Advances in seismic reflection profiling for US coal exploration

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The utilization of seismic reflection methods in US coal exploration increased during the last decade, as evidenced by the number of publications and papers presented at technical meetings. The increased application of innovative techniques adapted from the petroleum industry has resulted in improvements in seismic data acquisition, processing, and interpretation. The objective of this paper is to present some advances in the application of high-resolution seismic reflection methods to US coal exploration since they were adopted in the mid-1970s.

US coal companies traditionally have mined reserves with sound geologic conditions and have avoided known problem areas. As these better reserves are depleted, coal companies will have to mine through geologically more difficult areas to gain access to other good reserves. Also, more coal companies are utilizing the longwall mining method because it allows large blocks of coal to be mined very efficiently. However, highly productive longwall mining requires large reserves which are fairly level to be free of major geologic anomalies. The US Bureau of Mines estimates that an unscheduled interruption of a longwall face advance costs coal companies an average of $250 per minute. This translates into a loss of about $120 000 per eight-hour shift. A few weeks of downtime could cost a coal company millions of dollars. If the downtime was caused by significant geologic anomalies or disturbances, then the resulting loss might have been prevented if an adequate seismic and drilling exploration program had been conducted in advance.

Evolution. Seismic surveying for coal exploration requires some refinements in methodology because the targets fall between the very shallow objectives, less than 15.2 m (50 ft), normally encountered in engineering applications and deeper targets,

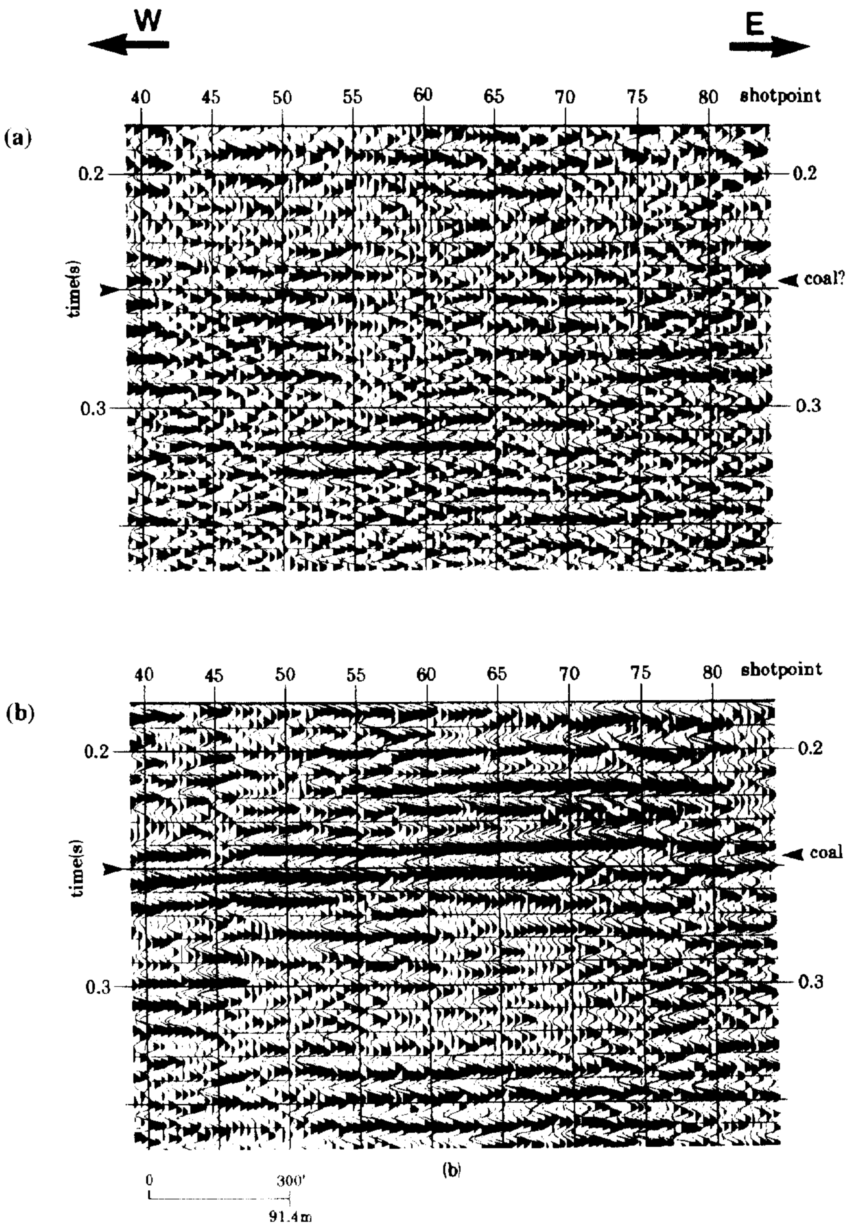

Figure 1. Results of linear (a) and nonlinear (b) sweeps.

