Employing the underground inseam seismic method to detect old abandoned mines and improve mine safety

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In July 2002, a high hydrostatic head pressure and thinner coal barrier caused a major water break that flooded the QueCreek Mine in southwest Pennsylvania. Nine miners were trapped for nearly 77 hours before they were rescued. This high-profile accident motivated the US government to investigate measures that would minimize similar accidents in the future.

As a result, several private companies and academic organizations received funding to develop and demonstrate remote-sensing geophysical technologies that could detect old mine works. This paper explores one of the geophysical methods—underground inseam seismic—employed by the principle investigators.

The first documented underground inseam seismic (ISS) tests were conducted in German coal mines during the late 1930s. In the 1960s and 1970s, German geoscientists advanced ISS technology even further (Arnetzl and Kreg, 1981; Dresen and Freystatter, 1976; Dresen and Freystatter, 1978; Krey, 1963; Millahn and Arnetzl, 1979) with the advent of digital technologies. The British followed with their own innovations in the 1970s and 1980s (Buchanan, 1978, Mason, et al.., 1980, Mason, 1981, Buchanan et al.., 1981, Buchanan et al., 1983).

In the mid-1970s, several companies attempted to introduce this technology in the United States, most notably through local conferences (Krey, 1976; Lagasse and Mason, 1975; Guu, 1975; Toksoz, 1979). BHP Americas opened an office in the U.S. in the mid-1980s, offering ISS services. The US coal industry, however, was slow to adopt this technology, and BHP's U.S. service operations closed in the early 1990s. However, CONSOL's internal coal geophysics program developed and used this technology successfully to improve their mine safety record by detecting potential hazards or geologic anomalies ahead of mining (Gochioco, 1996).

With coal's large acoustic impedance (density × velocity) contrasts relative to roof and floor rocks (mostly shales and sandstones), a majority of the seismic energy introduced to the seam will remain confined, propagating within the seam and subsequently making the coal seam act like a waveguide. When the seismic energy encounters geologic anomalies such as thin coal, washout, rock intrusions, faults, etc., its wavelet characteristics change predictably. With proper processing and computer modeling, the resulting data may be used to interpret the type and magnitude of geologic disturbance. In this case, the targets are old, abandoned, air-filled, or water-filled mines that result in partial reflection and transmission of seismic energy traveling through an otherwise uniform coal seam.

Data aquisition. The U.S. Department of Labor supported this demonstration of the ISS method at seven different sites with funding from the Mine Safety and Health Administration (MSHA). The principle investigators from the companies had collaborated previously in the early 1990s. This report highlights four surveys undertaken at three different coal mines.

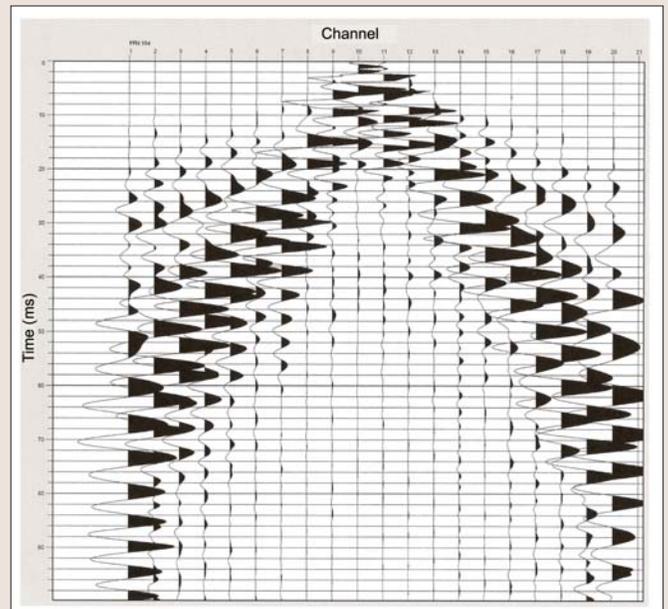**Figure 1.** *Preparing to collect the ISS data in low-roof conditions.*

Figure 2. *Raw ISS data with good quality. A sledge hammer was used as the seismic source. The total record length displayed is 100 ms.*

