Multiple Underground Inseam Seismic (ISS) field demonstration surveys to detect old abandoned mine workings at several coal mines

MSHA Contract # J53R1011

Submitted by

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SUMMARY

LM Gochioco & Associates Inc. received a contract from MSHA on April 2005 to conduct a total of six different inseam seismic (ISS) surveys, but the company conducted a total of seven instead. The first underground ISS field demonstration was conducted at the Carroll Hollow Mine of Sterling Mining Corporation. A major roof fall in late October accelerated the acquisition program to November 3, 2005 because the coal company could not guarantee keeping the proposed study area in fresh air environment. At the time of acquisition, the estimated abandoned mine works distance was between 600 and 650 feet away. Results of the ISS survey revealed the distance to the old mine works to range from 605 to 637 ft - a close correlation. At this site, the estimated percentage error was calcultaed to be less than 3%.

Two ISS surveys conducted at the Deep Mine 10 of Buckeye Industrial Mining Corporation yielded unusual results. Due to unique geologic conditions in which the coal seam had a very high P-wave velocity, the seam did not act as a good waveguide. As a result, more seismic energy “leaked out” and the aperture of the wavefront grew as it propagated towards the old mine works. Unfortunately, there was another shallower old mine works that extended further out than the target old works. Thus, the ISS survey detected the outline of the shallower old mine works with a high degree of accuracy instead of the #6A Deep Mine. From Site 2, majority of the reflection points feel within 50-ft radius of 25 closely-spaced dillholes. From an estimated range of about 1000 ft away, the estimated percentage error was calculated to be less than 3%.

Bell County Coal Corportion provided two different targets at their Cabin Hollow Mine. Results from the ISS survey conducted at Site 1 to detect the Old Reliance Coal Mine revealed estimated distances of between 997 and 1198. When the ISS data were digitally plotted on their mine map, the reflection points fell almost right on top of the projected mine boundary. Unfortunately, the coal company did not drill a verification hole to confirm the survey results within a year because the executives believed the results were accurate and they could save money from drilling the verification hole. Thus, LM Gochioco & Associates Inc. was required to conduct another ISS survey because the former survey did not meet the required guidelines set by MSHA.

As for Site 2 at the Cabin Hollow Mine, the ISS data indicated the old Coal Creek Mine was detected to range from 671 to 754 ft. Since the old Coal Creek Mine had a closed-loop survey done by the company with an accuracy of 1 to 5000 parts, its location is precise. Taking the known location and the measured distances from the ISS survey, the estimated percentage error was calculated to be approximately 3.6%. Even though there were known old mine works overlying and underlying the active mine, geologic conditions were appropriate such that this particular coal seam turned out to be a good waveguide to seismic energy.

MSHA recommended a blind test be conducted to test the team’s ability to detect and measure old mine works without any prior knowledge of its whereabouts and orientation. The team took the challenge and conducted an ISS survey at the Mine No. 1 of Bluff Spur Coal Corporation. Underground conditions were not conducive to collect good quality ISS data as the coal face was highly fractured. In addition, the geometry (a 3-4-5 right triangle) of the old mine works was complicated and seismic reflections could come from several travel paths and directions. The setup room location was on the hypotenuse of the right-angle problem. Only about 44% of the

receiver stations recorded seismic events. Reflection points calculated from the Setup 2 location yielded closer approximations to the old mine works. Thus, the blind test yielded mixed, but positive results.

On May 17, 2007, LMG&A Inc. conducted the 7th and last ISS survey under the MSHA contract. This was the second blind test conducted to replace the BCCC Site 1 project because the coal company failed to drill the verification hole within a year. MSHA selected the last test site because no verification drilling will be required as the old mine works had been surveyed and two horizontal holes intersected the old mine. The ISS data results showed a very good approximation to the estimated location of the old works. Measured distances were found to range between 213 and 258 ft away, but the actual distances were from 195 to 260 ft. Nearly half of the reflection points fell on top of the old mine face.

INTRODUCTION

On April 26, 2005, LM Gochioco & Associates Inc. was awarded a contract by the Mine Safety and Health Administration (MSHA), U.S. Department of Labor, to conduct field testing and to demonstrate three geophysical methods that can be used to detect air- or water-filled old mine workings. The three geophysical methods; namely, vertical seismic profiling (VSP), surface seismic reflection (SSR), and underground inseam seismic (ISS). This report covers the ISS contract in which detection of old mine works were conducted from seven different setup locations and at five different coal mines. The four coal companies involved in this study are Sterling Mining Corporation (1), Buckeye Industrial Mining (2), Bell County Coal Company (2), Bluff Spur Coal Corporation (1), and the NIOSH Bruceton Safety Research Coal Mine in Pittsburgh, PA (1).

In this underground ISS project, LMG&A Inc. partnered Dr. Rene Rodriguez of GECOH Exploration, to assist in the data acquisition and processing as the two principal investigators had previously collaborated on ISS projects conducted at Consol Energy Inc. since the mid-1990s. In addition, Dr. Rene Rodriguez currently has developed working software programs to process the ISS data.

UNDERGROUND INSEAM SEISMIC METHOD

The first documented underground inseam seismic work occurred in the late 1930s when German scientists conducted some experiments to map seam continuity and to detect geologic anomalies ahead of mining. Since their resource base is limited, the German scientists explored ways to maximize the utilization of their natural resources. A major milestone happened in the 1960s that significantly advanced our understanding of signal theory. As a result of advances in electronics technology, the conversion from analog-to-digital acquisition and processing permitted scientists to test their mathematical theories and algorithms (White, 1965, Felsen and Marcuvitz, 1973). Subsequently, the development and application of Fast Fourier Transforms (FFT), filters, deconvolution, etc. enhanced the processing and interpretation processes. The petroleum industry largely benefitted from this advancement as they are the heavy users of the seismic technology.

The Germans were the first to advance the ISS technology in the 1960s and 1970s (Arnetzl, et. al., 1981, Dresen and Freystatter, 1976, Dresen and Freystatter, 1978, Krey, 1963, Millahn and Arnetzl, 1979). Then, the British followed in the 1970s and 1980s (Buchanan, 1978, Mason, et. al., 1980, Mason, 1981, Buchanan et. al., 1981, Buchanan et. al., 1983). Attempts were made in the mid-1970s to introduce this technology through local conferences in the US (Krey, 1976, Lagasse and Mason, 1975, Guu, 1975, Toksoz, 1979). BHP Americas (a subsidiary of the Australian conglomerate BHP) opened an office in the US in the mid-1980s offering such ISS services. The US coal industry was not ready to adopt this useful technology, resulting in the closing of their American service operations in the early 1990s. However, CONSOL's internal coal geophysics program quietly used this technology to improve their safety by detecting potential hazards or geologic anomalies ahead of mining (Gochioco, 1996).

One of the primary reasons why the Germans and the British succeeded from the 1960s to 1980s were largely because they received critical subsidies and support from their respective governments. The subsidy and funding ended when their respective coal industries became a victim of globalization in which they could not compete in a global market. Subsequently, majority of their coal mines closed and the ISS technology was eventually archived.

How does the ISS method work? As a result of the large acoustic impedance (density x velocity) contrasts with respect to shales and sandstones, most of the seismic energy is confined to propagate within the seam; subsequently making the seam act like a waveguide. When there are rock intrusions in the seam, thin coal, faulting, etc., more seismic energy "bleeds out" and/or undergoes partial reflection and transmission. These anomalies coupled with the normal attenuation rate and seismic source used would affect the sounding range of ISS surveys.

DATA PROCESSING

Processing of the ISS data requires some deviation from the standard data processing workflow used on surface seismic data. The software used to process this ISS data is a proprietary program developed by Dr. Rene Rodriguez of GECOH Exploration. The generalized workflow presented below was applied to all the ISS data collected in this study.

1. Sort seismic traces according to geometry
2. Apply mormal moveout (NMO) corrections
3. Stack
4. Refraction inversion modeling
5. Calculate various velocities of disturbed and undisturbed coal
6. Apply filters (FFT and Maximum Entropy) to enhance data
7. Extrapolate two-way travel times
8. Calculate distances of reflected events

MIGRATION

It is important to note that software program used to process the ISS data is a straight ray approach used to back propagate reflection points based on the recorded two-way arrival times. This solution is accurate in cases where the old mine works is nearly parallel to the setup room. However, when the old mine works and the setup room are not parallel, and have considerable "angle" between them, then the margin of error increases as the reflection points are not really in front of the receiver or geophone, but could come from either side of the receiver station.

To better explain the migration issue, a schematice diagram is presented below (see **Figure 1**). The vertical cross section shows ten geophones on the surface recording a dipping reflector. Since the ten geophones recorded events in time, the seismic data display the reflector vertically in time, resulting in the imaging of an "apparent" reflector. However, the true reflector location is usually located updip from where the unmigrated seismic section shows.

By simply tranforming the schematic diagram in Figure 1 from vertical display to map view, the same problem is illustrated in using the ISS method to detect mine voids. The steeper the angle between the old mine works and the setup room would result in larger percentage errors and/or our inability to record reflection events from the old mine works unless longer receiver arrays are employed.

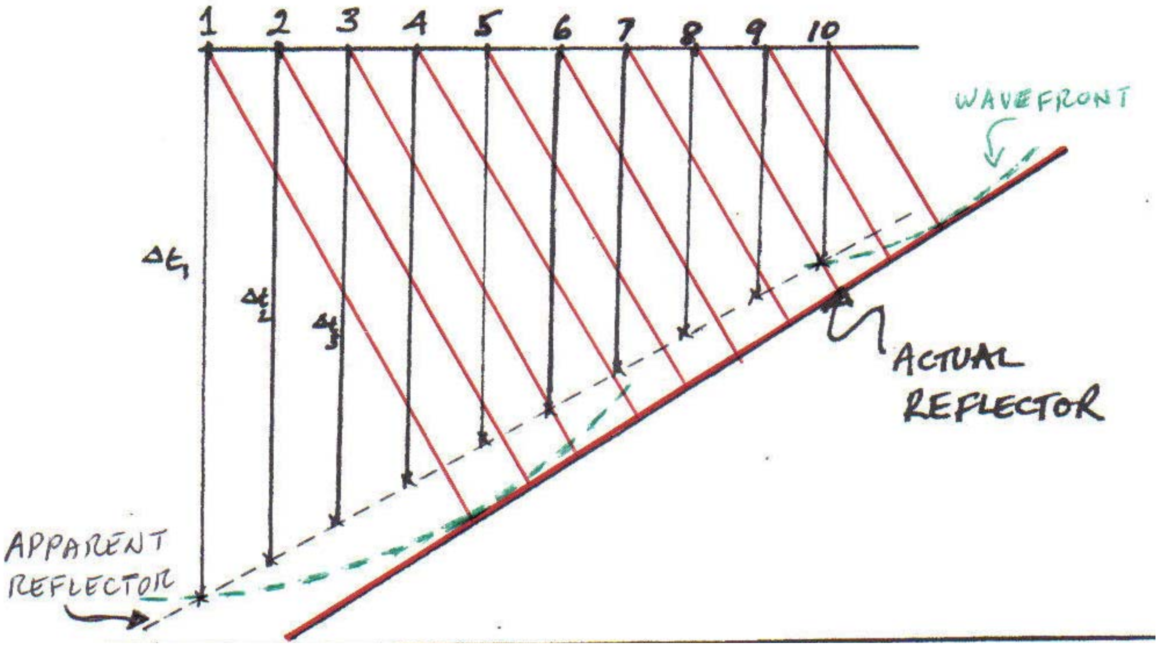


Figure 1. Schematic diagram shows how dipping reflectors can be improperly imaged without applying a migration solution.

To properly address this problem, a more sophisticated algorithm, called migration, will be needed and applied to the data set. Migration is an inversion process involving the rearrangement of seismic data elements so that reflections and diffractions are replotted to their true subsurface locations. There are several popular migration solutions (Finite Difference, Kirchhoff, and Wave Equation) being employed in large 3D seismic data volumes by the petroleum industry. Unfortunately at this time, the LMG&A Inc. and GECOH Exploration do not have the resources to develop this sophiticated algorithm for this demonstration.

Figure 2a shows an example of an unmigrated seismic image of a syncline that looks like a "bowtie". After the migration process was applied, the reflection events associated with the syncline is properly repositioned yielding a clear synclinal structure, as shown in **Figure 2b**. In addition, diffraction patterns had collapsed and replotted to their "secondary" point source positions in the section.

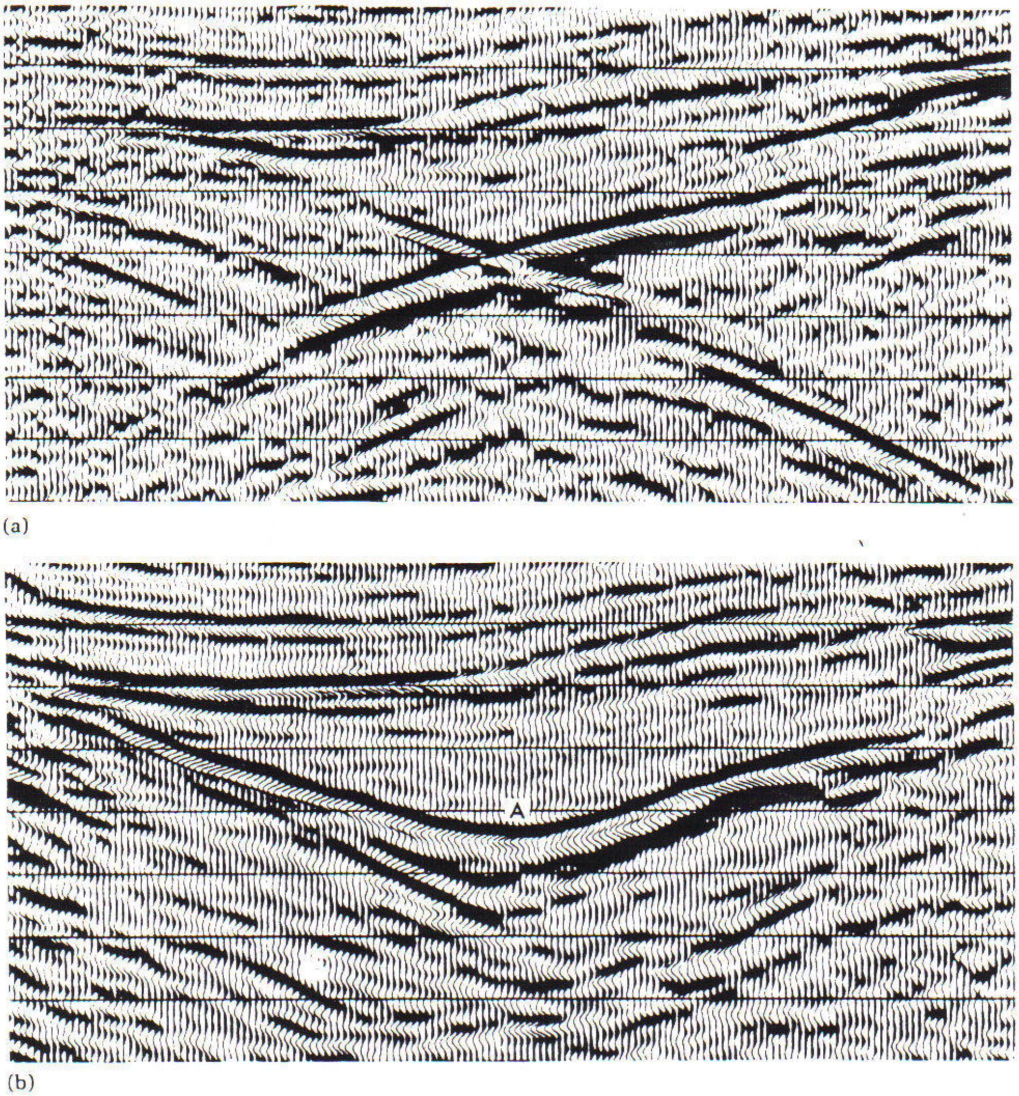


Figure 2. Unmigrated stack section (a) shows a "bowtie" feature usually associated with a syncline. After applying the migration solution, the true subsurface structure is revealed as a syncline (b).

The lack of the migration algorithm in processing the ISS data will explain why some reflection points are located outside or beyond the known old mine works when the orientation of the setup and old mine works are not parallel. When the orientation of the setup room and old mine works are nearly parallel, then the problem of mis-positioning the reflection points is minimized.

CASE STUDY 1: STERLING MINING CORPORATION (1)

Geologic Conditions - The overburden thickness at the Carroll Hollow Mine ranges from 200 to 350 feet. The surface is mostly gentle rolling hills with open fields and wooded areas. The mine is located in Fox Township, Carroll County, OH. The Mahoning coal (7A) seam is the lowest Conemaugh Age seam in the Pennsylvanian Formation in Ohio. The seam occurs in ~10 square mile area pods which can reach a maximum thickness of 45 inches, usually in the center of the pod. The coal is frequently channeled out on the edges and at times through the center. The coal is also slumped into by the overlying shale along the channel margins. The immediate overburden is the black shale grading upward by gray shale and sandstone.

In this mine, the average seam thickness is 34", but the mining height is about 42". The abandoned mine had the same mining height and is water-filled with up to 30 feet of head above the seam elevation. Hydrological testing was based on borehole drilling. The mine dips to the southeast where the pressure head reached up to 65 feet. The immediate roof has bone coal with 7 foot of shale, coarsening up to 5 feet of sandyshale which is then topped by 15 feet of sandstone.

Figure 3 shows the relative locations of the active mine works of Carroll Hollow Mine, located on the southwest corner of the map. The abandoned and flooded old mine works are shown in turquoise blue, located to the northeast corner. Separating these two mines is a solid blue band with an arrowhead on top that snaked across the reserve block on a north-south trend. This blue band corresponded to previous hole-to-hole tomography surveys conducted by the coal company in the 1990s to image seam continuity, thin coal areas, and to detect mine voids.

The map also showed washout areas in the reserve in which a major paleochannel system had eroded the seam completely. Based on results from surface drilling, underground observations, and hole-to-hole tomography surveys, the paleochannel system had a northward trend, which could explain why the old mine works ended abruptly.

A major roof fall occurred near the proposed study area in mid-October 2005. Not knowing how stable the area could be the following month and their potential inability to maintain fresh air at the working face, SMC management requested to move the ISS survey forward to an earlier date. As such, the 1st proposed underground ISS survey was conducted on November 3, 2005 instead of the originally proposed mid-November time frame. **Figure 4** shows the concurrent mine map showing the mains with respect to the target old mine works. The old works was estimated to be between 600 and 650 feet away from the mains.

ABANDONED OLD STERLING MINE (closed in 1962)

SMC did extensive research work in gathering historical information about the abandoned mine. The Mahoning coal at the old Sterling Mine was mined from 1890 to 1962 from a portal along State Route 39 (approximately 5 miles away from the area of interest). The J. M. Hirst and Company was a long time operator. 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 poor roof conditions, thin coal, and washouts were encountered. These adverse mining conditions indicated the presence 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. Miller's interpretation after reviewing the old Sterling Mine maps appeared to be simple "cut and paste" jobs and its accuracy was in question. As a result, 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 indicated that errors in the accuracy of the old map could increase as we head further north. The northern-most room is of most concern as there were distinct gaps or the lack of pillars in the drawing. However, an outline of the room's western tip was shown and the gap 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? To help resolve some of these important issues or concerns, the placement of the VSP hole and two SSR survey lines were thus concentrated in this section of the mine property.

There was less concern to the south as the location of the old works is fairly accurate based on past drilling, hole-to-hole tomography, and underground survey data collected. Thus, a single surface seismic line and the underground inseam seismic project was proposed at this site to test the accuracy of these two latter geophysical methods.

DATA ACQUISITION

In this underground field demonstration, the seismic recording system used was a Geometrics StrataView seismograph that has a 12-channel recording capability. Single 40-Hz geophones were used as receivers. The sampling interval was one-eighth (1/8) millisecond (ms) and record length was 400 ms. Planting the geophones on the coal face required the use of cordless handheld drills. Drilling was near the center of the seam and good coupling is achieved simply by hand-tightening the geophone in the drilled hole. Seismic sources used in this study were blasting caps and pieces of dynamic. Miller handled the explosives and Rodriguez operated the seismograph. Data acquisition was conducted on November 3, 2005.

The receiver interval was 20 ft, resulting in a maximum geophone spread length of 220 ft per setup. Source sounding initially started 10 ft outside of the geophone spread, i.e. 10-ft offset on both sides of the G1 and G12 positions. Then successive source positions were set at a 60-ft interval, until the 5th and last source position is completed at the other end of the receiver spread. Thus, the total surveying spread of each setup is actually 240 ft wide. A total of four setups, totaling 960 ft, was employed in this study, resulting in a total of 240 seismic traces recorded.

INTERPRETATION

Figure 5 shows a digital map of the study area where the receiver and source positions are located. The figure also shows the refraction inversion model based on the first arrival times. The graph shows two distinct velocity layers associated with disturbed and undisturbed coal. The first layer of lower velocity coal, ranging between 5745 and 5824 ft/s, is interpreted to be the immediate coal face that was disturbed or fractured due to mining operations. At this site, the layer of disturbed coal ranged from 40 to 50 ft in thickness from the working face. The second layer is interpreted 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 RMS velocity, which turned out to be about 6011 ft/s.

Figure 6 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 used to record soundings, only a total 17 geophones (from G31 to G47) recorded reflection events. 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 blue solid color 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 then calculated.

Table 1 shows the calculated distances to the old Sterling Mine works based on the recorded ISS data.

Receiver Station	Velocity (rms) ft/s	Two-way arrival time (milliseconds)	Calculated Distance (ft)
G30	6011	0	0
G31	6011	201.5	605.6
G32	6011	204.0	613.1
G33	6011	205.0	616.1
G34	6011	205.0	616.1
G35	6011	204.0	613.1
G36	6011	205.0	616.1
G37	6011	206.0	619.1
G38	6011	210.5	632.7
G39	6011	211.5	635.7
G40	6011	212.0	637.2
G41	6011	212.0	637.2
G42	6011	212.0	637.2
G43	6011	205.5	617.6
G44	6011	205.0	616.1
G45	6011	206.0	619.1
G46	6011	205.0	616.1
G47	6011	206.5	620.6

TABLE 1 – Measured and calculated distances to old mine works at the Carroll Hollow Mine, Sterling Mining Corporation

Using the information presented in Table 1, a graph is generated to show the location of reflected events. These reflections are interpreted to be coming from the near face of the old mine works in front of the receiver stations G31 to G47. These results also indicated that the old mine works did not extend beyond the G31 position, as shown in **Figure 7**.

The ISS data presented in Table 1 was given to Tim Miller for him to upload into their company's mine map to determine the accuracy of the ISS technique. **Figure 8** shows the actual measured reflection points in front of the receiver positions. It is apparent that six reflection points are located outside or beyond the tip of the mains. I believe the underground mine map is accurate and the six spurious reflection points resulted from the lack of applying the migration process to properly re-position the reflection points. Therefore, all seventeen reflection points should be shifted in an arc-like manner, simulating a wavefront, by about 120 to 140 ft towards the east.

VERIFICATION

As mentioned earlier, SMC believed the location of the old mine works to the south to be fairly accurate, based on old survey data and mine maps. To support their analyses, SMC drilled four well-placed holes (U03-4, MON03-2, MON03-6, and STVNS03-4) in 2003, in order for them to conduct hole-to-hole tomography surveys between hole pairs so that they can collect valuable subsurface information.

Figure 8 highlights the results of the hole-to-hole tomography surveys where solid turquoise 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 encounter any old mine works. However, the hole pair MON03-2 and U03-3 encountered a disturbance (in green) associated with old mine works and its detected (and expected) location is near the western tip of the mains. 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 and knowledge of the estimated location of the old mine works at the study area.

The hand drawn mine map shown in **Figure 2** indicated the estimated old mine works to be between 600 and 650 ft away. Table 1 shows the calculated distances to the old mine works to range between 605 to 637 ft away. Thus, there is a good correlation **(Calculated % error < 3%)** . As a result of their past successful experience in integrating geophysical data into their drilling program, SMC went ahead with their future mine plans and maintained the required 200-ft barrier.

