GEOPHYSICAL METHODS: REMOTE TECHNIQUES APPLIED TO MINING-RELATED ENVIRONMENTAL AND ENGINEERING PROBLEMS[1]

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Abstract: Acid mine drainage (AMD) and subsidence are two of the serious environmental and engineering problems associated with active, abandoned, and recently active mine lands. Geophysical methods are available to simply and inexpensively determine the location and extent of the problem area, to monitor the progress of remediation work, and to assess the long-term impact of mining-related environmental and engineering problems. Various techniques can be used to locate hydrologic flows through buried spoil, to study combustion areas in coal waste bank fires, and to detect the subsurface conditions that lead to the occurrence of mine subsidence. The utility of two of these geophysical tools has been demonstrated in specific case studies: the use of terrain conductivity to facilitate stream sealing and the application of seismic techniques to characterize longwall mine overburden conditions. Other geophysical methods are discussed in terms of their potential application to mining-related problems.

Introduction

The engineer implementing remediation programs for recently active or long abandoned mines is confronted with a wide spectrum of geotechnical problems. The solutions to many of these problems require detailed information on subsurface conditions. Geophysical tools for determining subsurface conditions include electromagnetics, electrical resistivity, magnetics, seismic refraction and reflection, gravity, and borehole geophysics (table 1). Several of these methods and their application to mining-related environmental problems are discussed in this paper. For a more comprehensive description of geophysical surveying methods, the following references are recommended: Kearey and Brooks (1991); Dobrin and Savit (1988); Telford et al. (1983); and Parasnis (1973). Ward (1992) is recommended for a review of the application of geophysical tools to a myriad of different near-surface environmental and engineering problems.

Theory and Application of Geophysical Techniques

Electromagnetics

Many different electromagnetic (EM) techniques exist, but all are based upon measuring the response of the earth to electromagnetic fields propagating through the earth. The electromagnetic field can be naturally occurring or manmade. Examples include ground conductivity surveying, the very low frequency (VLF) method, ground penetrating radar (GPR), magnetotellurics, time-domain electromagnetics (TDEM), and audio-frequency magnetics (AFMAG).

Ground Conductivity. Ground conductivity profiling (McNeil 1992) is an induction technique. No ground contact is necessary. The equipment for this system generates an electromagnetic field that induces a secondary field in the ground; the ratio of the secondary field to the primary field is proportional to bulk ground conductivity. Transmitter and receiver coils are the basic components of these systems. The earth volume sampled is a function of coil separation, operating frequency, and apparent conductivity of the ground. A number of different systems are commercially available, allowing conductivity mapping from shallow depths of

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Table 1. Summary of selected geophysical techniques applicable to mine land reclamation.

Technique	Physical basis	Application
Electromagnetics		
Ground conductivity	Measures induced EM field in ground to determine bulk terrain conductivity.	Stream sealing (Ackman et al. 1989).
VLF	Uses induced EM produced by low frequency radio transmitters located throughout the world and measures secondary field produced in conducting body to identify its location.	Water-filled fractures (Schueck et al. 1993).
GPR	Utilizes a radar pulse directed into the earth to image the earth in terms of boundaries of varying electrical properties.	Metal mine shafts (Friedel et al. 1990).
Resistivity	Measures the voltage across electrodes in contact with the ground while applying current to two other electrodes, to determine apparent resistivity of the earth.	Coal mine shafts (Gallagher et al. 1978).
Magnetics	Measures perturbations in the earth's magnetic field to determine anomalies due to the presence or absence of magnetic material in the subsurface.	Metal mine workings (Cohen et al. 1992); fires, AMD (Schueck 1993).
Seismic reflection or refraction	Measures the propagation of seismic waves in the subsurface to image the subsurface in terms of layers with varying velocities or layers with contrasting velocity and/or densities.	Underground coal mine workings (Steeples and Miller 1992).
Gravity	Measures perturbations in the earth's gravitational field to determine anomalies due to subsurface bodies with density contrasts.	Underground iron ore mine workings (Ghatge and Waldner 1991).
Borehole Geophysics	Uses various borehole tools to determine the physical properties of material adjacent to borehole; crosshole measurements determine the distribution of physical properties between two or more boreholes.	Hydrogeology of reclaimed strip mines (Diodato and Parizek 1992)

3 m (10 ft) or less, to over 45 m (150 ft). Readings are made at specified stations, and the data are usually presented in profile or contour map form. Advantages of these systems include their portability, the rapidity of surveying, the relatively low cost of the equipment, and the good representation of bulk ground conductivity obtained in conductive earth. Disadvantages include a limited depth of sounding (though adequate for many mining-related problems), unreliable results in highly resistive ground, and interference from manmade objects.