A portable, 24-channel seismograph and single 40-Hz geophones were used to collect the data. Seismic sources differed and their usage varied, depending on the location of the suspected target mine and underground working conditions. The two seismic sources most commonly utilized were the sledge hammer and blasting caps. Investigators planted geophones near the center of the coal face by drilling small-diameter holes and then hand-tightening the geophones' spikes into the wall to achieve good source-receiver coupling. The receiver intervals on this project were either
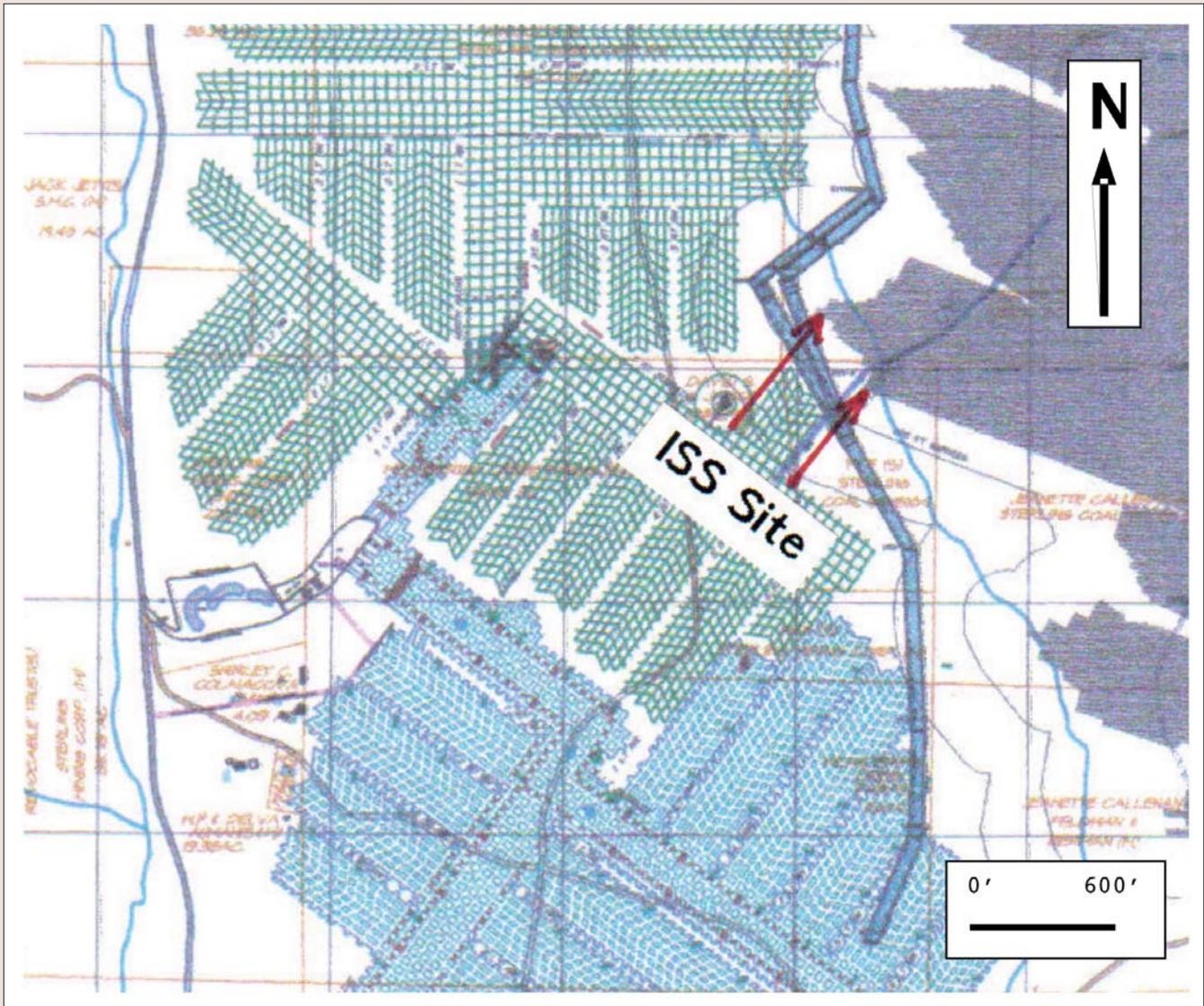
Figure 3. Map shows where the ISS survey was conducted with respect to the locations of submains of the abandoned mine which closed in 1962. The red arrows highlight the direction of the seismic energy toward the target submains.

10 or 20 ft. Source sounding was conducted outside, while inside the geophone was planted to allow normal CMP gathering and subsequent stacking of traces to improve signal-to-noise ratio.

The investigative team was bound by strict MSHA safety protocols for underground work. After setup, the team began to collect the ISS data in the claustrophobic conditions of this low-roof mine (Figure 1). Figure 2 shows typical raw ISS data prior to processing. The team operated only in fresh-air environments, and MSHA professionals were always on hand during acquisition to ensure mine safety and compliance.

Data processing. The software used to process the ISS data sets is a proprietary program, and the generalized workflow is shown below. The algorithms are designed around a straight-ray approach:

• Sort seismic traces according to geometry
• Apply normal moveout (NMO) corrections
• Stack
• Refraction inversion modeling

• Calculate various velocities of disturbed and undisturbed coal
• Apply filters (FFT and maximum entropy) to enhance data
• Extrapolate two-way travel times of reflections
• Calculate distances of reflected events

Verification. One of the primary objectives of this study was to determine the accuracy of different geophysical methods. The locations of the abandoned mine works had to be confirmed prior to the survey via a closed-loop survey with an accuracy of 1:5000. If not, then MSHA required post-survey drilling and/or other complementary geophysical data from the coal company participating in this study.

