APPLICATION OF GROUND PENETRATING RADAR TO EVALUATE THE EXTENT OF POLYURETHANE GROUT INFILTRATION FOR MINE ROOF CONTROL - A CASE STUDY

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ABSTRACT

Over the period 2000 to 2003, roof falls have accounted for 4 to 14% of the fatalities in underground mining operations. The National Institute for Occupational Safety and Health (NIOSH) is conducting research to reduce the frequency, exposure, and risk of these events through an ongoing program of field and laboratory studies. One area of research involves the evaluation of polyurethane grouting technology that is commonly used to stabilize fractured mine roof strata. Concurrently, NIOSH is conducting work to evaluate the application of ground penetrating radar for advanced delineation of problematic mining areas. In this study, NIOSH partnered with Sub-Technical, Inc. who injected a polyurethane grout (also known as glue) into a roof area of NIOSH's Safety Research Coal Mine. The mine roof area was scanned using ground penetrating radar technology before and after grout injection in an attempt to determine the extent of grout infiltration. A comparison of the pre-and post-grouting radar records showed a significant change at a mine roof depth of about four to five feet. The interpreted radar records were then compared with drill core information, borescope evaluation of roof-bolt holes in the study area, and underground observations. At this site, the interpretations of the radar records correlated with data obtained from the core holes, borescope evaluations and underground observations. This study showed that ground penetrating radar technology can be a useful tool for detecting changes in mine roof due to the injection of the grout.

BACKGROUND

In 2003, the U.S. mining industry achieved its best safety record since statistics were first compiled in 1910. Moreover, over the past three years mining fatalities have declined by 34 percent and injury rates by more than 20 percent (1). Despite the remarkable downturn in the accident statistics, injuries and fatalities continue to occur. In fact, during the period 2000 to 2003, mine roof falls have accounted for 4 to 14% of the fatalities for underground mining operations (2).

The National Institute for Occupational Safety and Health (NIOSH) is conducting research to reduce the frequency, exposure, and risk of mine roof falls through an ongoing program of field and laboratory studies. One area of research involves the evaluation of polyurethane grouting technology that is commonly used to stabilize rock surrounding a mine opening. As a part of this work, ground penetrating radar (GPR) is being used to map the distribution of injected polyurethane grout in mine roof strata. Sub-Technical, Inc., located in Mars, Pennsylvania, agreed to partner with NIOSH to evaluate a polyurethane grout (also known as glue), that was injected into a mine roof area at the NIOSH Safety Research Coal Mine (SRCM). NIOSH operates underground test facilities for research aimed at improving the health and safety of those working in the mine environment. The Safety Research Coal Mine, located near Pittsburgh, PA, is a specialized full-scale underground test facility that provides for realistic testing and research on newly developed equipment, procedures, and technologies (3). The SRCM became functional in the early 1970's and was developed as a room-and-pillar mine that is approximately the size of a working section in a commercial coal mine (4).

OBJECTIVE OF THE STUDY

The objective of this study was to test the capability of GPR to determine the extent of grout penetration into the mine roof strata in the 13-G room area of the SRCM (figure 1). We approached this problem by using a variety of antennas whose frequency spectra produced pulses centered at near 200-, 400-, 900-MHz. The area of mine was selected for study because a number of holes had been drilled into the roof for the testing of roof-bolts. It was felt that the roof-bolt holes would permit borescope evaluation of the mine roof conditions (fracturing and strata separations) prior to grout injection.

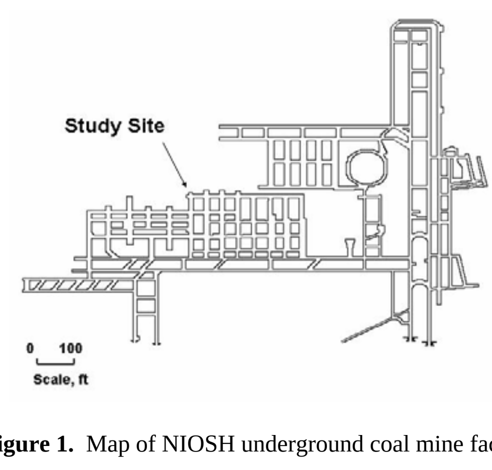

Figure 1. Map of NIOSH underground coal mine facility.

GROUND PENETRATING RADAR

GPR is a non-invasive geophysical method that uses reflected and backscattered electromagnetic waves to image, locate and quantitatively identify changes in electrical properties in the subsurface. Its primary feature is a very short electromagnetic pulse, which allows a vertical resolution ranging from centimeters to a few meters, depending on bandwidth. In general, GPR surveys can generate large quantities of field data and, under the right conditions, can provide detailed subsurface information of a scope that is superior to that obtained from single-point sources such as drill holes. However, when available, confirming data from drill holes should always be used as a means of ground truthing the conclusions drawn from the radar records.

