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USE OF GROUND PENETRATING RADAR TECHNOLOGY FOR MINING APPLICATIONS

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Abstract

In the mining industry, failure to recognize, understand, and respond to changes in the underground environment or geological conditions can lead to expensive and disastrous consequences. Some geophysical techniques that offer promise for non-invasive evaluation of the mine host rock include: high-resolution seismic reflection and refraction, microgravity, ground penetrating radar (GPR), electrical, electromagnetic, and magnetic surveys. Tomographic studies (seismic, electromagnetic, radio imaging method, etc) can be conducted through boreholes and mine workings and these studies can provide two- and three-dimensional views of the rock mass. The National Institute for Occupational Safety and Health's (NIOSH) Pittsburgh Research Laboratory is conducting research to evaluate off-the-shelf GPR technology for mining applications. In this paper, we present case studies of the use of GPR for the detection of adjacent mine workings, delineation of overburden conditions above a mine portal, and advance identification of anomalous geological features (roof fractures and joint-based solution channels).

Introduction

The literature is replete with studies of the effects of changing geologic conditions (influences of structure, facies changes, fractures, faults, etc) on the mining environment. A mine operator's ability to collect, recognize, understand, and respond to these changes can mean the difference between a successful and safe mining operation and one that may be fraught with expensive and dangerous conditions.

The National Institute for Occupational Safety and Health (NIOSH) was created by the 1970 Occupational Safety and Health Act to ensure safe and healthful conditions for the nation's workers through research, training, and prevention of work-related illnesses and injuries. In 1996, the mining health and safety research mission of the former U.S. Bureau of Mines (USBM) was transferred to NIOSH. The bulk of the NIOSH mining safety research function takes place through the Pittsburgh and Spokane Research Laboratories (both of which were former USBM research centers). One segment of the work at the Pittsburgh Research Laboratory has been focused on evaluating GPR technology for mining applications.

GPR is a non-invasive geophysical method that uses reflected and backscattered electromagnetic waves to locate and identify variations in the electrical properties of subsurface materials (Olhoeft, 2004). The basic principles of ground penetrating radar are summarized as follows (Daniels, 2000). An electromagnetic pulse wave is radiated into the ground from a transmitting antenna and travels at a velocity that is primarily determined by the relative permittivity of the material. The wave travels downward until it encounters a material with different electrical properties. At that point, a portion of the energy passes through the material, some of the energy is refracted away and part of the energy is reflected back to the surface. The reflected portion of the wave is captured by a receiving antenna and is recorded for processing. The round trip time or two-way travel time of the pulse is greater for deeply buried material or objects than for shallow material or objects. Therefore, the time of arrival for the reflected wave can be used to determine the approximate depth to a geological feature (fracture, etc) or mine opening, if the velocity of the wave in the subsurface is known.

There are two important electrical properties of geological materials that affect the pulse wave. The first is the dielectric constant or relative permittivity. Dielectric constant is a critical parameter because it controls the propagation velocity of electromagnetic waves through a material and the reflection coefficients at interfaces, as well as affecting the vertical and horizontal imaging resolution (Martinez, 2001). In rocks and minerals, dielectric properties are primarily a function of mineralogy, porosity, water saturation, frequency, lithology, component geometries, and electrochemical interactions (Martinez, 2001; Knight, 1990; and Knoll, 1996). Variations in each of these parameters can significantly change bulk dielectric constants (Martinez, 2001). The value of the dielectric constant ranges from 1 for air (fastest propagation) to 81 for water (slowest propagation) and the greater the difference between the two materials, the stronger the reflected pulse wave (GSSI, 1996). Table 1 shows select reported values for dielectric constants.

Table 1. Reported values of select bulk dielectric constants.

Rock Type, condition	Bulk Dielectric Constant
Coal, dry	3.5[1]
Coal, wet	8[1]
Limestone, dry	5.5[2]
Limestone, wet	8[1]
Sandstone, dry	2-3[1]
Sandstone, wet	5-10[1]
Shale, N/R[3]	5-15[1]
Shale, wet	6-9[1]

1 (Daniels, 1996)
2 (GSSI, 1996)
3 N/R - Condition not reported.

The second important property is electrical conductivity. Electrical conductivity is the ability of a material to conduct electrical current, and it determines the depth of penetration of the pulse wave, i.e., greater conductivity results in lesser depth of penetration. Conductivity can vary greatly and is primary governed by water content and dissolved salts, as well as the density, permeability, porosity, and the temperature of the material (Mowrey, 1995).

In terms of antennas, resolution increases with increasing frequency (decreasing wavelength), but at the expense of depth of investigation (which generally improves with decreasing frequency) (Olhoeft, 2004). In other words, high frequency antennas can provide high resolution, but have shallow depths of penetration and lower frequency antennas have lower resolution, but can detect deeper and larger-sized targets (GeoModel, 2004).

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.[1] The SIR-2 is a lightweight, portable, general-purpose radar system and is available as an intrinsically safe unit (figure 1). 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. The radar records generated during this study were analyzed using GSSI's Radar Data Analyzer for Windows (RADAN) version 6.0[1]. This package allows the user to operate in the Windows environment with application-specific modules (GSSI, 2004).

Figure 1. Engineer monitoring SIR-2 unit during a GPR survey.

Objective and Approach

The objective of our work was to determine the applicability of GPR to assist in geotechnical research at a number of mining sites. We approached this problem by using antennas whose frequency spectra produced pulses centered at near 80-, 100-, 200-, 400-, and 500-MHz. The 80-MHz antenna was unshielded and the others were enclosed in shielded cases. The antennas selected for use depended—on the mining condition under study, the required depth of penetration, and the necessary degree of resolution. Some of the antennas used were relatively lightweight and could be easily maneuvered and positioned on the mine roof and ribs areas, while other heavier antennas (up to 61 lbs) were held in place or pulled across the ground surface.

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

Field Studies

Site No. 1A - Detection of Adjacent Mine Workings – Underground Limestone Mine - Lake Lynn Laboratory (Monaghan, 2003)

As a result of the Quecreek Mine inundation incident, it was decided to test the capability of GPR to determine the location of adjacent mine workings. This work was conducted at two NIOSH locations: an underground limestone (Site No. 1A) and a coal mine (Site No. 1B).

