USING A MAGNETOMETER FOR INVESTIGATING UNDERGROUND COAL MINE FIRES, BURNING COAL REFUSE BANKS, AND FOR LOCATING AMD SOURCE AREAS ON SURFACE MINES[1]

by

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Abstract. A variety of problems ranging from post mining acidic discharges to underground mine fires may develop on completed coal mining sites. Unless the site conditions can be accurately defined, solutions to these problems have little chance of success. Studies indicate acid mine drainage (AMD) often forms in localized areas within a backfilled strip mine. Underground mine fires and burning waste banks do not burn in a laterally continuous pattern. Accurate definition of site conditions using drilling is almost impossible because of this lateral discontinuity. However, geophysical surveying can provide much of this information.

Chemical or thermal oxidation of pyrite forms magnetic minerals. Determining the locations of the transformed pyrite equates to a knowledge of the AMD production areas or areas which have burned and cooled. Magnetic surveying can determine the spatial distribution of the resultant magnetic minerals. Electromagnetic terrain conductivity can delineate pollution plumes on AMD production sites.

An underground mine fire, a burning refuse bank, and a reclaimed strip mine producing AMD were mapped using magnetometry. Terrain conductivity was also used on the AMD site. Areas of the underground mine and refuse bank which had burned and cooled were delineated. AMD source areas and the resultant pollutional groundwater plume were defined on the third site.

Additional Key Words: magnetometry, electromagnetic terrain conductivity, acid mine drainage, underground mine fires, burning refuse banks, magnetic susceptibility

Introduction

Acid mine drainage production and burning underground coal mines or refuse piles are two of the most significant environmental problems associated with coal mining. There are over 2500 miles of streams polluted by acid mine drainage (PaDER 1971) and more than 500 fires burning in abandoned coal waste banks and coal deposits across the United States (Chaiken, 1989). Subsidence and noxious gases related to underground mine fires caused hundreds of people to move from their homes and communities. Burning refuse banks cause air pollution. Living conditions near these piles are often intolerable due to high levels of noxious gases. Millions of dollars have been spent investigating and trying to abate these problems, usually with very limited success. An inability to define site conditions accurately leads to the limited success.

Underground mine fires often start along the crop line because of trash burning. Here the fire is visible and simple to define. However, once the fire spreads to the underground workings the location of the combustion zone is unpredictable. Venting smoke and fumes rising from subsidence cracks confirm that combustion is taking place but may appear hundreds of feet from the actual combustion zone. The US Bureau of Mines developed a deep mine fire diagnostics program to locate combustion zones (Justin and Kim 1988). However, this program requires extensive drilling and gas sampling. Knowing which areas have burned and cooled as well as areas which are heating or cooling would certainly aid in planning drill hole locations for this program.

Locating combustion zones in burning refuse banks is also quite difficult. Similar to a deep mine, venting gases may surface tens of feet from the combustion zone. Limited oxygen within the bank slows the rate of combustion and, to a large extent, controls the direction of the fire spread. Unlike underground mine fires which are stratigraphicaly controlled, a third dimension is added to refuse banks as many are over 100 feet in height. Refuse banks require definition of the combustion zones vertically as well as horizontally before solutions can be determined.

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Infiltrating precipitation or laterally moving groundwater entering a backfilled strip mine may come into contact with pyrite, forming acid mine drainage. The normal tendency is for this drainage to flow down-dip along the pit floor. It then emerges near the crop line as a toe of spoil discharge. Buried coal stockpiles, pit cleanings, and buried refuse piles often contain high concentrations of pyrite. Studies show these to be prime sources of AMD production even though they may be no larger than a few feet in any dimension. There is no apparent evidence on the reclaimed surface to indicate the locations of these toxic piles. Drilling programs seldom accurately delineate the AMD source areas. Drilling may locate a pile of toxics, but the investigator cannot determine the limits of the pile with confidence without extensive additional drilling. For this reason, past solutions to control AMD production at its source have been largely unsuccessful.

The ability of localized piles of pyritic materials to accelerate AMD production was observed on an active mine site in Fayette County. A small pile on pit cleanings intercepted water flowing across the pit floor. The changes in water quality were dramatic considering the short contact time. The acidity increased by 1600 mg/l, iron by 500 mg/l and sulfate by 1950 mg/l.

Geophysical mapping of these areas can provide valuable site information not obtainable through drilling. Each geophysical technique measures a physical property of the earth within the equipment's range of detection. Success with geophysics comes about when the physical property of the target which the technique measures differs sufficiently from the host material to permit detection. Combustion metamorphism causes significant changes in physical properties of coal and related pyritic materials. Chemical oxidation also causes major changes in physical properties of pyritic materials on AMD producing sites. In both cases, the physical properties change enough to allow detection by geophysical methods.

