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Modeling studies of interference reflections in thin-layered media bounded by coal seams

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ABSTRACT

High-resolution seismic data collected over a major U.S. coal basin indicated potential complex problems associated with interference reflections. These problems differed from those normally encountered in the exploration of oil and gas because of differences in the geologic boundary conditions. Modeling studies were conducted to investigate the effects of overlapping primary reflections and the composite reflection that result from stacking individual wavelets. A modified empirical formula of Lindseth's linear relationship between acoustic impedance and velocity is used to extrapolate velocity information from density logs to provide appropriate geophysical properties for modeling. The synthetic seismograms generated from density and synthetic sonic logs correlated well with the processed seismic data. A 150-Hz Ricker wavelet is used to convolve with the computer models, and the models showed that certain anomalous composite reflections result from the superposition of overlapping primary reflections. Depending on the traveltime delay of latter primary reflections, constructive or destructive interference could significantly alter the signature of the initial reflection associated with the bed of interest, which may lead to misinterpretations if not properly identified. The stratigraphic modeling technique further enhances the interpretation process and shows a close correlation with the seismic data, suggesting that more precise analytical methods need to be used to interpret, sometimes complex, high-resolution seismic data.

INTRODUCTION

Surface seismic surveys applied to shallow mineral exploration requires that the central frequency spectrum of the seismic trace be above 100 Hz to better resolve thinner beds with respect to petroleum exploration. Improvements in recording instruments, acquisition techniques, and data processing result in the recording of broadband seismic data having improved signal-to-noise (S/N) ratio. Additionally, the collection of geological and geophysical logs has become common in shallow exploratory drilling providing a host of valuable subsurface information for modeling and correlation with seismic data. Surface seismic surveys conducted in coal basins where thin-bed cyclothems predominate may yield unique problems that differ from those in the exploration of oil and gas because of differences in geologic boundary conditions. The media of investigation for shallow mineral exploration is normally composed of numerous interbedded thin beds that have large acoustic impedance contrasts. Thus, certain seismic reflections recorded at the surface may be a composite reflection of several individual reflections.

When interpreting high-resolution seismic data, it is essential to differentiate two important concepts; namely, detection and resolution. Detection deals with the recording of a composite reflection from a certain horizon with good S/N ratio, regardless of whether the composite reflection can be resolved into the separate wavelets that compose it. Thus, an event that is detectable may or may not be resolvable. Resolution deals with the ability to resolve the top and base of a thin bed which differs from the problem of detecting the presence of a bed. Resolution is primarily associated with frequency bandwidth of the recorded wavefield data, whereas detection is principally associated with acquisition technique. Studies in seismic resolution were conducted by Widess (1973), Schoenberger (1974), Meckel and Nath (1977), Niedell and Poggiagliolmi (1977), Koefoed (1981), Kallweit and Wood (1982), and Knapp (1990). Kallweit and Wood (1982) clarified and quantified the various criteria involved in resolving a thin bed which showed that resolu-

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tion depends mainly on the highest terminal frequency of the spectrum.

Modeling studies of seismic responses from thin beds and coal seams were previously conducted by Van Riel (1965), Meissner and Meixner (1969), Rüter and Schepers (1978), Koefoed and de Voogd (1980), de Voogd and den Rooijen (1983), and Gochioco (1991a). Coal seams as thin as one-fortieth of the predominant wavelength (1/40 λ_p) can give rise to a distinct reflection signal because of the exceptionally large acoustic impedance contrasts with surrounding rocks. However, individual reflections are not clearly visible from a sequence of layers containing numerous interbedded thin beds and coal seams because of "interference reflections." Interference occurs when two or more wavetrains cross one another, similar to the "principal of superposition" of light waves, wherein the resulting displacement at any given point and time is determined by adding the instantaneous displacements of the electric and magnetic vectors (Sears, 1964). The brilliant colors that are often seen when light is reflected from a soap bubble or from a thin layer of oil floating in water are produced by interference effects between two trains of light waves reflected from the opposite surfaces of the thin film of soap solution or of oil. In this case, interference reflections result from latter primaries and/or short-lag (intrabed) multiples such that the relatively larger amplitudes of latter and overlapping waveforms superpose and outweigh the amplitude of the initial primary reflection. This investigation assumes that latter primary reflections are major contributors to interference and amplitude anomalies. Thus, the effects of multiples and mode-converted shear waves are neglected.

The schematic diagram presented in Figure 1 demonstrates the effects of overlapping and superimposing impulse responses on a seismic record. Using a Ricker wavelet as the incident wavelet, Figures 1a and 1c show the unit responses of the wavelet from similar positive and negative reflection coefficient (RC) values. However, in the case of closely spaced RC values (see Figure 1b), the impulse responses will overlap in time, and where they overlap, the resulting waveform will be the sum or composition of several response pulses. Figure 2 shows a comparison of typical 150-Hz and 30-Hz Ricker wavelets, having the same unit amplitude, being used in modeling studies of seismic data collected for coal and petroleum exploration. This exercise will demonstrate some differences in their respective responses. An interactive interpretation workstation (Gochioco, 1991b) is used to generate the models and to understand the complex problems associated with interference reflections.

