GEOPHYSICS, VOL. 56, NO. 8 (AUGUST 1991); P. 1288-1295, 12 FIGS. 1 TABLE.

Tuning effect and interference reflections from thin beds and coal seams

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ABSTRACT

The Ricker and Widess criteria of resolving thin beds are established and widely accepted axioms. Analysis of tuning effects from an isolated thinning bed is commonly used in estimating the thickness of a thin bed. However, frequency and amplitude tuning effects may also result from a sequence of thin beds. Depending on the thicknesses, acoustic properties, and the relative location of thin beds in space, tuning effects from interference reflections can sometimes deform the seismic wavelet and cause complex waveforms. Coal seams as thin as 1/20 of the predominant wavelength can produce reflections, and these reflections may be a composite of primary and multiple reflections. Interference reflections from two closely spaced coal seams were recorded and used to interpret a seam anomaly (roll) that may create adverse conditions for longwall mining. The seismic data and computer model results correlated with findings of several boreholes.

INTRODUCTION

A seismic wavelet recorded at the surface may be composed of two or more individual reflections. Certain characteristic oscillations may provide some information regarding layer thickness and/or layer boundaries. The relationship between layer thickness, the signal wavelength, and the resolution of the top and bottom of a thin layer were first studied by Ricker (1953). The modeling studies of Meissner and Meixner (1969) showed that thin layers and layered boundaries can deform the seismic wavelets due to interference between primary and multiple reflections from the two or more boundaries involved. Further studies in seismic resolution and in resolving a thin bed were conducted by Widess (1973), Schoenberger (1974), Meckel and Nath (1977), Neidell and Poggiagliolmi (1977), Kallweit and Wood (1982), Robertson and Nogami (1984), and Knapp (1990).

Widess (1973) stated that when the layer thickness is beyond the range of resolution (less than one-fourth of the wavelength), the information on the layer thickness is encoded in the amplitude of the composite reflection. In the case of a thinning bed bounded by a homogeneous media, the complex wavelet is obtained by addition of a wavelet reflected from the top of the layer and one reflected from its bottom, the latter wavelet being phase-inverted and time-shifted with respect to the former, but having the same amplitude. This procedure implies that both transmission loss and internal multiple reflections are neglected. Widess (1973) considered these effects to be negligible as long as the acoustic impedance ratio between the thin layer and the surrounding rocks lies between the bounds of 0.5 and 2.

One of the important fields of application of the thin-layer theory is in coal exploration where coal seams form a notable exception to the above acoustic impedance rule. Coal seams, although extremely thin with respect to wavelength (λ), can produce distinct reflections because of exceptionally large acoustic contrast with respect to roof and floor rocks (impedance ratios ranging from 0.25 to 0.38). Van Riel (1965), Ruter and Schepers (1978), and Koefoed and de Voogd (1980) demonstrated the seismic response of coal seams by means of synthetic seismograms through which reflections from seams with thicknesses less than one-eighth of the wavelength were studied. Ruter and Schepers (1978) stated that a single coal seam with seam thickness of about 1/50 λ can give rise to a distinct reflection signal, but that individual reflections are not visible from a sequence of layers containing numerous seams and interfaces because of "interference reflections." The interference reflections are sometimes composed of short lag multiples such that the relatively larger amplitudes of the multiples outweigh the amplitude of the primary reflection.

The main objective of this paper is to demonstrate that coal seams as thin as 1/20 λ can cause a reflection and that reflections from intermediate thin beds can yield complex wavelets. This paper presents a case study in which interference reflections from two closely-spaced coal seams were recorded and used to interpret a seam anomaly (called a "roll") that may create adverse conditions for longwall mining. A computer workstation

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(Gochioco, 1989) was used to generate synthetic models to assist in the interpretation of the seismic data and to understand the complex interactions associated with thin beds and their effects on reflection amplitudes.

CASE STUDY

Underground mining activity in the region of investigation is being conducted in the Illinois No. 6 (I6) coal seam. The average seam thickness is 10 ft (3 m) and its depth ranges from 750 to 800 ft (229 to 244 m) beneath the surface. The Springfield No. 5 (S5) coal seam lies beneath the I6 seam and has an average seam thickness of 4 ft (1.2 m). The average interval between the two seams ranges from 13 to 25 ft (4.0 to 7.6 m). An extensive exploration drilling program revealed the S5 seam to lie on a nearly horizontal plane. However, a few drillholes indicated an anomalous area where the I6 seam elevation was found to be 30 ft (9.14 m) higher than normal. A geological disturbance associated with a roll was encountered in a neighboring coal mine located near the study area. This observation suggests that the I6 seam was deposited over some noncompactional bodies or topographic high areas resulting in severe changes in seam elevation which could impede longwall mining in the area (Gochioco, 1990). A grid of seismic survey lines was established to evaluate the reserve area and to detect the width and extent of the geologic disturbance. A roll is defined as an infill channel or lens of floor rock that produces locally steep dips that may abruptly thin or erode the coal seam. The Conoco prototype high-frequency Vibroseis® unit was used as the broadband source.