The Lake Lynn Laboratory is a highly sophisticated underground and surface laboratory located about 60 miles southeast of Pittsburgh, Pennsylvania, and 10 miles northeast of Morgantown, West Virginia, where large-scale explosion trials and mine fire research is conducted. The underground workings are sized to match those of US commercial coal mines (NIOSH 1999). The Lake Lynn Experimental Mine (LLEM) was built at an abandoned commercial limestone quarry where underground entries 49-ft wide by 33-ft high were developed when surface mining ceased in the late 1960's. Later, under the auspices of the U.S. Bureau of Mines, 7,545 ft of new underground development was constructed using approximately 20-ft wide by 7-ft high entries (figure 2). These entries can be configured to simulate modern-day mining, including room-and-pillar and longwall mining (Triebsch and Sapko, 1990). Roof support in the primary escapeway areas of the mine is provided through the use of fully-grouted roof bolts and screens. During development of the new workings, fully-grouted roof bolts were installed.

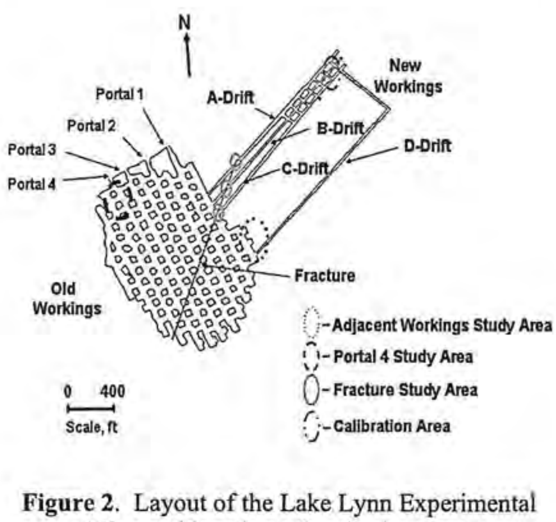

Figure 2. Layout of the Lake Lynn Experimental Mine and location of study site areas.

To test the capability of the GPR system at the LLEM site, an area of workings known locally as the "ramp" (primary escapeway) was selected that runs subparallel to the trend of the D-Drift. The ramp area forms the transition from the old workings to the new workings of the mine. The D-Drift is 1,706 ft long, approximately 7-ft high and 20-ft wide and it was thought that because this structure is so large that it would make a good target for testing the GPR system capabilities. A total of 11 stations (A-K) leading away from the intersection of the ramp and the D-Drift were selected for antenna locations (figure 3). At each station along the ramp, the antenna was elevated and held in place approximately 3 ft above the mine floor (because of the dip of the strata) and aimed toward the D-Drift. Straight-line measurements were made to the D-Drift at each antenna location. This measurement proved to be extremely helpful when examining the records during post-processing of the GPR data.

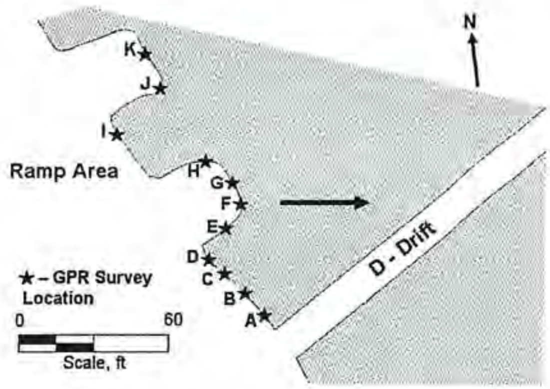

Figure 3. Layout of the GPR survey at the Lake Lynn Experimental Mine (Site 1A). Note arrow denotes approximate direction of transmitted GPR energy wave.

A calibration test pillar was selected that was located between the first and second cross-cuts of the A-and B-Drifts. The width of the test pillar was 38 ft and its length was 67 ft. Calibration tests were conducted at the midpoint of the pillar along its length and width. The tests included installing the antenna about 6-in above the mine floor and pointing it towards the other end of the pillar. The GPR system was then operated in an attempt to detect the opening on the other side of the pillar. At the onset of calibration testing, we used published dielectric constant values for limestone (range 5.5 - 8) (Daniels, 1996; GSSI, 1996). We also examined the perimeter of each calibration pillar for obvious signs of geologic anomalies, and none were observed. During the tests, the dielectric constant was adjusted in the SIR-2 unit until the arrival time of the reflected signal (expressed in term of depth) approximated the dimension of the calibration pillar. As a result of the tests, a dielectric constant of 6.0 was established for the limestone at the LLEM.

The parameters used for the radar records shown in this study are shown in Appendix 1. Figure 4 shows a comparison of interpreted radar records for the 80- and 100-MHz antennas. The vertical scale in the figure represents horizontal distance into the limestone. Note that the anomaly, believed to be the D-Drift, appears at about the same position in each radar record. Table 2 shows the results of all the static testes that were made during this study. A value of "Yes" in the table indicates that an anomaly in the record was observed at the approximate location of either the other side of the pillar (for calibration points A & B) or the approximate distance to the D-Drift. A value of "No" in the table indicates that no anomalies were observed in the record at the approximate location of either the other side of the pillar (for calibration points A & B) or at the approximate distance to the D-Drift. From the results of the tests at the LLEM, it appears the deepest depth of penetration at this site was about 85 ft.

Table 2. Results of GPR Tests at the LLEM Ramp and D-Drift.