Although the first GPR survey was performed in 1929 to sound the depth of a glacier, it was not applied until the 1940's to earth science problems and the 1950's for ice sounding and planetary exploration (5-9). Applications of GPR to evaluate rock and soil conditions did not occur until the 1970's when the systems became commercially available (9-11). Today, GPR is commonly used in archeological, construction, environmental, and geological studies to determine the location, orientation, lateral continuity, and depth of strata or buried objects.

A GPR system generates an electromagnetic pulse that is transmitted into the ground with an antenna that is moved along the surface, generally at a uniform speed and direction. The transmitted energy of the pulse is radiated in an elliptical conical pattern roughly 90 degrees wide in the antenna plane and 60 degrees wide in the perpendicular plane. Whenever there is a change in the dielectric constant of the subsurface material, a portion of the pulse energy is reflected back to the surface and is detected by the receiving antenna. This reflected pulse provides information on the attenuation characteristics (signal strength) associated with the subsurface material and the two-way travel time is recorded.

The capability of GPR depends on two electrical properties of the geological materials under investigation: dielectric constant (relative dielectric permittivity) and electrical conductivity. The dielectric constant affects the velocity of propagation of the radar pulse. In rocks and minerals, dielectric properties are primarily a function of mineralogy, porosity, water saturation, frequency, and depending on the lithology, component geometries, and electrochemical interactions (12-14). Variations in each of these parameters can significantly change bulk dielectric constants (12). The greater the difference in dielectric constant between two materials, the stronger the reflected pulse energy becomes. The dielectric constant ranges from 1 for air (fastest propagation) to 81 for water (slowest propagation). In addition, there is a notable increase in the value of the dielectric constant for a given rock type with an increase in the degree of water saturation.

Electrical conductivity controls the depth of pulse penetration. The lower the conductivity of the material, the deeper the pulse can penetrate. Conductivity is controlled by water, mineral, and clay content in the subsurface. The depth of penetration of the pulse also depends on the antenna frequency. Higher frequency antennas (e.g., 1200-MHz) provide high resolution, but shallow depths of penetration; conversely, lower frequency antennas (e.g., 80-MHz) have low resolution, but can detect significantly deeper targets.

The equipment used to conduct the ground penetrating radar surveys in this study was a GSSI SIR® System 2 (SIR-2) Model No. DC-2 control unit built by Geophysical Survey Systems, Inc (GSSI).[1] The SIR-2 is a lightweight, portable, general-purpose radar system and is available as an intrinsically safe unit (figure 2). The reflected pulse is processed by the control unit and the data are displayed on the monitor and stored on an internal hard disk. The output display can be (1) a single wiggle trace (analogous to an oscilloscope trace), (2) a waterfall plot of the wiggle traces, or (3) a multicolored line scan in which the reflected signal amplitudes are represented by various colors according to a user-selected color look-up table. The data can also be printed via an external printer.

Figure 2. Photo of Engineer using the SIR-2 unit.

The two-way signal travel time is determined by measuring the time interval between the start of the transmit pulse and start of the received reflected signal. The amplitude of the reflected signal is influenced by the size and geometry of the target, the signal attenuation characteristics of the geological materials, and the total distance that the pulse has to travel. In this study, the resulting radar records were processed using GSSI's Radar Data Analyzer for Windows NT (RADAN) software[1]. This package allows the user to operate in the Windows environment with application-specific modules.

POLYURETHANE RESIN TECHNOLOGY

From a historical perspective, Dr. Otto Bayer and his associates were awarded a patent in Germany on November 11, 1937, for a process to produce polyurethanes and polyureas. This work has long been considered to be the foundation patent for the polyurethane (polyisocyanate-polyaddition) process (15-16). During the 1960's, the mining engineering community in Germany began experimenting with the use of a low-density polyurethane grout (20 lb/ft^3) to consolidate or secure incompetent strata in coal mines. It was not until the 1980's, that high-density polyurethane grout (70 lb/ft^3) was introduced (17). This application became quite popular as a cost-effective alternative to traditional roof control maintenance plans. The polyurethane grouting process was introduced and pioneered for the U.S. mining industry by the former Mobay Corporation (18). Today, several companies offer a variety of polyurethane-based mine stabilization services and the

[1]Mention of specific product or trade names does not imply endorsement by NIOSH.

technology has evolved to the point where special formulations can be mixed to meet a variety of strata and in-mine conditions.