GEOLOGIC SETTING

The work is based on seismic data collected over a major U.S. coal basin wherein the Conoco prototype high-frequency vibrator was used as the seismic source. The coal basin has two dominant coal seams; namely, the No. 6 and No. 5 coals. Both coal seams are currently being mined, but in the immediate area of investigation, underground mine activity is conducted in the No. 6 seam. Extensive exploratory drilling shows that the No. 6 seam has an average seam thickness of 3 m and typical depth of 229 to 244 m. The No. 5 coal seam with an average seam thickness of 1.2 m lies on a nearly horizontal plane beneath the No. 6 seam. The normal separation interval between the two seams, as measured from the tops of the seams, ranges from 6.1 to 8.5 m.

A major paleochannel system is located immediately west of the reserve area. The paleochannel completely or partially replaced the coal seam with sandstones, siltstones, conglomerates, or interbedded sandstone-shale units. The major paleochannel and its associated distributaries are responsible for a variety of geologic anomalies that may affect the productivity of underground mining. A massive layer of nonmarine shale overlies the No. 6 seam. A few drill holes indicated an anomalous area where the No. 6 seam thickness may be thin, split, or unusually thick, and the elevation was found to be about 9.1 m higher than normal. This abrupt change in seam elevation (called a "roll") suggests that the No. 6 seam was deposited over an infill channel or thicker lens of floor rock that, upon vertical or differential compaction, produced locally steep dips that may thin the coal seam due to stretching. Rolls originate from crevasse-splay deposits after occasional flooding occurs in the peat swamp along major channels. Along this geologic anomaly, the coal seam may be thin or sometimes split from the main seam and create small shale lenses between the main bench and the rider seam. This kind of geologic disturbance could create difficult mining conditions.

Lithological cross sections of the three boreholes (BH1, BH2, and BH3) under investigation are presented in Figure 3 and are spaced 122 m apart. BH1 encountered normal seam thickness and elevations for the No. 6 and No. 5 coal seams. However, BH2 and BH3 revealed anomalous conditions for the No. 6 seam with elevations about 9.1 m higher than normal. The anomalous seam thicknesses in BH2 and BH3 were 0.9 m and 4.3 m with a 1.2-m split, respectively. Also,

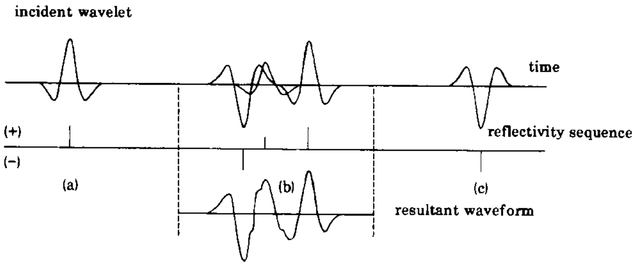

FIG. 1. Schematic diagram showing interference from overlapping and superimposed impulse responses.

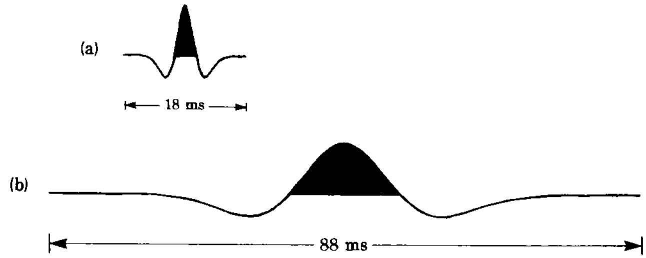

FIG. 2. Comparison of (a) 150-Hz and (b) 30-Hz Ricker wavelets in time domain.

the interval between the two seams increased to about 17.7 m. The average seam thickness of the No. 5 coal encountered by the three boreholes was 1.2 m.

SYNTHETIC SEISMOGRAMS

To support the assumption of latter primary reflections causing significant interference with the initial reflection associated with the bed of interest, computer modeling is necessary to determine the seismic signatures associated with the two dominant coal seams. Synthetic seismograms can demonstrate the wavelet characteristics associated with the complex lithology for subsequent correlation to the wavefield data. At the time of this investigation, density logs were only available for modeling studies in the area of interest, because the exploration drilling program was conducted to evaluate and assess seam thickness and depths prior to any thought of a seismic survey. However, velocity information is important in the modeling process.

In the absence of sonic logs, a synthetic sonic log can be extrapolated from the density log based on a simple empirical relationship presented by Lindseth (1979) which is widely used in the petroleum industry. By plotting density and velocity values for several rock types obtained from logging handbooks published by geophysical well-logging companies, Lindseth (1979) showed an approximate linear relationship between acoustic impedance (ρV) and velocity (V), as shown in Figure 4. The relationship

$$V = 0.308\rho V + 3460 \quad (1)$$

is based on rock properties from deep sedimentary basins. The estimated acoustic impedance and velocity values of bituminous coal are plotted in the graph, marked "x," in Figure 4. A new linear relationship is established from the graph, and the empirical formula becomes

$$V = 0.296\rho V + 4285 \quad (2)$$

to reflect the acoustic properties of shallower and younger rocks in the coal basin. Using the relationship in equation (2) yields synthetic sonic logs that require minimal editing to match with velocity values obtained from actual sonic logs collected in postseismic survey boreholes drilled in the study area. The calculated velocity information is then used with the three density logs to build the synthetic seismograms for more accurate seismic responses.