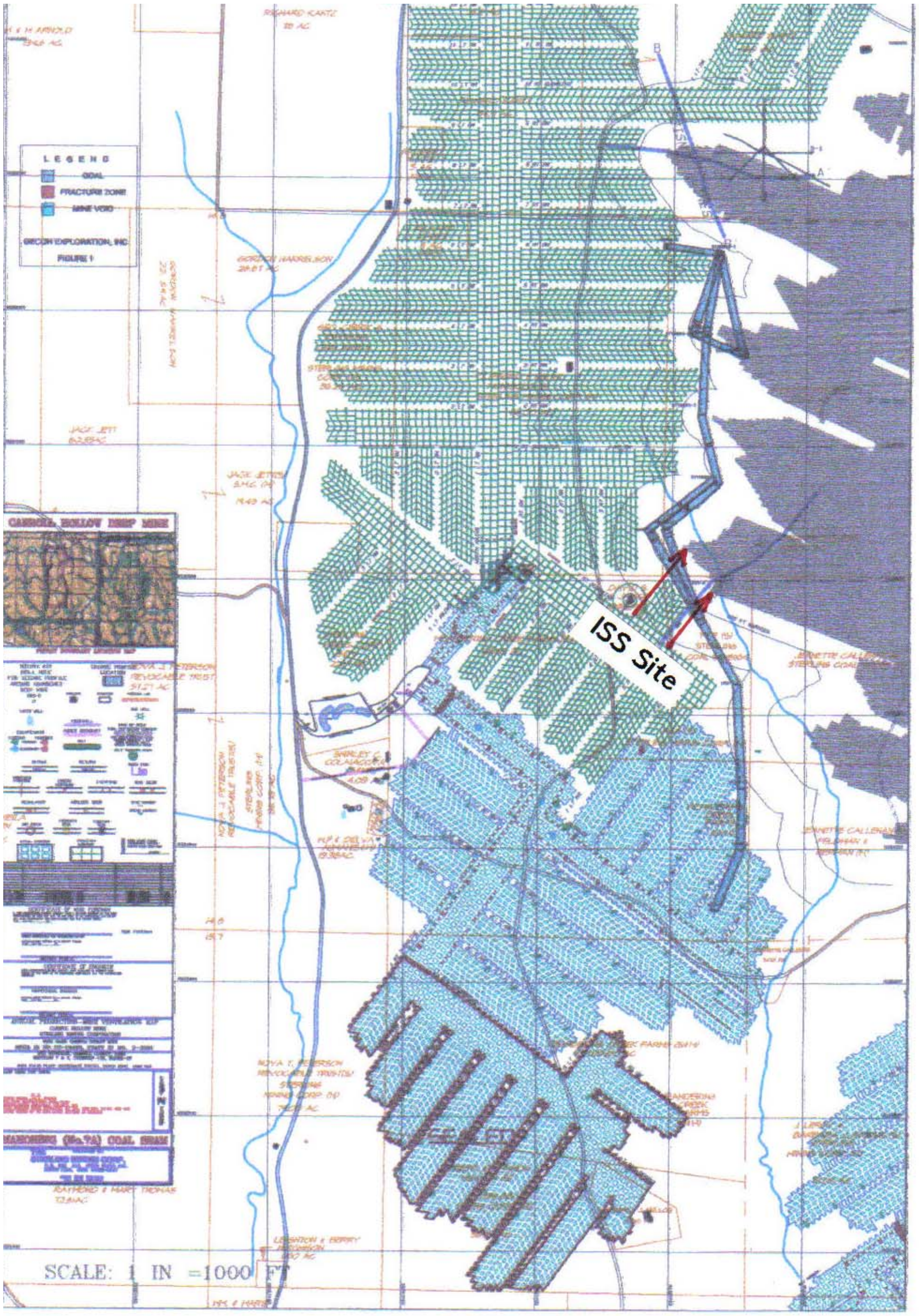
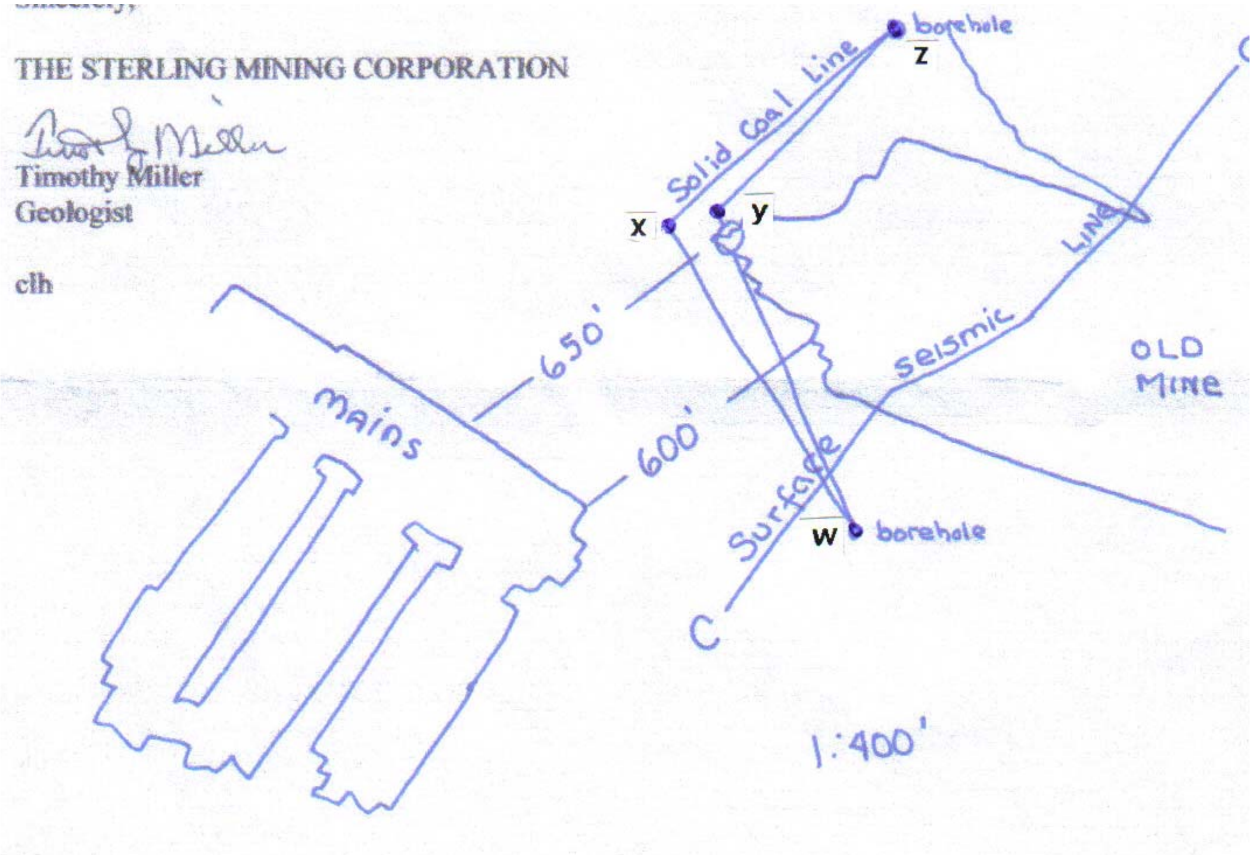


Figure 3. Map shows the location where the ISS survey was conducted with respect to the locations of the three surface seismic lines and VSP hole. The objective of the ISS survey is highlighted by the pair of red arrow lines showing the target old works.



THE STERLING MINING CORPORATION

Timothy Miller
Geologist

clh

Figure 4. Sketch of mine map provided by Miller in a letter dated October 28, 2005 showing their concurrent position with respect to the old works. As a result of a major roof fall and adverse geologic conditions,, mine manangement decided to abandon the present mains; subsequently, advancing the ISS program by two weeks. Boreholes w, x, y, and z were used in a hole-to-hole tomography program.

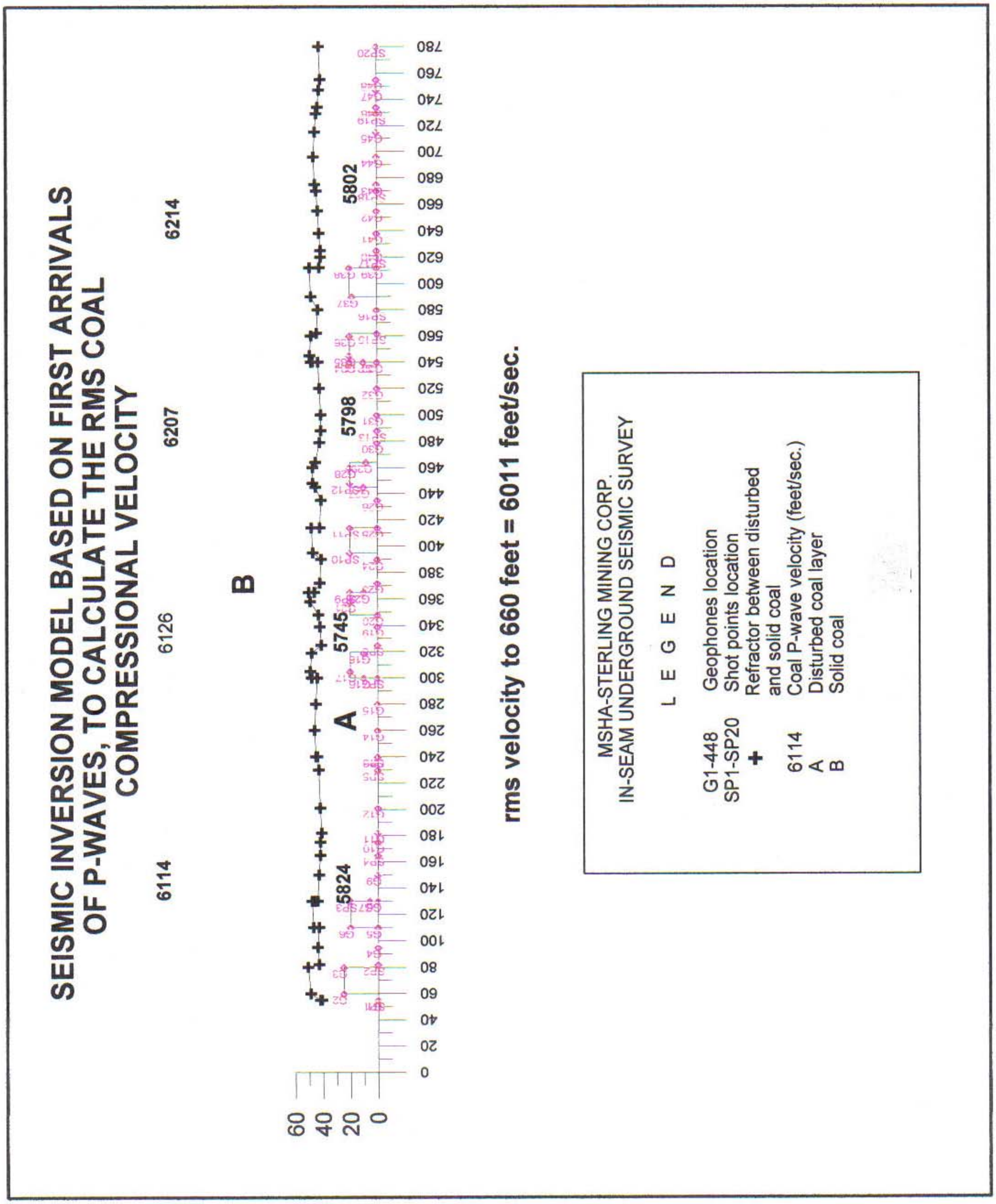


Figure 5. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal.

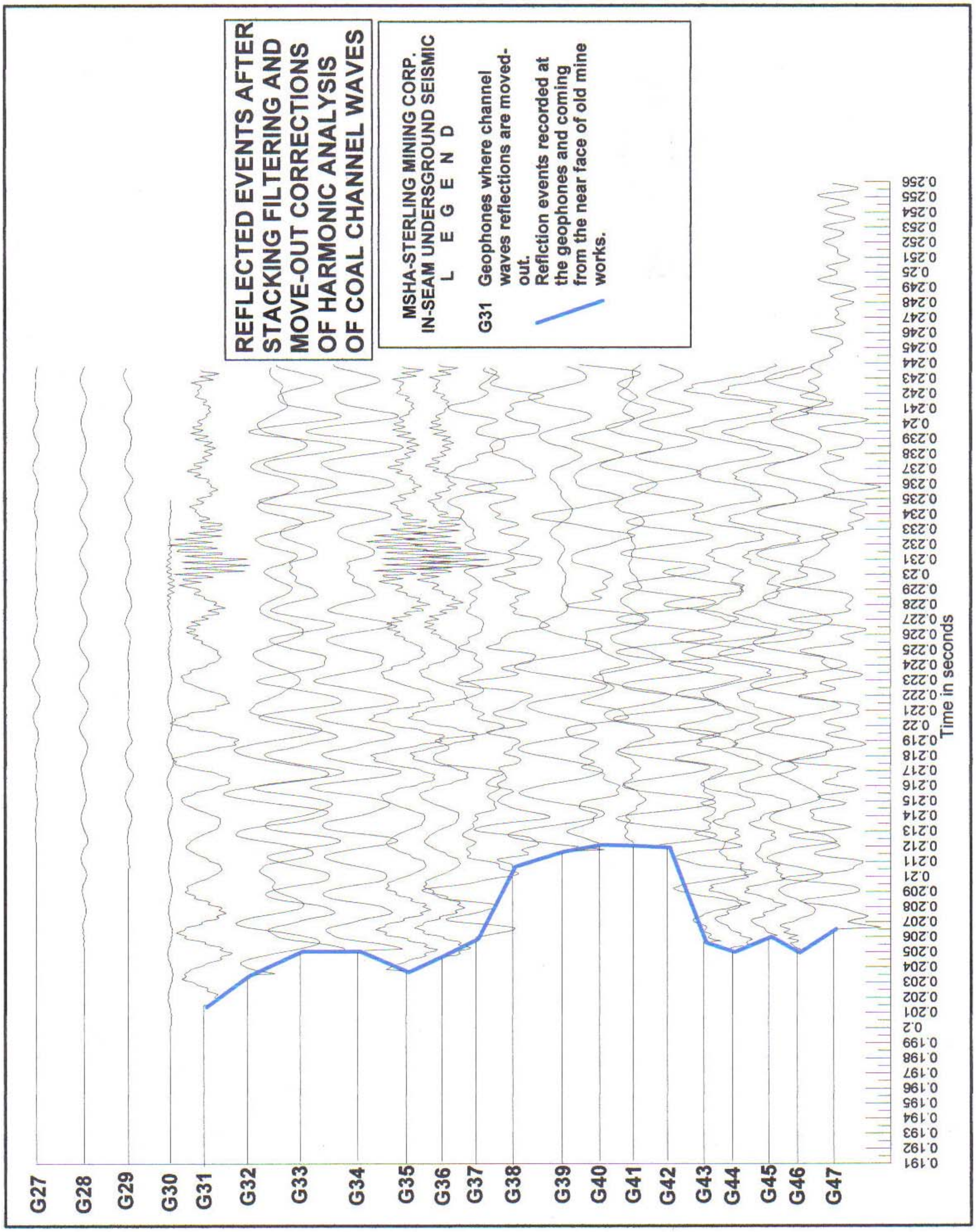


Figure 6. Stacked seismic traces showing the recorded two-arrival times of the seismic energy reflected from the near face of the old works.

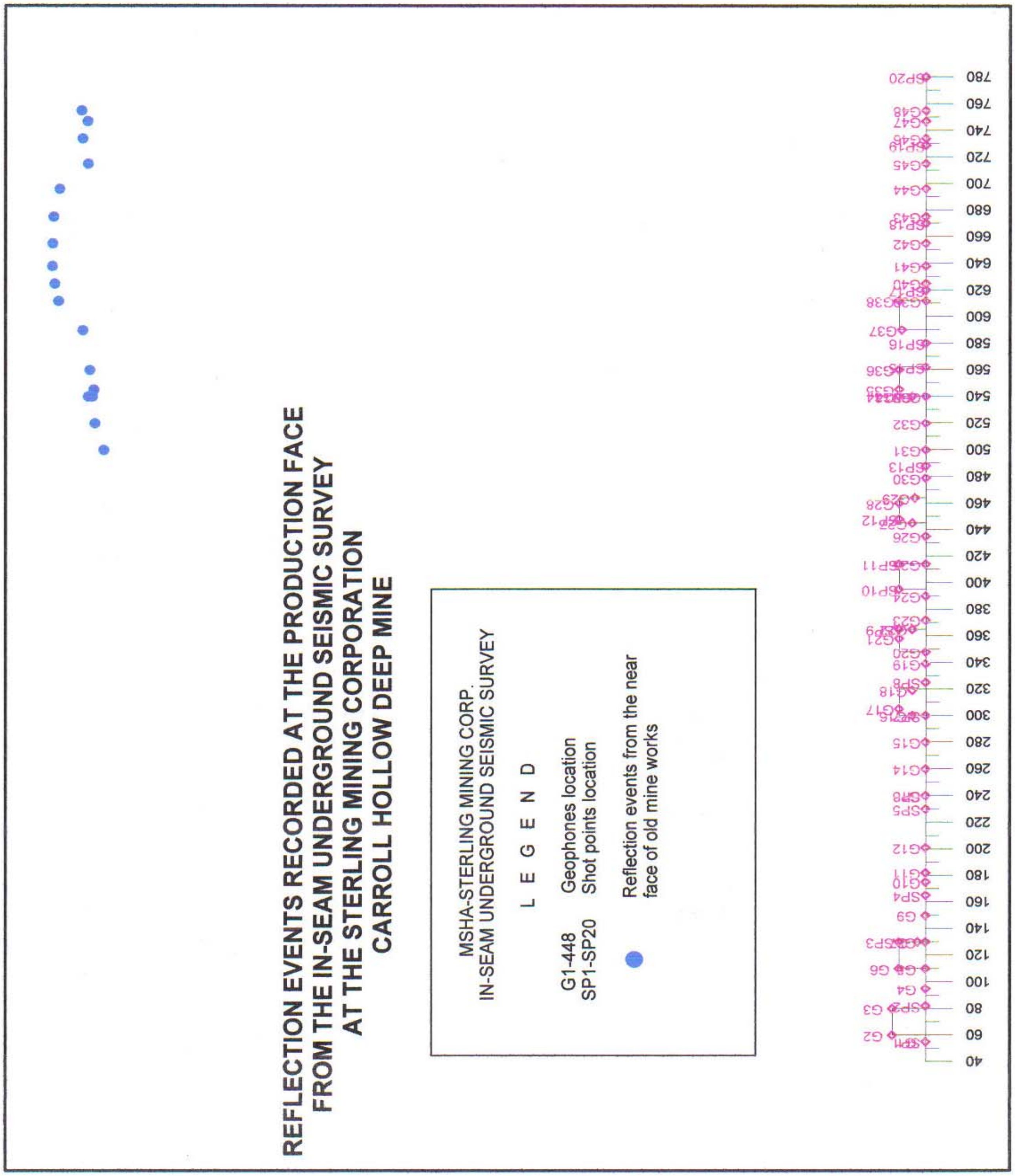


Figure 7. Graph shows the reflection points associated with the old works recorded only between G31 and G47 stations.

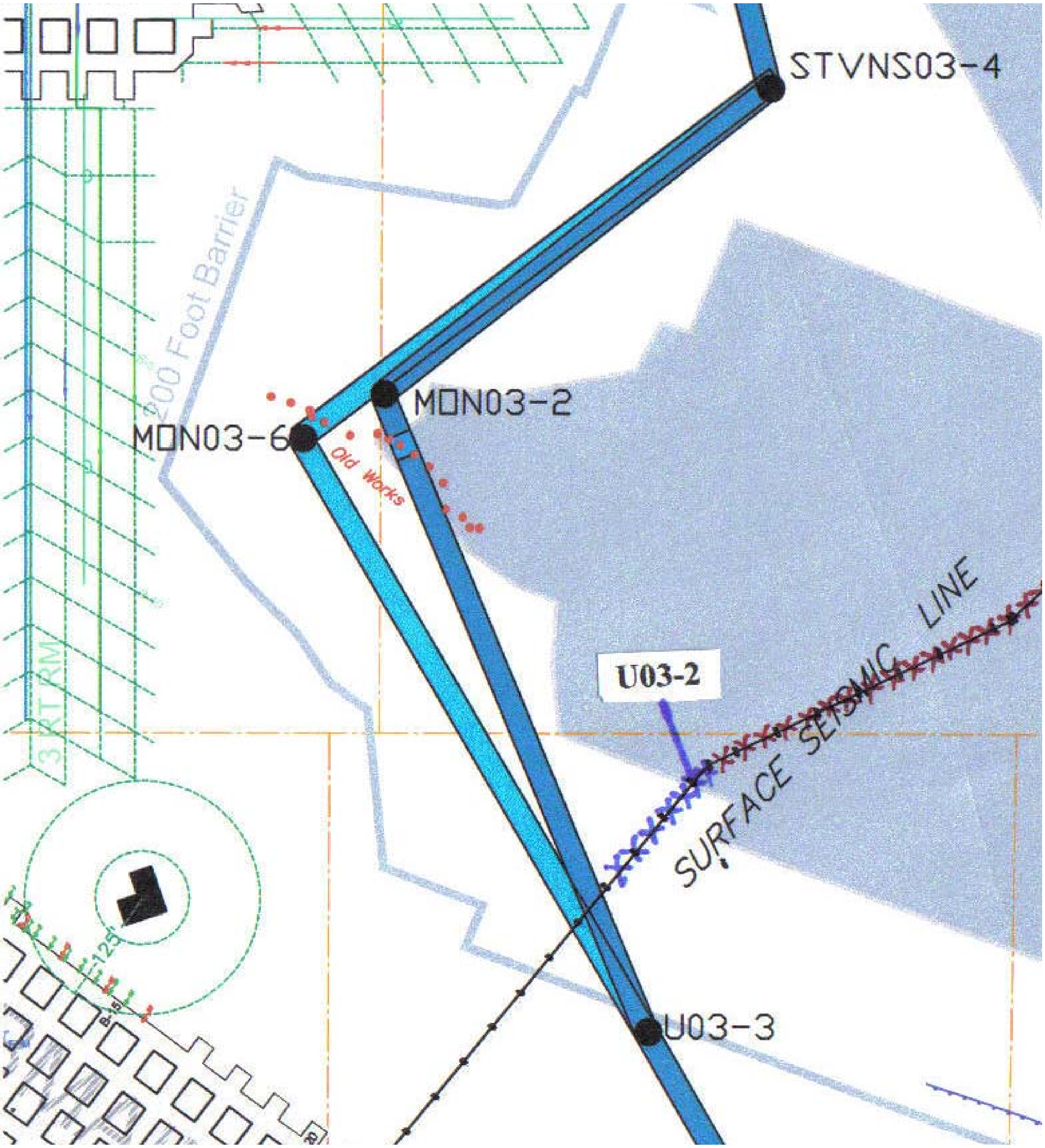


Figure 8. Measured ISS reflections points are plotted on the mine map. The six reflection points shown outside of the old mine works indicate that the data processing did not include the migration solution as the setup room (located on the SW corner) and the old mine works are not nearly parallel. As a result, the reflection points should be shifted or rotated slightly (clockwise) towards the southeast direction by about 120 to 140 ft. Otherwise, the ISS data correlated with the known location of the old mine works.

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CASE STUDY 2: BUCKEYE INDUSTRIAL MINING CORPORATION (2)

Geologic Conditions - Underground mining occurs at the Lower Freeport #6A coal seam and the average seam thickness is 36". The overburden thickness of the mine averages from 380 to 400 feet. The surface is described as a gentle rolling hill environment that is predominantly open field. The mine is located in Ross Township, Jefferson County, OH.

Figure 9 shows a map of Buckeye's active mine called, the Snyder Deep Mine #10. The old mine works, called 6A Deep Mine, is located on the west side of their property beneath the property owned by Denise and George Bach. The boundary of the target old mine works is highlighted by the black dashed lines hidden beneath the outline of a shallower #7 seam and more extensive old mine works (highlighted by the pinkish color). The average interval between the #6A and #7 seams is about 45 ft.

Figure 10 shows the same map in which the shallower old mine works had been "turned off" to highlight the 6A Deep Mine beneath it. This time, the black dashed line shows the boundary of the shallower and more extensive mine works. Evidently, the old mine works associated with the #6A Deep Mine had minimal mineral extraction. The red "X" shown in the figure corresponded to the first geophone (G1) position of each survey.

Based on the mine map, two setup rooms were identified to provide access in which two ISS surveys were conducted to detect the old mine works associated with the #6A Deep Mine (see **Figure 9**). Site 1 would be conducted from the northeast direction. From this position, the distance to the old works ranged from about 1150 to 1450 ft. Site 2 would be conducted from the southeast direction and the estimated range to the old works ranged at least 1300 ft. The outline of the shallower old works (dashed black line) extended further out by least 400 ft when compared to the projected 6A Deep Mine works.

DATA ACQUISITION

After weeks of preparation, the two proposed ISS surveys were finally conducted on December 6, 2005. Due to the greater range to the old mine works, a request was made to Buckeye Industry Mining Corporation (BIMC) to use blasting caps as seismic sources as the target range is greater than a thousand ft away. Unfortunately, none of the operations personnel were certified to handle such materials. As a result, the team had to rely on the backup source – a sledge hammer.

