High-resolution 3-D seismic survey over a coal mine reserve area in the U.S.—A case study

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ABSTRACT

A high-resolution three-dimensional (3-D) seismic survey was conducted in advance of coal mine development in the Illinois basin in May 1989 to better define a geologic structure with the potential to adversely affect longwall mining conditions. The 3-D seismic data indicate that an abrupt change in seam elevation, or roll, encountered near the northern property line trends south into the reserve area and then turns southeast. A personal computer-based workstation was used to integrate borehole and seismic data for modeling in which 3-D block diagrams of the calculated seam elevations were generated. The block diagrams show a steep slope on the west flank of the roll that gradually decreases as the roll turns to the southeast. The survey also reveals a geologic structure beneath the roll at an estimated depth of 46–62 m. Horizontal time-slice sections of this feature suggest the presence of a paleochannel that meanders on a similar course as the roll, which apparently was connected to a larger paleochannel system. A Conoco high-frequency vibroseis unit was successfully used as the seismic source to generate the high frequencies necessary to detect and resolve the thin coal beds.

INTRODUCTION

Longwall mining has become the lowest cost underground coal mining method because of its high productivity. Efficient longwall mines require large coal reserve areas which are relatively level and free of any significant geologic disturbances. Therefore, it is valuable to have reliable subsurface information prior to longwall panel development. Surface seismic reflection surveying can augment an exploration drilling program by providing continuous subsurface profiles between boreholes (Ziolkowski and Lerwill, 1979; Ruskey, 1981; Fairbairn et al., 1986; Greenhalgh et al., 1986; Lyatsky and Lawton, 1988; Gochioco and Cotten, 1989; Gochioco, 1991a; Henson and Sexton, 1991). Conventional two-dimensional (2-D) seismic surveys are normally conducted to evaluate seam continuity and to detect potential seam anomalies that may create adverse mining conditions. However, 2-D seismic surveying does not always provide an adequate image of the subsurface, and misinterpretations may result when geologic anomalies are small relative to spatial resolution, have unpredictable trends, or have complex structures. Three-dimensional (3-D) seismic surveys can enhance a conventional grid of 2-D survey lines by providing more concentrated data over a specific target for better imaging and mapping. Shallow 3-D seismic surveys applied to coal exploration have been previously conducted by Krey (1978), Bading (1986), and Lambourne et al. (1990).

A 3-D seismic survey was conducted at a CONSOL mine reserve in May 1989 as part of an exploration program to fully evaluate the reserve prior to longwall mining. Another coal mine north of the reserve area encountered an abrupt change in coal seam elevation, or roll (at the point marked X in Figure 1), as well as other geologic anomalies which forced that mine to leave behind several blocks of coal along the property line. Of more than 40 exploration holes drilled, a few boreholes within the reserve encountered inseam anomalies apparently associated with the roll, suggesting that this structure may exist in the CONSOL reserve, possibly connecting with a roll encountered underground in the West Mains (marked Y in Figure 1). The 3-D study was conducted in an area (shown in Figure 1) where a grid of 2-D seismic lines and borehole data suggest a rapid change in both seam elevation and structure orientation. The 3-D study area measured 293 × 512 m. Seven boreholes were located in the 3-D study area, and information from these holes was later used for control in the interpretation. In addition, checkshot surveys also were conducted in several open boreholes prior to the 3-D survey, and numerous geophysical logs (sonic and density) were gathered for subsequent modeling studies.
GEOLOGIC SETTING

The coal seam of interest in the study area is the Illinois No. 6 (Herrin) seam. The average seam thickness is 3 m, and the overburden depth ranges from about 229 to 244 m. A thick wedge of nonmarine shale immediately overlies the coal seam. The shale is interpreted as a crevasse-splay deposit originating from a major paleofluvial system which existed at the time of peat accumulation. Splay deposits form when a river’s natural levees are breached by seasonal flooding or by a regional rise in sea level. The flooding results in a wedge of clastic sediments which are deposited in the river’s flood plain or, in this case, the peat swamp. A major paleochannel system delineates the western limit of possible mining in the reserve block. At this limit, the coal seam is completely or partially replaced by sandstones, siltstones, conglomerates, interbedded sandstones, or shales. The paleochannel and its associated tributaries are also responsible for a variety of other geologic anomalies that may adversely affect the mining of coal in the reserve area (Nelson, 1983).