Assuming a homogeneous environment, computer modeling showed a 30-ft (9.14-m) roll would result in an approximate 6-ms difference in two-way traveltime with respect to a horizontal reflector. In an inhomogeneous environment, a change in arrival time is not a reliable indicator because velocity anomalies, regional dip, and/or residual statics may also produce traveltime differences in the seismic data. Thus, there is a need for exploring other methods of identifying a seismic signature that can be associated with the detection of the roll.

WEDGE MODEL

The seismic data gathered in the study area have a frequency bandwidth ranging from 60 to 250 Hz and recorded a peak frequency of 125 Hz from the target coal seam horizon. To evaluate the seismic response of a thinning coal seam, a Ricker wavelet having a dominant frequency of 125 Hz was used and convolved with a wedge model. Figure 1 shows the amplitude spectrum of the 125 Hz Ricker wavelet and the wavelet in the time domain. To study the effects of a thinning bed on reflection amplitudes, a wedge model was generated and is presented in Figure 2. The *P*-wave velocities in bituminous coal and shale are 7500 ft/s (2500 m/s) and 12 000 ft/s (3650 m/s), respectively. Their respective densities are 1.35 g/cc and 2.4 g/cc. The acoustic properties were obtained from geophysical logs gathered in nearby boreholes. A synthetic seismogram of the wedge model is presented in Figure 3. The one-eighth wavelength thickness establishes the limit of resolvability of the thin bed because further decreases in seam thickness do not appear to produce visible changes in peak-to-trough times.

In principle, beds thinner than 1/4 λ can be resolved by measuring changes in the composite reflection amplitude. Above the tuning thickness, peak-to-peak time measurements are good approximations of bed thicknesses, whereas below the tuning thickness, amplitude information must be used. The Ricker and Widess criteria demonstrated the tuning effects of an isolated thinning bed bounded by two homogeneous media. In a case study, Ensley (1985) found that amplitude anomalies can also

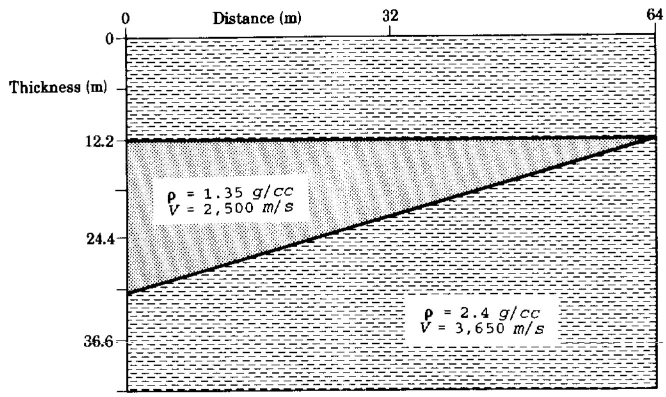

FIG. 2. Geometry of wedge model.

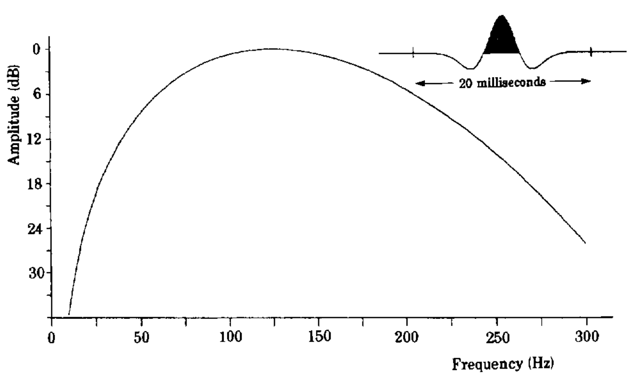

FIG. 1. Amplitude spectrum of 125-Hz Ricker wavelet and the wavelet displayed in time-domain.