Thermal oxidation of pyrite as in a mine fire (Cisowski 1987) or chemical oxidation of pyrite as in a site producing AMD (Henderson 1984) results in the formation of magnetic minerals. Under proper conditions, these magnetic minerals can be detected and their distribution mapped through magnetic surveying. Acid mine drainage is a good electrical conductor because of ions in solution. On the other hand, mine spoil is a poor electrical conductor. Electromagnetic terrain conductivity can successfully delineate plumes and pools of AMD because of this contrast.

Magnetic Surveying - Theoretical Considerations

The earth's magnetic field consists of lines of magnetic flux surrounding the earth similar to that of a large bar magnet. The total field intensity at any given point depends upon the flux line density which is twice as great at the poles as it is at the equator. A proton processing magnetometer measures the total field intensity. The magnetometer records magnetic intensities in units of gammas. In Pennsylvania, the total field intensity is about 55,500 gammas.

A magnetic object creates a local disturbance, or anomaly, in the earth's magnetic field. The magnitude of the anomaly as recorded by the magnetometer depends on several factors. These include: 1) the mass of the magnetic material present, 2) the magnetic material's ability to enhance the field locally (magnetic susceptibility), 3) the burial depth or source-to-sensor distance, 4) the shape and size of the source, and 5) the amount of magnetic material in the source compared to the adjacent rocks.

The ability of a material to enhance the local field is called magnetic susceptibility, k. For most materials k is much less than 1 and is usually 10^{-6} cgs or smaller. The susceptibility or k of magnetite is approximately 0.3 cgs. The magnetic susceptibility of a rock containing magnetite or any other magnetic mineral is simply related to the amount of magnetite is contains. For example, rock containing 1% magnetite will have a volume susceptibility of 3×10^{-3} cgs. The volume magnetic susceptibility for most sedimentary rocks is 10^{-6} to 10^{-5} cgs. (Breiner 1973).

Similar to a bar magnet, magnetic objects are polar, that is north and south seeking poles are present. When magnetic targets are mapped and the results contoured, the effects of the poles are reflected in the shape of the anomaly. Values of magnetic intensity greater than background levels (positive anomalies) will be recorded directly above the target. Values lower than background (negative anomalies) will normally be recorded adjacent to the positive anomaly (Breiner 1973). For clarity, only the positive portions of the anomalies are shown in the figures used in this paper.

At the three sites included in this study the targets were magnetic minerals resulting from chemical or thermal alteration of pyrite. The percent pyrite and the process by which the pyrite is altered ultimately determines the volume magnetic susceptibility, hence its ability to be detected. In the case of the underground mine fire and the burning refuse bank the volume magnetic susceptibility of the ash, also known as klinkers or red dog, was determined to be approximately 2×10^{-3} cgs. The volume magnetic susceptibility of the chemically altered pyrite at the AMD site was determined to be approximately 4×10^{-5} cgs. Since thermally altered pyrite exhibits a volume magnetic susceptibility two orders of magnitude greater than that of chemically altered pyrite, the magnetometer can more readily detect thermally altered pyrite.

The burning material in an underground mine fire consists of the coal pillars, binder material, and sometimes roof rock. Pyrite is common to all these materials. Temperatures in the burning zone commonly are in the range of 800 to 1000 degrees C, well above the Curie temperature (Chaiken et al 1989). Upon heating above the Curie temperature, magnetic minerals lose their natural magnetism. Small regions, called domains, within the crystal structure reorient themselves. Upon cooling they align themselves more or less in the direction of the ambient magnetic field and thus parallel to each other. This remanent magnetism may be several orders of magnitude greater than the natural magnetism (Breiner,1973). The minerals which are formed and their respective magnetic strengths depend on the temperatures reached and the amount of oxygen available (Cisowski 1987).

The chemical reactions which produce acid mine drainage also provide a mechanism for the pyritic source areas to be detected and mapped using a magnetometer. When proper pH-Eh conditions exist, a magnetic mineral phase of iron oxide forms. This mineral is thought to be maghemite, Fe_2O_3, a dimorphous form of hematite (Henderson 1984). When this mineral forms in a localized area, such as in buried piles of refuse or coal stockpiles, the volume magnetic susceptibility is sufficient for detection by a magnetometer.

Tipple refuse detection may be enhanced by one or two additional magnetic sources not found in pit cleanings or coal stockpiles. Two sites were mapped in 1987 where tipple refuse was buried. Analysis of the refuse at both sites revealed traces of magnetite crystals and ash particles. Magnetite crystals used in the coal separation process were lost to the refuse. It is thought that the ash particles resulted from spontaneous combustion. Both the magnetite and the ash exhibit high magnetic susceptibilities (Schueck 1988).

Magnetic Surveying - Field Methods

A proton processing magnetometer with a sensitivity of 0.1 gamma was used for this study. It consists of a sensor mounted on top of an 8 foot aluminum staff. The sensor is connected to a power source and recording device carried in a harness worn on the chest.

