High-resolution 2D surface seismic reflection survey to detect abandoned old coal mine works to improve mine safety

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A serious coal mine accident in southwest Pennsylvania in July 2002 occurred when mining activity came too close to an old abandoned flooded mine. A high hydrostatic head and thin coal barrier caused a major water breakthrough and flooded the QueCreek Mine. Nine miners were trapped underground for nearly 77 hours before they could be safely rescued. This high-profile accident motivated the U.S. government to investigate and explore measures that could minimize similar accidents in the future. As a result, several groups from private companies and academia were funded to develop and demonstrate remote-sensing geophysical technologies that could detect old mine works. The focus of this study was to evaluate the potential of a high-resolution 2D surface seismic reflection survey to detect abandoned mine works near an active coal mine in Ohio.

Geologic conditions. The overburden thickness in this coal mine ranges from 200 to 350 ft. The ground surface is mostly gentle rolling hills with open fields and wooded areas. The mine is located in Fox Township, Carroll County, Ohio, USA. The Mahoning coal seam is the lowest Conemaugh age seam in the Pennsylvanian Formation in Ohio. The seam occurs in ~10 square mile pods which can reach a maximum thickness of nearly 4 ft, near the center of the pod. The coal is frequently characterized by channels on the edges and at times through the center. The overlying shale along the channel margins tends to slump into the coal. The immediate overburden is a black shale that grades upward to a gray sandyshale and sandstone. The average seam thickness is around 3 ft but the mining height is about 3.5 ft. The target abandoned mine had the same mining height and was water-filled at elevated pressures resulting from up to 30 ft of hydrostatic head above the seam elevation. Hydrological characteristics were based on borehole drilling. The mine seam dips to the southeast where the pressure from the head resulted in water levels as much as 65 ft above the seam. The immediate roof has bone coal with 7 ft of shale, coarsening up to 5 ft with sandyshale which is topped by 15 ft of sandstone.

Figure 1 shows the relative locations of active mine works in the southwest corner of the map. Proposed future mine development (green) lies on the west. The abandoned and flooded old mine works are shown in dark gray and lie east of the property. Separating these two mines is a solid north-south trending blue band with an arrowhead on top that lies between the abandoned mine works and active mining reserve. This blue band corresponded to previous hole-to-hole tomography surveys conducted in the 1990s to image seam continuity, thin coal areas, and to detect mine voids. The map also highlights washout areas in the reserve suggestive of a major paleochannel system which has completely eroded the seam. Based on results from surface drilling, underground observations, and hole-to-hole tomography surveys, the paleochannel system had a north-south trend, possibly explaining the abrupt end to the old mine works near this boundary. Surface seismic Lines 2B and 3C are located at the northern end of the study area (Figure 2).

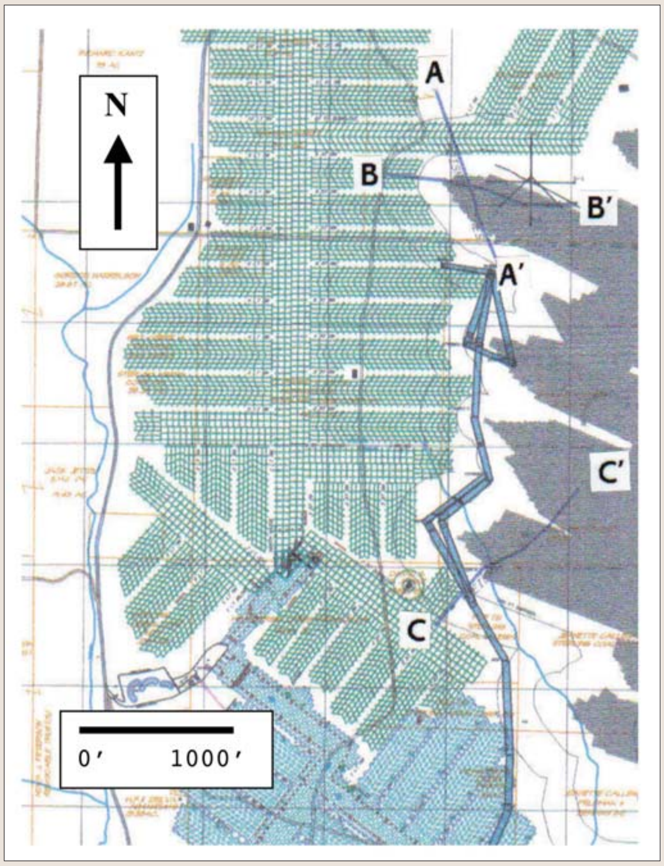

Figure 1. Map of study area showing the relative locations of the three surface seismic lines (A-A′, B-B′, and C-C′) with respect to the old Sterling Mine located to the northeast. Seismic survey lines were based on good surface access and on the latest knowledge of locations of old mine works, as indicated by the darkly shaded areas.

Table 1. *Acquisition parameters of surface seismic survey.*

Recording system	Geometrics geode
Record length	0.3 s
Sample rate	0.125 ms
Source	12-gauge seisgun
Receiver	Single 40-Hz geophone
Receiver interval	6 ft
Source interval	12 ft
Number of channels	96
Nominal fold	24

A geologic cross-section of two drillholes, Kantz05-7 and Kantz05-13 (Figure 3) confirms the depths to the tops of the