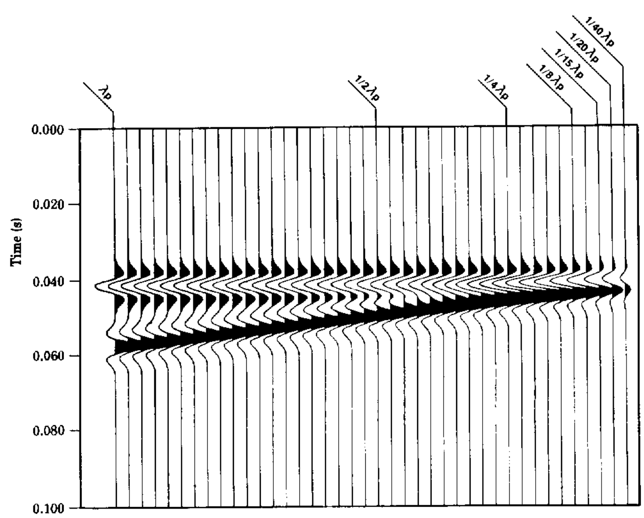

FIG. 3. Synthetic seismic section of wedge model using a 125-Hz Ricker wavelet.

be caused by lithological features other than just being DHI (direct hydrocarbon indicators). Depending on the thicknesses of the thin beds, their acoustic properties, and their relative location to other thin beds in space, tuning effects can result from interference reflections.

COMPUTER MODELING AND INTERPRETATION

A seismic survey line intersected four boreholes that revealed a dramatic change in seam elevation and structure. The average spacing between the boreholes is 400 ft (122 m). Figure 4 shows the density logs of all four boreholes, and the two coal seams are indicated. Boreholes A and B encountered seam thicknesses of 12.5 and 11 ft (3.8 and 3.65 m), respectively, at the normal seam elevation. The roll lies near borehole C where the I6 seam was found to be only 3 ft (1 m) thick and about 30 ft (9.14 m) higher than normal. Borehole D intersected a split in a thicker I6 seam also lying at a higher elevation than normal. The separation betwen the I6 and S5 coal seams beneath boreholes C and D was approximately 60 ft (18.3 m). The average thickness of the S5 seam is 4 ft (1.2 m).

Figure 5 is the seismic section from the survey line that crossed three of the boreholes. The borehole locations are indicated

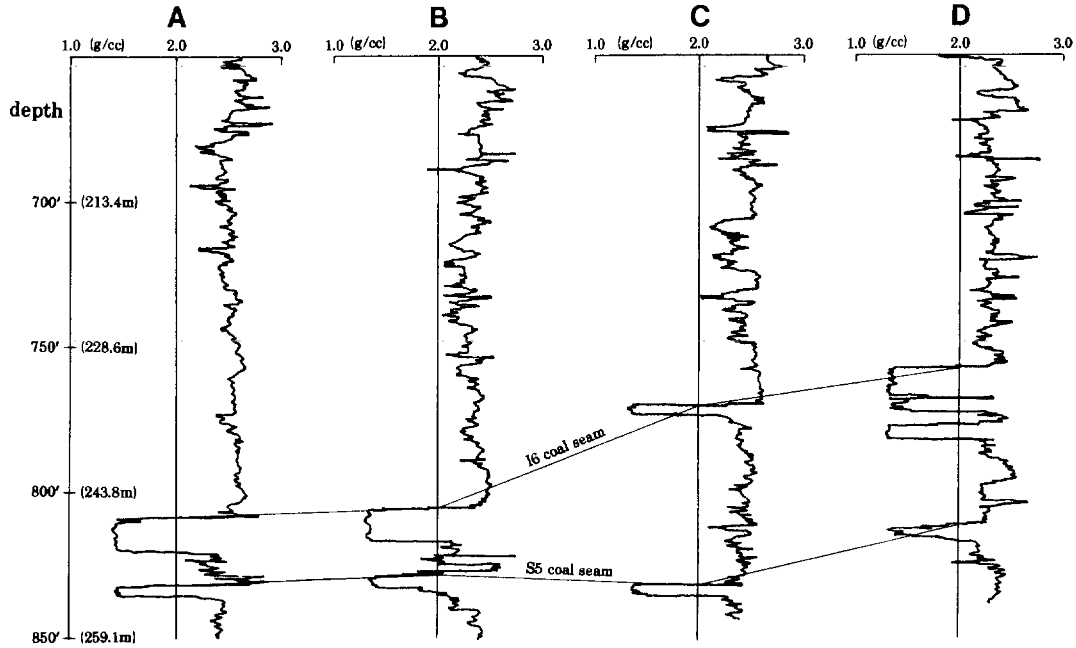

FIG. 4. Density logs of the four closely-spaced boreholes across the seismic survey line. Key reflectors are indicated.