Spectrum analysis of seismic traces recorded in the study area indicated a dominant frequency of about 150 Hz. Thus, the 150-Hz Ricker wavelet is used in modeling to simulate the synthetic seismic response of geologic models. Figure 5 shows the digitized synthetic sonic and density logs of BH1, highlighting the depth interval between 198 and 259 m. Two Ricker wavelets (30 Hz and 150 Hz) are used to convolve with the reflectivity sequence to demonstrate the concepts of detection and resolution as well as interference reflections. Despite a relatively lower frequency spectrum typical of seismic data collected for petroleum exploration, the low-frequency synthetic seismogram (convolution by a 30-Hz Ricker wavelet) in Figure 5 shows a reflection (trough) from the No. 6 coal seam horizon. The No. 6 seam and the

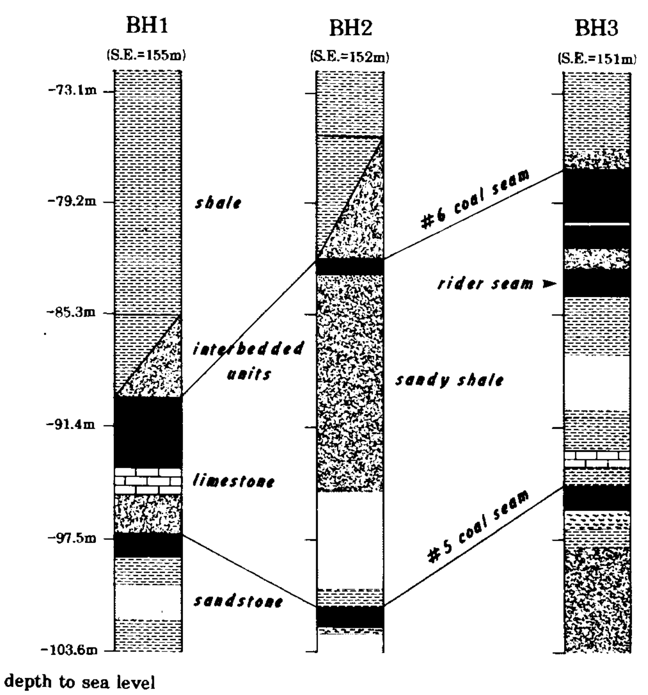

FIG. 3. Lithological cross sections of three closely spaced boreholes in the study area.

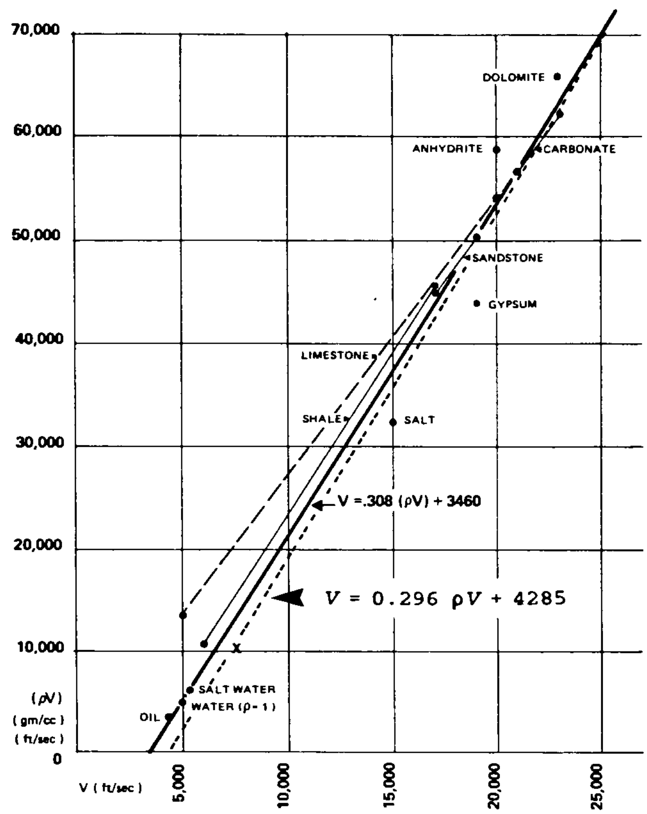

FIG. 4. Plot shows a modified empirical formula of Lindseth's linear relationship between acoustic impedance and velocity for shallow mineral applications (from Lindseth, 1979).

massive shale unit above it yielded a smaller net acoustic impedance contrast with respect to the combined sandstone-sandy shale-No. 5 coal-limestone units. This means that the respective coal seams are detectable as combined units with the addition of roof and floor rocks, similar to "blocking" or averaging of log data over a given depth interval. On the other hand, the high-frequency synthetic seismogram (convolution by a 150-Hz Ricker wavelet) of BH1 shows two distinct coal-seam reflections associated with the No. 6 and No. 5 coal seams for typical thickness and separation distance. The separation interval of 6.4 m was sufficient to yield distinct reflections from each seam, and the No. 6 reflection amplitude is larger than the No. 5 reflection, as expected. Therefore, the coal-seam reflections are normal and do not show any indications of amplitude anomalies associated with interference reflections.

