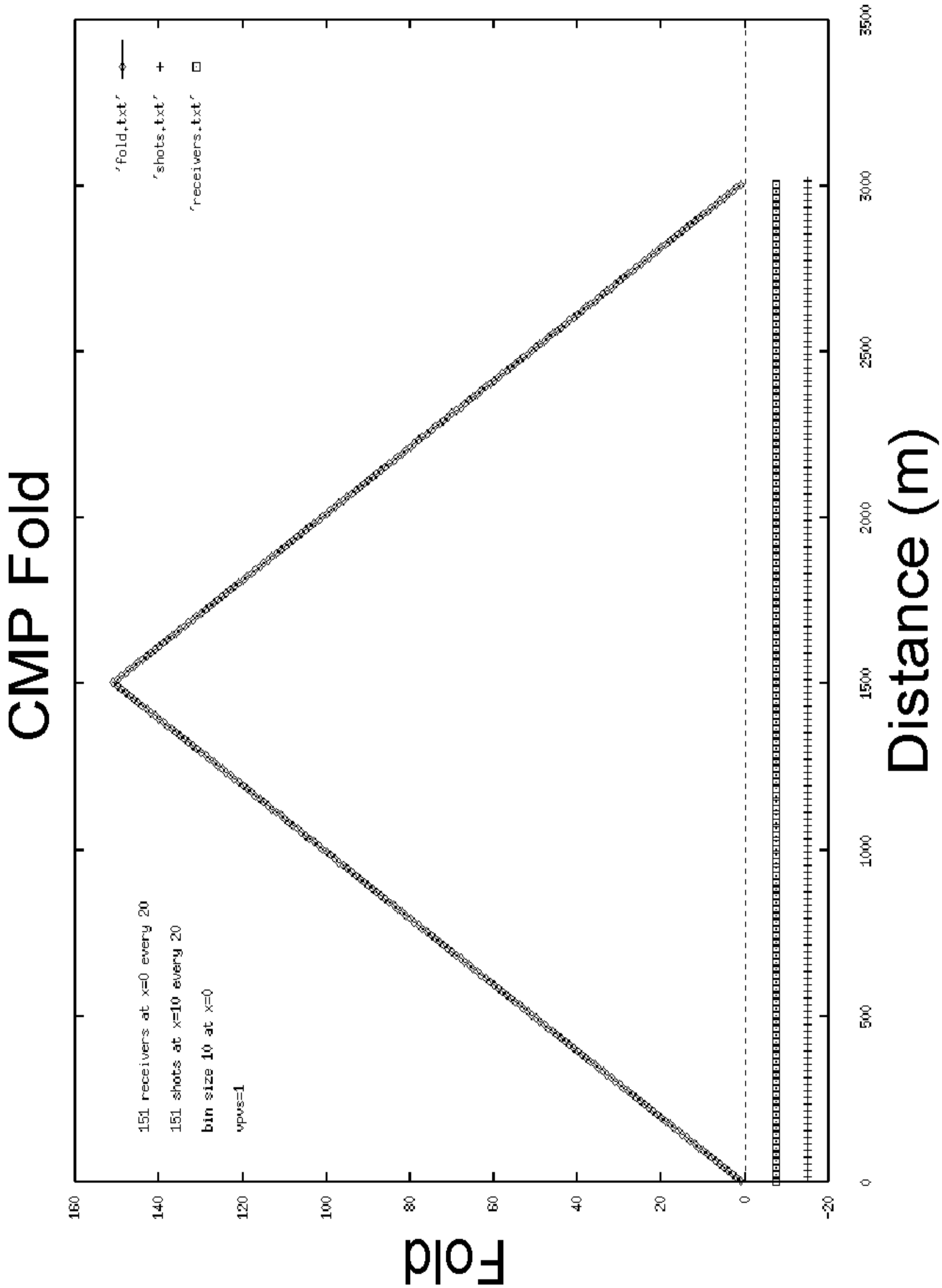

Figure 2(a). CMP fold for the "conventional" (20 m shot and 20 m receiver) portion of the Blackfoot high-resolution survey.

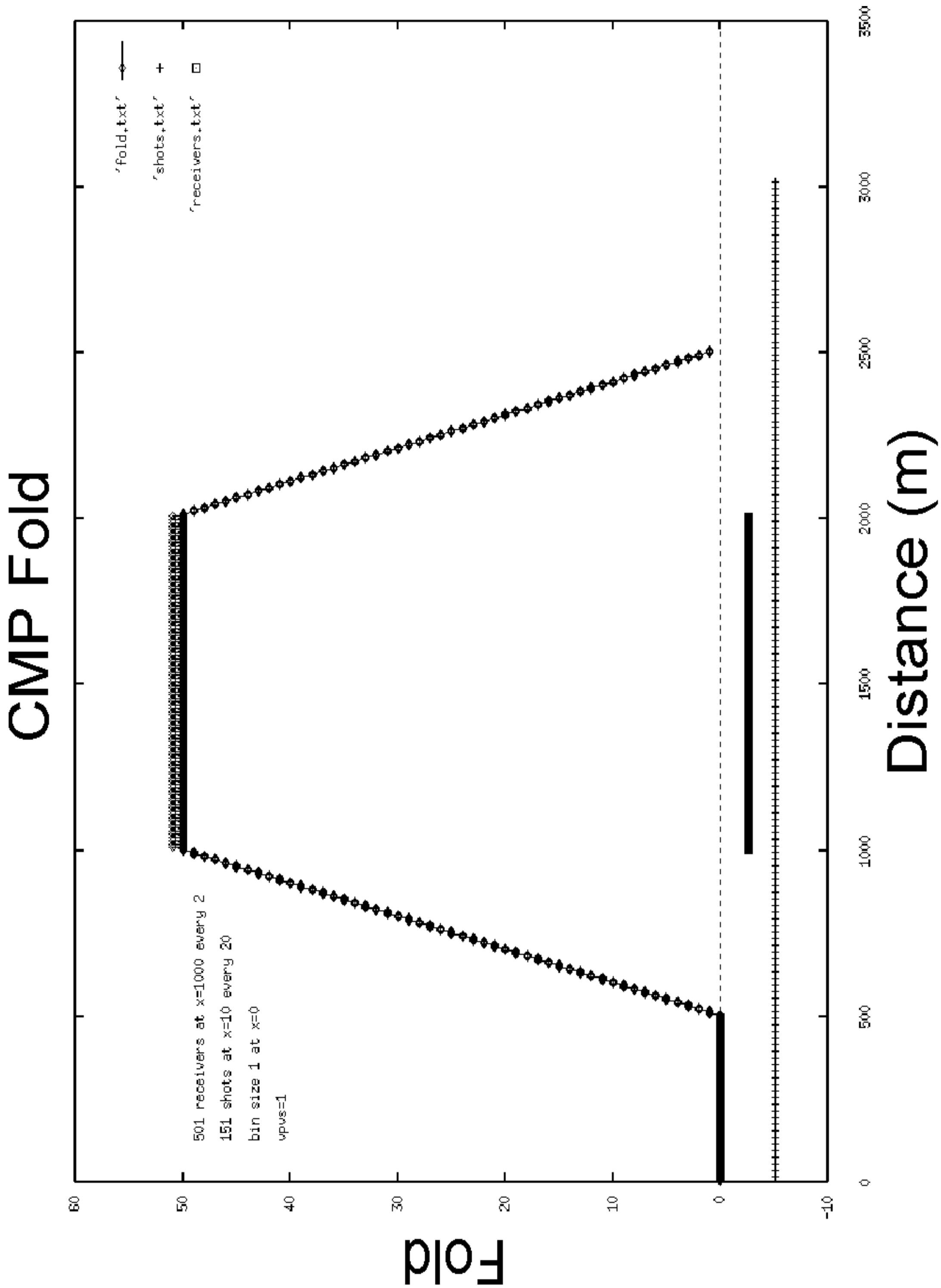

Figure 2(b). CMP fold for the high-resolution (20 m shot and 2 m receiver) portion of the Blackfoot high-resolution survey.

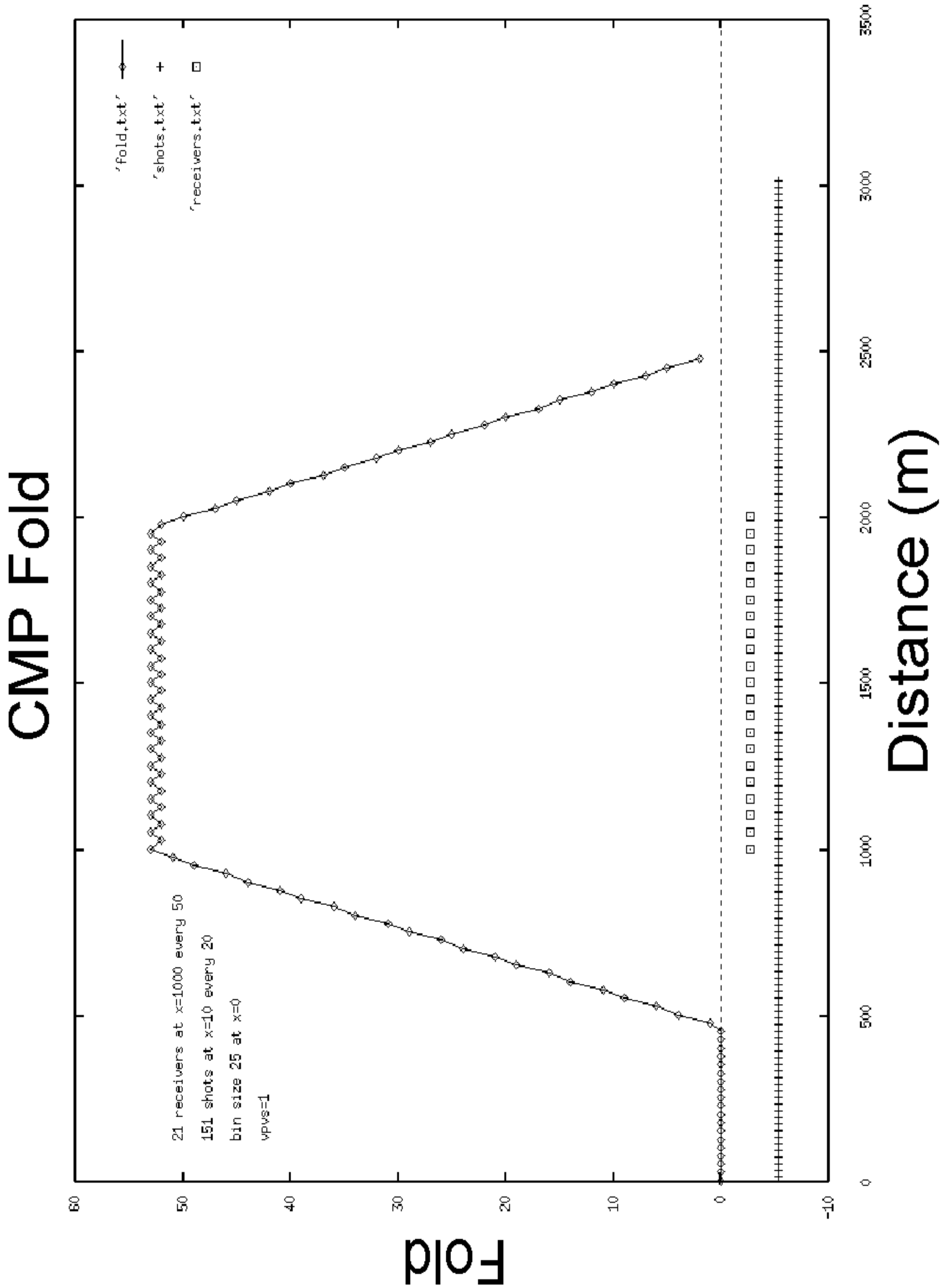

Figure 2(c). CMP fold for the buried (20 m shot and 50 m receiver) portion of the Blackfoot high-resolution survey.

