**U.S. Department of Labor**

Mine Safety and Health Administration
Pittsburgh Safety & Health Technology Center
P.O. Box 18233
Pittsburgh, PA 15236

Mine Waste and Geotechnical Engineering Division

August 27, 2007

MEMORANDUM FOR IRVING McCRAE
Contracting Officer, Acquisition Management Division
MSHA - Headquarters, Arlington

THROUGH: STANLEY J. MICHALEK
Chief, Mine Waste and Geotechnical Engineering Division

GEORGE H. GARDNER
Senior Civil Engineer, Mine Waste and Geotechnical Engineering Division

FROM: STEVEN J. VAMOSSY
Civil Engineer, Mine Waste and Geotechnical Engineering Division

SUBJECT: Summary of Geophysical Void Detection Demonstration Projects - Surface Seismic Reflection, Vertical Seismic Profiling, and In-Seam Seismic Reflection by L.M. Gochioco & Associates, Incorporated, MSHA Account Number B2532533, RFP No. MSHA J53R1011

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## BACKGROUND

The contract was awarded to Gochioco & Associates on April 25, 2005. John Fredland, Mine Waste and Geotechnical Engineering Division, was the initial COTR for these projects. He oversaw nearly all of the field surveys and dealt with a majority of the

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**BACKGROUND**

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invoicing and other contract issues. However, due to a changing workload, he was unable to continue as the COTR. Therefore, on July 24, 2006, Steven Vamossy was assigned as the COTR for the remainder of the projects.

Gochioco & Associates was the prime contractor for these demonstration projects. Lawrence Gochioco, President, Gochioco & Associates, is a geophysicist and served as the project manager. Geophex, Ltd., was subcontracted to assist with the surface seismic reflection survey. GECOH Exploration, Incorporated, was subcontracted to assist with several of the in-seam seismic reflection surveys. The demonstrations were conducted at five different coal mines including Sterling Mining Corporation's Carroll Hollow Mine, Buckeye Industrial Mining Corporation's Deep Mine 10-6A, Bell County Coal Corporation's Cabin Hollow Mine, Bluff Spur Coal Corporation's Mine No. 1, and NIOSH's Bruceton Safety Research Coal Mine. At the Bell County Coal site, there were two separate adjacent old mine workings that were investigated, the Old Reliance Mine and the Coal Creek Mine. Most of the field work and data acquisition was completed between May 2005 and March 2006.

After the field data was processed, the project summary reports were prepared. Gochioco & Associates submitted three separate reports, one for each method demonstrated for these projects: surface seismic reflection, vertical seismic profiling (VSP), and in-seam seismic reflection. The draft versions of the reports were submitted by June 28, 2006. However, the in-seam seismic project was not actually finished at that time since verification drilling was not completed at one of the demonstration sites (Bell County Coal, Old Reliance Mine). Following the receipt of each draft report, copies were disseminated to the Peer Review Team members for feedback. Comments from the team members were then collected and forwarded on December 15, 2006, to Gochioco & Associates to be addressed. Hard copies and a CD version of the final surface seismic and VSP reports were received by March 30, 2007.

Meanwhile, the drilling to verify the distance to the Old Reliance Mine had yet to be completed and several contract time extensions were issued. Gochioco & Associates relied entirely on Bell County Coal to perform the verification drilling, in accordance with their agreement. In March 2007, the company indicated that they would not be performing the drilling due to budget constraints and changes to the mining plan. In order to fulfill the contract and finish the project, we agreed to Mr. Gochioco's offer to perform another in-seam seismic test at another coal mine where the location of mine voids was previously determined by drilling, in lieu of completing the verification drilling at the Old Reliance Mine. The test was performed with no additional cost to the government. The additional test was conducted at the Bruceton Safety Research Mine on May 17, 2007. Following the completion and data processing from the Bruceton Mine test, the in-seam seismic report was finalized. Hard copies and a CD version of

the final in-seam seismic report was received on June 22, 2007. Based on our review of all three final reports, we have found that the comments from the Peer Review team of the draft reports have been satisfactorily addressed.

In their initial proposal, Gochioco & Associates requested funding for software and hardware so that they could carry out the surface seismic reflection and VSP data processing. MSHA agreed to provide this equipment as Government Furnished Equipment (GFE). The GFE consisted of a Hewlett Packard (HP) computer system and SPW seismic processing software. MSHA purchased the equipment directly from the software producer, Parallel Geoscience. The GFE had to be returned to MSHA at the completion of the project. On July 6, 2007, we received the computer system with preloaded software from Gochioco & Associates. On July 16, 2007, we received the software CDs. Through previous discussions with the Contracting Officers, it was decided that the returned GFE will remain at Technical Support's Pittsburgh Safety and Health Technology Center.

## DEMONSTRATION OF SURFACE SEISMIC REFLECTION METHOD

On July 26 - 28, 2005, surface seismic surveys were conducted at Sterling Mining Corporation's Carroll Hollow Mine in Carroll County, Ohio. Data acquisition for the surface seismic surveys was performed by Geophex, Ltd., under the direction of Mr. Gochioco. For the surface seismic method, both the receivers (geophones) and seismic sources are used along the ground surface.

The surface seismic testing attempted to verify the location of mine workings in the old abandoned Sterling Mine, located to the north and east of future mining in the active Carroll Hollow Mine. These old workings are known to be water-filled. On the old mine map for the Sterling Mine, sections typically end in a tapered pattern, but some of the sections are shown as ending abruptly, without the tapered pattern. This raised concern that portions of the mine map may be missing for these blunt-ended sections. The mining is approximately 250 to 270 feet deep and the mining height is in the range of 34 to 39 inches. The tests were conducted over terrain that was a mixture of open fields and dense woods. The terrain was hilly with fairly steep slopes.

Testing was performed along three lines of geophones designated as Line 1C, Line 2B, and Line 3A. Each line measured approximately 1550 feet in length. The lines started out above areas of solid coal and extended over those areas suspected of overlying old mine workings. The geophones were single axis and spaced at 8-foot intervals. The geophones were installed by clearing the ground of loose material and simply pushing the geophone spike into the ground. A total of 193 geophones were used per line.

The seismic source was provided by a "seisgun," which simply consisted of a pipe with a 12-gauge shotgun shell attached at one end (Figure 1). The loaded end of the gun was

lowered into a 10 to 12 inch deep hole. A rod was then inserted through the pipe to contact the shotgun shell. The other end of the rod extended above the top of the pipe. The shot was fired by sharply striking the end of the rod with a hammer. A trigger mechanism, taped to the top of the rod and activated by the hammer strike, provided the signal for timing the initiation of the shot. Shots were typically made next to every other geophone along the line, i.e., on a 16-foot spacing. However, shot spacing varied from 8 feet to 32 feet, depending on the field conditions. Typically, three shots were put off at each shot location to "stack" the data in order to improve the signal-to-noise ratio. The signals were recorded with a Geometrics Geode system and a laptop computer.

The demonstration showed that the surface seismic work can be highly labor intensive, especially when using a "seisgun" for the seismic source and digging holes using only a heavy, sharply-pointed steel bar. The "seisgun" requires that a 10 to 12-inch hole be dug at every shot location. Digging the holes with the steel bar was exhausting work, especially in the hard-packed open fields. According to Mr. Gochioco, the "seisgun" was used because the rugged terrain made use of a heavy hydraulic or mechanical impact hammer impractical.

Discussion of Results

The seismic reflection results were graphically displayed based on distance and time. The horizontal scale represented the surface position (in feet) of each geophone along the survey line, which is called the shotpoint (SP) station. The vertical scale was measured in time (milliseconds) and represented the recorded two-way travel time for the seismic energy to propagate from the surface down to the target horizon and reflect back to the geophones.