Conoco prototype vibrator being used as a high-frequency source in coal exploration.

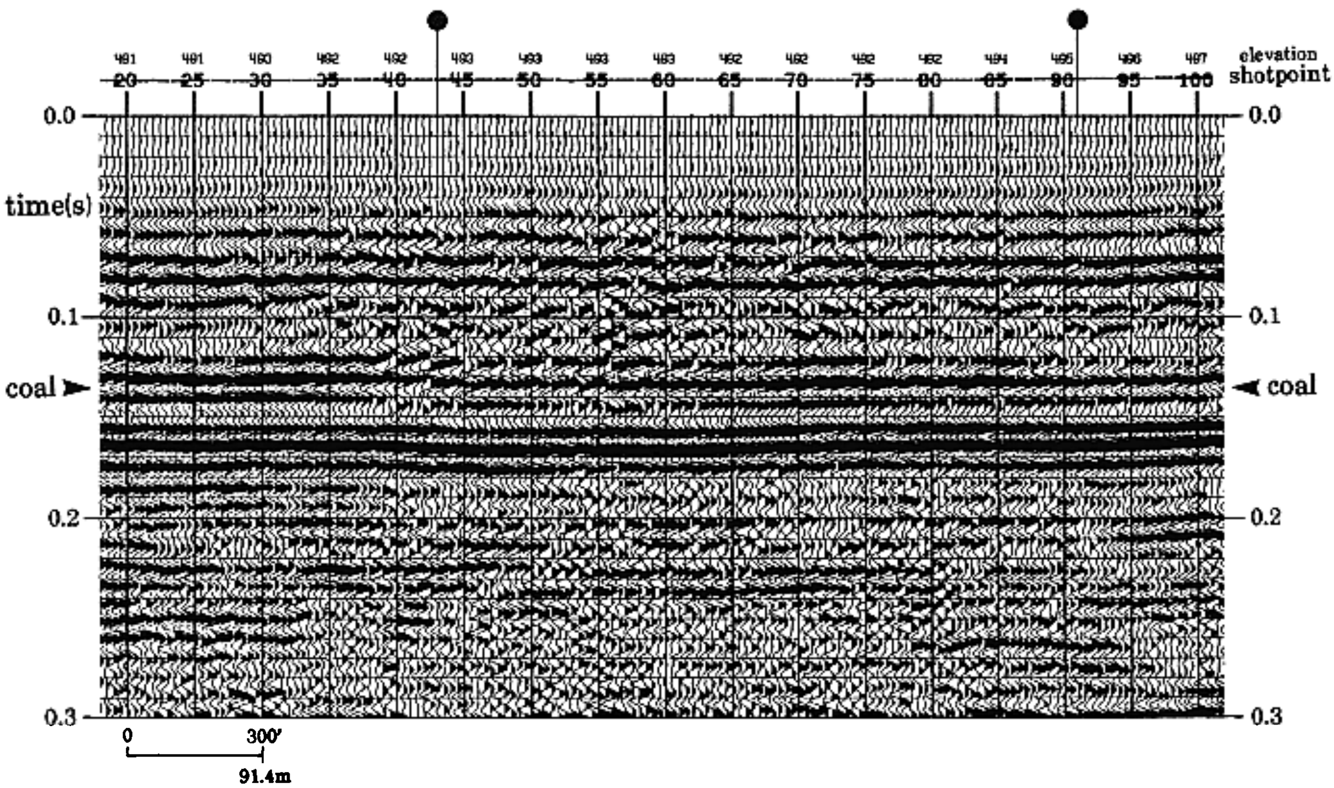

Figure 2. Seismic section showing a robust and continuous coal-seam reflection. This indicates uniform seam thickness with no detectable geologic disturbance.