The *P*-wave velocity in bituminous coal is about 2285 m/s. Using 150 Hz as the predominant frequency, the bed thicknesses of the No. 6 and No. 5 coals range from one-fifth to one-fifteenth of the predominant wavelength ($1/5\ \lambda_p$ to $1/15\ \lambda_p$). Widess (1973) stated that for beds thinner than the one-quarter wavelength ($1/4\ \lambda$) criterion, amplitude information must be used in the interpretation process to estimate the bed thickness. In this case, the technique is used to solve the problems associated with interference reflections rather than estimating bed thickness. Therefore, using the No. 6 reflection amplitude as a reference (unit value = 1.0), analysis of the No. 5 reflection amplitude indicated an approximate magnitude of 0.7.

The seismic signatures associated with the two coal seams changed dramatically near BH2, even though it was located only 122 m east of BH1. The low-frequency synthetic seismogram presented in Figure 6 clearly shows a significant change in the seismic signature caused by the very thin No. 6 coal seam and increased separation interval. The thin coal seams failed to effectively lower the net acoustic impedance value relative to the surrounding sandstones and sandy shale beds so as to yield a trough for the group. Instead, the massive shale unit that overlies the No. 6 seam had a smaller average acoustic impedance relative to the average value of the interbedded sandstone-coal units combined. This indicates that the low-frequency wavelet cannot resolve distinct coal-seam boundaries in a consistent manner because the seismic response depends largely on "average" acoustic values over a depth interval with no predictable boundaries. However, the high-frequency synthetic seismogram shows a completely different seismic response. The No. 6 reflection remained robust with an amplitude value of 1.0, despite the fact that the seam thickness is only 0.9 m thick, indicating an amplitude anomaly. The increased separation of the two coal seams from 6.4 to 17.0 m caused a broadening of the seismic wavelet beneath the No. 6 reflection. The reflection associated with the No. 5 coal seam is still clearly defined, but the measured amplitude response increased from 0.7 to 0.85, even though the seam thickness is still 1.2 m.

BH3 revealed the interval between the two coal seams remained anomalously large at about 17.7 m. Additionally, major differences exist in the lithology between the two coal seams as evidenced by more thin beds, unusually thick No. 6 coal and split coal, as seen in Figure 3. The low-frequency synthetic seismogram in Figure 7 shows a similar seismic response to Figure 5, wherein the No. 6 seam and the massive shale unit above it produced a net trough. Studies of a coal wedge model suggest that a 4.3-m thick seam would yield a larger reflection amplitude compared to a 3-m thick seam. However, results from the high-frequency synthetic seismogram developed from log data are different. The respective coal-seam reflections are indicated, and measurement of the No. 6 reflection amplitude revealed a magnitude of only 0.8. The doublet waveform between the two dominant coal-seam

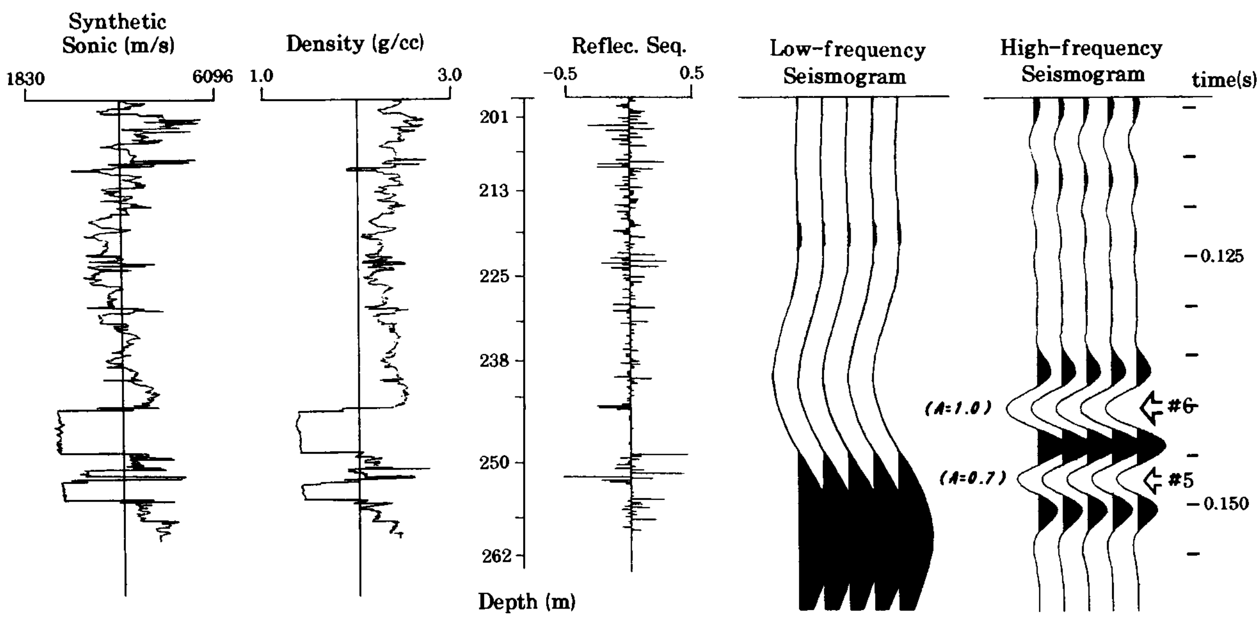

FIG. 5. Digitized log data and synthetic seismograms of BH1 after convolution with respective 30-Hz and 150-Hz Ricker wavelets.

reflections resulting from the sequence of thin beds and the trough being anomalously small in magnitude, is associated with the split coal or rider seam having a thickness of 1.5 m. The robust No. 5 coal-seam reflection shows an amplitude anomaly and analysis of the No. 5 reflection yielded a magnitude of 1.0, despite a uniform seam thickness of 1.2 m.