Case study 1: A coal mine in Ohio. The overburden thickness in this coal mine ranges from 200 to 350 feet. The ground surface is mostly gentle rolling hills with open fields and wooded areas. The mine is in Fox Township, Carroll County, Ohio. The Mahoning coal (7A) seam is the lowest Conemaugh Age seam in the Pennsylvanian Formation in Ohio. The seam occurs in ~10 square mile pods which can
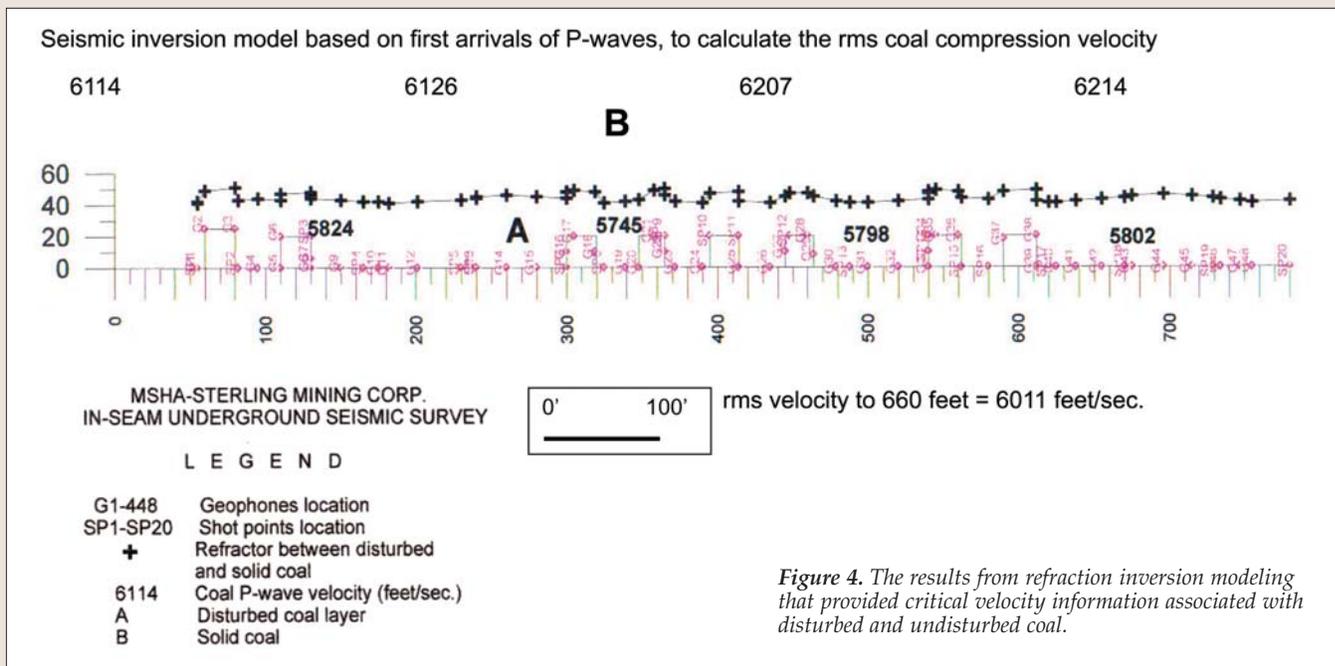
Figure 4. The results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal.

reach a maximum thickness of almost 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 tend to slump into the coal. The immediate overburden is a black shale that grades upward to a gray shale and sandstone.

The average seam thickness is 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 mined 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 3 shows the relative locations of active mine works in the southwest corner of the map. The abandoned and flooded old mine—which closed in 1962—is shown in dark gray, in the northeast corner (right) of the map. Separating these two mines is a solid blue, north-south trending band that corresponds 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 shows washout areas in the reserve where a major paleochannel system had eroded the seam completely. Based on surface drilling results, underground observations, and hole-to-hole tomography surveys, the paleochannel system had a northward trend, which could explain why the old mine ended abruptly.

The ISS survey was conducted in an active development section where the target was one of the submains of the abandoned mine.

Data results and interpretation. Figure 4 shows the refraction inversion model based on the first arrivals. Two distinct velocity layers associated with disturbed and undisturbed coal are evident. The first layer of lower velocity coal ranges between 5745 and 5824 ft/s and is interpreted to be the immediate coal face that was disturbed or fractured from mining operations. At this site, the layer of disturbed coal ranged from 40 to 50 ft thick relative to the working face. The second layer is determined to be solid and competent undisturbed coal with velocities ranging from 6114 to 6214 ft/s. These two velocity layers were used to calculate the 6011 ft/s rms velocity.

Figure 5 shows the stacked ISS data after normal moveout (NMO) correction, filtering, FFT, and maximum entropy had been applied. The graph shows that out of 48 receiver surveying stations, only 17 geophones (from G31 to G47) recorded reflections. Outside of the G31 and G47 geophone spread, no reflections were recorded, as evident by the relatively very low amplitude signals found on receiver locations G27 to G30. The solid blue line indicates the two-way arrival times associated with the time it took for the seismic energy to propagate from the source through the coal seam and reflect back from the anomalies (i.e., old mine works) to the geophones. Using these recorded arrival times and the rms velocity, distances to the old mine works were found to range between 605 and 637 ft. The results were subsequently integrated into the coal company's digitized mine map to determine the accuracy of the ISS results (Figure 6).

Figure 6 shows the actual measured reflection points in front of the receiver positions. It is apparent that six reflection points are outside or beyond the tip of the submains. The underground mine map is considered accurate and without migration, the six spurious reflection points are not properly positioned as a direct result of the 15–20º misalignment between the submains and the setup room. Therefore, all 17 reflection points should be shifted in an arc-like manner, simulating a wavefront, by about 120–140 ft toward the southeast.

Verification. The coal company believed the location of the southern portion of the old mine as defined by ISS to be fairly accurate, based on old surveyed data and mine maps. To support their belief, four holes were drilled (U03-4, MON03-2, MON03-6, and STVNS03-4) in 2003, to conduct hole-to-hole tomography surveys to enhance the subsurface information.