Location	Distance, ft	Antenna Frequency, MHz				
		80[4]	100	200	300	400
A (C)[1]	38[2]	Yes	Yes	Yes	Yes	Yes
B (C)[1]	67[2]	Yes	Yes	Yes	Yes	Yes
A	9[3]	Yes	Yes	Yes	Yes	Yes
B	29[3]	Yes	Yes	Yes	Yes	No[5]
C	45[3]	Yes	Yes	Yes	Yes	Yes
D	58[3]	Yes	Yes	Yes	Yes	Yes
E	66[3]	Yes	No[5]	Yes	Yes	Yes
F	71[3]	Yes	No[5]	Yes	No	No
G	85[3]	Yes	No[5]	No	No	No
H	128[3]	No	No[5]	No	No	No
I	159[3]	No	No	No	No	No
J	157[3]	No	No	No	No	No
K	178[3]	No	No	No	No	No

1 Calibration Site.

2 Distance to other side of the calibration pillar.

3 Distance to D-Drift.

4 Multiple Low Frequency Antenna

5 Incorrect range used.

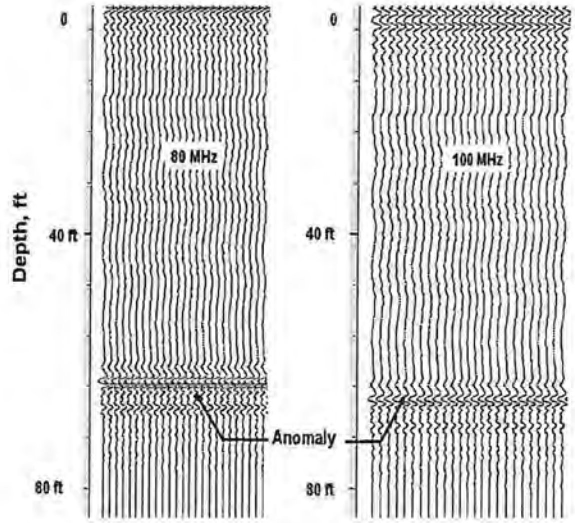

Figure 4. Comparison of interpreted radar records from GPR survey at the Lake Lynn Experimental Mine (Site 1A) Station D.

Site No. 1B - Detection of Abandoned Mine Workings - Underground Coal Mine, SRCM (Monaghan, 2003)

The NIOSH Safety Research Coal Mine (SRCM) and Experimental Mine complex is a multi-purpose research coal mine located near Pittsburgh, PA. The SRCM portion of the mine is a room-and-pillar layout approximately the size of a working section of a commercial US coal mine (NIOSH 1998). The mine was developed in the Pittsburgh Coalbed and abandoned mines are located nearby. The mine opening averages about 14-ft wide and 6.5-ft tall (includes the Pittsburgh Coalbed and the overlying drawslate and rider coal).

As mentioned earlier, an unnamed abandoned mine was located adjacent to the SRCM. Maps obtained from the Office of Surface Mining's Mine Map Repository indicated that the mine had been entered in June 1922, but it is not clear if mining or if only surveying work was conducted in the mine at that time (Robertson, 2003). Therefore, only the approximate extent of the workings could be determined. In addition, an in-seam borehole was drilled in the late 1980's from the SRCM to the northeastern part of the abandoned mine as part of an environmental research project by the USBM. Since the drilling records no longer exist, it is unknown if the borehole was accurately surveyed. Nevertheless, the information available from the mine map, indicated that the abandoned mine workings were penetrated at a depth of about 210-ft.

At the SRCM, two underground sites were selected for calibration tests. Calibration tests were performed, parallel to the coalbed's dominant joint set (face cleat, also known as the main or master cleat) and parallel to the subdominant joint set (butt cleat, also known as the cross or board cleat) (McCullogh, 1974). In the Pittsburgh Coalbed, the face cleat is well developed, exhibiting larger more continuous fracture surfaces. The butt cleat trends approximately perpendicular to the face cleat and is much less continuous and frequently terminates against the face cleat (McCullogh, 1976).

Once the locations were selected, the calibration tests were conducted in the same manner as the tests at the LLEM. The width of the pillar where the antenna was oriented parallel to the butt cleat was 47 ft and the width of the pillar where the antenna was oriented parallel to the face cleat was 42 ft. A second calibration test site was selected where the pillar length was 76 ft. In this case, the antenna was oriented parallel to the butt cleat direction.

Similar to the LLEM site, we began the calibration study with a published value of 4.5 for the dielectric constant for coal (Daniels, 1996; GSSI, 1996). We also examined the perimeter of each calibration pillar for obvious signs of geologic anomalies, and none were observed. During the tests, the dielectric constant was adjusted in the SIR-2 unit until the arrival time of the reflected signal (expressed in term of depth) approximated the dimension of the calibration pillars. The value of the dielectric constant when the antenna was placed parallel to the face cleat was determined to be 3.0 and the when placed parallel to butt cleat was 4.5. It is believed that this difference is related to the orientation of the coalbed joint system possibly the discontinuous nature of the butt cleat and the impact of the variables previously discussed.

To test the GPR system's ability to detect the nearby location of the abandoned mine workings, it was decided to select locations near the site of the borehole in the SRCM (figure 5). A total of five stations (D-H) were selected. During each test, the antenna was elevated and held in place approximately six inches above the mine floor and aimed toward the abandoned mine. Straight-line measurements of propagation distance were made from the mine map to the abandoned mine at each station. This measurement again proved to be extremely helpful when examining the records during the post-processing work on the GPR data. The parameters used for the radar records shown in this study are shown in Appendix 1. Figure 6 shows a comparison of interpreted radar records for the 80- and 100-MHz antennas. The vertical scale in the figure represents horizontal distance into the coalbed. Note that the anomaly, believed to be the abandoned mine workings, appears at the same position in each radar record.

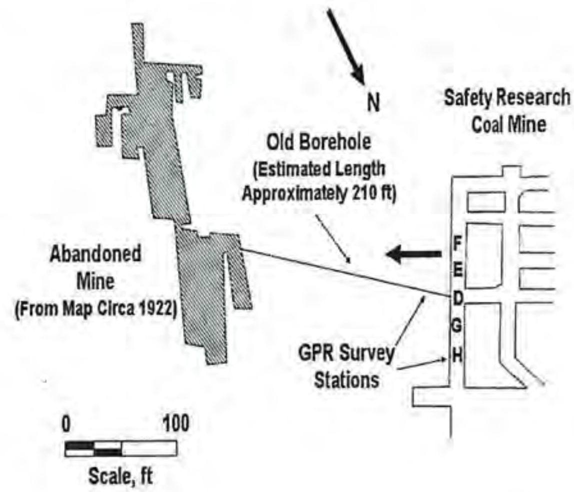

Figure 5. Layout of stations for GPR survey at the SRCM (Site 1B). Note the arrow shows the direction of the transmitted GPR energy wave.