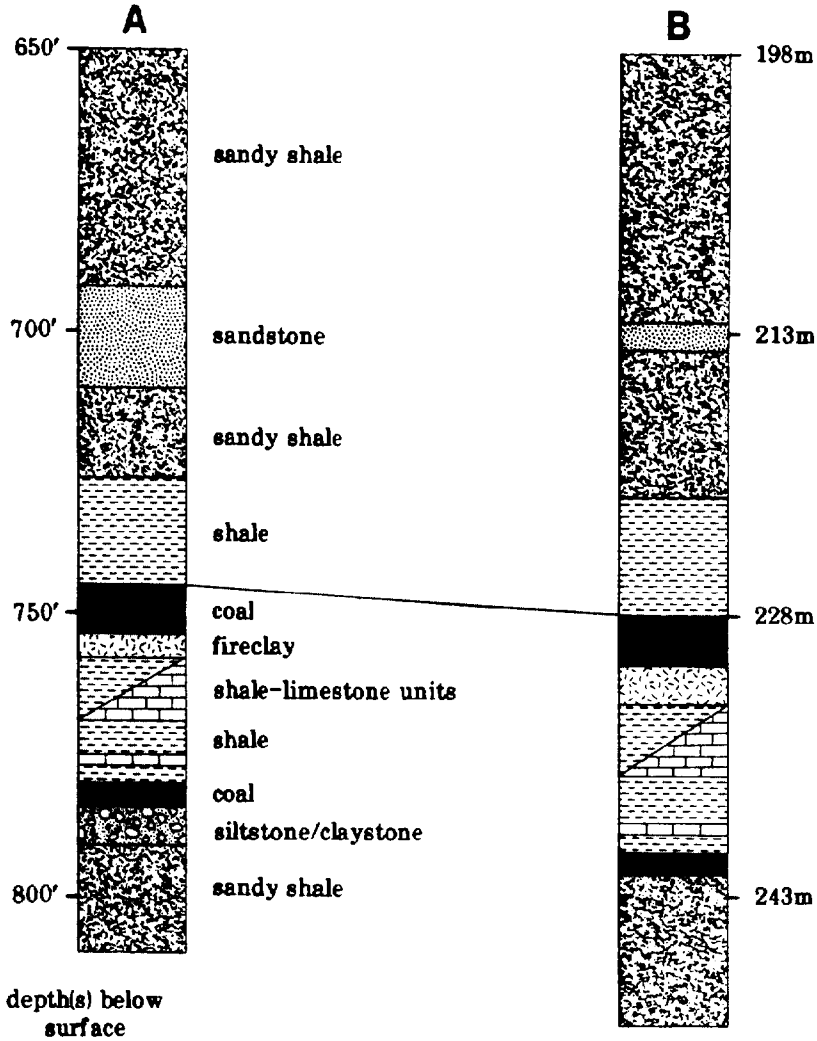

Figure 3. Lithologic cross-section of the two boreholes in Figure 2.

greater than 914 m (3000 ft), of petroleum exploration. Underground mining of bituminous coal in the major US basins occurs at depths ranging from 45–762 m (150–2500 ft) beneath the surface. Fortunately, seismographs that were designed for engineering applications and petroleum exploration can be adapted for coal exploration. Data acquisition techniques have evolved from the early '70s when 12-channel, 10-bit, fixed-gain engineering seismographs were commonly used in field surveys. As microcomputer technology improved during the 1980s, 24-channel, 15-bit, instantaneous floating point engineering seismographs became the standard. Current engineering seismographs and recording systems are capable of yet higher digital sample rates, broader dynamic range, and more recording channels. This has resulted in better signal-to-noise ratios due to higher fold, which effects an improvement in both vertical and lateral resolution. Additionally, some conventional recording systems used for petroleum exploration have the capability to record seismic data at sample rates of 1 ms and 1/2 ms with up to 48 channels per record.

Some current engineering seismographs and conventional recorders have built-in software packages that can be used to evaluate the data while still in the field. Digital filtering, correlation, spectrum analysis, normal moveout corrections, common offset gathers, and brute stack are common utilities in these systems. This useful technology is being implemented in the field to enhance analysis of the recorded seismic data to ensure quality control in data acquisition.