Another coal seam, identified as the Illinois No. 5 (Springfield) seam, has an average seam thickness of 1.2 m and lies on a nearly horizontal plane beneath the No. 6 seam. The average interval between the No. 6 and No. 5 seams ranges from 4 to 7.6 m. However, several borboles in the reserve area revealed the elevation of the No. 6 seam to be as much as 9.1 m higher than expected. This abrupt change in seam elevation suggests that the No. 6 seam was deposited over an infill channel or thicker lens of sandstone rock that, upon vertical compaction, produced locally steep dips which may have abruptly thinned the coal seam, thus impeding longwall mining. Figure 2 shows a geologic cross section of the roll encountered by drilling and confirmed in a nearby underground coal mine located to the north (Nelson, 1983).

FIELD ACQUISITION AND DATA PROCESSING

The survey employed a total of 33 closely-spaced parallel seismic lines. Seismic line 1, the northernmost survey line, was oriented west to east. The remaining 32 survey lines were placed at 9.1-m intervals toward the south. A Conoco prototype high-frequency vibroseis (Chapman et al., 1981; Gochioco, 1991a), built in 1974, was used as the seismic source. A MDS-15 seismograph system was used to record and store the data on magnetic tapes. The survey used 24-channel recording and employed a source-receiver interval of 9.1 m, resulting in a maximum stacking fold of 12. Single high-frequency 100-Hz geophones were used as receivers. Table 1 shows additional field acquisition parameters used in this survey.

CONSOL and Conoco had already established a working relationship by 1986 in which CONSOL has been using Conoco’s software programs to process its high-resolution seismic data through a computer network linking the two research centers. Field tapes were then sent to Conoco’s data processing center in Ponca City, Oklahoma. Conoco technicians assisted in data preparation such as tape handling, demultiplexing, and vibroseis correlation. Thereafter, the reformatted seismic data files were then processed accordingly from Library, Pennsylvania, where job files were executed and plot files received. Careful editing of seismic traces and application of velocity filters were employed to improve the signal-to-noise ratio. Table 2 shows the general processing sequence flow used to process the high-resolution 3-D seismic data.

COMPUTER MODELING

In February 1987, CONSOL acquired and developed a PC-based seismic interactive interpretation workstation that can be used to integrate various geological and geophysical data sets in order to generate reliable computer models (Gochioco, 1991b). Sonic and density logs in an analog format were digitized and stored in the database. Log data were used to develop reflectivity models near the drillhole locations. Synthetic seismograms generated from geophysical logs were then used to determine the seismic response associated with the No. 6 and No. 5 coal seams. Figure 3 shows the digitized density and sonic logs collected from borehole No. 87196 in the study area, which encountered normal seam thickness and elevation for the two coal seams. A 150-Hz Ricker wavelet having a frequency spectrum similar to the recorded wavefield was then convolved with the reflectivity sequence to generate the desired synthetic seismogram. The results indicate the anticipated seismic response in normal polarity for the two coal seams.

In a previous paper (Gochioco, 1992), the same seismic and borehole data sets located in the 3-D study area were modeled to demonstrate the phenomena of interference reflections from coal seams and thin bed cyclothems. In this paper, a simple 2-D model is presented. Figure 4a shows a 2-D geologic model with the two coal seams bounded by a massive sandy shale unit. Acoustic properties of these two rock types were obtained from

**FIG. 1.** Map of coal reserve area showing grid of 2-D seismic survey lines and location of 3-D survey conducted.
log data and are noted in the figure. The exploration drilling program revealed the No. 5 seam lies on a nearly horizontal plane in the reserve area. To simulate increasing seam separation, the No. 6 seam was inclined at an angle of 5° while seam thicknesses of both coals were kept constant. The interval between the tops of the two coal seams gradually increases over a horizontal distance of 137 m from the average observed value of 6 m on the left side of the model to a maximum of 18.3 m on the right. Figure 4b shows the synthetic seismic response of the model after convolution with a 150-Hz Ricker wavelet.

Table 1. Data acquisition parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Seismic source</td>
<td>Conoco prototype high-frequency Vibroseis</td>
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<tr>
<td>Maximum peak force</td>
<td>33,000 lb</td>
</tr>
<tr>
<td>Electronics</td>
<td>Pelton No. 5</td>
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<tr>
<td>Frequency range</td>
<td>60–250 Hz, nonlinear sweep</td>
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<td>Recording system</td>
<td>Geophone MDS-15</td>
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<td>Sample rate</td>
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<td>Record length</td>
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<tr>
<td>Sweep length</td>
<td>15 s</td>
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<tr>
<td>Number of channels</td>
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<tr>
<td>Receiver</td>
<td>Single 100-Hz geophone</td>
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<tr>
<td>Source-receiver interval</td>
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<tr>
<td>Maximum fold</td>
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<tr>
<td>Near offset</td>
<td>55 m</td>
</tr>
<tr>
<td>Far offset</td>
<td>265 m</td>
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</table>

Table 2. Seismic data processing sequence.