Taking advantage of the source-to-sensor distance fall-off factor, a second sensor can be mounted on the staff two or four feet lower than the top sensor. The magnetic gradient is measured in this mode and the magnetometer functions as a gradiometer. Field intensity readings taken by both sensors helps to resolve and better define the source.

A recording base station was used at the AMD site. This permits rapid removal of diurnal fluctuations in the magnetic field from the field readings, thus improving accuracy.

Grids were established in the field at the three sites. Readings were then taken at each grid intersection. The required grid spacing depends on the expected target size, burial depth, and volume magnetic susceptibility. The grid spacing varied from site to site but averaged 25 feet. This spacing was adequate to locate the magnetic sources. Several of the smaller anomalies required mapping on a five by ten foot grid in the gradiometer mode for better definition.

A commercially available magnetic forward modeling computer program was used to interpret the recorded anomalies. Parameters such as shape, burial depth, and magnetic susceptibility are input into the program. The output is a theoretical field curve which is compared to the actual field readings. Changes in the input data are made until a close agreement is reached between the theoretical and recorded values.

Electromagnetic Terrain Conductivity - Theoretical Considerations and Field Operation

Electromagnetic terrain conductivity (EM) has been used successfully for several years to map contaminant plumes (Ladwig 1982). EM operates as follows. A sinusoidally varying magnetic field from a transmitter electromagnetically induces currents in the ground. This is done in such a manner that their amplitude is linearly proportional to the terrain conductivity. The magnitude of these currents is determined by measuring the magnetic field which they in turn generate (McNeill 1980). The receiver displays these measurements in units of mmhos/m.

The depth of investigation for EM can be varied by using different coil orientations and spacings. Thus the near surface conditions as well as conditions at depth can be determined. The instrument used during this study was a single man unit with capabilities of determining terrain conductivities to depths of about ten and 20 feet.

The ground is generally a poor electrical conductor. By contrast acid mine drainage is an excellent conductor because it is an electrolytic solution. Thus, plumes and pools of mine drainage are excellent targets for EM and are easily detected. The electrical conductivity of an entire mine site can be determined rather quickly by obtaining readings along a grid system. The recorded values are then plotted and contoured. Correlation of the results can be achieved with a limited amount of drilling.

EM may provide information about a mine site which monitoring wells may not. Following a precipitation event, water commonly moves through the mine spoil as a wetting front. Monitoring wells located within the plume may not indicate the presence of water unless it pools in the area of the well. However, as the wetting front moves through the spoil, the rocks remain wet. Water associated with AMD source areas and flow paths will contain more dissolved ions than water in areas not producing mine drainage. These areas can then be defined with EM even though their presence is not indicated by monitoring wells.

Case Studies

An Underground Coal Mine Fire

An underground coal mine in southwestern Pennsylvania has been burning for decades. Three fires of separate origin are slowly spreading through this mine. Designated DMF1, this 120 acre deep mine was developed in the Pittsburgh coal seam. The coal averaged a thickness of nine feet. The carbonaceous shale roof rock is also combustible. The maximum cover over the mine is 120 feet. Retreat mining was extensive, according to the mine maps. Thus, roof collapse would have been prevalent and the previously established headings would no longer be well defined. This restricts air circulation, slowing the fire spread. Both the state and federal governments have spent considerable sums of money investigating and flushing various portions of the mine with fly ash to protect homes in the area. Active subsidence beneath a highway crossing the mine fire is a continual maintenance problem.

About 70 of the 120 acres were mapped during June, 1988, using magnetic surveying. Twenty five acres were remapped in June, 1989. The purpose of the mapping was to determine the magnetometer's ability to define three features associated with the fire. These include 1) the distribution of the of the areas which had burned and cooled, 2) the actual fire locations, and 3) areas within the mine which were heating up and those which were cooling down.

Total magnetic field readings were recorded on a 25 by 50 foot grid. After correction for diurnal variation, the readings were plotted and contoured. Based on visual observation, areas of the mine along the crop line which had burned and cooled resulted in positive magnetic anomalies. Total field intensities of more than 700 gammas above background levels were recorded for these areas. The contour plots show a continuance of the ash into the mine workings. Under a maximum cover of 120 feet the recorded field intensities were still 280 gammas above background levels. Magnetic modeling was used to define the limits of the burned areas within the workings. Figure 1 shows the positive magnetic anomalies superimposed over the deep mine workings within the study area. The areas interpreted to have burned and cooled to ash are shaded. When determining the limits, it was assumed that a portion of the carbonaceous shale roof rock also burned.

