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Locating faults in underground coal mines using high-resolution seismic reflection techniques

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ABSTRACT

A high-resolution seismic reflection technique was used to locate faults in coal seams that were not visible on the surface and could only be observed in underground coal mines. An 8-gauge buffalo gun, built by the research and development department of Consolidation Coal Company, was used as the seismic source. The coal seam at a depth of 700 ft produces a reflection with a predominant frequency of about 125 Hz.

The high-resolution seismic data permitted faults with vertical displacements of the same magnitude as the seam thickness to be detected at depths of several hundred feet beneath the surface. Several faults were detected and interpreted from the seismic sections, and the magnitudes of their displacement were estimated by matching the recorded seismic data to synthetic seismic data. Subsequent underground mine development in the study area confirmed two interpreted faults and their estimated displacements. Mining engineers were able to use the information provided by the seismic survey to plan an entry system through the fault zone so that less rock needed to be mined, resulting in a safer and more productive mine.

INTRODUCTION

Consolidation Coal Company (Consol) and Conoco initiated a seismic program for coal-mining applications in the mid-1970s (Coon et al., 1979). During this time, the U.S. Bureau of Mines and other investigators were also developing seismic-reflection techniques for coal-mining applications (Daly, 1979; Ruskey, 1981; Dobecki and Bartel, 1982). Drilling is the most common method used in coal exploration and most coal companies rely heavily on drill-hole data for evaluating their mine properties. Evaluation by drilling is expensive and offers only limited information because drilling provides single data points. Seismic surveys, on the other hand, provide a continuous subsurface profile. Consol occasionally conducts a combined seismic and drilling program to detect and locate coal-seam anomalies that may create adverse mining conditions. Any anomalies detected by seismic surveys are subsequently tested by some drilling to confirm the interpretation, so that appropriate plans can be made to mine the coal efficiently and safely.

The objectives of the seismic survey described in this paper were to detect the faults in the unmined property and to locate the most efficient and cost-effective path through the fault zone to reach the coal reserves on the other side. Figure 1 is a schematic map showing a five-entry to seven-entry system (four to six pillars) driven through an area of the fault zone with the least amount of displacement. Less rock must be mined and haulage roads and belt lines have minimal gradients if areas of small displacement are identified through a combined seismic and drilling program. To the coal industry, a small fault is defined as one having a displacement of less than the coal seam thickness, while a large fault is considered to have a displacement of more than the seam thickness.

Faults pose potential problems in mining coal. Coal companies prefer to deal with the effects of faults in coal mining at the early stages of development, effects that sometimes include stability of roof and ribs in underground workings. In those instances, extra reinforcements are required to make the work area safe. Also, studies have shown that faults act as trap zones for gas that, if encountered, could easily vent into underground workings. Therefore, the early detection of faults would allow coal companies to degasify the coal seam in advance of mining operations. Larger vertical displacements of coal seams mean lost productivity. In underground coal mines, large displacements require mining through rock, a process that rapidly wears out equipment designed for mining coal. Faults frequently force the operator to change the mine plans, and at times, blocks of coal have

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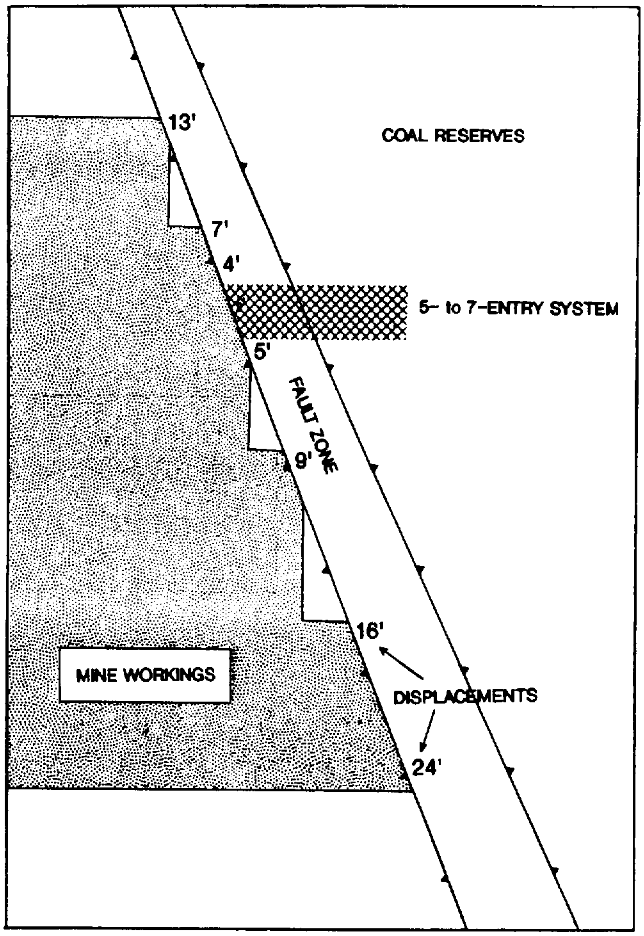

