High-resolution 3D surface seismic method and former coal geophysics program of a US coal company

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Introduction

One of the best kept technology secrets in US coal mining history was that there was once a robust coal geophysics program that was fully utilized by a local coal company to detect and map various geologic anomalies and man-made structures ahead of mining. Several original mine plans were changed as a result of findings from seismic data that indicated the presence of geologic anomalies in reserve areas that could adversely impact future mine development and longwall production. By combining the surface seismic and exploratory drilling methods, the coal company was able to properly leverage its risk by gathering a lot of useful subsurface information ahead of mine development.

By the middle of the 1970s oil crises, most US major oil companies acquired local coal companies as part of their business strategy in expanding their hydrocarbon reserve base. Companies like Exxon, Shell, Chevron, Conoco, Arco, Occidental, etc. were also in the coal business. Attempts were made by most of them to test the application of oil field technologies to coal mining operations in order to improve the safety and productivity of their mines. Out of this group of companies, the Conoco-CONSOL partnership was considered to be the most successful in advancing the development of coal geophysics.

From 1985 and 2000, I developed and directed CONSOL's multi-faceted coal geophysics program used to address various exploration, engineering, and environmental challenges. When all the former Conoco executives at CONSOL retired, the coal geophysics program became a victim of a reorganization plan in 2000 under the new management. With no geophysical technology in place, CONSOL stepped back to its old traditional drilling method of evaluating reserves, and with great hope (and luck) that drilling would be able to detect geologic and man-made anomalies.

Coal Geophysics Program

CONSOL's coal geophysics program was developed and employed to address a variety of challenges related to mining operations (i.e. exploration, engineering, and environmental). As such, various geophysical methods were tested. Table 1 shows the list of geophysical capabilities CONSOL had during the time period of between 1985 and 2000.

Table 1

Geophysical Methods Employed at CONSOL (1985-2000)
• High-resolution surface seismic reflection and refraction
• Borehole geophysics: logging, VSP, & tomography
• Underground inseam seismic
• Borehole camera
• Ground probing radar
• Ground conductivity
• Electrical resistivity
• Magnetometer

Among the geophysical capabilities listed above, the surface seismic method was the most utilized because it was site specific and provided reconnaissance surveying capabilities to provide a lot of useful subsurface information. The surface seismic method had been successful in detecting geologic anomalies ahead of mining, such as faults (Gochioco and Cotton, 1989), washouts (Gochioco and Kelly, 1990), rolls (Gochioco, 2000), and old (and flooded) mine workings. When mine engineers felt uncertain or uneasy of underexplored areas, seismic imaging provided additional insurance that no detectable major geologic anomalies would adversely affect near-future longwall production and mining of unmined reserve areas (Gochioco, 1990, 1991c, 1994, 1998, 2000, and 2002a). The main reason why the seismic program was very successful was because leading edge technologies adopted from the oil industry were properly modified to suit the boundary conditions of shallow and thin-layer targets (Gochioco, 1991a, 1992, 1998, and 2000).

Non-seismic geophysical methods employed at CONSOL were usually used to address engineering and environmental issues at mine sites and properties. Due to the highly sensitive nature of these projects, management did not want to release the data to the public in the form of abstracts or papers. However, reports related to these successful projects were written and archived. The borehole camera method was the only non-seismic geophysical method published since it was a non-proprietary technology (Gochioco et. al., 2002). It is a simple system that provided invaluable benefits to the coal company.

Since the assigned topic of my presentation is supposed to be on the surface seismic method, I shall discuss in detail some of the specifics. For example, various seismic sources were available to address a variety of different field conditions and targets. These varied source capabilities were unprecedented because no other company, institution, or research center in the world had this resource base. By adopting the most advanced seismic technologies from the petroleum industry, US coal geophysics was the international technology leader from the mid-1980s to the mid-1990s. For example, the seismic interactive interpretation workstation was first introduced and deployed to coal mining applications to facilitate the interpretation process (Gochioco, 1989). Table 2 shows the various seismic sources with its accompanying objectives.

Table 2

SEISMIC SOURCES
• High-frequency Vibroseis
• 8-gauge buffalo gun
• 12-gauge shotgun
• Elastic wave generator
• Sledge hammer
PROGRAMS & OBJECTIVES
• Exploration
• Engineering
• Environmental
COAL SEAM THICKNESS
• 0 – 10 feet
TARGET DEPTHS
• Near-surface to 2,200 feet

3D surface seismic – a case study

Actual seismic data showing detection of washouts or mine voids will not be presented because the data were never released by CONSOL. Mine voids in the Appalachian coalfields are predominantly located at shallow depths of < 500 ft. The absence of coal (even when flooded) would result in very weak recorded reflections from the coal seam horizon. The phase, frequency, and amplitude attributes of the wavelet change as a result of this anomaly. Thus, a properly designed surface seismic program to detect mine voids is not difficult to execute.