A seismic survey line intersected the three boreholes, and that portion of the seismic section is presented in Figure 8. Borehole locations as well as the coal-seam reflections are noted in the figure. Wavelet characteristics of the high-frequency synthetic seismograms associated with the two dominant coal seams correlated closely with those of the seismic data. The synthetic seismogram of BH3 is placed at the borehole location alongside the seismic data and shows an excellent correlation. Therefore, the coal-seam reflections are anomalous and result from interference caused by some latter and overlapping primaries whose amplitudes altered the signature of the initial reflection associated with

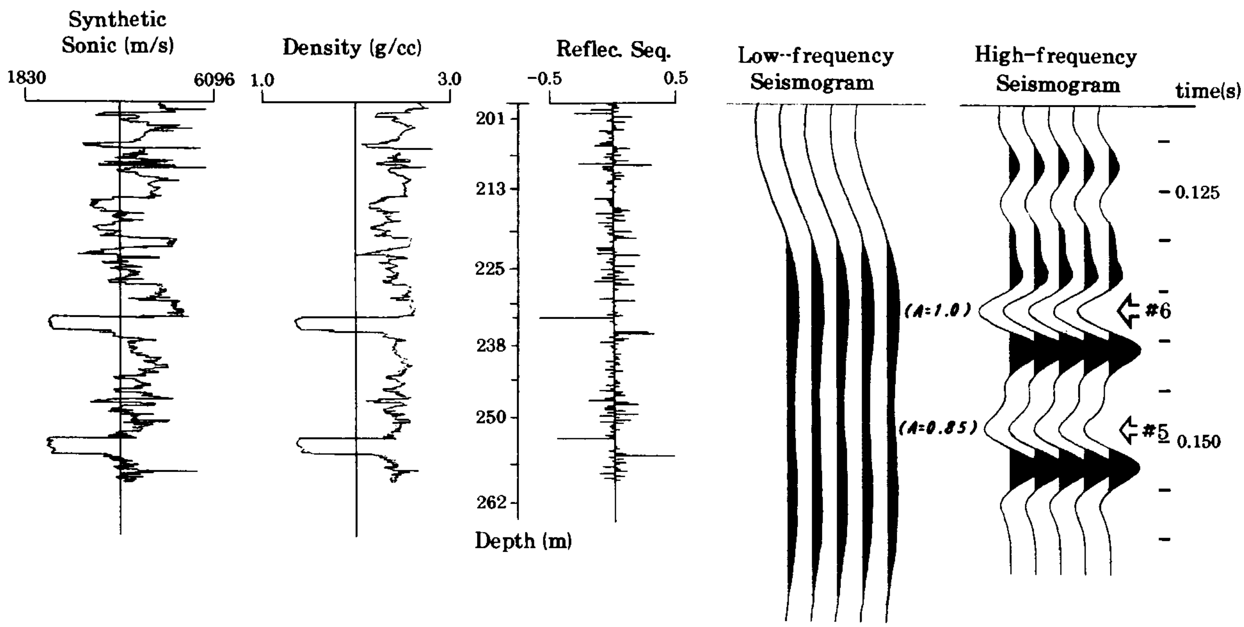

FIG. 6. Digitized log data and synthetic seismograms of BH2 after convolution with respective 30-Hz and 150-Hz Ricker wavelets.