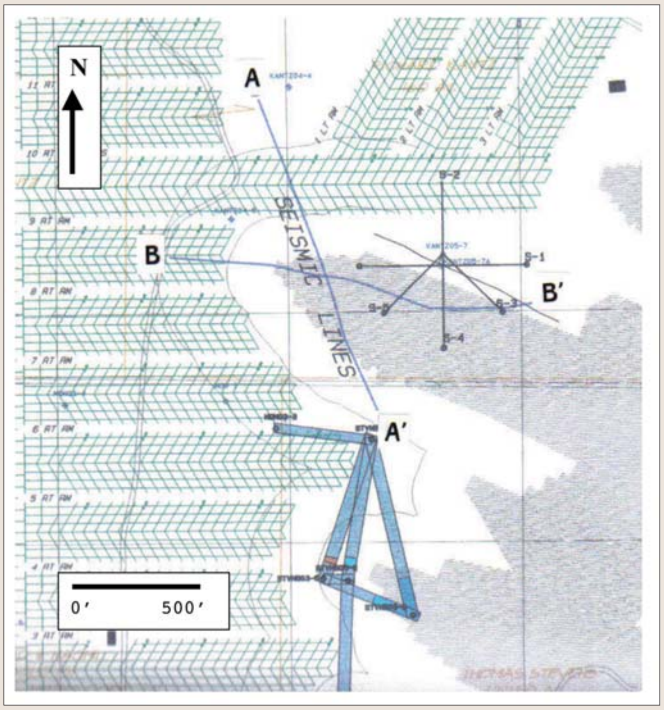

Figure 2. Expanded scale of study area showing the surface seismic Lines 2B and 3A with respect to the old Sterling Mine works (on the right). The blue-shaded arrowheadlike diagram is associated with hole-to-hole tomography surveys conducted by the coal company. Placement of the seismic survey lines was based on the concurrent understanding and interpretations of projected mine works.

coal seams at 261 and 227 ft respectively. The two drillholes are located near seismic survey Lines 2B and 3A and are approximately 330 ft apart.

Old abandoned mine works (closed in 1962). The coal company extensively researched all available historical information about the abandoned mine. The Mahoning 7A coal was mined from 1890 to 1962 from a portal along State Route 39 (approximately 5 miles away from the area of interest). The mine ran submains every 500 ft from which individual rooms were mined and the coal was hand-loaded. Individual rooms usually measured 200 ft long and 24 ft wide. On the western edge of their reserve, some rooms in the south were cut short because of poor roof conditions, thin coal, and washouts. These adverse mining conditions were indicative of a nearby paleochannel system.

Ever since the mine was closed, water had been accumulating in the empty chambers, and had built a hydrostatic head of up to 65 ft above the seam elevation in 2005. An interpretation, after reviewing the old Sterling Mine maps, was questioned because hand-drawn drafting of old mine maps (prior to AutoCad systems) was prone to errors (Figure 3). As a result, Sterling Mining Company (SMC) conducted a series of hole-to-hole (seismic) tomography surveys in the 1990s to better image the thin coal areas and old mine works. The survey results were interpreted to suggest errors in the accuracy of the old map could increase further north of the tomography surveys. The large northern-most room was of greatest concern because there were distinct gaps or missing pillars in the drawing. However, an outline of the room's western extreme was shown with a gap that appeared to be linear. Was the absence of pillars the result of poor data transfer from one map to another? If the cut-and-paste method was used, did this process accidentally omit some pillars or entries? Was the old map also accidentally rotated during the process?

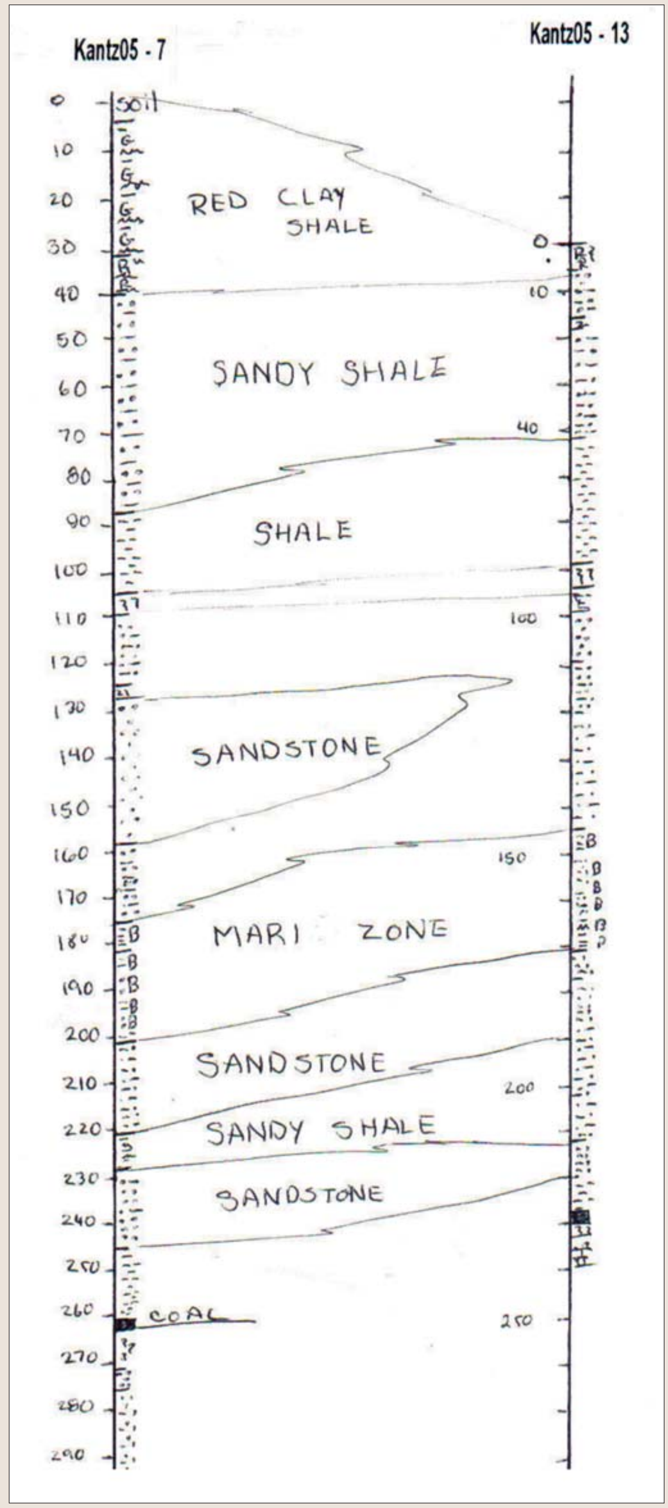

Figure 3. Hand-drawn geologic cross-section of two drillholes (Kantz05-7 and Kantz05-13). The two holes are about 330 ft apart.