FIG. 1. Schematic map showing a five- to seven-entry system driven through the fault zone in an area of least potential displacements.

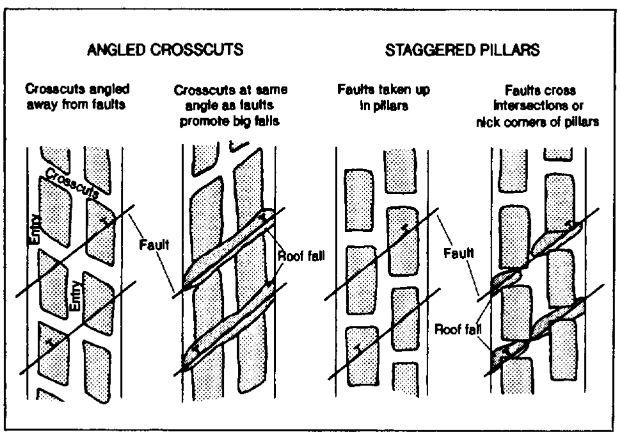

FIG. 2. Placement and angling of crosscuts in faulted areas where faults cross mine headings at oblique angles (from Krausse et al., 1979).

been left unmined because of excessive cost. Knowing the location and orientation of the faults is very helpful in pillar design. Proper design and location of the pillars would help to stabilize the roof near or at the fault zone as shown in Figure 2. Placement and angling of crosscuts in faulted areas where faults cross mine headings at oblique angles help stabilize the roof and make the work area safer (Nelson, 1981).

GEOLOGIC SETTING

Faults are exposed only in underground workings of the coal members of the Carbondale formation of Pennsylvanian age. Because this is a region of thick and relatively low-sulfur bituminous coal, the coal has been mined extensively, which has resulted in a high degree of resolution for tracing the path of the fault system. The faults dip both to the east and to the west; the dips vary in angle between 45° and 90°, with most lying in the 60° to 70° range. The dominance of high-angle normal faults indicates a vertical maximum compressive stress at the time of faulting, yielding an east-west extension along the southern part of the fault system and an east-northeast to west-southwest extension along the northern part. In the mine property, the section of the projected fault zone was oriented in the southeast to northwest direction.

Observations made from nearby mines that completely traversed the fault system revealed the width of the fault zone varies from a few tens of feet to over half a mile. Wide sections of the fault system are composed of numerous small faults with smaller displacements; a narrow fault zone would likely yield larger displacements. Individual faults are quite discontinuous and unpredictable: as one fault dies out, another slightly staggered fault may appear. Small reverse faults and sharp flexures that have been observed at several places in the fault zone invariably occur adjacent to and parallel with larger normal faults, which they may join. The reverse faults and flexures have little lateral continuity. They probably formed in response to purely local compressive forces developed within the major blocks moving along normal faults. Some small faults encountered in underground workings have created horst and graben features (Keys and Nelson, 1980).

The study area offered good conditions for conducting high-resolution seismic profiling. Flat surface topography is surrounded by woodlands and farms, and the area is accessible only to a small seismic crew with portable seismographs. Near-surface material is fine-grained, and there is a very shallow water table. The target depth of the coal seam is about 700 ft; the average seam thickness is 8 ft.