In this underground field demonstration, the seismic recording system used was a Geometrics StrataView seismograph that has a 12-channel recording capability. Single 40-Hz geophones were used as receivers. The sample interval was one-eighth (1/8) ms and the record length was 400 ms. Planting the geophones on the coal face required the use of cordless handheld drills. Drilling was near the center of the seam and good coupling is achieved simply by hand-tightening the geophone in the freshly drilled holes.

The receiver interval was 20 ft, resulting in a maximum geophone spread length of 220 ft per setup. Source sounding initially started 10 ft outside of the geophone spread, i.e. 10-ft offset on both sides of the G1 and G12 positions. Then successive source positions were set at a 60-ft interval, until the 5th and last source position is completed at the other end of the receiver spread. Thus, the total surveying spread of each setup is actually 240 ft wide. Sites 1 and 2 required only two setups each. Thus, a total of four setups, equaling 960 linear ft of ISS data, were collected at this mine.

INTERPRETATION

During the acquisition process, the team recorded good quality ISS data despite the fact that the seismic source was just a sledge hammer. Initial concerns about using such a light seismic source were later unnecessary because the coal seam was very hard and competent.

Figures 11 and 12 show the seismic refraction inversion graphs used to extract critical information velocity information. The two graphs show two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The respective source and receiver positions are also shown on the bottom of the graphs. What is unusual about the measured velocities at this mine was that the undisturbed coal showed a very high velocity of about 11,000 ft/s. Normally, the P-wave velocity in coal averages only 8,000 ft/s. Thus, the measured high velocity of 11,000 ft/s for coal at this mine is about the same velocity properties of typical shales and sandstones. Such unusual condition would indicate that the #6 coal seam could not act as a good waveguide to seismic energy, but would permit some seismic energy to “leak out” during propagation.

The seismic refraction inversion graphs of **Figures 11 and 12** also show that the thickness of disturbed coal ranged in thickness from 25 to 40 ft. Even the disturbed coal section revealed a high velocity of from 7200 to 7900 ft/s. For comparartive purposes, the measured P-wave RMS velocity in solid/undistrubed coal at the Carroll Hollow Mine (Sterling Mining Corporation) was only at 6011 ft/s. Evidently, the #6A coal seam at this site has high acoustic properties.

Figures 13 and 14 show the stacked ISS data from respective Sites 1 and 2 after normal-moveout (NMO) correction, filtering, FFT, and Maximum Entropy had been applied. Out of 24 receiver positions from Site 1, G1, G2, G3, and G21 did not record any reflected seismic event. From Site 2, receiver stations G12 to G24 only recorded reflected seismic events. It is easy to pick the two-way travel times off **Figures 13 and 14**. Using the extrapolated RMS velocities of 10,980 and 11,005 ft/s from respective Sites 1 and 2 and recorded two-way arrival times, distances to the old mine works can be calculated.

Tables 2 and 3 show the measured two-way arrival times, RMS velocity, and calculated distances to the old mine works from respective Sites 1 and 2.

Figures 15 and 16 show graphs of reflection points plotted in front of the receivers that recorded the seismic events. However, its accurary can be measured only when it is plotted on the mine map.

Receiver Station	Velocity (rms) ft/s	Two-way arrival time (milliseconds)	Calculated Distance (ft)
G1	10,980		
G2	10,980		
G3	10,980		
G4	10,980	189.5	1040.3
G5	10,980	181.7	997.5
G6	10,980	179.8	987.1
G7	10,980	174.8	959.5
G8	10,980	169.8	932.0
G9	10,980	164.2	901.6
G10	10,980	160.1	878.8
G11	10,980	156.6	859.8
G12	10,980	152.8	838.9
G13	10,980	147.1	807.5
G14	10,980	152.3	836.0
G15	10,980	151.6	832.2
G16	10,980	157.1	862.6
G17	10,980	155.7	855.0
G18	10,980	157.3	863.6
G19	10,980	158.5	870.2
G20	10,980	159.7	876.9
G21	10,980		
G22	10,980	166.6	914.9
G23	10,980	162.7	893.0
G24	10,980	157.3	863.6

TABLE 2 – Measured and calculated distances to old mine works from Site 1 at the Deep Mine #10, Buckeye Industrial Mining Corporation.

Receiver Station	Velocity (rms) ft/s	Two-way arrival time (milliseconds)	Calculated Distance (ft)
G10	11,005		
G11	11,005		
G12	11,005	188.2	1035.5
G13	11,005	186.5	1026.0
G14	11,005	183.4	1008.9
G15	11,005	181.6	999.4
G16	11,005	179.9	989.9
G17	11,005	178.4	981.4
G18	11,005	177.8	978.5
G19	11,005	175.9	968.1

G20	11,005	172.8	951.0
G21	11,005	172.8	951.0
G22	11,005	172.5	949.1
G23	11,005	171.3	942.4
G24	11,005	171.4	943.4

TABLE 3 – Measured and calculated distances to old mine works from Site 2 at the Deep Mine #10, Buckeye Industrial Mining Corporation.

Ths calculated ISS reflection data points were then replotted on the mine map, as shown in **Figure 17**. It is evident that the two ISS surveys conducted at this mine detected the outline of the old works associated with the shallower #7 seam. Despite the relatively thin overburden thickness, the #6 seam was found to have an unusual high P-wave velocity, almost equaling the velocities of typical shales and sandstones. That means that the #6 seam was highly compacted. As a result of this condition, the seam did not act as a good waveguide, resulting in more seismic energy "leaking out" of the seam with an expanding aperture.

We know that the average interval between these two seams was just about 45 ft. The interval separation of 45 ft with respect to the average horizontal distance of 1000+ ft sounding range is considered small. Thus, as the seismic energy wave propagated with a growing aperture wavefront, the first mine void it detected was from the shallower #7 seam. Attempts were made in data processing to possibly filter out the seismic reflections from the shallower seam in order to enhance any subsequent data associated with the #6 Deep Mine. Unfortunately, no useful interpretable data could be extracted.

VERIFICATION

Since the measured ISS reflection points fell nicely along the outline of the shallower #7 old mine works, BIMC felt there was no need to drill additional verification holes as the original target (#6A Deep Mine) was not detected. In addition, BIMC drilled numerous holes prior to the ISS surveys to confirm the outlines of the #7 and #6A old works. In particular, there was a phalanx of 25 closely-spaced holes at 10-ft centers (see Figure 17) highlighted in "orange" color. They ranged from 940 to 1080 ft. Majority of the 13 reflection points from Site 2 fell inside the 50-ft radius of the boreholes. Therefore, ISS method detected and imaged the outline of the shallower old mine works with a high degree of accuracy, even though it was the wrong target objective.

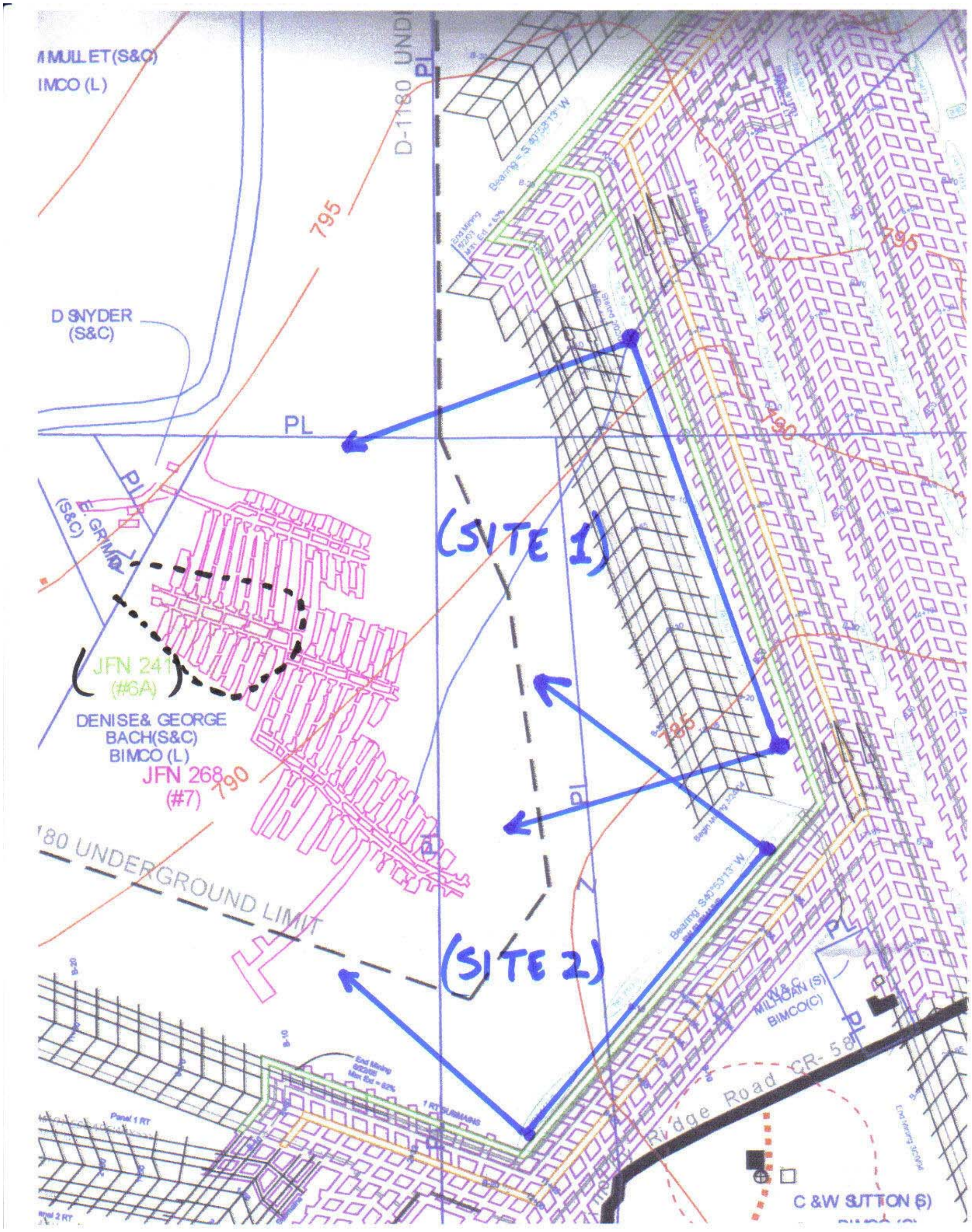

Figure 9. Map shows the active works of Buckeye's Deep Mine #10 mine. The two old mine works are located on the western reserve area beneath the property of Denise and George Bach. Sites 1 and 2 were the setup locations where ISS surveys were conducted to detect the 6A Deep Mine. (Scale 1" = 300')

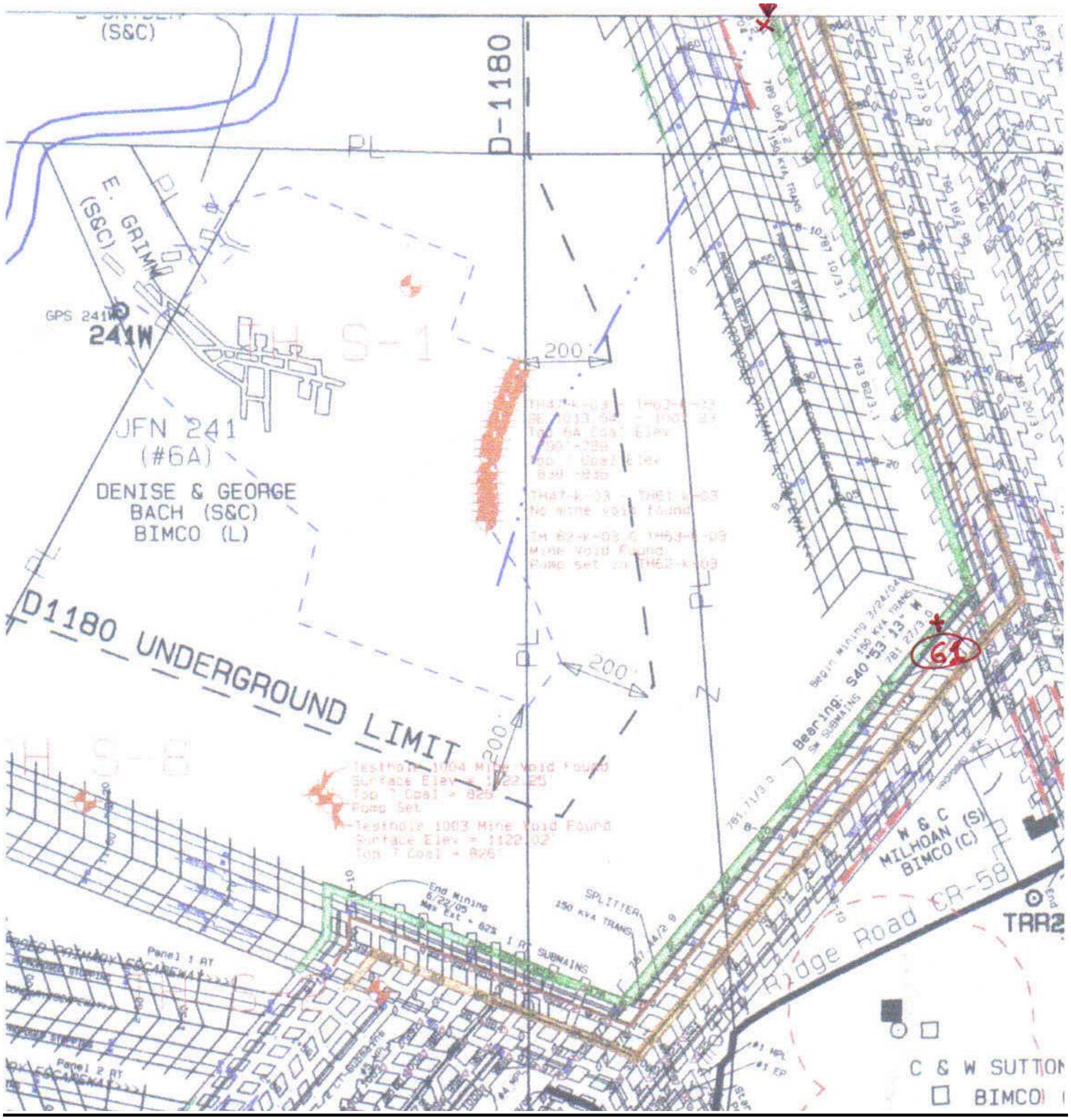

Figure 10. The shallower #7 old mine works was removed to highlight the less extensive #6A Deep Mine. The black dashed line outlined the boundary of the shallower #7 old mine works. Near the middle of the figure is a phalanx of 25 holes (in orange) drilled by BIMC to confirm the the location and edge of the shallower old works. (Scale 1" = 300')

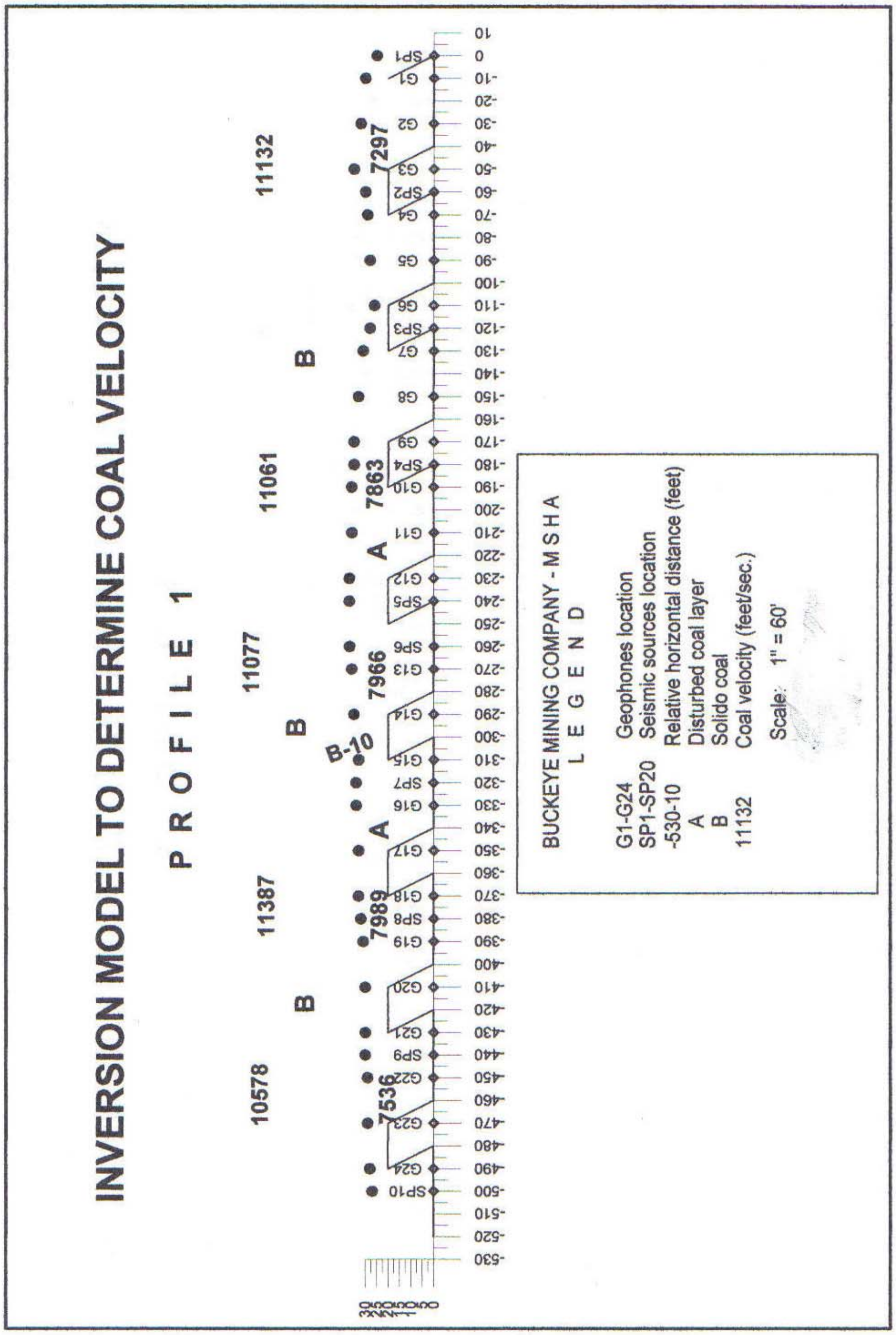

Figure 11. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Site 1. Please note the unusual high coal seam velocity of nearly 11,000 ft/s.

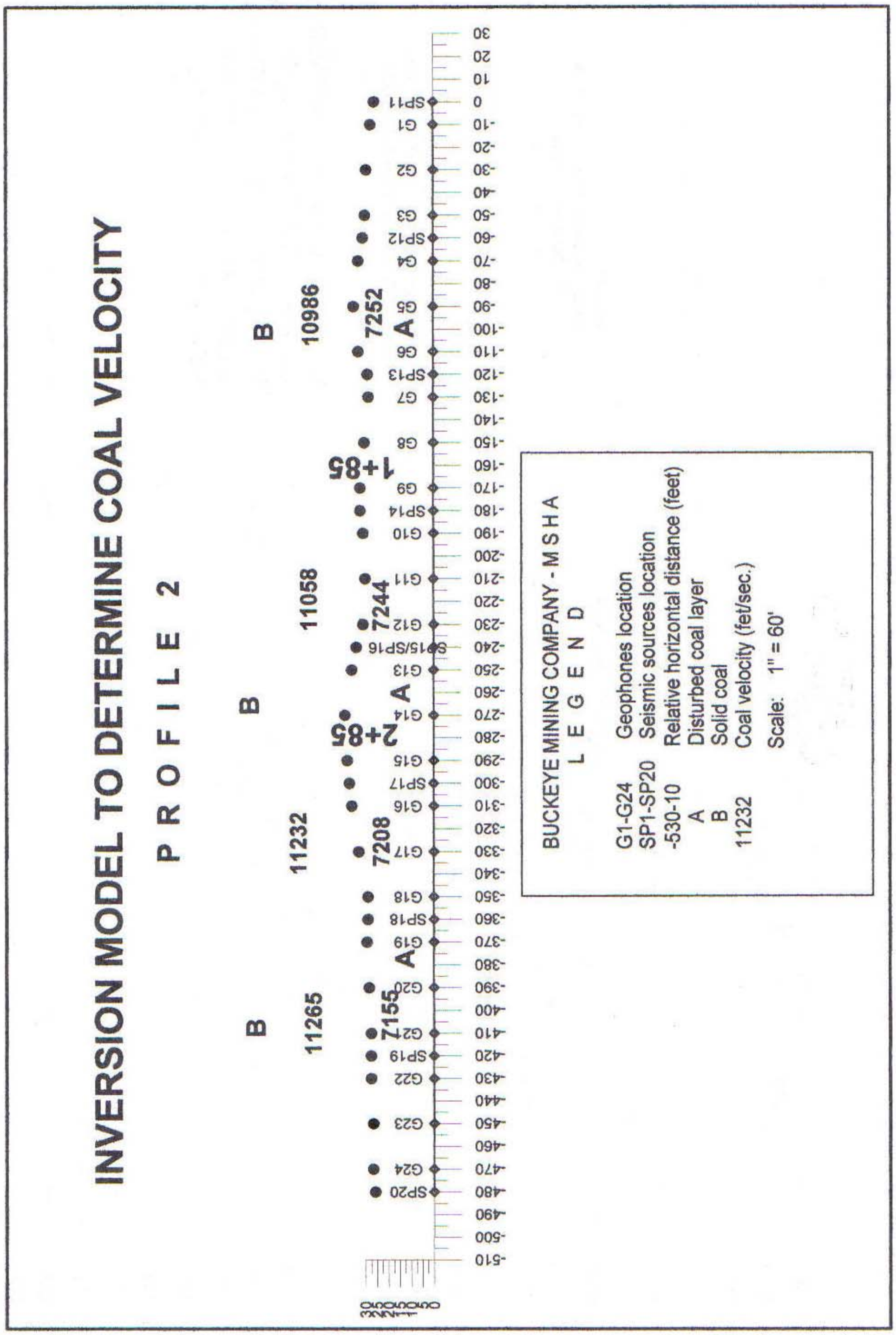

Figure 12. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Site 2. Please note the unusual high coal seam velocity of over 11,000 ft/s.

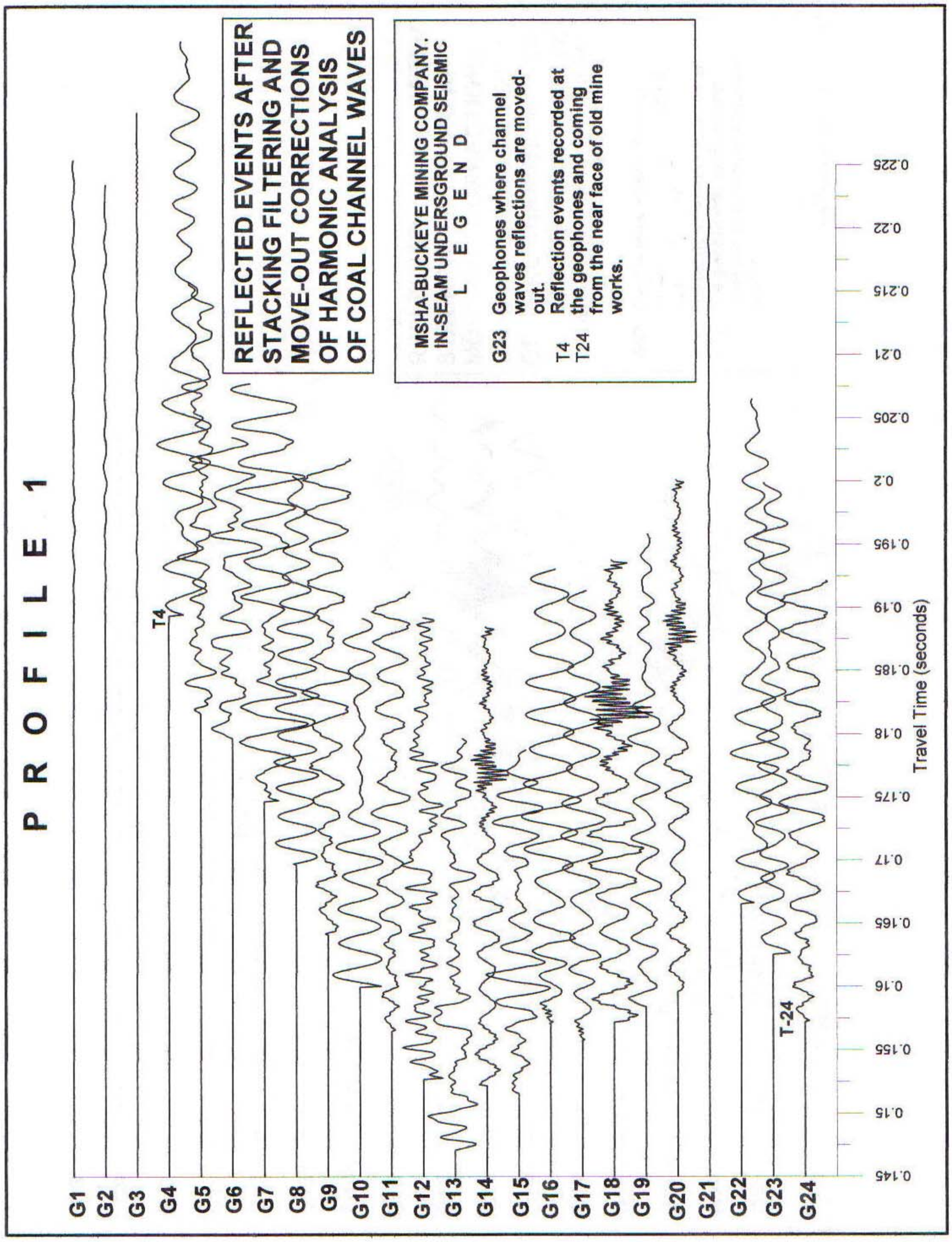

Figure 13. Stacked seismic traces showing the recorded two-arrival times of the seismic energy reflected from the near face of the old works from Site 1.