Line 1C was located in the southern part of the mine property. Mr. Gochioco indicated that the signal-to-noise ratio of the seismic data along Line 1C was below average, making it difficult to interpret the data with a high degree of confidence. Coherent coal seam reflection was found between stations SP-23 to SP-53, indicating areas of solid coal. The signals were distorted from SP-54 to SP- 79, indicating subsurface anomalies that could be associated with thin coal, a washout, or even old mine works. Given the quality of the data set, it was not possible to distinguish the nature of these anomalies. From SP-80 to the end of the line, the reflection data was highly disturbed and of lower frequency and amplitude. The contractor interpreted this as corresponding to the presence of water-filled mine works. Therefore, SP-80 should correspond to the boundary of the old Sterling Mine. In 2003, Sterling Mining had previously drilled a surface borehole along the edge of the old mine based on the mine map. The borehole encountered old mine workings. However, this borehole, when compared to Line 1C, intersects station SP-77. Two additional boreholes were drilled near Line 1C in areas interpreted as solid coal and they confirmed the presence of solid coal.

Lines 2B and 3A were located on the northern part of the mine property (Figure 2). Line 2B was located mainly above areas of solid coal with only a small portion of the line straddling the edge of the old Sterling Mine according to the mine map. Based on the interpreted results, there were no disturbances detected that are normally associated with old mine workings. Thus, solid coal was detected beneath the entire survey line. Three verification boreholes were drilled along the line at stations SP-41, SP-60, and SP-180. As expected, the boreholes at SP-41 and SP-180 confirmed solid coal. However, the borehole at SP-60 encountered old mine works. Station SP-60 is along the small portion of the line straddling the edge of the old Sterling Mine as previously mentioned. Since the survey line was near the edge of the old mine, Mr. Gochioco believes that both the solid coal and old mine works contributed to the recorded reflections and resulted in complex waveforms that could not be interpreted as old mine workings.

Line 3A was placed nearly perpendicular to Line 2B and a significant portion of the line was placed above the old Sterling Mine according to the mine map. Coherent coal seam reflection was found up to station SP-98, indicating areas of solid coal. At SP-98, a major disturbance was found that could be interpreted as a fault or old mine works. The disturbance continued until SP-132. From SP-132 to the end of the survey line, the data showed a complete scattering of the seismic signals in which no coherent seismic reflections were recorded (Figure 3). Mr. Gochioco suggested that this is part of the old mine works and that the roof rock is highly fractured. From SP-98 to SP-132, he indicated that the disturbance is most likely old mine works with competent roof rock. Two verification boreholes were drilled along the survey line at stations SP-82 and SP-175. As expected, the borehole at SP-82 encountered solid coal and the borehole at SP-175 encountered old mine works.

## DEMONSTRATION OF VERTICAL SEISMIC PROFILING METHOD

Two separate VSP surveys were conducted at Sterling Mining Corporation's Carroll Hollow Mine in Carroll County, Ohio. The first VSP survey was conducted on May 24, 2005, but the borehole used for the survey turned out to be in an area where there was no underground mining where it was suspected to exist. To fulfill the requirements of the contract and to demonstrate that the method can locate mine voids, a second VSP survey was performed on March 13, 2006. For the second survey, Tim Miller, Geologist, Sterling Mining Corporation, was confident that the new borehole was located near the old mine workings (old Sterling Mine).

The VSP method typically utilizes hydrophone receivers that are lowered down a water-filled borehole and a seismic source that is generated on the ground surface (Figure 4). The location of the two VSP sites with respect to the old Sterling Mine is shown on Figure 5. The borehole for the second VSP survey, designated by Sterling as KANTZ05-8, was located in a farm field. The borehole extended 15 feet deeper than the coal seam, which was at a depth of approximately 150 feet. Seismic sources were then

created on the surface at set distances along two surveyed lines going away from the borehole. As in the surface seismic demonstration, a "seisgun" was used as the seismic source. Along the first line, which extended from the borehole over old mine workings, shots were discharged at distances of 50, 100, 150, and 200 feet from the borehole. Along the second line, which extended from the borehole over what was expected to be solid coal, shots were discharged at distances of 50, 100, and 150 feet from the borehole.

The receiver string consisted of twelve hydrophones spaced at 3-foot intervals. Separate shots were made when the bottom of the entire hydrophone string was positioned at 10 feet below the coal seam, and then at 27 and 63 feet above the seam. With this positioning of the hydrophones within the borehole, seismic data was collected over a vertical interval of approximately 100 feet. Data was collected, displayed and saved using a Geometrics Geode system and a laptop computer.

Discussion of Results

In order to successfully detect old mine workings, the VSP method relies on good quality data acquisition (high signal-to-noise ratio) in order to identify the "first breaks" from the data record. The first breaks are the first recorded seismic arrivals that reflect off the edge of the mine workings and travel back to the hydrophones.

The borehole for the first VSP survey was supposed to be about 80 feet away from the old mine works, but instead turned out to be 250 feet away. The data quality from this test turned out to be poor (low signal-to-noise ratio), and the data was dominated by multiple downgoing and upgoing tube waves. Tube waves are seismic signals that propagate up and down the water-filled borehole and they can normally be filtered out during data processing. However, due to the poor signal-to-noise ratio, the tube wave velocity was very similar to the primary compression wave (P-wave) velocity reflecting from the old mine works, and could not be separated/filtered out. Thus, the first break arrivals could not be identified.

The borehole (KANTZ05-8) for the second VSP survey was estimated to be 50 feet away from the old mine works. During processing, it was evident that the data acquired during the second survey was also of poor quality. Once again, the data was dominated by tube waves. However, the first break arrivals from the closest source offset (50-foot) could be interpreted. Based on his interpretation, Mr. Gochioco felt the old mine works were closer than 50 feet away from the borehole. The company drilled a second borehole into the old mine works. This borehole was 100 feet away from KANTZ05-8 and the company conducted their own crosshole seismic testing between the two holes. The crosshole seismic testing detected the old mine works about 15 to 20 feet away from KANTZ05-8. It is noted that in an actual engineering survey we would not generally accept the results of one geophysical method to confirm the results of another geophysical method without drilling.

To minimize the problem of tube waves, Mr. Gochioco suggests that a wall-locking geophone system could be used instead of hydrophones. The geophones would still record tube waves but at a lesser amplitude since they are less sensitive to tube waves than hydrophones. However, Mr. Gochioco is not aware of a current, commercially available wall-locking geophone system. Such a system would be expensive to develop. In the past, when Mr. Gochioco worked for CONSOL Energy, they had developed a wall-locking geophone system that cost over $110,000.

## DEMONSTRATION OF IN-SEAM SEISMIC REFLECTION METHOD

In-seam seismic tests were conducted at five different mine sites and are summarized below. The same general procedures were followed at each mine. Each survey utilized single-axis geophone receivers that were installed along the coal rib. The geophones were installed by simply drilling a small hole into the rib and pushing the spike of the geophone into the hole until a snug fit was obtained (Figure 6). Seismic sources were created by either detonating a single blasting cap and small explosive charge in holes drilled into the rib, or by striking the rib with a sledge-hammer (Figure 7). The selection of a suitable seismic source depends on various mining conditions including the distance to the target and hardness of the coal. The seismic response data was recorded with the Geometrics Geode system and a laptop computer (Figure 8). For each source shot, the response waves are displayed on the laptop screen, allowing the quality of the collected data to be observed. The data is then analyzed and the mine voids are located based on measuring the P-wave velocity in the coal and identifying the arrival time of the wave that is reflected from the edge of the mine workings. Reportedly, experienced geophysicists can usually tell whether a void is air-filled or water-filled, if they are within 200 to 300 feet of the void, by the difference in frequency of the reflected P-wave.

The software that Gochioco & Associates used to process the in-seam seismic results is based on a straight ray approach that calculates reflection points based on the recorded two-way wave arrival times. The results are most accurate in cases where the old mine workings are nearly parallel to the test setup barrier. When the two are not parallel and have considerable "angle" between them, then the margin of error increases as the reflection points are not actually in front of the geophone, but could come from either side of the geophone. To correct this problem, a more sophisticated algorithm called migration is usually applied to the data set. Migration is an inversion process that rearranges the seismic data elements so that reflections and diffractions are re-plotted to their true subsurface locations. Gochioco & Associates claims that they did not have the resources to develop the migration algorithm for this demonstration. Therefore, they indicate that some of the results from this demonstration project will have reflection points located outside or beyond the old mine works in situations where the orientation of the test barrier and old mine works were not parallel.