Field testing and data acquisition. The typical seismic sources used for coal exploration in Europe, Asia, Canada, and Australia are small explosive charges or mechanical weight-drop devices. However,

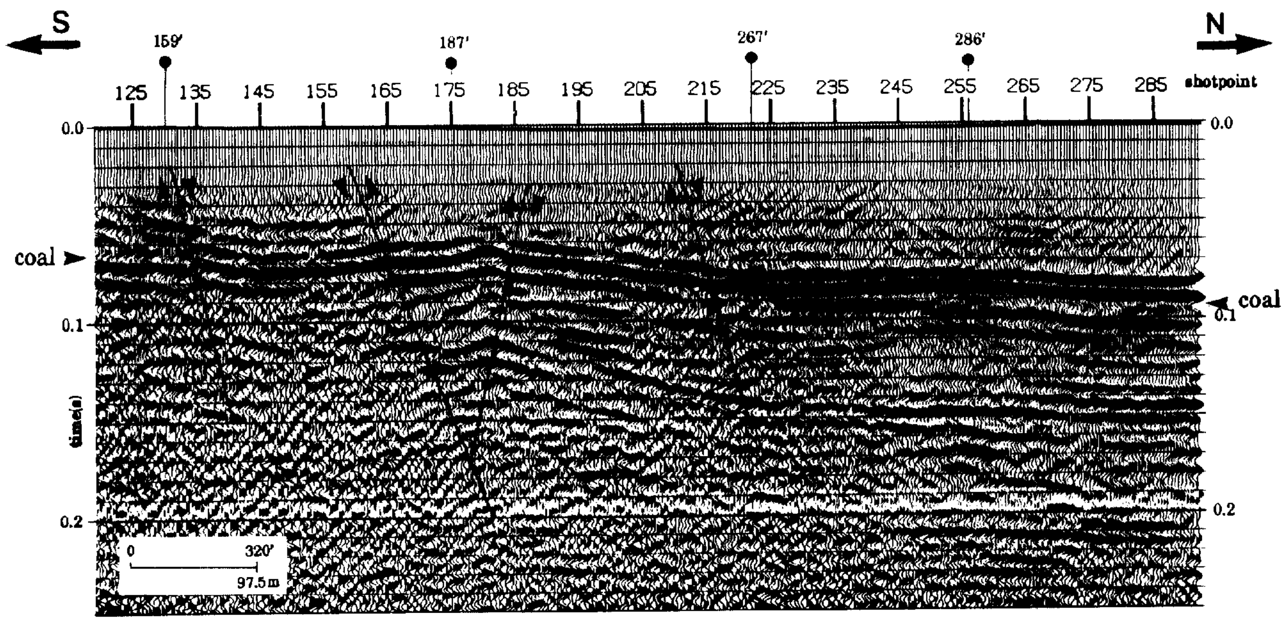

Figure 4. Seismic section showing shallow coal-seam reflection interrupted by multiple faults.

there are a limited number of published case histories in which a vibrator was effective for shallow high-resolution work. This paper focuses on results obtained using a high-frequency vibroseis source for coal exploration. The Conoco prototype unit shown at the beginning of the article can generate sweep frequencies as high as 400 Hz with up to 33 000 lb peak force. When utilizing a vibroseis source, proper selection of sweep parameters—like frequency sweep range, sweep length, linear and/or nonlinear sweep—is an important part of the acquisition process.

Example 1. Two seismic sections are presented in Figure 1 to demonstrate field testing of different vibroseis sweep parameters to optimize the recording of high-resolution seismic data. The tests were conducted in a deep Appalachian coal field where the target coal seam lies about 610 m (2000 ft) beneath the surface and the average seam thickness is 1.8 m (6 ft). Synthetic seismograms generated from sonic and density logs indicate a datum corrected arrival time of approximatly 246 ms for the coal seam reflection. Figure 1a is a seismic section obtained using a linear sweep. The reflection associated with the target coal seam is rather weak and hard to interpret. A second test over the same interval was made with a nonlinear sweep. The resulting section is shown in Figure 1b. Similar data processing sequences were employed to assemble both sections. The seismic data obtained with the nonlinear sweep show a robust and continuous reflection associated with the coal-seam horizon; this suggests uniform near-seam conditions. The nonlinear sweep method concentrated more energy in the desired frequency bandwidth and improved the signal-to-noise ratio. Moreover, coherent reflections from greater depths were also recorded, as indicated by comparison of reflector continuity at 345 ms. The depth of this deeper reflector is estimated to be 823 m (2700 ft).