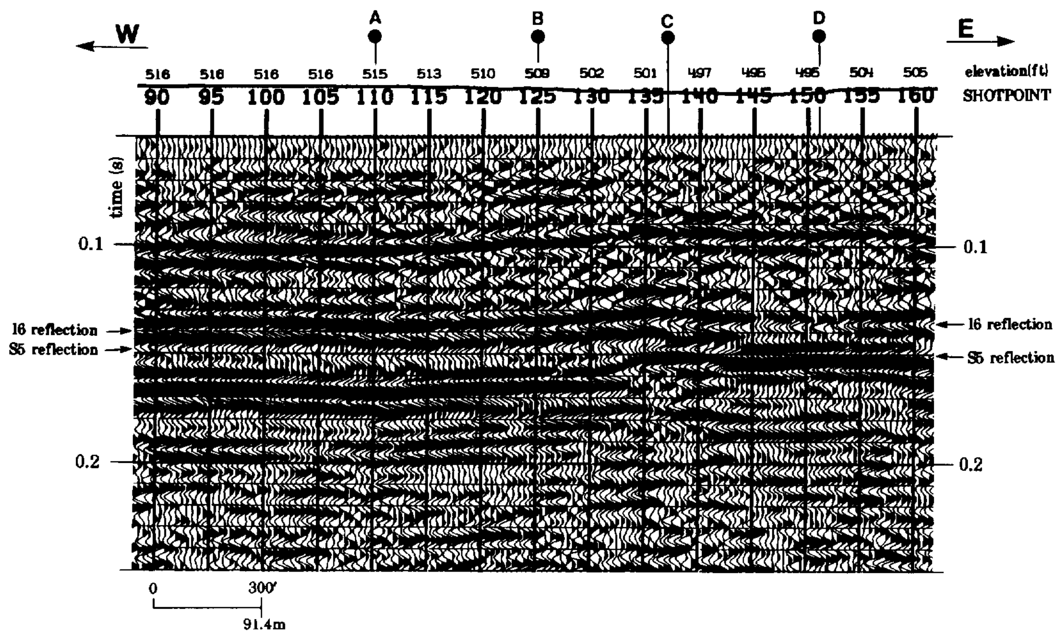

FIG. 5. Seismic section of survey line that intersected the four boreholes shown in Figure 4. Reflections associated with the I6 and S5 coal seams are indicated.

above the section. The reflections associated with the I6 and S5 coal seams determined from checkshot and sonic log information are also indicated on the section. The robust and continuous I6 reflection betwen SP-88 and SP-135 suggests uniform seam thickness of about 10 ft (3 m). Broadening of the seismic wavelet with a relatively smaller reflection amplitude centered at SP-138 indicated a potential seam anomaly as intersected by borehole C. A noticeable change in arrival time is evident between boreholes B and C. The doublet waveform beneath the I6 reflection between SP-145 to SP-160 suggests a thicker formation with

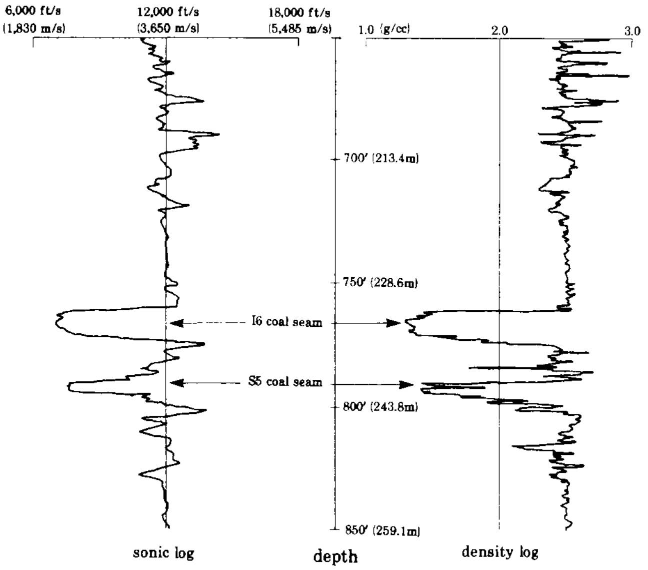

FIG. 6. Geophysical logs from a nearby borehole where acoustic parameters were extrapolated for the geological model. Key reflectors are indicated.

either small acoustic impedance contrasts or a sequence of thin beds. Borehole D is actually located 120 feet south from SP-151 and encountered a split in a 14-ft (4.3-m) seam.

The weaker S5 reflection is continuous from SP-88 to SP-130, indicating uniform seam thickness. The seismic signature remains fairly constant over the same interval suggesting that the roof and floor rocks did not change. However, a dramatic change in the S5 signature occurs from SP-131 to SP-143, indicating changing geological conditions between the I6 and S5 coal seams. Boreholes C and D showed that the interval between the I6 and S5 seams increased from the normal 25-ft (7.6-m) interval to as much as 60 ft (18.3 m). An amplitude anomaly in the reflection associated with the S5 coal seam was recorded from SP-135 to SP-161, even though nearby borehole data showed the S5 seam to average only 4 ft (1.2 m) in thickness. The seismic wavelet tunes to a dominant frequency of approximately 150 Hz, and the amplitude increases in magnitude by about a factor of two.