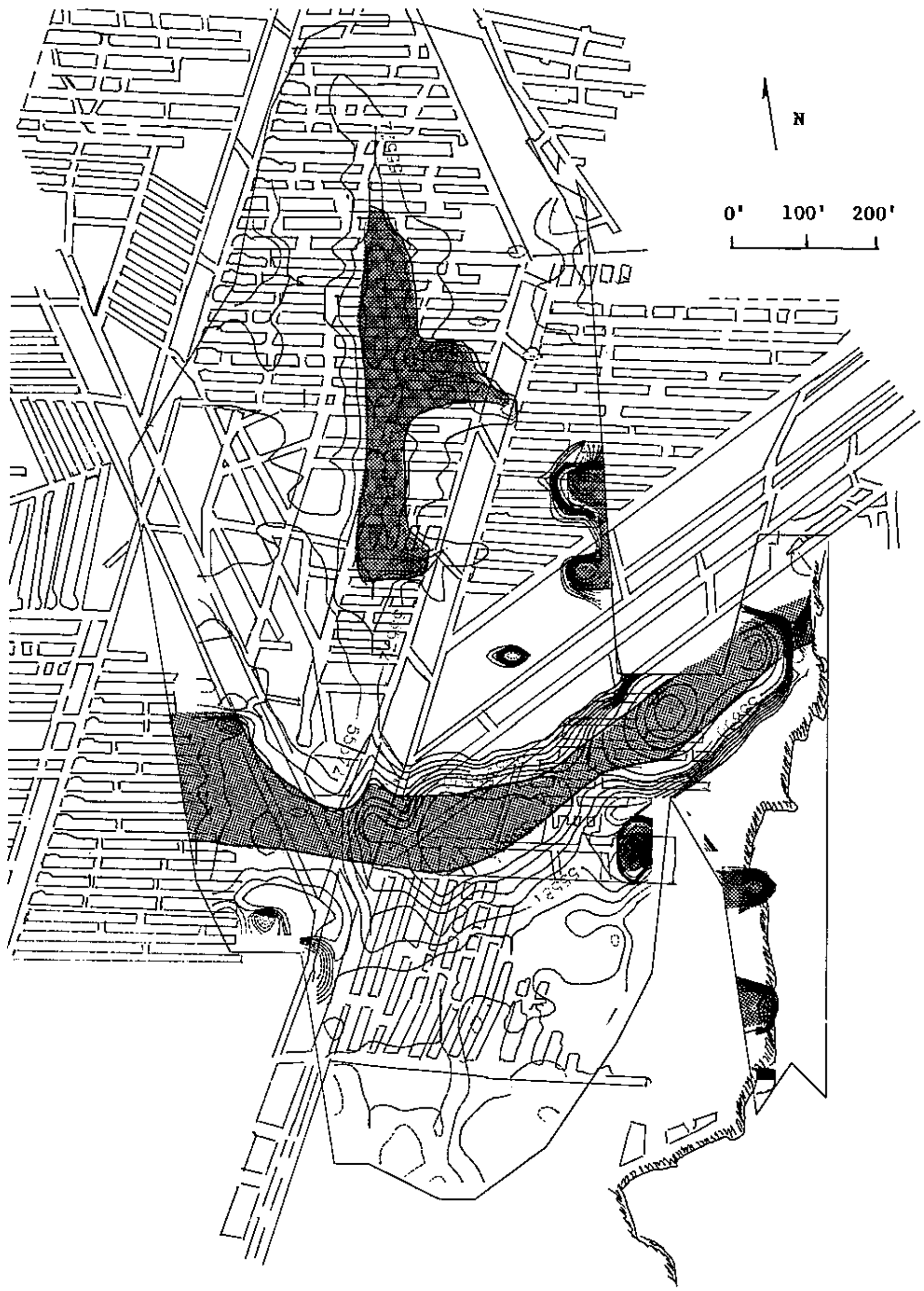

FIGURE 1. DMF1 POSITIVE MAGNETIC ANOMALIES SUPERIMPOSED OVER DEEP MINE WORKINGS. SHADED AREAS SHOW AREAS INTERPRETED TO HAVE BURNED AND COOLED.

The magnetic surveying did not provide a clear definition of any fire zones. Heating to above the Curie temperature results in a loss of natural magnetism. Since sedimentary rocks contain at least traces of magnetic minerals, a local reduction in the total magnetic field in the vicinity of the mine fire would result. The magnetometer used for this study had a sensitivity of only + or - 1 gamma and no recording base station was available. It is possible that a more sensitive magnetometer along with a base station might have been successful in areas of low cover. However, other geophysical methods, especially electrical resistivity, are likely to be more successful in locating fire zones.

On the other hand, the progress of a mine fire might be successfully monitored with magnetics by repeatedly mapping the same area over time. Increases in magnetic intensity would indicate areas which are cooling. Decreases in magnetic intensity would indicate an increase in burning activity. However, any decreases in magnetic intensity are likely to be seen only in areas which were previously partially burned and cooled. These areas would have developed enough magnetic susceptibility that a later decrease would be detectable.

Twenty five acres of the area mapped in 1988 were resurveyed again in June, 1989. The differences between the two sets of readings were plotted and contoured, (Figure 2). Figure 2 outlines the area surveyed in 1988. The areas which have burned and cooled are shaded. Cross hatching shows where the magnetic intensity has increased (cooling zones) and where the magnetic intensity has decreased (increased burning activity). Noted changes in magnetic intensity were slight. This is consistent with the slow movement of many deep mine fires, considering that mapping efforts were only one year apart. However, when using this technique, care must be taken to reoccupy the same grid locations.