The experiences gained in conducting these field tests will assist in proper selection and usage of sweep parameters to optimize the recording of good quality seismic data. The following two examples demonstrate case studies where collection of seismic data with very good signal-to-noise ratio provided assistance in evaluating subsurface geologic conditions.

Example 2. Figure 2 is a seismic section from a high-resolution survey conducted to evaluate seam continuity between boreholes. The reflection associated with the target coal seam is indicated, as well as the locations of two boreholes (A and B) which are separated by 439 m (1440 ft). Borehole data revealed seam thickness to be about 3 m (10 ft) and seam depth about 228.6 m (750 ft). Lithologic information from the two boreholes is presented in Figure 3. Information from these two boreholes alone could not guarantee that the seam was continuous and uniformly thick over this interval. Geologic disturbances or anomalies that might create adverse mining conditions could be present between the boreholes. The section shows the coal-seam reflection to be robust and continuous from SP-20 to SP-100, indicating uniform seam thickness across the entire section. Moreover, reflections associated with the immediate roof and floor rocks appear to be constant, suggesting nearly uniform lithology with minimal lateral changes. Thus, seismic data coupled with the borehole data provided additional assurance of satisfactory mining conditions.

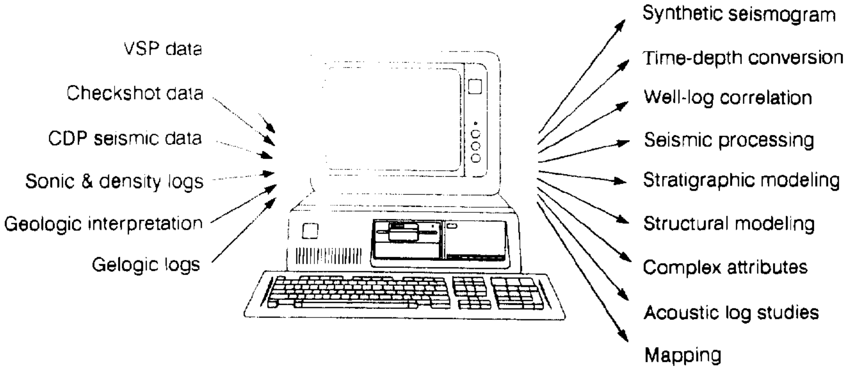

Figure 5. Schematic diagram of interactive workstation environment in coal mining. Data types are on the left and typical applications on the right.

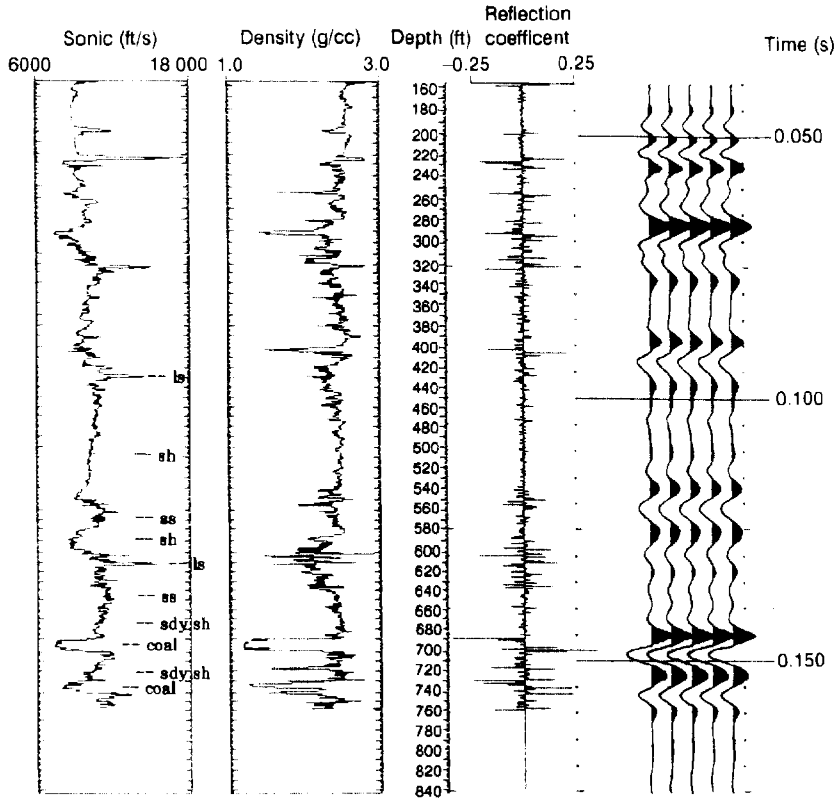

Figure 6. Synthetic seismogram generated from available geophysical logs.