The four confirmation holes were used for 2D hole-to-hole tomography surveys (Figure 6)**.** The solid blue bands indicate solid coal. Thus, hole pairs U03-3 and MON03-6, U03-3 and STVNS03-4, MON03-6 and STVNS03-4 did not
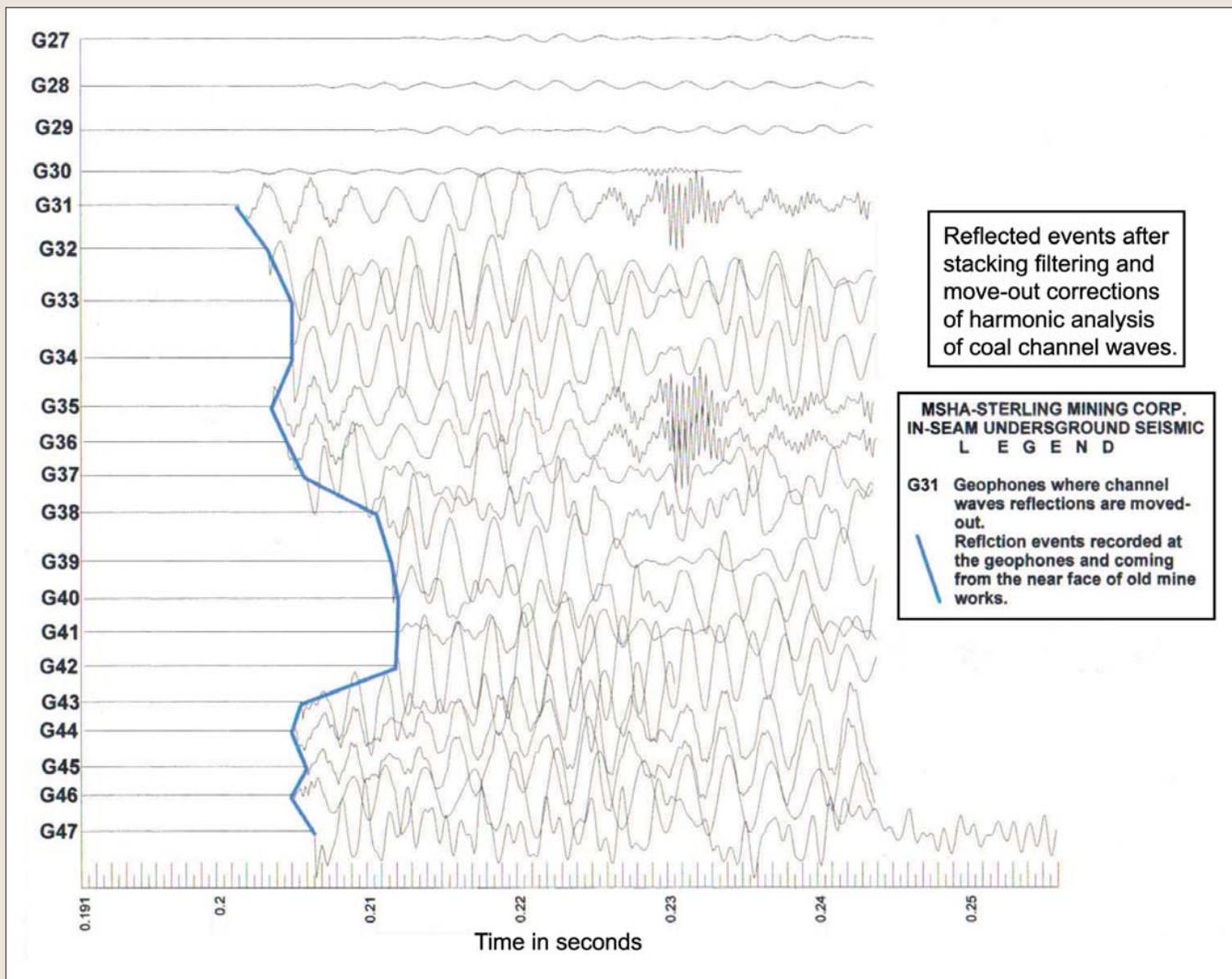
Figure 5. *Stacked seismic traces showing the recorded two-way arrival times of the seismic energy reflected from the near face of the old works. Geophone station interval is 20 ft.*

encounter any old mine works. However, the tomography survey between MON03-2 and U03-3 encountered a disturbance associated with old mine works located near the western tip of the submains. A small cluster of reflection points is evident inside or near the detected anomaly, indicating a good correlation with the hole-to-hole tomography data.

Case study 2: A coal mine near the Tennessee-Kentucky border. The coal company provided two separate targets for testing the underground ISS method at a mine located near Fork Ridge, Tennessee. The mined coal seam, called the Buckeye Springs, ranges from 2.5 to 3 ft thick with an average elevation of about 2000 ft above sea level and has a predominantly thick shale overburden from 800 to 1100 ft.