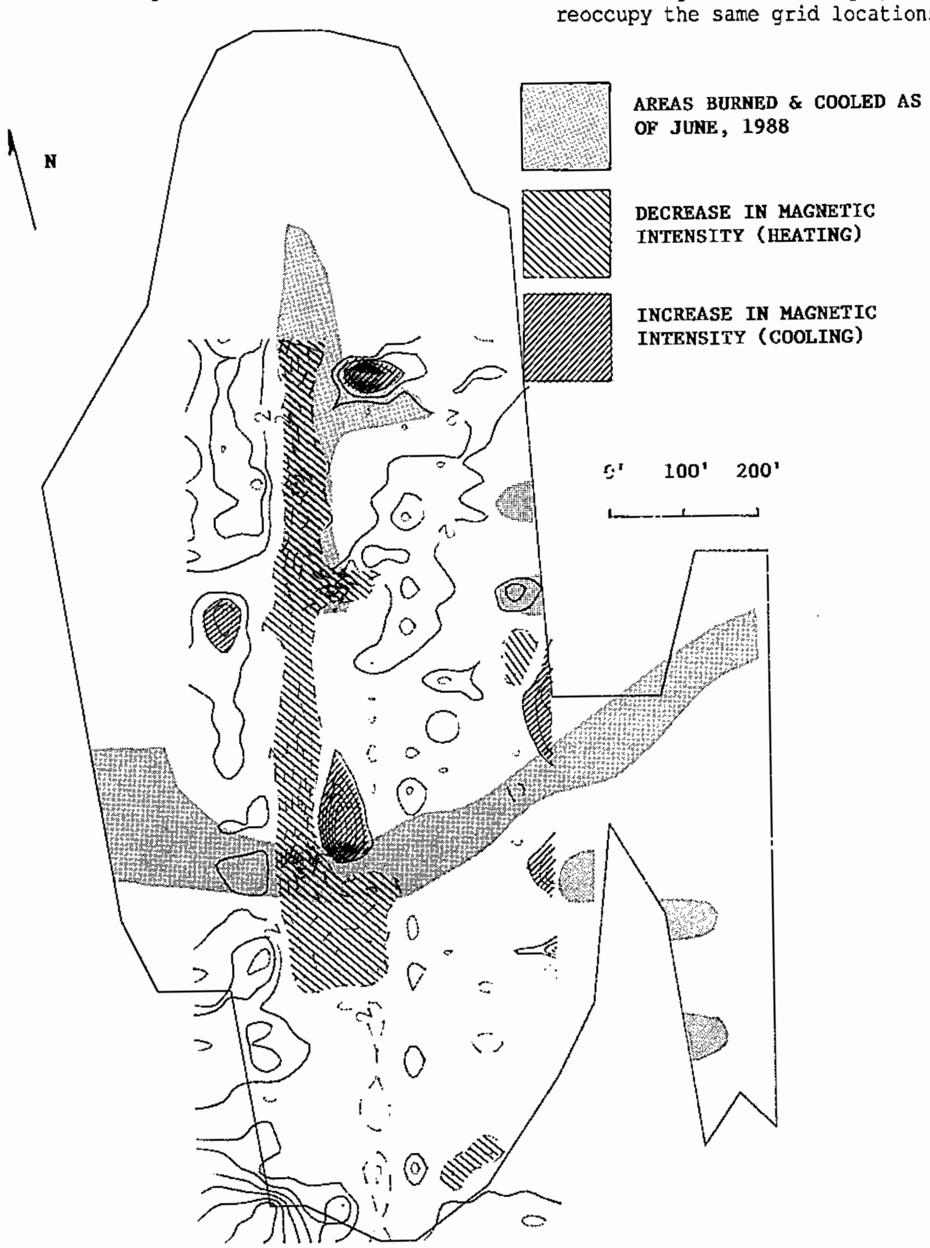

FIGURE 2. DMF1 CHANGES IN MAGNETIC INTENSITY BETWEEN JUNE, 1988 & JUNE, 1989

A Burning Coal Refuse Bank

Combustion metamorphism of pyrite provides for magnetic mapping of burning refuse piles in the same way as is does for mapping deep mine fires. The primary difference is that combustion in an underground mine fire is limited to the deep mine and overlying or underlying strata. Combustion can occur anywhere within a refuse pile and determining the combustion depths becomes more difficult. Piles higher than 100 feet high are common.

There are also differences in the characteristics of fire propagation. Oxygen is more limited in a refuse pile than in a deep mine, thus burning occurs at a slower rate. Combustion zone temperatures may also be lower. This would ultimately limit the maximum magnetic susceptibilities realized. In a refuse bank the tendency is for the fire zone to be contiguous with the burned zone. Fire in an underground mine can break out anywhere conditions are right.