Instead, a 3D seismic case study conducted in 1989 to detect and map a more difficult and complex geologic anomaly (roll) is presented to demonstrate the ability of this useful geophysical method to detect such challenging subsurface targets (Gochioco, 2000). The 3D survey was conducted as part of an exploration program to fully evaluate the reserve block prior to longwall mining. Another coal mine to the north of the reserve area encountered an abrupt change in seam elevation, or roll (as shown in Figure 1, marked X), 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 likely existed in the reserve block, possibly connecting with a roll encountered underground in the West Mains (marked Y in Figure 1). At the time of the survey, longwall mining of Panel A was nearly completed and Panel B would be next. Thus, there was about a three-to four-year lead time to gather and interpret the data.

The 3D survey was conducted in an area where a grid of 2D seismic lines had been conducted. Seismic and borehole data suggested a rapid change in both seam elevation and structure. The study area measured 293m x 512m. Seven boreholes were located in the 3D study area, and information from these holes were later used as control in interpretation. In addition, checkshot surveys were also conducted in several open holes and numerous geophysical logs (sonic and density) were gathered for subsequent computer modeling.

GEOLOGIC SETTING

The coal seam of interest is the Illinois No. 6 (Herrin) seam. The average seam thickness is 3 m, and the overburden depth ranges from about 229 to 244m. A thick wedge of non-marine 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, a 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, and/or shales.

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 4.0 to 7.6 m. However, several boreholes in the reserve revealed the elevation of the No. 6 to be as much as 9.1 m higher than normal. This abrupt change in seam elevation suggests that the No. 6 seam was deposited over an infill channel or thicker lens of hard sandstone rock that upon vertical compaction produced locally steep dips that could potentially impede longwall mining. Figure 2 shows a geologic cross section of the roll.

COMPUTER MODELING

In February 1987, a PC-based seismic interactive interpretation workstation was acquired and enhanced to integrate various geological and geophysical data sets in order to generate reliable computer models (Gochioco, 1991a). Sonic and density logs in analog format were digitized and stored in the database. Synthetic seismograms generated from geophysical logs were then used to determine the seismic response and signature associated with the Nos. 6 and 5 coal seams. More detailed and extensive modeling to image this complex geologic anomaly can be studied more thoroughly in two previous publications (Gochioco, 1991b and 1992).

In this paper, a simple 2D model is presented to illustrate the uniqueness of interpreting the signature associated with this roll. Figure 2a shows the 2D geologic model with the two coal seams bounded by a massive sandy shale unit. Acoustic properties of these two rock types were obtained from log data and are noted in the figure. The exploration drilling program revealed the No. 5 seam lies on a nearly horizontal plane. To simulate increasing seam separation, the No. 6 seam was inclined at an angle of 5° while the seam thicknesses 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 vertical separation of 18.3 m on the right. Figure 2b shows the synthetic seismic response of the model after convolution with a 150-Hz Ricker wavelet.

The synthetic traces in Figure 2b are 9.1 m apart. In the case of the average 6 m separation interval between the two coal seams, the model shows normal wavelet characteristics in the Nos. 6 and 5 reflections. However, as the seam separation increases, corresponding anomalous amplitude responses are observed in the No.5 reflection. This wavelet character is identified as 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 and multiple reflections from the coal seams and thin-bed interfaces (Gochioco, 1992).

RESULTS & INTERPRETATION

Inside the 3D survey grid area (293 m x 512 m), a total of 33 closely-spaced seismic lines are located. Figure 3 shows the seismic sections of Lines 4 (north), 12, 20, and 28 (south). The four parallel 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 logs data, reflections associated with the two coal seams were estimated to arrive between 0.135 and 0.145 s, and are noted in the figures.

The seismic data gathered beneath Line 4 show a small temporal relief of about 4 ms for the No. 6 reflection (in yellow) with the apex centered near 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 anomaly closely corresponded to the width of the block of coal left behind along the property line. This observation also suggests the roll trends south from the property line toward the northern section of the 3D study area.