VLF. The VLF (very low frequency) method (McNeil 1992) is a tilt-angle technique in which the VLF receivers utilize low-frequency electromagnetic energy (15 to 25 kHz) generated by radio transmitters for long-range communications and navigational systems. Contact with the ground is not necessary. At large distances from the transmitter, the electromagnetic waves are planar and induce ground current and a secondary electromagnetic field in conductive earth. The VLF unit is a receiver that tunes into this frequency energy. To complete a survey, traverses are made with the VLF unit in a direction perpendicular to the strike of the conductive body, and at right angles to the transmitted electromagnetic waves. Measurements are made of the in-phase (tilt-angle) and quadrature (ellipticity) portion of the vertical magnetic secondary field. Traversing a conductive body with vertical dip, the tilt angle of the field over the body will vary from negative (out of the ground) to positive (down into the ground). Zero tilt of the field lies over the conductive body. Thus, the position of a conductor can be located. Numerous VLF transmitting stations in the necessary frequency band are positioned around the world. These signals can be received thousands of kilometers from the station. Both ground and aerial surveys are possible. Station readings are usually plotted in a profile for the study area; measurements can also be filtered so that zero tilt values result in peaks, which can be plotted on a map and contoured by standard procedures. The technique is useful in detecting faults and conductive fracture zones, conductive clay zones, and conductive ore bodies. The equipment is portable and relatively inexpensive, and surveying can be completed rapidly in a simple operation. Other advantages are a good depth of exploration in nonconductive ground and good response to small conductive bodies producing anomalies. However, the VLF method is largely qualitative, and highly conductive ground limits depth of exploration. Also, in some locations, an appropriate VLF transmitter station may not be available.

GPR. In a GPR system (Alsup and Simmons 1984), an antenna emits a radar pulse in the frequency band of 10 to 1000 mHz that is directed into the ground. The pulse propagates through the ground and is reflected, refracted, diffracted, or scattered back to the surface, where it is detected by a receiver antenna. Two-way traveltime of the returning energy is used to image the subsurface in terms of boundaries with contrasting electrical properties. Dielectric properties and conductivity of earth material control the propagation of this energy. Extremely high resolution can be achieved with GPR because of the high frequency of energy used. However, depth of penetration may be severely limited when water-saturated zones, clay zones, or highly conductive material such as salt or manmade metallic objects are encountered; these zones either attenuate or reflect most of the energy back to the surface. Depending on conditions, the depth of imaging may be as little as a few meters or as great as 300 m (1,000 ft). Surveying is usually done with the GPR unit towed over an area to develop a scan of the subsurface. These scans are analogous to seismic reflection records in many ways. The two-way traveltime for the energy returns are recorded and displayed as a profile scan in real time; traveltimes can be converted to depth. The technique is useful in detecting shallow soil inhomogeneities and buried manmade objects such as drums and pipelines. Advantages of the GPR technique are that it can produce high-resolution imaging of the shallow subsurface under optimum conditions and that it operates in real time. However, GPR equipment is expensive, subsurface conditions may not be conducive to imaging or may limit the depth of investigation, and manmade factors (buried pipes, powerlines) may cause interference.

Magnetics. In magnetometry (Hinze 1992), various elements of the earth's magnetic field are measured using a magnetometer. The earth's main magnetic field is approximately dipolar and is perturbed by near-surface rocks and material, which are magnetic to variable degrees. From these perturbations or anomalies in the expected magnetic field, subsurface conditions can be deduced. Because the field is a vector quantity, measured parameters include total field intensity, direction (declination and inclination), and field gradient. Gradient is obtained by measurement of the field at two locations, simultaneously, using two sensors separated by a fixed distance. Contact with the ground is not necessary, and both ground and aerial surveys are possible. Magnetic surveying commonly consists of measuring total field intensity values at stations along a survey line or at an array of stations that cover an area. Total field data must be corrected for daily changes in the earth's magnetic field, and depending upon application, separation of anomalies due to different sources may be necessary. The data can be used to determine shallow subsurface conditions of 3 m (10 ft) or less, or deep crustal conditions. Data can be displayed as profiles or as contour maps. The information can be used qualitatively to determine where magnetic sources are located. Quantitative models can be derived to determine dimensions, geometries, and depths of subsurface magnetic bodies. The magnetic surveying technique can be used to detect subsurface voids, to map bedrock, to map contacts between bodies of varying magnetic properties, to map fracture zones, and to locate metallic manmade objects such as well casings, drums, and pipelines. The advantages of the technique are that the equipment is inexpensive and portable, large areas can be rapidly surveyed, and data processing is relatively simple. However, cultural interference can generate noise, and a data set may produce nonunique solutions.