To help address these important concerns two surface seismic lines were planned to optimally image these questionable areas on the mine maps. About two-thirds of the survey lines were located inside wooded areas with severe surface elevation changes, steep slopes, rock outcrops, and natural springs which created adverse conditions for drilling. Drilling permits from the state and permission from the landowner were denied because the target drilling area is part of a watershed for natural springs that are used by the landowner for domestic consumption around his house.

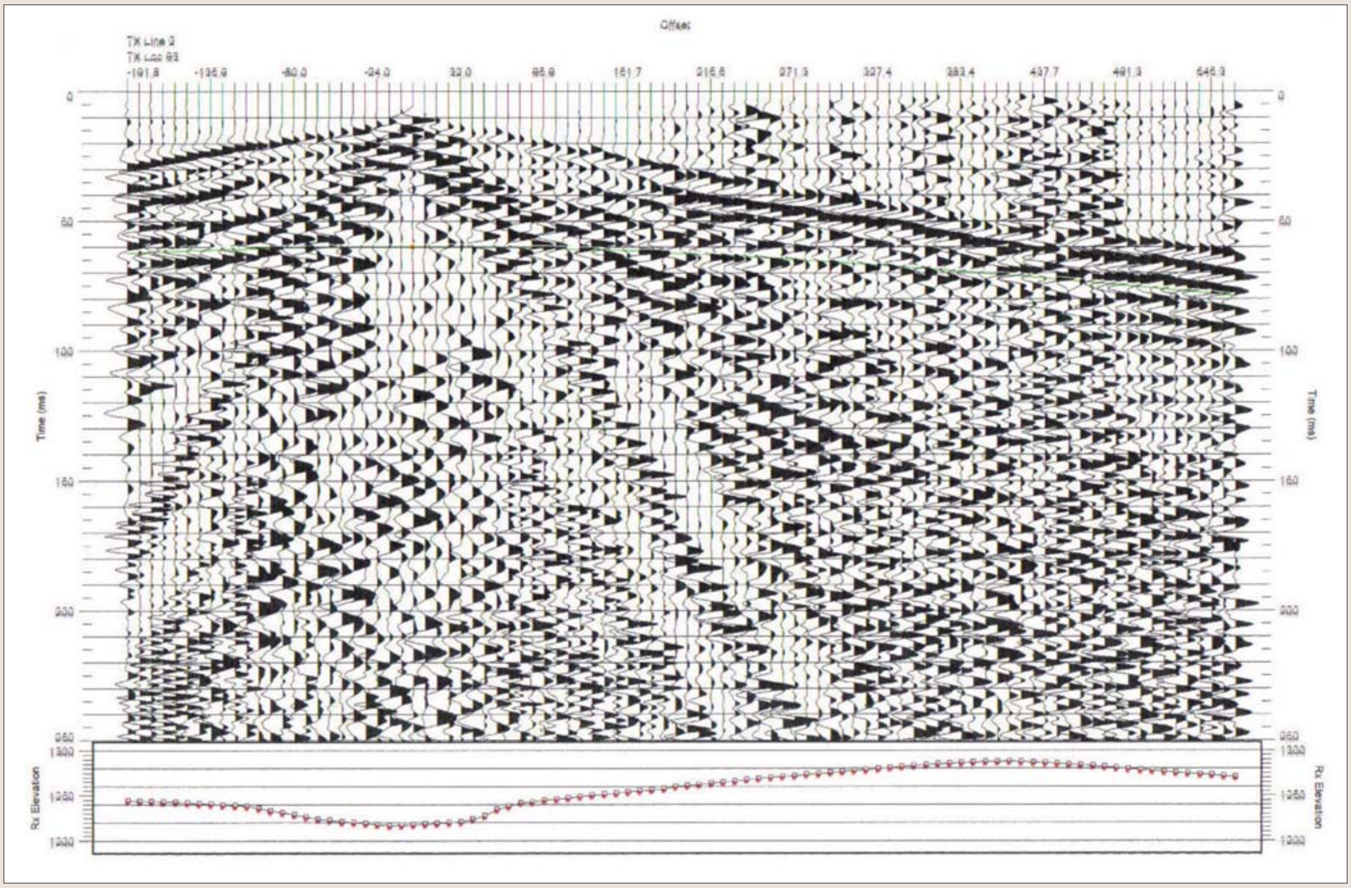

Figure 4. *Shot gather collected in the study area.*

High-resolution 2D surface seismic survey. There are numerous case studies in which the high-resolution 2D surface seismic reflection method successfully enhanced coal exploration programs by detecting geologic anomalies (washouts, faults, thin coal areas, and rolls) in advance of mine development. Prior to the internet, these published case studies were difficult to search-out in the public domain. As a result, geophysical technologies applied to coal were hard to find.

High-resolution surface seismic can augment an exploration drilling program by providing continuous subsurface profiles between boreholes. Conventional 2D surface seismic surveys are conducted to evaluate and image seam continuity and to detect potential geologic seam anomalies and mine voids that could create adverse mining conditions later on. Advances made in the 1980s in 3D seismic acquisition and processing from the petroleum industry were adopted. However, there are only a few published case studies in which the high-resolution 3D seismic had been successfully applied in the coal fields.

The southernmost seismic line is called 1C, and the two northern seismic lines are called 2B and 3A (Figure 1). Seismic lines 1C, 2B, and 3A were 1656′, 1592′, and 1448′ long, respectively. The starting point of each seismic line is designated by the letters A, B, and C, and ending at the primed letters A′, B′, and C′.

Given the geologic conditions and target depth of the coal seam, the following field parameters were employed. Figure 4 shows a shot gather collected at the study area.

Interpretation. To enhance the interpretation process, 2D synthetic seismograms, generated from sonic and density logs, are routinely incorporated into the process. However, for this project, the interpretation aids were not critical considering the principle investigator's extensive experience in acquiring, processing, and interpreting high-resolution surface seismic data targeting shallow coal seams. Some of these enhanced interpretation tools such as the seismic interactive interpretation workstation were described in publication from the early 1990s.