The forward modeling technique was used to study the seismic response from a sequence of thin beds. Acoustic parameters for the two-dimensional synthetic model were extrapolated from geophysical logs gathered in a nearby borehole (see Figure 6), and are presented in Table 1. The geological cross-section of Figure 7 was generated based on information from the four boreholes in Figure 4. The geological model was datum corrected using sea level as the reference datum. A 180-Hz Ricker wavelet

Table 1. Acoustic parameters used in modeling.

	Velocity (m/s)	Density (g/cc)	Acoustic Ratio (α_1/α_2)
Bituminous Coal	2500	1.35	—
Shale	3650	2.4	0.385
Sandy Shale	4265	2.5	0.317
Sandstone	4570	2.6	0.284
Limestone	4875	2.7	0.256

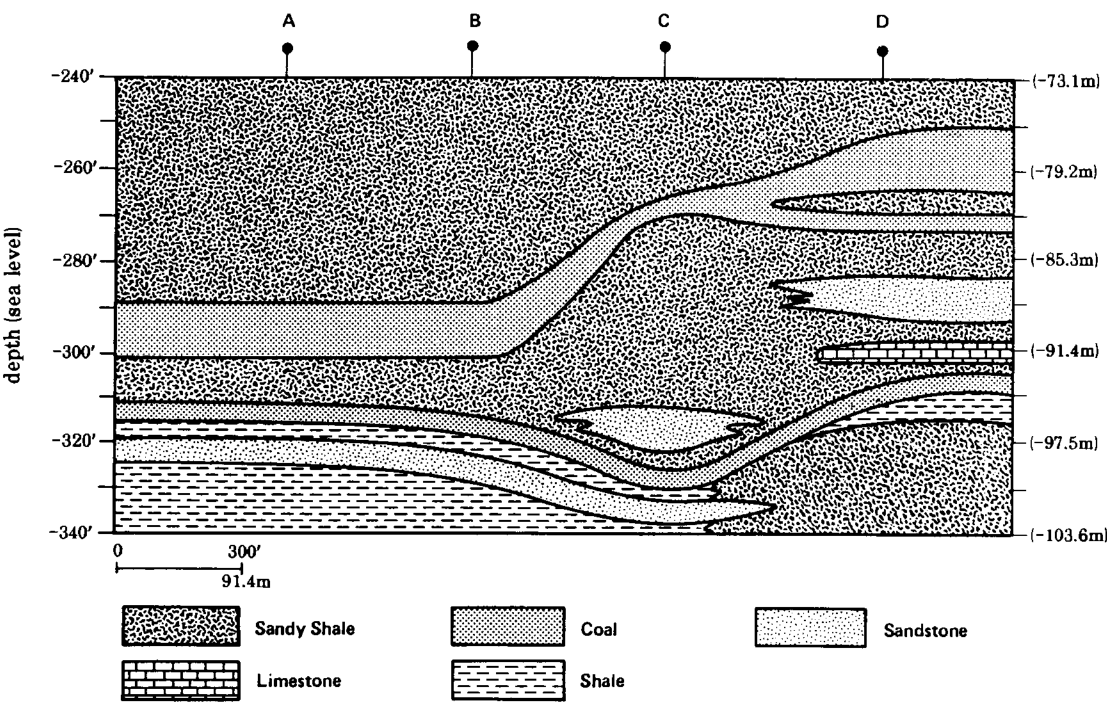

FIG. 7. Geologic cross-section based on information from the four closely-spaced boreholes.

convolved with the geological model was found to yield a synthetic seismic response that agreed best with the field data. Figure 8 is the synthetic seismic section of the geologic model with key reflectors indicated.

The I6 reflection is robust and continuous across the synthetic model. The thin coal area apparently did not cause a significant change in the reflection amplitude. The model shows a difference in arrival time of about 6 ms as a result of the 30-ft (9.14-m) roll while the seismic data showed a difference in arrival time of about 5 ms measured from trough-to-trough between boreholes B and C. The I6 reflection between SP-140 and SP-160 showed nearly identical seismic response from the normal and split coal seams suggesting that the frequency spectrum of the seismic data was not able to resolve the difference. Additional modeling studies showed that a 300-Hz Ricker wavelet would be required to resolve the main and lower benches of the split I6 coal seam beneath borehole D. The doublet waveform beneath the I6 reflection near borehole D of the model correlates with that observed on the field data associated with an interval of a sequence of thin sandstone, sandy shale, and limestone beds between the two coal seams.

