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Short Note

Shallow VSP work in the U.S. Appalachian coal basin

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INTRODUCTION

Most geophysical applications in North American coal exploration have centered around the conventional surface seismic reflection method to provide continuous subsurface coverage for evaluating both good and anomalous coal reserve areas (Ruskey, 1981; Dobecki and Bartel, 1982; Greaves, 1984; Lawton, 1985; Lyatsky and Lawton, 1988; Gochioco and Cotten, 1989; Lawton and Lyatsky, 1989; Gochioco and Kelly, 1990; Gochioco, 1991; Henson and Sexton, 1991). The surface seismic reflection method, however, has inherent resolution limitations because the seismic wavelet must propagate substantial distances through the weathered layer, resulting in rapid attenuation of the desired higher frequencies. Since the depths and thicknesses of coal seams are usually known beforehand, it is imperative that the seismic reflection associated with the target coal seam is absolutely identified in the seismic section to avoid misinterpretations. However, it is common that checkshot data and sonic and density logs are not available to generate synthetic seismograms to assist in the interpretation of coal seismic data. To overcome some of these limitations, the vertical seismic profiling (VSP) technique was tested in a coal exploration program to provide additional information for correlation with surface seismic reflection [or common-depth-point (CDP)] data and a synthetic seismogram generated from density and sonic logs.

VSP has an advantage over the surface seismic reflection method in that the receiver is placed in the borehole beneath the weathered layer, which is responsible for severely attenuating higher signal frequencies. As a result, VSP data tend to have a broader frequency spectrum. The recorded VSP field data also provide better insight into the fundamental properties of reflection and transmission of seismic wavelets in the subsurface near the borehole location because the receiver records both upgoing and downgoing seismic events. In this study, the VSP data are correlated to the CDP seismic data as well as to a synthetic seismogram for comparative analysis of its accuracy for measuring acoustic velocities and resultant traveltime differences (Stewart et al., 1984).

The acquisition technique for VSP is similar to that of a well-velocity (checkshot) survey in that the same source-receiver geometry is employed to measure traveltimes at certain depths in the borehole. However, the VSP technique employs a higher spatial sampling interval than does the checkshot procedure, which results in a data set that may be used for a variety of data processing and interpretation applications. Although VSP is used widely in petroleum exploration (Gal'perin, 1974; Wuenschel, 1976; Hardage, 1983; Oristaglio, 1985), it has seen limited application in coal exploration (Greenhalgh and Suprajitno, 1985). The work presented in this paper demonstrates the VSP method to be a useful tool that can be used in a shallow exploratory environment.

GEOLOGIC SETTING

The study area is located in West Virginia in the central Appalachia coal basin (see Figure 1). The target coal seam is part of the Allegheny Formation, which is a complex sequence of coalescing sandstone bodies of gray to dark gray shales or claystone interbedded with irregular, multibenched coal seams. The sandstones are thin to massive bedded, fine to coarse grained, and locally conglomeratic. Their lenticular nature results in rapidly varying intervals and thicknesses between major coal seams. Three major seams lie within the Allegheny Formation with the deepest being the only economically mineable seam within the reserve block.

This seam is a locally thick, laterally discontinuous coal characterized by numerous shale, claystone, and bone partings. The seam thickness ranges from 1.2 m (minimum mineable limit) to 3.8 m, and averages 1.9 m. The mountainous surface topography of the reserve area is heavily wooded. Three exploration holes were drilled on a ridge top to determine coal quality and thickness, as shown in Figure 1. Boreholes BH-11, BH-12, and BH-13 encountered seam thicknesses of 2.9 m, 2.5 m, and

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1.8 m, respectively. The average depth to the top of the seam beneath the ridge was 122 m. Figure 2 shows the geologic log of borehole BH-12 in which the VSP survey was conducted.