The active mine was flanked by three abandoned mines located to the

Figure 6. *Measured ISS reflections points (red) were plotted on the mine map. The six reflection points shown outside of the old mine works indicate that the straight ray approach was inadequate and would require a migration solution to yield better results. As a result, the reflection points should be shifted or rotated slightly (clockwise) towards the southeast direction by about 120 to 140 ft.*
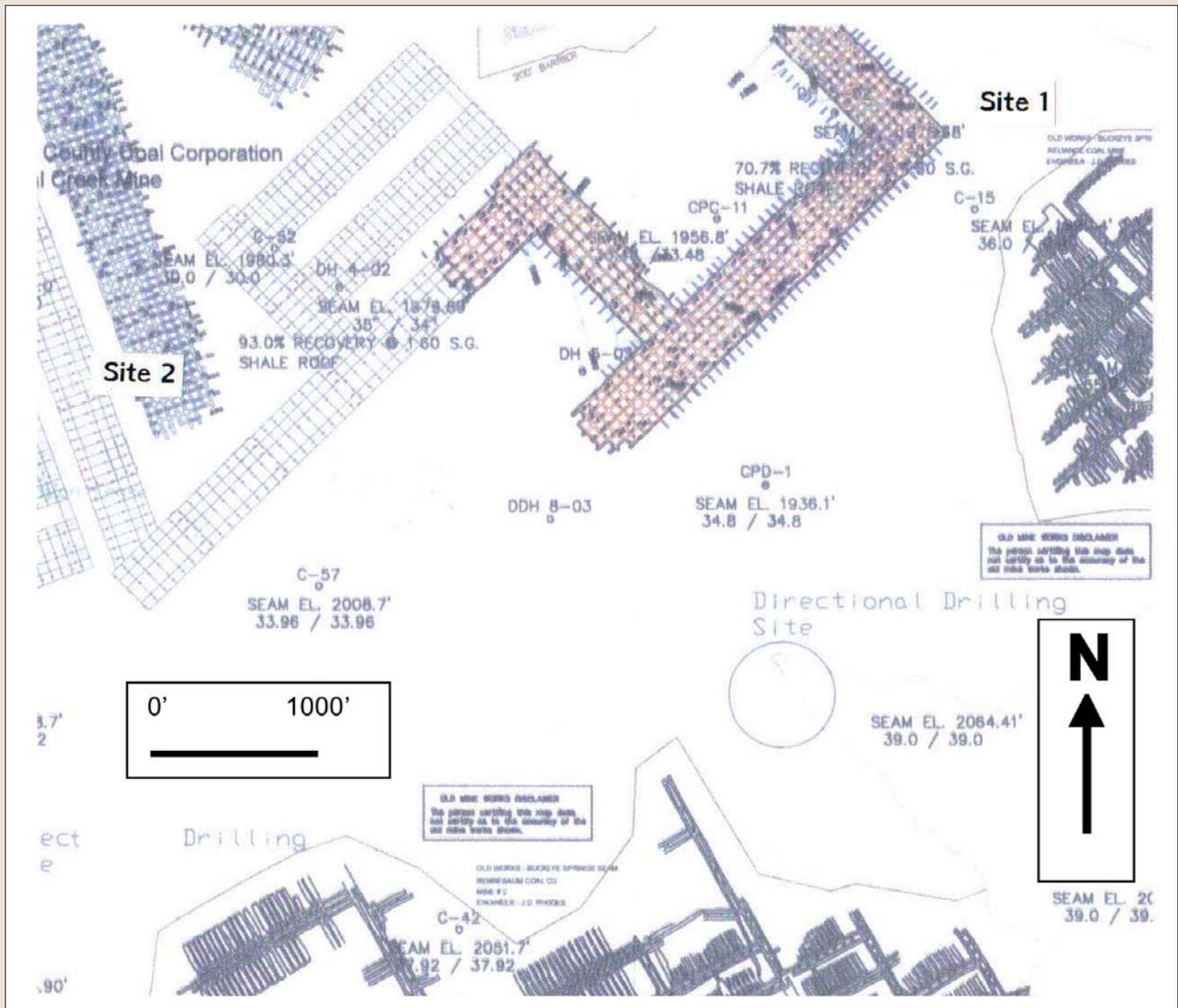
Figure 7. Map shows the location of a coal mine near the Tennessee—Kentucky border with respect to the old Reliance Coal Mine (southeast), old Rennebaum Mine (southwest), and the Coal Creek Mine (northwest). The two proposed ISS survey sites are highlighted.

northwest (Coal Creek Mine), southwest (Rennebaum Mine), and southeast (Reliance Mine). The two latter mines were closed and sealed in the early 1940s. Two worksites—each with a different target—were identified (Figure 7). The objective of site 1 was to measure the distance to the old Reliance Mine located in the southeast corner. The objective of site 2 was to determine the accuracy of the ISS method by estimating the distances to the old Coal Creek Mine located to the west. Since the coal company operated Coal Creek Mine, accurate records based on a closed-loop survey were kept with an internal accuracy standard of 1:5000. Thus, post-survey verification drilling was not necessary at the second worksite.

Interpretation. Using the same processing flow as described for Case Study 1, the seismic refraction inversion graph was used to extract critical velocity information. Two distinct velocity layers associated with disturbed and undisturbed coal were recorded. The fractured or disturbed coal seam varied in thickness from 35 to 65 ft, and the average measured velocity was about 6594 ft. Thereafter, the competent or undisturbed coal had a measured average high velocity

of about 12 077 ft/s. This measured high velocity was expected as a result of the much larger overburden thickness. The rms velocity was calculated to be 12 102 ft/s.

After applying normal-moveout (NMO) correction, filtering, FFT, and maximum entropy, the recorded two-way arrival times of the seismic energy reflected from the near face of the old Reliance Mine were calculated. Only receivers located from G1 to G15 recorded seismic events. The ISS data indicated that the distances to the old Reliance Mine ranged from 997 to 1198 ft. Again, the ISS data were integrated into the coal company's existing digital mine map (Figure 8). An excellent correlation is obvious between many of the calculated reflection points and the western-most boundary of the old Reliance Mine. A migration solution for this problem was unnecessary since the relative orientation between the setup room and old Reliance Mine was almost parallel.