The process typically used involves drilling of 1-3/8-in diameter injection holes to an average depth of the roof-bolts used in the area. The injection holes are drilled on a 10-ft spacing along the rib areas on both sides of the entry, and in some circumstances a row of holes may also be drilled along the centerline of the entry. The drilling plan calls for the drilling of every other hole followed by grout injection. A second set of holes are then drilled between the first set of holes and injected with grout. The holes are completed using a specialized packer and an extension rod. The packer serves to seal the near end of the hole and also contains a static mixing unit (figure 3). The setting depth of the packer is usually determined by the conditions at the underground site. During grout injection, the two components of the grout are pumped under a controlled pressure to the extension rod and then to the packer where the grout components are thoroughly mixed and injected into the rock mass (figure 4). Pumping continues until either a pre-determined amount of material is injected or specified pressure increase is achieved (17).

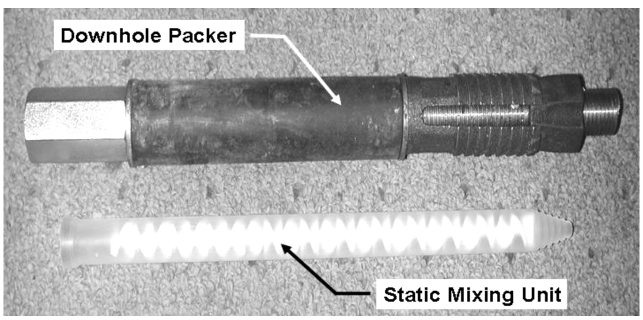

Figure 3. Downhole packer and a static mixing unit. Note, static mixing unit is contained in the packer assembly (mixing unit is shown is for illustration purposes only).

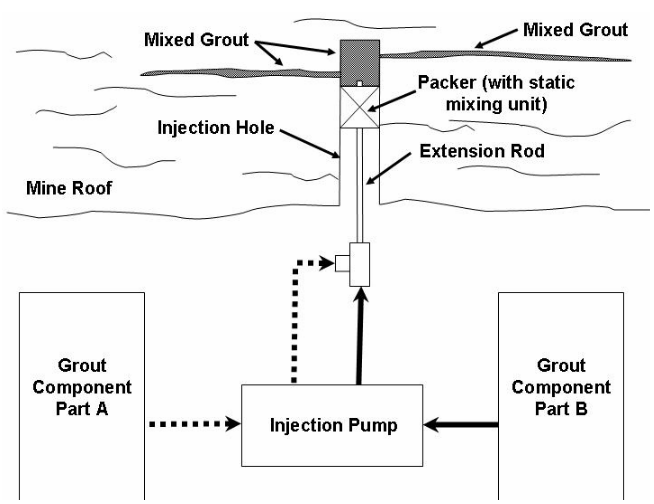

Figure 4. Grout injection process.

The site selected for study at the SRCM was previously used for testing roof-bolts and, as such, numerous holes had been drilled into the mine roof and some of the holes were outfitted with roof-bolts of various configurations. Some of the holes containing roof-bolts were open and others were sealed as part of the roof-bolt testing program. These holes were not included as part of this study and were also not shown on the location maps of this study. In the study area, six, 1-3/8-in diameter, injection holes were drilled into the mine roof (figure 5). The holes were drilled to a depth of eight feet and the mixer/packer-extension rod unit was placed to a depth of three feet in each hole. During injection operations the pressure on the system varied from 200-1200 psi with no fixed grout injection rate. In all, a total of 100 gallons of 70 lb/ft^3 grout was injected into the holes. Table 1 shows the volume of grout injected into each hole. The order of grout injection began with hole No. 2 and concluded with hole No. 7.

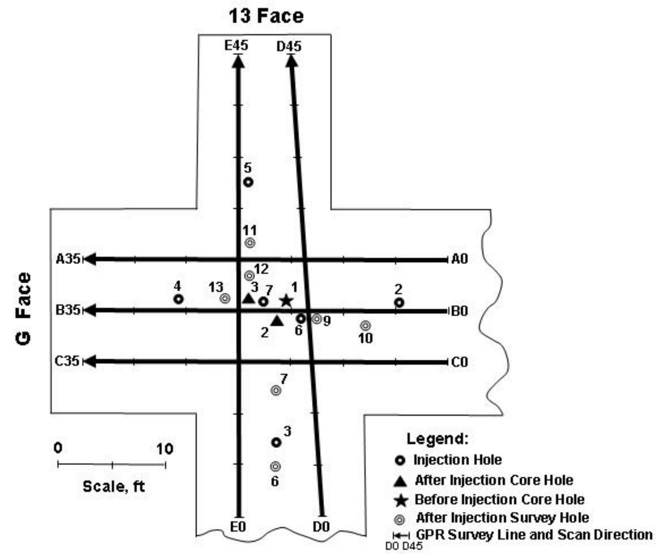

Figure 5. Detailed layout map of SRCM study site.