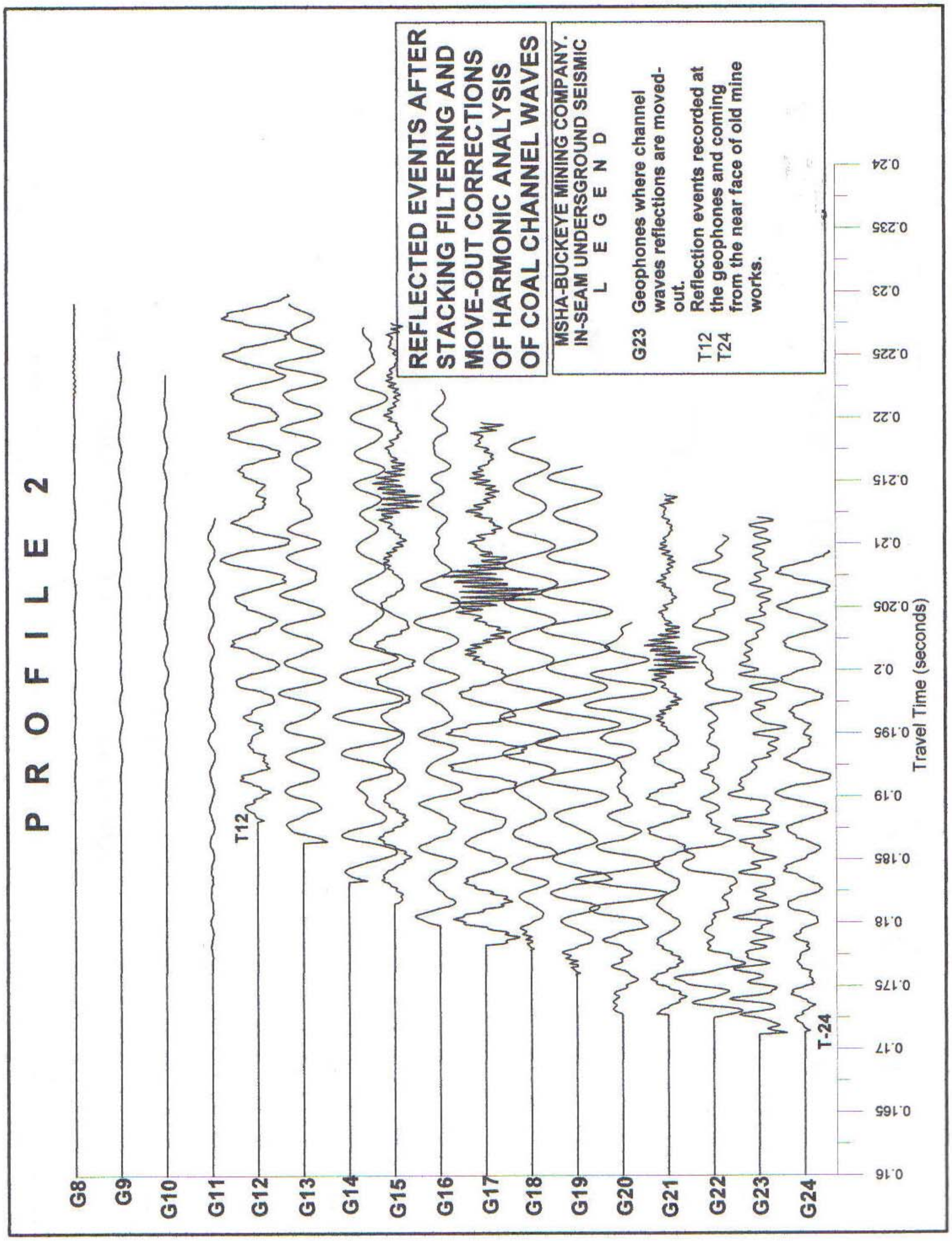

Figure 14. Stacked seismic traces showing the recorded two-arrival times of the seismic energy reflected from the near face of the old works from Site 2.

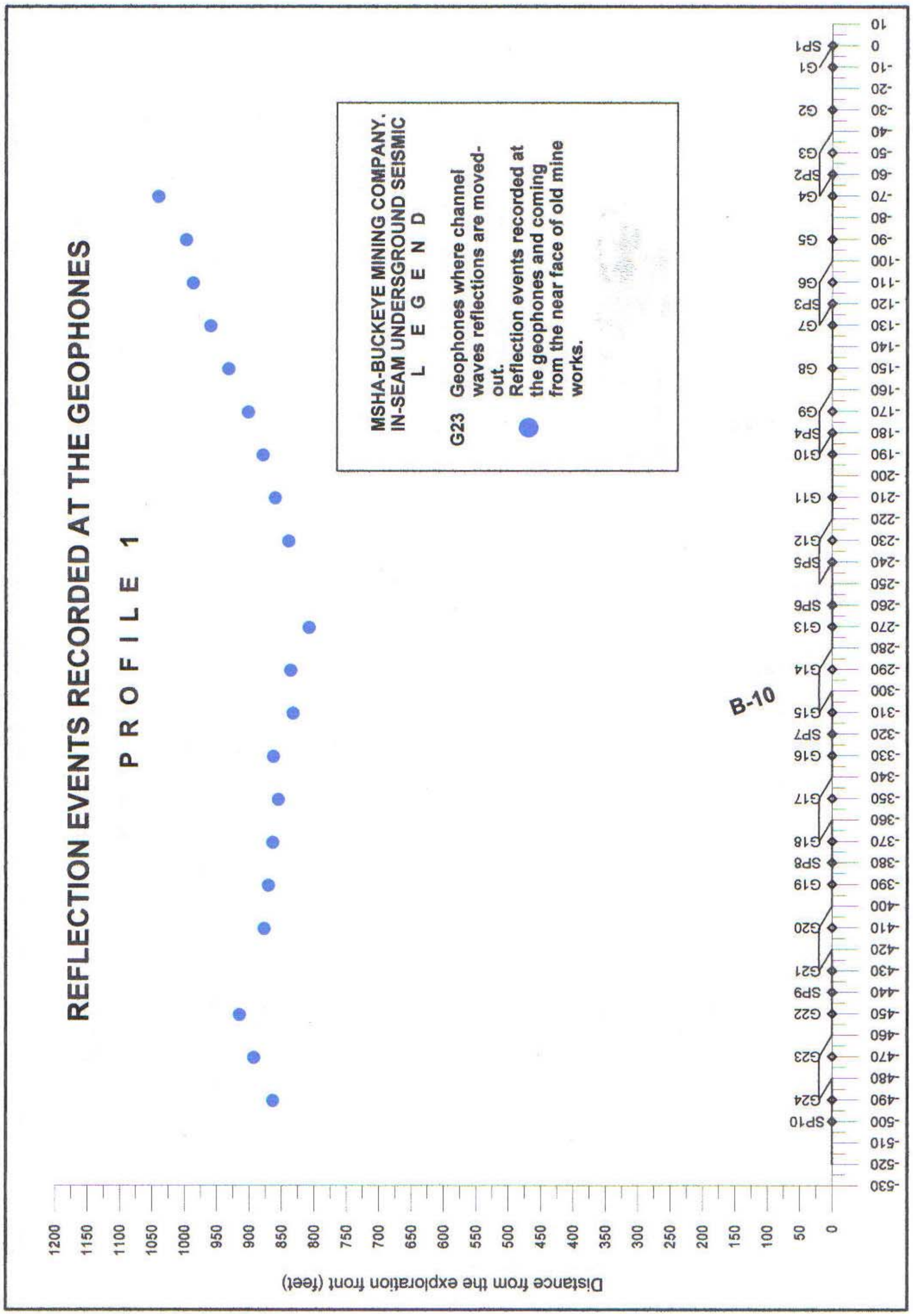

Figure 15. Graph shows the reflection points associated with the old works recorded from G4 to G20 and from G22 to G24 receiver stations from Site 1.

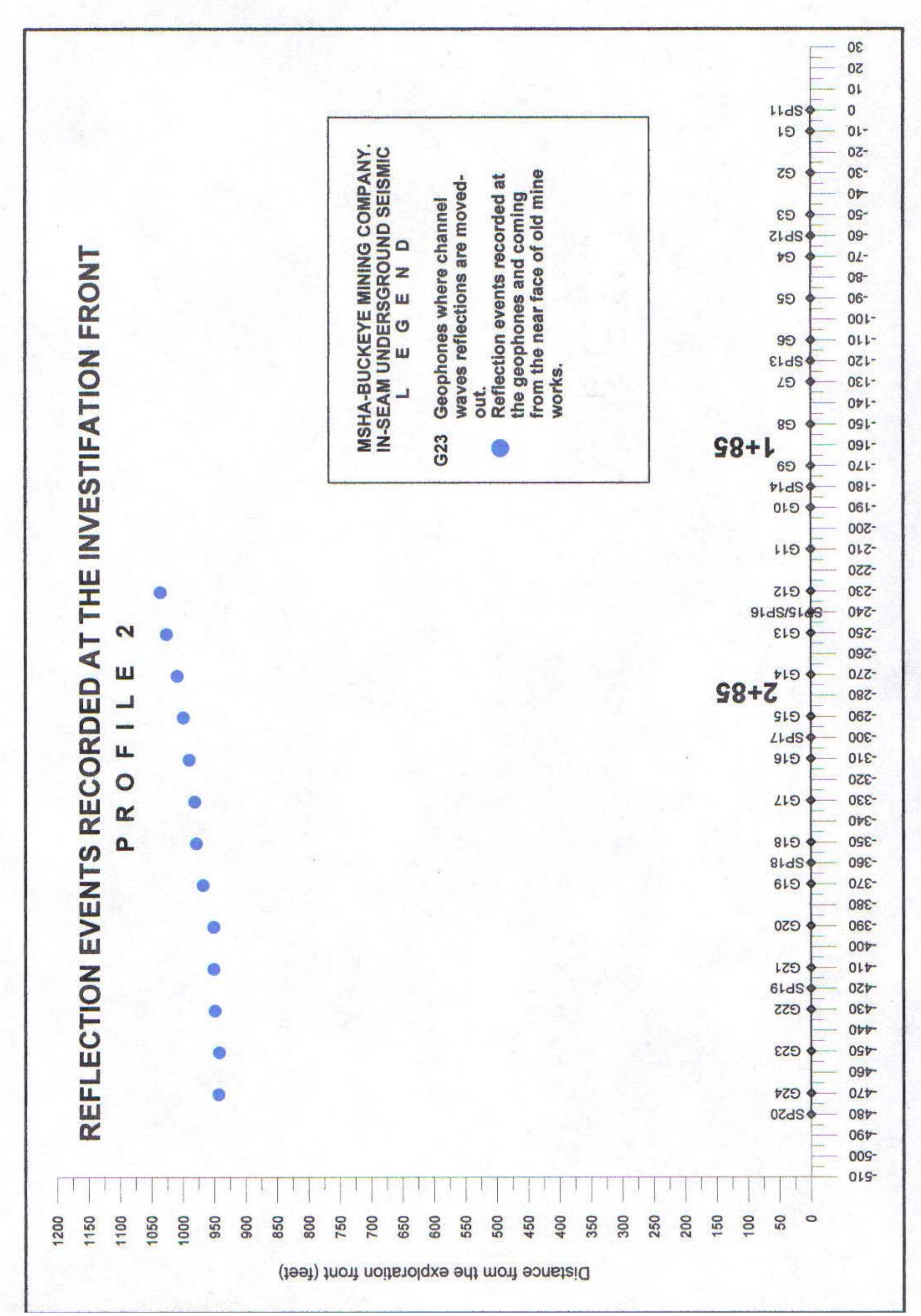

Figure 16. Graph shows the reflection points associated with the old works recorded only between G12 and G24 stations from Site 2.

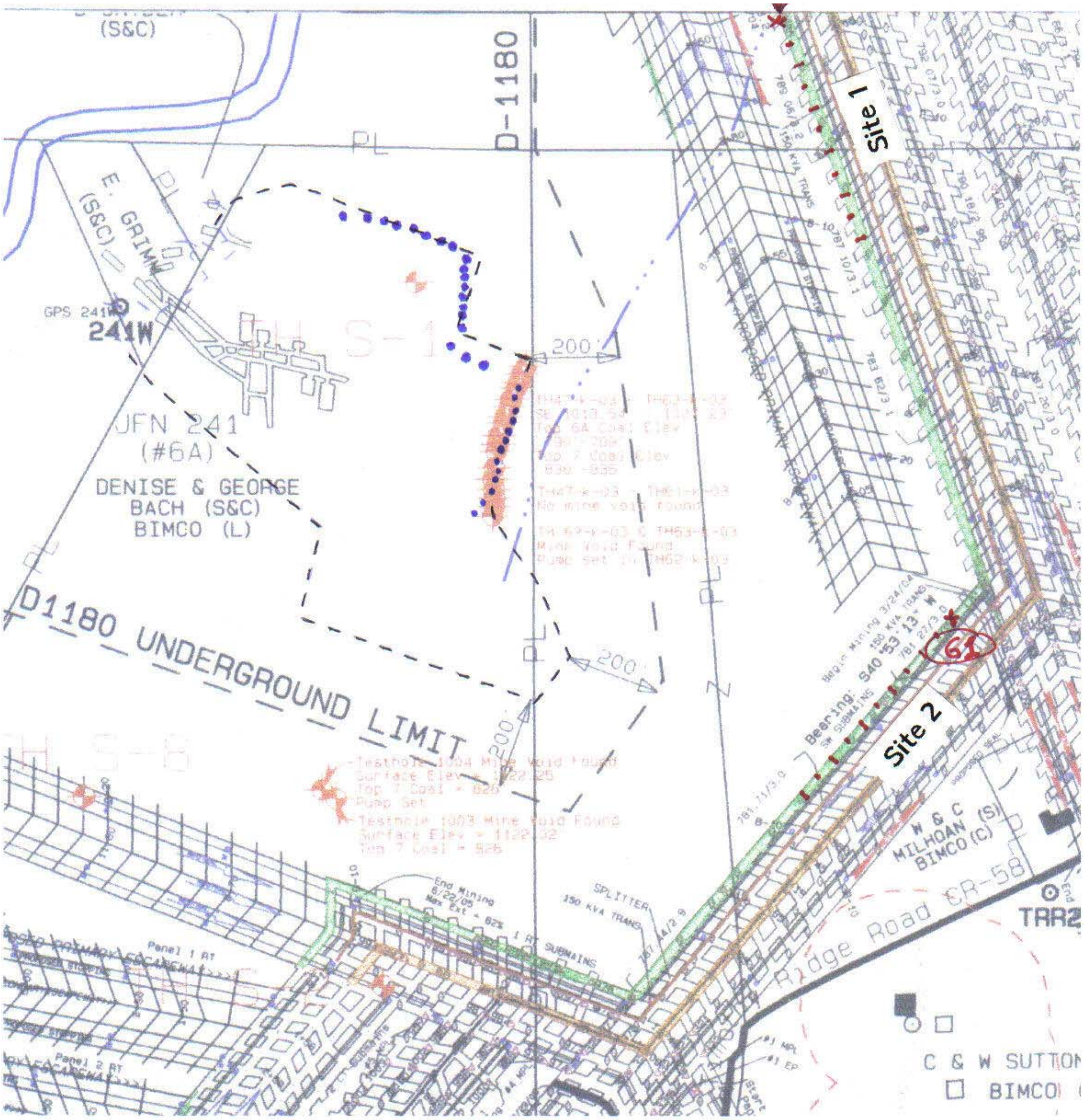

Figure 17. Measured and calculated ISS reflection points (blue dots) are plotted on the mine map. The pattern of reflection points strongly indicated that the ISS survey detected the outline of the shallower #7 old mine works with a high degree of accuracy instead of the #6A Deep Mine.

CASE STUDY 3: BELL COUNTY COAL CORPORATION (2)

Geologic Conditions – Bell County Coal Corporation (BCCC) provided two separate targets for testing the underground ISS method. The mine is called the Cabin Hollow Mine and is located in the northern border of Claireborne County near Fork Ridge, TN The coal seam being mined is called the Buckeye Springs which has a seam thickness ranging from 2.5 to 3 ft. The average seam elevation is about 2000 ft above sea evel. The overburden thickness ranged from 800 to 1100 ft. However in the proposed study area, the overburden thickness averaged about 1100 ft. The overlying rocks above the seam is largely shale. Given the large overburden thickness, it is expected that the P-wave velocity in coal would be high.

After gaining the unusual experience from the Buckeye Mining Industrial Company test site, the team asked BCCC engineers whether there were other mines above or below their active mine. Their response was positive. There were overlying and underlying mines with respect to Cabin Hollow. The underlying Mason Mine had a seam thickness of between 5 and 7 feet. The interval between these two seams is about 260 ft. The overlying Sterling Mine had been mined above Cabin Hollow and the interval between these two seams ranged from 190 to 220 ft.

As for the adjacent old mines, the same seam had been mined to the north by BCCC and the mine was called, Coal Creek Mine. Two other smaller mining operations that were active in the early 1940s were closed and sealed. To the south of Cabin Hollow Mine is the Rennebaum Coal Co., Mine No. 2, and the old Reliance Coal Mine lies to the southeast.

Two worksites with two different targets had been identfied, as shown in **Figure 18**. The objective of Site 1 was to measure the distance to the old Reliance Coal Mine located to the southeast corner of Cabin Hollow. The objective of Site 2 was to determine the accuracy of the ISS method by conducting a sounding tests to measure the distances to the old Coal Creek Mine located to the west. Since BCCC operated and mined Coal Creek Mine, the company kept accurate records which was based on a closed-loop survey method with an internal accuracy standard of 1 part in 5,000. Thus, the second worksite would not need a post-survey verification drilling.

DATA ACQUISITION

The two previous ISS projects conducted at the Sterling Mining Corporation and Buckeye Industrial Mining Corporation utilized a 12-channel seismograph owned and operated by Dr. Rene Rodriguez of GECOH Exploration. The two successive ISS projects will demonstrate the use of a new Geode seismograph capable of 24-channel recording. The resultant larger aperture would permit greater dynamic range recording of data and can improve field productivity. The new system was owned and operated by Lawrence M. Gochioco of LMG&A Inc. However, the sampling rate of one-eighth (1/8) ms and using single 40-Hz geophones remained the same for the rest of the ISS projects for consistency. **Figures 19a and 19b** show images of the newer recording system being operated underground.

Planting the geophones on the coal face required using cordless handheld drills. Holes drilled were near the center of the seam and good coupling was achieved simply by hand-tightening the geophone. Fortunately, some mine personnel had the experience and were licensed to handle explosives. As a result, the seismic source used in this study were blasting caps. Data acquisition was conducted on January 15, 2006.

Since a 24-channel system was being used, one setup was only required at each proposed worksite. The receiver interval was also 20 ft, resulting in a maximum geophone spread length of 460 ft. Source sounding initially started 10 ft outside of the geophone spread, i.e. 10-ft offset on both ends of the G1 and G24 positions. Thereafter, successive source positions were set at a 60-ft interval, until the 9th and last source position is completed at the other end of the receiver spread. Thus, the total surveying spread of one setup is actually 480 ft wide.

INTERPRETATION

Figure 20 show the seismic refraction inversion graph used to extract critical velocity information from Site 1. The graph shows two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The fractured or disturbed coal seam varied in thickness from 35 to 65 ft, and the average measured velocity was about 6,594 ft/s. 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 overburden thickness. Respective source and receiver positions are also shown on the bottom of the graph.

Figure 21 displays the stacked seismic traces after normal-moveout (NMO) correction, filtering, FFT, and Maximum Entropy had been applied. It also shows the recorded two-way arrival times of the seismic energy reflected from the near face of the old Reliance Coal Mine at Site 1. Only receivers located from G1 to G15 recorded sesimic events. Combining the information from **Figures 20 and 21**, a spreadsheet was generated containing information that can used to calculate the distances to the old Reliance Coal Mine (see **Table 4)**. The ISS data indicated that the distances to the old Reliance Coal Mine ranged from 997 to 1198 ft. The calculated reflection points were then plotted on a simple graph to show their relative positions (see **Figure 22)**.

The information were later given to BCCC engineers so that they can plot the calculated reflection points on their mine map. **Figure 23** shows an excellent correlation of the measured distances to the old Reliance Coal Mine. Many of the calculated reflection points fell nearly on top of the western-most boundary of the old mine. (Please note the orientation of the setup room with respect to the old Reliance Coal Mine are nearly parallel, indicating that the data would not have migration issues.)

Receiver Station	Velocity (rms) ft/s	Two-way arrival times (milliseconds)	Calculated Distances (ft)
G1	12,102	166.6	1008
G2	12,102	166.8	1009
G3	12,102	167.3	1012

G4	12,102	165.1	999
G5	12,102	165.0	998
G6	12,102	164.8	997
G7	12,102	165.1	999
G8	12,102	182.0	1101
G9	12,102	182.3	1103
G10	12,102	182.6	1105
G11	12,102	182.5	1104
G12	12,102	196.5	1189
G13	12,102	196.9	1191
G14	12,102	197.4	1194
G15	12,102	198.0	1198
G16			
G17			
G18			

TABLE 4 – Measured and calculated distances to the old Reliance Coal Mine works at Site 1 of the Cabin Hollow Mine, Bell County Coal Corporation.

The seismic refraction inversion graph associated with Site 2 is presented in **Figure 24**. The graph shows two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The fractured coal seam layer was more constant and measured about 60 ft in thickness. The average measured velocity was about 6,599 ft/s. Thereafter, the competent or undisturbed coal had a measured average high velocity of about 11,943 ft/s. This measured high velocity was expected as a result of the overburden thickness. Respective source and receiver positions are also shown on the bottom of the graph.

Figure 25 shows a graph with the reflection points associated with the old works. Only receiver stations G15 to G24 recorded seismic events at Site 2 (old Coal Creek Mine). Combining the information from **Figures 24 and 25**, a spreadsheet was generated containing critical information that can used to calculate the distances to the old Coal Creek Mine (see **Table 5)**. The ISS data indicated that the distances to the old mine ranged from 675 to 758 ft.

Again, the information were given to BCCC engineers so that they can plot the calculated reflection points on their mine map. From **Figure 18,** it is evident that the relative orientation of the setup room with respect to the old Coal Creek Mine works would create some migration issue as there was an approximate 30° angle between them. Therefore, we can expect to have a migration issue with this data set, especially when sounding near the edge of the old mine works.

Figure 26 shows the ISS reflection points plotted on their mine map. Receiver stations G15 to G24 recorded seismic events that were "supposedly" to be in front of them. A few reflection points extended beyond the old mine works, which are untrue. As a result of the ~30° angle between the setup room and the 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 is properly migrated, the reflection points will be closer to the boundary of its true reflector.

Receiver Station	Velocity (rms) ft/s	Two-way arrival time (milliseconds)	Calculated Distance (ft)
G13			
G14			
G15	11,912	126.6	754
G16	11,912	125.4	747
G17	11,912	123.3	734
G18	11,912	122.1	727
G19	11,912	120.6	718
G20	11,912	118.8	707
G21	11,912	117.8	701
G22	11,912	115.9	690
G23	11,912	113.7	677
G24	11,912	112.7	671

TABLE 5 – Measured and calculated distances to the old Coal Creek Mine works at Site 2 of the Cabin Hollow Mine, Bell County Coal Corporation.