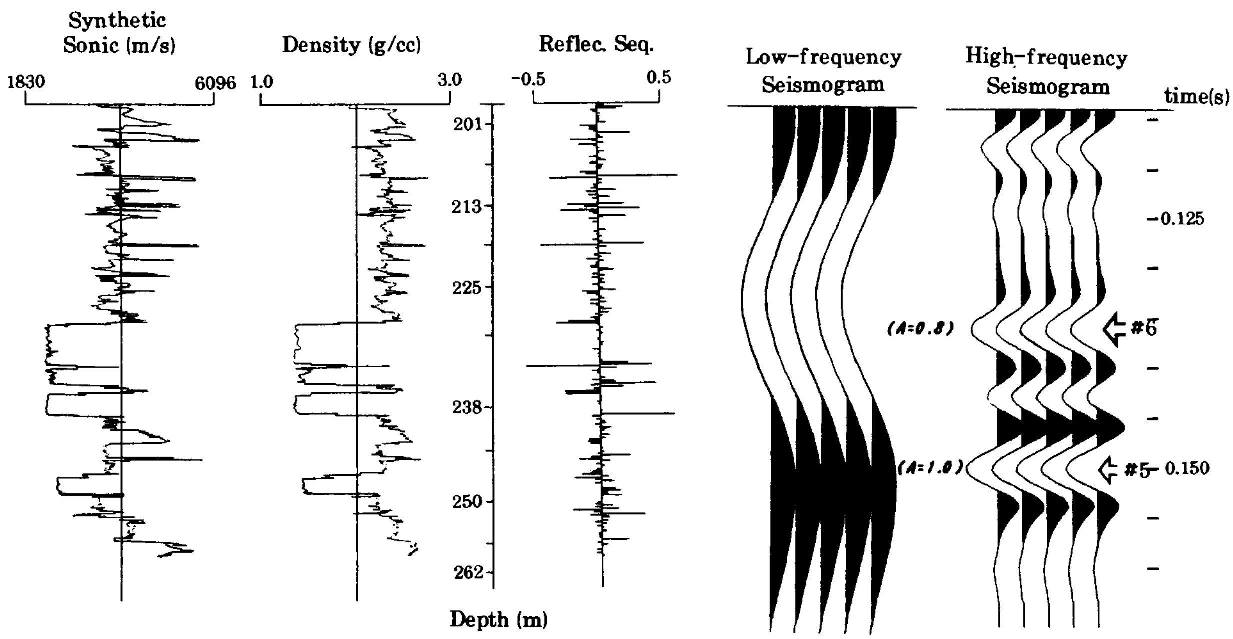

FIG. 7. Digitized log data and synthetic seismograms of BH3 after convolution with respective 30-Hz and 150-Hz Ricker wavelets.

the bed of interest. The models and seismic data revealed a combination of constructive and destructive interference reflections. Constructive interference reflections are evident in the amplitude anomalies associated with the No. 6 and No. 5 coals near BH2 and the robust No. 5 reflection near BH3. The relatively smaller reflection amplitudes of the No. 6 and rider seams near BH3 resulted from destructive interference.

STRATIGRAPHIC MODELING

The stratigraphic modeling technique is employed to further enhance the interpretation process. The synthetic sonic logs of BH1, BH2, BH3, and a fourth borehole located 122 m west of BH1, are used to build the model. The fourth borehole has a lithology similar to that of BH1. Figure 9 shows the stratigraphic model after interpolation, resulting in a cross section with similar subsurface coverage and group interval as the seismic data presented in Figure 8. The four original (input) logs which acted as control points in the interpolation process are highlighted. A 150-Hz Ricker wavelet is then used to convolve with the stratigraphic model to yield a synthetic seismic response, as shown in Figure 10. Borehole locations and appropriate coal-seam reflections are noted in the figure.

There is a good correlation of the seismic signatures associated with the No. 6 and No. 5 coal seams between the synthetic model and seismic data. The model shows a continuous synthetic profile of constructive and destructive interference reflections over the geologic anomaly. The rapid change in the signatures of seismic reflections between BH2 and BH3 indicate an abrupt change in lithology near BH2 where both the thick No. 6 and the rider seams thinned and pinched out. From SP-143 to SP-160, the No. 5 coal-seam reflection exhibits frequency and amplitude tuning as a result of constructive interference. This amplitude anomaly revealed the signature of the geologic disturbance (roll) which could be used to identify areas of above normal seam elevations for the No. 6 coal.

A three-dimensional (3-D) surface diagram emphasizing the various amplitude anomalies associated with the No. 6, rider, and No. 5 seams near BH3 is presented in Figure 11. With an increased vertical scale ratio of 2:1, the plot shows the relative reflection amplitudes associated with each coal seam calculated from the synthetic model. The coal seams and their respective thicknesses are noted in the figure. Apparently, the robust amplitude corresponds to the thin No. 5 seam that has a thickness of only 1.2 m, while the smaller amplitudes correspond to the No. 6 and rider seams that have thicknesses of 4.3 m and 1.5 m, respectively.

CONCLUSIONS

High-resolution seismic surveys applied to coal exploration indicated the existence of complex problems associated with interference reflections in the recorded wavefield data. The case study showed how two dominant coal seams and a rider seam could easily affect the resulting reflection by their thicknesses, separation distance, and sequence layering. The assumption that latter primaries are major contributors to interference with the initial primary reflection associated with the bed of interest is valid only for cases that have a few