The relatively smaller reflection amplitude associated with the S5 seam in the synthetic model correlates with the seismic data from SP-90 to SP-130. The model predicts a different seismic response for the roll beneath borehole C compared to the measured seismic data. The difference may be attributed to the fact that the seismic data probably recorded complex interference reflections. The S5 reflection beneath the anomalous structure and extending beyond borehole D is larger compared to the model results for the west side that correlates with the measured seismic data. The amplitude anomaly likely results from constructive interference reflections from intermediate thin beds, namely, the sandy shale and shale units near borehole D. The model predicts that the seismic wavelet tunes to a dominant frequency of approximately 160 Hz and the amplitude nearly doubles in magnitude. Near SP-160 of the seismic data, the difference in arrival time between the I6 and S5 reflections is approximately 10 to 12 ms, while the synthetic model showed a difference of about 10 ms measured from trough-to-trough.

Another coal company encountered the same roll while mining to the north and left a block of coal behind because of difficult mining conditions. Consol drilled two holes near the area and along the property line. One of the boreholes confirmed the location of this geological feature. Lithologic cross-sections of the two boreholes are presented in Figure 9. Borehole E shows typical normal seam thickness and elevation while borehole F encountered the geological anomaly. A seismic survey was then conducted near the property line to determine the seismic signature associated with the geological disturbance. The extraction of coal causes the roof rocks above the seam to shear and break. As a result of previous mine activity, the broken and sheared roof rocks subside and fill mine voids resulting in higher attenuation rates for the high frequencies of the seismic wavelet.

Figure 10 is the seismic section from that survey line. The locations of boreholes E and F are annotated on top of the seismic section. The disturbed roof rocks near the property line likely affected the seismic reflections because the central frequency spectrum of this data is less than the previous seismic data gathered from a survey line located 600 ft (183 m) south. From SP-80 to SP-115, the I6 reflection is robust and continuous indicating a uniform seam thickness of about 10 ft (3 m). The seismic section does not show a change in arrival time even though borehole F revealed a 30-ft (9.14-m) change in seam elevation. Borehole F also encountered a split in the I6 seam and showed similar lithology to borehole D. In this case, the seismic data did not show a change in arrival time associated with the roll. This may be due to velocity anomalies created by the broken and sheared roof rocks.

Since boreholes D and F showed nearly identical lithology, a synthetic seismic response of a similar geological model (Figure 7) near borehole F is presented in Figure 11. As a result of a lower central frequency spectrum, a 150-Hz Ricker wavelet was used and convolved with the geological model to yield a synthetic seismic section that agreed best with the field data near borehole F. There is a good correlation between the data and computer model of the I6 and S5 reflections and the apparent doublet waveform (peak) associated with a sequence of thin beds between the two coal seams, as seen from SP-97 to SP-111. However, this data set does not show a clearly defined doublet waveform compared to the previous seismic section.

The only reliable indicator of the detection of the roll in Figure 10, is the amplitude and frequency tuning effects from

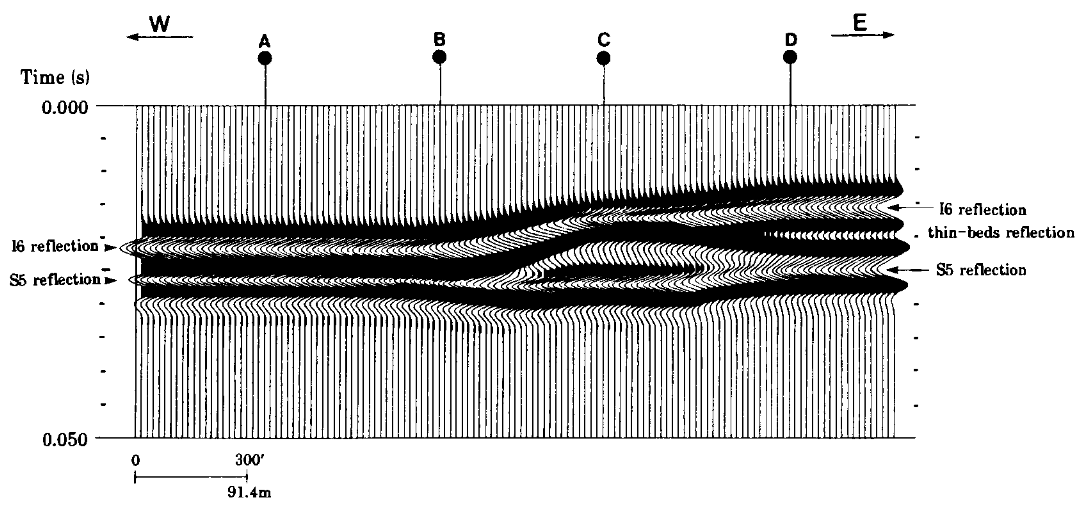

FIG. 8. Synthetic seismic section of geologic model using a 180-Hz Ricker wavelet.