The seismic sections of Lines 12, 20, and 28 shows the western slope of the roll gradually tapers off. Lateral velocity variations above the roll may have flattened the No. 6 reflection. However, because of the increased separation, the No. 5 reflection recorded mostly constructive interference reflections, resulting in amplitude anomalies. 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. Interpretation of the 3D seismic data suggests the roll feature initially meandered south into CONSOL's property from the property line and turned sharply southeast trending outside the study area near Line 28.

Since the end users of the 3D seismic data are mine engineers and geologists with minimal geophysical background, a 3D block diagram showing the calculated seam elevations is presented in Figure 4 to highlight the roll. The locations of seven boreholes are also shown. The 3D block diagram provided a perspective view of the roll from the southeast corner. A vertical exaggeration of 4:1 was applied to highlight the rapid change in seam elevation, as shown in Figure 5. The model shows the roll strikes south from the property line and has a steep slope on its western flank which could pose difficult longwall mining conditions. However, the slope is predicted to decrease as it headed in the southeast direction. The east side of the roll apparently levels off to a higher elevation plane than on the west and connects to the roll feature encountered in the West Mains.

Conclusion

Since the seismic program was conducted a few years in advance of mine development, the unpleasant news permitted CONSOL to make appropriate adjustments to the original mine plans and development schedules. Since the roll was less severe near the West Mains, Panel E was developed and mined as originally planned. Mining started from the east and headed towards the west. Panel lengths for F and G were shortened and extended up to only the western flank of the roll (see Figure 6). The initial proposed 4th panel (Panel H) was eliminated because of adverse geologic conditions and the panel would have been too short to be mined economically. The success of this major endeavor yielded tremendous financial benefits to CONSOL.

The 3D seismic case study presented in this talk was based on 1980s technology. By adopting current hardware and software seismic imaging technologies being employed in the petroleum industry (Gochioco, 2002a, 2002b), I expect major improvements of an order of magnitude better than the data presented here. Therefore, the surface seismic method is one several geophysical technologies that can be used to detect mine voids, *as long as the geophysicist has the necessary skills and required expertise to conduct such challenging surveys.*

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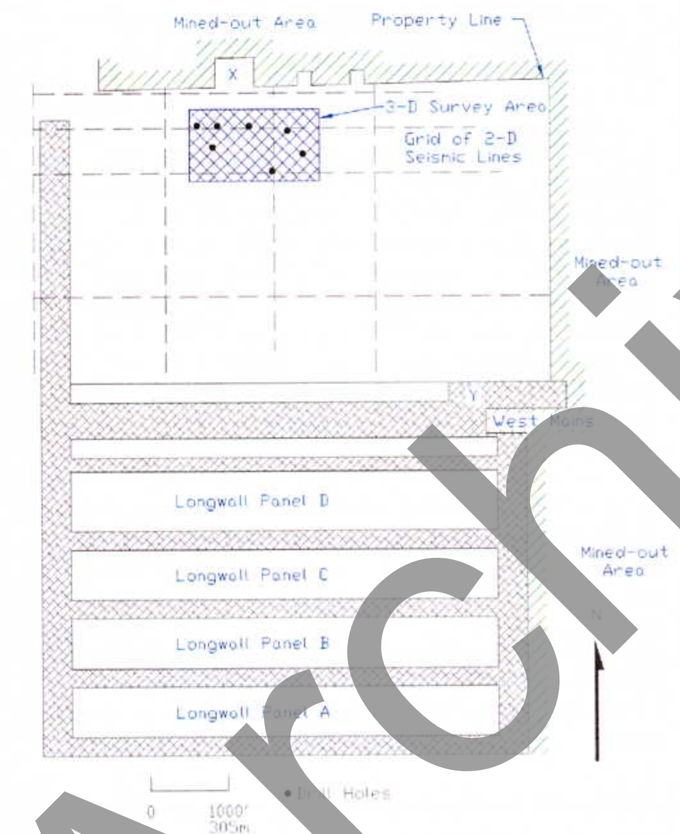

FIG. 1. Map of coal reserve area showing grid of 2-D seismic survey lines and location of 3-D survey conducted.