After undergoing several iterations of velocity analyses and statics corrections, the final stack section of Line 1C is presented in Figure 5. Based on drillhole data, the average depth of the coal seam ranged from 220 to 265 ft beneath the ground surface in the study area. Based on dozens of past coal seismic studies in the Appalachia Coal Basin, the calculated average rms velocity of the overburden was about 12 000 ft/s. Thus, using the drillhole data and applying the known rms velocity, the coal seam horizon reflection (a trough) is interpreted to arrive between 38 and 44 ms. Thus, the most robust and coherent seismic reflection in this section is highlighted in yellow (~ 44 ms). This event is interpreted to be the reflection associated with the target coal seam horizon.

To facilitate the interpretation process, the authors need to explain the difference between "resolution" and "detection." Resolution is defined as imaging the top and bottom of a layer based on the simple formula, $1/4\,\lambda$, where λ is the recorded predominant wavelength. As a result of coal's very low acoustic impedance (ρ = 1.3 g/cc and V = 8000 ft/s) properties with respect to shales and sandstone, thin coal seams of less than $1/16\lambda$ thickness could still be detected on the ground surface but the reflecting layer is composed of the target seam coupled with several ft of roof and floor rocks. In this case, interpretations are focused in detecting the target coal seam horizon and not on resolution as the frequency bandwidth of the seismic data is not high enough to resolve the top and base of the thin coal seam.

