MAPPING BURIED TIPPLE REFUSE - IS THE MAGNETOMETER BETTER THAN TERRAIN CONDUCTIVITY?[1]

Joseph H. Schueck, P.E.[2]

Abstract.--It is occasionally desirable to detect and map tipple refuse buried beneath strip mines. Reasons include: acid mine drainage (AMD) treatment and/or abatement, and economic recovery for reprocessing. Until now terrain conductivity (EM) has been the most efficient, cost effective method of mapping refuse. However, it is difficult to delineate between refuse and other features such as AMD using EM. Remanent magnetism, a property somewhat 'unique' to refuse in the strip mine environment allows refuse to be mapped independently of other features using a magnetometer. Two sites were mapped using both EM and the magnetometer. Refuse disposal completely filled large pits at the first site but was limited to widely scattered, small pods at the second. When the proper grid density was used, the EM was able to define general disposal areas but was unable to pinpoint refuse locations, especially on the site where the refuse was in scattered pods. The EM was unable to discriminate between the refuse and AMD. On the other hand, the magnetometer was able to clearly define the refuse limits on both sites without interference from the AMD. Acquisition of data is seven times faster with the magnetometer and the magnetometer data provides much better quantitative information about the refuse than does the EM data.

INTRODUCTION

Many advances have been made in recent years toward preventing, mitigating, abating, and treating acid mine drainage. Research efforts have concentrated on the source of the acid mine drainage as well as the discharge. Buried tipple refuse is a source of many acid mine drainage discharges. However, treatment at or elimination of the source cannot be accomplished until the refuse has been delineated. Additionally, refuse from certain older plants may be rich enough to be reprocessed, provided it can be found and mapped efficiently. This paper discusses a rapid and efficient method to accurately map buried tipple refuse.

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[2]Joseph H. Schueck, P.E., is a Hydrogeologist, Pennsylvania Department of Environmental Resources, Bureau of Mining and Reclamation, Harrisburg, Pa.

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Tipple refuse is commonly disposed of at both active and abandoned strip mines. Pits may be completely filled with refuse at abandoned sites, and the refuse 'pods' or buried piles may be quite large. At active sites burial locations are dictated by the location of the working pit. Widely scattered pods of limited aerial extent commonly result. Following reclamation, there is little evidence to indicate the locations of the buried refuse. Producing accurate maps of these locations has been difficult until now.

Subsurface features on strip mines have been successfully mapped in recent years using geophysical techniques such as DC electrical resistivity and electromagnetic terrain conductivity (EM). Refuse usually responds well to both methods if it is an electrical conductor. However, features such as subsurface accumulations of acid mine drainage also conduct electricity well and may produce anomalies similar to refuse. This property makes delineation of refuse difficult using either method.

Another property of at least some refuse, magnetism, allows the refuse to be detected with a magnetometer. Magnetometer operation requires only one person. It will be shown that buried refuse can be mapped in greater detail and several times faster with a magnetometer than with EM or DC resistivity.

Two sites, referred to as SW1 and NW1, were mapped during this study. Tipple refuse was buried in abandoned strip mine pits at SW1. The resultant pods of refuse were up to 700 ft long. Refuse was buried in scattered pods controlled by the location of active pits on NW1. The majority of these pods probably are no larger than one or two truckloads of refuse. Magnetic detection of the buried refuse at both sites was quite successful.

PRINCIPLES OF MAGNETISM

The earth's magnetic field resembles the field of a large bar magnet near its center. Flux lines of the earth's field exhibit a pattern like that of a bar magnet, figure 1. The field intensity is a function of the flux line density. Similar to a bar magnet, the density is twice as large in the polar regions as in the equatorial regions, or approximately 60,000 and 30,000 gammas respectively. The total field is approximately 55,500 gammas in Pennsylvania. By convention in the geophysical community, gauss is the cgs unit of magnetic intensity and 1 gamma=10^{-5} gauss. The earth's total magnetic field intensity is measured using a magnetometer (Breiner 1973). Most commercially-available magnetometers measure the magnitude of the total field intensity. Older, "fluxgate"-type, magnetometers are sometimes seen. These measure components of the total field intensity vector.