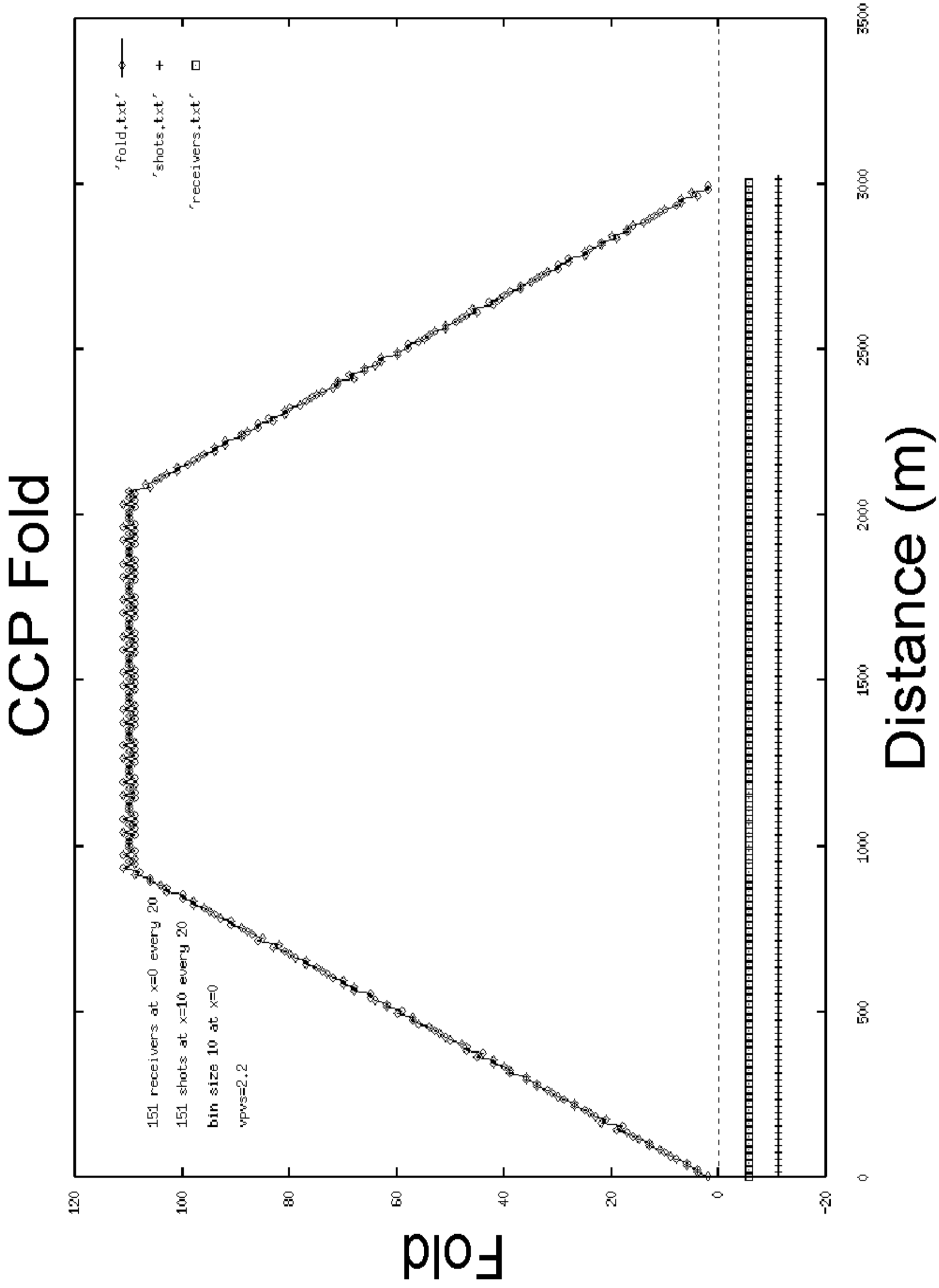

Figure 3(a). CCP fold for the "conventional" (20 m shot and 20 m receiver) portion of the Blackfoot high-resolution survey

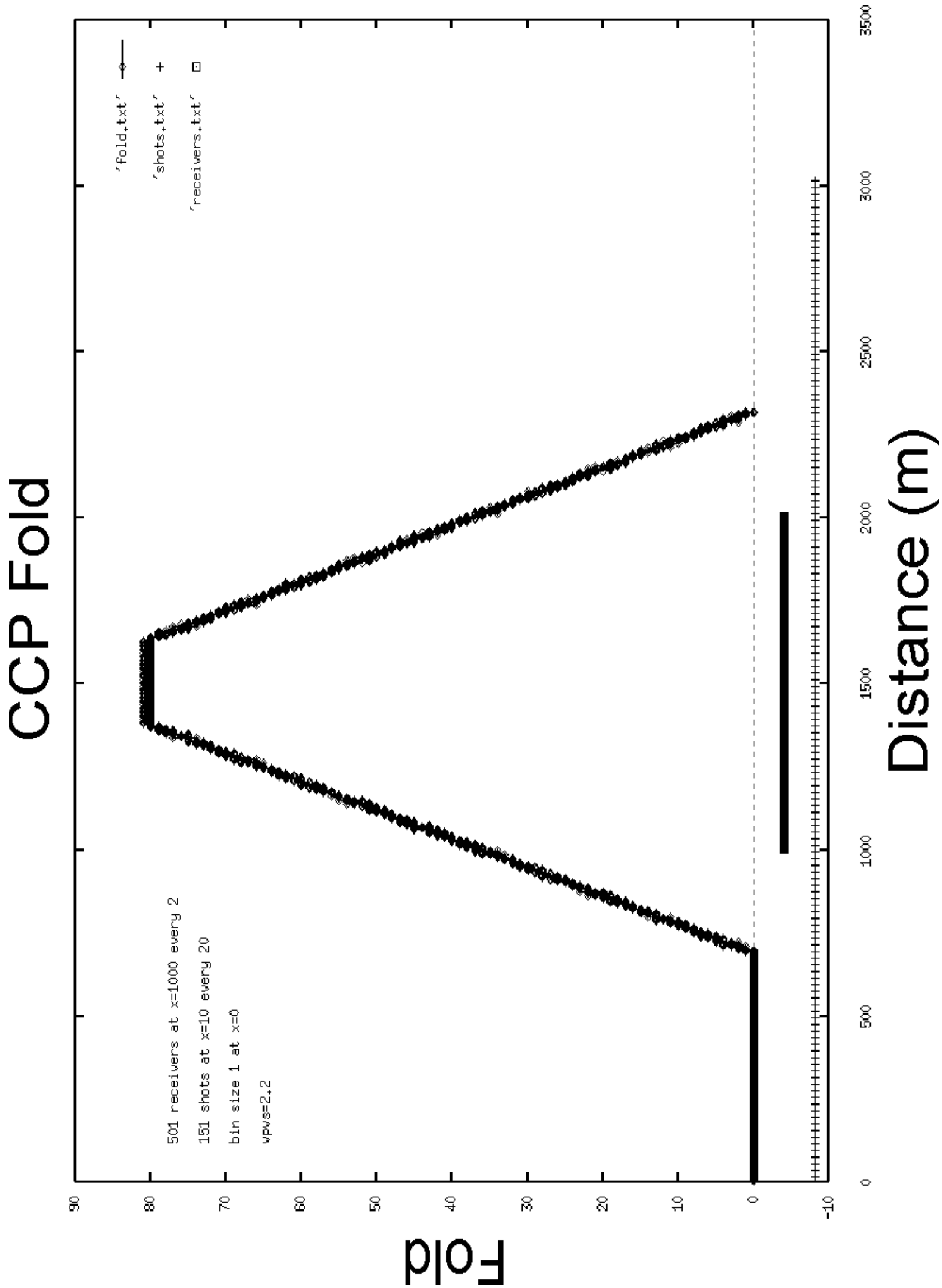

Figure 3(b). CCP fold for the high-resolution (20 m shot and 2 m receiver) portion of the Blackfoot high-resolution survey.