Table 1. Volume of grout injected into each hole.

Hole No.	Volume of Grout Injected, gallons
2[1]	20
3	3
4	7
5	5
6	30
7	35
Total	100

[1] Hole No. 1 was not used for grout injection.

Prior to grout injection, each hole was inspected with a borescope to determine if any void spaces could be detected and none were found. In addition, a core hole was drilled near the center of the intersection to a mine roof depth of 17-ft. Again, no significant void spaces or fracture systems were observed in the recovered core samples (18). During injection operations, grout was observed to be flowing from nearby open holes and roof-bolts in the area (as discussed earlier the holes and bolts were from a from previous roof-bolt testing program) (figure 6). The actual amount of grout material that flowed into the mine opening is unknown.

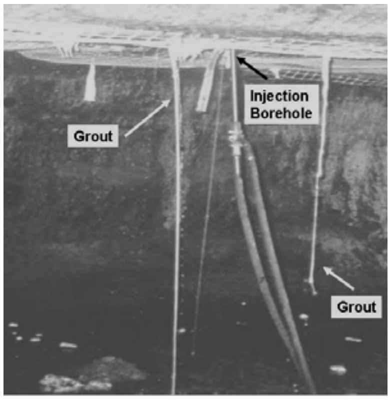

Figure 6. Photo of grout flowing from drill holes.

Upon completion of the grouting operations, seven drill holes (drilled to about 8.5 to 9-ft deep) and two core holes (drilled to about 12-ft deep) were completed into the mine roof in the study area (figure 5). The drill holes were inspected with a borescope to see if grout material had penetrated to the location of the drill hole. The samples recovered from the core holes were logged and similarly inspected for grout infiltration (figure 7). In all holes, the most significant show of grout was 0.5 inch or less in thickness (19). The data from the drill hole and core holes form the basis for ground truthing the post-processed GPR records.

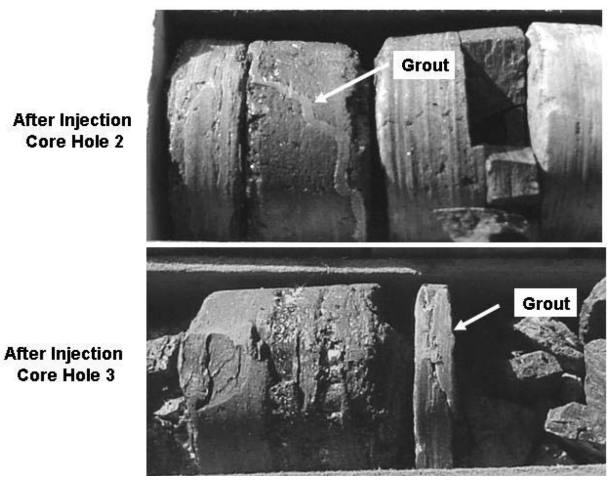

Figure 7. Photos showing samples recovered from after injection core holes (19).

GPR SURVEYS

The SRCM was developed in the Pittsburgh Coalbed and the mine opening averages about 19-ft wide along the "G-Entry" and 15-ft wide tapering to 12.5-ft wide along the "13-Entry". The mine opening is about six feet in height. In general, the immediate mine roof is composed of about 2.5-ft of interbedded coal and carbonaceous shale that is overlain by 1.5-ft of shale, 0.5-ft of coal and then a shale unit to a height of seven feet (19).

A GPR survey grid was established in each entry area with survey lines trending across the room to each face area. In the "G-Entry", three parallel survey lines (labeled A to C), each approximately 35-ft long, were located and spaced five feet apart. Each line contained reference stations located five feet apart. In the "13-Entry", two sub-parallel survey lines (labeled D and E) were located and spaced eight feet apart at one end and then converged to five feet apart (due to the reduced width at the "13-Face" area). These lines also contained reference stations located five feet apart. In each entry, survey lines were positioned parallel to the trend of the rib with the exception of the D line (figure 5).

During calibration of the radar equipment, the dielectric constant for the mine roof material was adjusted until the arrival time of the reflected signals (expressed in terms of depth) matched the stratigraphic information obtained from the pre-grouting core samples and drill holes (the dielectric constant for the mine roof was determined to be 7.5). Table 2 shows the SIR-2 System set-up for each antenna used in this study. The values shown in the table, with the exception of the vertical high-and low-pass filter settings, are standard default values. Adjustments to the vertical low-pass filter settings were made to eliminate high frequency noise (snow) from the data. Adjustments to vertical high-pass filter settings were made to eliminate low-frequency noise (tilt) from the data (20).