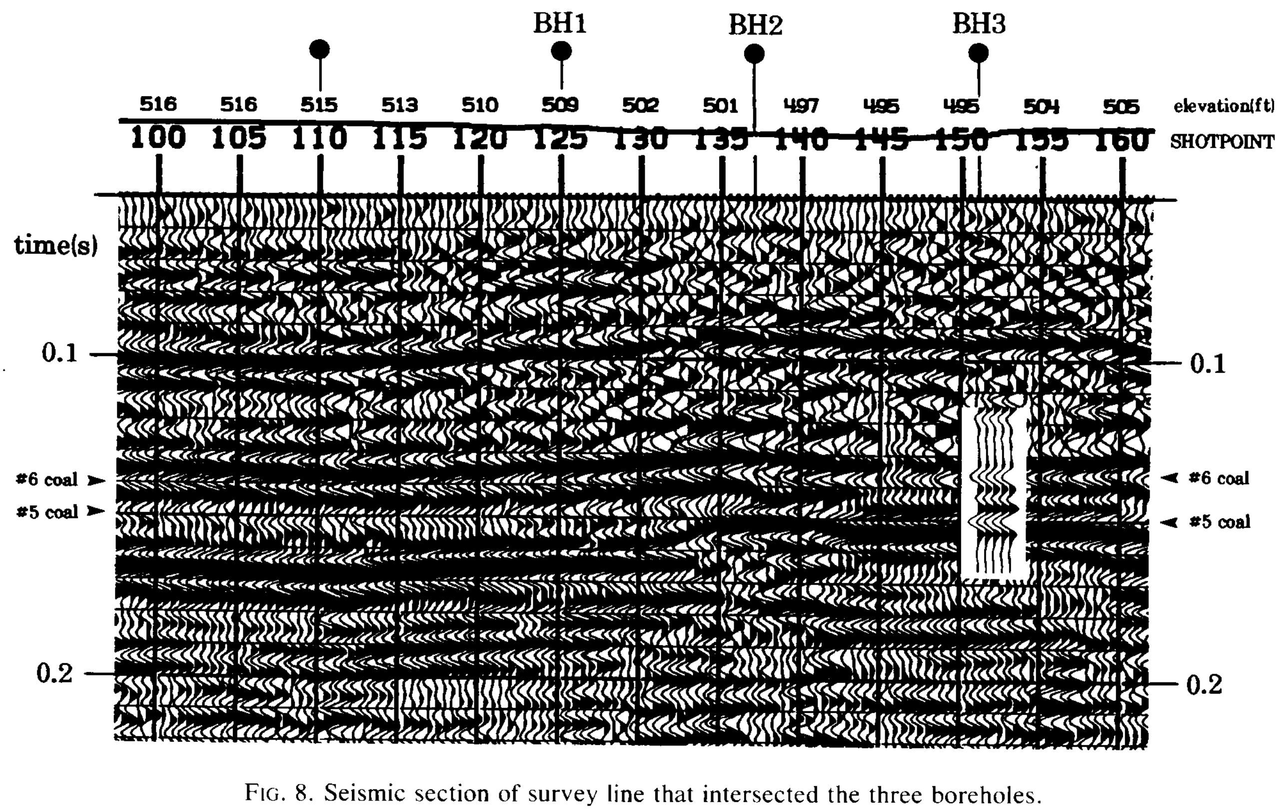

FIG. 8. Seismic section of survey line that intersected the three boreholes.

seams. However, in other coal basins where numerous seams and interfaces exist, the interference reflections are likely to be dominated by short-lag or intrabed multiples such that the latter primaries have little significant influence. Without the proper solutions, only the top few seams could be reliably interpreted from the seismic data.

Computer modeling is essential in the interpretation process so that anomalous composite reflections could properly be identified to avoid misinterpretations. Since the 150-Hz Ricker wavelet is significantly shorter than the 30-Hz wavelet, blocking or averaging of log data in modeling is not recommended. To yield a more accurate synthetic seismic response from geologic models, stratigraphic modeling built with digitized log data should be employed. The good correlation of the seismic signatures between the computer models and seismic data indicates that the modified empirical formula of Lindseth's linear relationship (Lindseth, 1979) between acoustic impedance and velocity could be used to extract velocity information from density logs for high-resolution seismic modeling.

Comparison of the seismic responses from two Ricker wavelets after convolution with high-density reflectivity sequences demonstrate that differences in certain boundary conditions exist in the recorded wavefield data as applied to

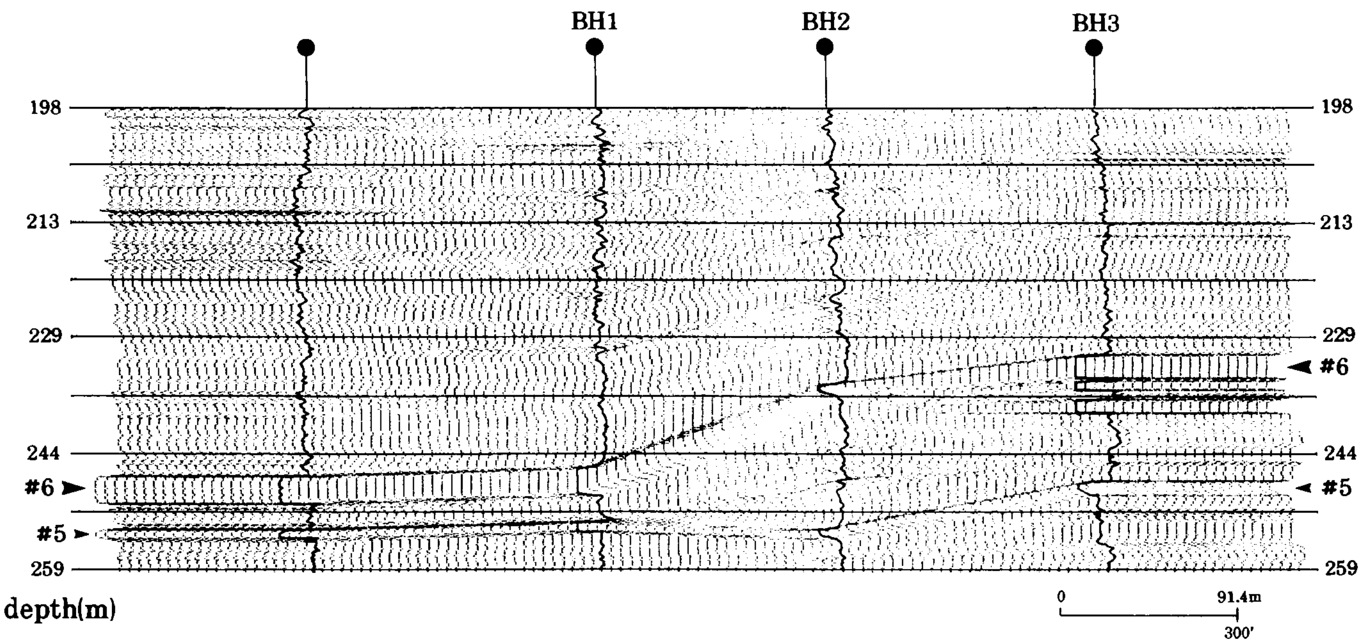

FIG. 9. Model shows interpolated synthetic sonic logs over the same area of subsurface coverage. The four principle logs used in the model are highlighted.

