Zero-offset vertical seismic profiles of coalbed methane strata: a comparison of three vibrating sources

Sarah E. Richardson and Don C. Lawton

SUMMARY

Zero-offset vertical seismic profiles (VSPs) were acquired at a coalbed methane test site using three different sources. A 44,000 lb. P-wave source ("big-P") sweeping 8-150 Hz, a smaller vibratory P-wave source ("mini-P") sweeping 8-250 Hz, and a shear-wave source ("mini-S") sweeping 8-150 Hz all effectively imaged the target coal zone. Bandwidth comparisons show useable frequencies of 8-150 Hz in the big-P data, whereas the mini-P data contains frequencies ranging 8-220 Hz. Shear wave attenuation was considerably higher than that of P-waves, with the mini-S source yielding useable bandwidth of 8-80 Hz. Such low attenuation of the mini-P source suggests that high-bandwidth converted-wave data may be obtained using the mini-P source. Although Ardley coal zone contacts at the Red Deer site may be effectively imaged using any of the three sources tested, lithological changes within the coal may only be detected using the high-frequency mini-P source.

INTRODUCTION

Vertical seismic profile data were acquired at the Cygnet 9-34-38-28W4 lease, located northwest of Red Deer, Alberta (Figure 1). Suncor Energy Inc., industry partners, and the Alberta Research Council are evaluating this site for enhanced coalbed methane recovery. Methane production and carbon dioxide sequestration are both being tested for viability within the lower Tertiary Ardley coal zone (Figure 1), one of Alberta's most prospective CBM targets.

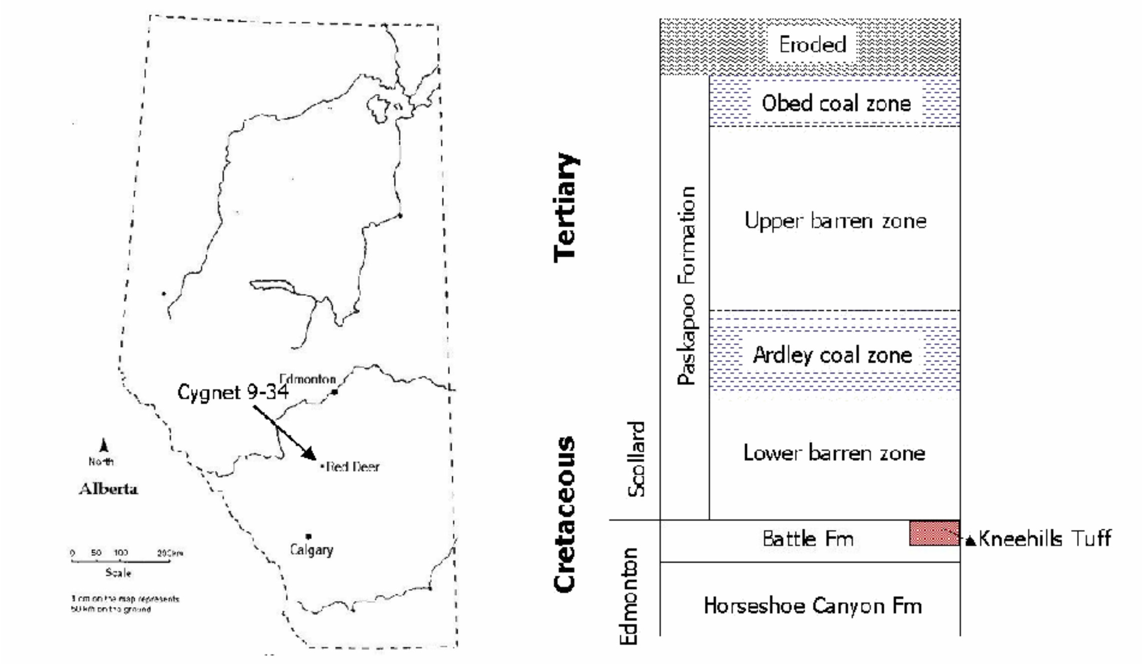

FIG. 1. Location and stratigraphy of the Red Deer study area (Natural Resources Canada, 2002, and after Gibson, 1977)

Ardley coal seams are overlain by sandstones and shales of the Paskapoo formation, and underlain by the Edmonton Group, which is of similar lithology.

Zero-offset VSPs were acquired using a 44,000 lb. P-wave source ("big-P") sweeping 8-150 Hz, a smaller truck-mounted P-wave source ("mini-P") sweeping 8-250 Hz, and a truck-mounted shear-wave source ("mini-S") sweeping 8-150 Hz. In each case, sweep design was limited by the operational limitations set by the operator. Although high-bandwidth (and thus, high resolution) data was desired to effectively image the coal, it was unknown whether the mini-P Vibroseis source would produce enough energy to generate clear reflections at the depth of the coal. For this reason, both the mini-P and big-P sources were used, to determine what the best source for imaging coal seams at this site is. A shear source was used such that shear-wave velocities in the shallow section could be determined, and to test shear-wave attenuation within the strata. The mini-S source was configured such that the polarization of the S-waves was oriented normal to the source-receiver plane. A five-level, three-component VSP tool with a 15 m receiver spacing was used in an interleaved manner such that receivers were spaced at 5 m intervals from TD (300 m) to surface within the wellbore. All recording was undertaken at a 1 ms sampling rate.

RAW DATA

Data recorded at the Red Deer test site are of excellent quality. Raw data shows only one poorly coupled receiver (at 114 m depth) throughout all surveys. The uppermost receiver, at 20 m depth, shows considerable noise. Both downgoing and upgoing energy can be distinguished on raw data for the mini-P, big-P and mini-S sources, illustrated in Figure 2, Figure 3, and Figure 4, respectively.