**Site No. 1: Sterling Mining Corporation's Carroll Hollow Mine**

On November 4, 2005, an in-seam seismic survey was conducted at Sterling Mining Corporation's Carroll Hollow Mine in Carroll County, Ohio. Dr. Rene Rodriguez, of GECOH Exploration, Inc., provided assistance during this survey. The survey was conducted in the 1st Right Submains of the Carroll Hollow Mine, approximately 2000 feet inside the mine's drift opening. The mine is in the Mahoning 7A coal seam. The seam is typically 36-inches thick and the mining height varies from approximately 38 to 40 inches.

The test site was along a coal barrier between the Carroll Hollow Mine and the old Sterling Mine, which is located to the north and east. The old mine workings were estimated to be between 600 and 650 feet away from the test site. Future development in the Carroll Hollow Mine is anticipated to the north, adjacent to the old workings, which are known to be filled with water and dipping toward the active mine.

The in-seam seismic survey consisted of four separate lines, with each line consisting of 12 geophones spaced at 20-foot intervals. For the four adjacent setups, a length of 960 feet along the pillar was surveyed. Seismic sources were created by detonating small explosive charges in holes drilled into the ribs. For each setup, five charges were detonated, one 10-foot outside each end of the geophone string and three at 60-foot intervals within the string. The charges, detonated at different times, consisted of either approximately a one-half-inch long portion of a stick of dynamite or a "stinger." Detonation was by an electric blasting cap. Based on the signal traces measured by the seismograph, it appeared that good data was obtained.

Discussion of Results

Only 17 out of the 48 geophones (G31 to G47) detected the old mine workings. Very low amplitude signals were recorded by the remaining geophones, which can be interpreted as areas of solid coal. By using the recorded arrival times and measured P-wave velocity of the coal seam, the distance to the old mine works was calculated. The calculated distances ranged between 605 and 637 feet. The 17 reflection points were then plotted on the company's mine map. Six of the reflection points were located beyond (outside) the edge of the old mine works (Figure 9). The company believes that their mine map is accurate. Therefore, Mr. Gochioco believes those six reflection points most likely result from not applying the migration process to reposition the reflection points. This conclusion seems correct since two verification boreholes were drilled near two of those outer reflection points (G33 and G36) and both holes encountered solid coal. If migration was applied, Mr. Gochioco indicates that all 17 reflection points would be rotated (slightly clockwise) about 120 feet in the southeast direction.

**Site No. 2: Buckeye Industrial Mining Corporation's Deep Mine 10-6A**

On December 6, 2005, two in-seam seismic surveys were conducted at Buckeye Industrial Mining Corporation's Deep Mine 10-6A near Bergholz, Ohio. Dr. Rene Rodriguez of GECOH provided assistance during these surveys. The surveys were conducted in the 3 Left Submains and in the Southwest Submains of Mine 10-6A. The survey sites were located approximately 3000 and 4500 feet inside the Mine No. 10-6A drift opening. The mine is in the Lower Freeport No. 6A coal seam and the mining height was only 36 inches. The surveys were conducted in an intake airway. The outer coal rib in these areas faces an old abandoned mine called the 6A Deep Mine. According to the mine map, the old mine works ranges between 1000 to 1200 feet from the 3 Left Submains and about 1300 feet away from the Southwest Submains. The old mine works are reportedly filled with water. There is another abandoned mine located directly above the 6A Deep Mine in the No. 7 coal seam. The interburden thickness between the two coal seams is approximately 45 feet. The mining in this shallower seam is much more extensive and had an influence in the geophysical results, which will be discussed below.

At each survey location, two separate lines were set up along the rib, with each line consisting of 12 geophones spaced at 20-foot intervals. Each line covered a length of 240 feet along the rib and the two combined lines covered 480 feet along the rib. Since this mine does not use explosives, seismic sources were created by striking a 10-pound sledgehammer against the rib. For each setup, the rib was struck in five different locations, one 10-foot outside each end of the geophone string, and three at 60-foot intervals within the string. A triggering device was taped to the head of the sledge-hammer.

Considering the small size of the abandoned mine, and the distance to it, there was some concern about the strength of the seismic signal that would be generated by using the sledge-hammer. However, since the coal in this area is relatively hard and competent, Mr. Gochioco indicated that good signals were obtained. There was no need to "stack" the signals by striking the same spot multiple times. Based on the signal traces measured by the seismograph, it appeared that good data was obtained.

Discussion of Results

During the initial data processing, it was evident that the coal seam at this site yielded rather high P-wave velocity values of about 11,000 feet/second (ft/sec). Typically, the P-wave velocity in coal averages 8,000 ft/sec. Since the surrounding shale and sandstone layers also have the same high velocity (around 11,000 ft/sec), this means that the coal seam would not act as a good wave guide for the seismic energy and it would allow the signals to "leak out" during propagation. By using the recorded arrival times from the recorded reflection events, the distance to the old mine works

was calculated. The calculated distances ranged between 830 to 1040 feet from the 3 Left Submains survey line and between 942 and 1035 feet from the Southwest Submains survey line. These distances differed significantly from the distances indicated on the mine map. However, when these reflection points were then plotted on the mine map, the reflections points clearly coincided with the outline of the old mine works in the shallower No. 7 coal seam (Figure 10). Mr. Gochioco's assessment is that the seismic waves "leaked out" of the No. 6A coal seam with an expanding aperture, and the first mine voids that were detected were from the No. 7 coal seam. Attempts were made to filter out the reflections from the shallower seam in order to enhance the data associated with the 6A Deep Mine, but no useful data could be extracted. The company had already drilled a series of 25 boreholes at 10-foot centers to confirm the outline of the old mine works in the No. 7 seam. The majority of the reflection points fell within a 50-foot radius of the boreholes. Therefore, Mr. Gochioco feels that the boundary of the old mine works in the No. 7 coal seam were detected with a high degree of accuracy even though it was the wrong target objective.

**Site No. 3: Bell County Coal Corporation's Cabin Hollow Mine**

On January 14, 2006, two in-seam seismic surveys were conducted at Bell County Coal Corporation's Cabin Hollow Mine, which is located in Claiborne County, Tennessee. Dr. Rene Rodriguez of GECOH also provided assistance during these surveys. Each survey line consisted of 24 geophones. The geophones were spaced on 20-foot centers covering approximately 480 feet along the rib. A seismic source was provided by detonating a single blasting cap in a hole drilled into the rib. The source was separately detonated 10 feet off each end of the line of geophones, as well as at 60-foot intervals within the line. This resulted in nine total source shots. The mine is located in the Buckeye Springs coal seam and the mining height varied between 4 to 5 feet in the survey areas.

The first survey was conducted approximately 2000 feet into the mine at the point where the mains turn a ninety-degree angle to the right. If the mains continued straight, they would eventually intersect with the old workings of the Old Reliance Mine, which are located approximately 1000 feet away from the point where the mains turn. The 24 geophones were installed in the rib starting from a point approximately 15 feet from the corner and extending 460 feet along the rib closest to the old workings.

The second survey site was approximately 8000 feet into the mine near the active mining face. The site was in an area where a southwest-facing rib is adjacent to workings in the Coal Creek Mine. This portion of the Coal Creek Mine is reportedly sealed, but the mine is otherwise active. According to the mine maps, the Coal Creek workings vary in distance from about 600 to 800 feet from the test site. Since the Coal

Creek Mine is run by Bell County Coal, there is a high level of confidence in the maps. According to the company, the maps for both mines are based on closed-loop surveys using the same common reference points.