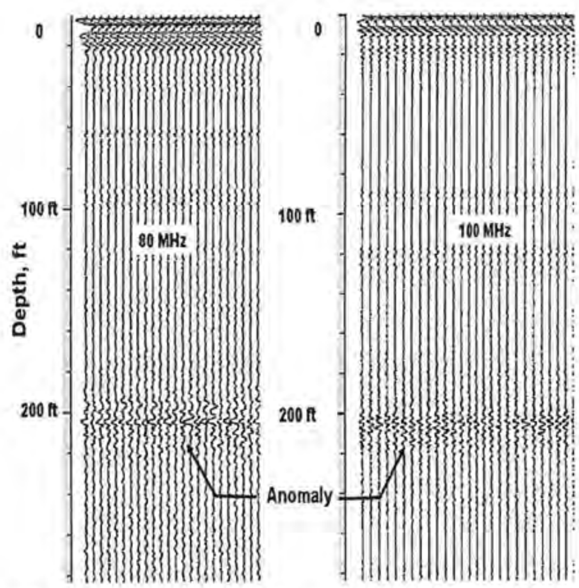

Figure 6. Comparison of interpreted radar records for the 80- and 100-MHz antennas at station E – SRCM (Site 1B).

Table 3 shows the results of all the static tests that were made during this study. Similar to the test at the LLEM site, a value of "Yes" in the table indicates that an anomaly in the record was observed at the approximate location of either the other side of the pillar (for calibration points A-C) or the abandoned mine (points D-H). A value of "No" in the table indicates that no anomalies were observed in the record at the approximate location of either the other side of the pillar (for calibration points A-C) or at the distance to the abandoned mine (points D-H). From the results of the tests at the SRCM, it appears that deepest depth of penetration at the test site was about 205-ft. As a means of ground truth verification, a horizontal hole was drilled by Target Drilling of Pittsburgh, PA from the SRCM to the abandoned mine to confirm the presence and location of the abandoned mine workings. The borehole penetrated the abandoned mine working at a depth of 238 ft. It is unknown why the borehole did not penetrate the workings at a depth of about 220 ft as measured from the mine map. Perhaps the outline of the mine does not accurately reflect the extent of the mine workings in this area.

Table 3. Results of GPR tests at the SRCM

Location	Distance, ft	Antenna Frequency, MHz				
		80[4]	100	200	300	400
A (C)[1]	47[2]	Yes	Yes	Yes	No	No
B (C)[1]	42[2]	Yes	Yes	Yes	No	No
C (C)[1]	76[2]	Yes	Yes	No	No	No
D	200[3]	Yes	Yes	No	No	No
E	205[3]	Yes	Yes	No	No	No
F	250[3]	No	No	No	No	No
G	195[3]	Yes	Yes	No	No	No
H	220[3]	No	No	No	No	No

1 (C) - Calibration Site.
2 Distance to other side of the calibration pillar.
3 Estimated distance to abandoned mine.
4 Multiple Low Frequency Antenna.

Site No. 2 - Delineation of Overburden Conditions Near a Mine Portal – Underground Limestone Mine – Lake Lynn Laboratory

In 1994, a large sinkhole developed southeast of the No. 4 Portal of the LLEM. Over time, the original sinkhole expanded along with the nearby development of three additional sinkholes. A concern developed that the overburden instability could also expand and affect the structural integrity of the highwall and the No. 4 Portal. It was too dangerous to conduct a detailed underground survey of the mine in this area because the mine roof conditions near the No. 4 Portal had deteriorated significantly. It was therefore decided to investigate the overburden conditions near the No. 4 Portal using GPR.

A GPR survey grid was located along an access road that passes over the top of the portal (figure 7). A measurement showed that at the mouth of the portal the overburden was 30 ft thick. Two 80-ft long survey lines (lines 1 and 2) were positioned 10-ft apart and trended approximately perpendicular to the portal. Survey line 3 was located 10 ft away and parallel to Line 2, but was only 60 ft long due to accessibility constraints. A layout map of the survey grid is shown in figure 8. To delineate the mine conditions near the portal, a bistatic antenna whose frequency spectra produced pulses centered at near 100-MHz was used. The shielded antenna was set in the high-power position and it was believed that this antenna would provide the maximum depth of penetration and sufficient resolution to identify the mine working or roof collapse structures.

Figure 7. Photo of Portal No. 4 at the Lake Lynn Experimental Mine (Site 2). Note relative position of GPR survey line is shown at the top of highwall.

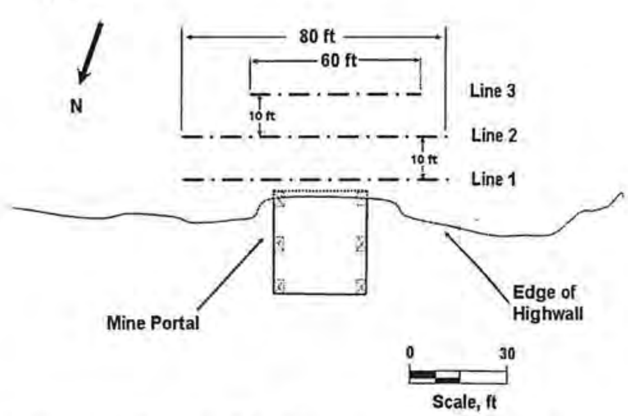

Figure 8. Layout of the GPR survey of Portal No. 4 - Lake Lynn Experimental Mine (Site 2).