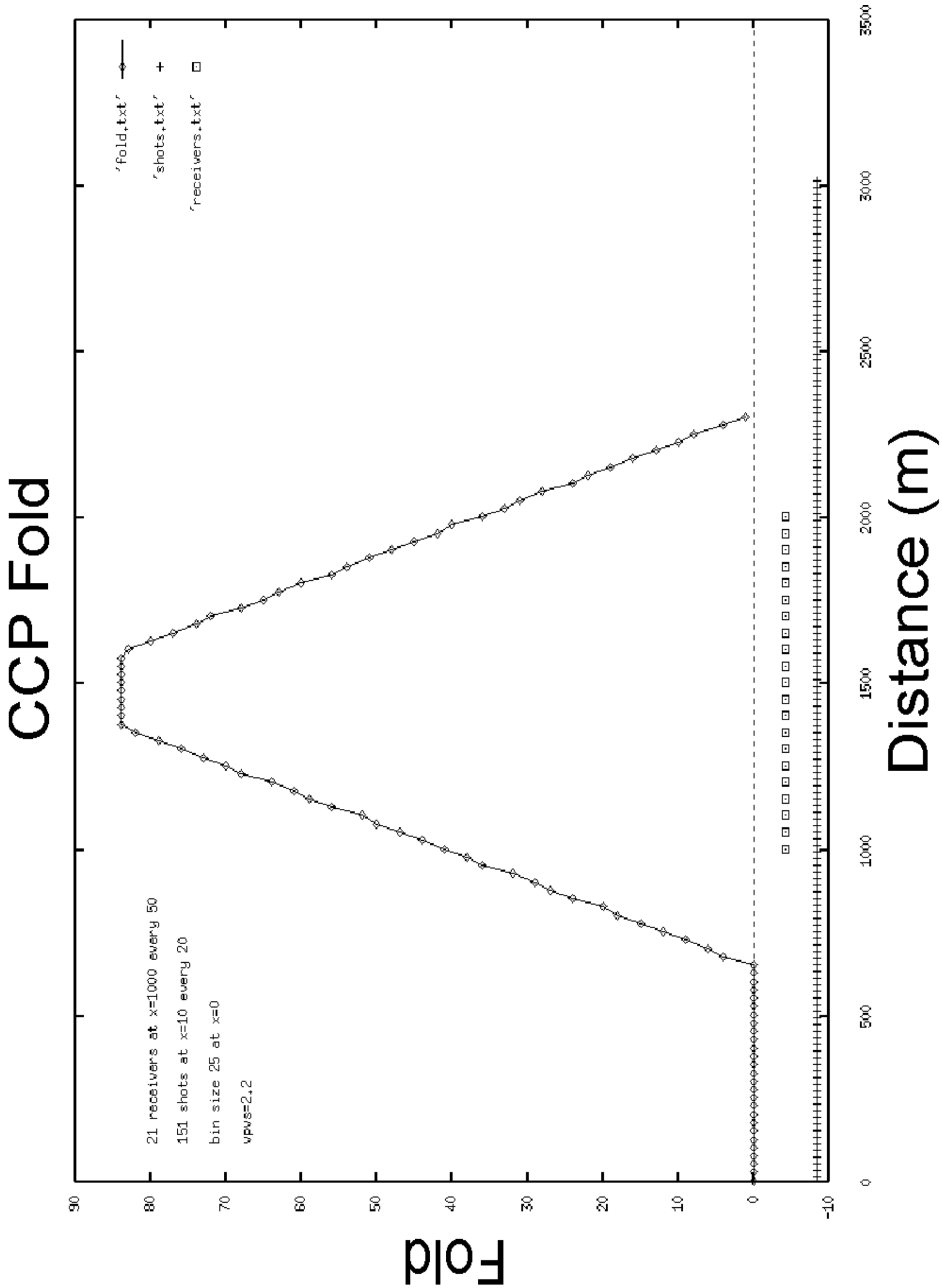

Figure 3(c). CCP fold for the buried (20 m shot and 50 m receiver) portion of the Blackfoot high-resolution survey.

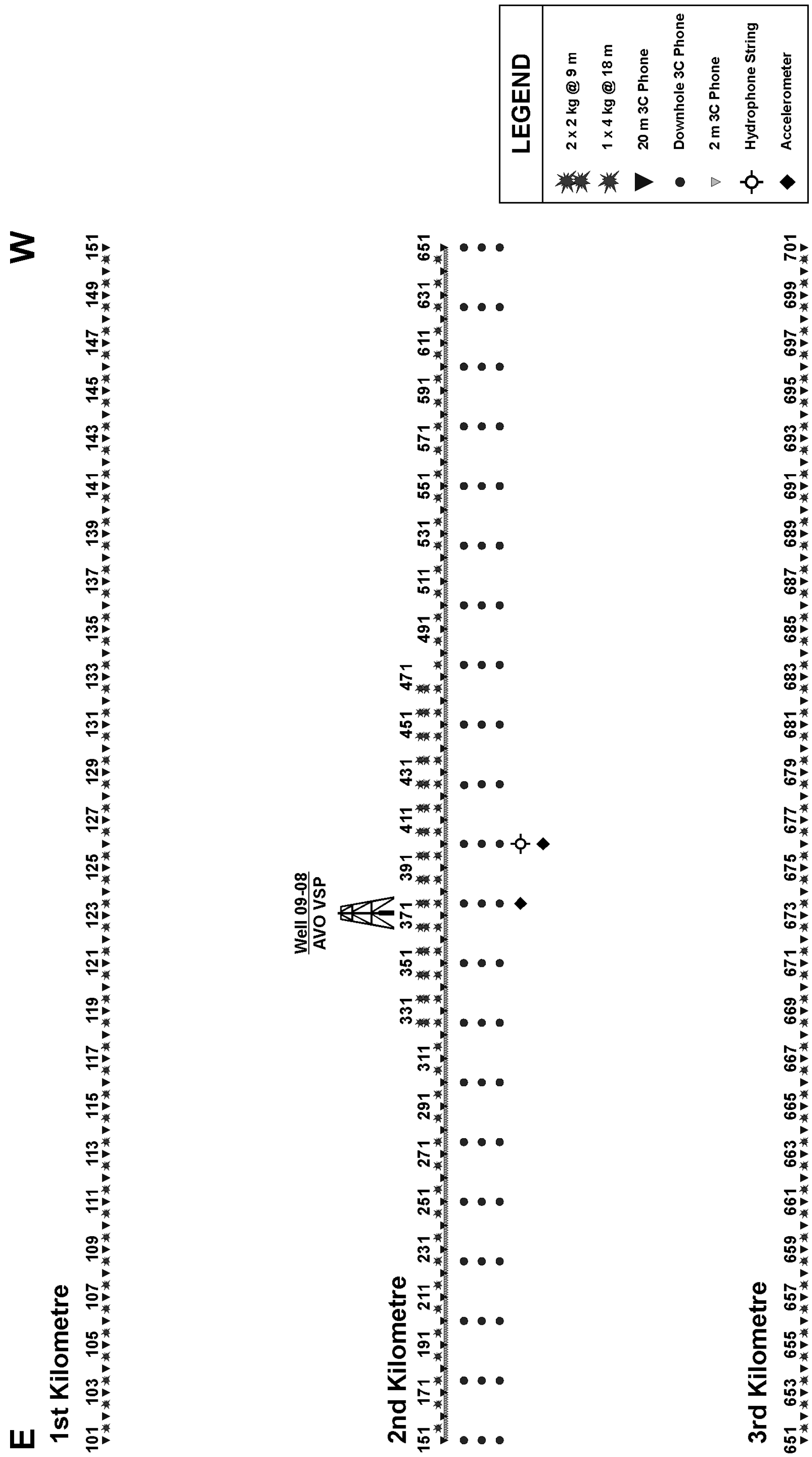

Figure 4. Field layout for the Blackfoot high-resolution survey showing the station numbering scheme and positions of well 09-08, buried geophones, hydrophone cable and accelerometers.

resolution of the profile at a receiver interval of 50 m (21 geophones × 3 holes; see Figure 4). These holes were drilled with a conventional shot point drilling rig using a $4\frac{1}{2}''-5''$ bit. The geophones were deployed using a loading pole especially equipped with a custom-made bracket or “cup” designed to hold the geophone in place while planting. The geophones themselves were equipped with longer leads (8, 14 and 20 m) in order to reach the surface for connection into the spread and $\frac{3}{8}''$ aircraft cable for retrieval from the hole after use. All buried 3-C geophones were recovered from the holes upon completion of the survey.

(c) Vertical Hydrophone String

To test whether vertical cable data can provide useful seismic reflection information, a hydrophone cable was deployed in an 100 m cased and water-filled hole situated in the center of high-resolution spread (see Figure 4). This hydrophone cable was generously loaned to the CREWES Project by Noranda Technology Centre for use in this survey. This 48-channel hydrophone cable consists of Benthos AQ-4 hydrophones at 2 m separation with AQ-302 preamps molded into the cable which is terminated by an Amphib-122 connector. Adapter plugs had to be constructed in order to tie these channels into the surface recording spread. In addition to the vertical hydrophone string, 2 Wilcoxon 755G triaxial accelerometers, also loaned by Noranda Technology Centre, where deployed at the hydrophone string location and an adjacent buried 3-C geophone location to the east (see Figure 4).

Spread Layout

A schematic diagram for the spread layout is illustrated in Figure 5. There were 7 separate recording lines (≈ 60 km total cable length) deployed for the survey. Stations 151 - 651 encompassed the high-resolution portion of the spread and was laid out as three recording lines: Line 11 - vertical component (red), Line 12 - transverse component (black) and Line 13 - radial component (white).

The "conventional" (1st and 3rd km; stations 101-150 and 652-701 respectively) and buried geophone portions of the spread where combined and comprised another 3 recording lines (see Figure 5): Line 14 - vertical component (red), Line 15 - transverse component (black) and Line 16 - radial component (white).

The 48-channel hydrophone cable and the 2 triaxial accelerometers comprised the final recording line, Line 17. The hydrophone cable was situated at station 401, the center of the spread. The 2 accelerometers were deployed at stations 401 and 396. If a cable went bad during shooting, it would be replaced but not picked up. On completion of the survey, the cables were picked up in the opposite order they were laid out.

Walk-Away AVO VSP

Schlumberger of Canada Wireline and Testing Division were contracted to acquire the VSP data. The VSP was performed in PanCanadian's producing 100/09-08-23-23W4 oil well using a multi-level ASI tool. This multi-level tool is equipped with 5