At site 2, the seismic refraction inversion process showed two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The thickness of the fractured coal seam layer was more constant, measuring about 60 ft with an average measured velocity of ~ 6599 ft/s. Thereafter, the competent or undisturbed coal had a mea-
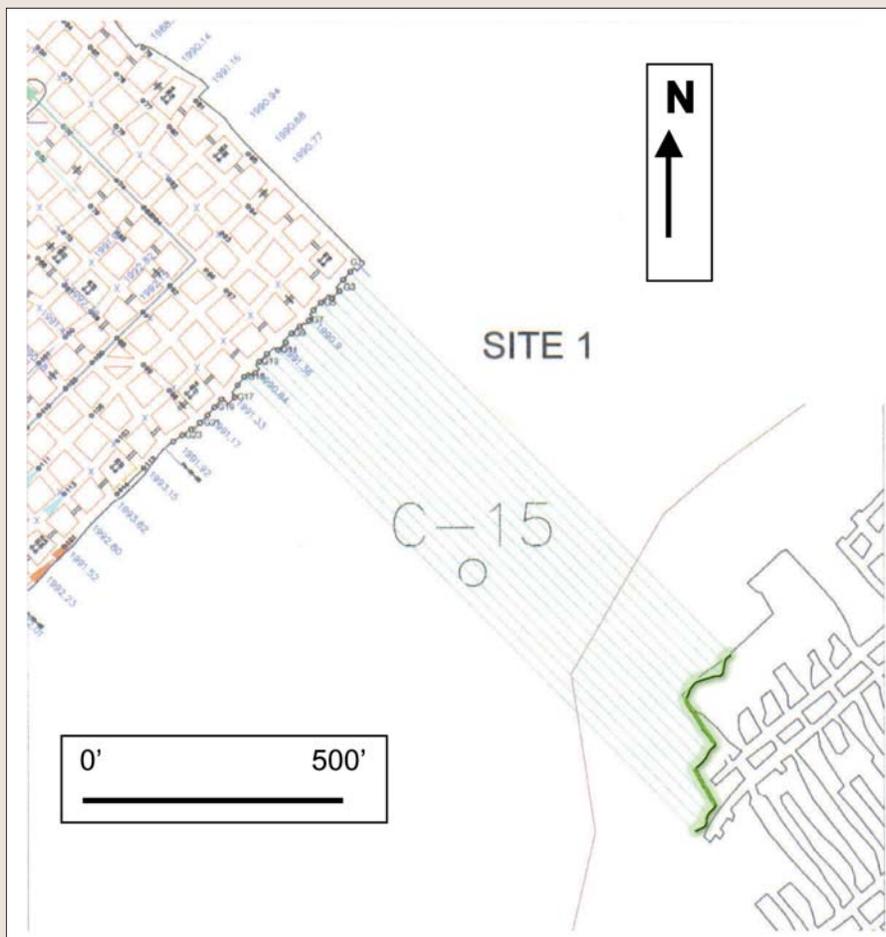
Figure 8. *The ISS reflection points show an excellent correlation with the estimated known boundary of the old Reliance Mine.*

sured average high velocity of ~11 943 ft/s and rms velocity calculated to be 11 912 ft/s. The ISS data indicated that the distances to the old Coal Creek Mine ranged from 675 to 758 ft. Only receiver stations G15 to G24 recorded reflections.

The coal company integrated the ISS data results into their mine map (Figure 9). It is apparent the reflection points are consistently off as a result of applying the straight-ray solution. The orientation of the setup room (geophone and source spread locations) with respect to the old Coal Creek Mine was approximately 30°; thus, a migration solution was required. By migrating the reflection points toward the near face, as indicated by the pair of red arrows, the ISS reflection points fall nearly on top of the old works' boundary.

To ascertain the level of accuracy, let us take the measured distances from receiver stations G24 and G15 to the mine wall with their respective calculated distances of between 671 and 754 ft. A hand-migration method was applied to the ISS data to properly realign the reflection points with the true reflector surface, which is orthogonal to the receiver station spread. After migration, we could more accurately recalculate the actual distance to the reflecting surface. The estimated distances for the new G24 and G15 reflected surfaces ranged from 650 to 725 ft, respectively. In this case, the ISS data over-estimated the distances to the old mine works by about 25 ft over an average distance of 688 ft. Therefore, the calculated percentage error is ~3.6%.

Verification. *Site 1:* To date, the coal company has not drilled to confirm the ISS results at site 1. However, the coal company executives believed the ISS data to be accurate based on the findings of the engineering company and surveyors that mapped both the old Rennebaum and Reliance Mines. With limited funds, the coal company decided to drill a horizontal hole to intersect the old Rennebaum Mine as development advanced in that direction.

Site 2: Since the Coal Creek Mine is still being operated by the coal company, current data from previous closed-loop surveys eliminated the need for any further verification drilling.