Appendix 1 shows the SIR-2 system set-up used. Since previous GPR work had determined that a value of 6.0 was reasonable value for the dielectric constant for the LLEM, it was decided to use this value for this study site (Monaghan, 2003). Dynamic scans of the area were made over the grid following the trend of each survey lines. An example of an interpreted radar record from this study is shown in figure 9. In the figure, the survey begins at the 80-ft mark and ends at the 0-ft mark. The vertical scale in the figure represents depth into the limestone and the horizontal scale represents distance along the survey line. Reference points (short vertical line segments with dotted extensions) were added to the horizontal scale showing the beginning and end of the survey and the edges of the portal. 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. In the figure, the overburden rock units appear to be laterally consistent to a depth of about 15 ft. Below that point, from the right edge of the portal to the 60-ft mark along the survey line, the overburden appears to be significantly disturbed and was thought to represent a large roof fall. Two high-energy reflections are also seen in the record. These reflections are most likely the supports for the metal structure positioned at the mouth of the mine portal (refer to figure 7). A follow-up ground truth survey of the mine roof conditions was conducted remotely from a safe area at the mouth of the portal. The observations made from the radar records appear to be correct. A large roof fall was observed in the mine area near the portal. Furthermore, laser distance measurements of the height of the mine roof, made from the portal show the collapsed area was within 15 ft of the ground surface. These measurements also agree with the observations made from the radar records.

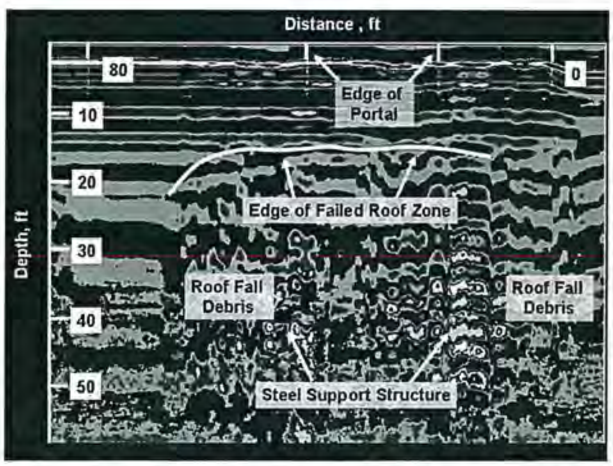

Figure 9. Interpreted radar record for Line 1 (Site 2).

Site No. 3 – Mine Roof Fracture – Underground Limestone Mine – Lake Lynn Laboratory (Trevits, 2004)

In the old workings of LLEM, a large fracture was exposed in the mine roof. The fracture extended northeastward through the intervening pillars towards the new workings (figure 2). Displacement of underlying rock units was not apparent in any of the pillars transected by the fracture. When the new workings were developed, the fracture was observed at the transition point between the old and new workings trending towards the mouth of the C-Drift. The fracture extended across the mine roof area and then disappeared near the mouth of the C-Drift. The mine roof in the fracture zone near the transition point between the old and new workings deteriorated significantly before the roof bolts and screens could be installed, however once the roof control system was installed the roof conditions seemed to stabilized. The trend of the fracture was traced to intersecting points along the A- and B-Drift areas of the new workings. Here, portions of the mine roof failed exposing slickensided surfaces. To prevent further roof deterioration, the exposed surfaces were sprayed with gunite. Because the fracture extended through a significant area of the mine, it was decided to examine mine areas with GPR, along the trace of the fracture, where the roof was deemed good and bad.

Appendix 1 shows the SIR-2 system set-up used at the LLL. To calibrate the SIR-2 system, a large uniform block of limestone (40 in by 36 in by 16 in thick) was selected and measured so that the exact dimensions of the block were known. The block was then imaged with the 500-MHz antenna and the value of the dielectric constant was adjusted until the arrival of the reflected signal, expressed in term of depth, approximated the dimensions of the block. In addition, a section of roof screen was placed on the surface of the limestone to simulate the materials used as the roof support in the mouth of the C-Drift. As a result of the calibration tests, a dielectric constant of 6.0 was established for the limestone and was used for the roof surveys. This value also agrees with that determined during other GPR studies at this mine (Monaghan, 2003).

It was decided to use the 500-MHz antenna for this study because this antenna provided the appropriate depth of penetration and resolution. Furthermore, this antenna was lightweight and could be positioned and easily moved along the mine roof for the dynamic scans. The area of significant interest was the mouth of the C-Drift where all traces of the fracture seem to be nonexistent. In order to learn as much as possible about the characteristics of the fracture, GPR survey grids were also established in each drift opening with survey lines trending across the exposed fracture zone. In the A-Drift, seven survey lines, spaced approximately 15-to 20-ft apart, were established (labeled 1-7) as shown in figure 10. In the B-Drift, eleven survey lines, spaced from 5-to 20-ft apart, were established (labeled 1-11) as shown in figure 11. In each drift, the survey lines were positioned perpendicular to the trend of the drift through and across the fracture area. In addition, a survey line (line 11) was also positioned along the centerline of each drift opening through the fracture zone.

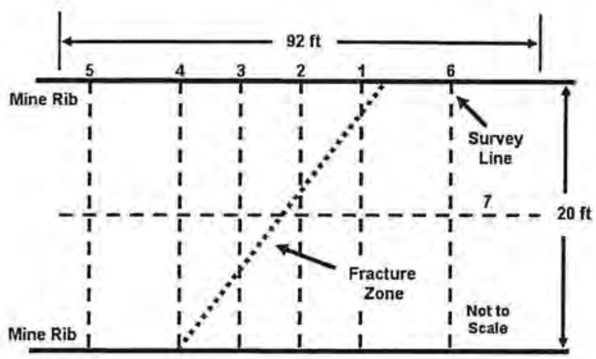

Figure 10. Layout of GPR mine roof survey area in A-Drift (Site 3).

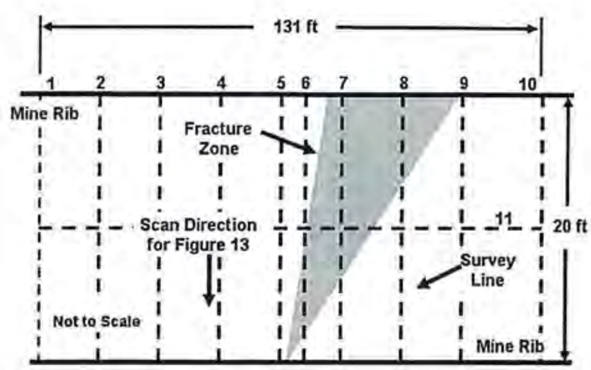

Figure 11. Layout of GPR mine roof survey area in B-Drift (Site 3).