FIELD PROCEDURES AND DATA PROCESSING

The surface seismic survey employed a CDP method and incorporated an off-end shooting-geometry configuration with a 30 ft receiver group interval. Each receiver station was composed of six 100 Hz geophones (connected in series) equally spaced and centered at each shotpoint station. Each record was composed of 12 channels. The shotpoint interval was also 30 ft, resulting in a maximum stacking fold of 6. The near-offset distance was 120 ft. The field acquisition geom-

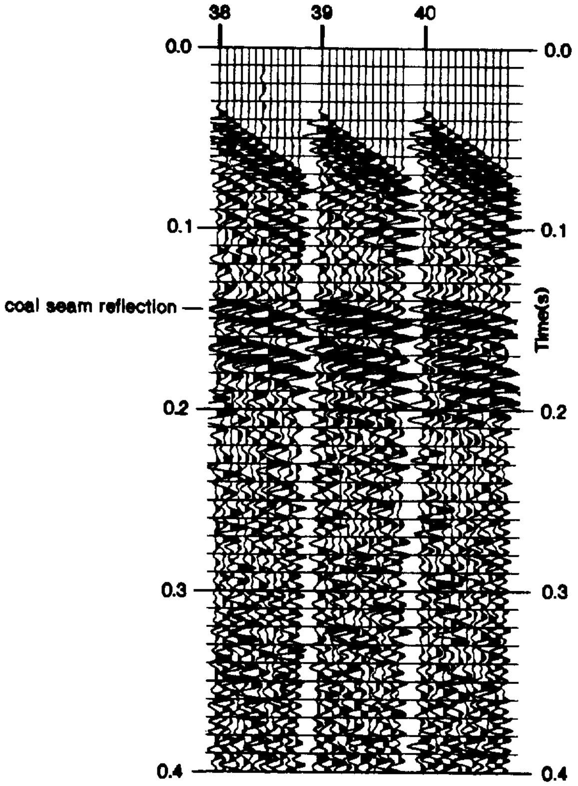

FIG. 3. Three field records after band-pass filtering and AGC were applied. The reflection from the coal-seam horizon is indicated.

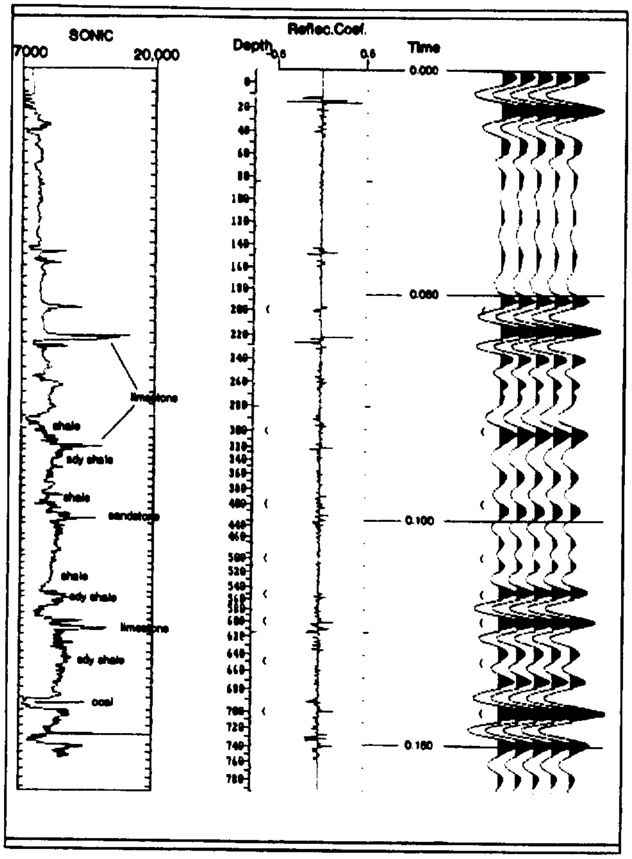

FIG. 4. The synthetic seismogram is generated from a sonic log gathered in a drillhole along seismic line 2. Key reflectors are indicated.

etry was designed to optimize the imaging of the target coal seam (Knapp and Steeples, 1986).

A Geometrics ES-1210F engineering seismograph was employed with a low-cut filter of 80 Hz. The recording sample rate was 0.5 ms, and the record length was 0.5 s. An 8-gauge buffalo gun (Pullan and MacAulay, 1987) was used as the seismic source; the 8-gauge shell has a 3 oz lead slug that can generate about 30 000 J. Small-diameter holes were drilled at each shotpoint to a depth of 12 to 18 in; then the holes were filled with water to damp the air blast and confine more energy in the ground during detonation. On average, signals from three shots were recorded at each shotpoint, and the records were vertically stacked to enhance signal-to-noise ratio. Three field records are shown in Figure 3 after band-pass filtering and automatic gain control were applied. The Geometrics DMT-911 tape recorder was used to store field records.