interference reflections. From SP-87 to SP-111, the S5 reflection tunes to a dominant frequency of 110 Hz and the amplitude nearly doubled in magnitude over the same interval as a result of increased separation between the two seams. The estimated width of the geological disturbance measured from the seismic data is 720 ft (216 m). Figure 12 shows the complex trace attributes of Figure 10. Tuning effects resulting from interference reflections that were caused by a sequence of thin beds are highlighted in the instantaneous frequency and reflection strength attribute displays. The phase attribute display shows mostly a zero-phase data set with subtle changes over the anomalous area. This interval closely corresponds to the block of coal left behind by the other coal company because of difficult mining conditions. Therefore, the seismic data and computer models correlated and revealed the seismic signature of the roll.

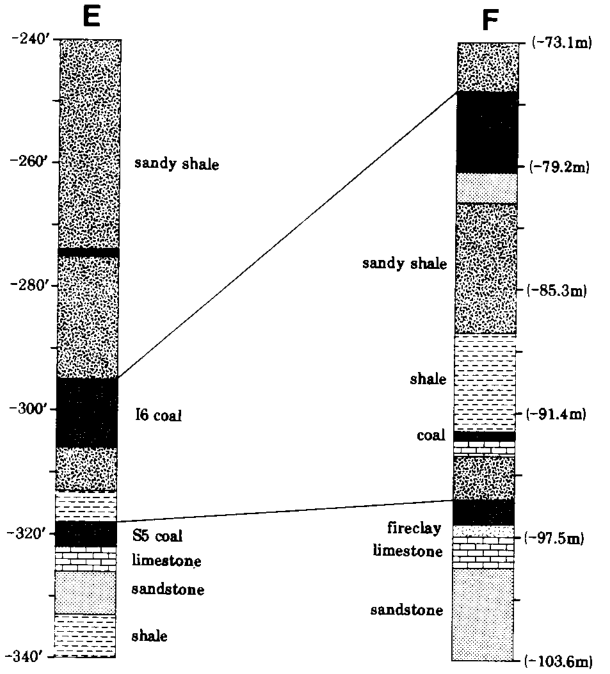

FIG. 9. Lithologic cross-sections of two boreholes drilled along the property line. Borehole E shows typical normal seam thickness and elevation.

CONCLUSIONS

The recording of amplitude and frequency tuning in the seismic wavelet is not only an indication of a thinning bed, but may also suggest the detection of a sequence of thin beds. Reflections from the thin beds can result in constructive or destructive interference depending on the traveltime delay of the wavelet. The thicknesses of thin beds, their acoustic properties, and their location relative to other thin beds in space can cause the seismic wavelet to tune to a specific frequency with a resultant increase in amplitude that can double in magnitude. In this case study, interference reflections recorded from the coal seam horizon provided the seismic signature associated with a seam anomaly called a "roll" that may create adverse longwall mining conditions. The availability of numerous borehole data and subsequent forward modeling technique enhanced the interpretation process.

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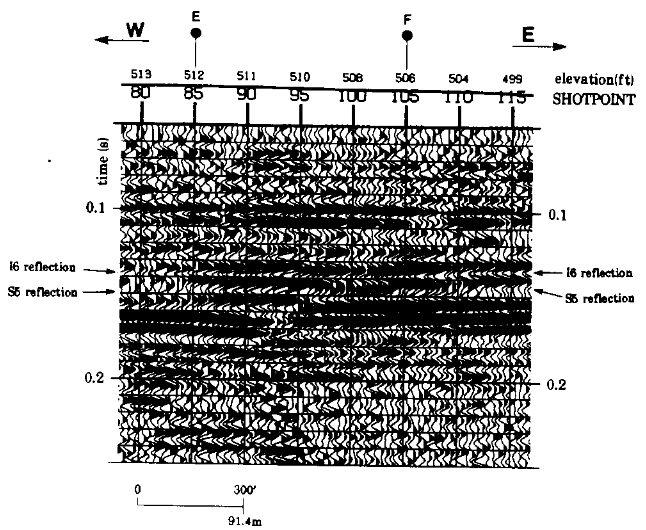

FIG. 10. Seismic section of survey line gathered near the property line. Reflections associated with the I6 and S5 coal seams are indicated.