In area of the mouth of the C-Drift, three survey lines (labeled lines 1-3) were established trending across the fracture zone. In addition, survey reference stations were positioned at 5-ft intervals along each line. The survey lines with select survey stations are shown in figure 12. Line 1 was 40-ft long (survey stations 1A-1H) and located near the mouth of the C-Drift in the area where the fracture was not exposed. Line 2 was 50-ft long (survey stations 2A-2K) and was placed roughly between the other two lines. Line 3 was 150-ft long (stations 3A-3EE) and was located near the transition between the old and new workings.

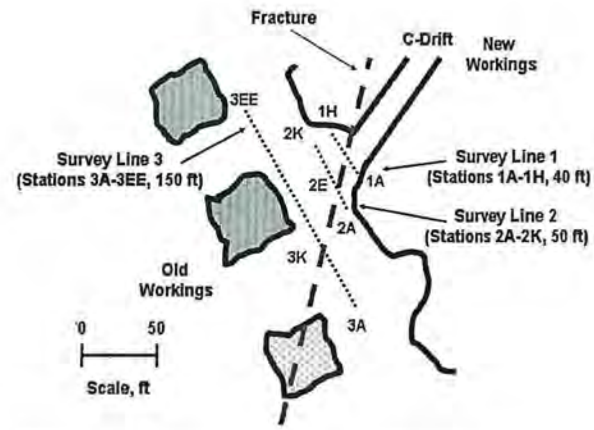

Figure 12. Layout of GPR mine roof survey area at the mouth of the C-Drift (Site 3).

Figure 13 shows interpreted radar records for the B-Drift (refer to figure 11 for the layout of the survey lines). In the figure (and all other radar images for this site) 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. The mine roof interface in the figure is at the bottom of the figure and penetration of the roof increases in an upward direction. The vertical dotted line near the center of the image represents the center of the drift opening. The trend of the survey is northwest and the survey begins on the left margin of the figure. As can be observed in the figures, there is no obvious lateral displacement of the roof members. Again there is an apparent anomaly that projects diagonally across the image and it is believed to represent the trace of the fracture. Figure 14 shows the interpreted radar record for a portion of Line 1 in the C-Drift (refer to figure 12 for the layout of the survey lines). Reference points (shown as vertical dotted lines and labeled 1A-1E) have been added to the figure for comparative purposes. In the figure, the mine roof interface is at the bottom of the figure and penetration of the roof increases in an upward direction. An anomaly is observed in the figure trending diagonally across the image. Again in this case, the anomaly is believed to be the fracture even though the trace of the fracture cannot be directly seen in the exposed mine roof.

The results of the GPR survey show that although the immediate roof conditions appeared to be good in the area of the mouth of the C-Drift near Line A, the fracture was indeed present. In fact, it is believed that the use of roof bolts and screens in this area prevented the roof from deteriorating as observed in other areas where the fracture was exposed.

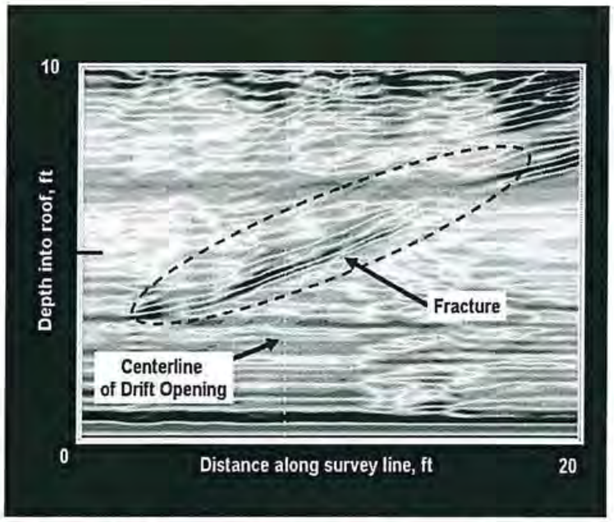

Figure 13. Interpreted radar record survey line 6, B-Drift (Site 3).

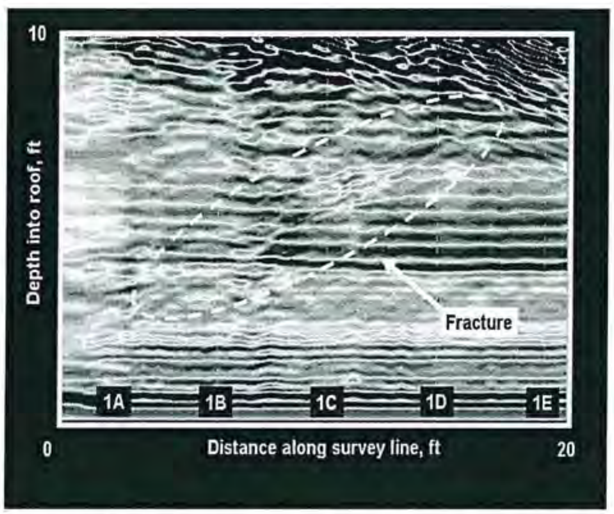

Figure 14. Interpreted radar record for survey line 1, stations 1A to 1E, near the mouth of the C-Drift (Site 3).

Site No. 4 – Joint-Based Solution Channels – Underground Limestone Mine – Pleasant Gap Mine (Trevits, 2004)

This study site is part of Graymont (PA) Inc.'s Pleasant Gap Mine located in central Pennsylvania in Centre County. The limestone unit being mined is a Lower Middle Ordovician carbonate sequence of the Valentine Member. The mine roof is made up of limestone units from the Center Hall Member that contains solution cavities to depths of several hundred feet and the footwall is composed of limestone units from the Valley View Member (Rones, 1969). The limestone mined is extremely pure and is used for paper processing, pharmaceuticals, steel making, environmental mitigation, and agriculture.