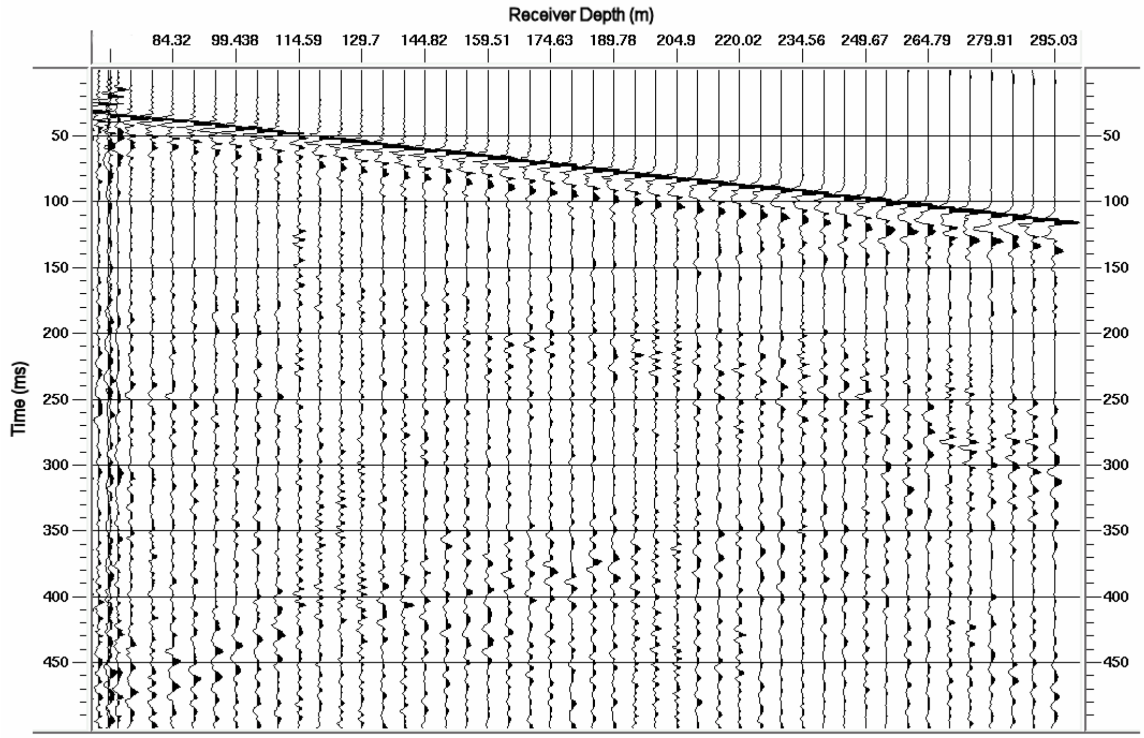

FIG. 2. Summed raw vertical-component data recorded for mini-P zero-offset vertical seismic profile at Red Deer. Automatic gain correction (200 ms operator length) applied.

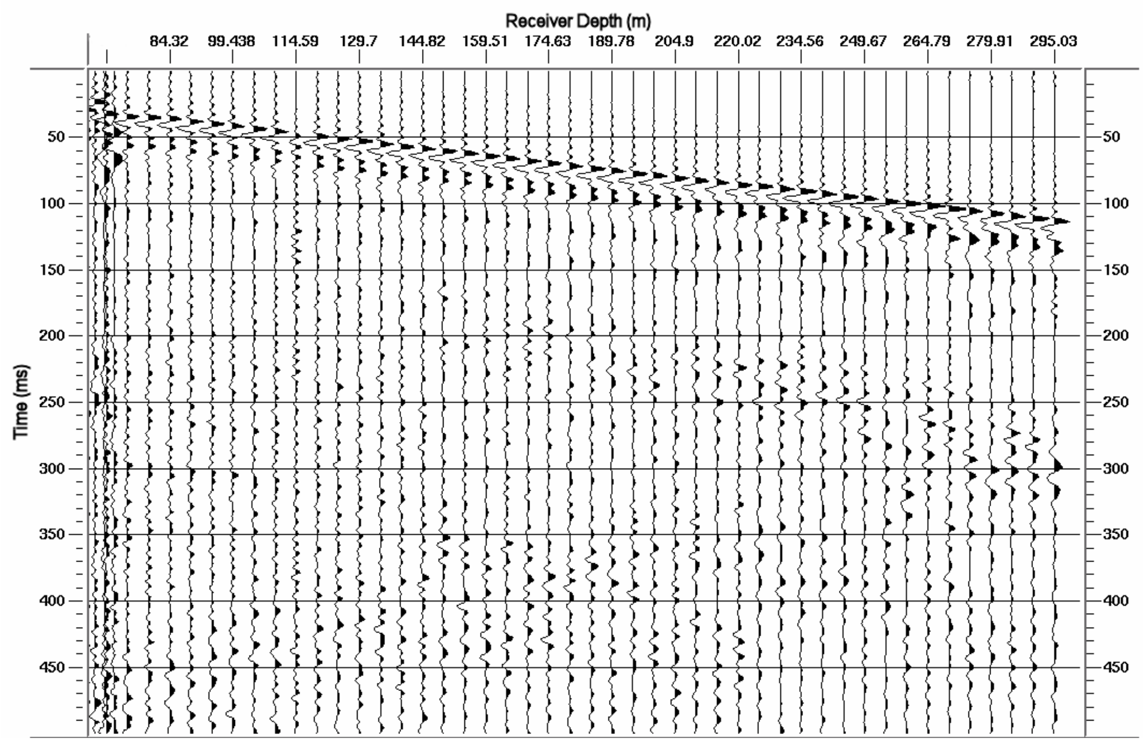

FIG. 3. Summed raw vertical-component data recorded for big-P zero-offset vertical seismic profile at Red Deer. Automatic gain correction (200 ms operator length) applied.