Seismic Techniques

Seismic surveying (Steeples and Miller 1992; Pullan and Hunter 1992; and Lankston 1992) includes a number of different techniques based upon the propagation of seismic energy in the earth. Regardless of the methodology, seismic energy generated at or near the surface propagates through the earth, where it is refracted, reflected, and diffracted. Traveltimes of the returning energy are used to determine subsurface conditions. Equipment consists of an energy source (sledge hammer, explosives, firearms, airgun, or others), a recorder, seismic detectors (usually geophones), and cable. In seismic refraction, returning arrivals refracted along subsurface boundaries can be used to determine a velocity distribution of the subsurface from which a model of subsurface conditions can be inferred. Seismic velocity must increase with depth to utilize the refraction technique. In seismic reflection, energy is reflected at subsurface boundaries at which there is a significant contrast in seismic velocity and/or density. Energy that returns to the surface is displayed on records in terms of two-way traveltimes, and the subsurface can be imaged as a function of reflecting boundaries. The resolution of the techniques and depth of exploration depend on such factors as energy source and recording parameters. Voids in coal seams as shallow as 3 m (10 ft) have been imaged using the seismic reflection technique (Steeples and Miller 1992); in contrast, research consortiums have imaged to depths over 30 km (48 miles) and the crust-mantle boundary (Brewer and Oliver 1980). Under optimum conditions, seismic techniques can provide a rather detailed image of the subsurface. However, seismic equipment is relatively expensive, surveys can be time and labor intensive, and processing techniques can be complex, expensive, and time consuming. Culturally developed areas may be difficult to work in, and the techniques may not work well when subsurface boundaries are moderately or steeply dipping. Both vertical and horizontal resolution are limited.

Environmental Problems - Geophysical Technology

Although problems differ significantly from one site to another, the questions asked are often similar. Due to site-specific conditions of mine sites, it is frequently difficult to recommend one geophysical technique over another. Table 2 lists common questions often encountered in remediation work and offers techniques that may potentially answer them. This evaluation is based on existing case studies; however, site-specific conditions may allow other applications not listed in this table. AMD and subsidence rank high among abandoned mine land problems and are discussed in more detail below.

AMD problems raise questions relative to hydrologic flow path through pyritic spoil or coal refuse piles, location(s) of ground water entering or leaving a disturbed area (mine site), depth to ground water, locations of mine voids and features such as water-filled fractures, and extent of inundation. Geophysical techniques can provide qualitative and quantitative answers to some of these questions and only qualitative answers to others. In addition, creative approaches incorporating a combination of several techniques are currently being investigated.

Subsidence of mine lands usually involves two basic issues: (1) risk assessment and prediction, i.e., which mined areas are susceptible and where and when subsidence is imminent, and (2) remediation of the affected area. Specific information that could be acquired using geophysics includes general areal extent of workings; thickness and other physical properties of the overburden; depth and dimensions of mine voids and pillars left for support; and whether mine voids are open or filled with air, water, or rubble.

Case Studies

Repairing Stream Channels to Reduce Water Loss into Underground Mines

Multiple zones of infiltration (natural and induced fractures) normally exist in stream channels overlying shallow (approximately 60 m (200 ft) or less) mined areas. These may cause water-handling and/or acid drainage problems in underground mines, as well as loss of stream flow. Total or partial water loss can occur within a stream channel. Partial losses are often undetectable by visual observation, making it difficult to accurately locate loss points. Therefore, conventional methods of stream repair, such as plastic membranes or clay and rock rip-rapping, are inefficiently applied to both damaged and undamaged portions of the stream channel.

Table 2. Common questions and potential geophysical techniques.