The mine operates using a modified form of room-and-pillar mining with vertical benching. There are multiple upper development drift headings and several benching areas in the mine. The extraction ratio is about 70%. Although roof bolts were used only in select areas during early mine development, the mine roof is now supported by a full pattern bolting using mechanical point anchor bolts. Graymont mine officials have confirmed that they are operating in a Karst valley and that a very elaborate hydrologic system exists. Recharge to the water table is accomplished via surface water feeding to an underground transport system founded in the solution cavities and forming a network based on primary and secondary joints. Ground water is prevalent is this area and it is necessary to continuously discharge water from the mine.

During production drilling in one of the mine face areas, significant water flow was encountered and it was believed that a major joint-based solution channel system had been penetrated. Mine management was concerned that the water inflow rate could be excessive so it was decided to further explore the area immediately behind the face using GPR technology. Since NIOSH was conducting ongoing ground control research at the Pleasant Gap Mine, it was decided to extend this work to include a GPR study to provide better definition of the water-bearing structures.

The layout of the problematic mine face area is shown in figure 15. The mine face is about 50-ft wide and at the time of the GPR study, four 3-in diameter probe holes had been drilled into the limestone and were cased with two-inch pipe. The boreholes penetrated the water-bearing structure on the right side of the face at depths of 12 and 18 ft and on the left side of the face at a depth of five feet. Each probe hole continuously produced water at rates that varied in proportion to surface runoff and/or precipitation events.

Unfortunately, only the middle 12 feet of face area could be studied due to accumulations of water in the down-dip heading. Therefore, a survey grid was established on the accessible mine face area with seven survey stations positioned about two feet apart (labeled A to G) for vertical dynamic GPR surveys. The vertical dynamic surveys began at a point about eight feet above the water level and progressed downward to the surface of the water. In addition, a horizontal dynamic survey was conducted progressing from station A to G and was conducted at a height of six feet above the surface of the water. Figure 16 shows the layout of the survey lines in the middle of the face area.

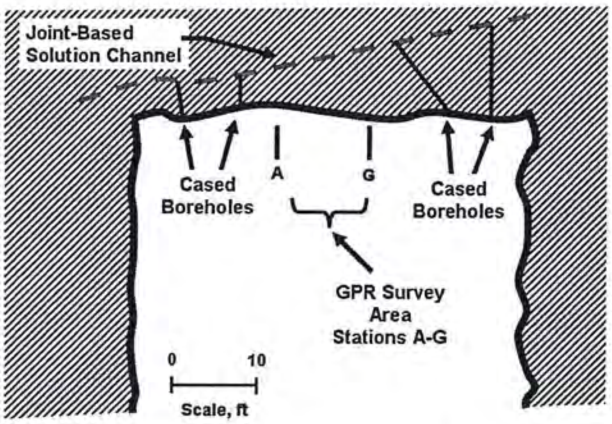

Figure 15. Layout of GPR study area at the Pleasant Gap Mine (Site 4).

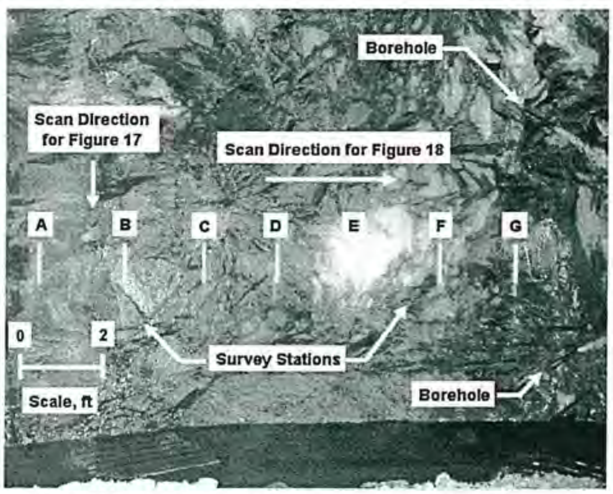

Figure 16. Layout of GPR study area at the Pleasant Gap Mine (Site 4).

We used a 200-, a 400-, and a 500-MHz antenna for this study because these antennas provided the required depth of penetration and the necessary degree of resolution. It was decided to use a dielectric constant of 6.0 (within the 5.5 to 8.0 range observed in the literature) for the GPR surveys and this proved to be a good choice because detectable features in the post-processed surveys were shown at the same depths measured during the probe drilling operations (Daniels, 1996; GSSI, 1996). Appendix 1 shows the SIR-2 set-up used for the 500-MHz antenna. Figure 17 shows an example of a post-processed vertical GPR survey at station A. Reflected pulse energy is shown in this figure (and all other radar images for this site) 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. In the image, the survey begins at the left margin area at a height of eight feet and progresses downward towards the mine floor. The vertical scale in the figure shows the distance traveled downward and the horizontal scale represents depth into the limestone face. An anomaly is shown in the figure at a depth consistent with drilling information and is believed to be the joint-based solution channel in the limestone. The anomaly slopes downward in the image suggesting that the structure is positioned at an inclined angle trending away from the mine face. Figure 18 shows the post-processed results of the horizontal dynamic survey. The vertical scale in the figure represents depth into the limestone face and the horizontal scale shows the survey stations (spaced at 2-ft intervals) across the mine face. In this image, an anomaly is seen trending away from the face area. This trend is also consistent with the results of drilling. Also, shown in the survey is the location of one of the boreholes that was completed near station G.

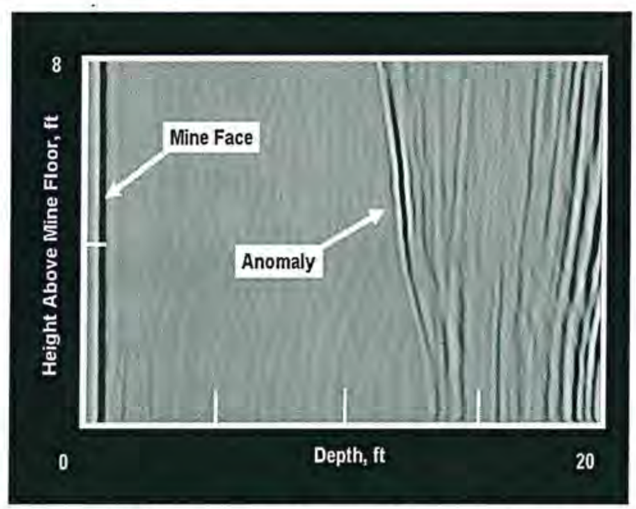

Figure 17. Interpreted radar record for vertical survey at Site 4, Station A.