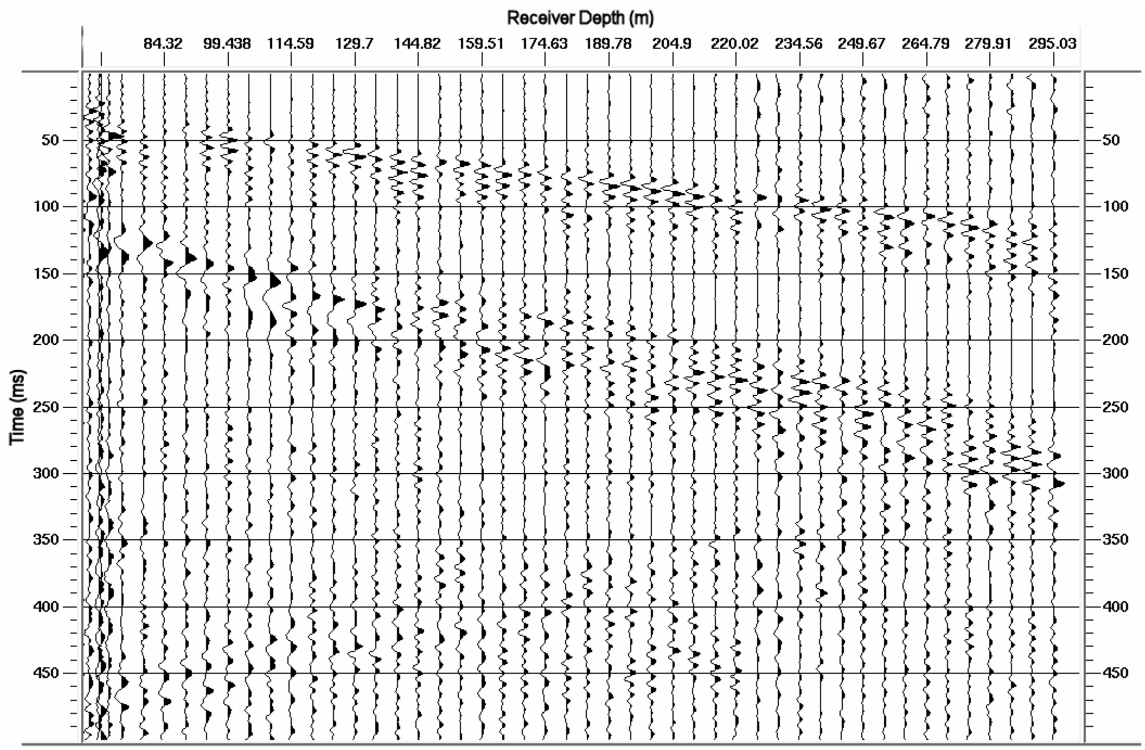

FIG. 4. Summed raw horizontal-component data recorded for mini-S zero-offset vertical seismic profile at Red Deer. Automatic gain correction (200 ms operator length) applied.

DATA PROCESSING

Zero-offset VSP vertical-component data sets were processed by Schlumberger Canada, using the flow outlined in Figure 5. After geometry assignment and separation of vertical components, multiple shots were summed using a median algorithm, and first breaks were picked. Temporal amplitude recovery (with a time-power constant of 1.7) and spatial amplitude normalization RMS (with a 0.1 s time window) were used to compensate for spherical divergence and transmission losses. Wavefield separation was accomplished by use of an eleven-trace median filter. Another median filter (5 traces) was applied to enhance the separated upgoing wavefield, and waveshaping bottom level deconvolution (using a 0.6 s time window and 1.0% white noise) was used to remove the effect of the source signature from the upgoing energy. The data were once again enhanced with a three-trace median filter. A corridor stack was produced by defining the top and bottom of the corridor, and by adding first arrival times to convert the data to two-way time (Figure 6). Various bandpass filters were tested on the final corridor stack.

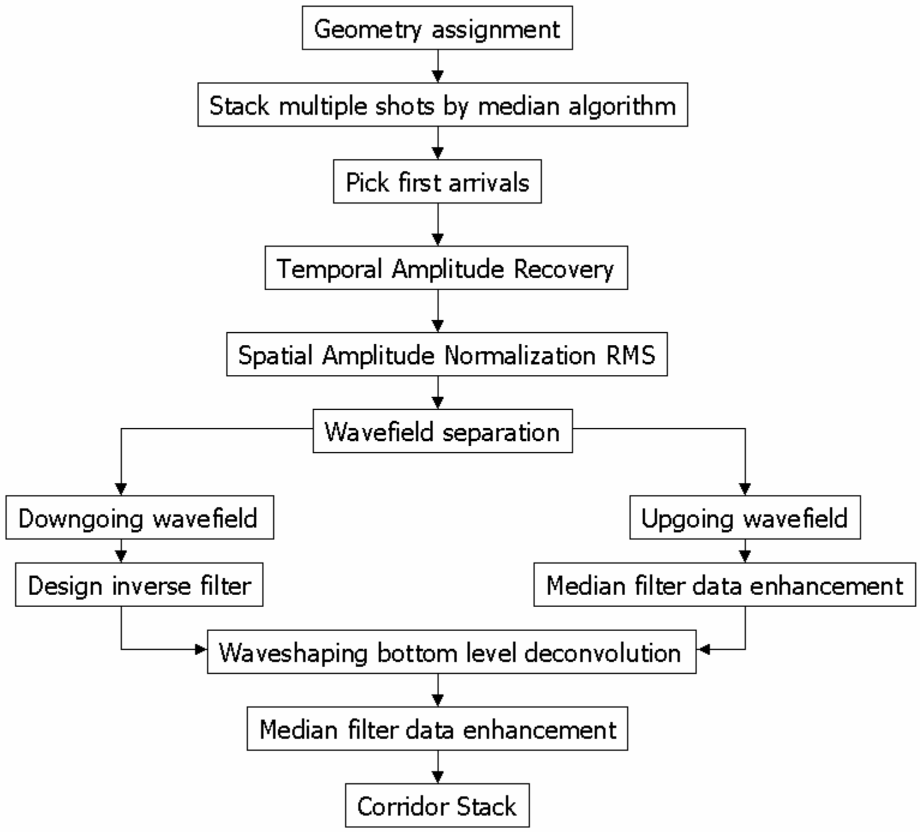

FIG. 5. Processing flow used to process zero-offset mini-P VSP data (Schlumberger).