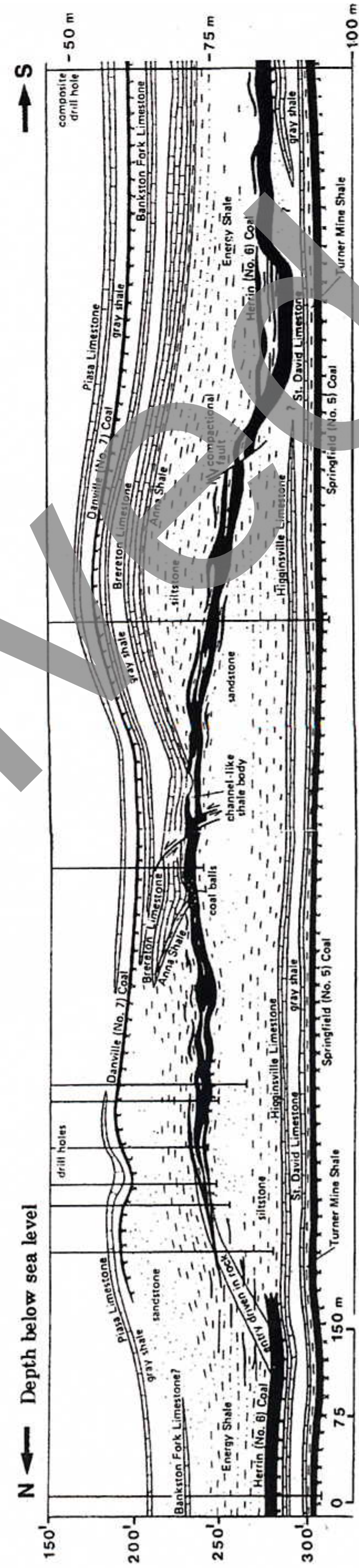

FIG. 2. Geologic cross section of a roll encountered in a nearby mine

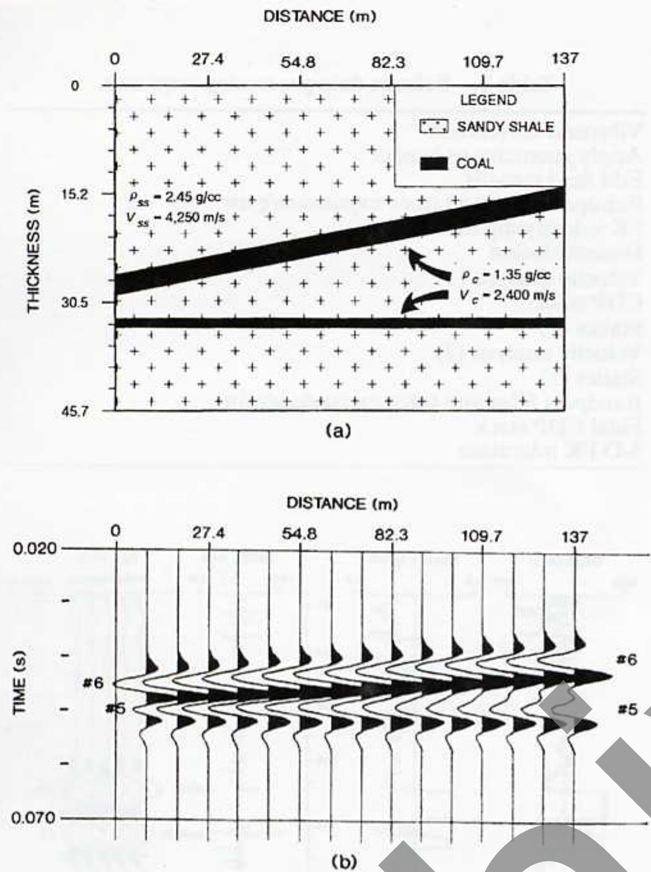

FIG. 3. A 2-D geologic model (a) for simulating increasing spatial interval between the two coal seams. After convolution with a 150-Hz Ricker wavelet, the synthetic seismic response of the model (b) highlights the effects of seam separation, creating amplitude anomalies in the No. 5 coal seam reflection.