Table 2. SIR-2 System set-up used for GPR scans at the SRCM.

Parameter	**Setting for 200-MHz Antenna**	**Setting for 400-MHz Antenna**	**Setting for 900-MHz Antenna**
Data collection mode	Continuous	Continuous	Continuous
Range, ns	Varied[1]	Varied[1]	Varied[2]
Samples per scan	512	512	512
Resolution, bits	16	8	8
Number of gain points	5	5	4
Vertical high pass filter, MHz	30	30	100
Vertical low pass filter, MHz	400	800	1800
Scans per second	32	32	32
Horizontal smoothing, scans	5	4	4
Transmit rate, KHz	64	64	64
Dielectric constant	7.5	7.5	7.5

1. Varied from 300 to 1000 ns.
2. Varied from 300 to 1200 ns.

In order to determine the extent of grout penetration into the mine roof, dynamic GPR surveys were performed before and after the grouting process at the "13-G Room" study area. Dynamic GPR surveys of the mine roof were conducted by placing the antenna in the immediate vicinity of the mine roof and then the antenna was moved along the survey line at a constant speed (figure 8). In each case, the surveys were conducted in both directions and the resultant data were compared to ensure repeatability. If a problem was observed in the record, then the survey was repeated.

DISCUSSION

It was decided to only use the radar data from the 900-MHz antenna because this antenna provided the highest resolution and the required depth of penetration. Here, we were trying to discern the location where grout had been injected into the mine roof (at a depth of four to five feet) and we were aware that the zones where the grout was observed were on the order of 0.5-in or less. Figure Nos. 9-11 show selected post-processed results of the GPR surveys before and after the grout was injected in the "13-G-Room" area (refer to figure 5 for the layout map of the GPR survey lines). In the figure, the survey begins at the left margin of the figure. The depth into the mine roof is shown in the left hand column and the boxes with numbers and short line segments at the top of the figure show the location of the reference stations along the survey line. The designation "before" represents the scan information before the grout was injected (pre-grouting) and the designation "after" represents the scan that was conducted after grout injection (post-grouting). A generalized stratigraphic column has been added to aid in the interpretation and is shown in the right side of both the pre-and post-grouting radar records. The vertical white dotted lines that transect the post-grouting scan represent the location of the post-grouting drill and core holes projected onto the GPR survey line. In general, data from an observation hole was used only if the hole was in the immediate vicinity of the subject survey line. The symbol used to identify the type of hole is the same as used in figure 5. The white stars are used to show the observed location of grout (19).

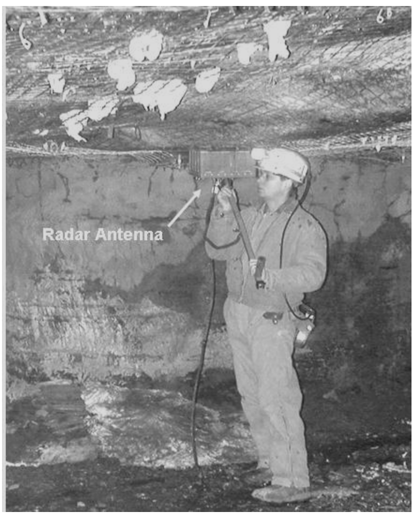

Figure 8. Researcher conducting GPR study in SRCM.

Figure 9 shows the post-processed results of the dynamic GPR survey for the B-Line. The radar records show a good correlation with the generalized stratigraphic section shown on the right side of each record. In the radar records, the reflected pulse energy is shown in terms of a grayscale, with near-white being the highest level of reflected pulse energy and near-black the lowest. Areas in the record shown with similar gray tones should be interpreted as similar levels of reflected pulse energy. As discussed earlier, the greater the difference in dielectric constant between two materials, the stronger the reflected pulse energy. In the pre-grouting radar record, there is a band of reflected pulse energy at a mine roof height of four to five feet. At this depth, there is a coal unit that most likely contains some water which could account for the high level of reflected pulse energy at this location. Recall that water has a dielectric constant of 81 as compared to the value of 7.5 used for the mine roof strata in this study and that the level of water saturation can cause a notable increase in the value of the dielectric constant for a given rock type. In the post radar record, the higher level of reflected pulse energy does not appear, and this is also the depth where grout was noted in the post-grouting core and survey holes. This could have occurred because grout may have infiltrated and displaced water that was contained in the coal unit and would then explain the absence of the high-level pulse energy reflections in the post-grouting radar record.

Note, the vertical anomalies in the pre-grouting record most likely represent nearby roof-bolt holes (refer to previous discussion about the roof-bolt testing program). As mentioned earlier, most of these holes were filled with grout and do not show in the post-grouting record. Two anomalies are also observed in the post-grouting record (as highlighted by the ellipses). The first anomaly projects from the lower right to the upper left of the record, between stations 5 and 10. The second anomaly projects from the upper left to the lower right of the record, between stations 20 and 30. It is unknown if these anomalies are related to the mine opening or geological in nature.