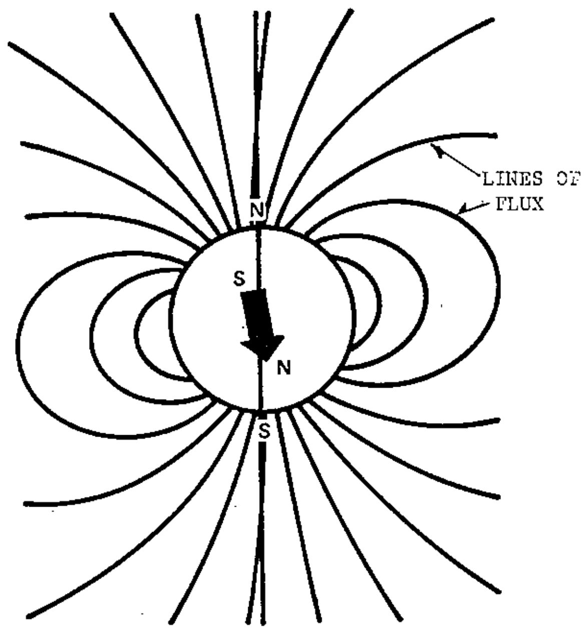


Figure 1. The earth's magnetic field resembles the field of a large bar magnet. The flux line density is greater at the polar regions than at the equator (Breiner 1973).

An anomaly represents a local disturbance in the earth's magnetic field due to a local change in magnetization. Magnetic minerals and iron have properties which cause these anomalies. Natural anomalies are due chiefly to the presence of magnetite ($FeFe_2O_4$), or its related mineral suite: ulvospinel, maghemite, etc. All rocks contain some magnetite from a very small fraction of a percent up to several percent. Iron objects produce strong, local magnetic anomalies (Breiner 1973).

Magnetic anomalies are caused by two different kinds of magnetism: induced and remanent or "permanent" magnetization. Induced magnetization refers to the effect on a material placed in an external magnetic field in which the field within the material is enhanced, so that the material itself acts as a magnet. Induced magnetization is always parallel to the inducing field (usually the earth's), and would vanish if this inducing field were removed. The magnetization of such material is directly proportional to the intensity of the ambient field and to the ability of the material to enhance the local field. This property is called magnetic susceptibility. The induced magnetization is equal to $I_i=kF$, where I_i is the induced magnetization per unit volume in cgs electromagnetic units, k is the volume magnetic susceptibility, and F is the field intensity in gauss. k is usually between 10^{-6} and 10^{-3} cgs or for most rocks. For pure magnetite, k is approximately 0.3 cgs. k may vary between 1 and 10^6 for iron alloys(Breiner 1973).

Materials cooling from high temperatures may attain a remanent magnetization. This remanent magnetization, once gained, is independent of external fields..it need not be parallel to the external field and will remain even if the external field is removed. Remanent magnetization, I_r, is often ten or more times greater than induced magnetization in many igneous rocks and iron alloys. Permanent magnetization depends upon the metallurgical properties and the mechanical, thermal, and magnetic history of the specimen. Prior to heating, small regions, called domains, within each magnetite crystal are randomly oriented. The domains reorient themselves during heating. Upon cooling, they align parallel to each other in the direction of the ambient magnetic field. This creates a net magnetization fixed with respect to orientation of the object. Magnetite may have a remanent magnetization, I_r, of perhaps 0.1 to 1.0 gauss (10^4 to 10^5 gammas). Ordinary iron may have a permanent magnetization between 1 and 10 gauss (10^5 and 10^6 gammas). Thus the net magnetization might be considerably higher and oriented in a different direction than would be indicated merely by consideration of the susceptibilities (Breiner 1973).