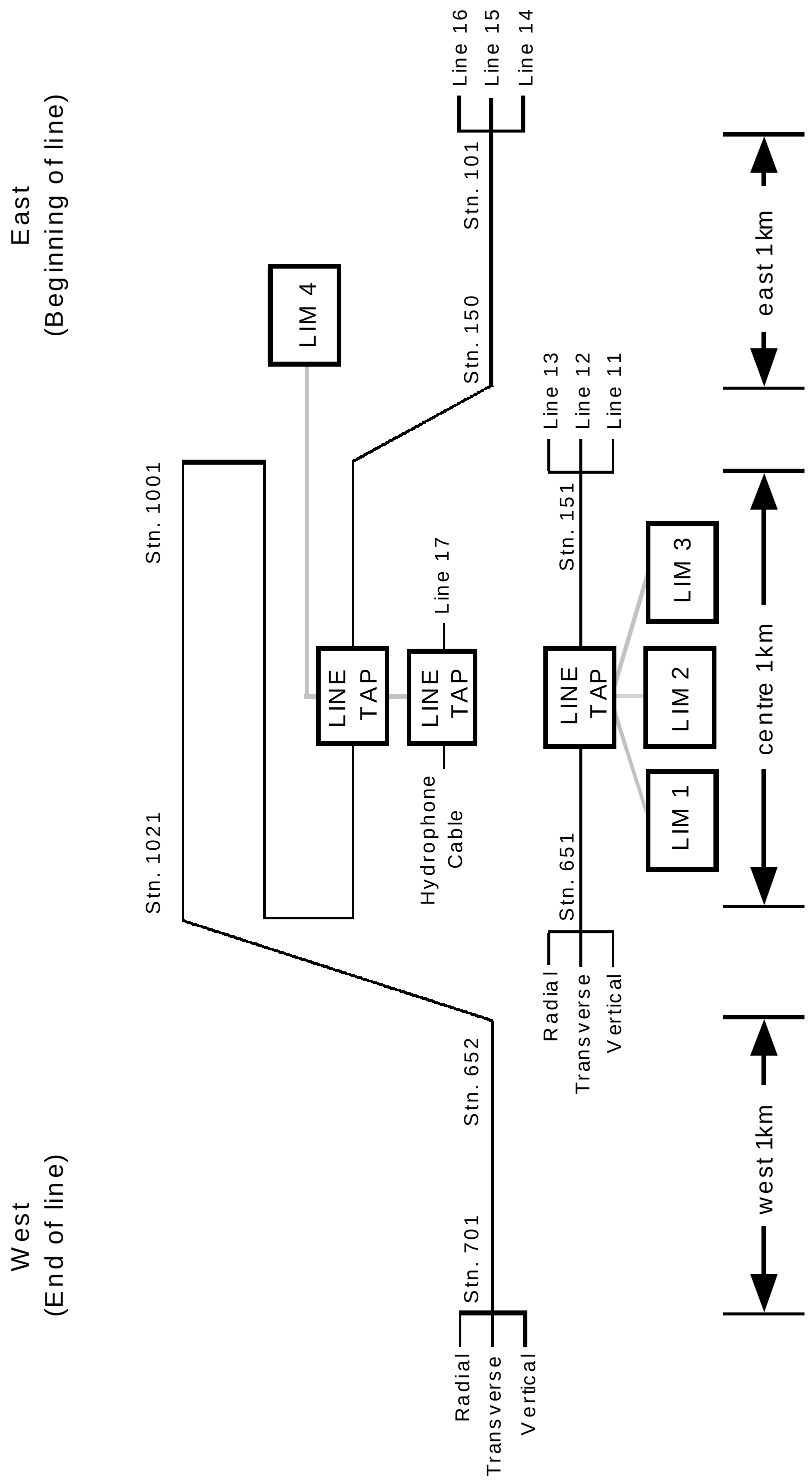

Figure 5. Spread layout or "snake" diagram for the Blackfoot high-resolution experiment.

3-C receiver elements with a 15 m receiver separation (60 m array length). Before the VSP tool could enter the well, production was shut down, the well head was fitted with a BOP (Blow Out Preventer) and production tubing was then pulled from the well.

A schematic diagram of how the VSP was recorded is illustrated in Figure 6. The bottom of the tool was first clamped at a depth of 1560 m and recorded surface seismic shots 101.5, 105.5, 109.5 ... (every 4th; Figure 6a) The tool was then unclamped and moved 75 m (one tool length + 15 m) uphole and re-clamped at 1485 m. Surface shots 102.5, 106.5, 110.5 ... (every 4th; Figure 6b) were recorded at this depth. The tool was then moved uphole to 385 m and shots 103.5, 107.5, 111.5 … (every 4th; Figure 6c) were then recorded. The tool was then raised to 310 m and shots 104.5, 108.5, 112.5 … (every 4th; Figure 6d) were recorded. Positioning the tool at these four different depths allowed a VSP recording at 10 evenly spaced and continuous receiver intervals (15 m; 135 m total length) at all shot offsets for levels 1425 – 1560 m and 250 – 385 m within the well. In addition to these four VSP depths, the tool was again moved to a depth of 460 m to record the 15 two hole pattern shots (2×2 kg @ 9 m) situated in middle of the spread.

PRELIMINARY RESULTS

On completion of the survey, the data were transmitted to Matrix Geoservices for processing. While the data were being processed another copy of the data was obtained by the authors and sorted into different collections and domains for cursory review and analysis. Since the survey was performed only days before the publication deadline, only portions of the processed data are presented.

The low-resolution (20 m shot, 20 m receiver) subset of the data was extracted from the full dataset and plotted in the form of shot records (Figures 7 and 8). Only the vertical and radial components contain any significant reflection energy. Data from the high-resolution spread was also extracted as a different set of shot records (Figures 9 and 10). The 2m receiver station interval produces an unusually flat looking shot gather.

The central 1 km of the survey contained 21 stations with receivers at four different levels: surface, 6m, 12m and 18m depth. Receiver gathers were generated for all the geophones located at a common station (Figures 11 and 12). Comparison of these receiver gathers shows that there are noticeable differences in measured signals from different depths. The deeper geophones appear to contain data with higher frequency. It appears however, that these buried geophones have a poorer signal-to-noise ratio than the surface geophones. This is most likely due to the quality of the geophone plants. The surface geophones can be carefully planted by hand, ensuring that the geophone spike is firmly inserted into hard soil. The buried geophones were planted using a friction clamp on the end of a loading pole. As a result, we suspect that many of the geophone plants were of poor quality.

Structural and migrated stacks of both the vertical (P-P) and radial (P-S) components from the "conventional" or low-resolution (20 m shot, 20 m receiver) portion of the Blackfoot survey are shown in Figures 13, 14, 15 and 16. All of these

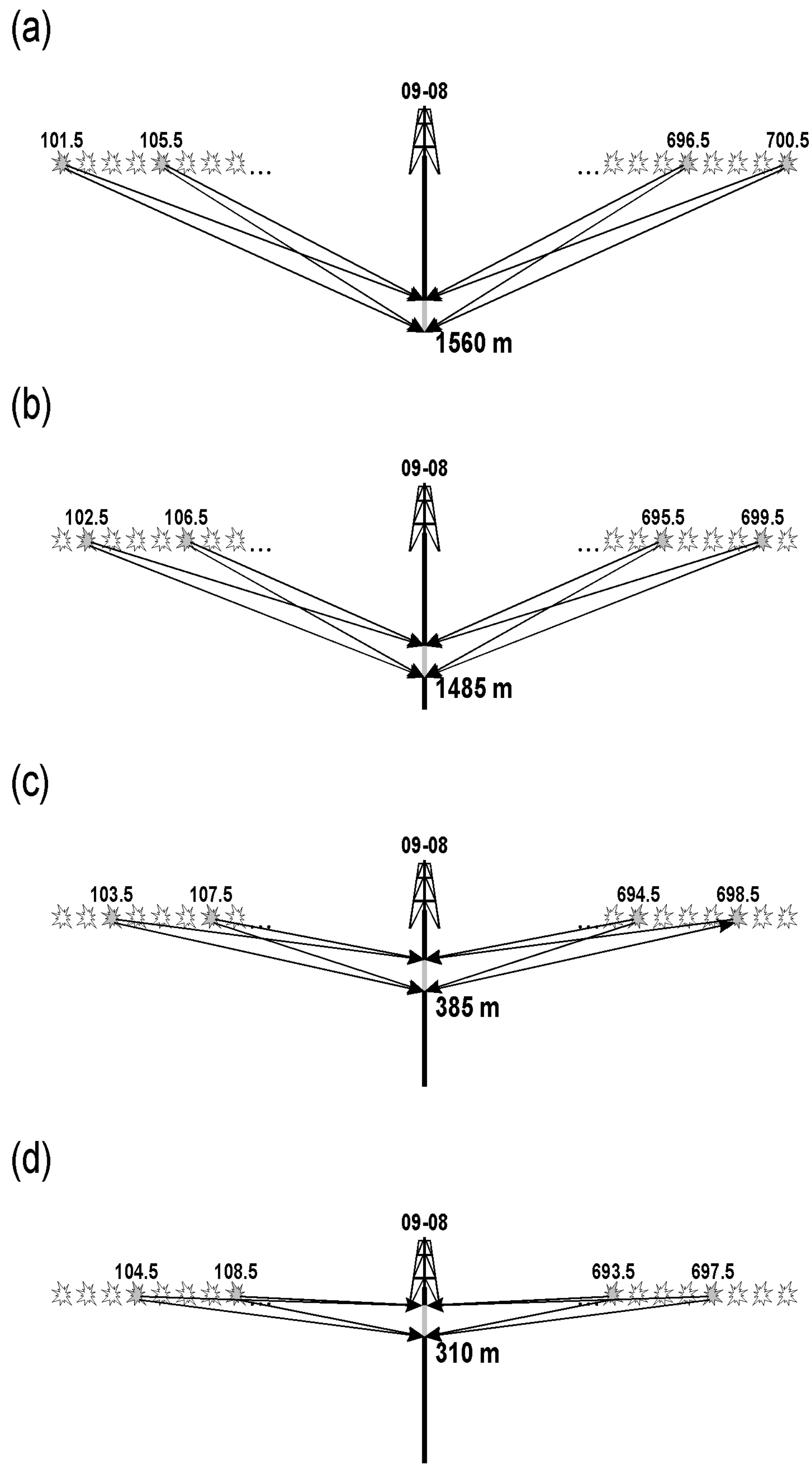

Figure 6. The shooting and recording configurations for the Blackfoot walk-away AVO VSP conducted in PanCanadian's 09-08 well. Every 4th surface seismic shot was recorded by a five-level 3-C ASI tool at four individual different well depths listed in (a), (b), (c) and (d).