Example 3. The high frequency vibrator can also be an effective source for shallow targets that lie a few hundred feet beneath the surface. Figure 4 is a section of a survey conducted to aid an exploration drilling program by mapping a major fault system which caused dramatic changes in seam elevation. Several boreholes across the survey line revealed that the average depths of the mineable coal seam located south and north of the fault zone are 48.4 m (160 ft) and 91.4 m (300 ft), respectively. The average seam thickness is 3 m (10 ft). The locations of several boreholes and the depths of the coal seam are noted on top of the section. The reflection associated with the coal seam is indicated. Two major seam disturbances associated with the fault system were interpreted near SP-134 and SP-165. A smaller fault that may connect with the southern fault was also interpreted near SP-184. The robust and continuous coal-seam reflection from SP-135 to SP-185 indicates a uniformly thick coal seam of about 3 m (10 ft). Dramatic changes in the arrival time of the coal-seam reflection over this interval suggest probable steep dips in the seam near interpreted faults. From SP-185 to SP-292, the seam reflection is robust and continuous, indicating a uniform thickness. A relatively small fault was interpreted near SP-214 where a noticeable change in arrival time is evident (note some disruption in reflections from the deeper strata). The data between SP-185 and SP-227 suggest that the seam dips to greater depth and remains fairly level from SP-228 to SP-292.