Discussion of Results

The data for the first survey was processed. The calculated distances to the Old Reliance Mine ranged between 997 to 1198 feet. The reflection points were then plotted on the mine map. Many of the calculated reflection points fell nearly on the edge of the old mine workings. The company had indicated that the results for the Old Reliance Mine would be verified by horizontal drilling. However, as mentioned earlier, this drilling was never performed. Therefore, we cannot comment on the accuracy of the results from this survey.

When the data for the second survey was processed, Mr. Gochioco felt that there would be migration issues at this site since the Coal Creek Mine workings were oriented at a 30° angle from the test site. The calculated distances to the old mine works ranged between 671 to 754 feet. As expected, when the reflection points were plotted on the mine map, several of the points were located beyond the edge of the mine workings. Mr. Gochioco chose two of the reflection points, G24 and G15, which had calculated distances of 671 feet and 754 feet, respectively. He applied the migration method (by hand) to those two points to determine their true reflecting surface location (Figure 11). The estimated distances based on the new reflected surfaces for G24 and G15 were 650 feet and 725 feet. These new distances coincided closely with what the mine map indicated. Verification drilling was not performed since the old mine had previously been accurately surveyed. Due to the lack of applying migration to the data set, the survey results were not completely accurate.

**Site No. 4: Bluff Spur Coal Corporation's Mine No. 1**

On January 22, 2006, an in-seam seismic survey was performed at Bluff Spur Coal Corporation's Mine No. 1 in Wise County, Virginia. This survey differed from the other in-seam seismic surveys performed in that this testing was "blind." That is, Mr. Gochioco was not provided access to a mine map showing the location of the target workings. Mr. Gochioco agreed to perform the testing "blind" and he surveyed two adjacent setups along the No. 1 West Mains in Mine No. 1. The target workings are in a sealed section of the same mine about 500 to 600 feet away from the test setup area. The mine is located in the Taggart coal seam and the mining height was approximately 4 feet.

Each survey line consisted of 24 geophones. The geophones were spaced on 20-foot centers covering approximately 480 feet along the rib. A seismic source was provided by detonating a single blasting cap in a hole drilled into the rib. Sources were

separately detonated 10 feet off each end of the line of geophones, as well as at 60-foot intervals within the line. This resulted in nine total source shots.
During the initial test setup, the coal face was found to be highly fractured.
Mr. Gochioco indicated that when the coal face is highly fractured, it leads to poor source-receiver coupling, and usually results in the recording of poor quality data.

Discussion of Results

Mr. Gochioco indicates that the data was of poorer quality when compared to the other in-seam seismic tests. Due to the highly fractured coal face, the signal-to-noise ratio was low. Only 44 percent of the geophones recorded an interpretable reflection event. The distance to the old mine works was then calculated and ranged between 603 to 676 feet. Mr. Gochioco was then given a copy of the mine map. When the reflection points were plotted on the mine map, several of the reflection points were off target (Figure 12). The targeted entries and crosscut sections were oriented at different angles to the test setup area; so once again, the migration issue played a role in the accuracy of the survey results. Verification drilling was not needed at this test site since the mine is accurately surveyed.

**Site No. 5: NIOSH's Bruceton Safety Research Coal Mine**

As mentioned, Gochioco & Associates had performed one of their in-seam seismic tests at Bell County Coal's Cabin Hollow Mine. Prior to the test, Bell County Coal agreed to perform horizontal drilling to verify the distance to the Old Reliance Mine. However, the company did not conduct this drilling due to economic factors and changes in their mining plans. As a suitable compromise with MSHA to fulfill his contract, Mr. Gochioco agreed to conduct an additional in-seam seismic survey at another coal mine, in lieu of completing the verification drilling at the Old Reliance Mine. The additional test was conducted at no additional cost to the government.

After a series of meetings with Mr. Gochioco, we came up with the option to test at the Bruceton Safety Research Coal Mine located at the Pittsburgh Safety and Health Technology Center. The test was conducted on May 17, 2007. The mine is operated by NIOSH for experimental purposes. There are abandoned mine workings located between 200 and 260 feet away from the active mine section which he attempted to detect. The location of the abandoned mine has already been verified through horizontal drilling in connection with a past NIOSH project. We did not give Mr. Gochioco a copy of the mine map or inform him how far away the old mine is, so we treated this test as another "blind" test.

The Safety Research Mine is located in the Pittsburgh coal seam and has an average mining height of 6.5 feet. The abandoned mine is air-filled and is located to the east of the Safety Research Mine. The survey was conducted along a 200-foot-long rib located

in the southeast corner of the mine. A single survey line consisting of 20 geophones spaced at 10-foot intervals was setup along the rib. The seismic source was created by striking a 10-pound sledge-hammer against the rib. The rib was struck in seven different locations, equally spaced at 30-foot intervals within the line of geophones. A triggering device was taped to the head of the sledge-hammer. Mr. Gochioco felt that they gathered quality data during the survey. After his initial review of the first arrivals and reflections from the raw data, he felt that the abandoned mine was fairly close in distance, about 200 to 300 feet away.

Discussion of Results

The abandoned mine is oriented nearly parallel to the active mine, so the migration issue did not affect the data from this survey. The conditions were ideal, therefore high quality data was obtained. All 20 geophones recorded a reflection event. The distance to the abandoned mine was then calculated and ranged between 213 and 258 feet. After Mr. Gochioco informed us of his results, we provided him with a copy of the mine map. The reflection points were plotted on the mine map and coincided closely with the boundary of the old abandoned mine (Figure 13). Therefore, the survey results turned out to be very accurate. As mentioned, verification drilling was already performed at this site.

## CONCLUSION

In summary, Gochioco & Associates had limited success in detecting mine voids with the in-seam seismic and surface seismic methods. The VSP method was not successful in this situation. The in-seam seismic method performed better when the test setup area and the target mine works were oriented nearly parallel to one another. It appears that the migration process, as explained earlier, should be employed in every in-seam seismic survey to avoid any issues when the target mine workings are not parallel to the test location.

The Peer Review Team members provided mixed opinions of the results.
Dr. Robert Nigbor indicated, "the results of the in-seam seismic surveys were mixed; three surveys did a good job of imaging the designated targets, but the first blind test did not yield good results." Dr. Dayakar Penumadu feels that the VSP method should not be given a "bad name" even though it was not successful in this situation. He suggests that a stronger seismic source could have improved the results of both the surface seismic and VSP surveys.

If you have any questions, please contact me.

cc: M. Terry Hoch – Chief, PSHTC
K. Fields – TS
J. Fredland - TS

Figure 1: Overview of "seisgun" seismic source.