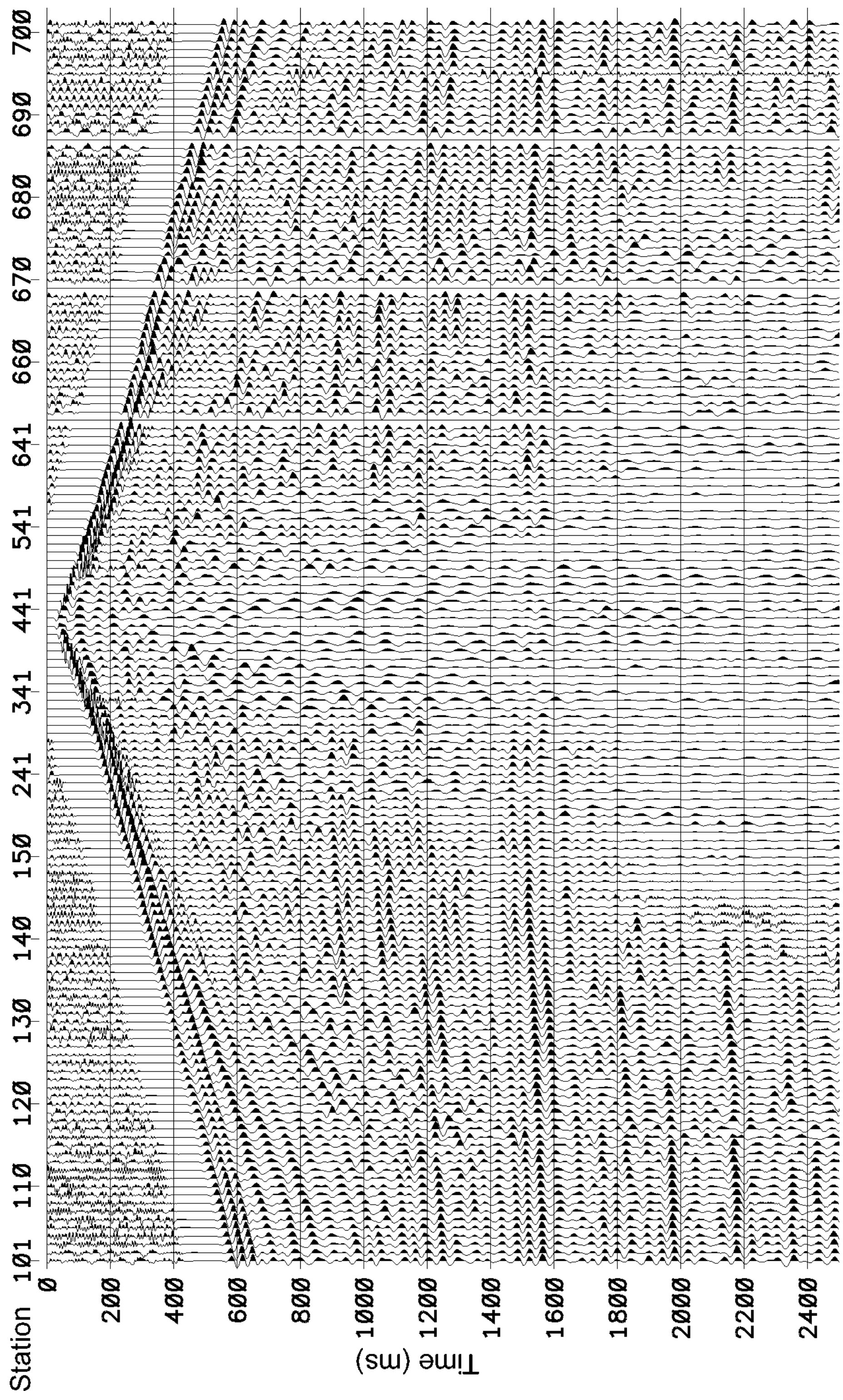

Figure 7. A shot record from the Blackfoot seismic survey showing vertical component data. Traces included in this record are a subset of all live receivers spaced 20 m apart across the entire 3 km profile. An AGC and bandpass filter (8-10-80-90) has been applied.

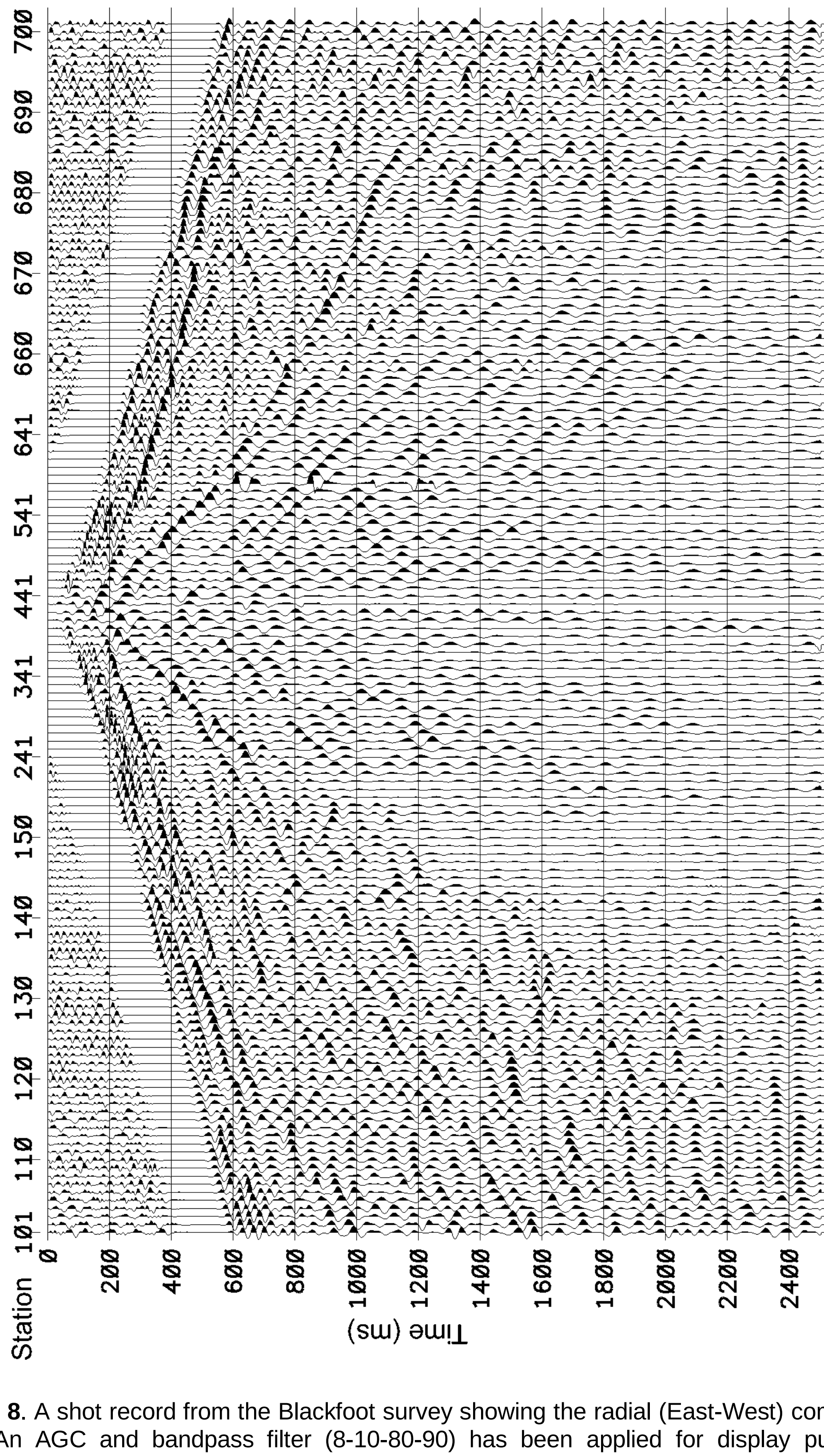

Figure 8. A shot record from the Blackfoot survey showing the radial (East-West) component data. An AGC and bandpass filter (8-10-80-90) has been applied for display purposes. Traces were acquired with a record length of 6 seconds and have been truncated for display.

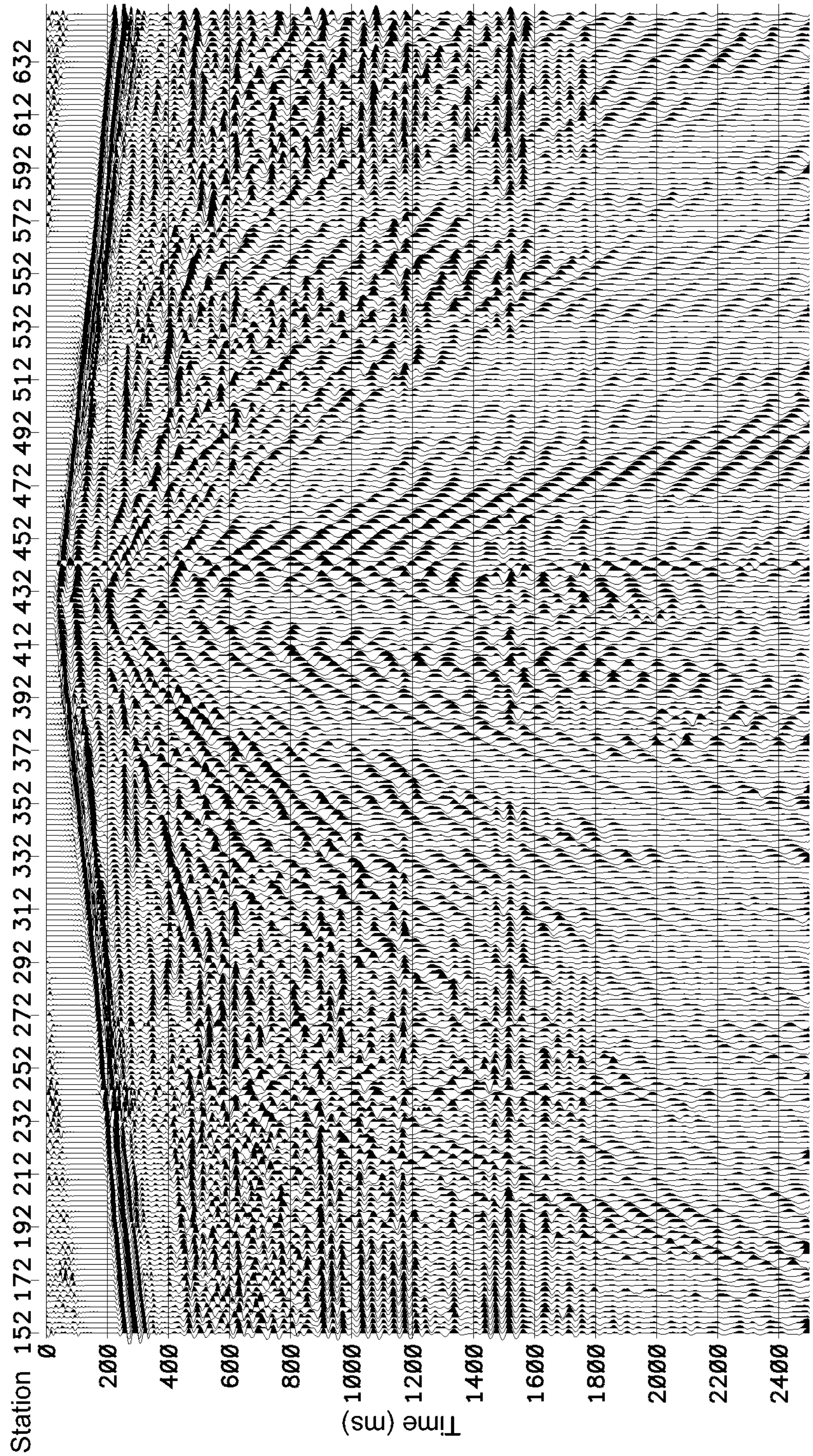

Figure 9. A shot record showing the vertical component data from the central, high-resolution portion of the survey.