A five acre refuse bank, designated SWRB1, was mapped in Fayette County using magnetics during May, 1988. This pile occupies the south side and the head of a hollow and is about 160 feet high. Patches of ash, termed red dog, are visible on the outslopes. Venting vapors and noxious fumes were visible in one area along the side of the hollow during the mapping.

The purpose of the mapping was to determine the ability of the magnetometer to locate zones which had burned and cooled. The premise was, that any active combustion zones would be adjacent to these areas. The refuse bank was crossed by an overhead high voltage line which interfered with readings in the center of the study area. Thus, the pile was surveyed in two segments. Readings were obtained along a ten by ten foot grid on this site. Neither a recording base station nor an additional sensor were available for this mapping.

The positive anomalies resulting from the magnetic surveying of the western portion of the bank are shown in Figure 3. Maximum field intensities recorded were 260 gammas above background. The positive magnetic anomaly in the lower left portion is the one of primary interest. This is the area which was venting during the investigation.

Theoretically, the portion of the combustion zone which had burned and cooled would be beneath the positive anomaly although its size would be slightly smaller. Any active combustion should be along the perimeter of this anomaly. A drilling project which occurred nine months before the mapping shows this to be the case.

The site was drilled in June, 1987, under the direction of the Pennsylvania Department of Environmental Resources Bureau of Abandoned Mine Reclamation. Drill hole locations are shown in Figure 3 with an *. Temperatures were recorded in degrees Fahrenheit for each hole. Maximum temperatures recorded for each hole are plotted next to the drill hole location. Note that the highest recorded temperatures are along the perimeter of the magnetic anomaly, especially to the east and west. Temperatures toward the center and beyond the perimeter of the anomaly are substantially lower.

Additional supporting evidence is the relative amounts of ash, or red dog, encountered. The drill holes located within the positive anomaly penetrated intervals where red dog was the predominant material. Drill holes along and beyond the perimeter only encountered traces of red dog. Thus the positive magnetic anomaly is located above the area of the most complete combustion.

There has been no attempt to determine the depths of the burned zones through magnetic modeling. A second sensor should be added and the

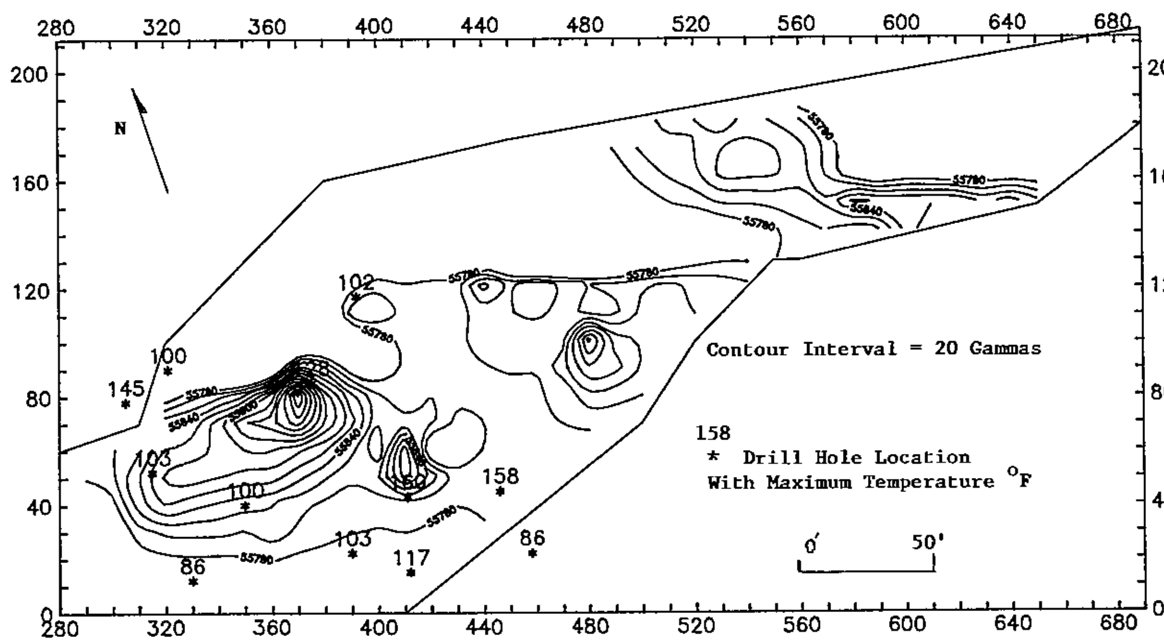

FIGURE 3. POSITIVE MAGNETIC ANOMALIES RECORDED AT SWRB1.

magnetometer used as a gradiometer for confidence in modeling at this type of site. A recording base station would also be helpful.