Prior to the VSP survey, sonic and density logs were collected from the three exploration boreholes. The digitized geophysical logs from borehole BH-12 are shown in Figure 3. Previous CDP seismic data collected in the reserve area yielded seismic traces having a spectrum with a central frequency of about 150 Hz. Thus, a 150-Hz Ricker wavelet was convolved with the reflectivity sequence in Figure 3 to produce the synthetic seismogram. The seismic reflection associated with the target coal seam is noted in the figure and has a predicted two-way arrival time of about 73 ms.

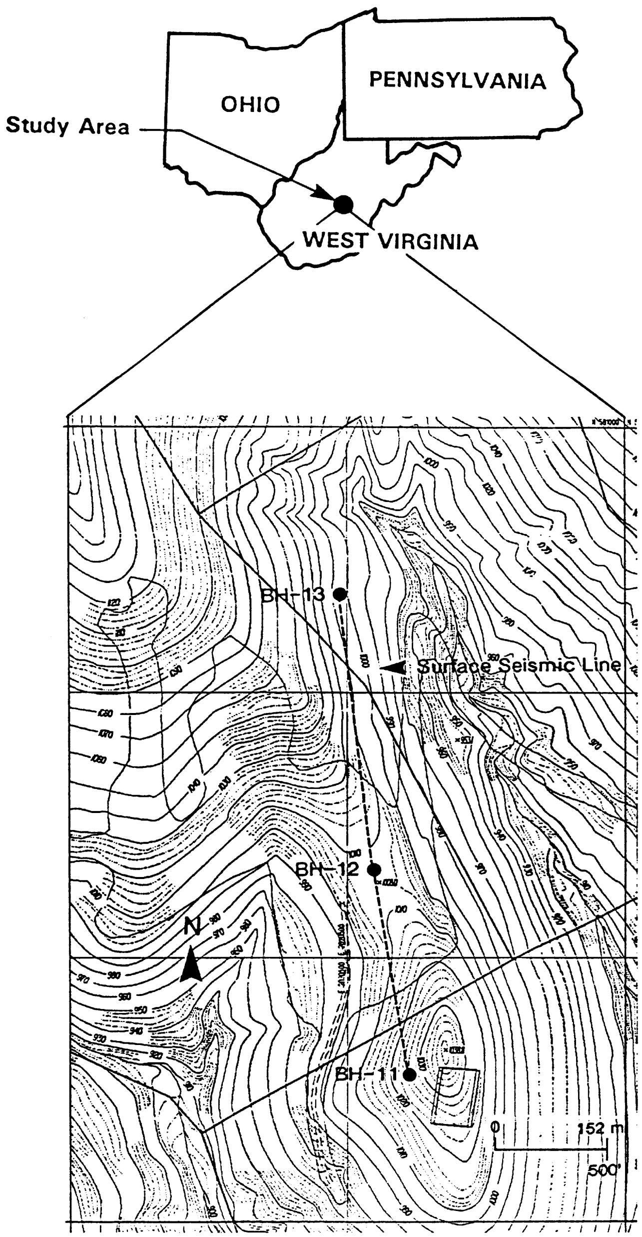

FIG. 1. Map of study area.

FIELD ACQUISITION AND DATA PROCESSING

Most domestic coal exploration boreholes have small diameters of 7.6 cm or less. As a result, a slimline wall-locking tool with a 3-D geophone package was employed. A zero-offset VSP survey was conducted in borehole BH-12. The survey employed a 3-m receiver interval starting at a depth of 37 m and ending at 130 m. An 8-gauge buffalo gun (Pullan and MacAulay, 1987; Miller et al., 1992) was used as the seismic source. A 24-channel engineering seismograph was interfaced with the downhole receiver to record the VSP data at a 0.25-ms sampling rate. The associated surface seismic reflection survey employed an off-end shooting geometry with the same source and a 24-channel recording system. Each receiver station consisted of a single 100-Hz geophone. The source and receiver intervals were 5 m, resulting in a maximum stacking fold of 12. Data were also recorded at the 0.25-ms sampling rate.