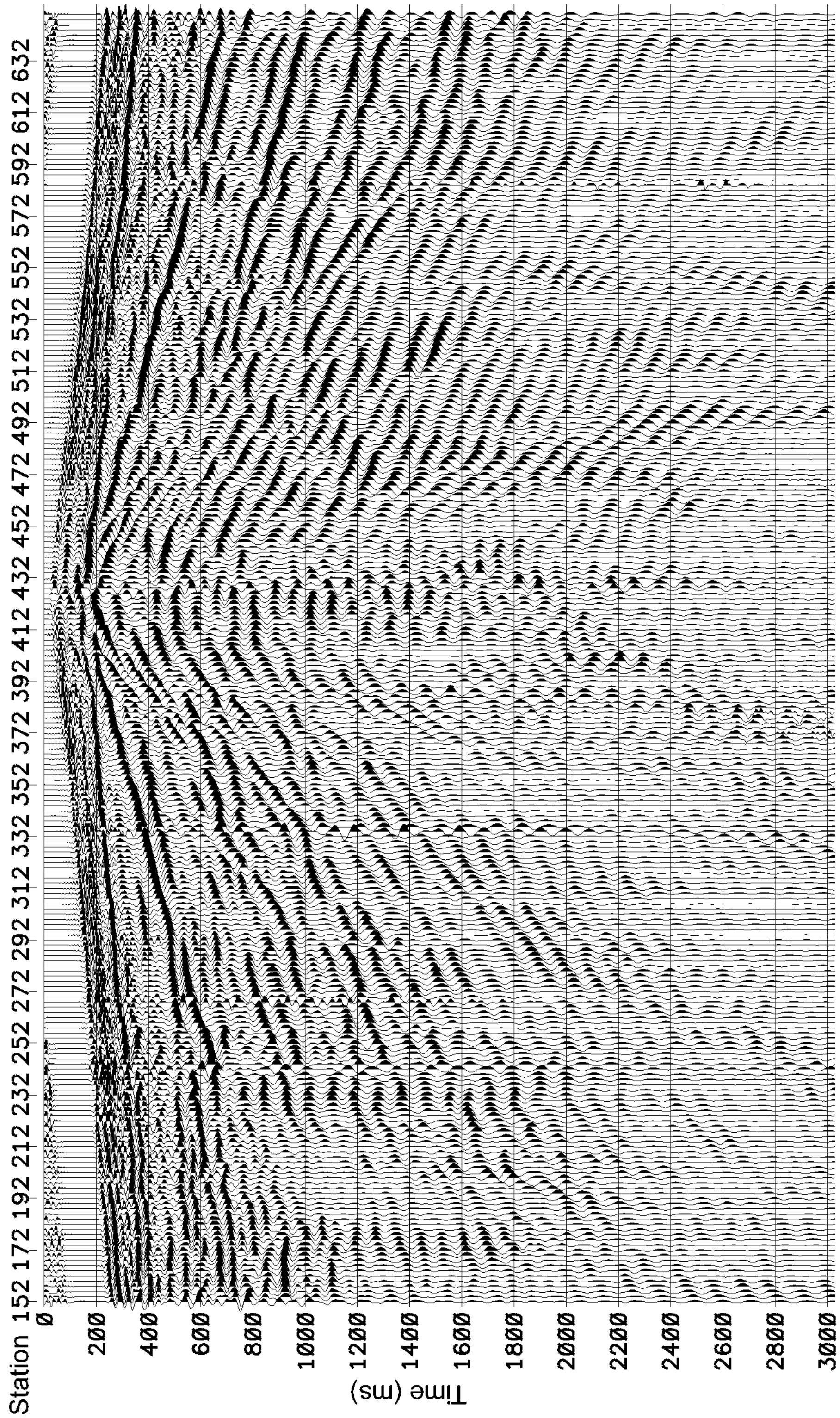

Figure 10. A shot record showing the radial component data from the central, high-resolution portion of the survey.

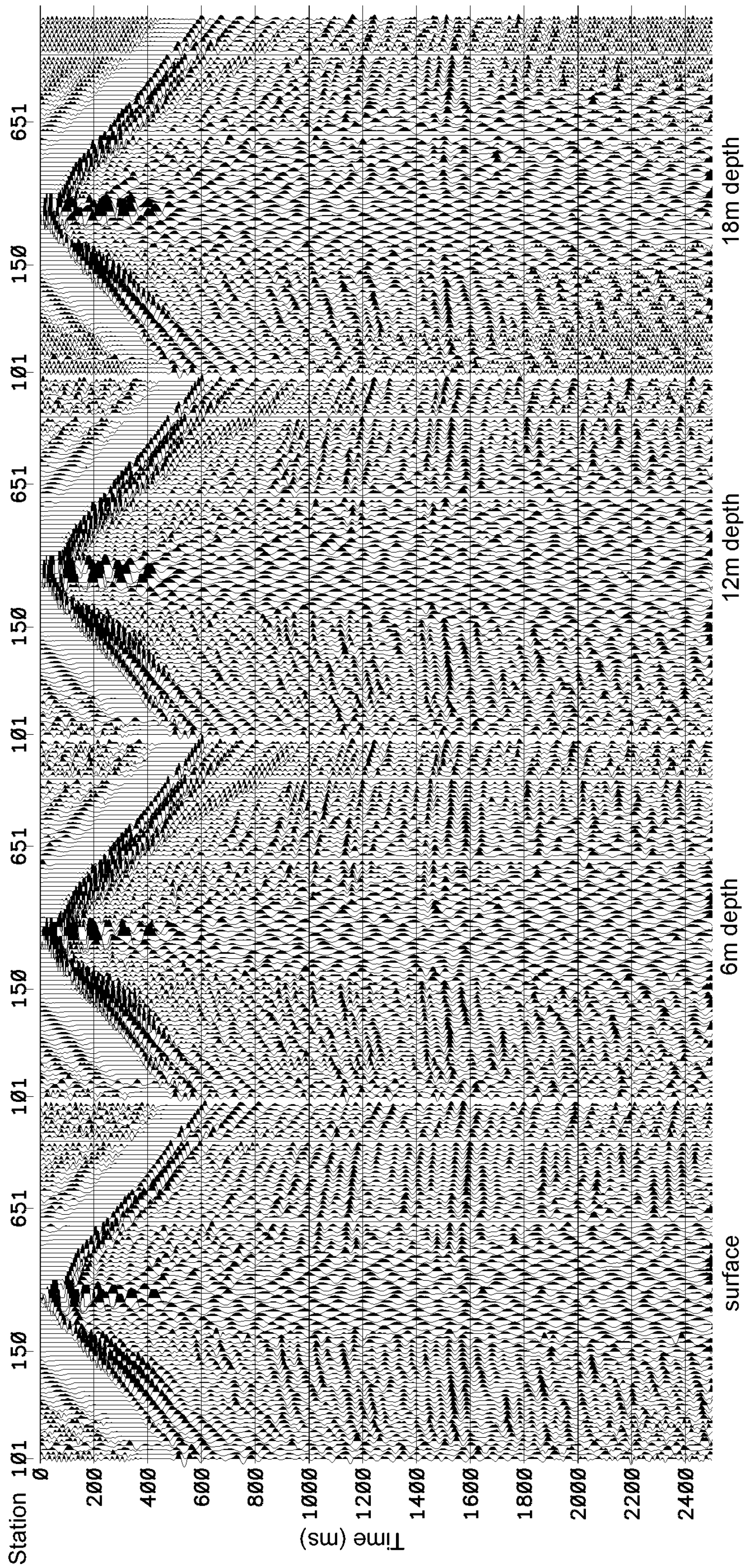

Figure 11. Receiver gathers (surface, 6, 12 and 18 m depth) showing the vertical component data for one of the 21 buried geophone stations located in the central, high-resolution portion of the survey.

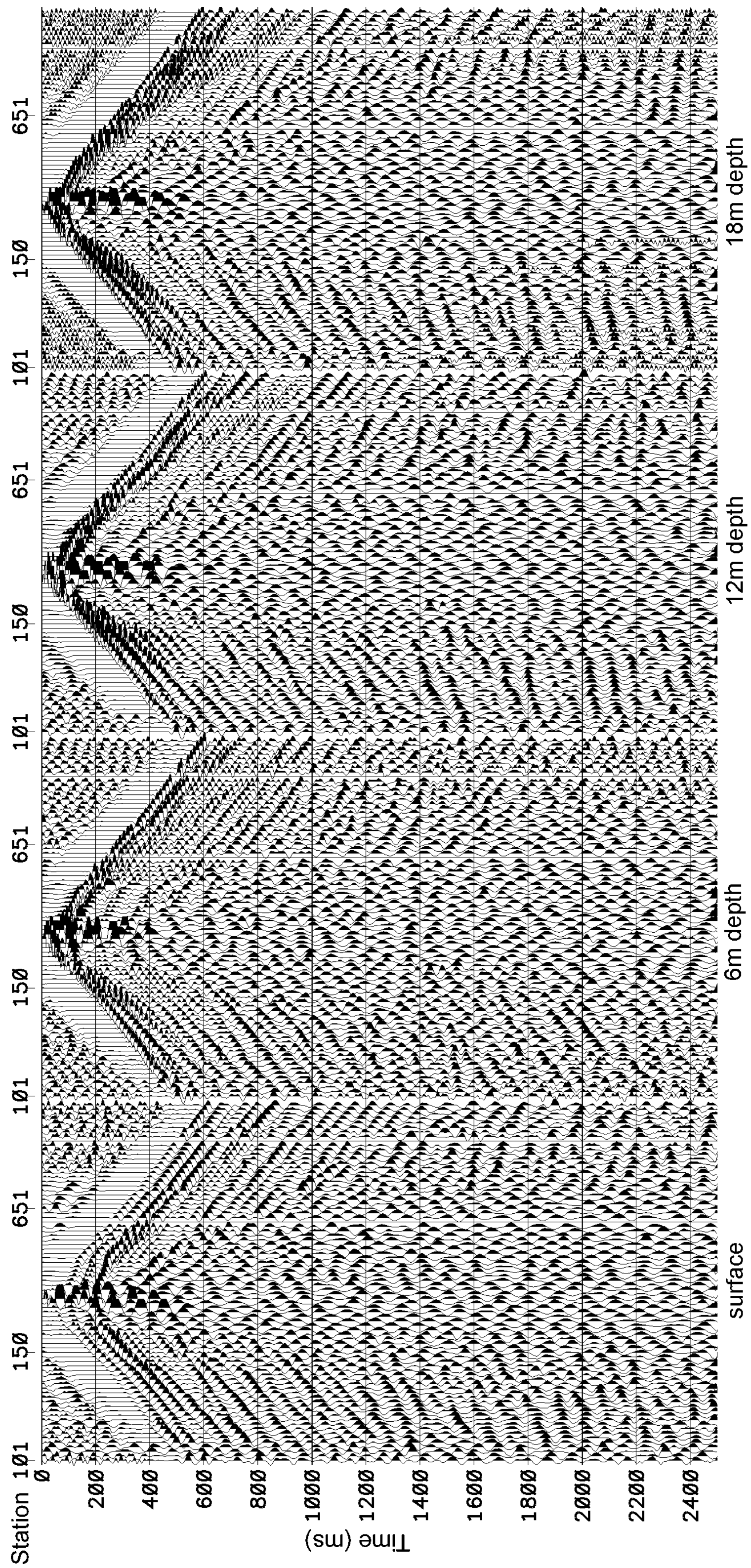

Figure 12. Receiver gathers (surface, 6, 12 and 18 m depth) showing the radial component data for one of the 21 buried geophone stations located in the central, high-resolution portion of the survey.