	Electromagnetic techniques	Resistivity	Magnetics	Seismic techniques	Gravity
What is the areal extent of mine workings?	X	X		X	
Where are the mine voids located?	X	X		X	X
What is the depth to the mine workings?		X		X	
What is the extent (location) of the mine pool?	X				
Where are the resources that were left in place (pillars, highwall)?				X	
What is the depth/nature of the ground water table?	X	X		X	
What is the character of the overburden?	X	X		X	
What is the character of the mine workings (collapsed, water-filled, burnt)?			X	X	
Where are the fractures in the overburden?	X	X			
What is the character of the spoil?	X		X		

The approach initially developed by the U.S. Bureau of Mines (USBM) accurately locates loss zones by using electromagnetic terrain conductivity surveys and stream gaging. Ground water is transported to and from a stream through fractures intersecting the stream bottom; consequently, the ground beneath these fracture zones exhibits increased conductivity due to saturation. Conductivity is measured at fixed spacings, typically 7.6 to 15 m (25 to 50 ft), depending on the instrument and observation depth while the surveyor is walking the stream channel. The zones of high or anomalous conductivity are targeted as potential stream loss zones. Because of natural (e.g., presence of clays) or cultural (e.g., buried metal) interferences that can affect terrain conductivity data, stream-gaging stations are then established around the targeted stream loss zones to confirm the results of the geophysical measurements.

At one site where this approach was used, a stream was in the path of an advancing longwall panel. The direction of the stream channel was at an oblique angle to the advancing longwall face (fig. 1), which would pass beneath a segment of the stream at a depth of approximately 60 m (200 ft). Terrain conductivity stations were established on 10-m (33 ft) intervals within the stream channel and overlapped the headgates and tailgates (supported sides) of the panel. Surveys were completed before, during, and after passage of the panel, using a terrain conductivity instrument with effective depths of about 3 and 6 m (10 and 20 ft) (fig. 2).

A positive conductivity anomaly was identified between stations 26 and 32 prior to mining (fig. 2A). A land survey parallel to the stream also depicted high conductivity readings adjacent to the anomalous stream zone, thus indicating that this was a natural fracture zone (fig. 2A). Shortly after the longwall panel passed beneath this anomalous zone (fig. 1), a 100% flow loss occurred between stations 30 and 32. Polyurethane grout was injected approximately 1 m (3 ft) beneath the surface of the streambed at the loss zone to seal