SOURCES OF MAGNETISM IN TIPPLE REFUSE

Samples of refuse and spoil material from both sites were analyzed to determine the magnetic components unique to the refuse. The samples were obtained by air rotary drilling. A magnetic separator, known as a ferrofilter, was used to remove the magnetic portion of the sample. In all cases the magnetic portion of the sample amounted to only a small fraction of a percent. Two magnetic materials were identified: magnetite crystals ($FeFe_2O_4$), and reddish grains and black glassy B.B.'s that appear to be combustion products containing magnetite or maghemite (Fe_2O_3) unintentionally synthesized during combustion (Smith 1987). These particles commonly exhibited a 'slag'-like appearance and were often fused with quartz crystals. The portions of the samples which had undergone combustion were so minute that they were not detected in an unfiltered sample using a hand lens. Maghemite forms by slow oxidation at low temperatures from magnetite or from the slow thermal dehydration of lepidocrocite (FeO(OH)) below temperatures of 750°. The magnetic properties of maghemite are similar to those of magnetite (Palache, et. al 1944). Company officials from both source tipples indicated that the source plants used magnetite in the coal separation process at the time the refuse was buried on the subject sites.

An increase in the net magnetism caused by the combustion or heating and dehydration of the refuse appears to be a significant factor in the magnetometer's ability to detect refuse. Microscopic examination of several samples indicates that magnetite is common at SW1 where refuse was buried in large pods. Combustion products are also present but are uncommon. By contrast, at NW1, combustion products are common and magnetite crystals are rare. The recorded intensities per unit mass of refuse were much higher at NW1 where the combustion products are predominant than they were at SW1 where magnetite is predominant.

MAGNETIC ANOMALY CHARACTERISTICS

Magnetic anomalies are highly variable in shape and amplitude; they are almost always asymmetrical, sometimes appear complex even from simple sources, and usually portray the combined magnetic effects of several sources. An anomaly's shape or signature depends upon the inclination of the field, and several properties of the source: burial depth, size and shape of the source, the relative amounts of permanent and induced magnetization, the direction of the former, and the amount of magnetic material present in the source compared to the adjacent rocks (Breiner 1973).

The dip or inclination of the earth's field establishes the direction in which the components are measured for any local magnetic anomalies using a total field magnetometer. The magnetometer only measures the component of a local disturbance in the direction of the earth's field at the point of measurement, figure 2. Other factors being equal, the same source will produce three different anomaly signatures if measured at the equator, in Pennsylvania, and near the north pole.

The variation of intensity as measured by the magnetometer diminishes as the source-to-sensor distance increases. Depending on the shape of the source body, this fall-off factor usually goes as $1/r^3$ to $1/r^2$, where r is the distance between the source and the sensor. For this reason, anomalies will be larger in aerial extent than the actual source of the anomaly, figure 3.

The depth to and configuration of the source determines the anomaly wavelength; the deeper and larger the source, the broader the anomaly. Sources close to the ground surface exhibit a steep gradient between the negative and positive portions of the anomaly. Deeper sources exhibit a much flatter gradient. Figure 4 shows two anomalies which were mapped. The depth to the source on the left is about 12.5 ft compared to a 50 ft burial depth on the right.

The negative part of an anomaly is called its "polarity low". At the latitude of Pennsylvania, a body whose