- Vibroseis correlation
- Apply geometry to header
- Edit field records
- Bandpass filter and trace expansion/gain
- FK velocity/dip filter
- Deconvolution
- Velocity analysis (1)
- CDP stack
- Statics (1)
- Velocity analysis (2)
- Statics (2)
- Bandpass filter and trace expansion/gain
- Final CDP stack
- 3-D FK migration

Fig. 3. Digitized sonic and density logs from a borehole showing normal seam thickness and elevations for the No. 6 and No. 5 coals. The synthetic seismogram was generated after convolving the reflectivity sequence with a 150-Hz Ricker wavelet.
The seismic traces in Figure 4b are 9.1 m apart. In the case of the average 6 m interval between the two coal seams, the model shows normal wavelet characteristics in the No. 6 and No. 5 reflections, similar to results from the synthetic seismogram in Figure 3. However, as the seam separation increases, corresponding amplitude anomalies are observed in the No. 5 reflection. This wavelet character is the seismic signature of the roll and it proved to be a more reliable indicator than a change in arrival time for the No. 6 reflection. The amplitude anomalies result from constructive interference of overlapping primary reflections from the coal seams and thin-bed interfaces (Gochioco, 1992).

RESULTS AND INTERPRETATION

Figure 5 shows seismic sections from lines 4, 12, 20, and 28. The four parallel seismic sections, spaced 73 m apart, provide a good perspective view of the structure of the roll as well as the rapid change in its trend. The robust reflection at 0.1 s was associated with a major limestone-shale interface which is dominant in the area. Based on checkshot and sonic log information, reflections associated with the No. 6 and No. 5 coal seams were estimated to arrive between 0.135 and 0.145 s, and are noted in the figures. Another structure, referred to here as an anomalous geologic structure (AGS), was identified by the large reflection amplitude (blue) beneath the two coal seams. The AGS will be discussed later in the text.

The seismic data gathered beneath line 4 show a temporal relief of about 4 ms for the No. 6 reflection (yellow) with the apex centered at shotpoint (SP) 25. An amplitude anomaly in the No. 5 reflection is also evident between SP-18 and SP-33, indicating an increased separation between the two seams associated with the roll. The 137-m width of this interval closely corresponds to the width of the block of coal left behind along the property line. This observation also suggests the anomalous roll trends south from the property line toward the northern section of the study area. The processed data from lines 12, 20, and 28 shows that the western slope of the roll gradually tapers off. Considering reflection amplitude, the primary reflection associated with the No. 6 seam may be altered by destructive interference from other overlapping primary reflections and, possibly, intrabed multiples, which caused temporal relief to be an unreliable indicator of the roll. However, as a result of the increased separation between the two coal seams, the No. 5 reflection encountered mostly constructive interference creating an amplitude anomaly. This phenomenon is present in all four seismic sections, and the estimated centers of the amplitude anomalies from lines 12, 20, and 28 are located near SP-29, SP-41, and SP-50, respectively. This interpretation of the seismic data suggests the roll feature remains the same and turns sharply southeast, meandering outside the study area near line 28.
Since the end users of the 3-D seismic data are mine engineers and geologists with minimal seismic experience, a 3-D block diagram showing the calculated seam elevations is presented to highlight the roll rather than time-slice sections. In order to generate a seam elevation map of the No. 6 seam in the study area, the No. 5 seam was mapped on a horizontal plane. Velocity and drill hole information coupled with results of the amplitude modeling studies of Figure 4, were used to calculate the estimated bottom seam elevations of the No. 6 coal from seismic traces in all 33 survey lines. A 3-D block diagram (Figure 6) was then generated to illustrate the structure of the roll. The locations of seven drill holes are also shown. The block diagram provided a perspective view of the roll from the southeast direction. A vertical exaggeration of 4:1 was used to highlight the rapid change in seam elevation. The model shows that the roll strikes south from the property line and that it has a steep slope on its western flank which could pose difficult longwall mining conditions. However, the slope is predicted to gradually decrease to the southeast. The east side of the roll apparently levels off at a higher seam elevation than on the west.

As mentioned earlier, the strong reflection arriving between 0.150 and 0.170 s, identified as AGS in Figure 5, was recorded beneath the two coal seam reflections. Based on interval velocity information derived from stacking velocities, the AGS is estimated to lie from 46 to 62 m beneath the No. 6 seam. The seismic sections of lines 4 and 12 (see Figure 5) indicate a possible vertical displacement or fault. The two subsequent seismic sections (lines 20 and 28) suggest the anomaly gradually decreases in magnitude and appears to mend itself as it turned to the southeast.