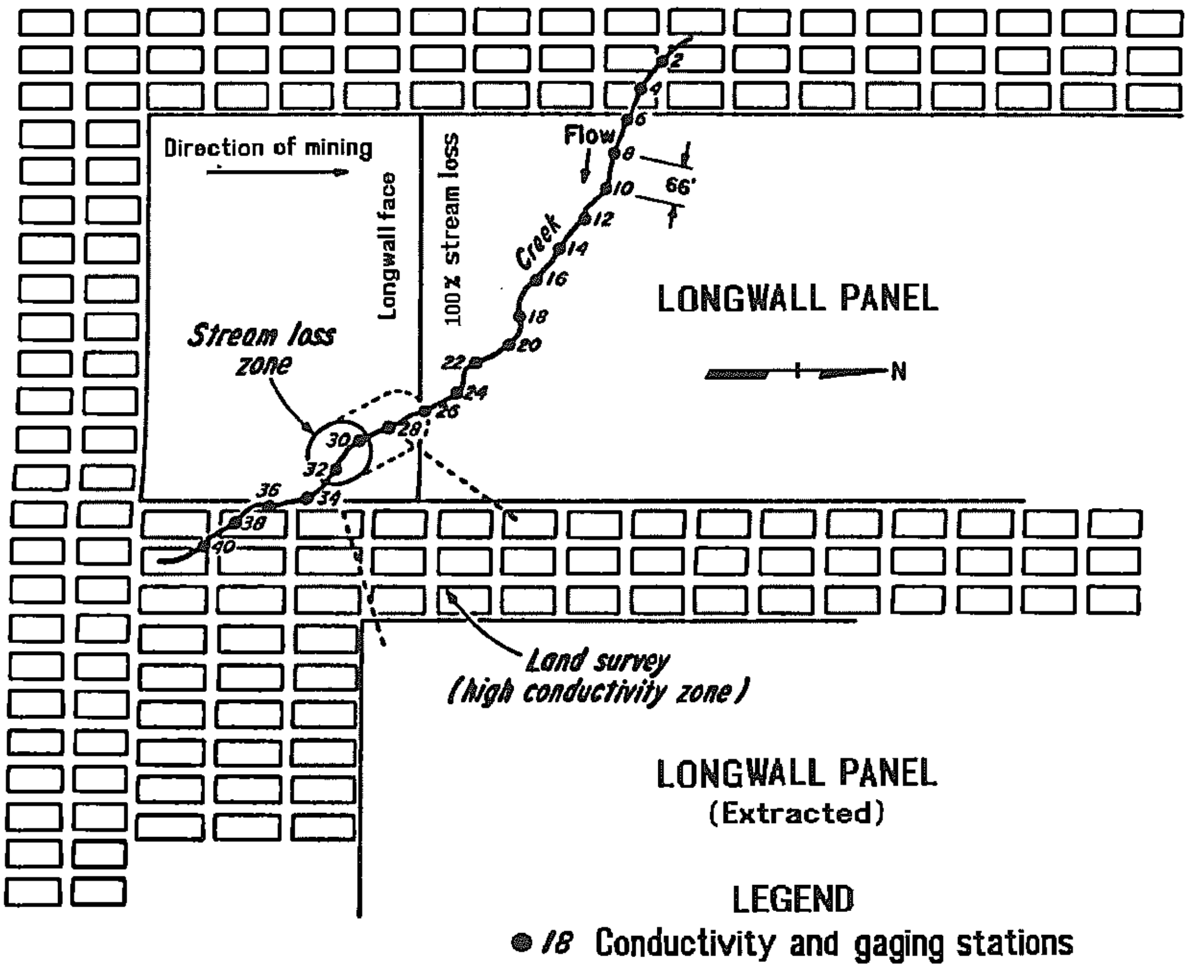

Figure 1. Map of longwall mining operation, stream position, and ground conductivity stations.

fractures. Surveys subsequent to grouting did not detect high or anomalous conductivity readings (fig. 2B), thus indicating that the fracture zone had been sealed beneath the stream channel. Gaging data also showed a 100% recovery across the damaged stream zone (Ackman et al. 1989).

Seismic Refraction To Characterize Longwall Panel Overburden

Subsidence above longwall panels can produce adverse engineering and environmental effects such as damage to infrastructure and changes in the hydrologic regime. Subsidence is generally predictable, with the greatest percentage of ground disruption taking place shortly after mining. Identifying and quantifying this ground disruption is important from both an environmental and engineering perspective. The USBM recently designed a seismic refraction study to characterize overburden conditions above a longwall panel in Maryland (ICF Technology Inc./SRW 1992). This study identified and quantified changes that took place in the overburden shortly after mining. The study demonstrates that premining and postmining conditions in the overburden can be monitored through remote, surface geophysical techniques such as those discussed in this paper. When this geophysical information is combined with borehole data, it can result in an improved assessment of overburden conditions.

The study site was located in Garrett County, western Maryland, and was underlain by Pennsylvanian-aged strata of the Conemaugh and Allegheny Formations. The coalbed mined was the Upper Freeport. The coal panel being mined was about 2.5 m (8 ft) thick, 158.5 m (520 ft) wide and 1015 m (3,330 ft) long. Prior to undermining, a surface seismic refraction survey (line A-A', fig. 3A) was conducted along the centerline of the coal panel (approximate depth of 180 m (600 ft)). The survey was repeated after the longwall face had progressed to about 200 m (660 ft) beyond the line surveyed (fig. 3A).

The seismic line consisted of four spreads, with each spread about 67 m (220 ft) in length (fig. 3A). Each spread consisted of twelve geophones spaced at 6 m (20 ft) intervals. Seismic energy was generated by detonating small explosive charges (0.45 kg (1 lb) dynamite) in shot holes; the shot holes had nominal depths of 1.8 m (6 ft). Shots were positioned at the ends and in the middle of the spreads. A seismograph was used to record seismic wave traveltimes. First arrivals on the seismic records were identified and their traveltimes were used to generate a velocity distribution for the subsurface.