Figure 10 shows the post-processed results of the dynamic GPR survey for the C-Line. Again, there are vertical anomalies in the pre-grouting record that most likely represent nearby holes from the roof-bolting program. These structures are not shown in the post-grouting record most likely because they were filled with grout. Additionally, in the post-grouting record, there is a vertical anomaly projecting downward between stations 20 and 25. This is most likely a nearby hole from the roof bolting program. Also, an anomaly is observed projecting downward from the upper left to the lower right of the record, between stations 20 and 35. It is unknown if this anomaly is related to the mine opening or geological in nature.

As shown in Figure 9, the radar records show a good correlation with the generalized stratigraphic section shown on the right side of each record. As in figure 9, there is a notable difference in the post-grouting radar record as compared to the pre-grouting radar record at a mine roof depth of four to five feet. The reason for the difference between the pre-and post-grouting radar records is the same as offered in the discussion of figure 9.

Figure 11 shows the post-processed results of the dynamic GPR survey for the D-Line. There are several vertical structures in the pre- and post-grouting radar records. These features are believed to be holes from the roof-bolting program. The radar records show a good correlation with the generalized stratigraphic section shown on the right side of each record. As seen in figures 9 and 10, there is a difference in the post-grouting radar record as compared to the pre-grouting radar record at a mine roof depth of four to five feet. The reason for the difference between the pre-and post-grouting radar records is the same as offered in the discussion of figure 9.

Two anomalies are also observed in the post-grouting record (as highlighted by the ellipses). The first anomaly projects from the upper left to the lower right of the record between stations 15 and 25. The second anomaly projects from the upper left to the lower right of the record, between stations 30 and 45. It is unknown if these anomalies are related to the mine opening or geological in nature.

SUMMARY AND CONCLUSIONS

In this study, NIOSH conducted research to evaluate the application of GPR to determine the extent of injected polyurethane grout infiltration into a roof area of the NIOSH Safety Research

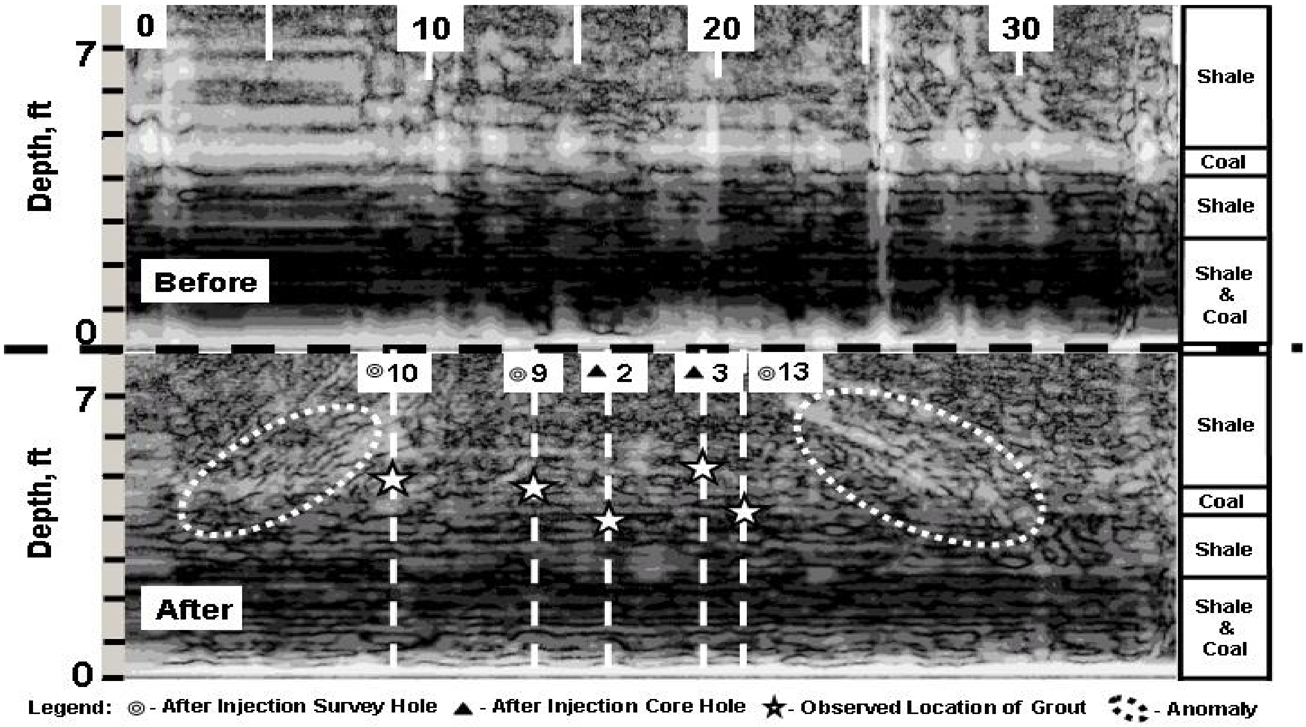

Figure 9. Post-Processed Radar Records with Ground Truthing – B-Line.