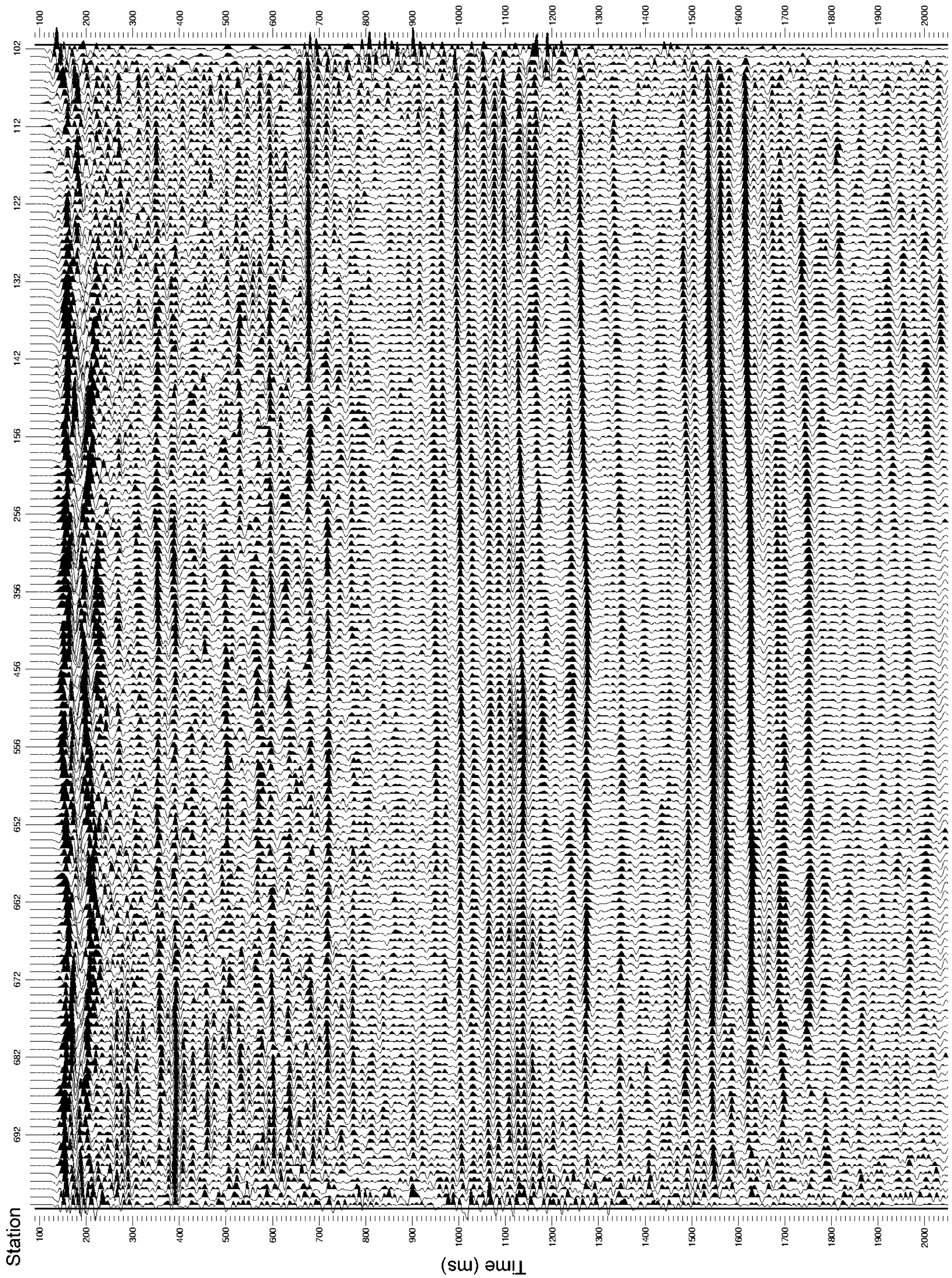

Figure 13. Structural stack generated from the vertical component of the low-resolution (20 m shot, 20 m receiver) portion of the survey.

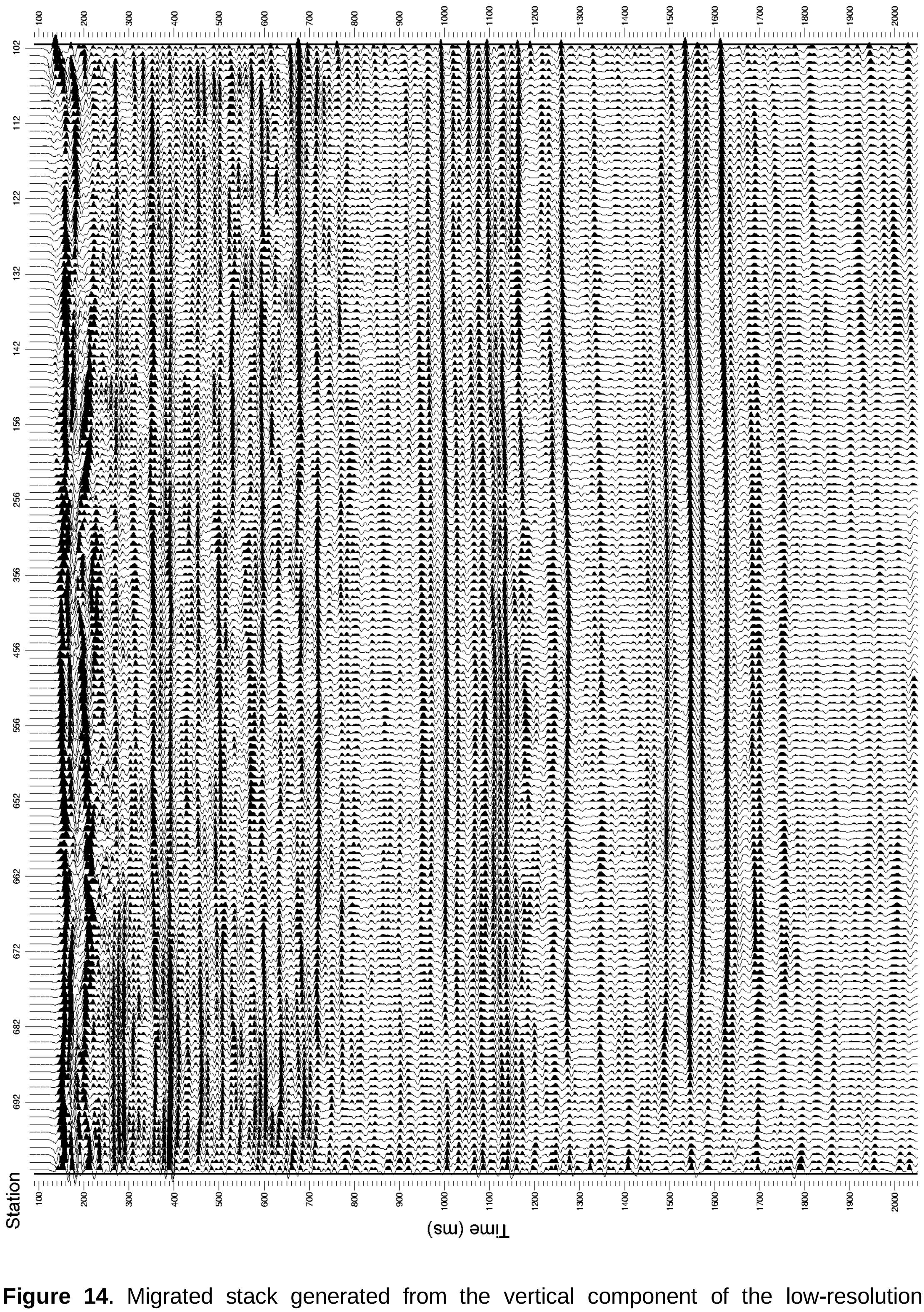

Figure 14. Migrated stack generated from the vertical component of the low-resolution portion of the survey.

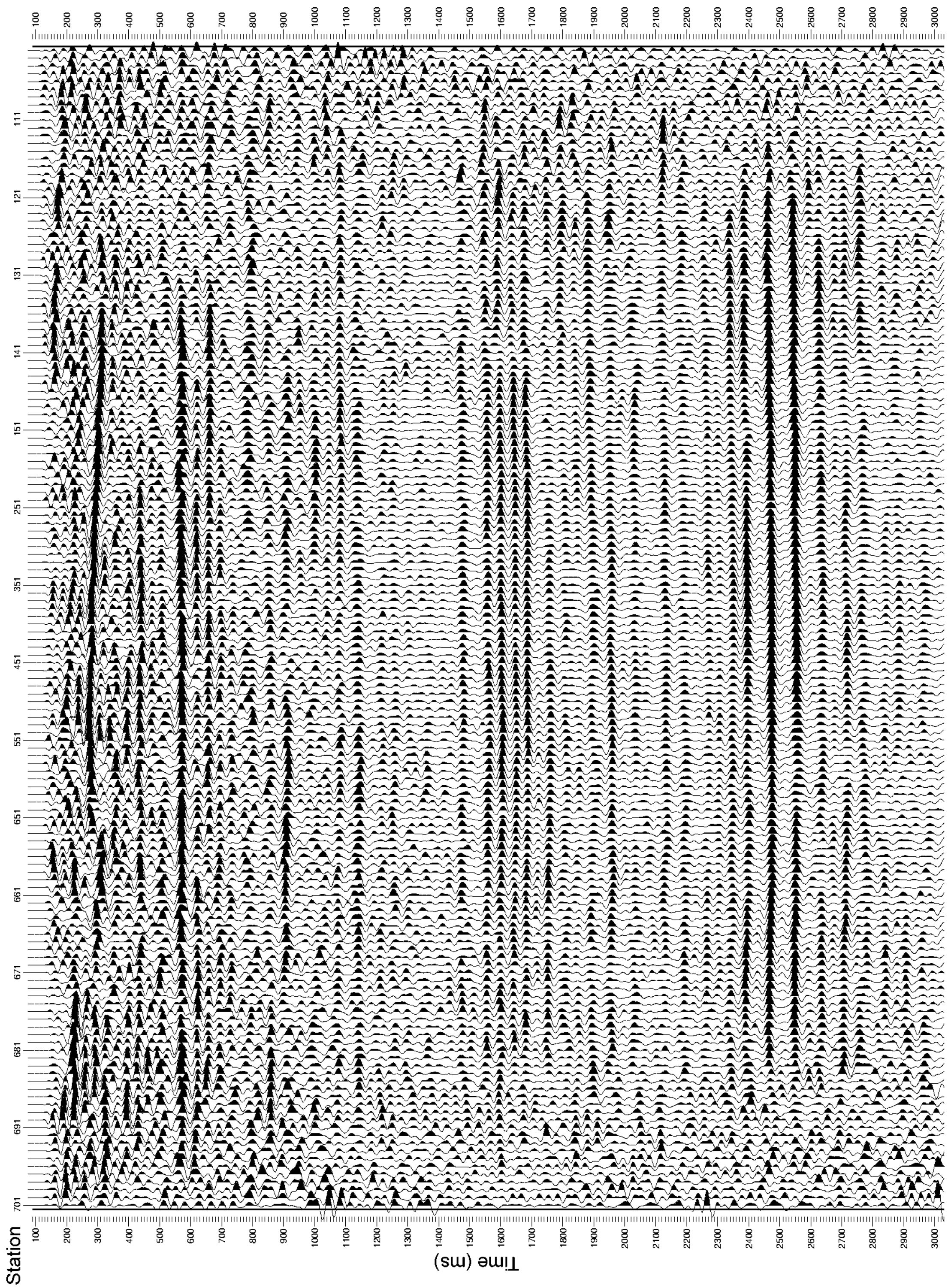

Figure 15. Structural stack generated from the radial component of the low-resolution portion of the survey.