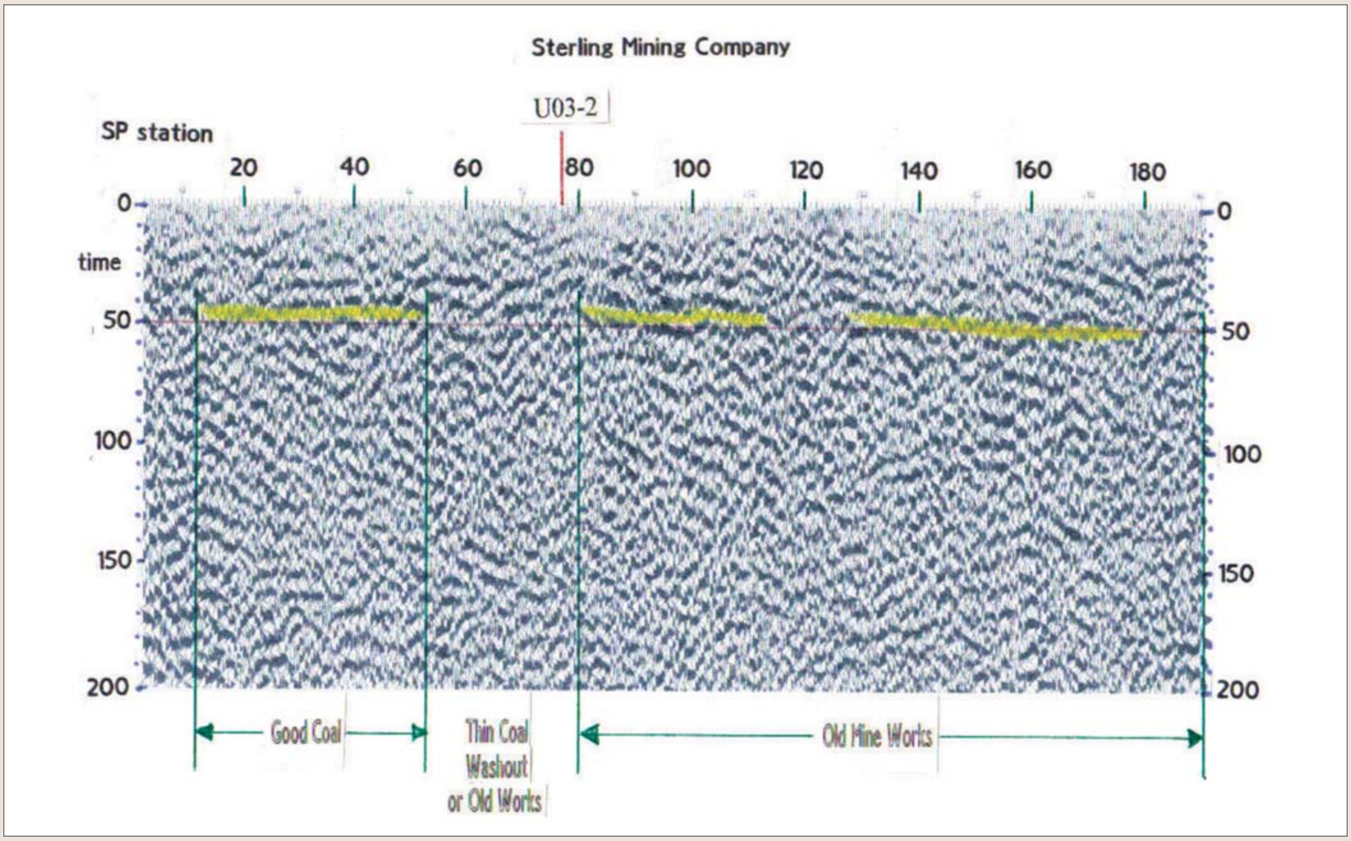

__Figure 5.__ Interpreted seismic section of Line 1C. Borehole U03-2 near SP-77 encountered old mine works.

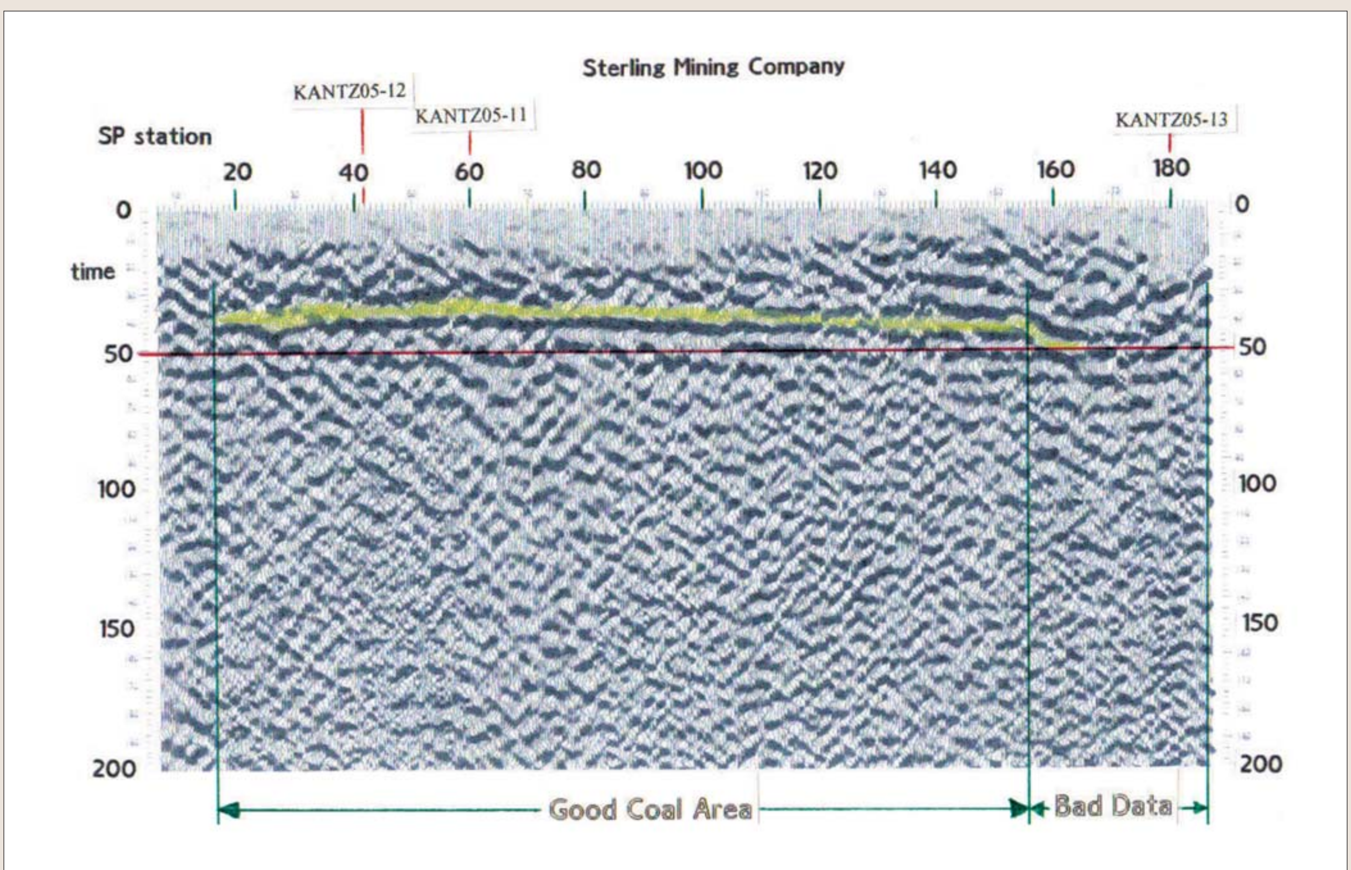

__Figure 6.__ Interpreted seismic section of Line 2B. Vertical scale in time is ms and horizontal SP interval is 8 ft.

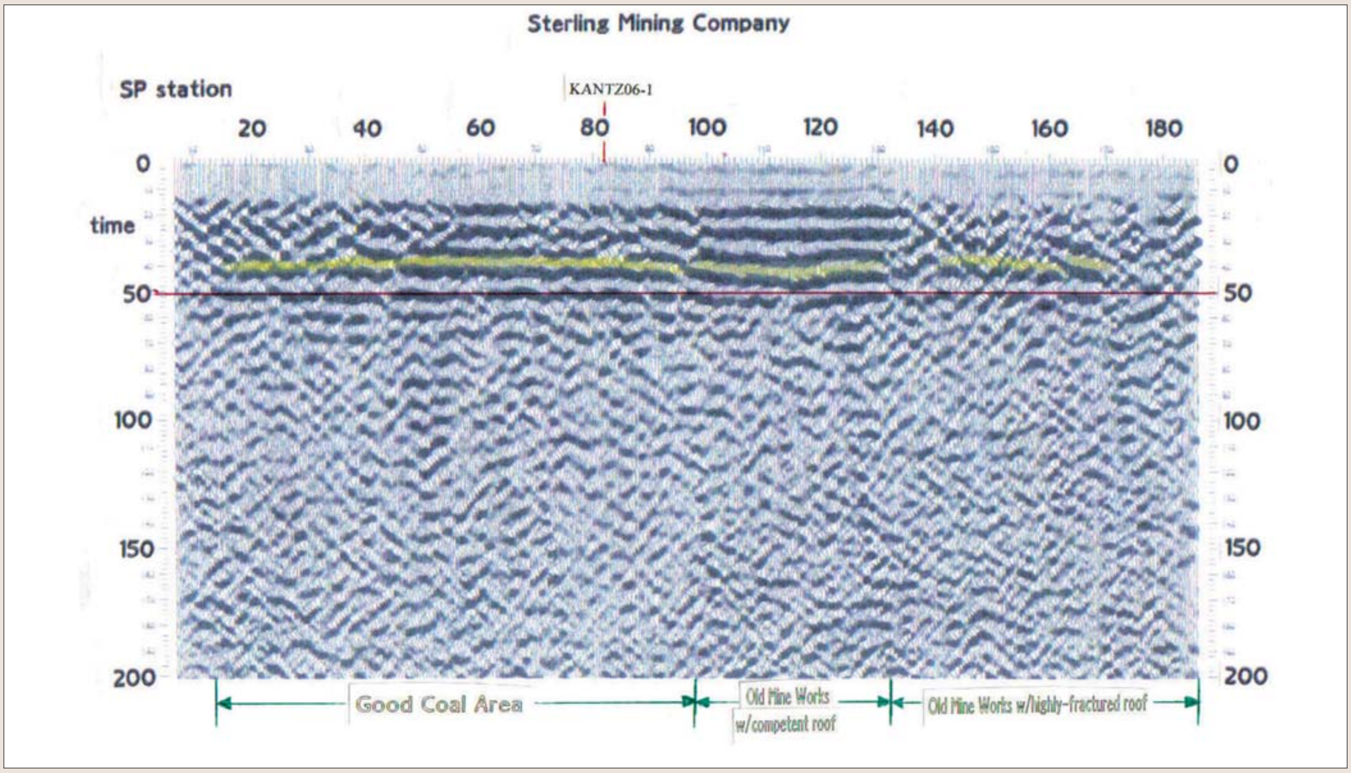

Figure 7. *Interpreted seismic section of Line 3A.*

A red horizontal line is drawn across Line 1C at the 50-ms timeline to serve as a marker (Figure 5). As expected, low-fold intervals of the seismic section yielded poor and uninterpretatble data. A coherent coal seam reflection appears only at about SP-23 and goes on continuously up to SP-53, indicating uniform seam thickness of about 3 ft. The distorted signals from SP-54 to SP-79 indicated subsurface geologic changes that could be associated with thin coal, a washout, or even old mine works. Given the lower quality of this data set, it is difficult to distinguish one anomaly from the others.

The coal seam horizon reflection reappears at about SP-80 and is continuous to SP-103. However, the seismic reflection is of lower frequency and amplitude, suggesting the polarizing effects of water-filled mine works. Over this interval, the coal seam reflection arrival time remained almost constant at about 44 ms. A major disturbance occurred near SP-105, followed by a short strip of robust reflection between SP-138 and SP-150. Thereafter, the seismic reflection is highly disturbed, coupled with a delay in arrival time. These two parameters (time delay and disturbed signals) are usually associated with the detection of old abandoned mines. Fractured and water-filled roof rocks typically would scatter the seismic energy and at the same time cause delays in arrival-time because water will slow down the average P-wave velocity in rocks.

Thus, the front end of the old abandoned mine is interpreted to be near SP-80, and to extend all the way to the end of the seismic survey line. However, since a major paleochannel system is known to exist at the western edge of the old mine works, the effects of thin coal or washout on the seismic wavelet could be the same as with the old mine works. Hole U03-2 was drilled in 2003 at the edge of the projected old mine works and confirmed its location. The seismic line intersected borehole U03-2 at SP-77. There appears to be a difference (or uncertainty) of about 3 shotpoint stations (between SP-77 and SP-80), which translates to 24 ft. The two northern seismic lines intersected each other at SP-82 (2B) and at SP-103 (3A).