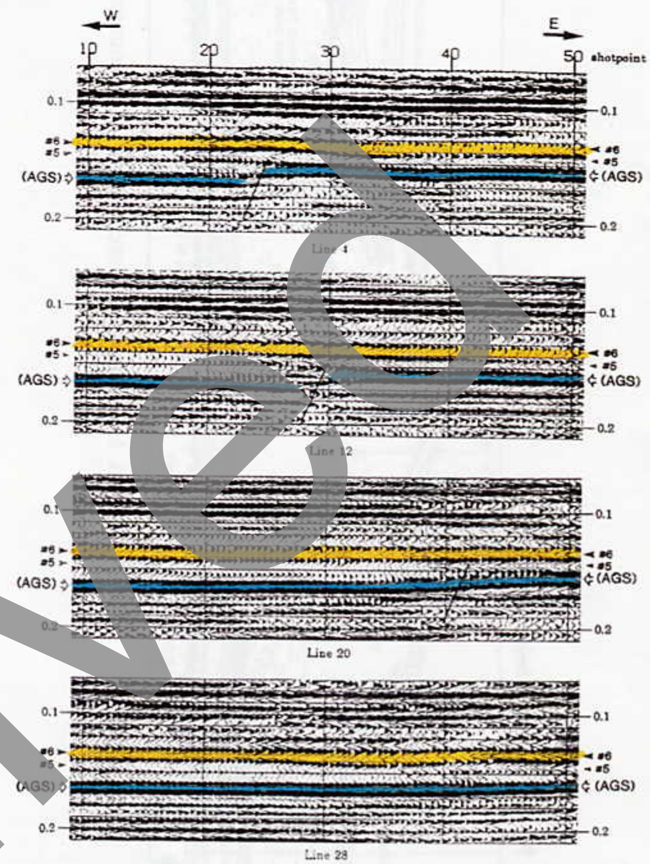

FIG. 4. Seismic sections of lines 4, 12, 20, and 28.

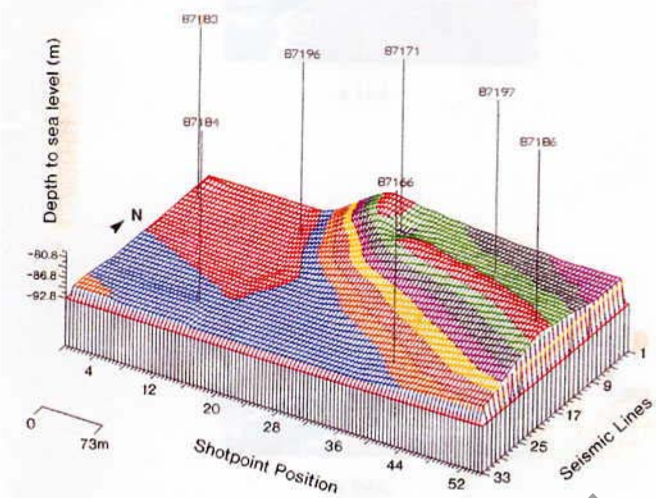

FIG. 5. Three-dimensional block diagram showing the structure of the roll. Each color contour corresponds to a 1.5-m interval.

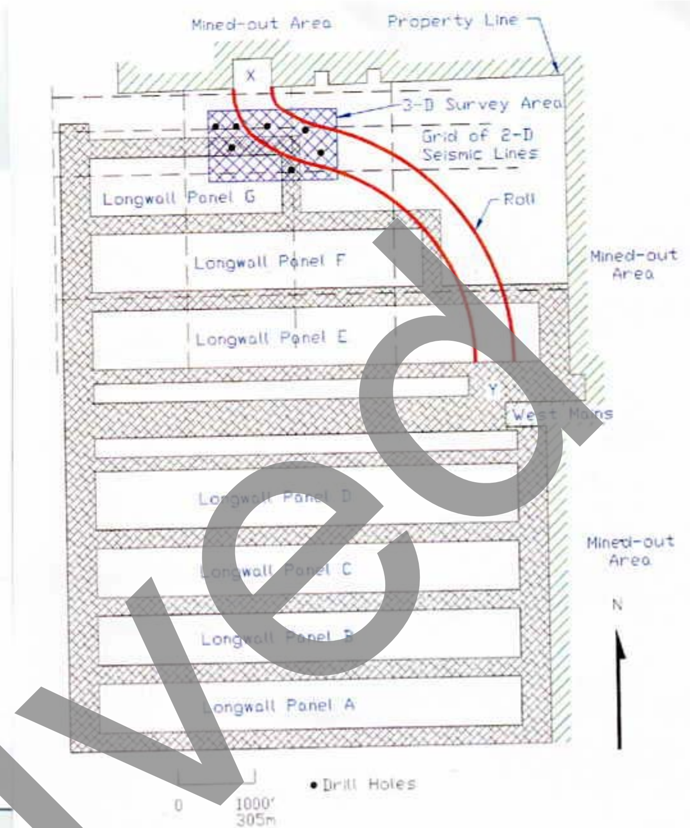

FIG. 6. The interpreted trend of the roll (red). As a result of the interpretation, proposed longwall panels in this reserve block were reduced from four panels to three, and subsequently shortened and staggered along the western flank of the roll.