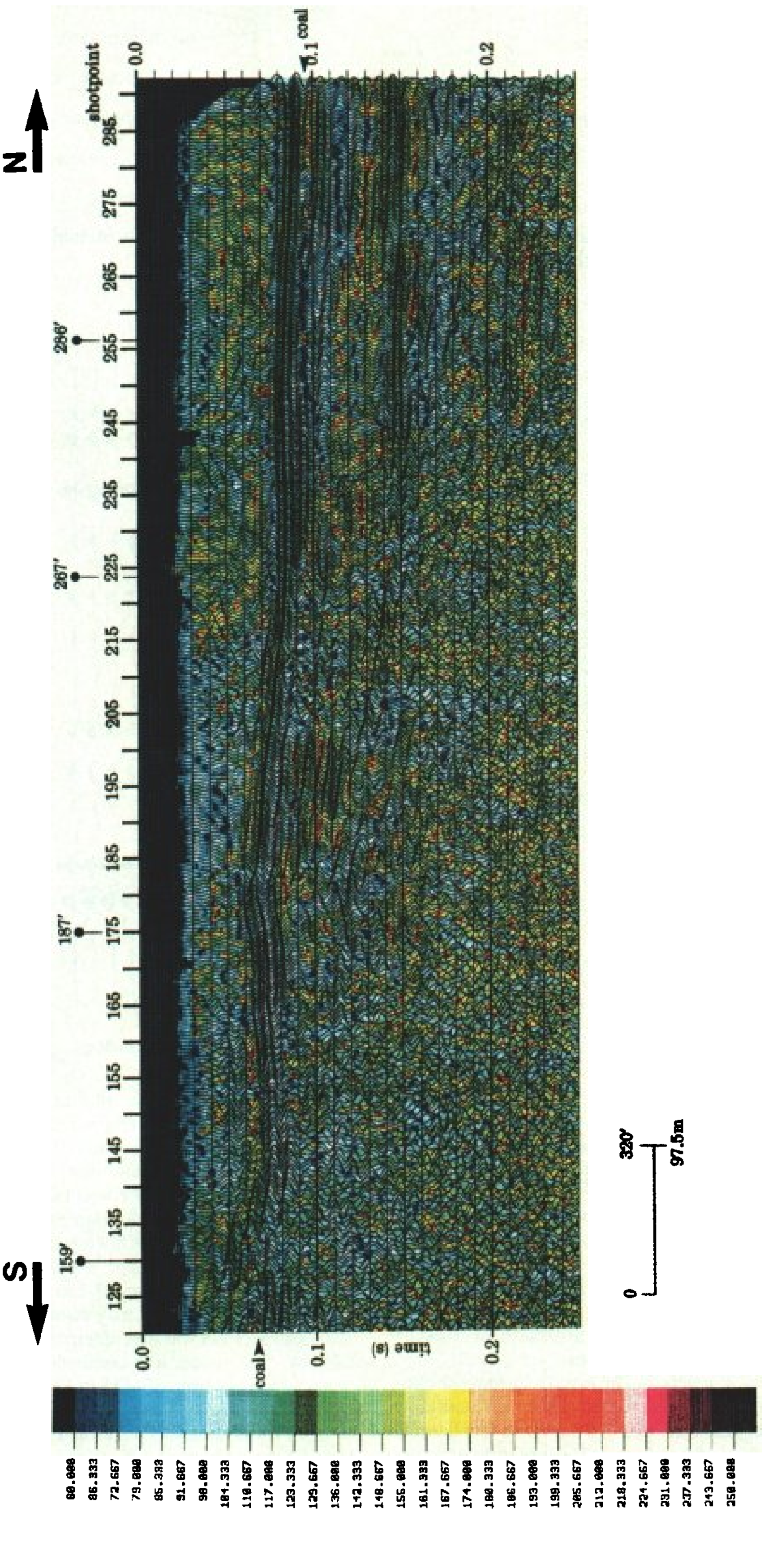

Figure 7. Instantaneous frequency attribute display of Figure 4.

Data analysis and computer modeling. Major oil companies utilize computer workstations to significantly improve interpretations of seismic data through the interactive process of cross-correlating geologic and geophysical data sets. Computer-generated models are matched with the recorded data to strengthen these interpretations. This same useful technology can be used to enhance the seismic program for coal-mining applications. Improvements in microcomputer technology and software development over the last 10 years have made seismic interactive interpretation workstation capabilities both affordable and accessible. With proper hardware and software configurations, a microcomputer-based workstation can process high-resolution seismic data to conduct modeling studies for improved interpretation and correlation to common-depth-point data. Figure 5 is a schematic diagram of the multitask capabilities of a workstation being employed for coal exploration.

During the last five years, the collection of sonic logs in exploration boreholes has been regularly conducted prior to seismic surveys. Vertical seismic profiling and checkshot data also are gathered in some of these boreholes for subsequent modeling studies. A workstation is then utilized to integrate the downhole geologic and geophysical information in order to generate synthetic seismograms for correlation to the processed CDP seismic data (Figure 6). Key reflectors are annotated in the figure. Recent conversion from analog to digital recording of well-log data has increased productivity and improved the definition of rock formations.

Although coal seams are extremely thin with respect to wavelength, they often produce distinct reflections because of an exceptionally large acoustic impedance contrast with respect to roof and floor rocks. In many cases, the seam thickness is less than the standard one-quarter wavelength criterion needed to resolve the top and base of a bed, but is close to the tuning thickness—one-eighth of a wavelength. Therefore, it is important to use computer modeling to study the effects of thin coal seams on reflection amplitudes (see *Tuning effects and interference reflections from thin beds and coal seams*, GEOPHYSICS August 1991).

The interpretation of broadband coal seismic data often requires advanced methods and techniques. The signature of the seismic wavelet provides a great deal of valuable geologic information. Subtle features and seam anomalies, not easily observed in conventional black and white sections, can be enhanced through color attribute displays. Detecting and interpreting small faults (less than seam thickness) is difficult, but this is extremely important in coal-mining operations because a fault with a vertical displacement of about one-half the seam thickness is enough to stop the advance of a longwall face. Figure 7 is the instantaneous frequency attribute display of the CDP seismic data presented in Figure 4. This display shows that the spectrum of the data extends to 200 Hz. The coal-seam reflection tunes to frequencies ranging from 100–140 Hz. Faults produce frequency and amplitude variations due to interference within the Fresnel zone that straddles the fault. Disturbances in the tuning frequency of the coal-seam reflection are evident in Figure 7 at SP-134, SP-165, SP-183, and SP-214. The instantaneous reflection strength attribute display is presented in Figure 8 and shows a robust coal-seam reflection. However, dimming of reflection amplitudes is observed at locations where the reflection frequencies are also altered, suggesting the likelihood of a geologic disturbance associated with faulting.