The coal seam horizon reflection on Line 2B is highlighted in yellow (Figure 6). The section shows the coal seam horizon reflection to be continuous, indicating almost uniform thickness. It appears, however, that roof rock conditions seemed to vary considerably from SP-56 to SP-108, as indicated by varying roof rock reflection signatures—not the usual clean peak-trough-peak signature. The only major problem shown on this section is between SP-156 and SP-189 in which there is an apparent sag in the coal seam reflection. The "sag" or "apparent roll" feature is too dramatic to be associated with any local geology and could mean an artifact or noise that may result from acquisition and/or processing. Since this problem appeared near the end of the seismic section, it could be ruled as a "roll-out" problem and is uninterpretable. This interpretation could be supported by examining the surface elevations near the end of Line 2B. From SP-156 to SP-199, the surface elevation dropped dramatically from 1278 to 1217, over a horizontal distance of 344 ft. Such large surface variance can have an adverse effect in the recording and processing of high-resolution shallow seismic data.

The final stack section of Line 3A (Figure 7) is the best among the three collected. The coal seam horizon reflection is highlighted in yellow and is observed to be robust and continuous from the start of the survey line up to SP-98, where a major disturbance could be interpreted as a "fault." This apparent fault appears to have a vertical displacement of over 20 ft. Since we know that shallow faults are nonexistent in this region, the anomalous feature is likely be associated with the front end of detected old mine works because the roof rocks are understressed, resulting in a velocity anomaly. Applying prestack depth migration to this data set would likely resolve this issue. The apparent "sag" in the coal seam horizon reflection with respect to near-horizontal shallower reflections indicate an apparent velocity anomaly caused by water saturating the micro-fractures in the roof rocks. This feature extends up to SP-132. From SP-132 to the end of the survey line, there appears to be a complete scattering of seismic energy in which

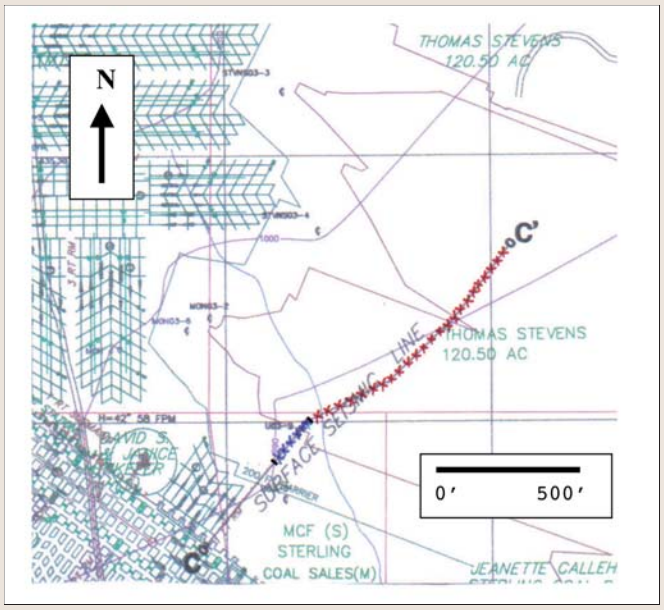

Figure 8. Interpreted seismic data of Line 1C is transposed on the mine map. The blue cross-hatched segment of the seismic line indicates a potential washout or old mine works. The red cross-hatched segment is assoiated with the old mine works.

no coherent seismic reflections were recorded. This suggests that the roof rocks above this portion of the old mine works are highly fractured.