Data processing is done in Library, Pennsylvania, through a network in which the VAX 11/750 computer is linked to Conoco mainframe computers in Ponca City, Oklahoma. Conoco seismic software programs were used to process the data. The processing sequence was very similar to that used for seismic petroleum exploration data; however, certain refinements in processing and interpretation were needed to fulfill the requirements of the coal industry. Sonic logs and velocity check-shot surveys from two boreholes assisted the interpretation process. The Earth Sciences Workstation (ESW) was used to digitize the sonic log in order to generate a synthetic seismogram, as shown in Figure 4 (Gochioco, 1989). Figure 5 shows the synthetic seismogram correlated to the seismic section. The trough of the reflected wavelet corresponds to the coal seam. The P-wave velocity in coal is about 7500 ft/s, while most of the surrounding rocks like shale and sandstone have P-wave velocities of more than 9000 ft/s and 12 000 ft/s, respectively.

RESULTS

The reflected wavelet from the coal seam has a predominant frequency of about 125 Hz. Using the interval velocity of 7500 ft/s for coal, the standard resolution, defined as one-quarter of the predominant wavelength, is approximately 15 ft. The seam thickness of 8 ft is close to the critical bed thickness (one-eighth of a wavelength) for seismic resolution. Constructive interference of the wavelets from the top and base of a bed yields maximum amplitude at a critical bed thickness, which is called the tuning thickness (Widess, 1973). Therefore, it is useful to study the amplitude of the reflection from the coal-seam horizon.

To estimate the magnitude of displacements of interpreted faults, a lithologic cross-section was developed from a geologist's log from a nearby drillhole. Faults with 5, 10, and 15 ft displacements were introduced into the data set, and appropriate velocity functions were assigned to each particular rock formation. A zero-phase wavelet with the same frequency spectrum found in the CDP seismic data was then convolved with the reflectivity function from the geologic model to generate a two-dimensional synthetic seismic section, as shown in Figure 6. A fault with a 5 ft displacement would be difficult to detect and interpret, while a fault with a

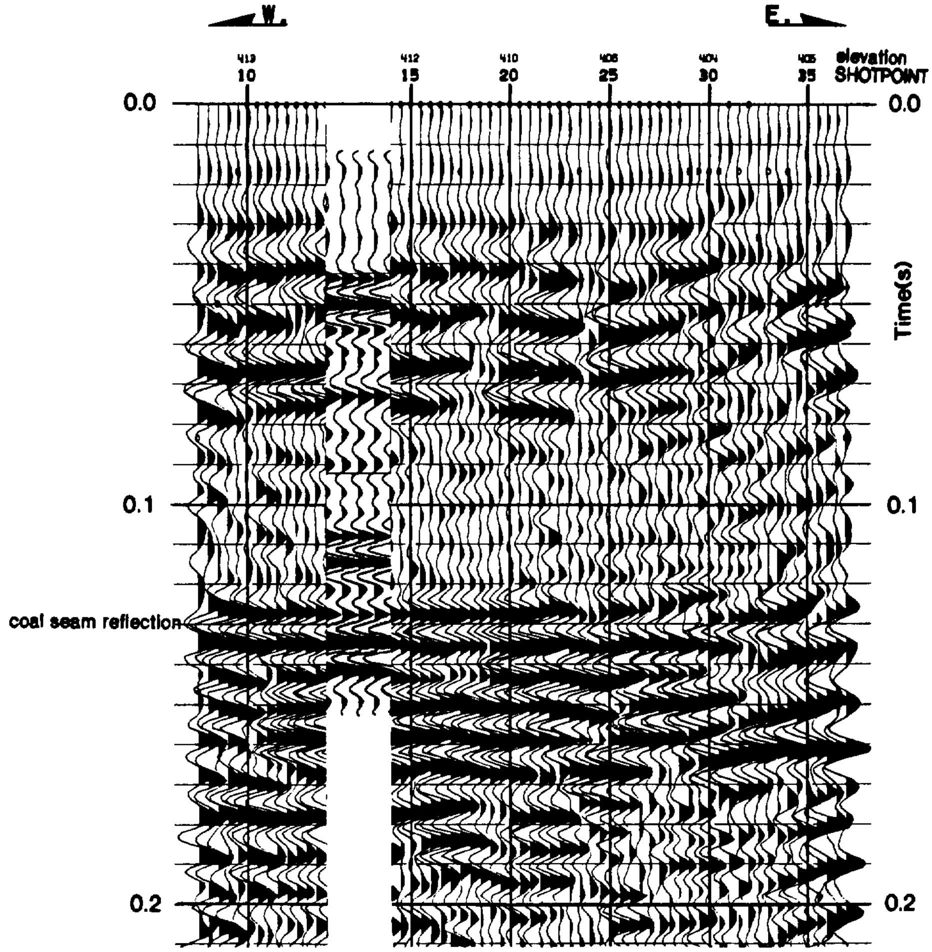

FIG. 5. The synthetic seismogram correlated to the CDP seismic section.