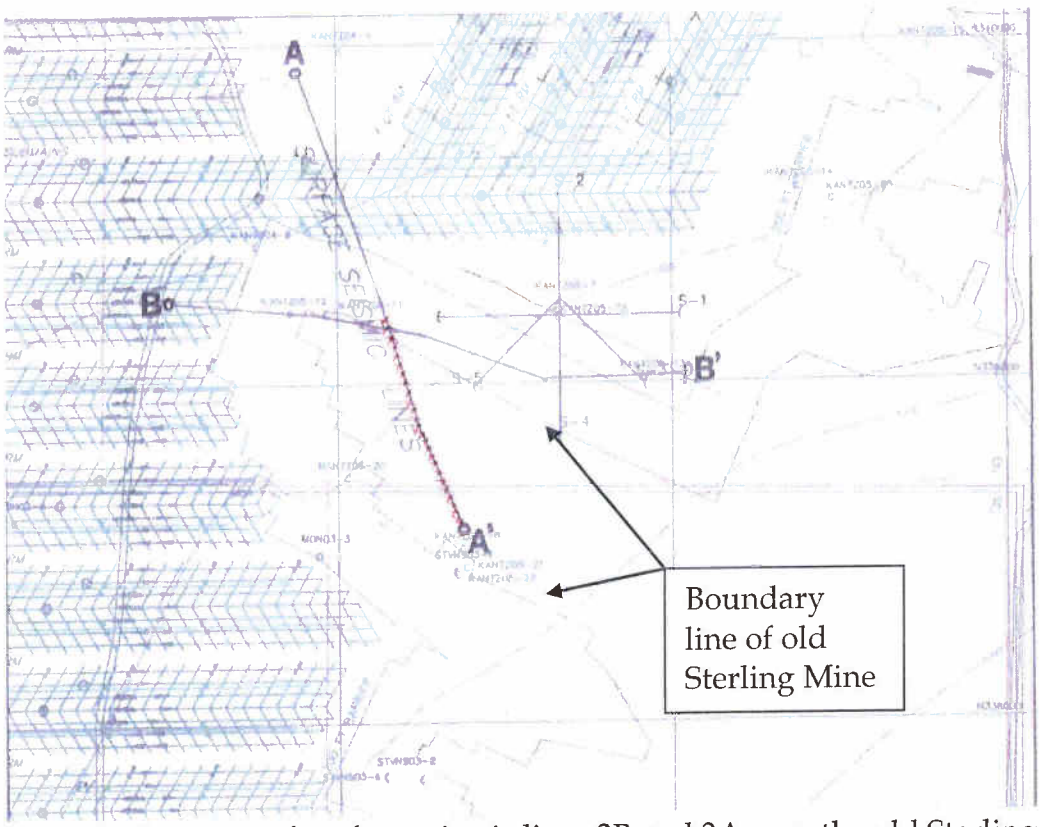


Figure 2: Location of surface seismic lines 2B and 3A near the old Sterling Mine.

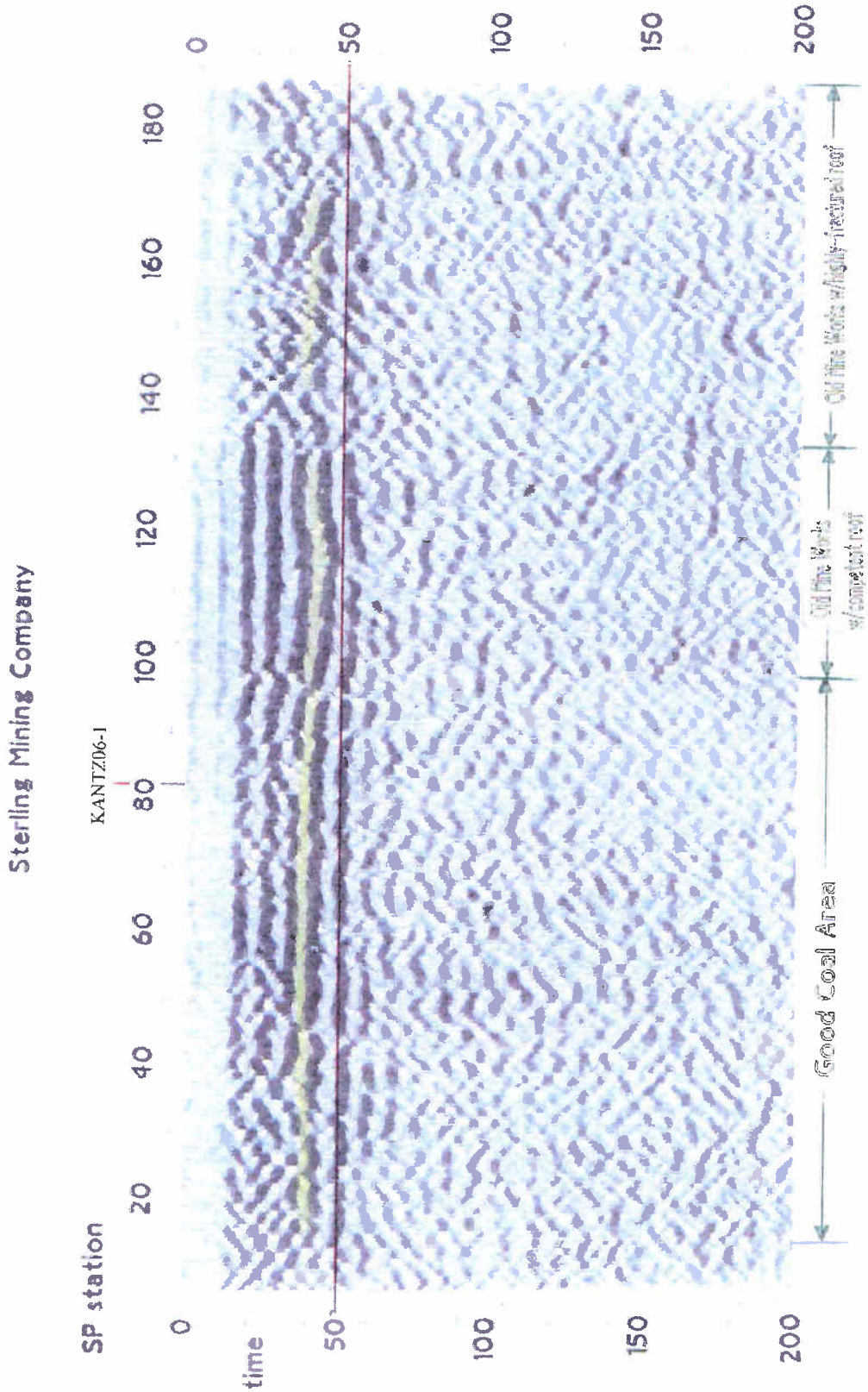


Figure 3: Interpreted seismic section from line 3A showing transition from areas of solid coal to old mine workings.

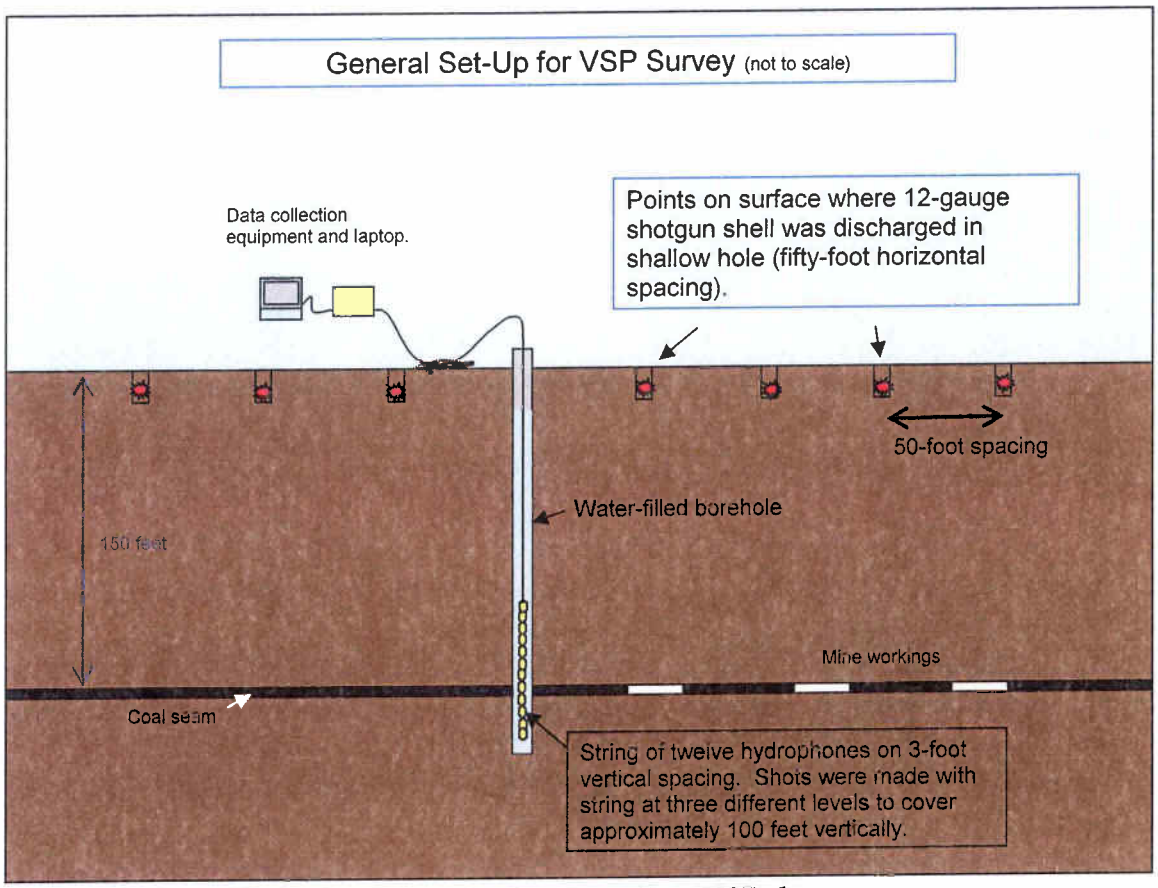


Figure 4: Simplified schematic of setup to collect VSP data.