When you examine the original expanded mine map shown in Figure 2, the latter two-thirds of Line 2B was supposed to be completely over old mine works. However, the seismic data collected beneath Line 2B showed a robust and continuous coal seam reflection across this interval. In addition, Line 3A showed the disturbed zone to be slightly smaller in magnitude and concentrated on the southern end of the survey line. These results were unexpected and would require some post-survey verification.

Interpretations from the three surface seismic reflection data sets were integrated into a concurrent mine map provided by the geologist. Figures 8 and 9 show the respective locations (red cross-hatched segments) where disturbances in the coal seam reflection were detected and interpreted to be the estimated boundary of the old Sterling Mine works beneath the survey lines.

Verification. In October 2005, preliminary results of the surface seismic reflection data were presented to Sterling Mining Corporation (SMC) because their fall drilling program was about to start and they needed to select surface locations to drill in order to verify the seismic results. Subsurface data collected beneath seismic line 1C correlated very well and confirmed with the known location of old mine workings in the southern property. The survey line also intersected one previously drilled borehole, U03-2, at SP-77 which was supposed to be located at the known edge of the old works. As expected, hole U03-2 encountered old mine works. Moreover, the seismic data was supported by a nearby borehole, U03-3 where the resultant tomograms generated from hole-to-hole tomography surveys conducted in 2003 between borehole U03-3 and two other boreholes, MON03-6 and MON03-2, indicated solid coal (Figure 10). Thus, SMC saw no need to drill new verification holes in this area as their concurrent mining activity is headed northward and have maintained at least a 200-ft barrier with respect to the nearest old mine works boundary.

In the northern study area where two surface seismic survey lines (2B and 3A) were conducted, detected anomalies

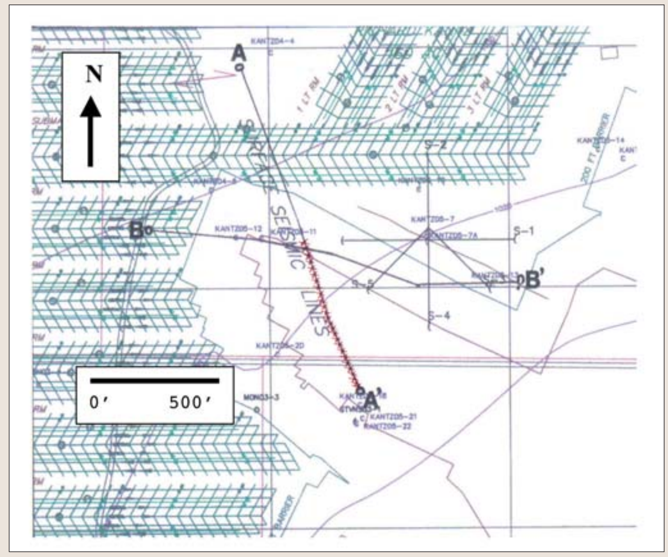

Figure 9. The interpreted disturbed zone beneath seismic Line 3A is shown as a red cross-hatched segment along the survey line. No disturbances associated with old mine works was detected beneath Seismic Line B.

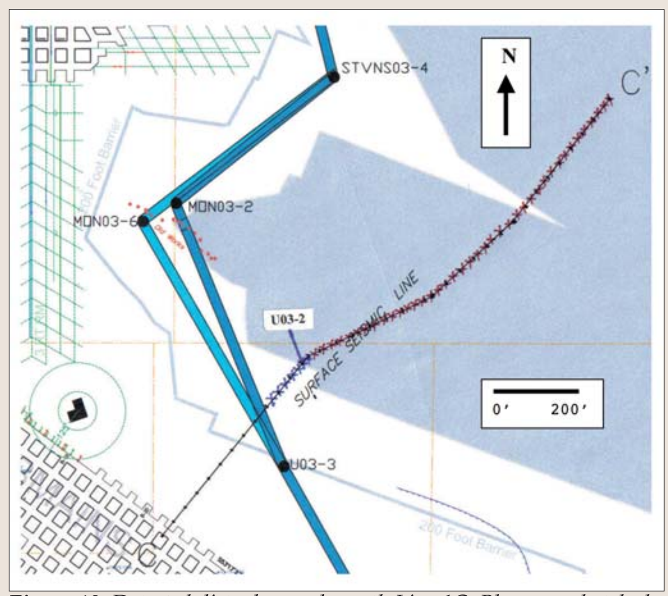

Figure 10. Detected disturbances beneath Line 1C. Blue cross-hatched segment along seismic line corresponds to interpretation of potential thin coal, washout, or old mine works while the red cross-hatched segment is interpreted to be associated with old mine works. The 200-ft barrier is also shown. (Verification: Hole U03-2 was drilled near SP-77 and two hole-to-hole tomography surveys were conducted. In this figure, solid blue lines between boreholes correspond to solid coal. A small segment just south of drillhole MON03-2 detected the tip of the old works.)

associated with the old mine works were unfortunately located inside the restricted heavy wooded area. To circumvent this major obstacle and to utilize their past successful experience with hole-to-hole tomography surveys since the early 1990s, SMC drilled a series of boreholes around the perimeter of the wooded area in order to directly and indirectly verify the seismic interpretation. Figure 11 shows four closely-spaced boreholes (Kantz05-18, Kantz05-21, Kantz05-21A, and Kantz21B) at about 50-ft centers were drilled near the end of Line 3A. In fact, Kantz05-18 was drilled near SP-175 and encountered old mine works, confirming the seismic interpretation. Further south, boreholes Kantz05-21, Kantz05-21A, and Kantz05-21B encountered solid coal as these holes were outside the area of seismic subsurface coverage. SMC drilled these three closely-