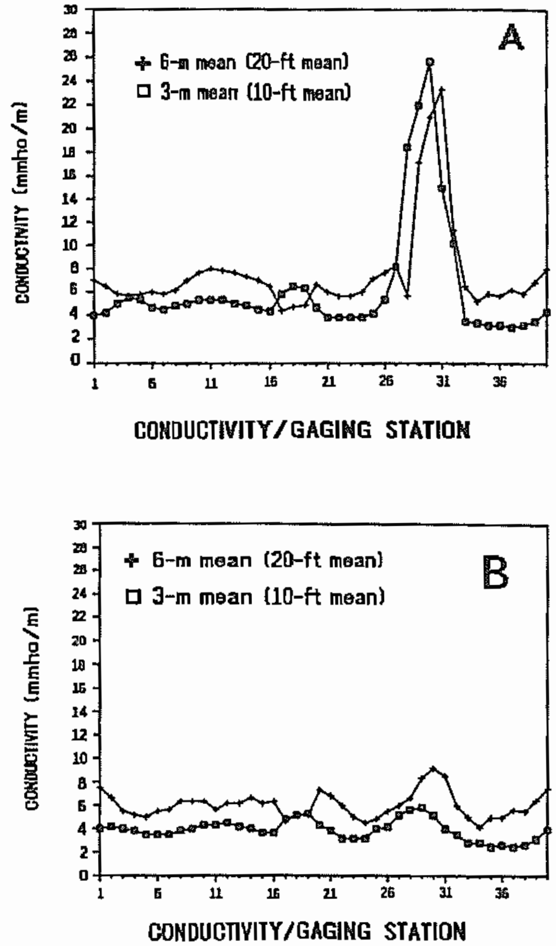

Figure 2. Ground conductivity survey before mining (A) and after mining and grout procedure (B).

From the initial premining survey, a two-layer subsurface model was derived in terms of velocities (fig. 3B). The uppermost layer with lower seismic velocities was interpreted as representing unconsolidated material and/or weathered bedrock. The second layer, with significantly higher velocities, was likely bedrock, known to be predominantly interbedded shale and sandstone at this location. As observed on figure 3B, depth to bedrock was determined as part of the seismic refraction model. Line A-A' was resurveyed (postmining survey) by seismic refraction techniques about 1 month after the initial survey and after the longwall face had passed the survey line. As before, a two-layer model was derived, but resultant velocities in both layers were lower (fig. 3B).

The velocity changes observed between the premining and postmining surveys were a result of changes that occurred in the overburden. Prior to the postmining survey, subsidence had occurred in the area; the greatest vertical change was a decrease of about 1.5 m (5 ft). The velocity changes observed in the overburden were likely induced by mining. Subsidence increases overburden fracture density, changes fluid saturation in overburden, and can change the density of the overburden rockmass. These factors, in part, determine elastic constants of the overburden. Elastic constants (Young's modulus and others) determine seismic wave velocity. An increase in fracture density, a decrease in fluid saturation (lowering of water table), or decrease in density of the overburden rock mass would each serve to lower seismic velocity values. One or all of these factors can explain the decrease in seismic velocities along the centerline of the longwall panel less than 1 month after undermining. Thus, one interpretation of these seismic data is that the lower velocities measured in the postmining survey were due to an increase in fracture density of the rockmass overburden. Consequently, an