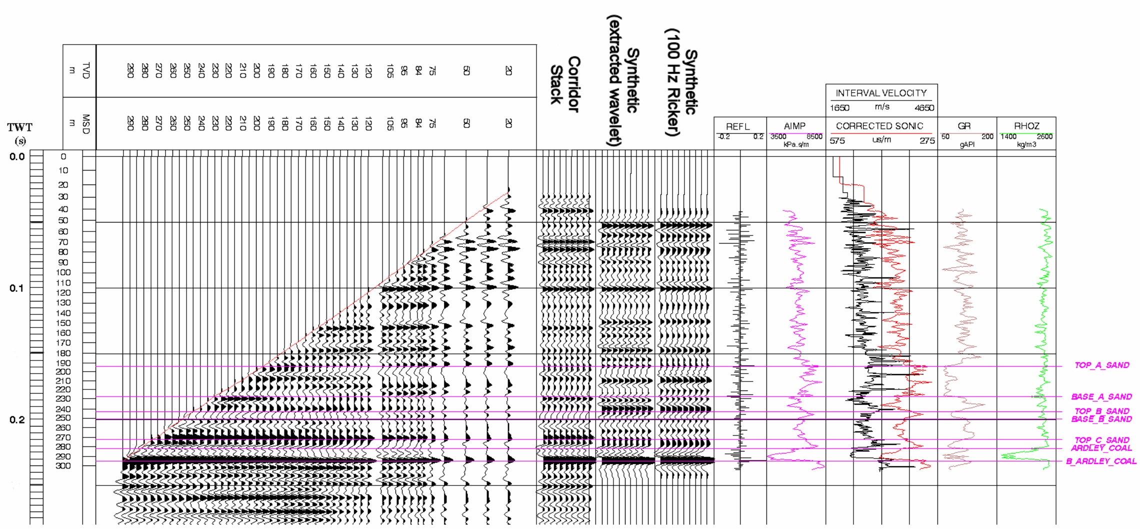

FIG. 6. Final corridor stack of upgoing P-wavefield from zero-offset mini-P data (Schlumberger).

The mini-P data show a high-amplitude coal event, with the upper coal contact imaged at approximately 220 ms, and the basal contact at approximately 230 ms. Processed data correlate well with the synthetic seismogram generated by convolution of the well logs with the extracted mini-P wavelet. Processed mini-P data are able to resolve not only upper and lower coal contacts, but also an intra-coal event at approximately 225 ms. Although it is possible this is the result of wavelet side-lobe interference, this event is also visible on the synthetic seismogram, and detailed examination of well logs suggest that this event may represent a shale parting or a calcite streak within the coal zone.

Using a flow nearly identical to that used for mini-P processing (Figure 5) zero-offset big-P vertical-component data was processed by Schlumberger. Changes were made only to minor parameters within the processing steps, such as the extents of bandpass filters. The final big-P corridor stack is illustrated in Figure 7.

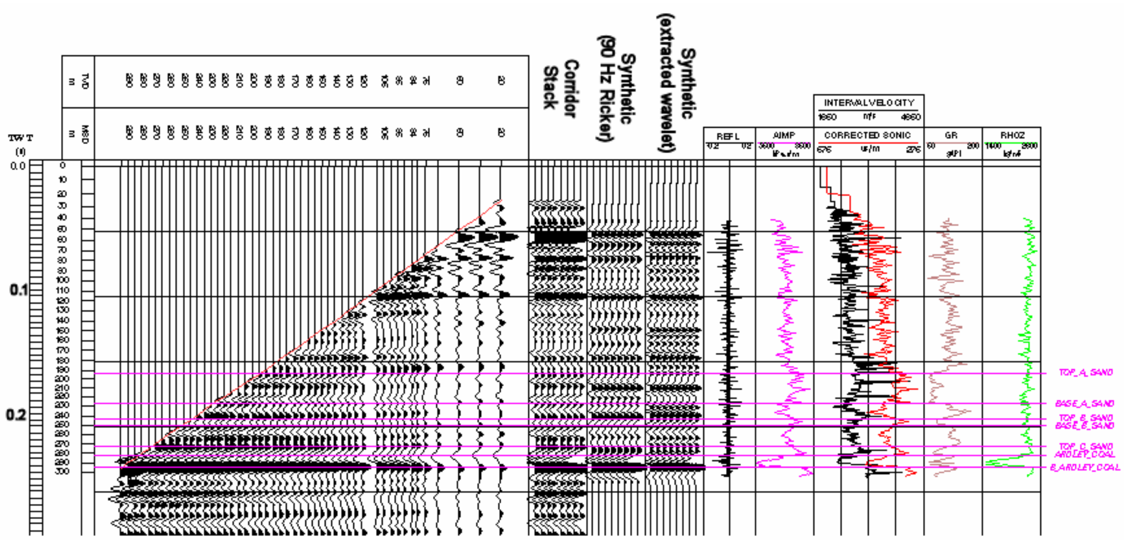

FIG. 7. Final corridor stack of upgoing P-wavefield from zero-offset big-P data (Schlumberger).

Schlumberger's processing flow for the mini-S data set is outlined in Figure 8. Horizontal components were rotated into the plane of the source and receivers. The horizontal component showing maximum energy was selected for processing. After picking first breaks, true amplitude recovery and amplitude normalization were applied. Shear wavefield separation was accomplished using a fifteen-trace median filter, and the resultant upgoing energy was enhanced using a nine-trace median filter. Waveshaping bottom level deconvolution removed the effects of the input source energy, and the deconvolved traces were once again enhanced with a median filter. No shear sonic log was recorded prior to processing the mini-S zero-offset data, so a model was built using the compressional-sonic log and the mini-S first arrival times to convert the data to P-time. The final corridor stack of the mini-S data is illustrated in Figure 9.