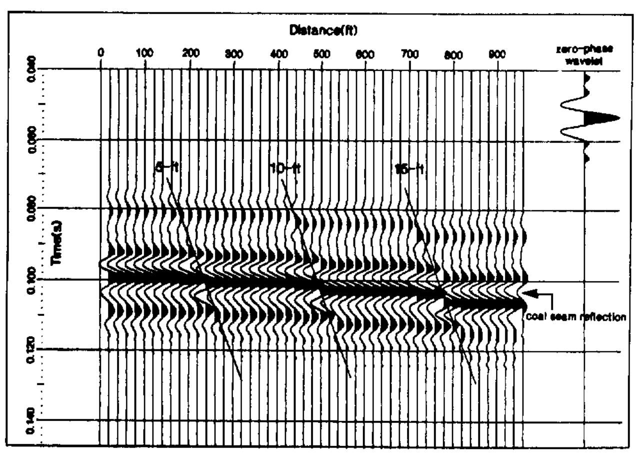

FIG. 6. A zero-phase wavelet was convolved with the reflecting function from the geologist's log to generate synthetic seismic responses to faults of 5, 10, and 15 ft displacements.

10 ft displacement (almost the seam thickness) would likely be interpretable.

Figure 7 is the seismic section of line 2. The estimated arrival time of the seismic reflection from the coal-seam horizon is about 0.132 s (as indicated). The reflector remains robust from SP-8 to SP-23, which indicates a fairly uniform coal-seam thickness and uniform roof and floor lithology. The first evidence of a disturbance occurs at SP-24, where the amplitude of the seismic signature changes. A small fault is interpreted at this location. Based upon computer modeling, a displacement of less than 10 ft was predicted here. Another fault, interpreted at SP-29.5, showed a higher level of disturbance to the seismic signature, suggesting a large displacement.

Mine personnel encountered the fault beneath SP-24 and measured the displacement to be 7.5 ft. The southwest block is down relative to the northeast. A geologist measured the dip of the fault plane to be 62.5°. The development entries went as far east as SP-27.5, before heading up north to complete the longwall panel. During the development of the northern entries, the fault, detected beneath line 2 at SP-24, died out while another fault with a large displacement was encountered a few hundred feet away. It is likely that this fault is associated with the one detected beneath line 2 at SP-29.5

Prior to the survey, Consol geologists learned that a major fault with a significant displacement was encountered in the adjacent property. Seismic line 3 was positioned along the property line to investigate this fault, and the fault plane was projected to intersect SP-20 of line 3. Figure 8 is the seismic section of line 3; the reflection associated with the coal-seam horizon is indicated. The reflector remains strong and continuous from SP-7 to SP-17.5. A major disturbance is detected at SP-19.5, which corresponds to the fault beneath SP-29.5 of line 2. Another disturbance is interpreted at SP-28 with probable displacement of less than 10 ft. Note the shallow reflectors between 0.040 to 0.080 s are incoherent and have small amplitudes. This incoherency is likely caused by subsidence as a result of mining done by the other coal company near the property line more than ten years ago. The broken strata above the coal seam extensively scattered the seismic energy, causing the dominant frequency of the reflection to be reduced to 100 Hz.

Seismic line 4 (Figure 9) covered nearly the entire width of the projected fault zone and was gathered over the unmined portion of the property. The reflection is robust from SP-8 to SP-24.5, suggesting no significant disturbance. The first evidence of a fault occurs at SP-25, where there were disturbances in the seismic reflections above and below the coal-seam reflection. The displacement of the interpreted fault is estimated to be small. The broadening of the seismic signature at SP-31 indicates the presence of a highly disturbed zone that possibly corresponds to a large displacement fault and/or severe lithologic changes at the coal-seam level that may result in poor roof conditions. The dispersive effects of two closely spaced fault planes are evident below 0.160 s between SP-25 and SP-31, where reflectors are poorly imaged. Two other disturbances detected at SP-41 and SP-56 probably correspond to faults with small displacements.