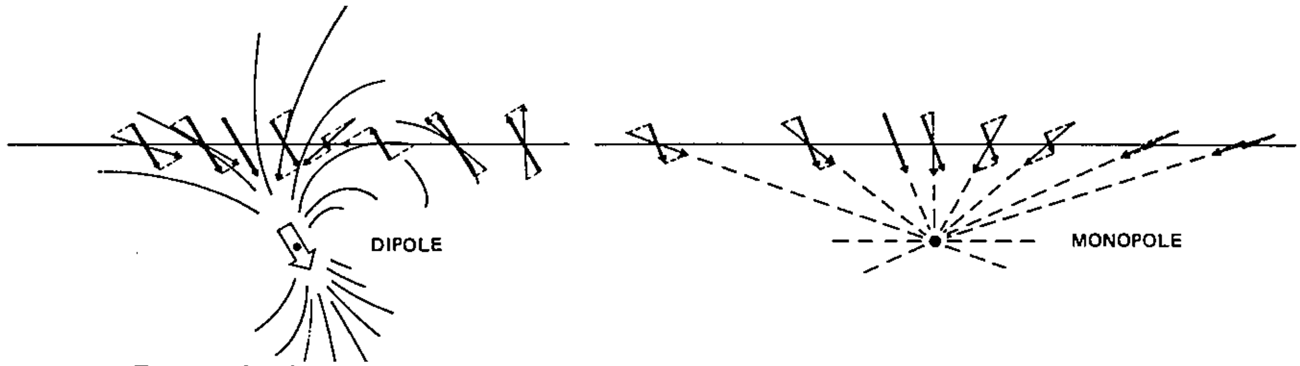


Figure 2. The portable proton magnetometer only measures the component of a local disturbance in the direction of the earth's field at the point of measurement (Breiner 1973).

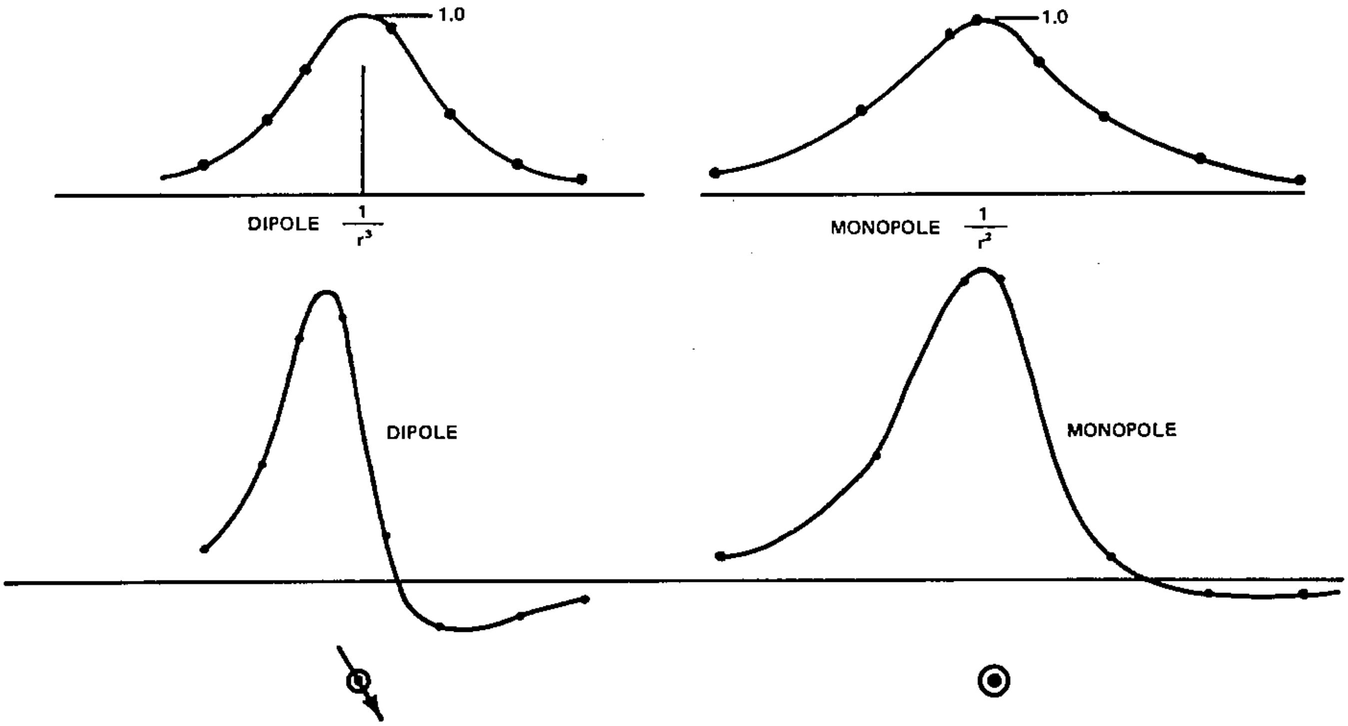


Figure 3. The variation of intensity as measured by the magnetometer diminishes as the source-to-sensor distance increases. The fall-off factor usually goes as $1/r^3$ for dipoles to $1/r^2$ for monopoles. Resultant anomaly signatures are shown at the bottom of the figure for dipoles, left, and monopoles, right (Breiner 1973).