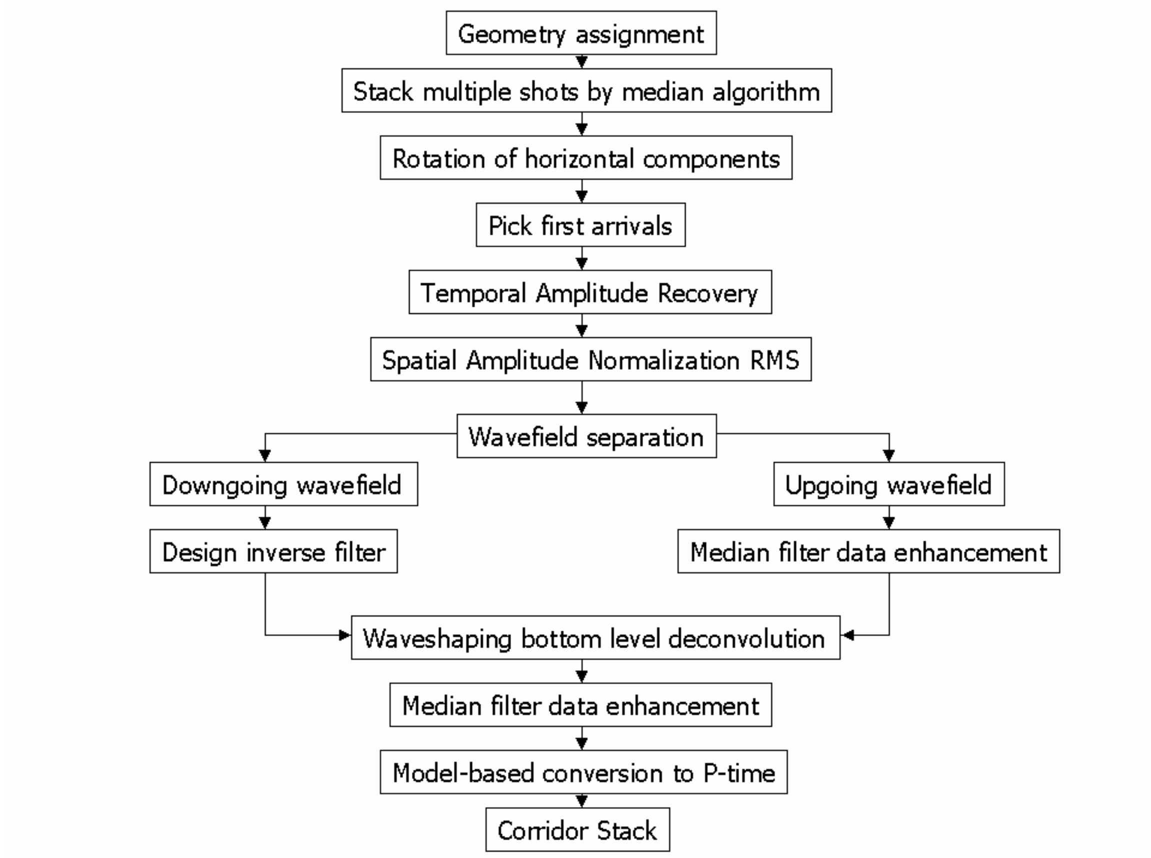

FIG. 8. Processing flow used by Schlumberger to process the zero-offset mini-S VSP data (Schlumberger).

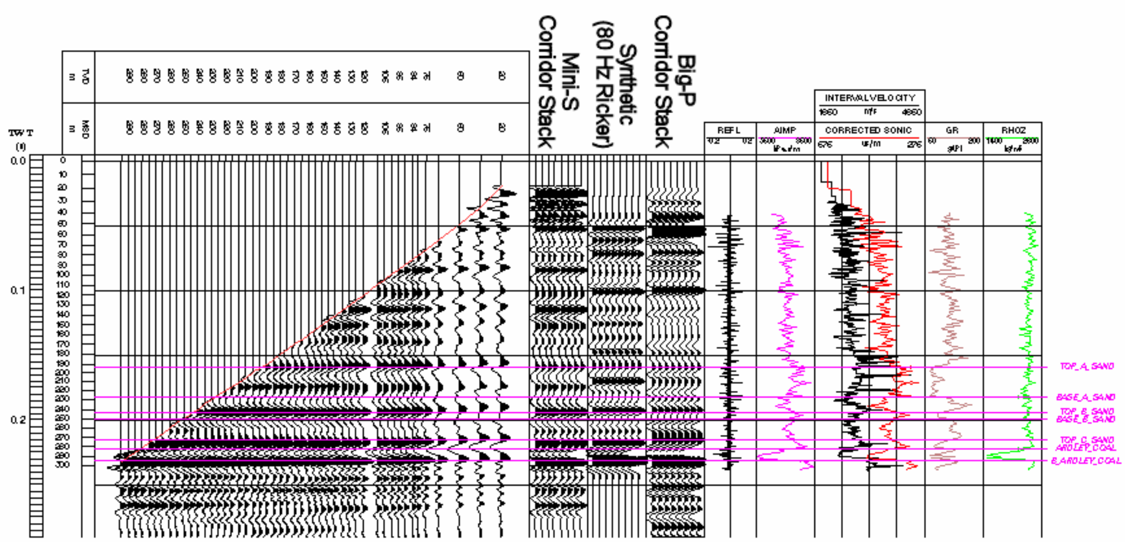

FIG. 9. Final corridor stack of upgoing S-wavefield from zero-offset mini-S data (Schlumberger).