CONCLUSION

The high-resolution seismic reflection technique was able to detect subsurface faults associated with the major fault system; the faults were not visible on the surface and can be observed directly only in underground coal mines. The results confirmed the predicted orientation of the fault zone made by geologists. Faults with displacements of the same magnitude as the seam thickness can likely be detected down to several hundred feet beneath the surface. Useful information provided by such work would assist the mining engineers in designing a safer and more productive mine. Recent

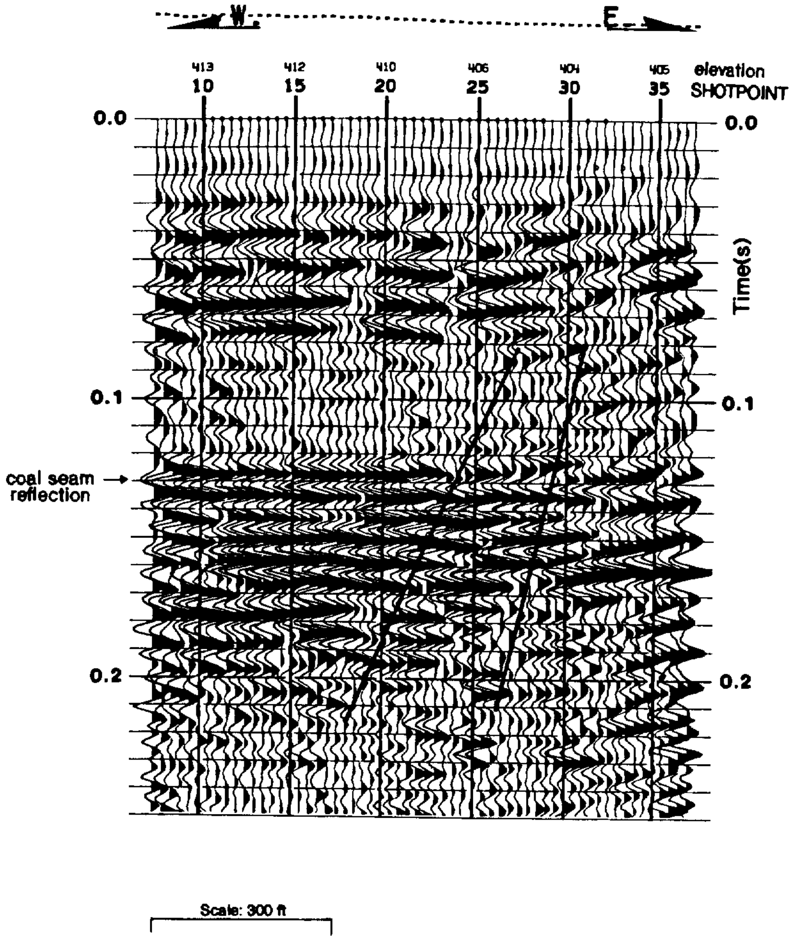

FIG. 7. Seismic section of line 2.