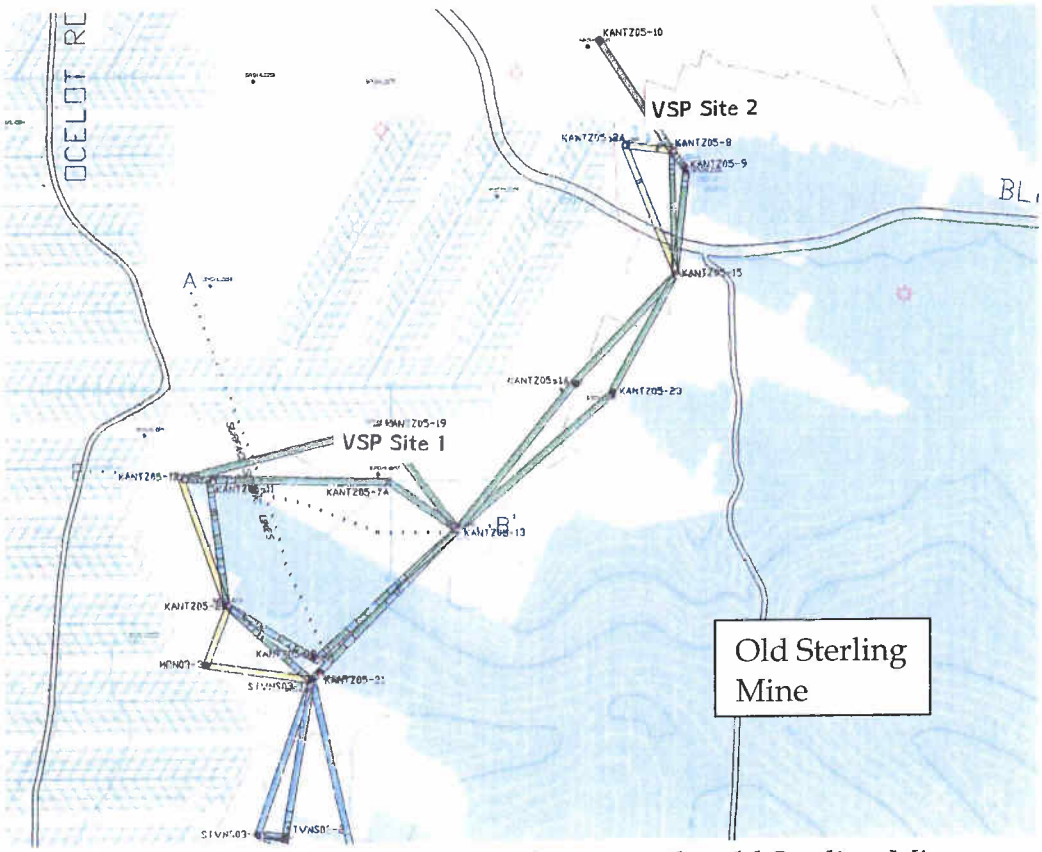


Figure 5: Location of two VSP sites adjacent to the old Sterling Mine.

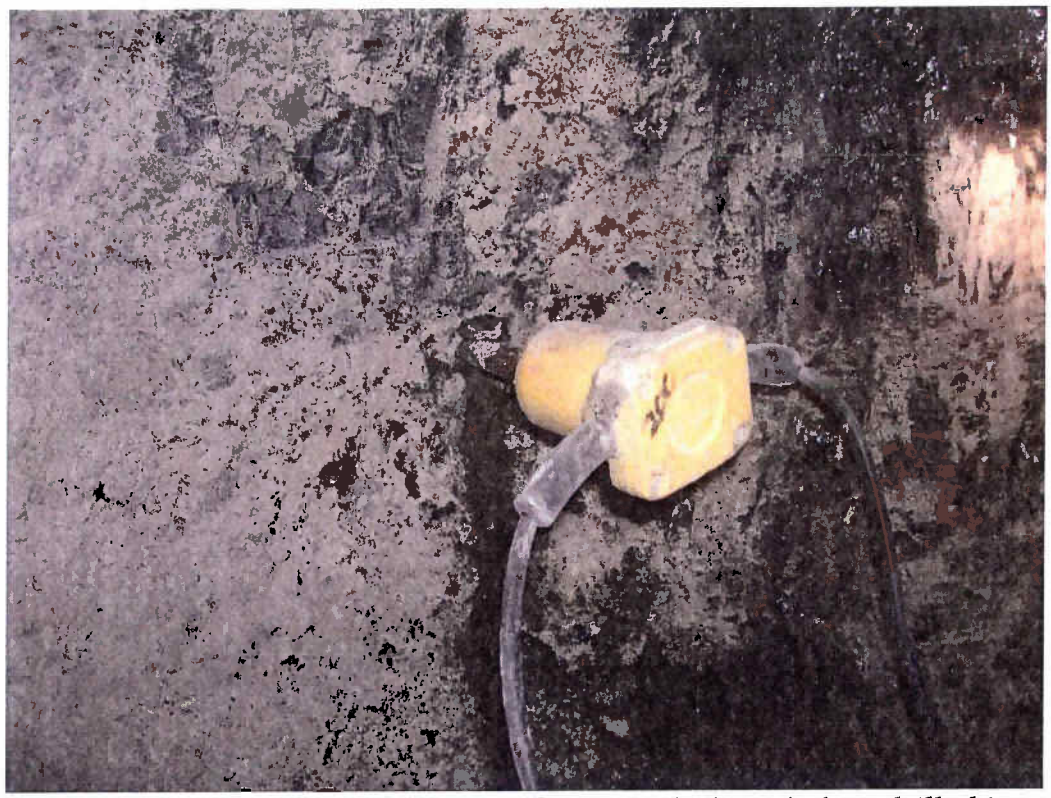

Figure 6: Example of geophone installed in coal rib. A hole is drilled into the rib and the spike on the geophone is pushed into the hole until a snug fit is obtained.

Figure 7: Striking rib with 10-pound sledgehammer to generate seismic source.