DATA ANALYSIS

A comparison of the three final corridor stacks is shown in Figure 10. An apparent phase shift is noted when comparing the compressional and shear data sets, as the mini-S coal top response is a zero crossing, whereas the P-data coal top response is the maximum of a trough. This is attributed to a difference in tuning between the two wavefields.

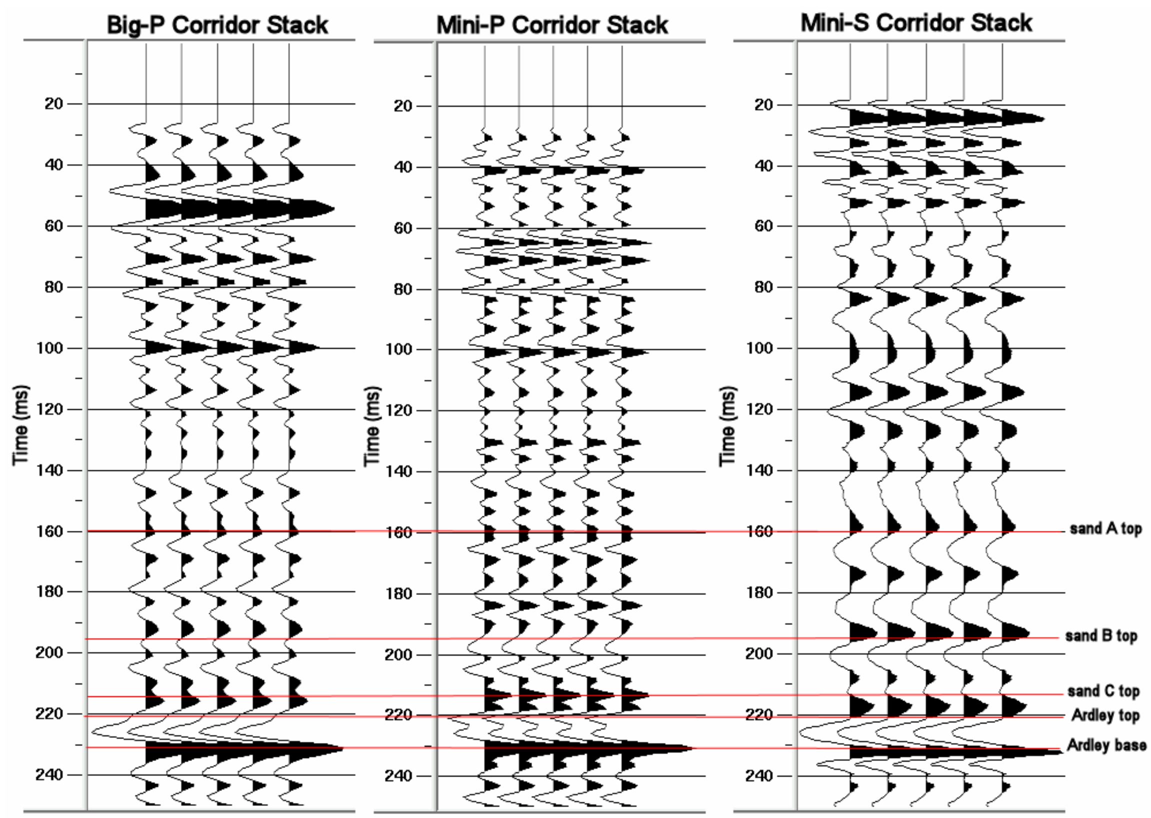

FIG. 10. Comparison of three final zero-offset corridor stacks. Improved resolution in the mini-P data set is immediately apparent.

When comparing the two compressional sources, Big-P data images the coal zone well, although it is not able to resolve the intra-coal event imaged by the higher-bandwidth mini-P source. This corridor stack shows, however, that a big-P source is suitable for detection of coal seams, but not for detecting intra-seam inhomogeneities.

Amplitude spectra of the final stacks for each source indicate that the mini-P data set has much higher bandwidth than the big-P data, as expected. Frequency analysis for the big-P dataset demonstrates useable frequency content of 15-150 Hz (Figure 11), virtually identical bandwidth to the source sweep. Assuming an average coal velocity of 2450 m/s in the study area, this results in a maximum theoretical possible resolution up to 4.08 m using the traditional l/4 formula, or up to 2.04 m using the Gochioco (1992) modified limit of resolution for coal. Little attenuation of the high frequencies has occurred, suggesting that even higher bandwidth would have been attainable, had the sweep not been limited by operating parameters. At the depth of the coal zone, the dominant frequency is approximately 80 Hz, resulting in a practical limit of resolution of 7.6 m (using l/4) or 3.8 m using Gochioco's modified limit.

Higher bandwidth was obtained in the mini-P survey, with useable frequencies ranging from 15-220 Hz (Figure 12). With an input sweep of 8-250 Hz, only the very lowest and highest frequencies have been attenuated. Dominant frequency at the depth of the coal is approximately 110 Hz. This results in a practical resolution as high as 5.6 m (using l/4) or 2.8 m (using l/8). The final corridor stacks clearly demonstrate the improved resolution of the mini-P data set, which is able to image an intra-coal event. Log data shows the largest impedance contrasts within the coal zone bound a layer only 0.5 m thick. The high bandwidth recorded suggests that strong impedance contrasts within a coal zone may allow detailed mapping of individual seams within a coal zone, or locating undesirable tight streaks prior to CBM development.