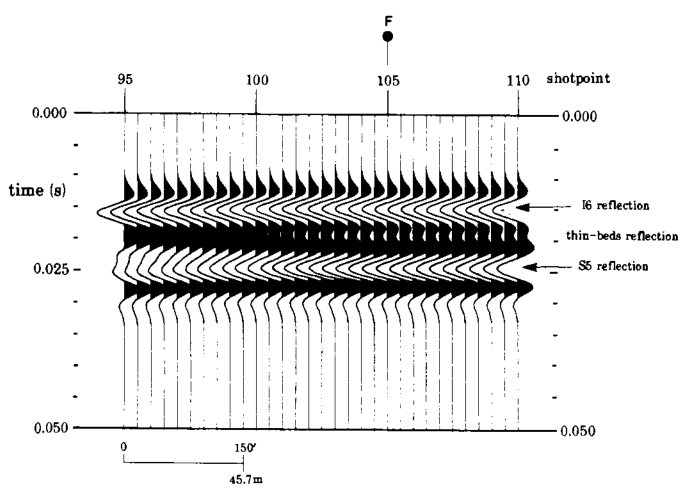

FIG. 11. Synthetic seismic section of geological model near borehole F using a 150-Hz Ricker wavelet.

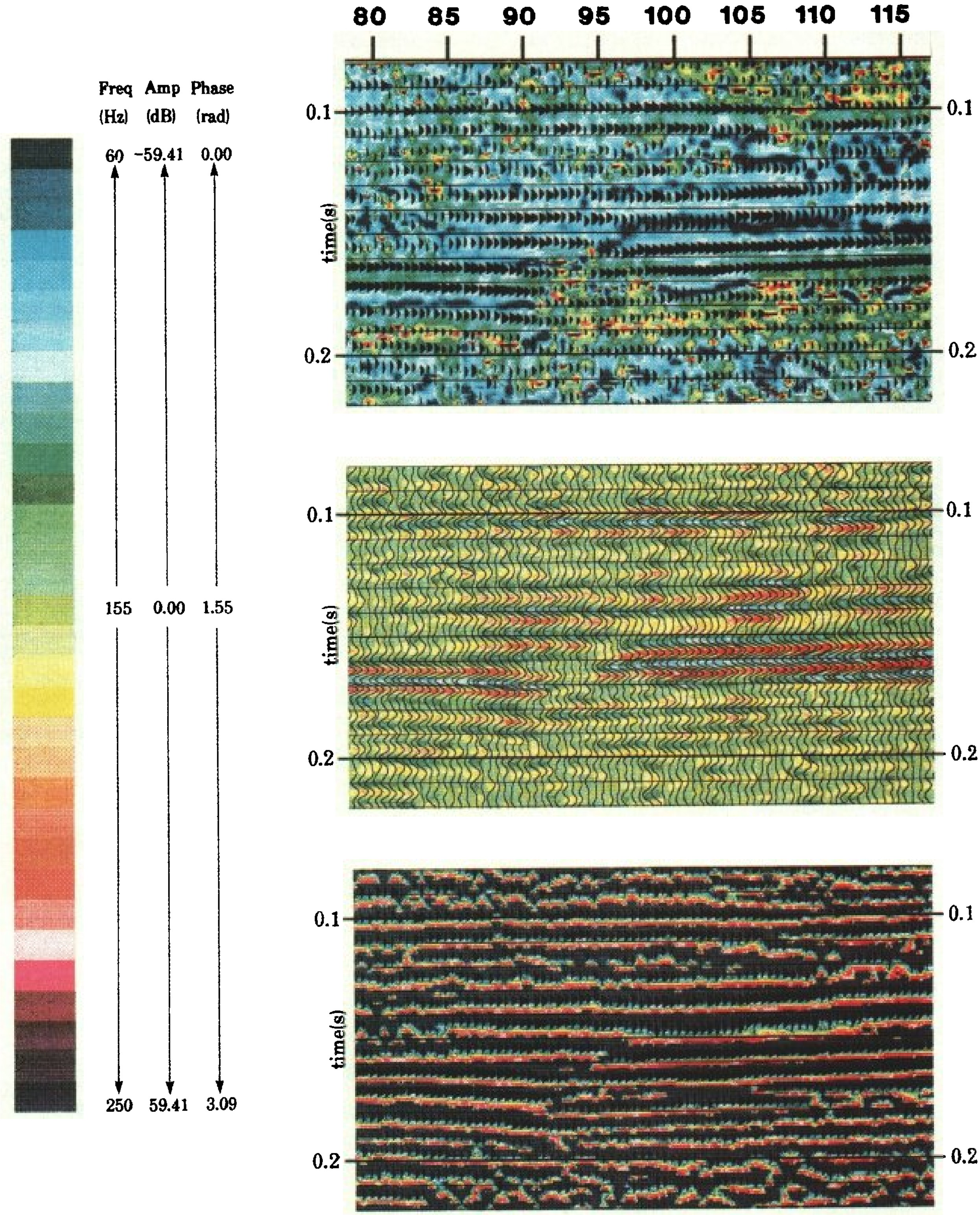

FIG. 12. Complex seismic trace attributes of Figure 10 highlighting the amplitude and frequency tuning effects.

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