Figure 4 shows the vertical component of the VSP data after band-pass filtering (100 to 500 Hz) and automatic gain control (AGC) were applied. As expected, downgoing waves dominated the section and overshadowed the weaker upgoing waves. Wavefield separation was accomplished by sequentially applying velocity filters to attenuate tubewaves, downgoing waves, and mode-converted shear waves. Displays were

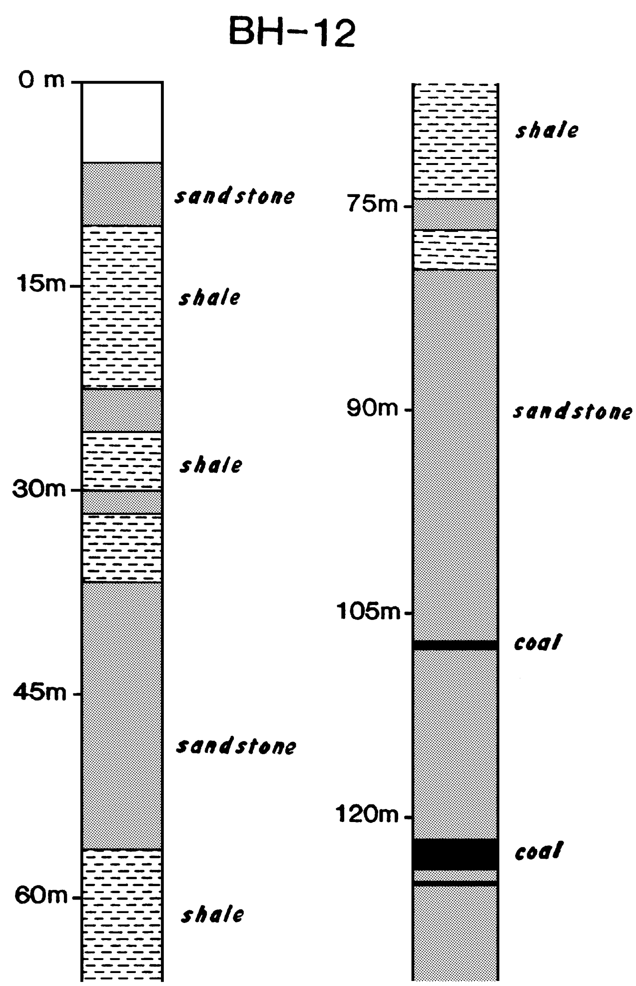

FIG. 2. Lithologic cross-section of borehole 12.

made along the processing flow to ensure quality control in the design and application of velocity and deconvolution filters. In the final stages of VSP processing, a bandpass filter having a shape similar to the frequency spectrum of the CDP data was applied to improve the correlation. Likewise, the VSP-derived decon filter was applied to the processed CDP seismic data for consistency. The VSP data were then converted into two-way traveltime by bulk shifting each seismic trace according to its first break information, as shown in Figure 5a. A corridor-mute pattern was employed before stacking to generate a composite trace and form the VSP seismogram in Figure 5b.

RESULTS

To demonstrate the usefulness of VSP to coal exploration, the VSP seismogram needs to show a good correlation with the synthetic seismogram and the processed CDP seismic data. Thus, the VSP seismogram in Figure 5b is placed alongside the synthetic seismogram for comparison, as shown in Figure 6. The reflection associated with the target coal seam is noted in both seismograms. The two seismograms show good correlations of seismic events at and above the coal-seam horizon (between 50 and 80 ms), including the apparent doublet peak (positive polarity) waveform immediately above the coal-seam reflection. However, a small difference in two-way arrival times in the coal-seam reflections is evident between the two seismograms; the synthetic and VSP seismograms show arrival times of 73 and 71.5 ms, respectively. The small discrepancy can be anticipated because of differences in geometry, source frequencies, trace signal/noise (S/N) ratios, and instrument timing errors. Even in petroleum exploration, VSP and sonic log velocities, and their subsequent calculated traveltimes, are often found to differ, with disagreements usually increasing with depth