Acid Mine Drainage Production Site

A 37 acre reclaimed strip mine in north central Pennsylvania was mapped in April, 1989, using a combination of magnetic surveying and electromagnetic terrain conductivity. The main portion of the site lies to the north and consists of about 29 acres of reclaimed spoil. A southern and an eastern lobe area are also present, each about four acres in size. Acid mine drainage from this site has destroyed five miles of trout stream. The purpose of the mapping was to locate AMD production source areas and to define the resultant pollutional plume. The ultimate goal for this site is to design and implement an AMD abatement plan.

The mining at this site, designated as NCPA1, was completed in 1977. The site exhibited rather uniform overburden thickness and composition, according to the drill logs and persons familiar with the site. The Lower Kittanning coal seam was present in two splits separated by 10' of clay. Only the upper split was mined which left behind a thick underclay as a pavement. Based on drill logs and discharge locations, the pavement dips SSE. The coal was overlain by 17' of black shale capped by a sandstone unit. This is a mountain top site and the only source of groundwater is infiltrating precipitation.

Two areas of perennial seepage occur. These are located to the south of the southern and eastern lobes. The average quality of the discharges is as follows: pH 2.5, acidity 3260 mg/l, iron 330 mg/l, aluminum 350 mg/l, and sulfates 3750 mg/l.

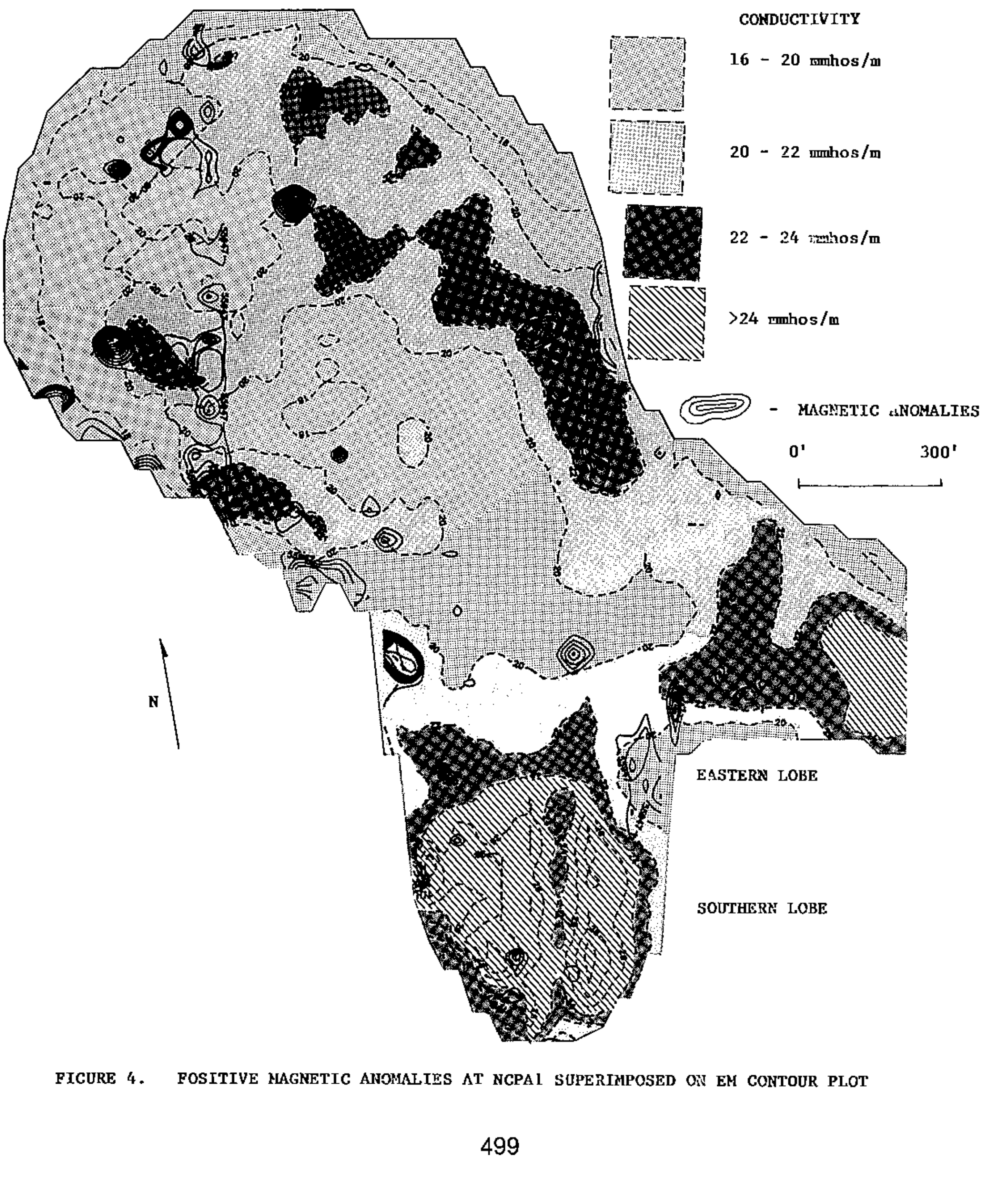

FIGURE 4. POSITIVE MAGNETIC ANOMALIES AT NCPA1 SUPERIMPOSED ON EM CONTOUR PLOT

A 25 by 25 foot grid was set up across the site. Readings were taken at each grid point during both the magnetic and EM surveys. Personnel from the US Bureau of Mines helped with the mapping.