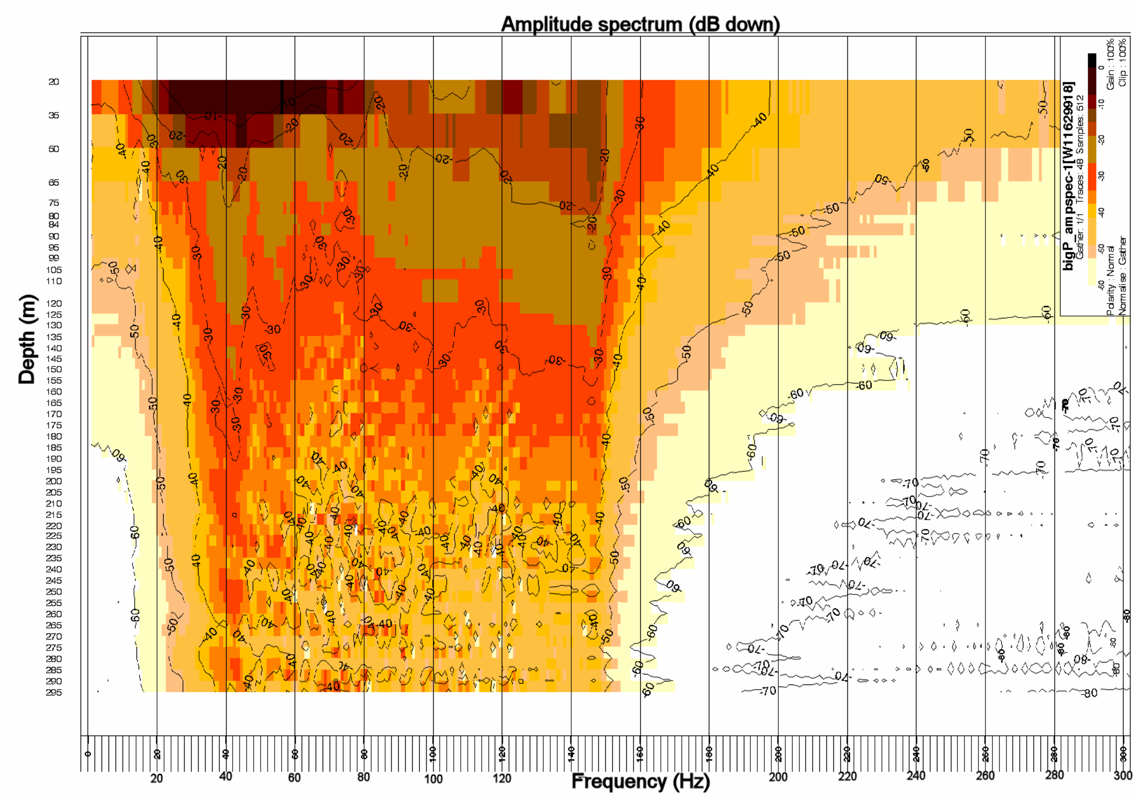

FIG. 11. Amplitude spectrum for raw big-P zero-offset VSP data. Useable bandwidth ranges from 15-150 Hz, with little attenuation of high frequencies, even at depth (Schlumberger).

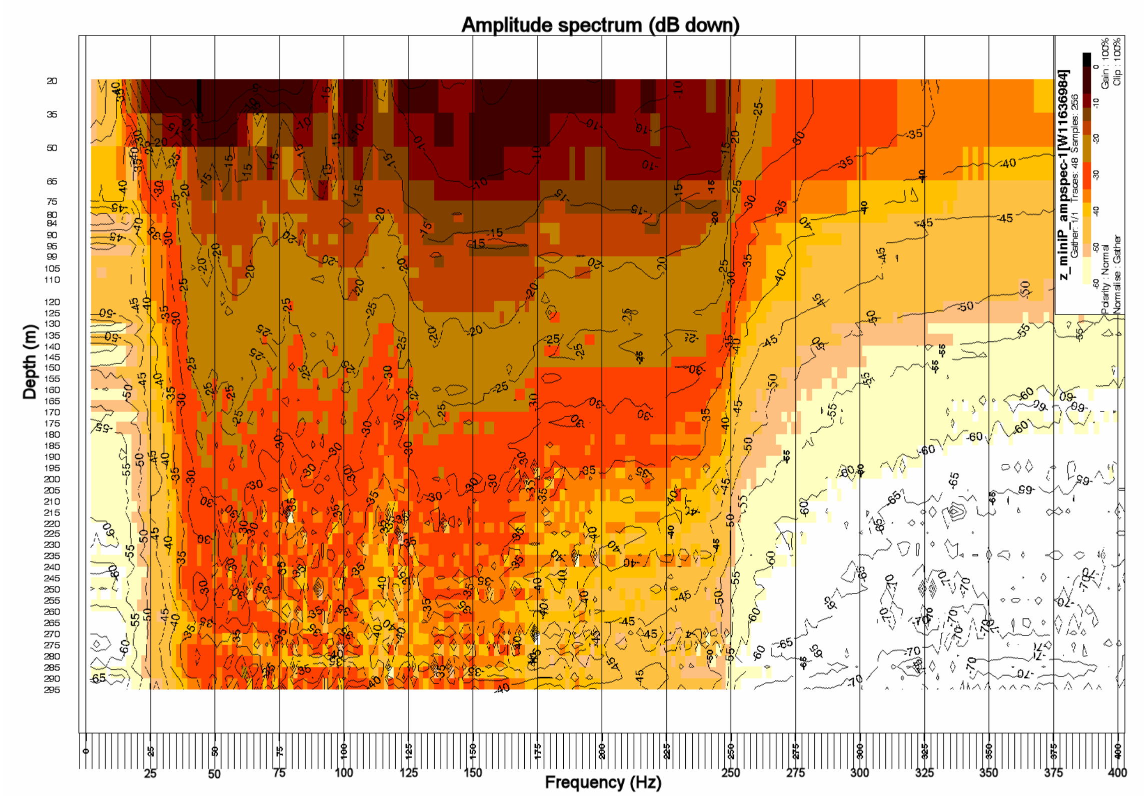

FIG. 12. Amplitude spectrum of raw zero-offset mini-P VSP data. Useable bandwidth ranges from 8-220 Hz (Schlumberger).

Comparing bandwidth and resolution of the two data sets, it can be concluded that in this study area, a mini-P source is preferable for imaging of the Ardley coal zone. The resolution attainable with the mini-P data is superior to that of the big-P source, and attenuation of the signal has occurred only at the highest frequencies. A big-P source, however, is suitable for coal seam detection, as it has effectively imaged both the upper and lower contacts of the Ardley zone.