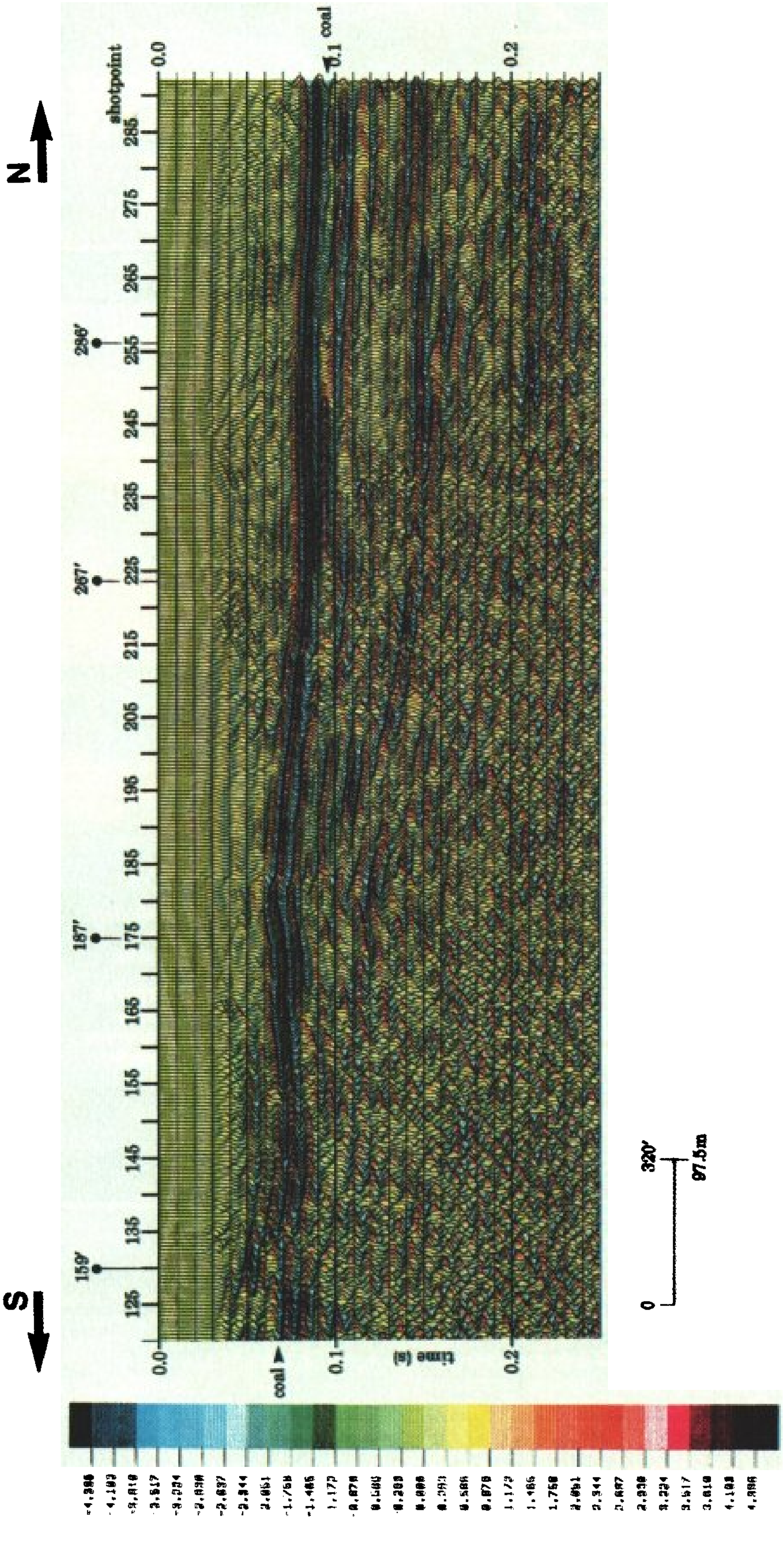

Figure 8. Instantaneous reflection strength display of Figure 4.

Conclusion. Seismic reflection profiling gained increased utilization in the 1980s but this technique will achieve its full utility for coal-mining applications only if the industry continues to utilize improving technology developed for the petroleum industry. For example, in a milestone event for US coal exploration, Consolidation Coal Company conducted its first 3-D seismic survey in 1989. The results provided more information for improved control in mapping the seam structure than data available from a grid of conventional 2-D lines. In the 1990s, it is likely that more 3-D seismic surveys will be conducted to fully evaluate coal reserves for improved mine planning. Collection of such data sets and the requirement for improved accuracy in interpretation implies that computer workstations will play a greater role in coal exploration. LE

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