Initially, no information was available from CONSOL’s drilling program about the AGS since the holes in the reserve area penetrated no deeper than 1–2 m below the No. 5 seam. However, the Illinois State Geological Survey documented observations from dozens of deeper core holes drilled in the region in petroleum exploration (Brownfield, 1954). A chart taken from Nelson (1983) is presented in Figure 7 showing the various rock groups developed from core samples, electric logs, and density logs. The No. 5 and No. 6 coal seams belong to the Pennsylvanian Carbondale formation, as indicated on the chart. Using the vertical scale on the chart and the calculated depth of this structure beneath the No. 6 seam, the AGS corresponds to a massive sandstone-shale unit on the upper sequence of the Pennsylvanian Caseyville-Tradewater formation. The presence of the No. 2 seam located above this formation likely enhanced the acoustic impedance contrasts between rock layers creating larger than normal reflection amplitudes.
Therefore, the AGS reflection may also signify the geologic boundary of these two different rock groups.

Six horizontal time-slice sections ranging from 0.161 to 0.166 s are presented in Figure 8. These time-slice sections reveal the structure of the main bench of the AGS, and the results show the signature of a small paleochannel, which meanders on a similar course as the roll, beneath the study area and connected to a larger channel system located in the southwest corner. Seismic detection of two different Pennsylvanian channels, one on top of another and having the same trend, supports some earlier research studies conducted by Illinois State Geological Survey geologists (Nelson, 1983).

Since paleochannels are widespread in this region and some can have serious effects on coal mining, detecting and mapping these geologic anomalies could minimize underground mining problems. In this case, experience proved that the roll can pose difficult longwall mining conditions in the No. 6 seam. Based on information provided by underground mining, as well as seismic and drill hole data, Figure 9 shows the interpreted trend of the serious effects of the roll feature as it meanders across the reserve block and connects with the roll encountered in the West Mains. This is consistent with the trends defined by the 3-D seismic survey. Due, in part, to the data provided by the seismic survey, this reserve block was developed with caution and mine development was adjusted accordingly. Panel lengths were terminated at steep slopes encountered during development. Since the roll was less severe near the West Mains, panel E was completely developed along its entire initial proposed length. Panel lengths were shortened for panels F and G, which extend up to only the western flank of the roll because of steep slope encounters of as much as 15° to 20°. The fourth proposed panel, north of panel G, was eventually eliminated because the anticipated anomaly encounter would have made the panel too short to be mined economically. With a revised mine plan, mining of the reserve block was completed in 1995 with minimal difficulty.
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**CONCLUSIONS**

When unexpected anomalous geologic encounters occur that causes a longwall mine to be inoperative for days or weeks, it is estimated that they can cost a coal company up to $1 million/day of lost productivity. Most coal companies do not have deep financial resources to weather such extended downtime. Thus, it is imperative that coal companies gather subsurface information that may spawn similar anomalies. When surface seismic surveys are used in conjunction with drilling, subsurface geological information can assist mine engineers in developing optimal mine plans. In particular, when geological features that could impact longwall mining are narrow and have unpredictable trends, 3-D seismic surveys can be a valuable tool to further enhance coal exploration programs, as demonstrated in this case. Most of the geological anomalies encountered in the study region are channel-like features developed while the coal-forming peat accumulated in vast tropical swamps during the Pennsylvanian. Some Pennsylvanian channels already existed as the peat was accumulating in vast tropical swamps during the Pennsylvanian. Some Pennsylvanian channels already existed as the peat was accumulating in vast tropical swamps during the Pennsylvanian. Some Pennsylvanian channels already existed as the peat was accumulating in vast tropical swamps during the Pennsylvanian. Some Pennsylvanian channels already existed as the peat was accumulating in vast tropical swamps during the Pennsylvanian

A PC-based geoscience workstation was useful in integrating geological and geophysical data sets for crosscorrelating and generating computer models to enhance the interpretation process. In this instance, the 3-D block diagrams provided a perspective view of the calculated base elevation of the target coal seam to show a detailed representation of the roll. This information assisted mine personnel in determining the feasibility of longwall mining in this area. Eventually, the anomaly was confirmed and encountered at the predicted location during development and panel lengths were shortened appropriately. In addition, Conoco’s prototype high-frequency vibroseis demonstrated that a system such as this can be used as a seismic source for shallow high-resolution surface seismic surveys.

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**REFERENCES**