Case study 3: Niosh Bruceton Safety Research Mine. The seventh ISS test was conducted at the NIOSH Bruceton Safety Research Mine in Pittsburgh, Pennsylvania. MSHA selected this site as a "blind test" to evaluate the team's capability without prior knowledge of the old mine's location and orientation. Moreover, the target at this location was confirmed through closed-loop surveys and two horizontal holes previously drilled to confirm its precise location.
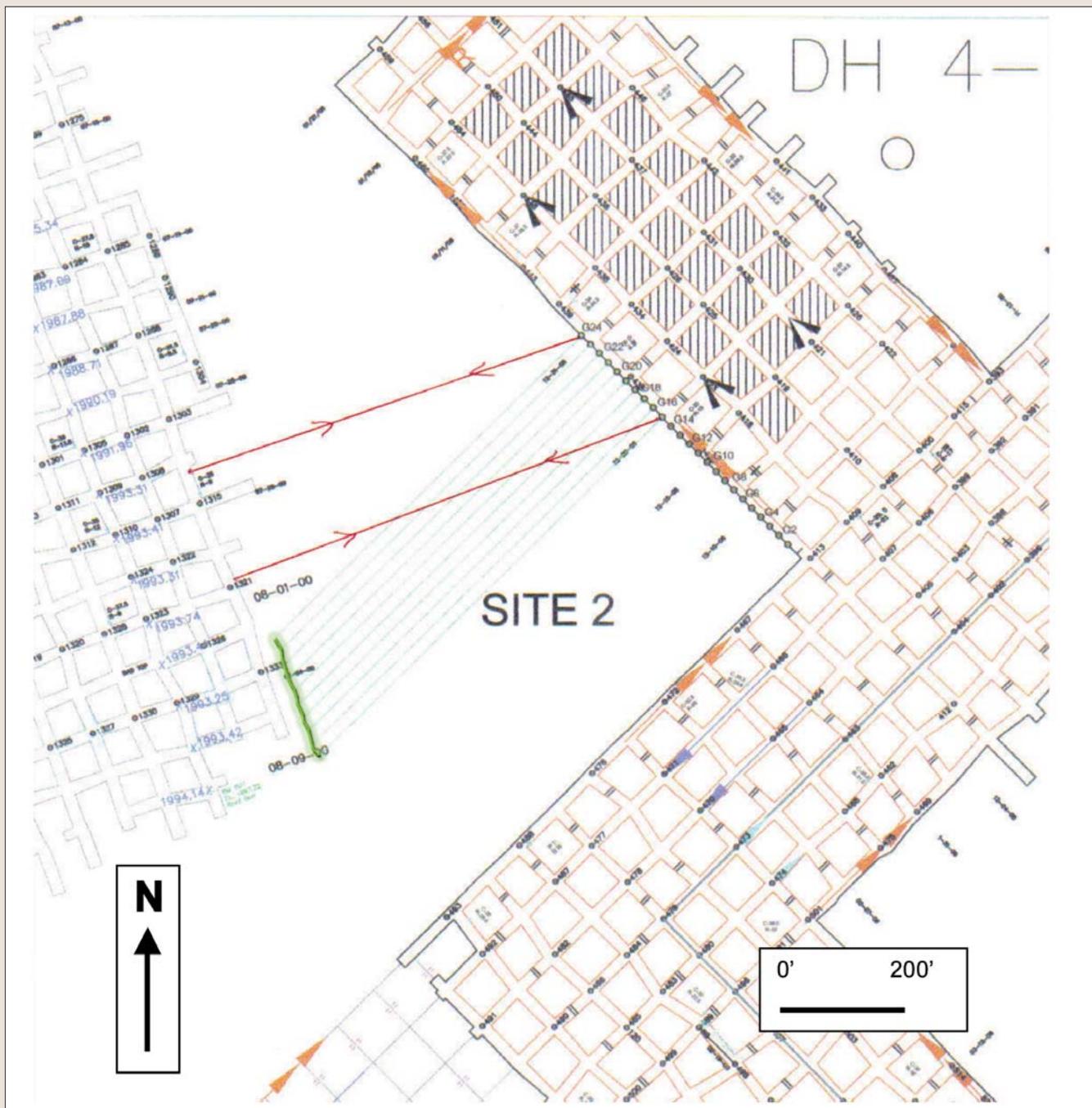
The old mine, which closed in 1905, is east of the setup room (Figure 10). Since the old works is above drainage, the mine void is air-filled. The average seam thickness of the Pittsburgh coal is about 5.5 ft, and the mining height was 6.5 ft. The first geophone station (G1) was 5 ft off the northern end of Entry No. 18, while G20 was the last geophone station (10-ft receiver interval) as the working face was only about 200 ft long.

After applying the seismic refraction inversion process, two distinct velocity layers associated with disturbed and undisturbed coal at the working face were interpretable. The fractured or disturbed coal seam thickness varied from 35 to 51 ft with an average measured velocity of 5975 ft/s. The competent or undisturbed coal had a measured average velocity of about 6276 ft/s. Given these two velocities, the Vrms was calculated to be about 6155 ft/s.

Calculated Vrms and picked two-way arrival times from the processed ISS data allowed the estimation of the distance to the old mine works. The working face ranged from 213 to 258 ft away from the old mine works based on data recorded by receivers at stations G1 to G18. After MSHA received the ISS results, they provided the complete mine map. According to the mine map, the closest and farthest distances from the working face to the old mine works were between 195 and 260 ft. Comparing the values with the ISS data of 213 and 258 ft suggests the ISS survey provided estimates within about ± 2% of actual. The reflection points were later plotted on their mine map (Figure 11).

No verification drilling was needed at this location as the old mine works had closed-loop surveys with an accuracy of 1:5000 and two previously drilled horizontal holes confirmed its location.

Conclusions. The underground ISS method has become a

Figure 9. *ISS reflection points are plotted on the mine map to show the recording of seismic events "supposedly" in front of the receivers. As a result of the ~30° angle between the setup room and old mine works, the reflection points were actually coming from a different location, as indicated by the pair of red lines. When the ISS data are properly migrated, the reflection points are closer to the boundary of its true reflector.*

proven technology around the world. From the seven ISS surveys conducted as part of this study, location percentage errors of approximately ± 3% were confirmed for old mines that ranged from 200 to 1200 ft away from the setup rooms.

Migration of the data could improve the accuracy of the finds at some mine sites. If the setup room and old mines have a relative orientation greater than 15°, then the migration algorithm would help reposition the reflection points to their true reflectors locations.

It is important to note that the ISS results were presented here in simple detail; data acquisition and processing are significantly more complex. Acquiring the data in underground conditions requires special training and attentive-

ness to mine safety. Moreover, ISS data require special processing tools and experience to extract critical information.

As the number of good coal reserve areas decrease, coal companies will have to venture into poorly charted territory that could be rife with complex geologic anomalies, old abandoned mines, etc.