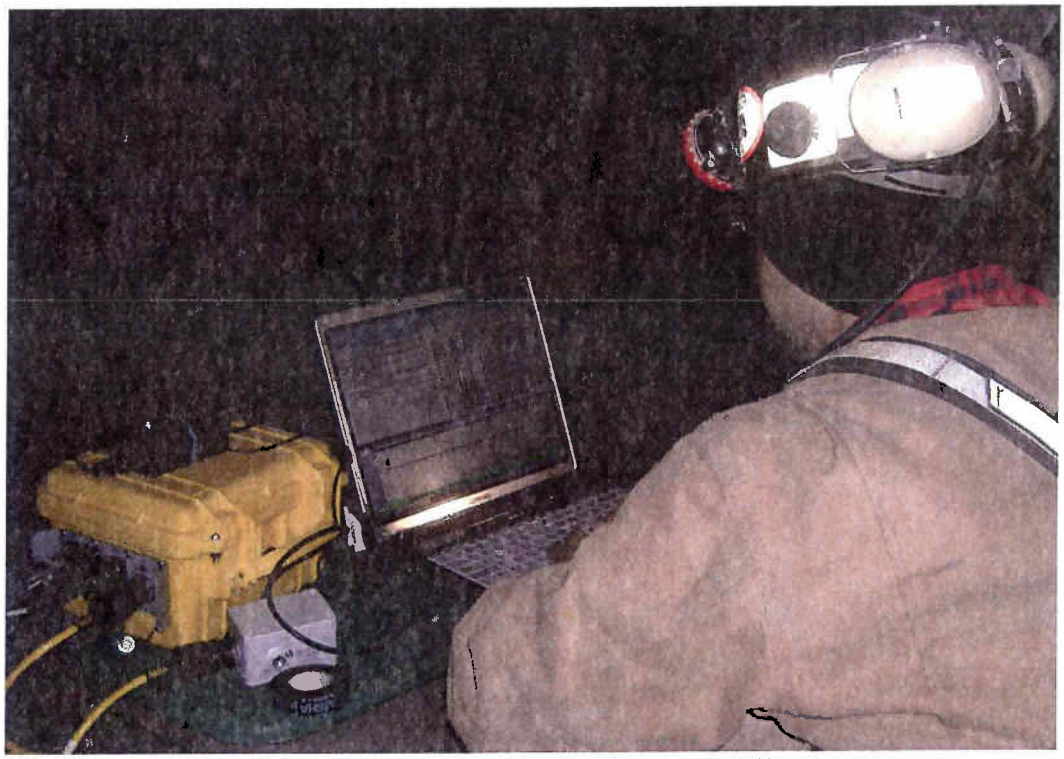

Figure 8: Lawrence Gochioco monitoring the data-collection equipment.

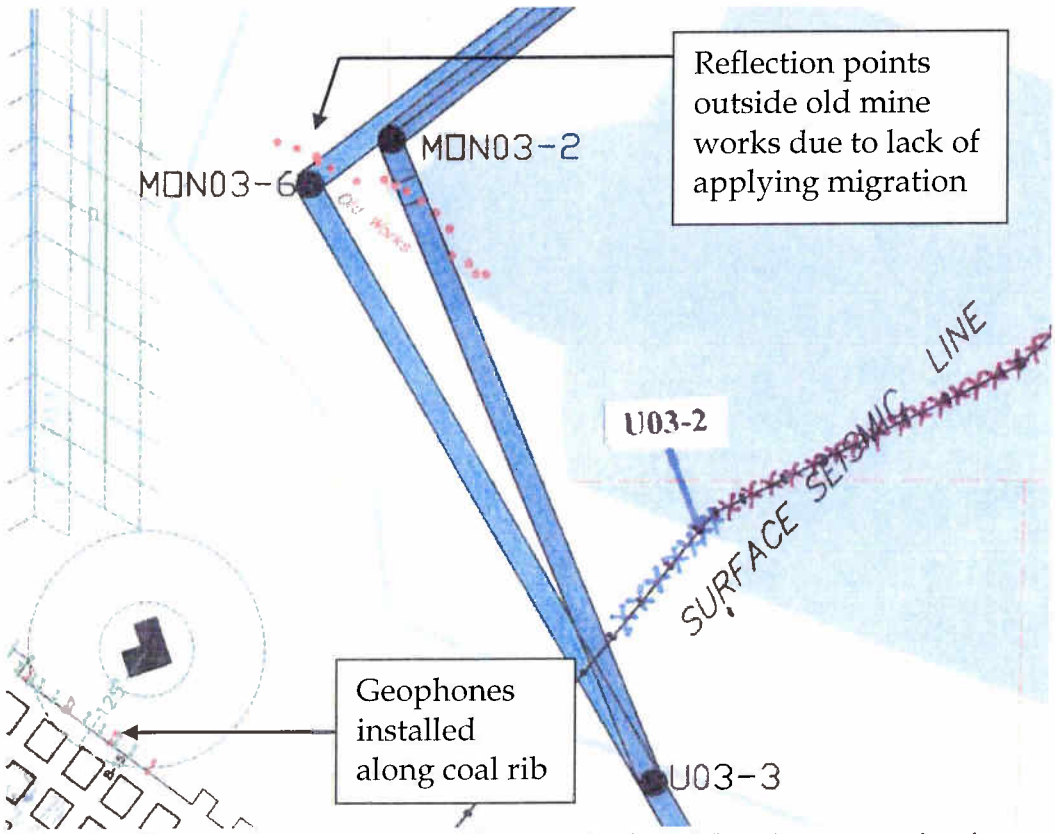


Figure 9: Reflection points plotted from Sterling Mine in-seam seismic survey. Boreholes MON03-06 and MON03-02 encountered solid coal.

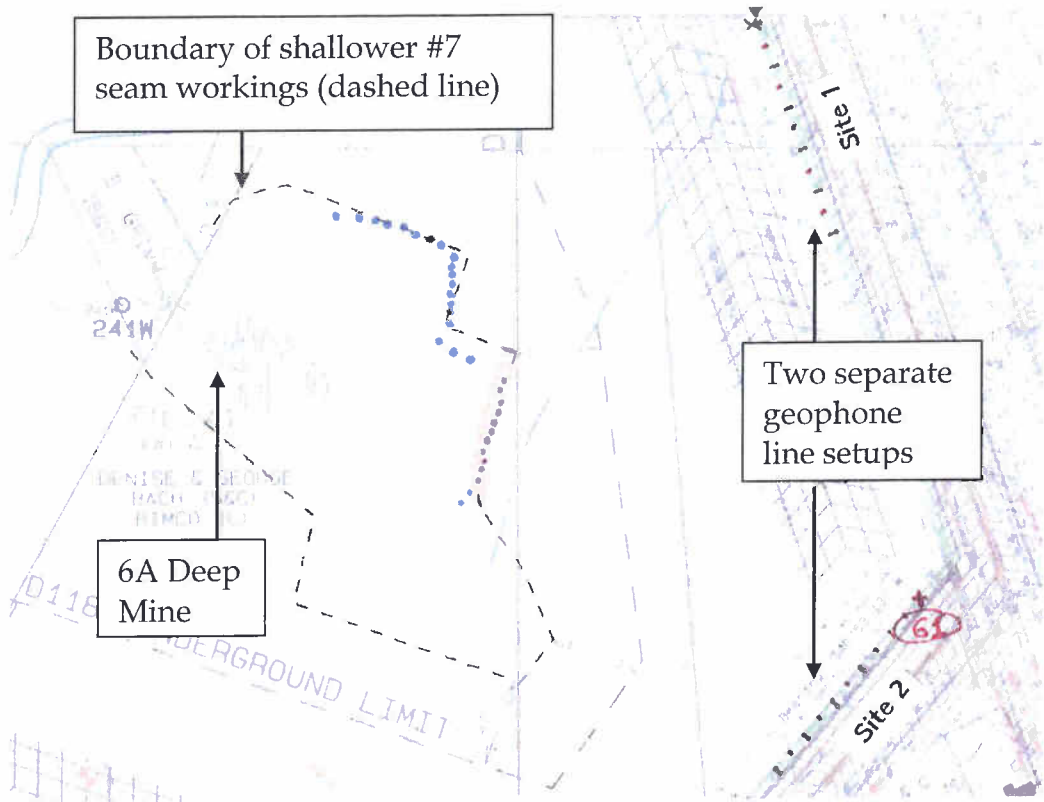


Figure 10: Reflection points plotted from Buckeye Mining survey.