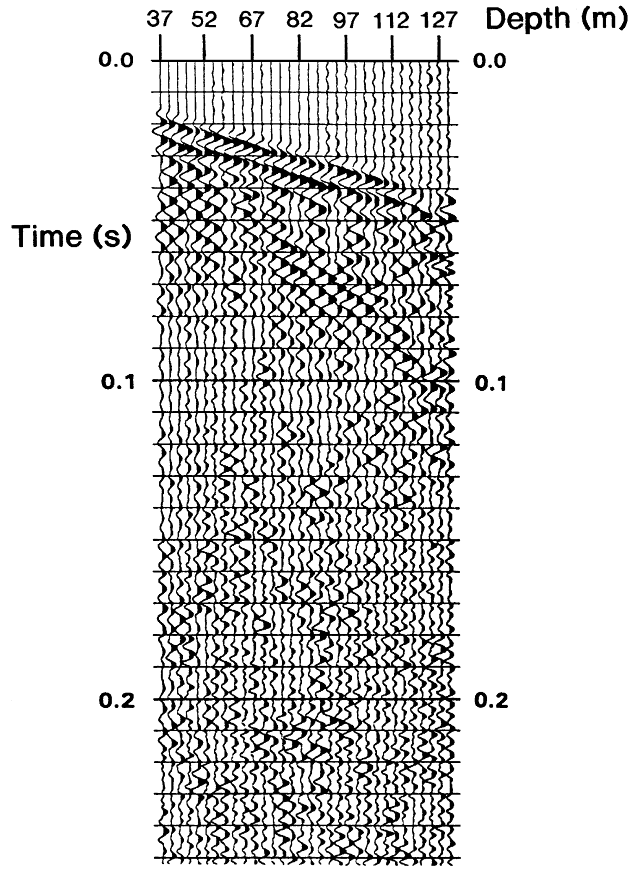

FIG. 4. VSP data after bandpress filter and automatic gain control were applied.