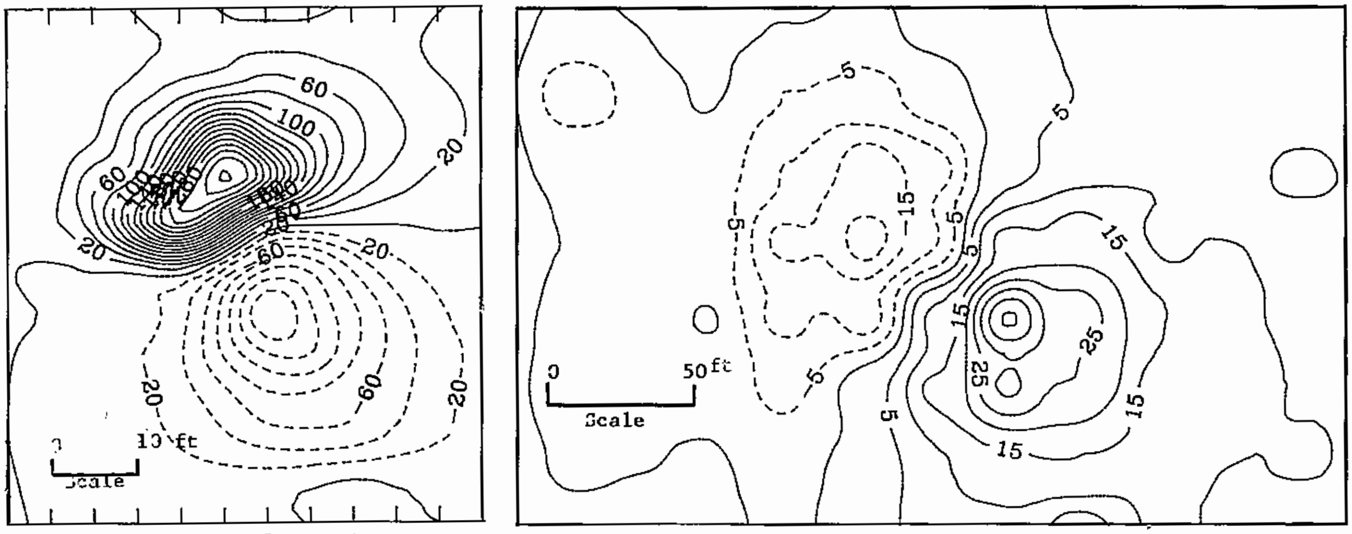
magnetization is mostly induced will usually have a small polarity low to the magnetic north, with the maximum part of its high over the southern part of the body. A body with very strong remanent magnetization, by contrast, will have an adjacent polarity low in some direction other than north. If such a pattern is seen on a magnetic map, it usually indicates sources with strong remanence.

Maximum anomaly amplitude depends upon several factors. These include depth, the contrast in the mass of magnetic material to the surrounding material, and the shape and configuration of the source. Small, compact sources will appear as a dipole, i.e. the anomaly signature will show both an anomaly high and a polarity low. If the source is narrow, broad, or long in one dimension, the anomaly may appear as a monopole, i.e. only a positive portion may be recorded or the polarity low may appear beyond one of the ends.

FIELD PROCEDURES

A portable proton magnetometer was used at both sites. This instrument measures total field intensity only. It has a sensitivity of + or - 1 gamma over a range from 20,000 to 90,000 gammas and a gradient tolerance which exceeds 800 gammas/ft. The instrument consists of a sensor mounted on a 8-ft long staff connected to a power pack and digital readout display (Geometrics).