After correction for diurnal variation, the magnetic data was plotted and contoured. Twenty magnetic anomalies were located during the magnetometer survey over the 37 acre site. The magnetic anomalies were superimposed on the terrain conductivity mapping and are presented in Figure 4. Most of the magnetic anomalies were small, indicating piles of pyritic material less than 50 feet across.

The maximum recorded field intensities of the anomalies fell into two distinct ranges, suggesting two different material types. A third of the anomalies were quite obvious even during the field mapping. Their maximum amplitudes ranged from 60 to 130 gammas above background and steep gradients indicated shallow burial. Most of these were located in the northwestern portion of the mine site which had been stripped before 1966. The rest of the anomalies were subtle with maximum intensities of only 5 to 20 gammas above background. Flat gradients indicated deeper burial. Most of these were located in the eastern and southern portions of the mine site which had been mined in the late 1970's (Figure 4).

A test pit excavated by a backhoe into one of the anomalies of low magnetic intensity (20 gammas above background) found pit cleanings to be the source of the altered pyritic material. The other anomalies (60 to 180 gammas above background) most likely result from tipple refuse. One person familiar with the mining during the 1970's indicated several truckloads of refuse from a nearby tipple were buried in the northwestern portion of the mine. His recollection of the dumping locations coincided with the mapped locations of the anomalies. Also, the source tipple for the refuse used magnetite in the separation process. Magnetite lost to the refuse would account for the higher magnetic intensities of these anomalies. A drilling program is planned for April, 1990. The drilling will be used to define the composition of all the anomalies and to install monitoring wells in the northern portion of the site.

Several of these anomalies were mapped on a 5 by 10 or a 10 by 10 foot grid with the magnetometer being used as a gradiometer. Using the magnetometer in the gradiometer mode and the closer grid spacing provides much greater detail about the target material. Using this information and the modeling program, reliable estimates as to the depth of burial and the lateral extent of the piles can be made.

The terrain conductivity data was obtained at the same grid locations as the magnetometry data. The conductivity values were contoured so the two surveys could be compared. This site was originally mapped by Ken Ladwig of the US Bureau of Mines in 1982, as part of a joint effort with Woodward-Clyde Consultants(Ladwig 1982). The results of the 1989 mapping compared favorably with Ladwig's results.

The terrain conductivity readings were fairly uniform across the northern portion of the site with a gradual increase toward the ESE, or down-dip direction. High conductivity readings were recorded in both the eastern and southern lobes.

The site was drilled shortly after Ladwig's mapping effort. The high conductivity zones in the two lobes are attributable to impounded water above the pavement. Intact monitoring wells in the two lobes indicate that this condition continues to exist. Virtually no pooled water above the pavement was found in the northern portion of the mine (Ladwig 1982).

Note in Figure 4 that, in almost every case, a magnetic anomaly (pyritic material) is adjacent to a conductivity high. The relationship between the terrain conductivity and the magnetic anomalies is a strong indication that the buried piles of pyritic material are prime sources of AMD formation. AMD is generated when infiltrating precipitation comes into contact with the oxidation products of pyrite. AMD, an excellent electrolyte, exiting the pile is the reason for the conductivity high in the immediate vicinity of the pile. After the water exits the pile, it spreads and is diluted. The recorded conductivities decrease. Overall, conductivity values increase downgradient as the water exiting several piles gradually merge, ultimately exiting as polluted toe-of-spoil discharges from the two lobes.

Summary and Conclusions

A proton processing magnetometer was used in an attempt to delineate fires and burnt areas within an underground coal mine and a coal refuse bank. The very small negative magnetic anomalies associated with fires makes detection of fire areas difficult. However, areas that have burnt and cooled create significant positive magnetic anomalies due to increased magnetic susceptibility. Magnetic surveying can readily detect and delineate these areas even at significant depths. The magnetometer also offers promise as a means of determining the progression of a mine fire. This is done by repeatedly mapping an area and determining the changes in magnetic intensity through time.

The magnetometer along with terrain conductivity has been used on a surface mine that is producing severe AMD pollution. Several positive magnetic anomalies were recorded. These were interpreted to be areas of concentrated pyrite oxidation products (altered to magnetic minerals). These anomalies were interpreted to be buried piles of tipple refuse or pit cleanings. Areas of high terrain conductivity were mapped adjacent to these piles. High EM conductivity on this site results from elevated dissolved solids in the groundwater due to AMD production. Thus, EM and magnetometry can be used together to identify sources of AMD production. This allows for potential remedial efforts to ameliorate the pollution problem.

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