Upper and lower coal contacts both produce strong amplitude reflections recorded on the horizontal component of the mini-S VSP data. In the compressional-wave data sets, the seismic response of the upper contact of the coal is the maximum of a trough, and a slight phase difference is noted between the P and S data sets. The amplitude spectrum of the mini-S data shows useable frequencies of 15-80 Hz (Figure 13), with a dominant frequency of approximately 30 Hz, meaning the input sweep of 8-150 Hz has been considerably attenuated. Using average S-velocities of 1010 m/s in the study area, the calculated limit of resolution is approximately 8.4 m, using $\lambda/4$ or 4.2 m, using the $\lambda/8$ criterion.

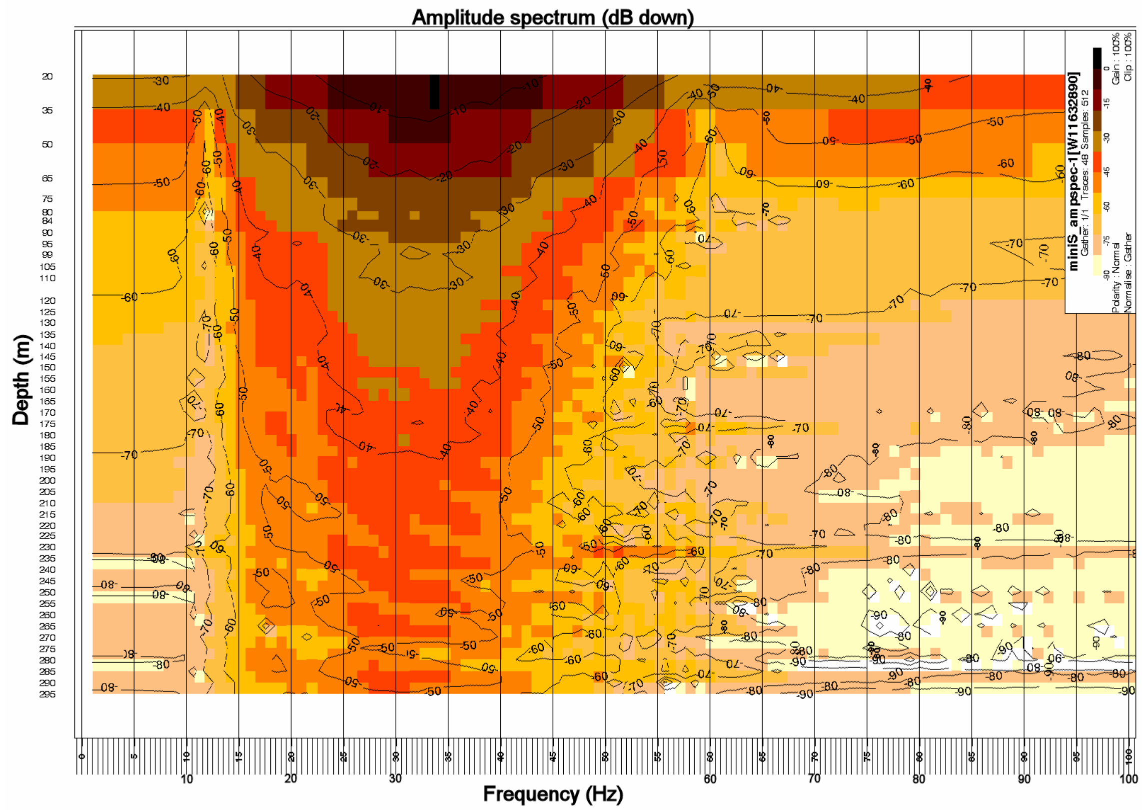

FIG. 13. Amplitude spectrum of raw zero-offset mini-S VSP data. Useable bandwidth ranges from 8-80 Hz (Schlumberger).

The attenuation of shear waves relative to P-waves is considerably higher. Whereas P-wave data retained a high proportion of the bandwidth of the original sweep, hyperbolic decay is noted in the S-wave data (Figure 13). Limits of resolution at the level of the coal are similar for mini-S and big-P data sets, with inherent shorter wavelengths compromised by lower frequencies.

CONCLUSIONS

Source tests illustrate that in this area, a mini P-wave truck-mounted Vibroseis unit is an ideal source for imaging coal seams at a depth of approximately 300 m, yielding much higher resolution data than a conventional heavy-duty Vibroseis source. Ardley coal zone contacts at the Red Deer site may be effectively imaged using any of the three sources tested, but lithological changes within the coal may be detected using the high-frequency mini-P source.

Bandwidth comparisons show useable frequencies of 8-150 Hz in the big-P data, whereas the mini-P data contains frequencies ranging 8-220 Hz. Shear wave attenuation was considerably higher than that of P-waves, with the mini-S source yielding useable bandwidth of 8-80 Hz. Such low attenuation of the mini-P source suggests that high-bandwidth converted-wave data may be obtained using the mini-P source.

REFERENCES

Gibson, D.W., 1977, Upper Cretaceous and Tertiary coal-bearing strata in the Drumheller-Ardley region, Red Deer River Valley, Alberta. Geological Survey of Canada, paper **76-35**.

Gochioco, L.M, 1992, Modelling studies of interference reflections in thin-layered media bounded by coal seams: Geophysics, **57**, 1209-1216.

Natural Resources Canada, 2002, Canadian Atlas online. http://atlas.gc.ca

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Suncor and its partner companies, the Alberta Research Council, and Larissa Bezouchko and Mike Jones of Schlumberger. Funding for this project was received from the Alberta Energy Research Institute (AERI) and the Natural Sciences and Engineering Research Council of Canada (NSERC). We also thank the CREWES project, its sponsors, and the Alberta Ingenuity Fund for financial support.