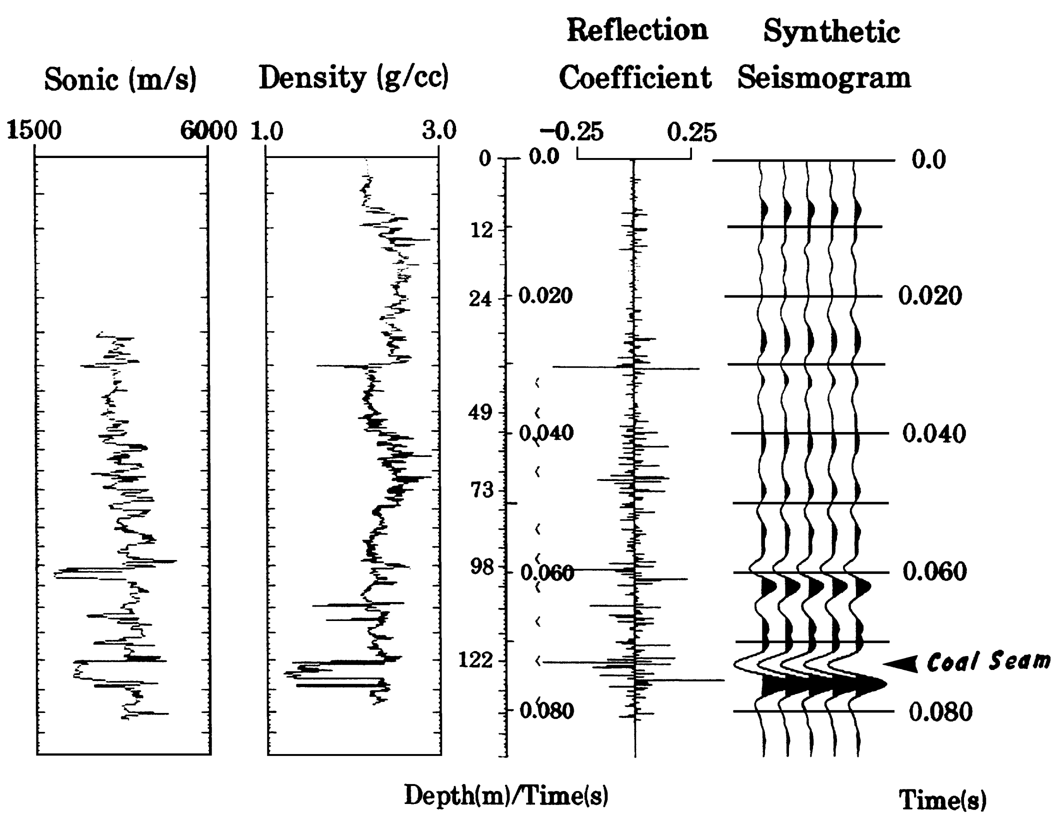

FIG. 3. Synthetic seismogram generated from sonic and density logs.

(Stewart et al., 1984). That is why VSP data are frequently used to recalibrate synthetic seismograms before they are correlated to CDP seismic sections.

In general, VSP traveltimes are delayed with respect to the integrated sonic times because sonic logs are based on measured interval velocities. The absence of sonic log information from 0 to 30 m (see Figure 3) required the use of Lindseth's (1979) empirical formula of acoustic impedance versus velocity to extrapolate synthetic sonic log information from the density log to fill the gap. However, the calculated pseudo interval velocities were relatively slow for the shallow environment, resulting in a delayed sonic traveltime relative to the VSP data. The difference of 1.5 ms is about one-fourth of the 5.9 ms period of a170-Hz wavelet, which is within the acceptable margin of error. One potential advantage of VSP is that it provides additional geophysical information well below the target coal seam, whereas the synthetic seismogram provides information for only the length of the borehole logs, as shown in Figure 6.

A better test to demonstrate the merits of shallow VSP is to correlate the seismogram with the processed CDP seismic data. The surface seismic survey line intersected all three boreholes (BH-11, BH-12, and BH-13) at shotpoint (SP) locations SP-11, SP-42, and SP-74, respectively (see Figure 1). The processed CDP section is presented in Figure 7. Since the VSP survey was conducted in borehole BH-12, the VSP seismogram is overlain on the CDP section at that location. Both data sets show excellent correlation of major seismic events above and below the coal seam horizon. The good correlations extend down to about 180 ms for the CDP data, suggesting that this depth was the limit of the effective range of the seismic source at this site. With information from the synthetic and VSP seismograms, the reflection associated with the target coal seam is interpreted properly. The seismic section shows a robust and continuous coal-seam reflection, indicating uniform mineable seam thickness with no major geologic disturbances or anomalies between the boreholes.

CONCLUSION

This exercise demonstrated the usefulness of VSP to shallow seismic applications and to coal exploration. In the absence of geophysical logs in some exploration projects, the VSP method