A grid network along with a base station or baseline should be established over the site before readings are taken. Grid spacing depends on the anticipated



—— Anomaly High
---- Polarity Low
Contour Interval = 20 Gammas

—— Anomaly High
---- Polarity Low
Contour Interval = 5 Gammas

Figure 4. The depth to and configuration of the source body controls the anomaly signature. The deeper and larger the source body, the broader the anomaly. Shallow sources exhibit a steep gradient between the anomaly high and the polarity low; deep sources produce a flat gradient. The depth to the source body on the left is 12.5 ft compared to a 50 ft burial depth on the right. Note scale and contour interval differences.

target size. Readings are taken along the grid intersections with frequent measurements made at the base station or along the base line.

Magnetometer operation is quite simple. The staff with the sensor mounted on top is placed on the ground at the point where the reading is to be taken and is held still. A read button is pushed. Seconds later a digital readout appears which is recorded. The sequence is repeated at each grid intersection. Data acquisition is quite rapid. However, a few precautions must be taken in order to insure meaningful data.

Quality control is a key to obtaining reliable field data. A proper grid density must be selected, natural variations in the earth's field intensity must be tracked, and local magnetic anomalies not associated with the target must be located and noted.

The aerial extent of the refuse dictates the maximum grid spacing or station density which may be used. Large pods on the order of tens or hundreds of feet can be adequately mapped on a 25 by 50 ft grid. Truck load sized pods of refuse can be located with a 25 by 25 ft grid; however, reasonable definition of the refuse requires returning to the target area and taking additional readings on a tighter grid.

Recording variations in the earth's total field with time and removing these variations from the field data are crucial to quality data. Magnetic storms and micropulsations due to solar winds acting on the ionosphere cause variations of 10's to 100's of gammas. These variations are not predictable. They may occur over a short period of 10's of minutes and be quite irregular or they may occur slowly over a period of a day (Breiner 1973). A recording base station magnetometer on or near the site can record these variations while field readings are being taken elsewhere. The base station readings are then used to correct the field readings. Otherwise it is necessary to establish a base station or base line and return to the station frequently, usually after every traverse, to record the variations. Figure 5 shows a variation of nearly 35 gammas which occurred at the base station on SW1 over an 8-hour time span. Daily variations such as this were common at both sites.

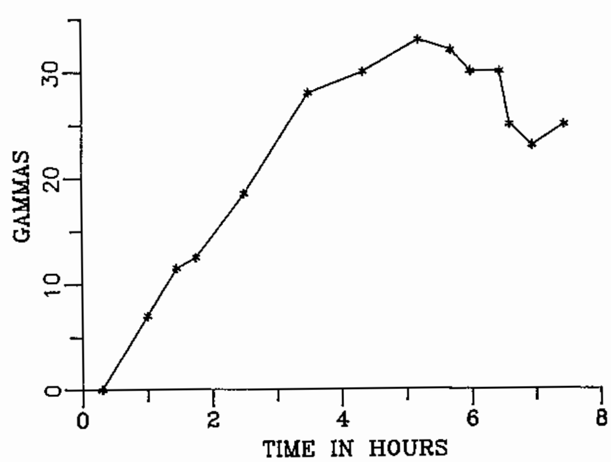


Figure 5. Normal Daily Magnetic Fluctuations

Scrap metal and other iron objects lying on the surface must be removed to an area beyond their influence on the readings. Locations of metal objects which cannot be removed from the area, such as well casings, should be noted and their influence taken into consideration during the interpretation. Examples of such interferences follow. At NW1 small plastic flags on wires were used to mark grid locations. Readings obtained adjacent to these flags resulted in 10 to 15 gamma anomalies. A metal well casing and a galvanized garbage can produced 225 and 170 gamma anomalies, respectively, with the magnetometer adjacent to the metal. The anomalous reading diminished to 0 at about 20 ft in both cases. A drag line cable buried just beneath the surface caused a 10,000 gamma anomaly on another site.