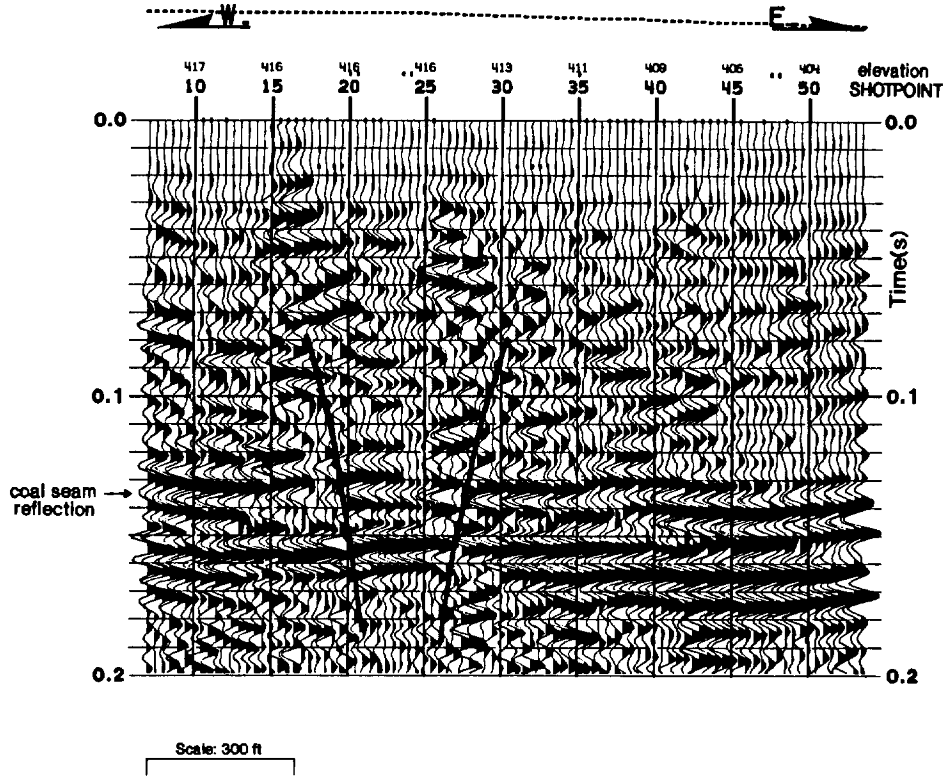

FIG. 8. Seismic section of line 3.

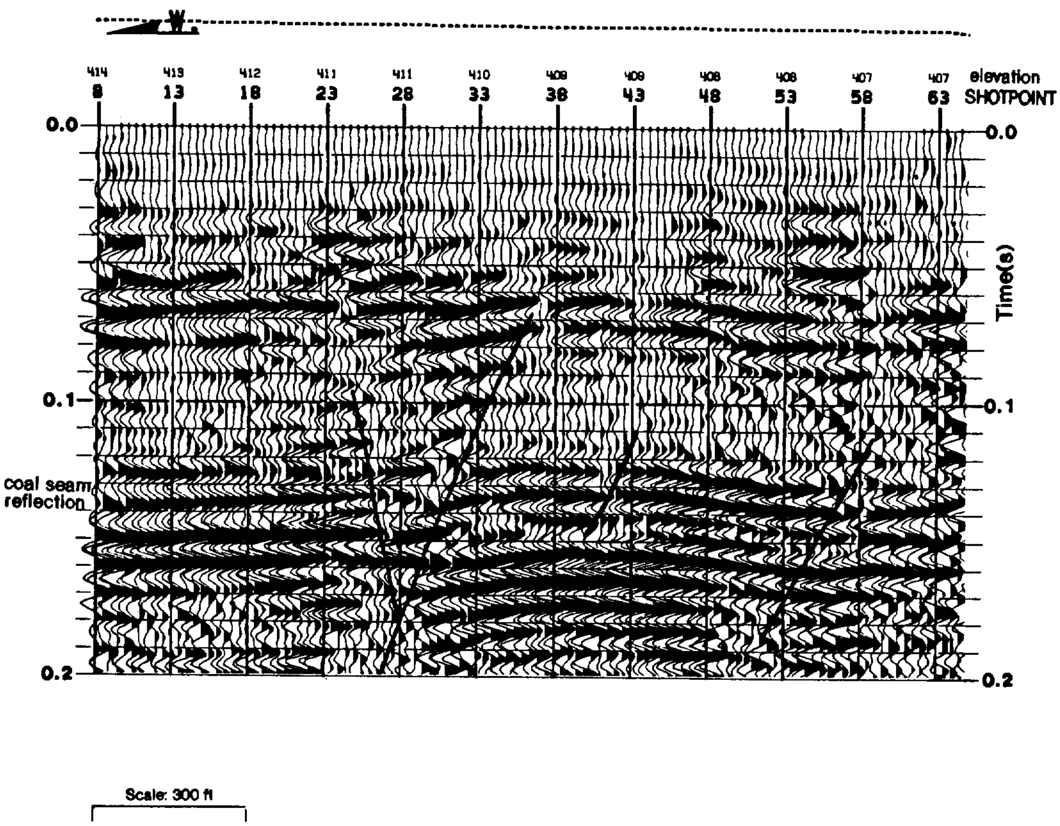

FIG. 9. Seismic section of line 4.

refinements and the introduction of new seismic techniques borrowed from the petroleum industry have increased the success rate of seismic surveys for coal-mining applications. Also, the 8-gauge buffalo gun proved to be a reliable seismic source for this project and could be effective for shallow mining applications.

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