To gather a level of accuracy from this ISS survey conducted at Site 2, let us take the measured distances from receiver stations G24 and G15 in which their respective calculated distances were between 671 and 754 ft. The migration method is applied (by hand) to the ISS data to properly sort the reflection points to the true reflector surface, which is supposed to be orthogonal to the receiver station. After the process, we could then recalculate more accurately the actual distance to the reflecting surface. The estimated respective distances associated with the new reflected surfaces for G24 and G15 ranged from 650’ to 725’. In this case, the ISS data over-estimated the distances to the old mine works by about 25 ft over an average horizontal distance of approximately 688 ft. Therefore, the **percentage error is ~ 3.6%**.

VERIFICATION

SITE 1 - After the ISS data were presented to BCCC in early February 2006, company president, B. J. Reynolds, promised to drill a verification hole to confirm the calculated distances to the old Reliance Mine. However, their main focus was actually driving the mains toward the old Rennebaum Mine located to the south – a higher priority. Thus, BCCC drilled a horizontal hole towards the old Rennebaum Mine the summer of 2006 and found the old mine map to be accurate. Mr. Reynolds informed me that BCCC spent about $325,000. to drill the hole.

After months of leaving messages and sending emails with no response, Mr. Reynolds finally called on March 2007 to inform me that the company changed its mind. Given the high drilling costs and tight coal price margins, BCCC decided not to drill the verification hole because they also learned that the same mine engineer drew and archived both the old Reliance and Rennebaum Mine maps. Since drilling results to the Rennebaum Mine and ISS data results to the Reliance were fairly accurate, Mr. Reynolds felt there was no need to waste company funds drilling the verification hole to confirm the ISS survey results as their priority in mine development is located elsewhere.

Thus, MSHA considered the Site 1 test to be unacceptable since it was unverified. LMG&A Inc. had to reconduct another ISS survey at a later date.

SITE 2 - Coal Creek Mine is still being operated by BCCC. The company has its own internal certified surveyors in which they use the closed-loop methodology with an accuracy standard of 1 part in 5000. As mine entries are advanced survey stations are installed in the mine roof, which are used by the miners to keep the mine entries straight. Typically, these survey stations are installed at two break intervals every 160 ft. Closed loop surveying is accomplished by surveying between the two parallel survey lines in mine entries at regular intervals and calculating the error of closure in comparison to the distance contained in the “loop” encompassed by the survey stations located within the appropriate mine entries. Maps are then submitted, reviewed, and certified by a professional engineer or land surveyor. Thus, survey results from this site would not require verification drilling.

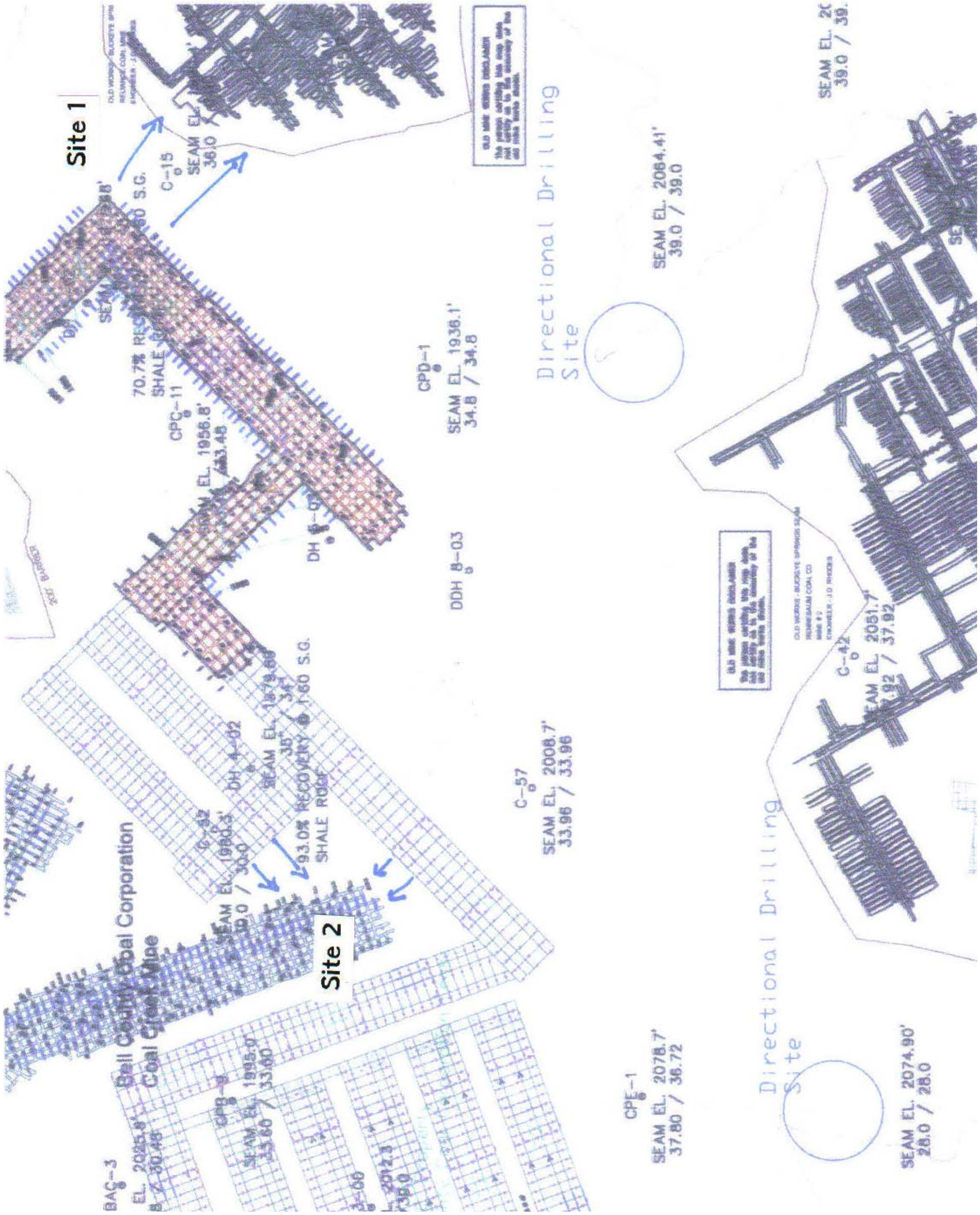

Figure 18. Map shows the location of Cabin Hollow Mine with respect to the old Reliance Coal Mine (east) and the Coal Creek Mine (west). The two proposed ISS survey sites are highlighted.

(a)

(b)

Figure 19. Two images show the newer Geode 24-channel recording system being operated underground.

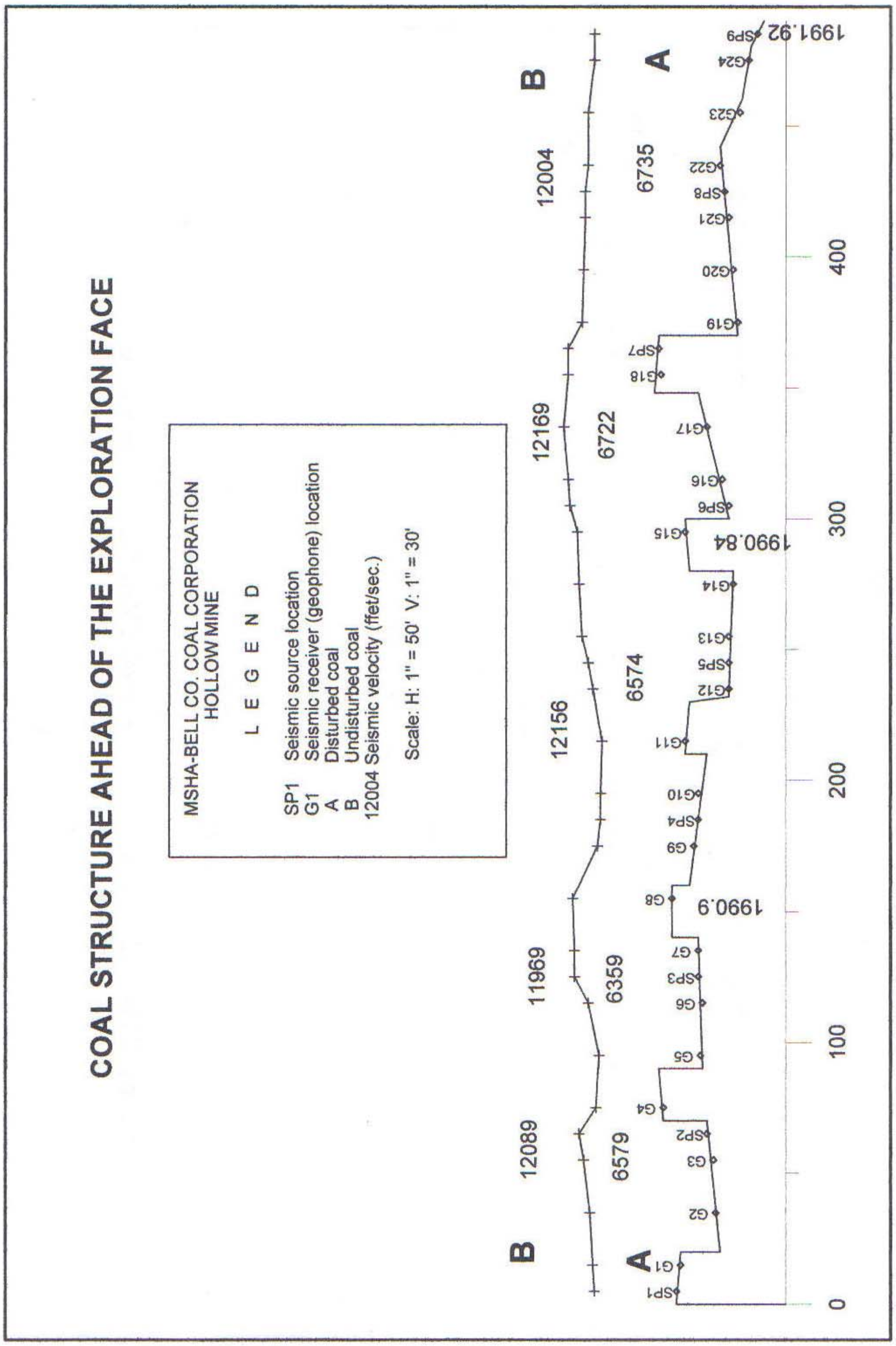

Figure 20. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Site 1 (Old Reliance Coal Mine). The RMS velocity associated with undisturbed coal was calculated to be about 12,102 ft/s.

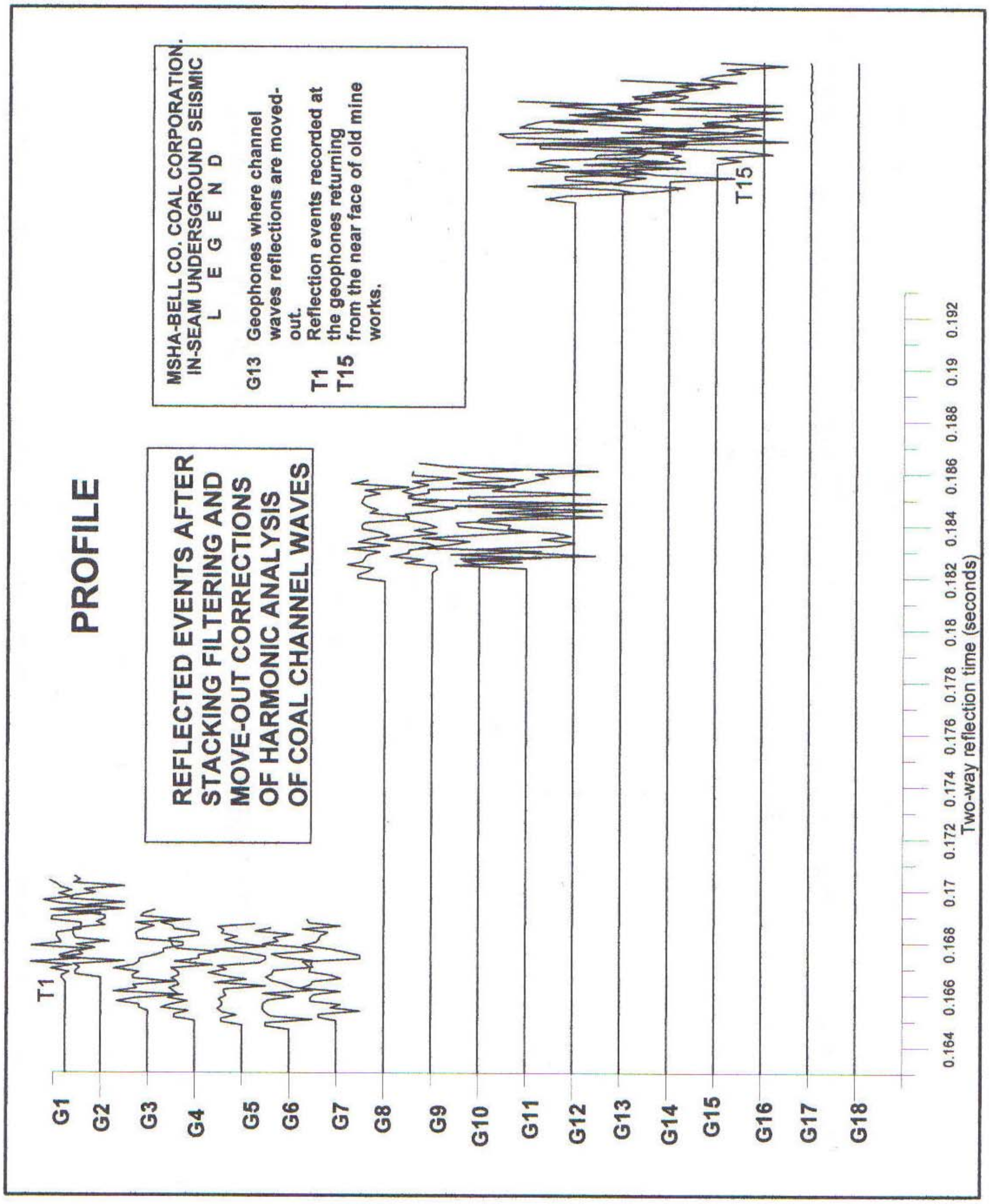

Figure 21. Stacked seismic traces show the recorded two-way arrival times of the seismic energy reflected from the near face of the old works from Site 1 (old Reliance Coal Mine).

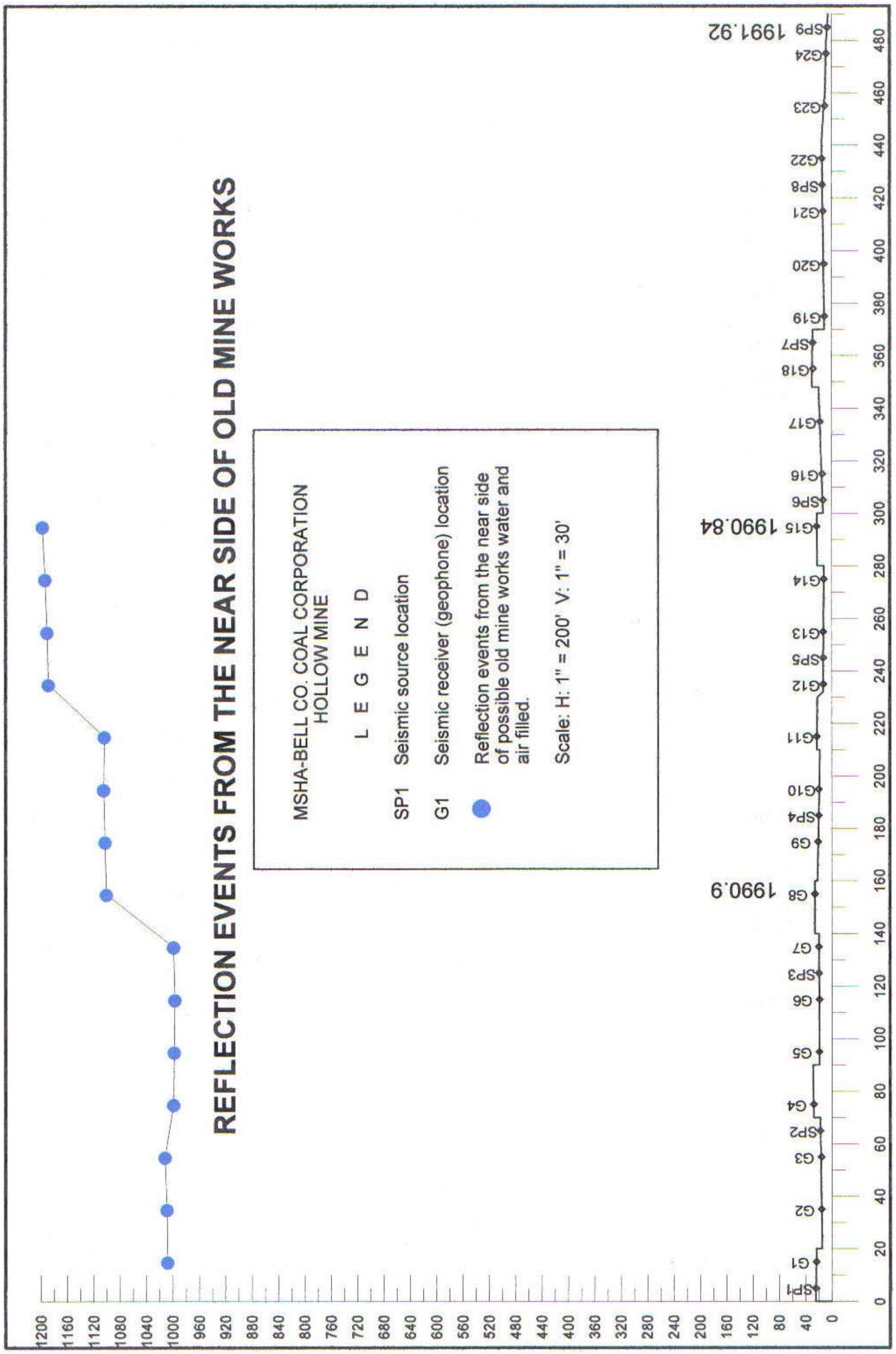

Figure 22. Graph shows the reflection points associated with the old works. Only reciever stations G1 to G15 recorded seismic events at Site 1.

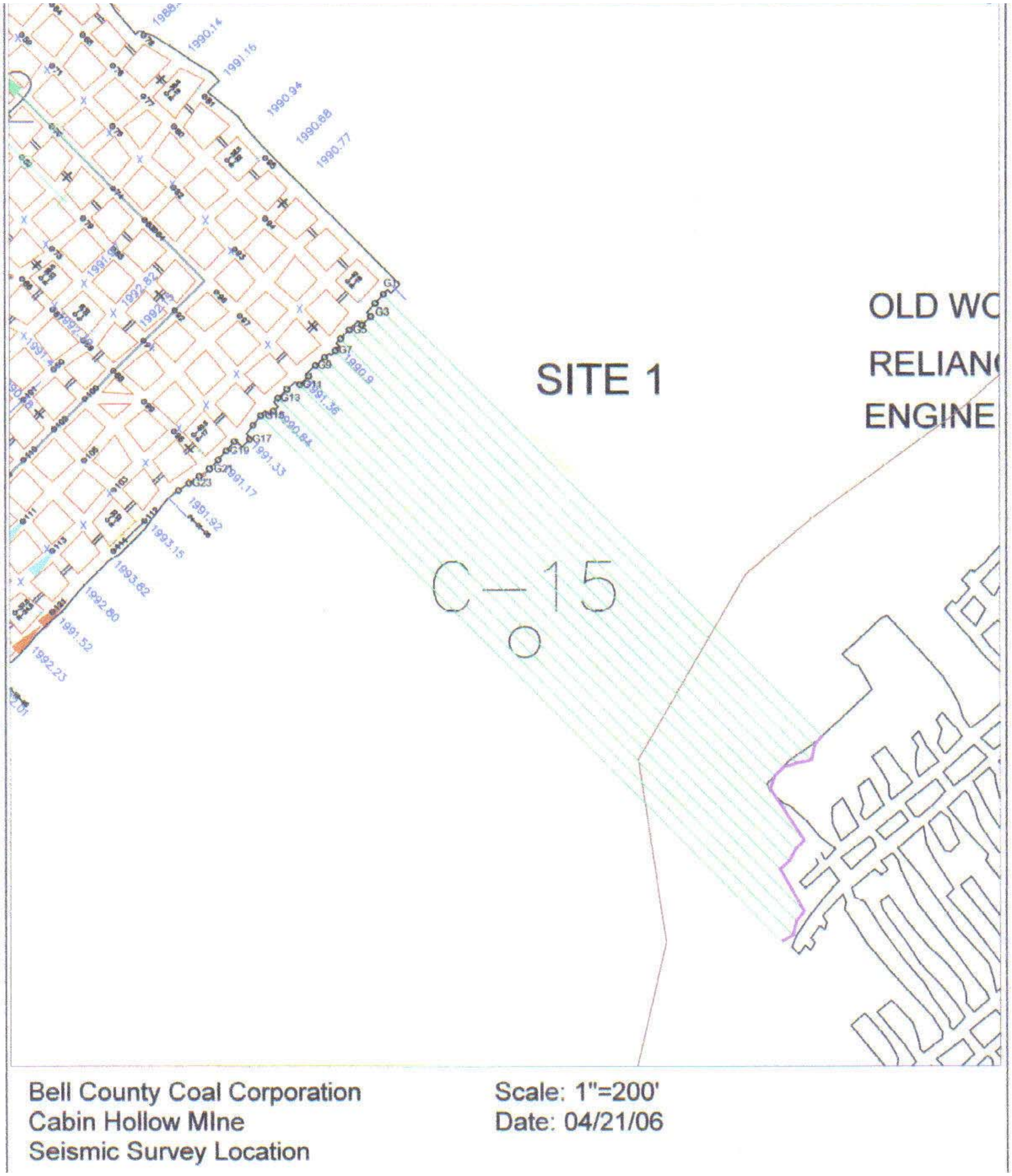

Figure 23. The ISS reflection points plotted on the Cabin Hollow mine map show an excellent correlation with the estimated known location of the old Reliance Coal Mine.

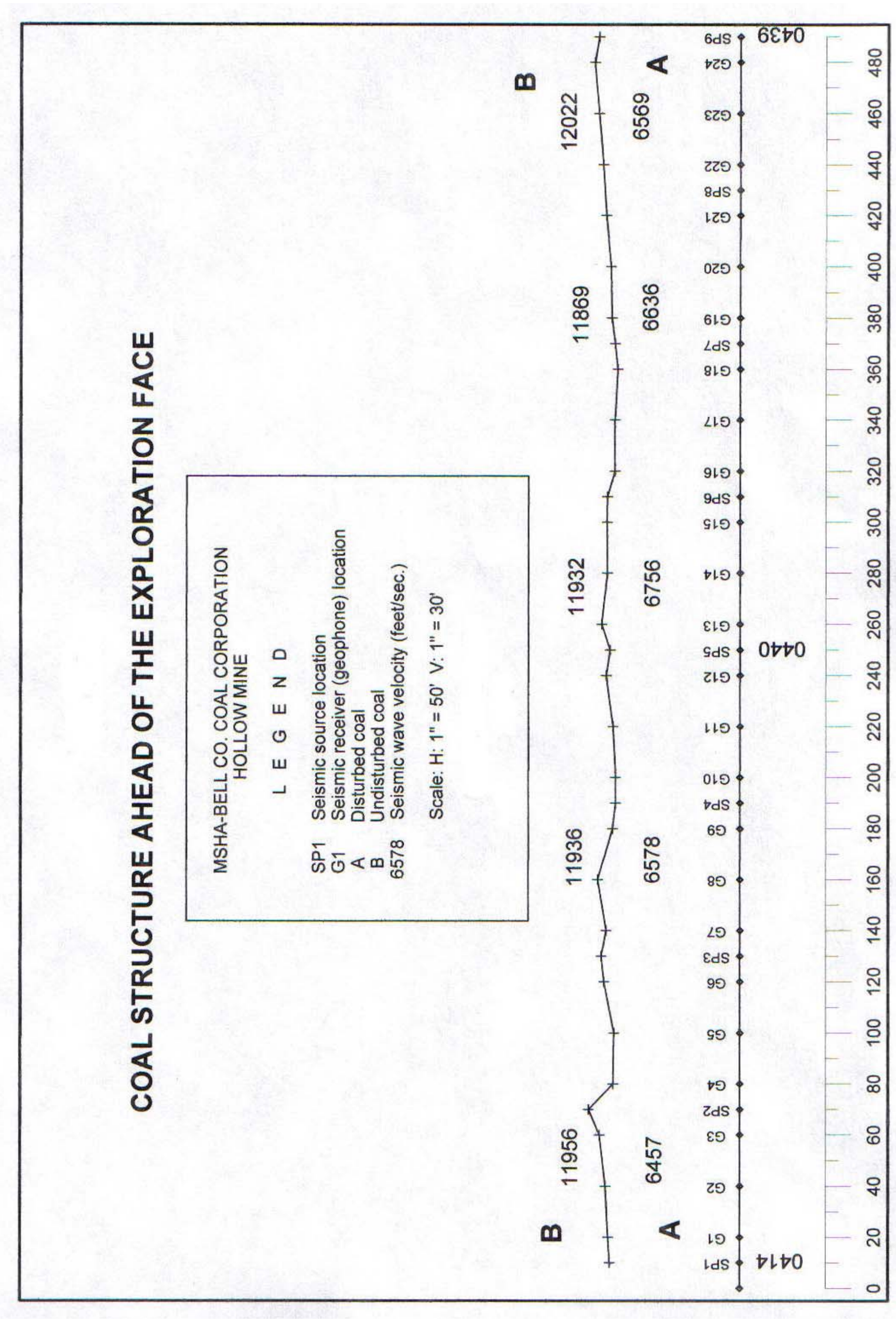

Figure 24. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Site 2 (old Coal Creek Mine). The RMS velocity associated with undisturbed coal was calculated to be about 11,912 ft/s.