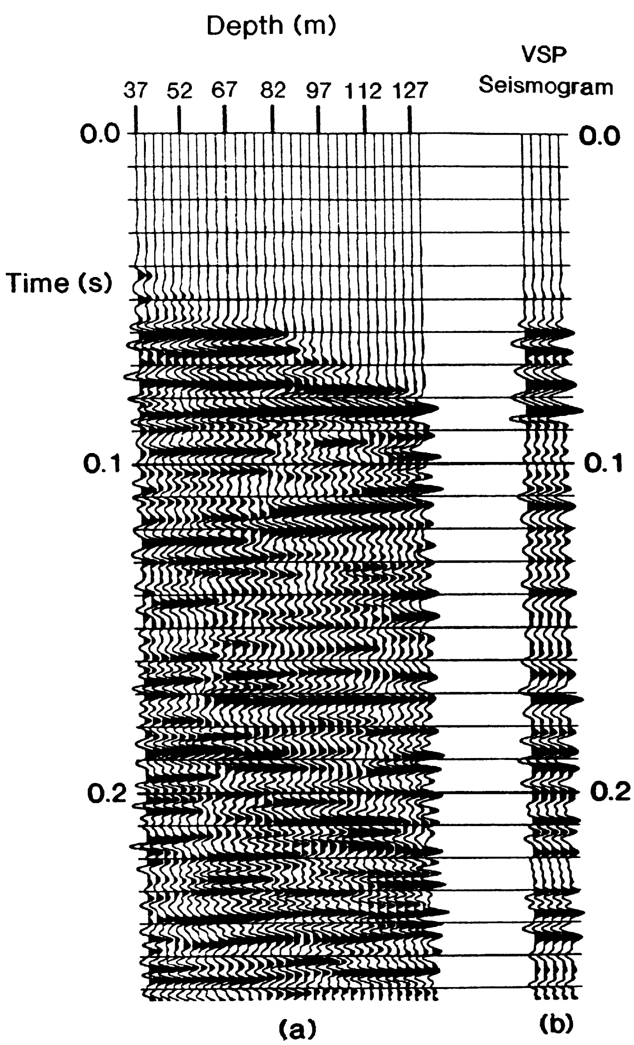

FIG. 5. Processed VSP data (a) and resultant VSP seismogram (b).

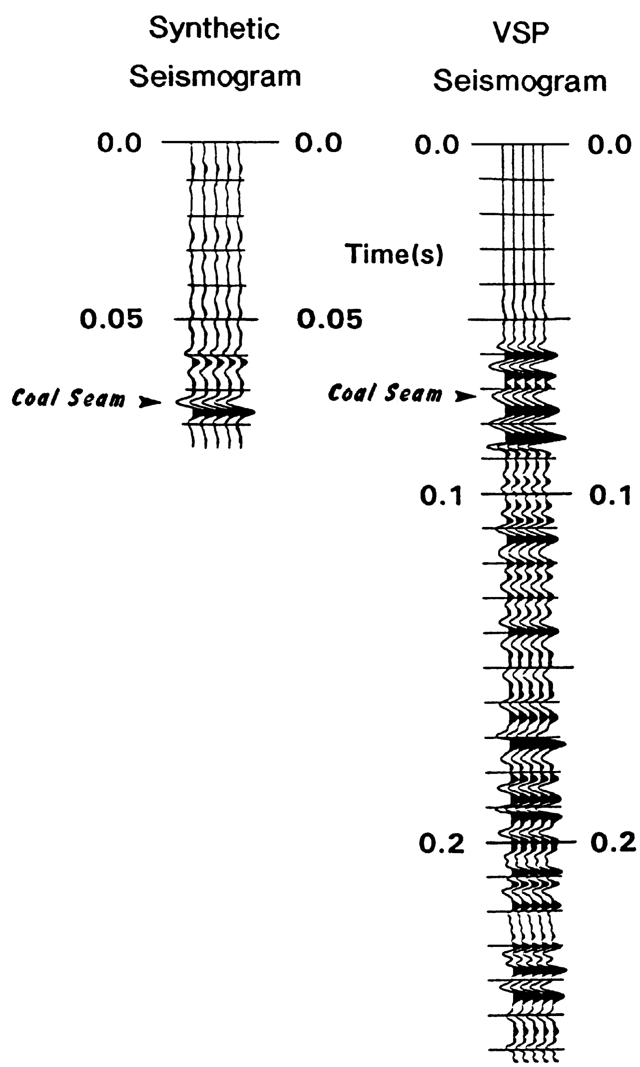

FIG. 6. Comparison of synthetic seismogram and VSP seismogram.