Thus, the mining industry needs to better leverage risk by employing more innovative remote-sensing technologies to address their complex challenges.
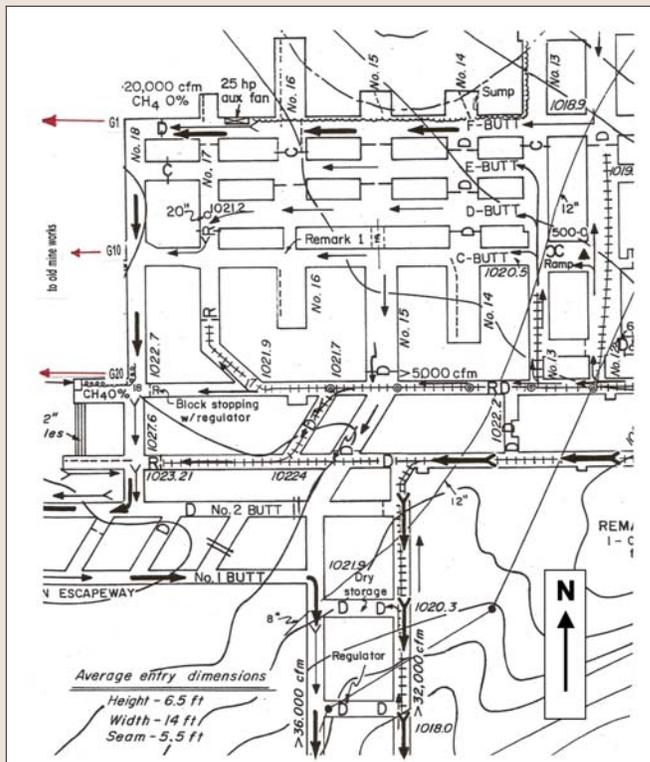
Figure 10. Map shows the Entry no. 18 worksite (upper left corner) where the ISS survey was conducted. Red arrows indicate the seismic energy pathway to old mine works.
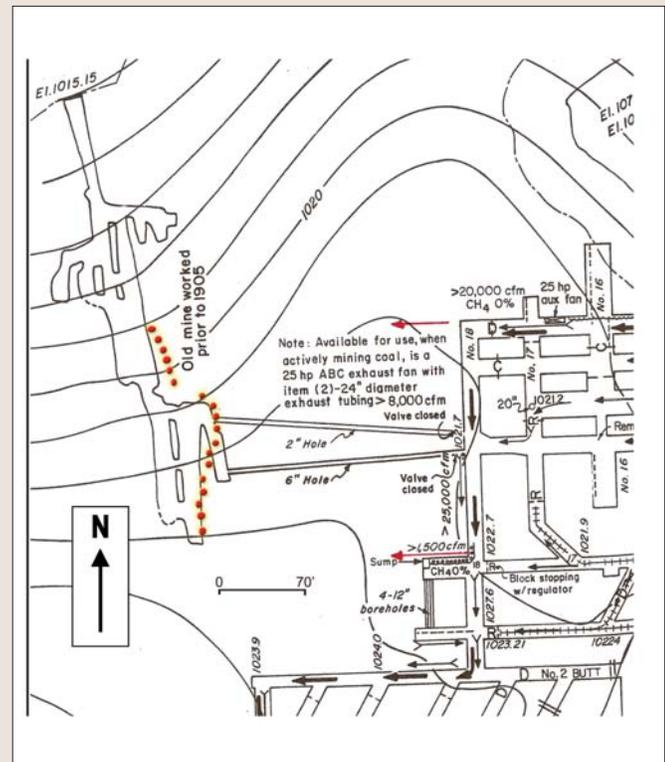

Figure 11. Calculated reflection (red) points were plotted on the mine map to show the accuracy and respective small percentage errors in the blind tests.

Suggested reading. "Theoretical and practical aspects of absorption in the application of inseam seismic coal exploration" by Arnetzl et al.. (SEG Expanded Abstracts, 1981). **"**The propagation of attenuated SH channel waves" by Buchanan, (*Geophysical Prospecting*, 1978). "Fault detection by channel wave seismology in United Kingdom coal seams," by Buchanan et al. (GEOPHYSICS, 1981). "Attenuation in anisotropy of channel waves in coal seams" by Buchanan et al. (GEOPHYSICS, 1983.) Rayleigh channel waves for the inseam seismic detection of discontinuities," by Dresen and Freystatter (*Journal of Geophyisics,* 1976.) "The influence of oblique-dipping discontinuities on the use of Rayleigh channel waves for the inseam seismic reflection method" by Dresen and Freystatter (*Geophysical Prospecting,* 1978). "Inseam seismic method to detect potential underground hazards" by Gochioco (Joint PCMIA/SME Meeting, 1996). "Studies by seismic guided waves of the continuity of coal seams" by Guu (PhD thesis, Colorado School of Mines, 1976).

"Channel waves as a tool of applied geophysics in coal mining" by Krey (GEOPHYSICS, 1963). "Possibilities and limitations of inseam seismic exploration" by Krey (Proceedings of the Coal Seam Discontinuities Symposium, 1976). "Guided modes in coal seams and their application to underground seismic surveying" by Lagasse and Mason (IEEE Ultrasonics Symposium, 1975). "Algebraic reconstruction of a two-dimensional velocity inhomogeneity in the High Hazles seam of Thoresby Colliery" by Mason (GEOPHYSICS, 1981). "Channel wave mapping of coal seams in the United Kingdom" by Mason et al.. (GEOPHYSICS, 1980). "Analysis of digital inseam reflection and transmission surveys using two components"by Millahn and Arnetzl (EAEG meeting, 1979). "Attenuation of seismic waves in dry and saturated rocks; Laboratory measurements" by Toksoz, et al..(GEOPHYSICS, 1979). T_lE

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