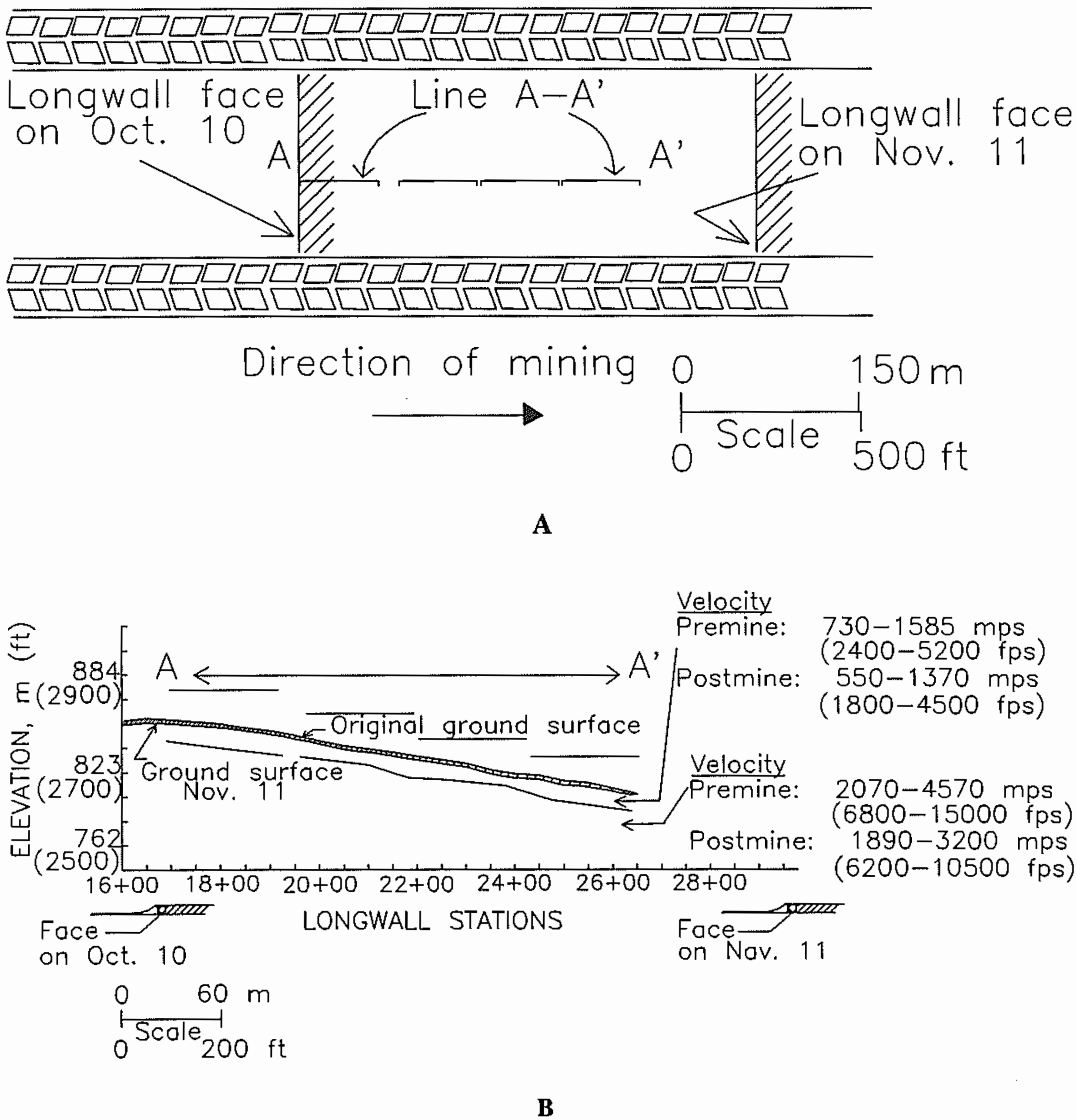

Figure 3. Map of and modeled profile through longwall mining operation where seismic refraction study was conducted. (Modified from ICF Technology Inc./ SRW 1992.) A. Map with surface seismic line (A-A') and subsurface coal mining operations (depth about 180 m (600 ft)). Changing position of longwall face indicated. B. Two-layer modeled profile through surveyed area with pre- and postmining seismic velocities indicated. MPS=meter per second and FPS=feet per second.

increase in fracture density could result in a lowering of the water table. Although not available for this study, borehole data could be used to substantiate these interpretations.

From these data, the distribution of overburden rockmass properties and changes in these properties were remotely measured over a large area using geophysical techniques. When combined with other information such as borehole data, they provide an improved assessment of premining and postmining overburden conditions.

Summary

A variety of geophysical techniques are currently available for application to mine-related environmental problems. Examples of case studies are described in published literature (table 1), and several were discussed in this paper. With continuous improvements in geophysical hardware and software, the industry will see increased use of this technology for mine-related environmental problems. In addition, the integration of multiple techniques has value and will see increased use. For example, in the problem area of AMD, magnetometry has already been coupled with terrain conductivity to successfully locate buried, acid-producing refuse in reclaimed surface mines (Schueck 1993). Future coupling of conductivity with VLF to locate water-filled fractures may eliminate the need for stream gaging to identify stream loss zones and will permit a more rapid stream remediation. The remediation and restoration of mine lands will continue for years to come; geophysical techniques utilized by experienced personnel may provide a powerful tool to answer many of the remediation questions in a cost-effective, expeditious way. However, creative applications and/or integration of geophysical techniques will be required.

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