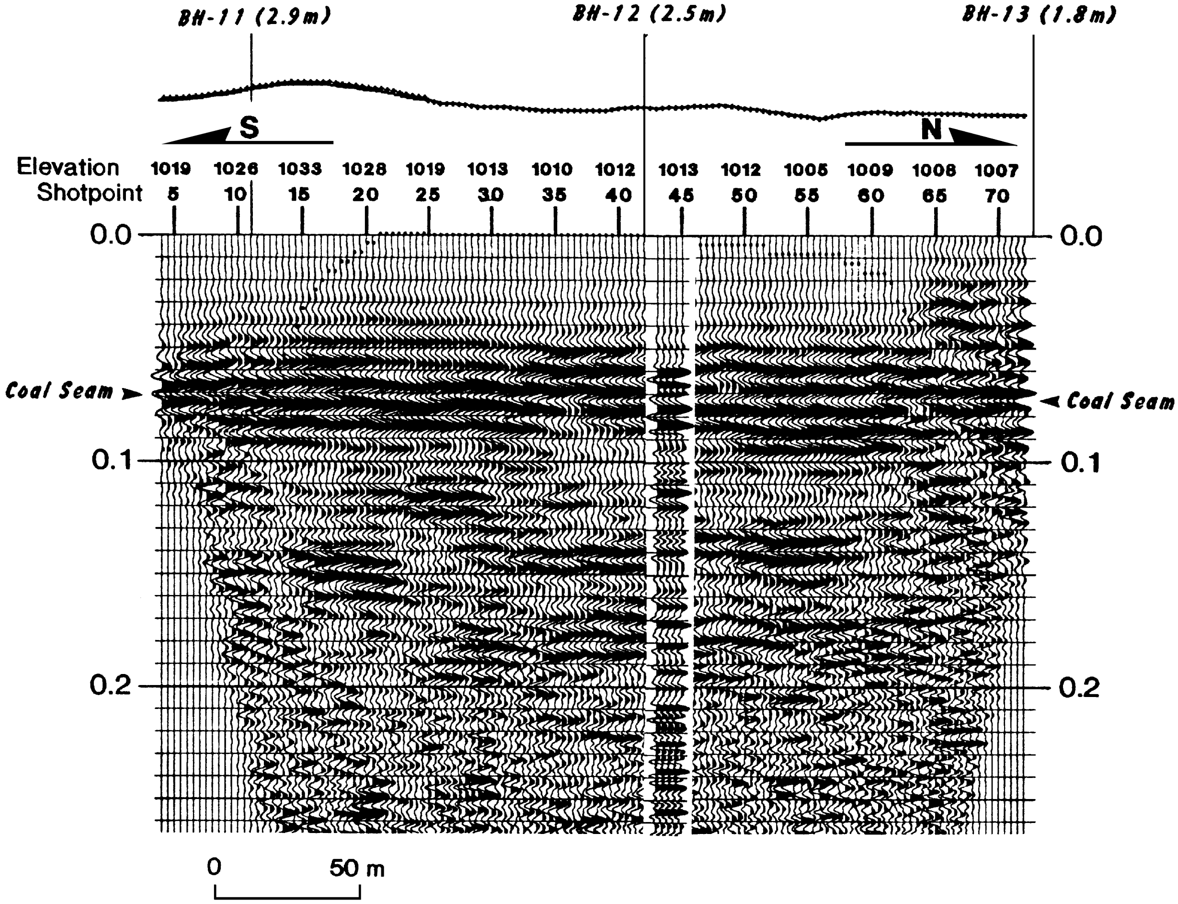

FIG. 7. The VSP seismogram is correlated to the CDP seismic section at the BH-12 location.

can be used to provide seismic velocities and interpretation of lithologic structures near the borehole. Correlation of the VSP seismogram to the CDP section helps assure that the reflection associated with the target coal seam is correctly interpreted, thereby removing uncertainty. Small discrepancies in traveltimes between the synthetic seismogram (generated from geophysical logs) and a VSP seismogram can be expected because of differences in geometry, frequency spectra, and S/N ratios.

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