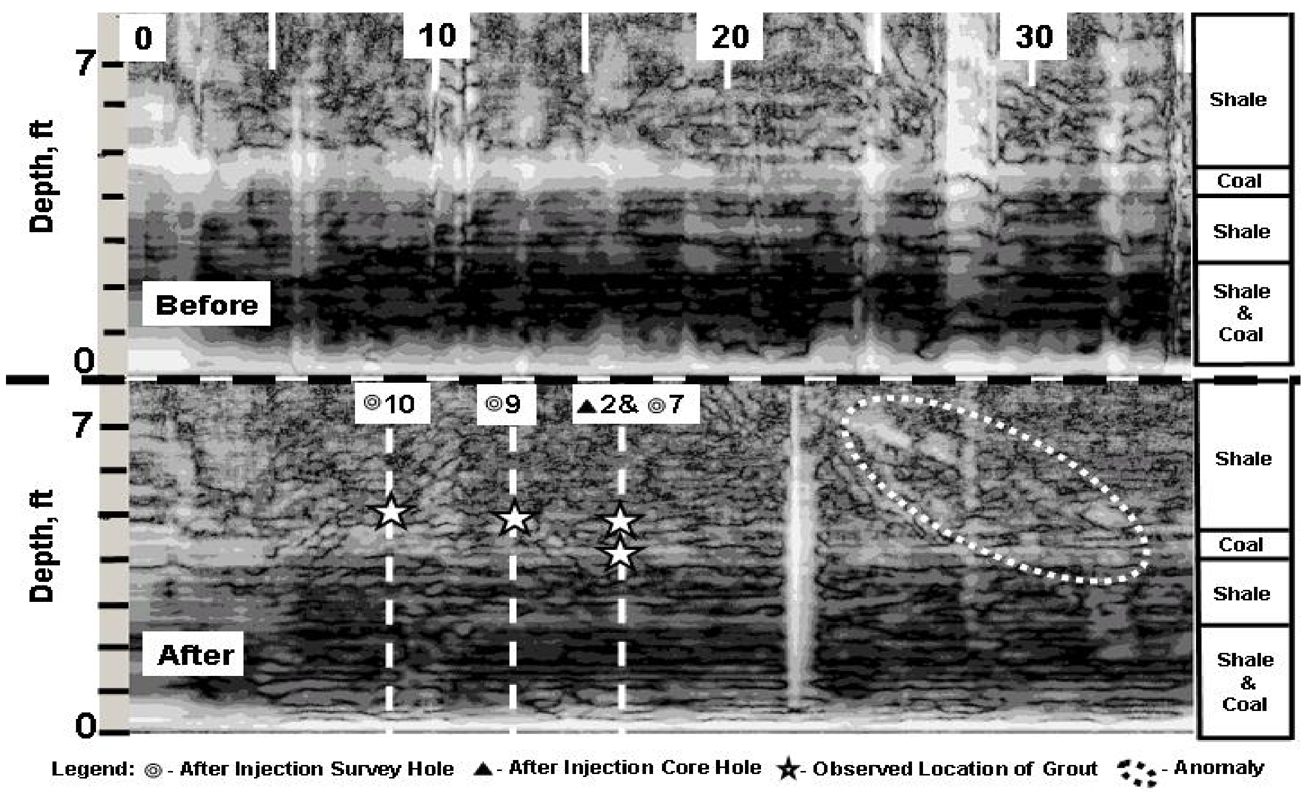

Figure 10. Post-Processed Radar Records with Ground Truthing – C-Line.