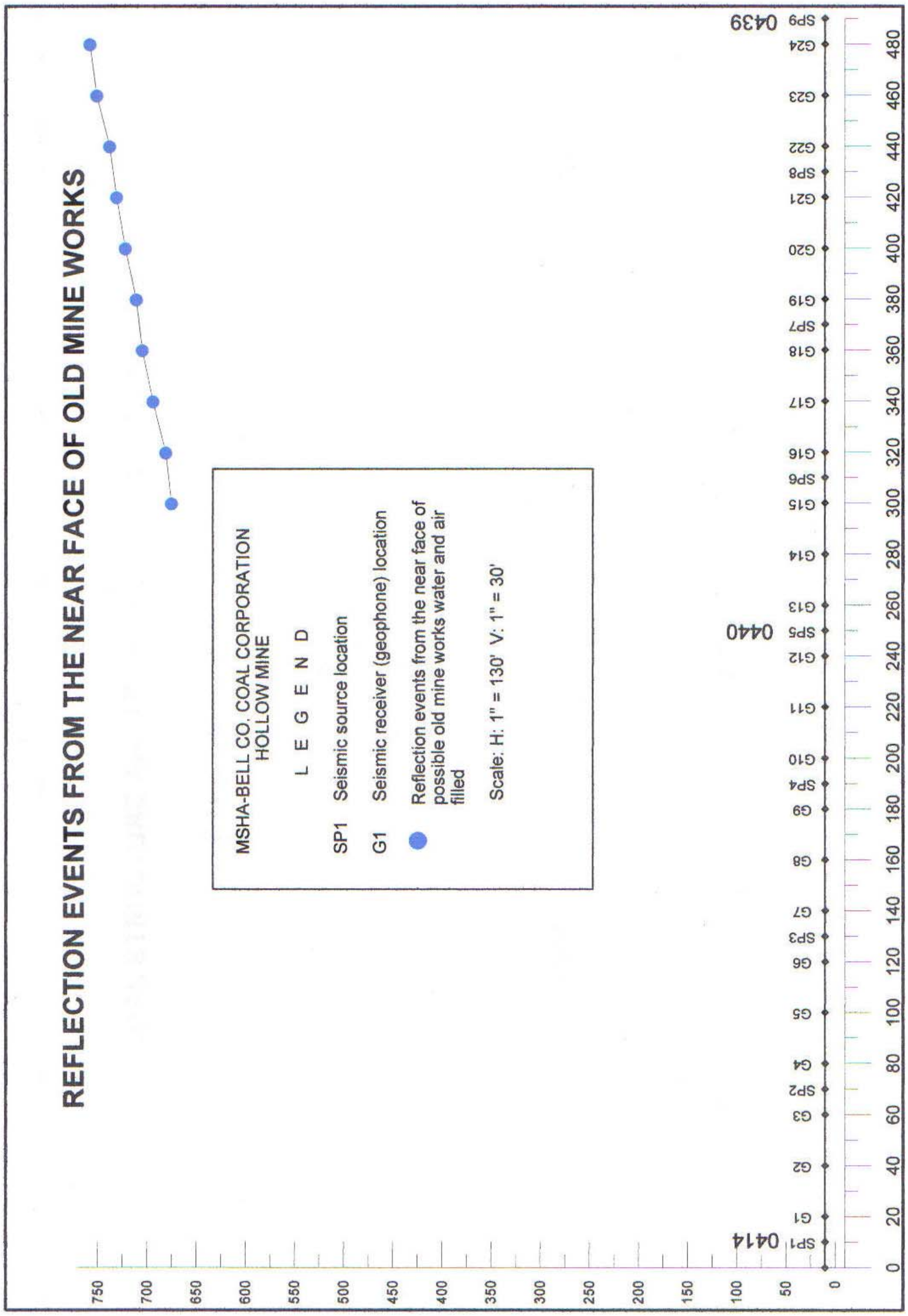

Figure 25. Graph shows the reflection points associated with the old works. Only receiver stations G15 to G24 recorded seismic events at Site 2 (old Coal Creek Mine).

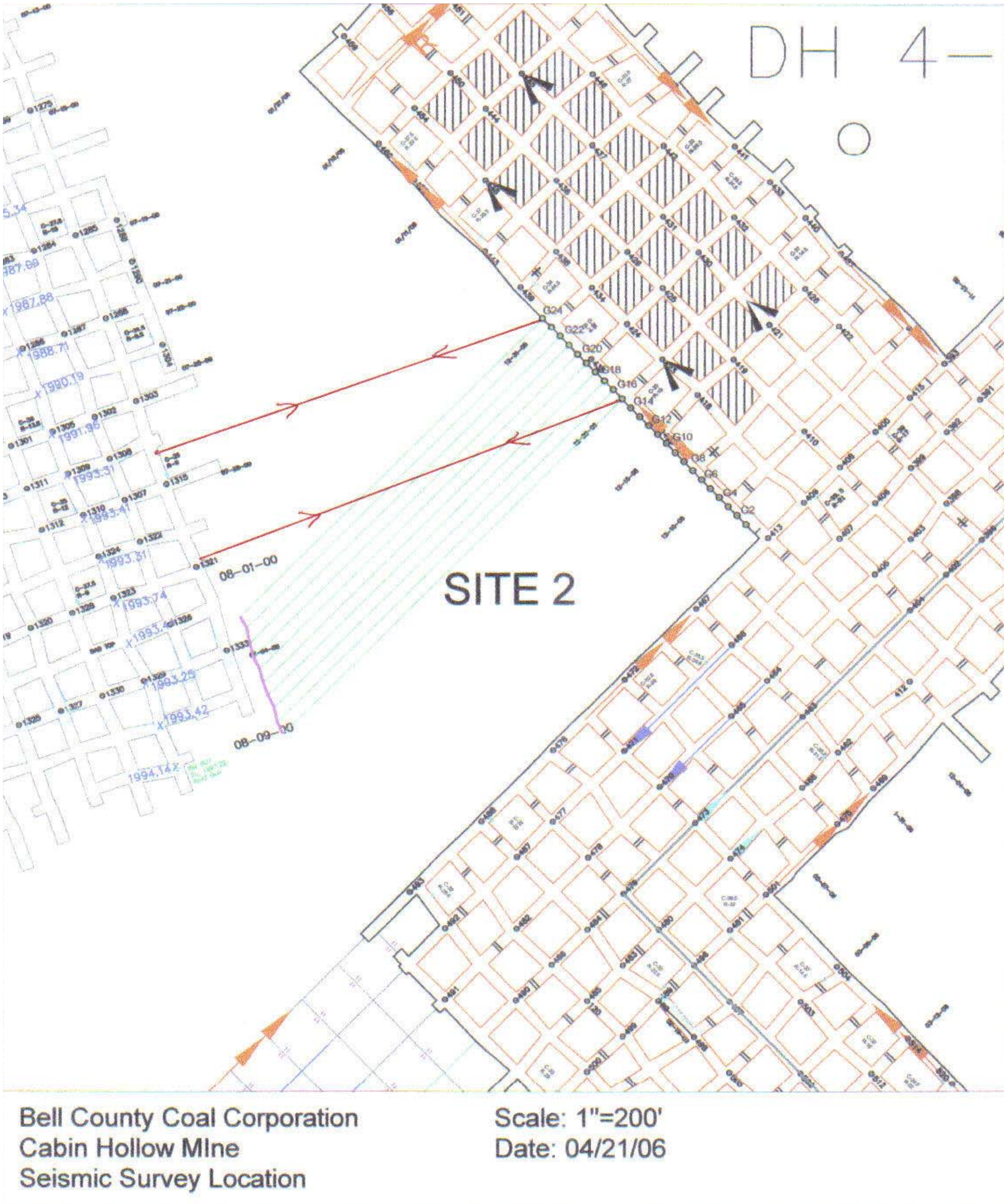

Figure 26. ISS reflection points are plotted on the mine map to show the recording of seismic events "supposedly" in front of the receivers. As a result of the ~30º angle between the setup room and old mine works, the reflection points were actually coming from a different location, as indicated by the pair of red lines. When the ISS data is properly migrated, the reflection points will be closer to the boundary of its true reflector.

CASE STUDY 4: BLUFF SPUR COAL CORPORATION (1)

Geologic Background – The active mine was formerly owned and operated by Westmoreland Coal before Bluff Spur Coal Corporation (BSCC) acquired the property. Coal mining is conducted at the Taggart seam, and the thickness ranged from 4 to 12 ft. As a result of the mountaineous topography, the overburden thickness varied significantly from 300 to 1700 ft.

MSHA selected this site as a "blind test" to test the team's ability to perform without any knowledge of indication of the old mine works' location and orientation. LMG&A Inc. took the challenge. **Figure 27** is a map of the Mine No. 1 of BSCC where the ISS surveys were conducted. The green arrow in the center of the map marked the center line where two ISS setups of 24-channel recording were conducted. The setup room was in the No. 1 West Mains and the target was the No. 1 Left Section of the South Mains. At the setup acquisition room, the seam thickness was 4 ft.

DATA ACQUISITION

The same field setup used at the BCCC project was also used in this blind test. The Geode 24-channel system was used as the seismograph and single 40-Hz geophones were used as receivers. The recording parameters were also similar. Planting the geophones on the coal face required the using cordless drills. Drilling was near the center of the seam and good coupling is achieved simply by hand-tightening the geophone in the drilled hole. The receiver interval was also 20 ft, resulting in a maximum geophone spread length of 460 ft. Source sounding initially started 10 ft outside of the geophone spread, i.e. 10-ft offset on both ends of the G1 and G24 stations. Thereafter, successive source positions were set at a 60-ft interval, until the 9th and last source position was completed at the other end of the receiver spread. Thus, the total surveying spread of one setup is actually 480 ft wide.

During acquisition, the crew experienced less desirable conditions because the coal face was found to be highly-fractured. The highly-fractured coal face indicated that the source-receiver coupling was poor, resulting in the recording of poor data quality.

Fortunately, some mine personnel had the experience and were licensed to handle explosives. As a result, the seismic source used in this study were blasting caps. Data acquisition was conducted and completed on January 22, 2006.

INTERPRETATION

Figures 28 and 29 show the seismic refraction inversion graphs used to extract critical information velocity information from Setup 1 and 2. The graph shows two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The fractured coal zone varied in thickness from 110 to 165 ft, and the average measured velocity was about 5,006 ft/s. Thereafter, the competent or undisturbed coal had a measured average high velocity of about 11,016 ft/s. This measured high velocity was expected as a result of the overburden thickness. Respective source and receiver positions are shown on the bottom of the graphs.

Figures 30 and 31 display the stacked seismic traces after normal-moveout (NMO) correction, filtering, FFT, and Maximum Entropy had been applied. It also shows the recorded two-way arrival times of the seismic energy reflected from the near face of the old mine works from Setup 1 and 2 respectively. It is apparent that the data is of poorer quality when compared to the other ISS projects. As a result of the thick highly-fractured zone, the signal-to-noise ratio recorded is low. Only about 44% of receivers recorded interpretatble seismic events.

Combining the information from **Figures 28 to 31**, two spreadsheets were generated containing important data used to calculate the distances to the old mine works (see Tables 6 and 7). The ISS data indicated that the distances to the old mine works ranged from 603 to 676 ft. The calculated reflection points were then plotted on a simple graph to show their relative positions, as shown in **Figures 32 and 33**.

Receiver Station	Velocity (rms) ft/s	Two-way arrival times (milliseconds)	Calculated Distances (ft)
G1	8,500	153	650.25
G2	8,500	149	633.25
G3	8,500		
G4	8,500	147	624.75
G5	8,500		
G6	8,500		
G7	8,500	153	650.25
G8	8,500		
G9	8,500		
G10	8,500	151	641.75
G11	8,500		
G12	8,500	148	629
G13	8,500		
G14	8,500	145	616.25
G15	8,500		
G16	8,500		
G17	8,500		
G18	8,500	152	646
G19	8,500		
G20	8,500	157	667.25
G21	8,500		
G22	8,500		
G23	8,500		
G24	8,500	159	675.75

TABLE 6. Measured and calculated distances to the abandoned mine works of Mine No. 1, Bluff Spur Coal Corporation from Setup 1 location.

Receiver Station	Velocity (rms) ft/s	Two-way arrival times (milliseconds)	Calculated Distances (ft)
G1	8,500	150	637.5
G2	8,500	151	641.75
G3	8,500	152	646
G4	8,500		
G5	8,500		
G6	8,500		
G7	8,500	148	633.25
G8	8,500	150	637.5
G9	8,500		
G10	8,500	155	658.75
G11	8,500		
G12	8,500		
G13	8,500	151	641.75
G14	8,500		
G15	8,500	153	650.25
G16	8,500		
G17	8,500		
G18	8,500		
G19	8,500	147	624.75
G20	8,500	148	620.5
G21	8,500		
G22	8,500		
G23	8,500	142	603.5
G24	8,500		

TABLE 7 – Measured and calculated distances to the abandoned mine works of Mine No. 1, Bluff Spur Coal Corporation from Setup 2 location.

The calculated reflection points were then plotted on the mine map, as shown in **Figure 34**. As a result of the complex geometery (3-4-5 right triangle), especially on the side of Setup 1 location, the cluster of reflection points were expected to be way off the target as the travel paths of the seismic energy could be several (like a bullet ricocheting from two or more sides) and the seismic events recorded by the geophones could come from several different directions.

However, the Setup 2 location is less complex and the distances are relatively shorter. As such, the cluster of reflection points shown in Figure 33 could be close approximations of the old mine works. Again, a migration algorithm option would properly position the reflection points.

VERIFICATION

No verification drilling was needed at this worksite as the mine had been properly surveyed. The target area for the ISS survey, the No. 1 Left Section, was advanced from the No. 1 South Mains in the late 70's when the mine was operated by Westmoreland Coal Company as the B Portal Mine. The section of the mine from which the seismic survey was conducted, the No. 1 West Section, was advanced by the current operating company, the Bluff Spur Coal Corporation under the name of Mine No. 1 in 2001.

Surveys performed by the Westmoreland Coal Company during the referenced timeframe utilized closed-loop survey methodology with an internal accuracy standard of 1 part in 5,000. While the Division of Mines (DM) has no maps on file certified by a professional engineer or land surveyor of the B Portal Mine, semi-annual maps were required to be submitted and certified by a professional engineer or land surveyor during the time it was operated under that name.

Mapping and Property Specialists, LLC (MAPS) of Big Stone Gap, Va, has performed all the surveying at the BSCC Mine No. 1. MAPS conducts surveys utilizing the closed loop method with an internal accuracy standard of 1 part in 5,000. Maps are currently required to be submitted annually to DM that are certified by a professional engineer or land surveyor. As mine entries are advanced survey stations are installed in the mine roof, which are used by the miners to keep the mine entries straight. Typically, these survey stations are installed at two break intervals or approximately every 160 feet. Closed loop surveying is accomplished by surveying between these parallel survey lines in mine entries at regular intervals and calculating the error of closure in comparison to the distance contained in the "loop" encompassed by the survey stations located within the appropriate mine entries.

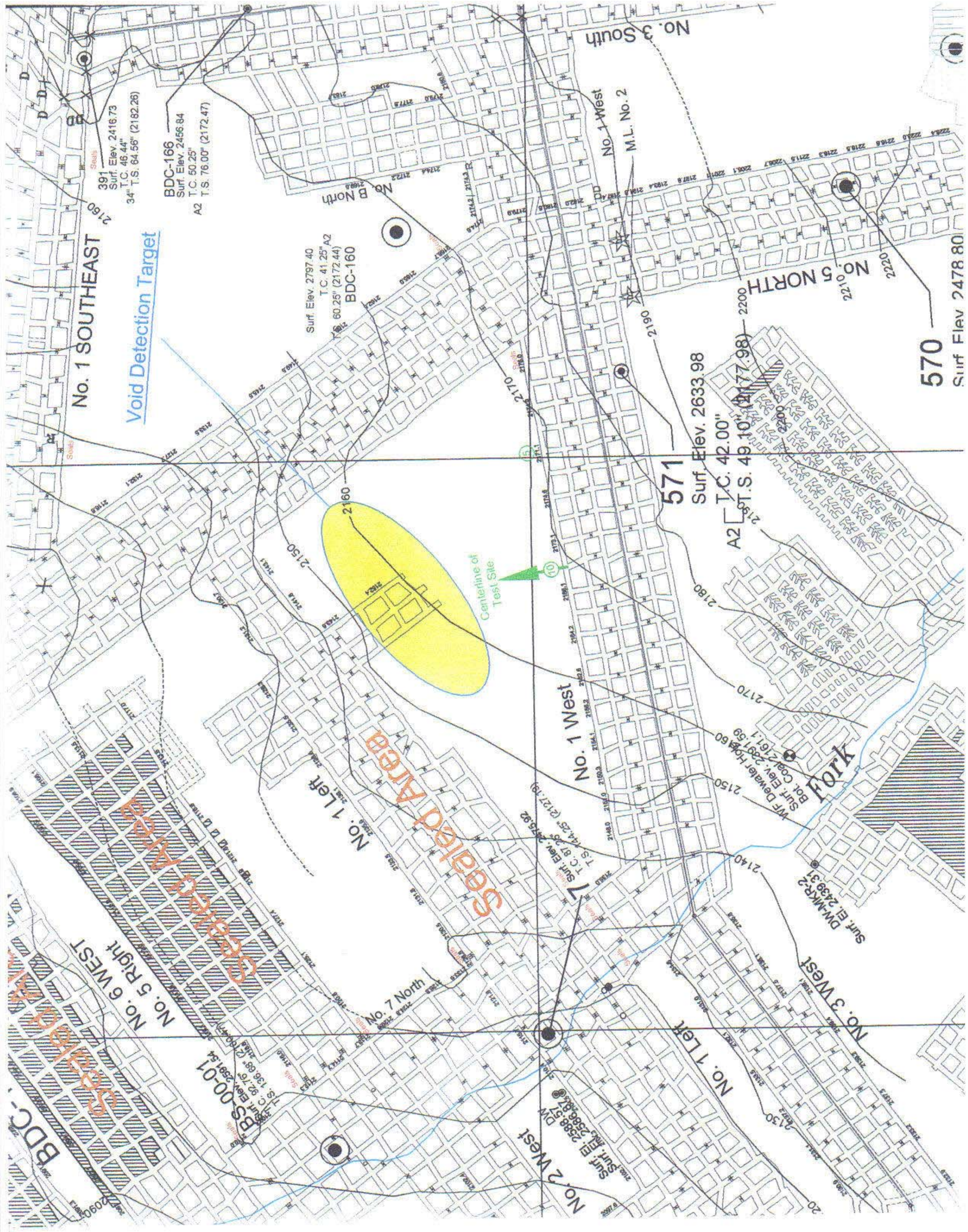

Figure 27. Map of the Mine No. 1 of Bluff Spur Coal Corporation where the ISS surveys were conducted as part of a blind tests. The green arrow in the center of the map marked the center line where two setups of 24-channel ISS surveys were conducted.

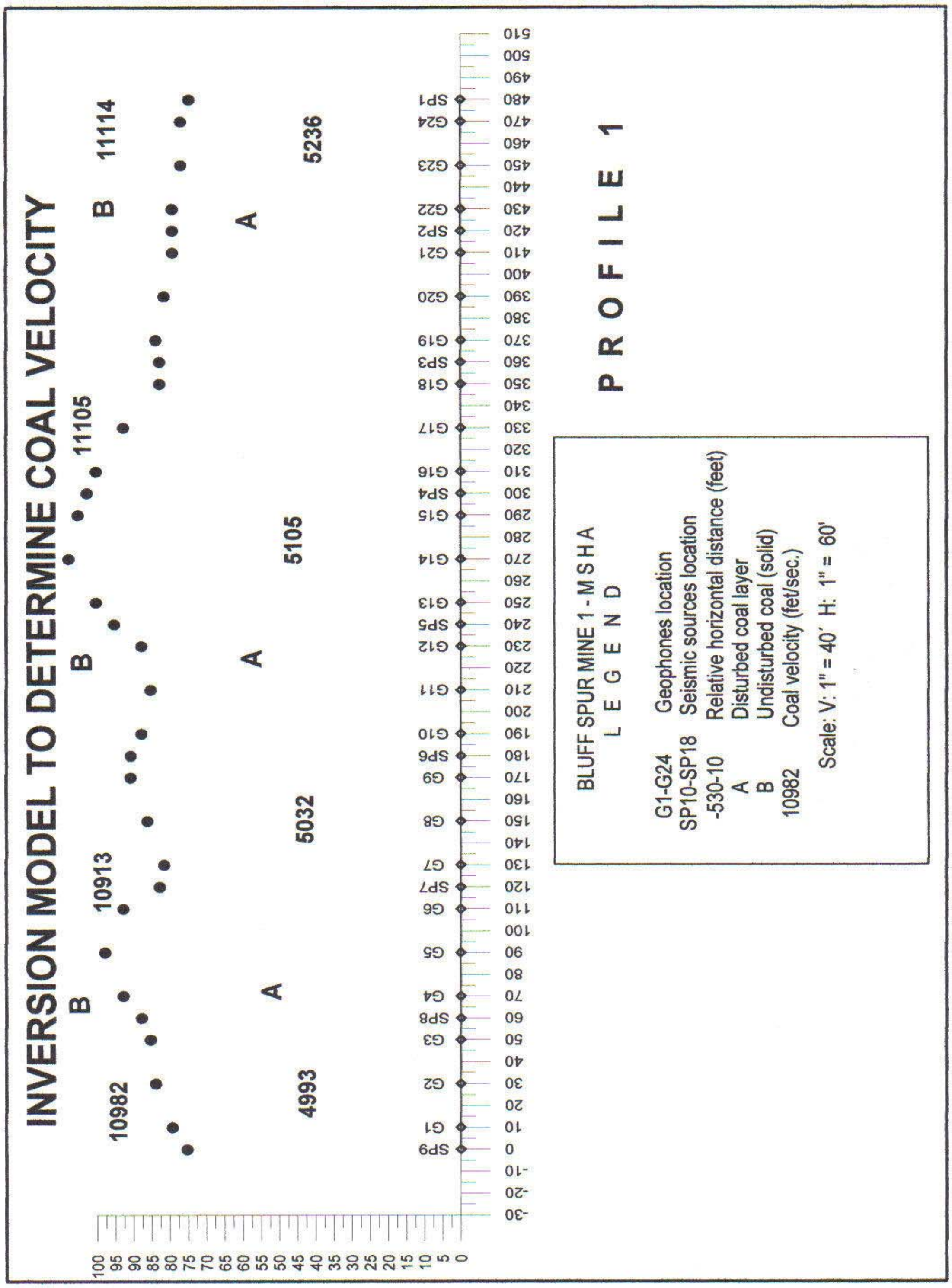

Figure 28. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Setup #1. Highly-fractured coal was up to 100 ft in thickness. The RMS velocity was calculated to be about 8,500 ft/s

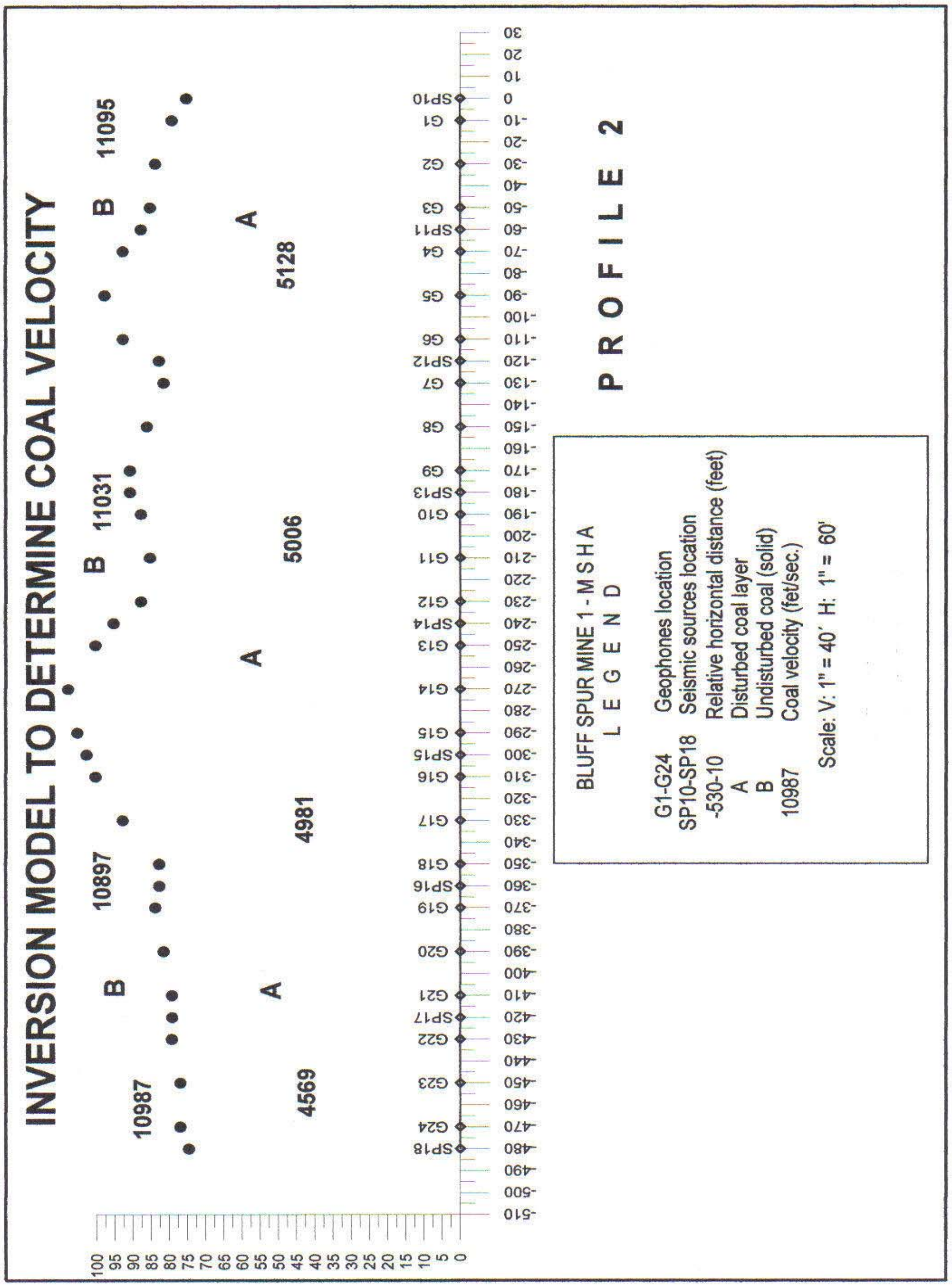

Figure 29. Graph shows results from refraction inversion modeling that provided critical velocity information associated with disturbed and undisturbed coal gathered from Setup #2. Highly-fractured coal was up to 100 ft in thickness. The RMS velocity was calculated to be about 8,500 ft/s.