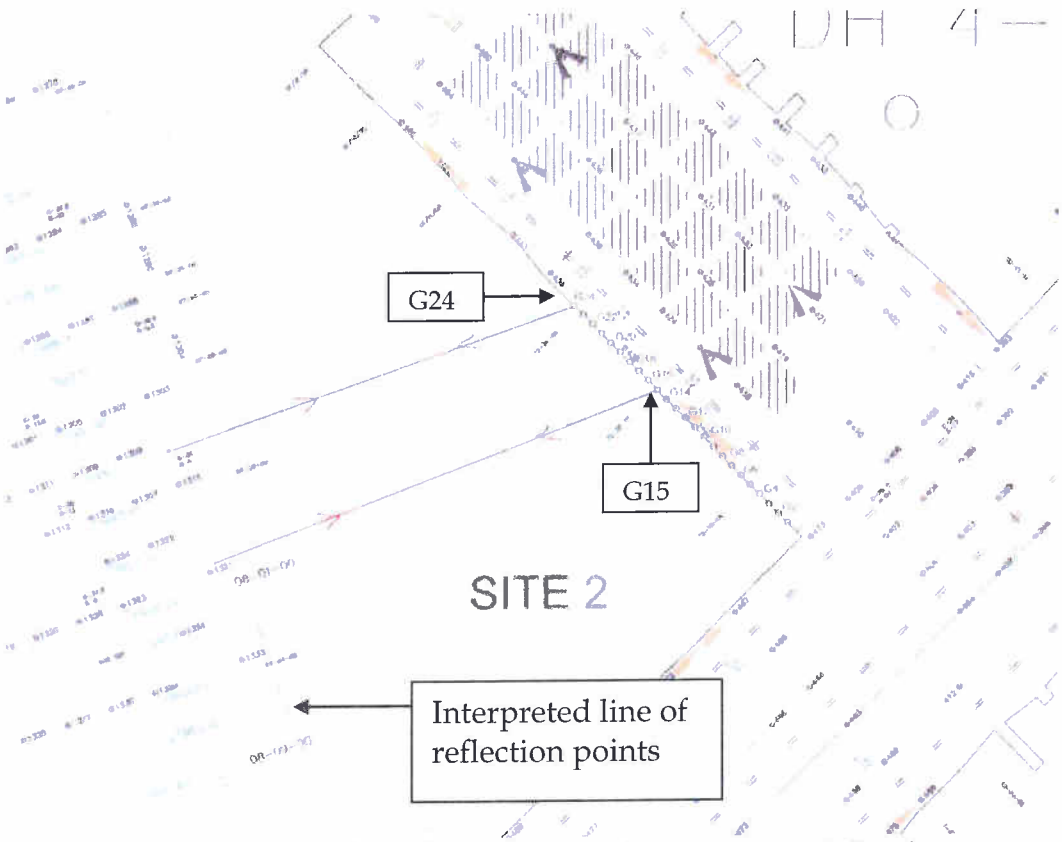


Figure 11: Reflection points plotted from Bell County Coal Creek mine survey. Estimated target paths from G24 and G15 also shown after applying migration.

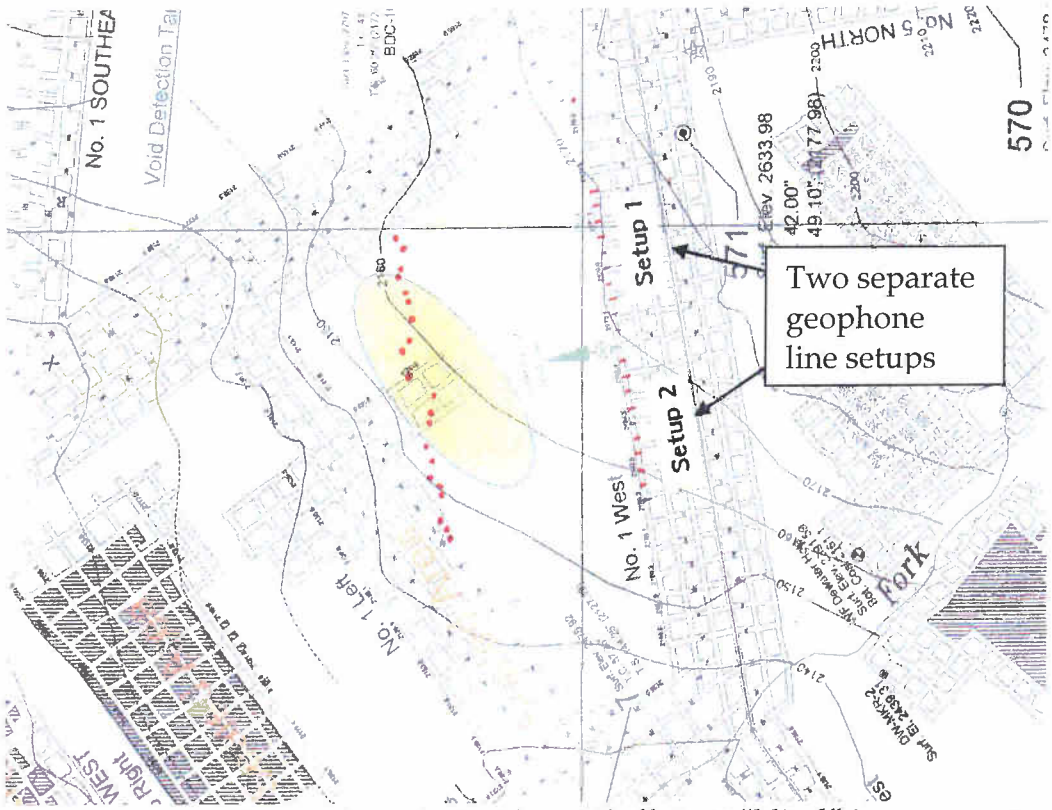


Figure 12: Reflection points plotted from Bluff Spur "blind" in-seam survey.

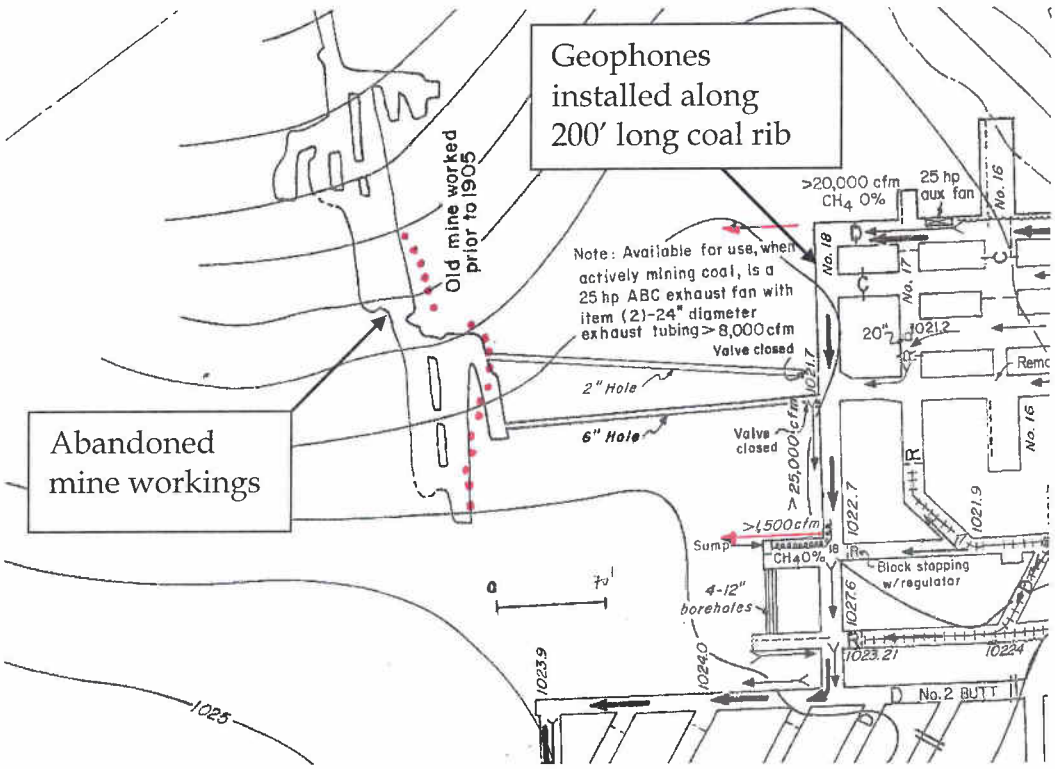


Figure 13: Reflection points plotted from NIOSH Bruceton mine survey. The results of this second "blind" test were fairly accurate.