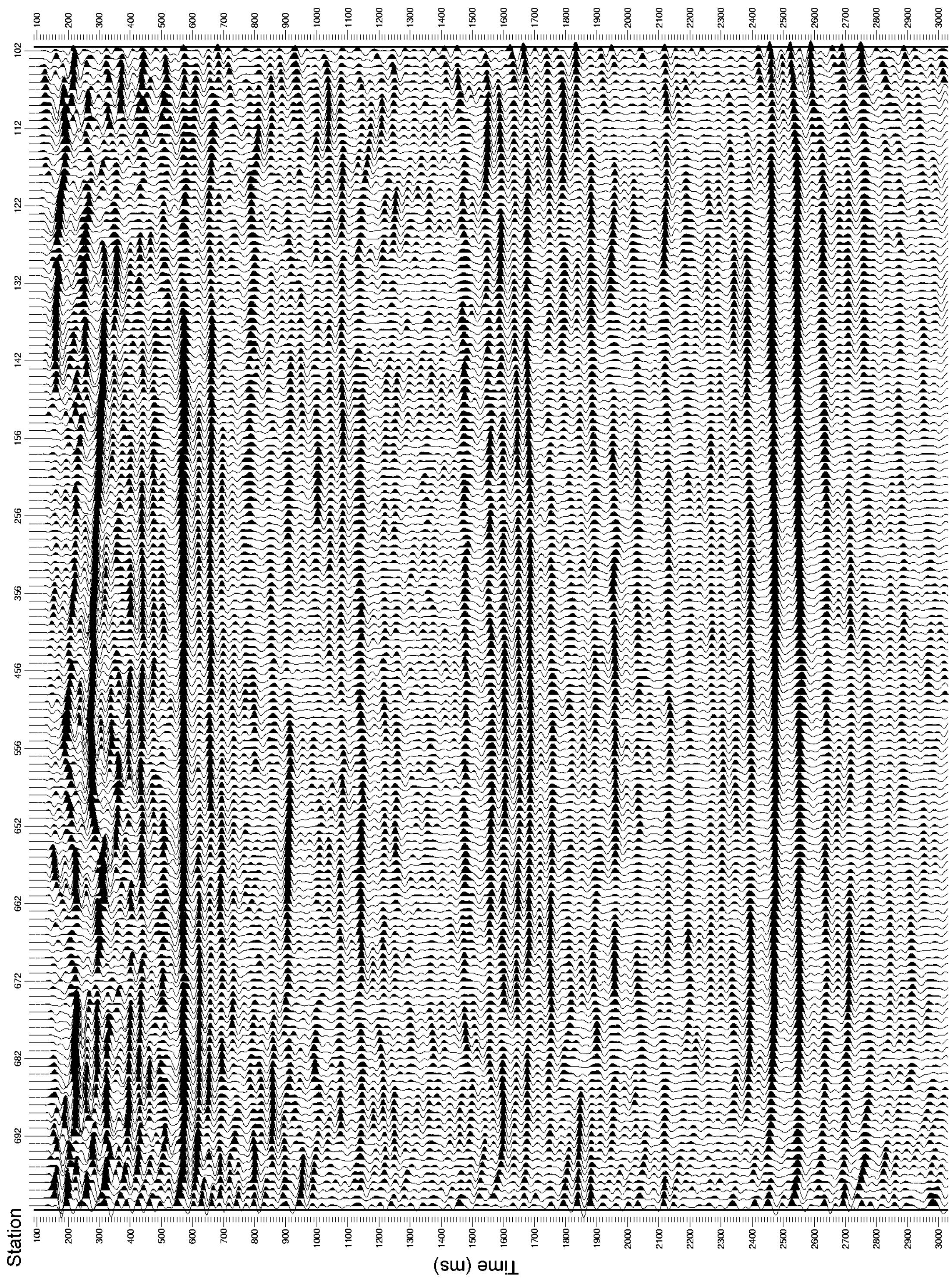

Figure 16. Migrated stack generated from the radial component of the low-resolution portion of the survey.

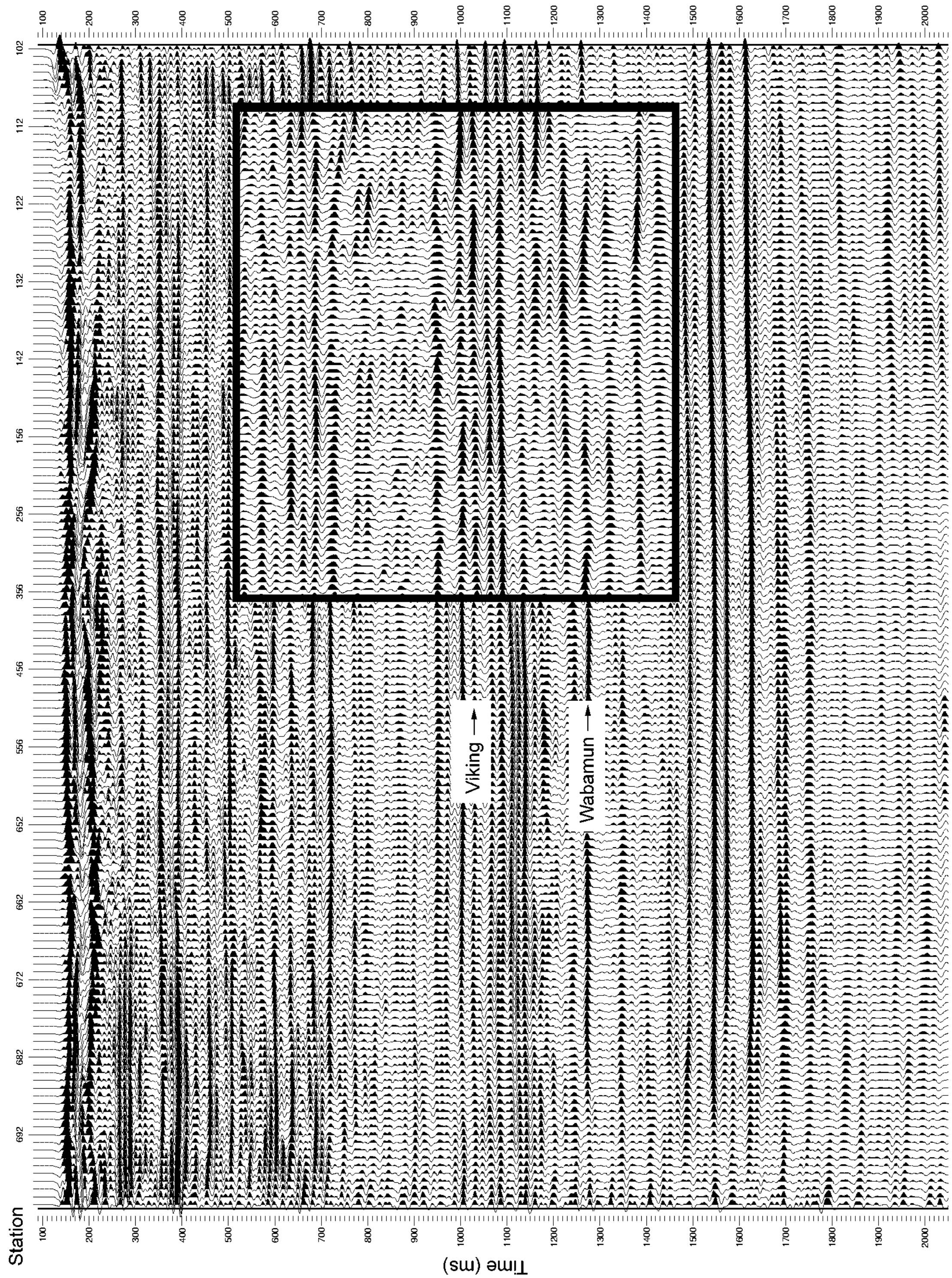

Figure 17. Migrated P-P stack with inset of a portion of the migrated P-S stack. The correlation shows good ties of the Viking and Wabamun events in the zone of interest.

sections are of high quality showing clear and coherent reflection events. Filter panels of portions of the P-P structural stacks show the presence of coherent reflection events up to frequencies of 110 Hz. The P-P and P-S sections (Figure 17) correlate well and exhibit interpretable ties between many of the major reflectors (i.e. Viking and Wabamun events) in the region spanning the Glauconitic channel.

CONCLUSIONS

The Blackfoot high-resolution survey was successfully completed and acquired a high-quality 3C-2D data set. The initial P-P and P-S sections of the "conventional" or low-resolution portion of the survey show a series of clear and coherent reflection events. Correlation between the P-P and P-S is good with interpretable ties between many of the major reflectors in the zone containing the producing Glaucontic sands.

ACKNOWLEDGEMENTS

We would like to thanks Dave Cooper and William Goodway of PanCanadian Petroleum Ltd. for their generous support of this project. Also John Boyd and Doug Eaton of Boyd PetroSearch for all their help in managing this project to a successful conclusion. Jeff Mackie and Jim Roy of Veritas DGC Land for their technical assistance in acquiring this unique 3C-2D survey. Mike Jones of Schlumberger Canada who played a major role in the planning and execution of the walk-away VSP. John McGaughey of Noranda Technology Centre who kindly loaned us the 48-channel hydrophone cable and accelerometers for use in this survey. Dave Grindell of OYO Geospace Canada who worked hard in successfully preparing the 3-C geophones for use in the buried portion of the survey. Andy Read of the Faculty of Science Workshop, University of Calgary who also offered technical assistance during the course of this project. Finally, we thank all sponsors of the CREWES Project for their continued technical and financial support.

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