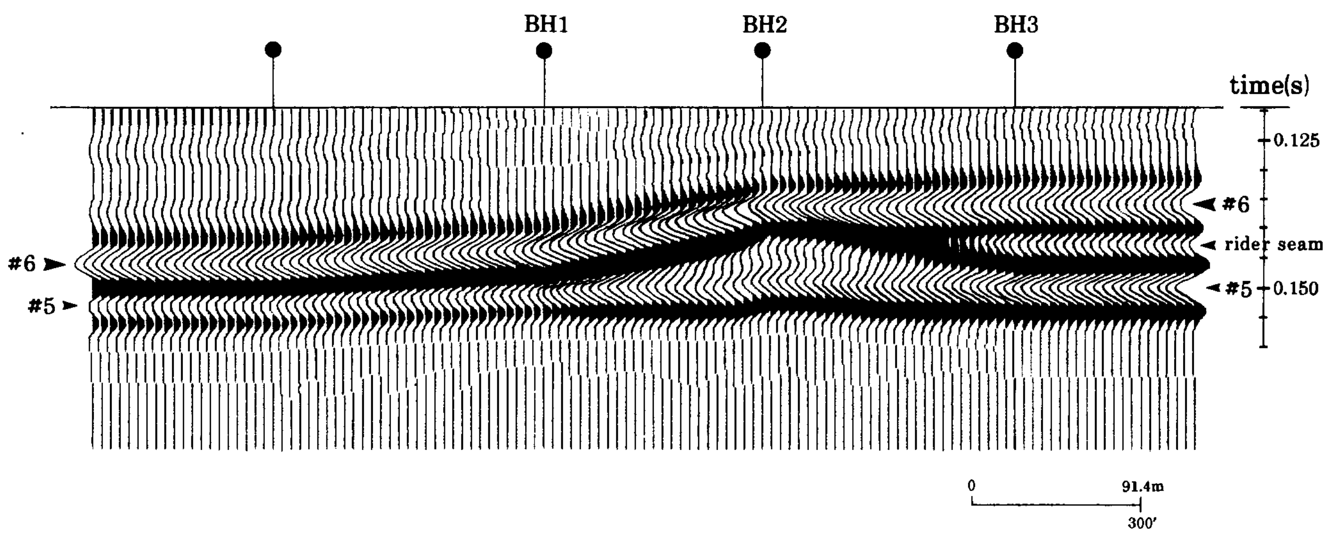

FIG. 10. Seismic response of a stratigraphic model after convolution with a 150-Hz Ricker wavelet.

mineral and petroleum exploration. Interpretation of low-frequency seismic data may require simpler solutions to address certain problems. However, problems are potentially more complex for shallow high-resolution seismic data because the wavelet is able to better resolve more thin beds and bed interfaces with respect to wavelength. Additionally, the characteristic properties of each reflected wavelet (frequency, amplitude, and phase) interact with other reflections from adjacent beds which results in the recording of complex waveforms. Therefore, interpretation of high-resolution seismic data requires more sophisticated and precise methods to properly dissect individual wavelets that form the composite reflection. The methodology is analagous to two important principles in Physics; namely, classical and quantum mechanics. As problems become more complex in trying to define small particle interactions, or in this case, high-frequency reflections from thin-bed cyclothems, quantum mechanical techniques need to be employed in interpretation.

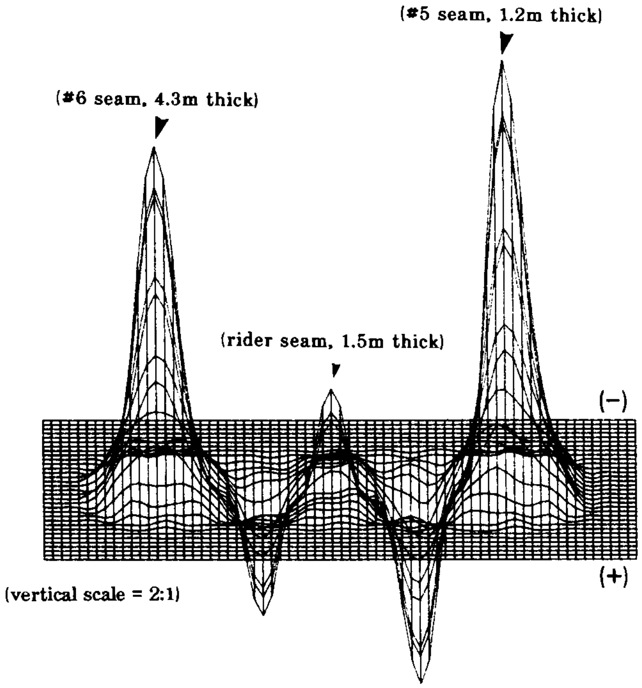

FIG. 11. 3-D surface diagram of the calculated anomalous reflection amplitudes associated with the coal seams near BH3.

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