The results of the GPR surveys helped to confirm that the water flowing from the boreholes was related to a large continuous eroded joint structure located behind the mine face. In all cases, the GPR surveys clearly identified the solution channel at depths consistent with the probe drilling records. Furthermore, the GPR surveys showed the orientation and inclination of the structure. Graymont Mine officials have decided not to proceed with mining in this area until grouting was conducted to seal the solution channel. The results of the post-processed GPR surveys contributed to this decision.

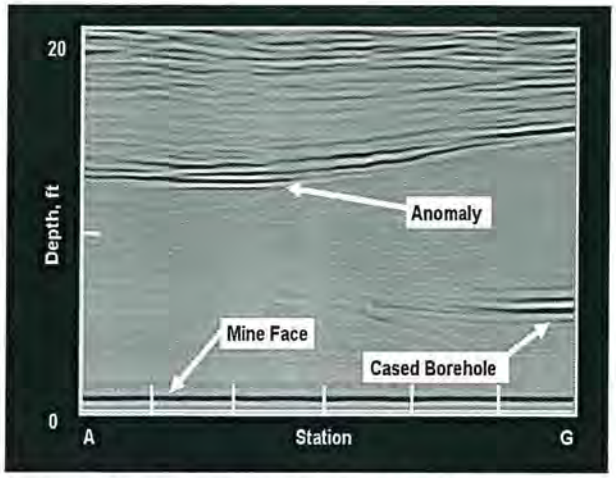

Figure 18. Interpreted radar record for the horizontal survey Site 4, Stations A-G.

Summary and Conclusions

In this study we used GPR to evaluate a variety of mining conditions. At site 1A, an underground limestone mine, we were able to successfully identify the approximate location of adjacent mine workings to a maximum lateral depth of 85 ft. At Site 1B, an underground coal mine, we were able to detect a reflected energy wave response that correlated well with the presence of an abandoned mine to a maximum lateral depth of 205 ft. At Site 2, we used GPR to identify and image a large mine roof fall near an underground limestone mine portal. At Site 3, we were able to use GPR to trace the presence of a long roof fracture in a limestone mine, even though the fracture could not be readily observed in the immediate mine roof. Finally, at Site 4, GPR was used to detect the presence of solution channels behind the face of an underground limestone mine.

In the field, mining and geological conditions will certainly dictate the extent or success of a study. In order to determine the applicability of GPR technology for a site, a well-planned study should be formulated. Some advance knowledge of the feature under investigation and accessibility to reasonable underground sites will be helpful in determining the feasibility of using this technology.

Antenna selection will be dictated by the orientation and depth of feature under investigation and the ability to securely hold or move the antenna along the mine roof and rib areas or along the ground surface. If sufficiently sized samples of the host rock can be obtained or if in-mine calibration can be performed, then it is possible to accurately estimate the dielectric constant of the material and thus make reliable estimates of the depth and location of the in-situ material, object or feature under study.

Under the proper conditions, GPR can provide valuable information that can be integrated into the mining plans to help define problematic areas or identify the source of a problem. Advance identification of problem areas will allow mine operators to plan for changing ground conditions or avoid predicted problem areas. Use of dynamic GPR surveys can generate large quantities of field data and, under certain circumstances, can provide detailed subsurface information of a scope that is superior to that obtained from single-point sources such as drill holes. Because of greater sample density, anomalous conditions are more likely to be detected, resulting in a more accurate characterization of subsurface conditions (Technos, 2004).

It should be kept in mind that numerous factors can cause misleading or erroneous interpretations of the radar information and mine operators are encouraged to seek out trained professionals familiar with the technology, geological setting, and current mining conditions. Ground truth assessments and measurements of radar data interpretations are strongly advised using direct in-mine observations or data obtained from core samples or drill holes. This information will help to verify the conclusions drawn from the radar studies.

Appendix 1. SIR 2- Set-up parameters used for the radar records shown in this study.

Site	Site 1A[1]		Site 1B[2]		Site 2[1]	Site 3[1]	Site 4[1]
Antenna Frequency, MHz	80[4]	100	80[4]	100	100	500	500
Range, ns	600-1000	200-1600	300-1200	300-1000	300-600	55	120
Samples per scan	512	512	512	512	2048	512	512
Resolution, bits	16	16	16	16	16	8	8
Number of gain points	4	4	4	4	4	5	5
Vertical high pass filter, MHz	25	25	15	25	15	30	30
Vertical low pass filter, MHz	200	200	160	200	200	1000	1000
Scans per second	32	16	32	16	8	32	32
Horizontal smoothing, scans	0	0	0	0	5	4	4
Transmit rate, KHz	32	64	64	64	32	64	64
Dielectric constant	6	6	3	3	6	6	6

1 Underground limestone mine
2 Underground coal mine
3 Surface location over a limestone mine.
4 Multiple Low Frequency antenna.

Note: Deep scan standard set-up parameters were used for each antenna to ensure the deepest depth of viewing window. The values shown in the appendix 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 (GSSI, 1996). During post-processing, the radar records were transformed for making interpretations. Typically, reflector amplitude and geometry are the primary types of information in GPR data that are used to make interpretations. The time-domain radar data is defined as time and amplitude of the reflected pulses. Another way of defining data is to transform it into frequency and phase information. The phase information is sometimes more sensitive to important subsurface (dielectric) changes than the amplitude or geometric information (GSSI, 1996). In the case of our radar records, at times we used a Hilbert Transform which expresses the relationship between the magnitude and phase of the signal (i.e., relationship between its real and imaginary parts). This transform is used to display subtle properties of the earth. The magnitude display is useful for indicating the raw energy reflected from an object or layer. The radar wavelet itself may not always be a clear indicator of energy levels because it consists of several cycles. The instantaneous frequency indicates how the earth is filtering the radar signal (GSSI, 1996).

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