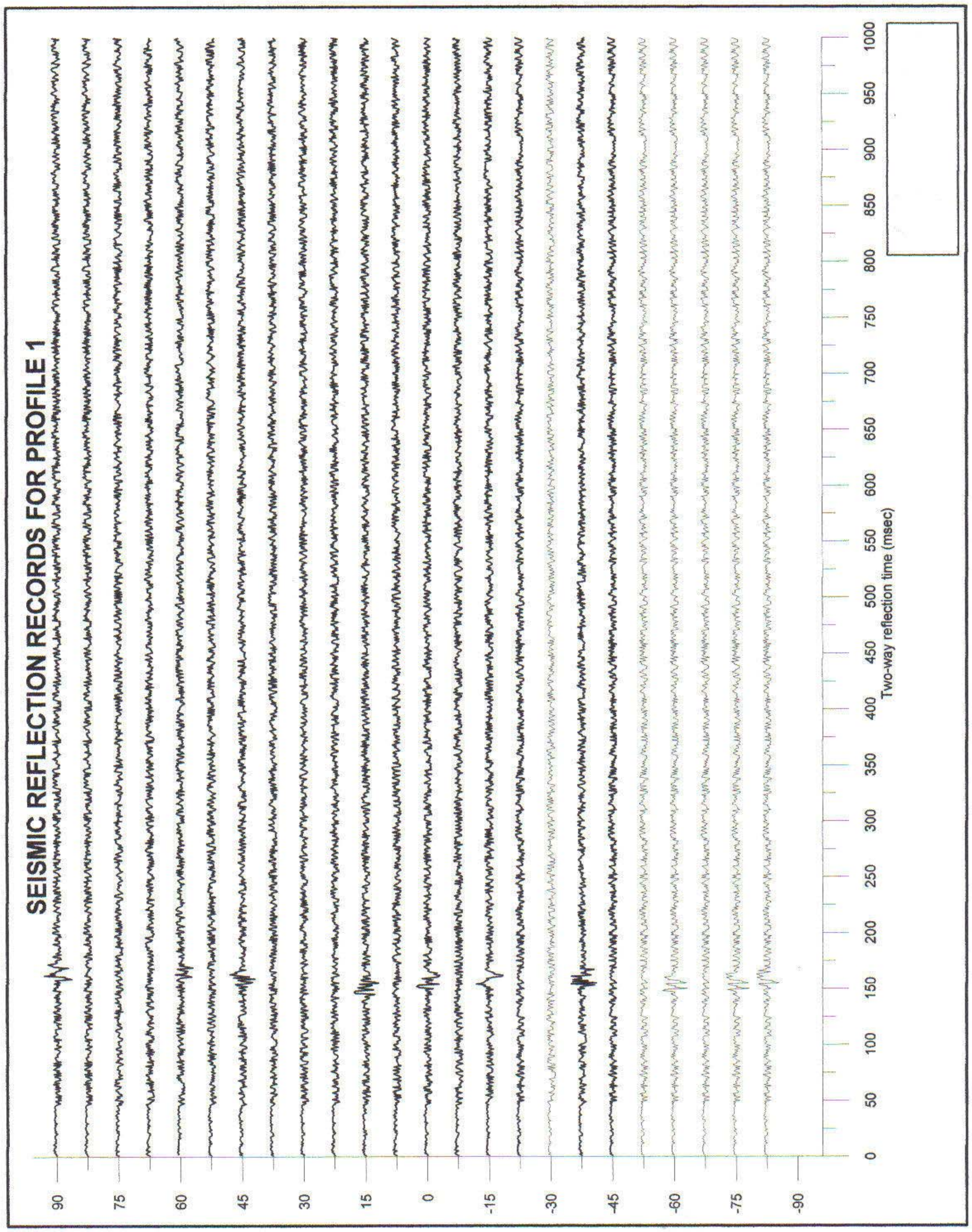

Figure 30. Stacked seismic traces show the recorded two-way arrival times of relatively weak seismic energy reflected from the near face of the old works from Setup #1.

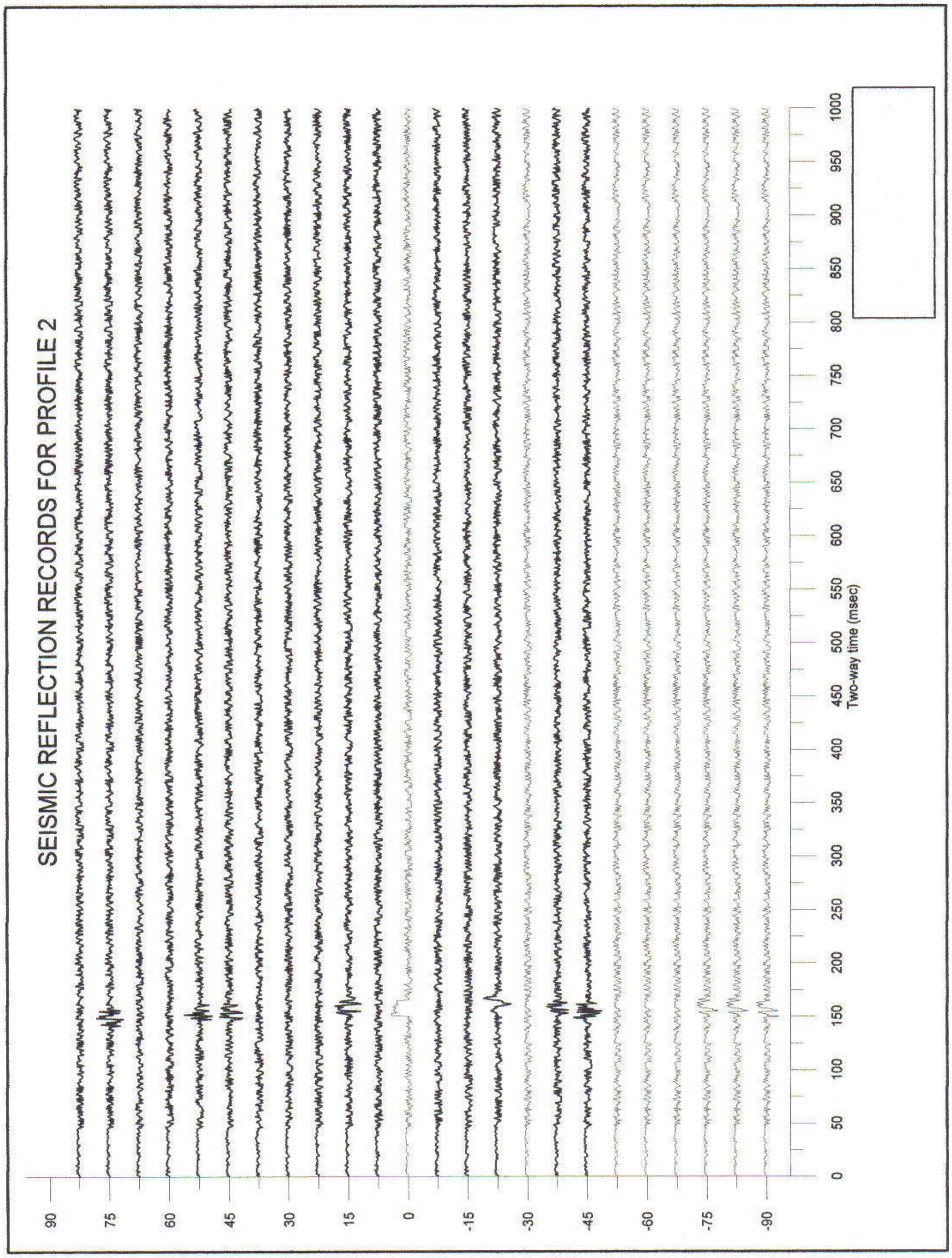

Figure 31. Stacked seismic traces show the recorded two-way arrival times of relatively weak seismic energy reflected from the near face of the old works from Setup #2.

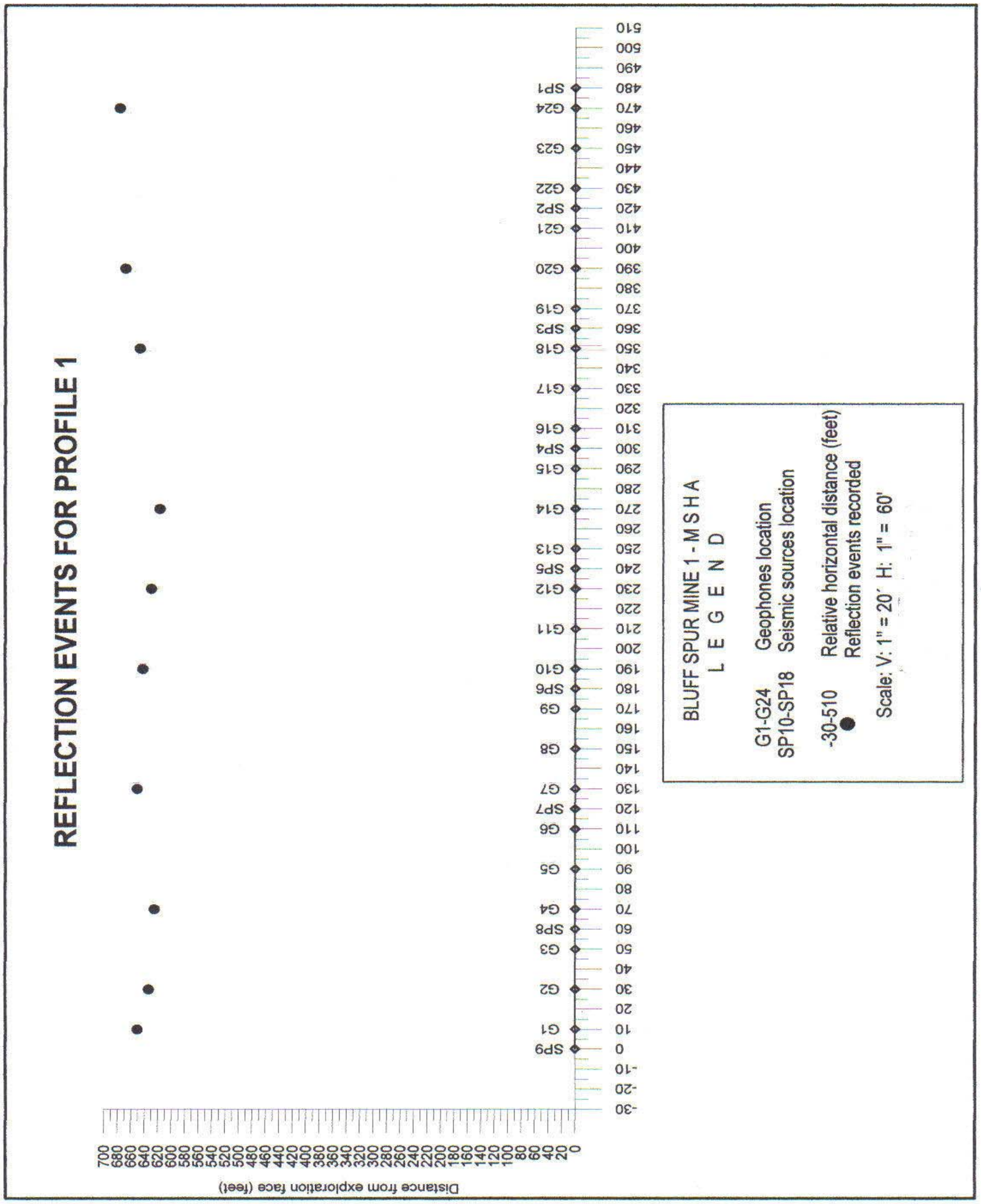

Figure 32. Graph shows the scattered reflection points associated with the old works from Setup #1 (east of the green center line marker).

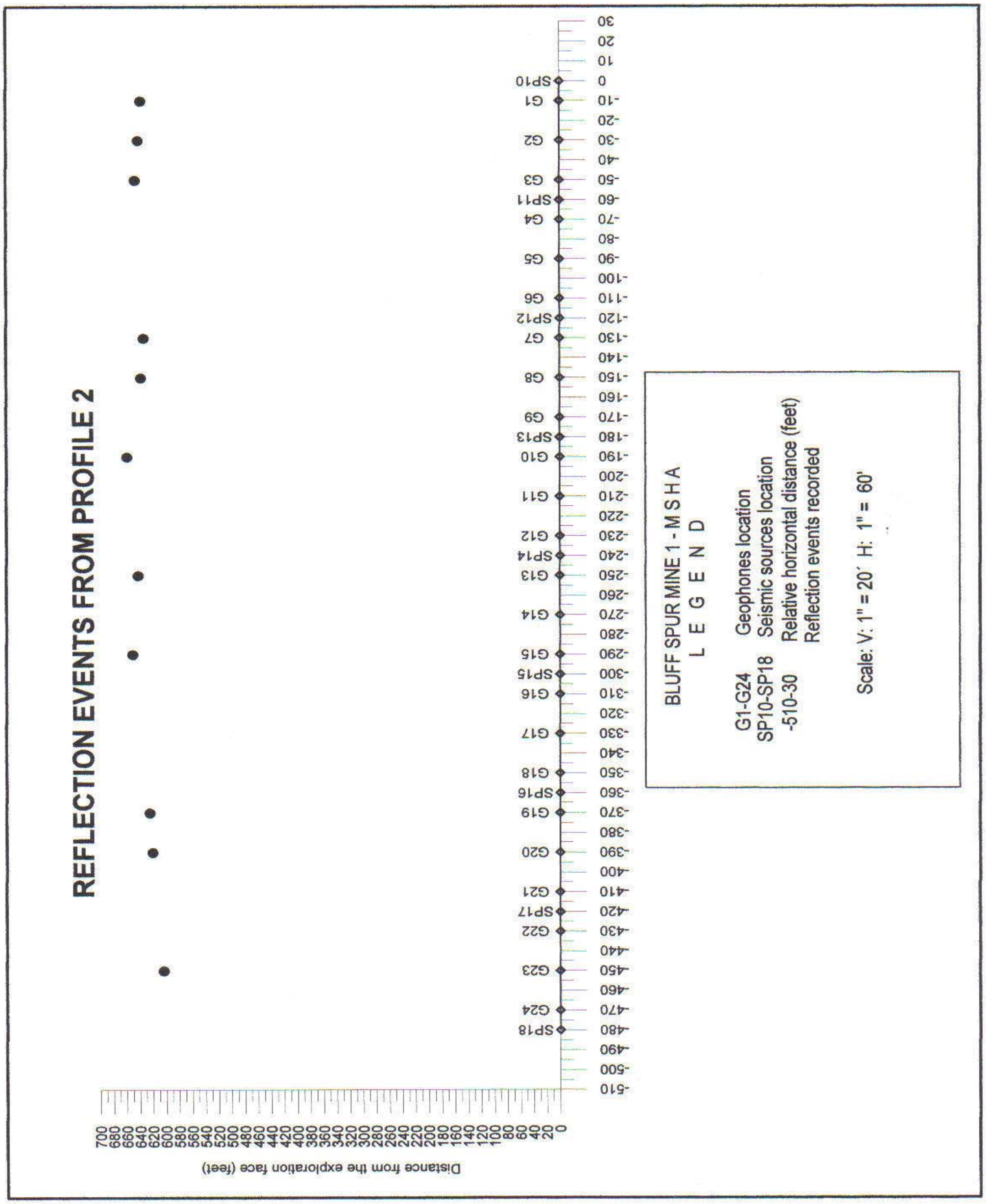

Figure 33. Graph shows the scattered reflection points associated with the old works from Setup #2 (west of the green center line marker).

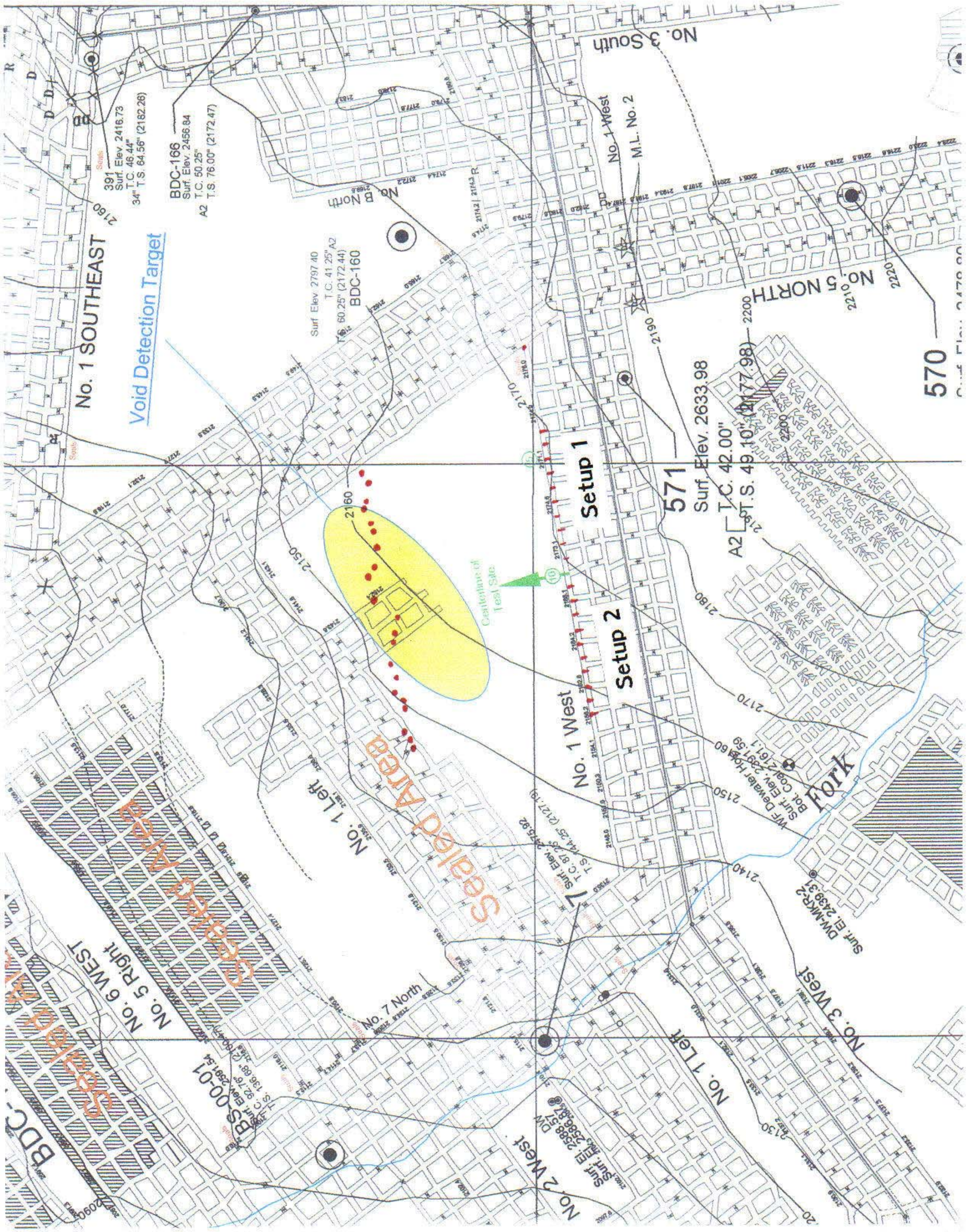

Figure 34. Cluster of reflection points (red dots) are plotted on the mine map. The 3-4-5 right triangle geometry and highly-fractured coal created complex conditions that made it very difficult to accurately detect the old mine works from Setup 1 position. However, the geometry is less complex at Setup 2 and the cluster of reflection points are interpreted to be close approximations of old mine works in front of the receiver stations.

CASE STUDY 5: NIOSH BRUCETON SAFETY RESEARCH MINE (1)

Geologic Background – The 7th ISS test was conducted at the NIOSH Bruceton Safety Research Mine in Pittsburgh, PA, to make up for the BCCC Site 1 study in which the coal company failed to drill the verification hole within a year. Given the time constraint and urgency to complete the contract, MSHA decided to conduct the last test at this site because the location of a nearby old mine is known through closed-loop survey and two horizontal holes were previously drilled to confirm its precise location. Since the old works is above drainage, the mine voids 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 last site was considered to be a second “blind test” in order to test the team’s ability to perform without any prior knowledge of the old mine works’ location and orientation. The old mine works, which closed in 1905, is located to the east of the setup room. **Figure 35** shows the location of the setup room. The first geophone station (G1) was located 5 ft off the northern end of Entry No. 18, while G20 was the last geophone station as the working face was only about 200 ft long.

DATA ACQUISITION

The Geode 24-channel system was used as the seismograph and single 40-Hz geophones were used as receivers. The recording parameters were similar to previous surveys. Planting the geophones on the coal face required the use of cordless drills. Drilling was near the center of the seam and good coupling is achieved simply by hand-tightening the geophone in the drilled hole. Since the study area was only about 200 ft long, a receiver interval of 10 ft was employed. In addition, only the first 20 geophones were planted and the last four were simply placed on the ground uncoupled.

Source sounding initially started 5 ft outside of the geophone spread, i.e. 5 ft off the first G1 station. Thereafter, successive source positions were set at 30-ft interval. Thus, there were a total of seven records collected.

A site investigation was conducted in mid-March 2007 in which the coal seam was found to be solid and working conditions were ideal. Thus, the sledge hammer was chosen as the seismic source as we had past successful experiences in using it to detect air-filled old mine works up to 800 ft away. Data acquisition was conducted on May 17, 2007, and was completed in about three hours. **Figure 36** shows the one of the raw record files, indicating data quality was very good.