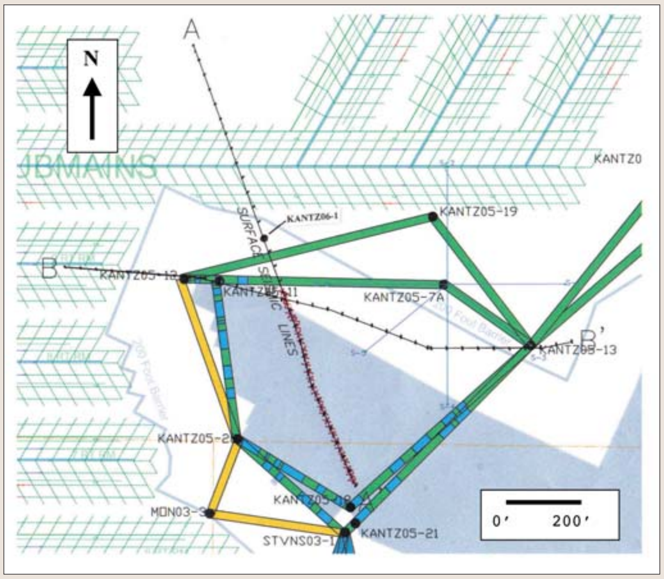

Figure 11. Detected disturbances beneath Lines 2B and 3A were smaller in magnitude than previously thought. A portion of Line 2B straddled the edge of old mine works. The red cross-hatched segment beneath Line 3A is interpreted to be associated with old mine works. The 200-ft barrier is shown. (Verification: As a result of concerns in this section of the reserve, Sterling drilled numerous boreholes around and outside the restricted wooded area to verify the seismic interpretation by conducting hole-to-hole tomography surveys to enhance the geophysical investigation. Solid yellow and green lines indicate solid coal while random blue-green bands were detected old works.)

spaced boreholes because the first two holes collapsed because of excessive water in the holes prior to conducting the tomography surveys. In February 2006, SMC drilled another hole (Kantz06-1) at SP-82 of Line 3A and found a 2-ft seam with a 2-ft shale top, indicating its close proximity to a paleochannel system.

From the start of the project, SMC had been concerned about the magnitude of old mine works beneath the northern study area. It was a surprise when they learned that the scale of disturbance beneath Lines 2B and 3A was smaller in size. In addition, the seismic section beneath Line 2B showed nearly a continuous coal seam reflection across the survey line, indicating no detected mine works. To verify the interpretation, SMC decided to drill three additional boreholes (Kantz05-13, Kantz05-11, and Kantz05-12) along Line 2B, and their respective shotpoint locations are at SP-180, SP-60, and SP-41. Kantz05-11 encountered old works. Boreholes Kantz05-12 and Kantz05-13 encountered solid coal; thus, confirming the results of the seismic data along line 2B. These holes were drilled not only to verify the surface seismic data, but also used in subsequent hole-to-hole tomography surveys.

Knowing the limited information provided by drilling alone, Sterling drilled four additional holes (Kantz05-20, Kantz05-7A, Kantz05-19, and Kantz05-13) outside the perimeter of the old works and surface seismic lines. These additional holes permitted the company to conduct multiple hole-to-hole tomography surveys in order to enhance the geophysical program in detecting and imaging the old mine works beneath the northern study area.

Figure 11 shows the results of the hole-to-hole tomography surveys superimposed over the old mine works and surface seismic data. The solid green and yellow line bands between drillholes show solid coal. However, alternating blue and green line bands between holes show detected old mine works. Integrating the results from the surface seismic reflection, drilling, and tomograms, a clearer picture emerges in which the estimated boundaries of the old Sterling Mine works beneath the northern study area begins to take shape. As a result of SMC's past successful experiences with other geophysical technologies, the company has a high degree of confidence in integrating these valuable geophysical data sets into their mine plans. As a result, SMC was able to develop their future mine plans based on a 200-ft barrier. Otherwise, without the additional geophysical data results, the coal company would be required by state and federal agencies to leave a 1000-ft barrier as a safety margin. That would mean leaving too much coal behind which would be uneconomical to the mining company.

Conclusions. As was demonstrated in this field project, the 2D high-resolution surface seismic reflection method is one viable method that can be used to detect old mine works as long as surface conditions are conducive to collecting good quality seismic data. The good correlation of direct and indirect verification of the surface seismic data via drilling and hole-to-hole tomography data added value to this project, resulting in higher confidence in interpretation. In this case, SMC had a positive experience in which they can safely mine more coal while maintaining the 200-ft safety barrier instead of 1000-ft.

Suggested reading. "How to optimize 3D seismic land surveys—some rules for areal data gathering" by Bading (in *Coal Geophysics*, SEG, 1986). "Case histories of the use of surface seismic method in the U.K. coal mining industry" by Fairbairn et al. (in *Coal Geophysics*, SEG, 1986). "Advances in seismic reflection profiling in U.S. coal exploration" by Gochioco (*TLE*, 1991). "Applications of the seismic interactive interpretation workstation for the coal industry" by Gochioco (*Mining Engineering*, 1991). "Modeling studies of interference reflections in thin-layered media bounded by coal seams" by Gochioco (GEOPHYSICS, 1992). "High-resolution 3D seismic survey over a coal mine reserve area in the U.S.—A case study" by Gochioco (GEOPHYSICS, 2000). "Will geophysical technologies return to U.S. coal fields?" by Gochioco (*Mining Engineering*, 2005). "Locating faults in underground coal mines using high-resolution seismic refection technique" by Gochioco and Cotten (GEOPHYSICS, 1989). "High-resolution seismic surveys to map paleochannels in an underground coal mine" by Gochioco and Kelly (*Canadian Journal of Exploration Geophysics*, 1990). "Shallow seismic reflection investigation of coal in the Sydney Basin" by Greenhalgh et al. (GEOPHYSICS, 1986). "Premine study of shallow coal seams using high-resolution seismic reflection method" by Henson and Sexton (GEOPHYSICS, 1991). "Vertical resolution of thick beds, thin beds, and thin bed cyclothems" by Knapp (GEOPHYSICS, 1990). "Areal coal seam mapping by 3D seismic reflection surveying—A case history from the Sydney Basin, Australia" by Lambourne et al. (*SEG 1990 Expanded Abstracts*). "Application of the surface seismic reflection method to shallow coal exploration in the plains of Alberta, Canada" by Lyatsky and Lawton (*Canadian Journal of Exploration Geophysics*, 1988). "A simple approach to high-resolution seismic profiling for coal" by Ziolkowski and Lerwill (*Geophysical Prospecting*, 1979). TLE

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