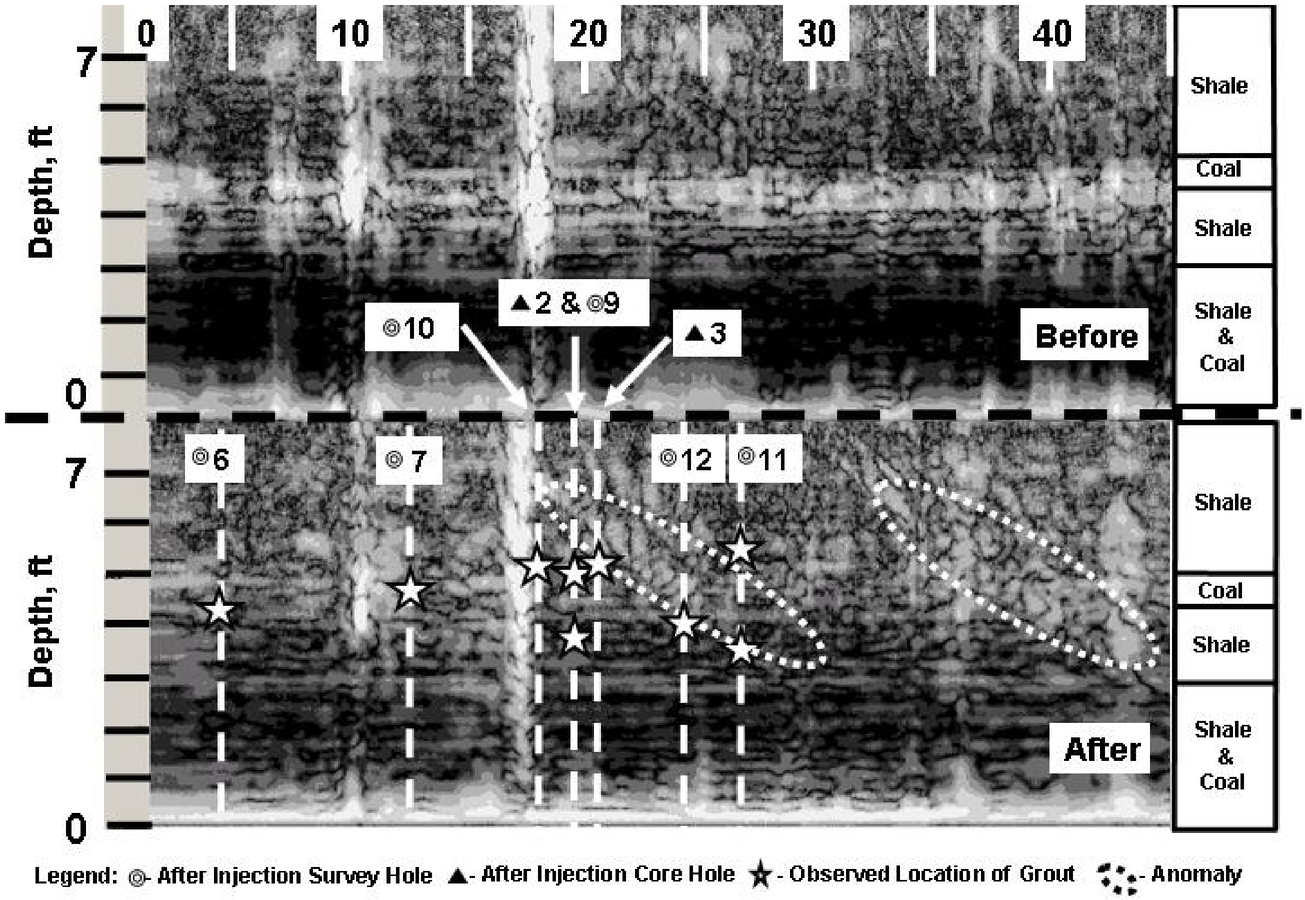

Figure 11. Post-Processed Radar Records with Ground Truthing – D-Line.

Coal Mine. Sub-Technical, Inc., partnered with NIOSH in this effort and provided the materials and grouting services.

GPR was selected for use in this study because it is a non-invasive technology and would not degrade the mine roof. The technology could also provide the level of resolution and depth of penetration needed to detect zones of grout infiltration. A grid was established in the study area and the mine roof was scanned using GPR technology before and after grout injection. A comparison of the pre-and post-grouting radar records showed a significant change (absence of high-level pulse energy reflections) at a mine roof depth of about four to five feet. The changes were correlated to the location where polyurethane grout had infiltrated the mine roof strata as observed in the post-grouting core and survey holes. The difference between the pre- and post-grouting radar records could have occurred because grout may have infiltrated and displaced water that was contained in a coal unit (thus affecting the pulse energy reflections in the post-grouting radar record).

Although the results of this study offers promising insight in to the application of GPR to determine the extent and effect of polyurethane grout infiltration, it should be kept in mind that this technology should be tested at other mine sites under a variety of mining conditions (varying geology, fractured roof strata and zones with and without water infiltration, etc). Future GPR research will focus on laboratory and possibly field studies to test the use of tagging material (e.g., metal fines) in the grout mixture. These materials should serve as a target and could possibly enhance the radar signal reflections.

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