INTERPRETATION

After processing the data, the seismic refraction inversion graph used to extract critical velocity information is presented in **Figure 37**. The graph shows two distinct velocity layers associated with disturbed and undisturbed coal at the working face. The fractured or disturbed coal seam thickness varied from 35 to 51 ft, and the average measured velocity was 5,975 ft/s. Thereafter, the competent or undisturbed coal had a measured average velocity of about 6,276 ft/s. Receiver ststaions are shown on the bottom of the graph. Given these two velocities, the Vrms was calcuated to be about 6,155 ft/s.

Table 8 shows the calculated Vrms and picked two-way arrival times from the processed ISS data. Results indicated that the distance to the old mine works ranged from 213 to 258 ft away from the working face.

Receiver Station	Velocity (rms) ft/s	Two-way arrival times (milliseconds)	Calculated Distances (ft)
G1	6,155	83.8	258
G2	6,155	81.9	252
G3	6,155	80.9	249
G4	6,155	80.3	247
G5	6,155	77.3	238
G6	6,155	75.4	232
G7	6,155	71.5	220
G8	6,155	69.9	215
G9	6,155	69.2	213
G10	6,155	70.2	216
G11	6,155	70.8	218
G12	6,155	70.8	218
G13	6,155	73.1	225
G14	6,155	73.8	227
G15	6,155	74.1	228
G16	6,155	74.7	230
G17	6,155	74.7	230
G18	6,155	74.4	229
G19	6,155	0	0
G20	6,155	0	0
G21	6,155	0	0
G22	6,155	0	0
G23	6,155	0	0
G24	6,155	0	0

TABLE 8. Measured and calculated distances to the abandoned mine works near the NIOSH Bruceton Safety Research Mine in Pittsburgh, PA.

Compiling all the information in Table 8, a graph is presented in **Figure 38** showing the calculated reflection points (in red) corresponding to each receiver/geophone station. MSHA later provided an accurate map and some details of the distances. For exampl,e the closest and farthest points were 195 and 260 ft, which correlated very well with the measured distances of between 213 and 258 ft (see **Figure 39**).

VERIFICATION

No verification drilling was needed at this worksite as the old mine works had a closed-loop survey with an accuracy of 1 part in 5000, and two horizontal holes were previously drilled to verify its location prior to the ISS survey conducted on May 17, 2007.

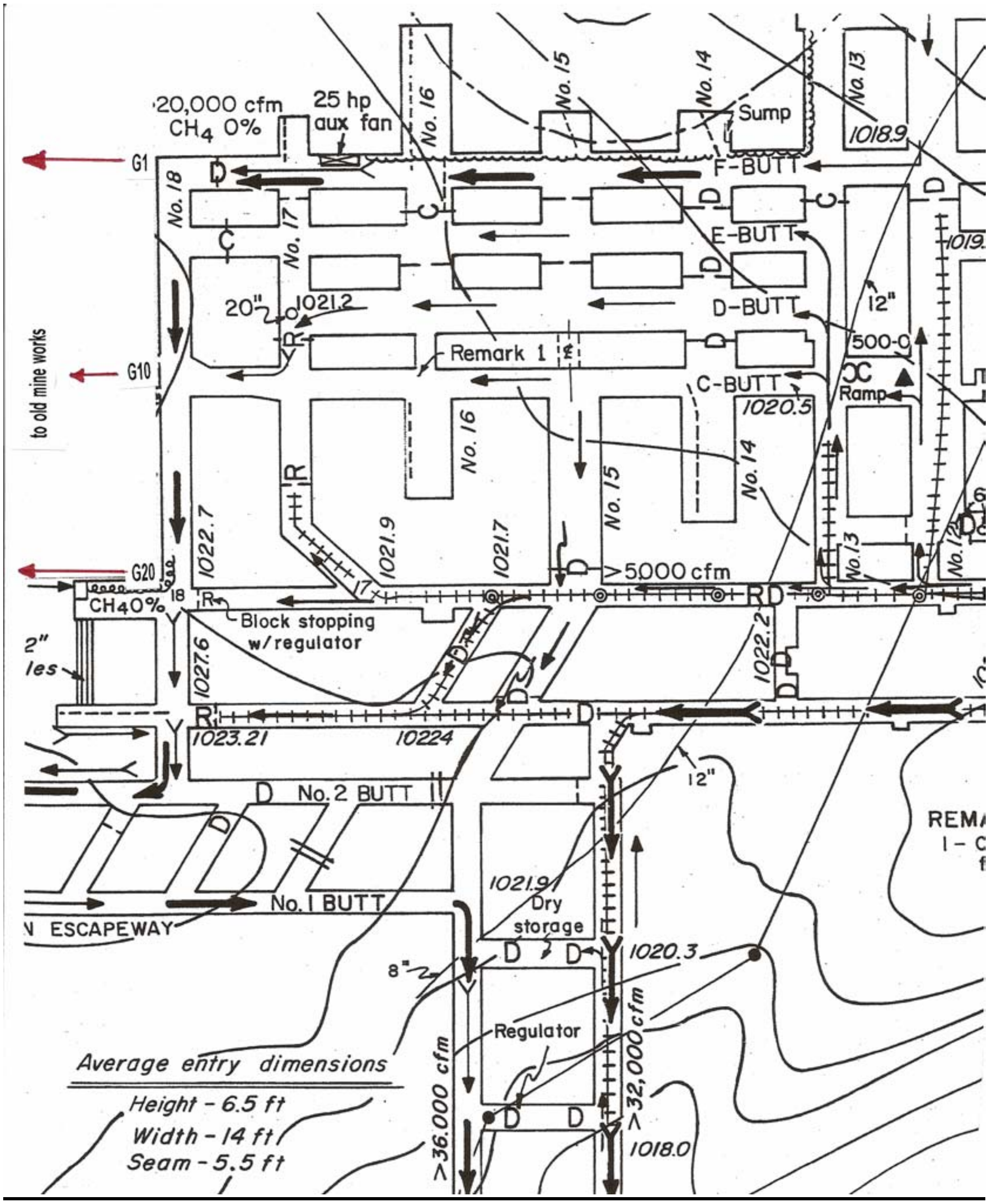

Figure 35. Map shows the Entry No. 18 worksite (upper left-hand corner) where the ISS survey was conducted. Red arrows indicate the seismic energy pathway to old mine works.

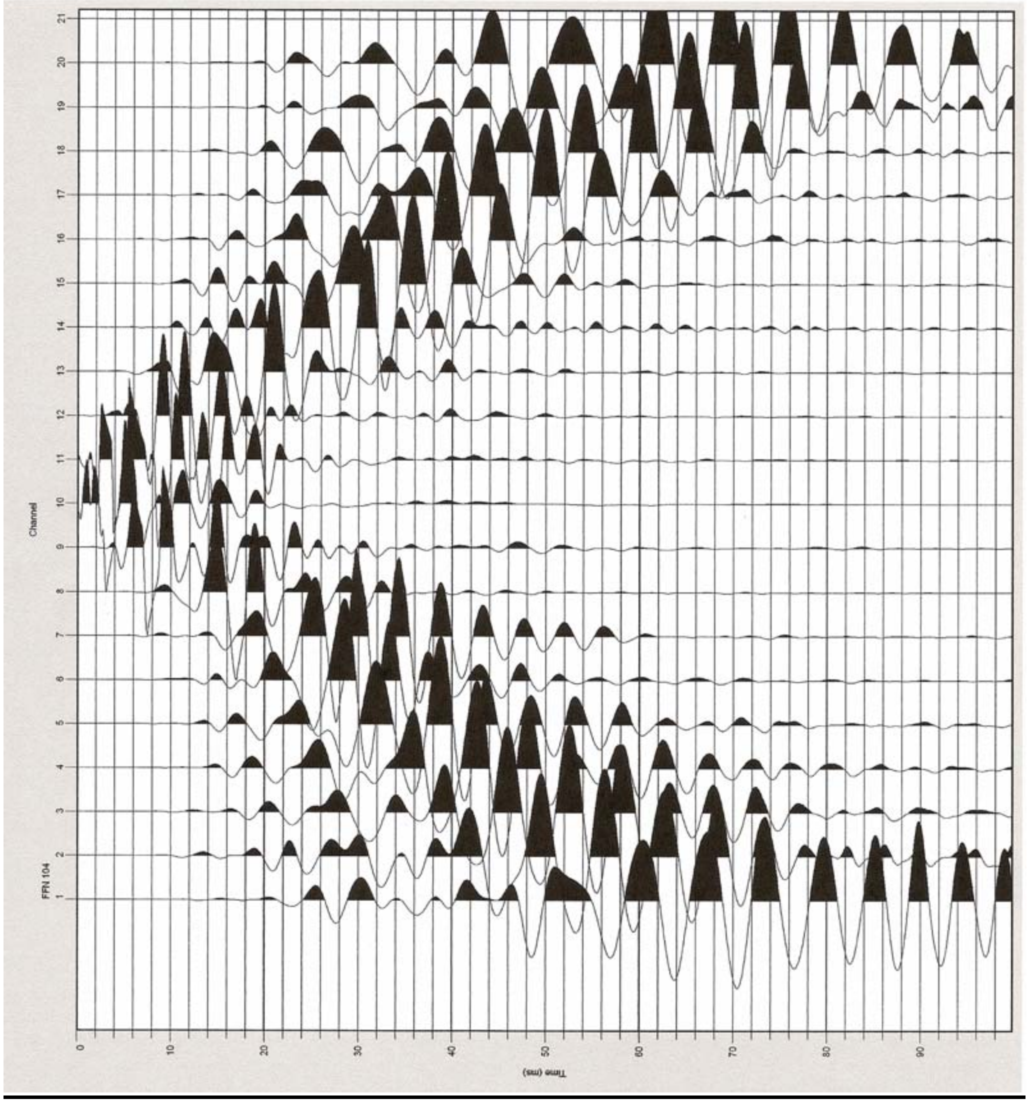

Figure 36. Raw ISS data of Field File No. 4 showing excellent quality data with good signal-to-noise ratio even when a sledge hammer was used as the seismic source.

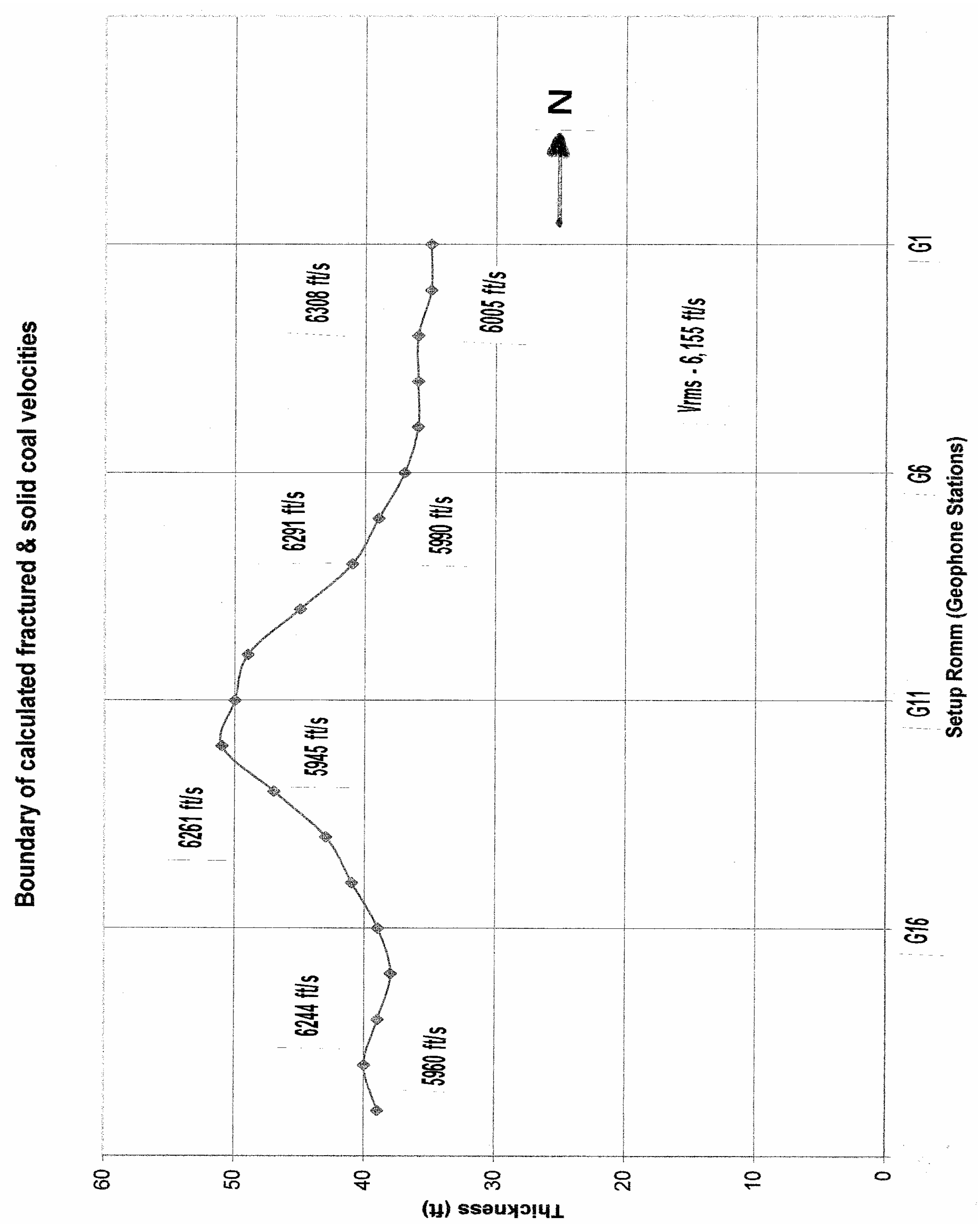

Figure 37. Graph shows the estimated velocities of the near-face fractured/disturbed as compared to more competent/solid coal. The Vrms of 6,155 ft/s was calculated from the average of these two velocities. The thickness of the fractured coal zone is about 41 ft.

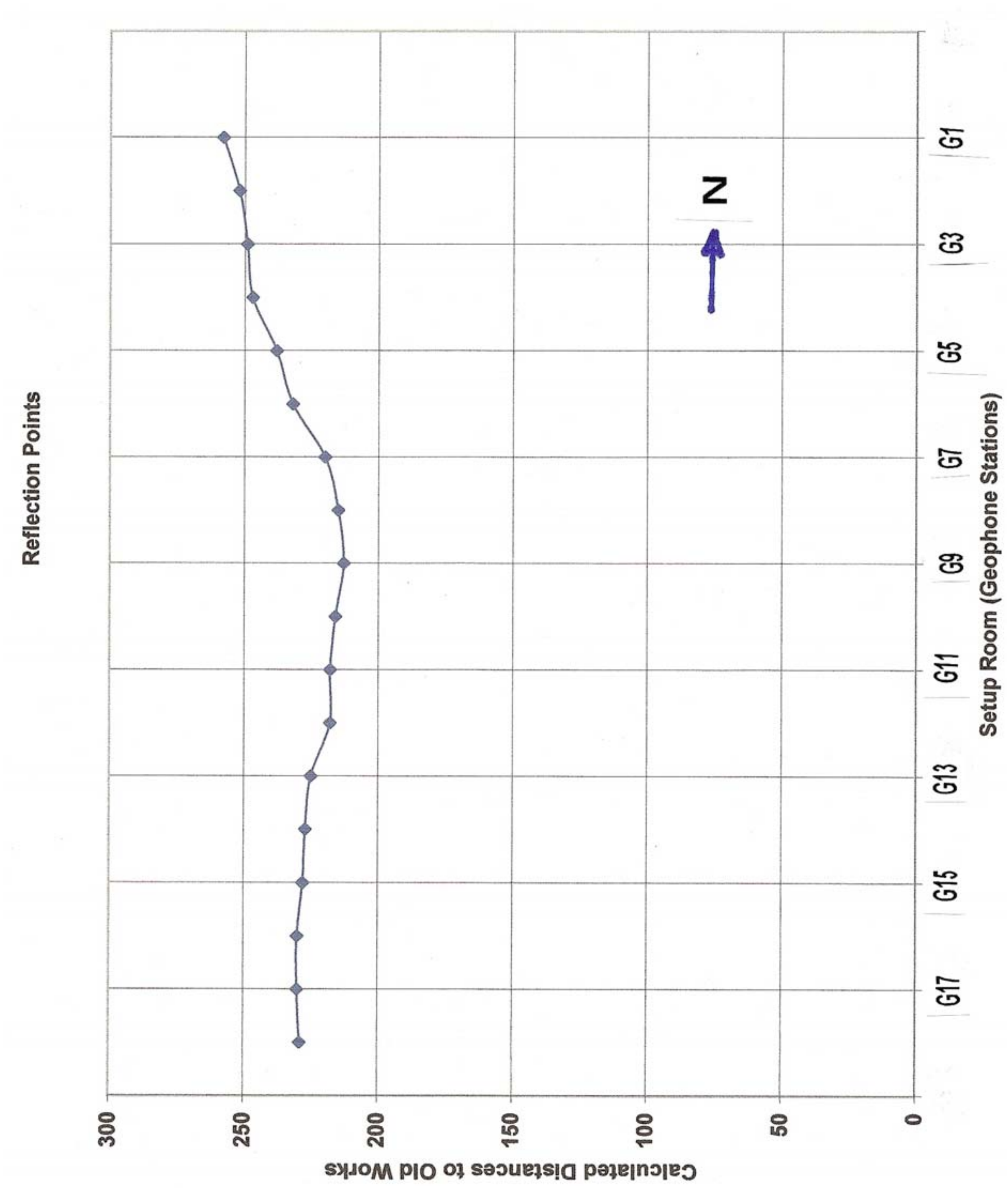

Figure 38. Graph shows the calculated reflection points corresponding to each receiver/geophone station. Results show the distances to the old mine works ranged from 213 to 258 ft.

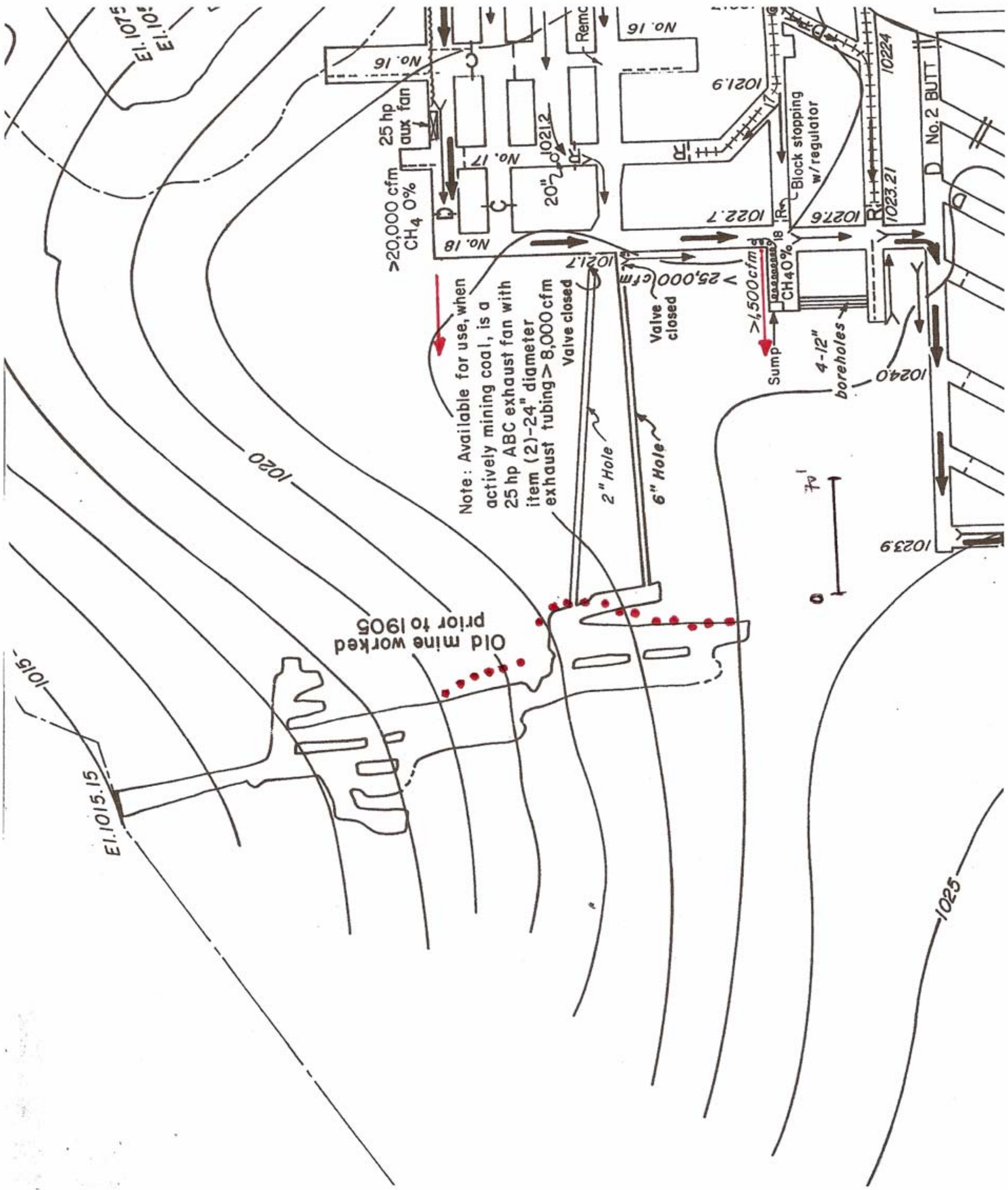

Figure 39. Calculated reflection points (in red) were plotted on the mine map to show the accuracy and respective small percentage errors in the second blind tests.

CONCLUSIONS

The seven ISS field projects presented in this report highlight the importance of experience, planning, and execution. Past experience in utilizing this useful geophysical technology provided the two principle investigators the necessary background to properly plan and execute the underground surveys effectively and safely. Based on past field projects in the 1990s, the percentage error experienced by the team was about +/- 10%, and the maximum effective sounding range was between 600 and 800 ft. Under this MSHA study, the estimated percentage error has improved and was less than +/- 4%, and the effective sounding range had increased up to 1100 ft.

Some interesting results came out of this study. We learned that other factors could come into play that were beyond our control, i.e., local geologic conditions. For example, despite our best efforts in planning and execution, the coal seam at Deep Mine 10, Buckeye Industrial Mining Corporation, did not act as a good waveguide to seismic energy. As a result of a higher leakage rate, the aperture of the seismic energy wave continued to broaden as it propagated towards the target old mine works nearly 1200+ ft away. Unfortunately, a shallower old mine works located about 45 ft above the main seam extended further out by as much as 300 ft which caused the first primary reflection. Thus, the ISS survey results detected and eventually mapped the shallower old mine works instead of the target one.

After the experience at Deep Mine 10, there were initial concerns about the two proposed ISS surveys at the Cabin Hollow Mine of Bell County Coal Corporation because the mine has underlying and overlying old mine works. The average interval between these two old mines with respect to Cabin Hollow was about 220 ft. However, the coal seam at Cabin Hollow turned out to be a very good waveguide. As such, good quality data were collected that properly detected the two target old mine works at respective distances of about 600 and 1000 ft. Lessons learned from these two different field trials strongly indicated that it was difficult to predict the outcome of any ISS survey until it was finally conducted because geologic conditions could play a major role.

The NIOSH Safety Research Mine survey was the second blind test that MSHA recommended. Survey results showed the calculated old mine works was located between 213 and 258 ft away. The actual distances over the receiver interval was from 195 to 260 ft. Nearly half of the reflection points fell on top of the old mine face while others were off by a maximum of 18 ft., equivalent to a maximum error of about 9%. However, taking the average overall percentage would yield about +/- 3 %.

Expanding the number from 12-channel to 24-channel recording would improve the collection of ISS data as the wider receiver aperture can record reflections from larger surface areas. This analysis is especially true in cases where the setup room and the target old mine works are not parallel. In addition, using the inversion technique to extract velocities of disturbed and undistrubed coal is important. As such, the 24-channel/shot will provide more data for better velocity control and analysis.

It is also apparent that some reflection points were mapped outside of the estimated boundary of old mine works. That is because the current software algorithm used to process the ISS data utilized a straight-ray approach that did not include a migration option. Applying the migration methodology would normally shrink the Freznel Zone and properly position the reflection points to their true reflecting surfaces, resulting in more accurate suvey results. At this time, neither LMG&A Inc. and GECOH Exploration have the capability to currently develop the migration algorithm because of limited resources. More funding and support from outside sources will be needed to develop the migration option.

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