FIELD STUDY AT SW1 SITE

Site Description

SW1 is a 43 acre reclaimed refuse disposal site in Somerset County, Pa. Once an active strip mine, the original operator abandoned the site after coal removal, leaving behind several unreclaimed pits and spoil piles. The pits were as deep as 60 ft and several were longer than 500 ft. Pit width varied from 50 to 200 ft. Some pits had vertical unreclaimed highwalls while others had sideslopes of spoil.

All major pits on the site were later permitted for tipple refuse disposal. Inspection reports and subsequent drill holes indicate that the operator completely filled the pits with refuse. The site was then regraded and reclaimed by this operator, leaving no surficial evidence of the buried refuse locations.

Conductivity Field Work

The southern half of SW1 was mapped in 1986 using electromagnetic terrain conductivity. The purpose was to determine the refuse limits so that monitoring wells could be strategically located. The area was mapped on a 50 by 50 ft grid and a total of 191 readings were made. A 10-m intercoil spacing with a horizontal coplanar dipole configuration was used. It was known that burial of the refuse extended to near the surface. This configuration has an effective exploration depth of 7.5 m and is more responsive to the near surface material (McNeill 1980).

Conductivity Survey Results and Interpretation

A contour map of the EM data is shown in figure 6. Delineation of the refuse from the EM data was difficult for two reasons. First, the conductivity values ranged from a low of 5.5 to a high of 17.5 mmhos/m. Conductivity measurements over refuse are commonly in the 20 to 40 mmhos/m range on many sites, especially considering the thickness and extent of the refuse here(Ladwig 1982). Second, a rapid increase in the conductivity contour gradient was not observed, making boundary determinations difficult. This suggests a gradual thickening of the refuse, as is the case. The contours did steepen slightly beyond 8.5 mmhos/m, and it was decided that values greater than this probably indicated refuse.

Highs on the EM contour map correspond fairly well with outlines of the pits scaled from aerial photos taken prior to refuse disposal. These boundaries compare well with the pit limits indicated on the permit maps. The maximum conductivity values generally coincide with or lie just to the north of

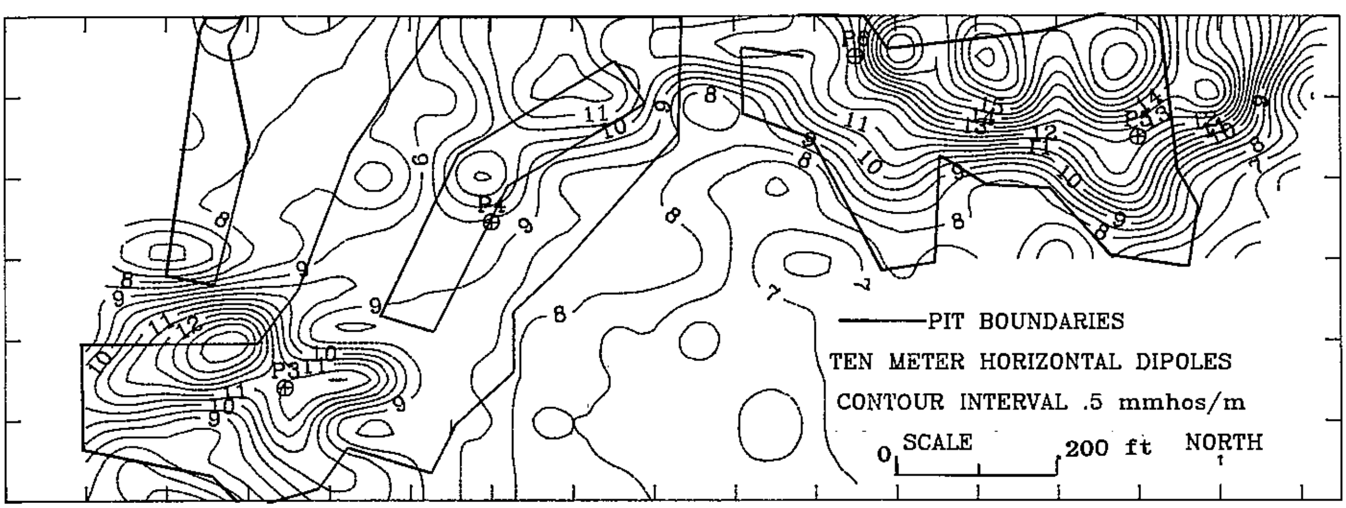


Figure 6. Electromagnetic Terrain Conductivity contour map resulting from the survey conducted on the southern half of the SW1 coal refuse disposal site. A 10-m horizontal dipole coplanar configuration was used. Refuse was disposed of within the pit boundaries which are indicated. Note the absence of rapid contour steepening and conductivity highs beyond the pit boundaries.

the deepest portions of the pits. Four monitoring wells were subsequently drilled within areas interpreted to be refuse. Refuse depths and thicknesses as indicated in the four wells correlate well with the conductivity data.

There are high conductivity values in two areas where very little refuse, if any, is thought to exist. The first is to the north of the pit in the southwestern corner. This area is on the nose of a steep pre-disposal spoil pile. The amount of refuse in this location should be minimal. The second area is to the east of the pit in the northeastern portion of the study area. Aerial photos indicate pre-disposal spoil piles in this area also. It is unlikely the operator excavated into the spoil to dispose of refuse. These values may indicate areas of AMD, however.

A maximum conductivity value of 12 mmhos/m is observed in the vicinity of well P4. This long narrow pit is filled with refuse to a total depth of 60 ft. By comparison, the maximum value observed over the pit to the east containing wells P6 and P5 is 17.5 mmhos/m. The thickness of the refuse in this pit is also 60 ft. The low value of 12 mmhos/m is misleading, but this may be a function of the pit geometry.

Magnetometer Field Work

SW1 was remapped in June 1987 using a portable proton magnetometer borrowed from the Pa. Geologic and Topographic Survey. The limits of the study were extended northward to cover the entire 43 acres. Readings were initially taken on a 50 by 25 ft grid. Some areas were remapped on a 25 by 25 ft grid for better resolution.

Magnetometer Survey Results and Interpretation

The magnetic anomaly map for SW1 is presented in figure 7. The positive anomalies are shown as solid lines. Dashed lines indicate the polarity lows. The pit boundaries are also indicated as in figure 6. Two basic anomaly signatures are repeated: 1) relatively flat gradient, maximum 40 gamma anomalies over the long pits to the northwest, and 2)relatively strong positive anomalies with steep gradients and maximum values of about 200 gammas over the pits in the southwestern and eastern portions of the figure. Keep in mind that the refuse pods in this figure are somewhat smaller than the area of the anomalies they cause. Considering this, the positive magnetic anomalies correlate quite well with the pit locations despite the different anomaly signatures that are present.

The anomalies over the northwestern pits are consistent with the signatures expected over long, narrow dike-like structures. The anomaly signature is like that of a line of monopoles, i.e. there is no distinct polarity low associated with the anomaly. Because the magnetometer measures the net magnetization of the mass within the radius of influence, the maximum amplitudes over long, narrow structures will be less than that observed over wider structures of similar total depth.

The anomaly signatures over the remaining pits are also consistent with those expected for wide, thick source bodies buried at a shallow depth. The prominent polarity lows to the north of these highs suggest their net magnetization is aligned with the earth's field, and so may be dominantly of the induced kind. The magnetic components of the source bodies here are therefore inferred to consist largely of magnetite rather than combustion products. It is further inferred that the magnetite's domains of permanent magnetization were randomized when the refuse was dumped in the pits. The high amplitude of the anomaly implies a relatively higher concentration of magnetic materials in these pits than in those to the northwest.

The southeastern pit in figure 7 is presented in figure 8 to illustrate how the observed values correspond to thickness of the source body. Lines indicating the pit boundary, pit bottom, and spoil pile intersections are included. Coal pavement was exposed in the western portion of the pit prior to filling with refuse. A vertical highwall of bedrock formed the western pit boundary. The eastern portion of the pit was formed by spoil piles at their angle of repose joining near the center of the pit. The haul road into the pit was located in the extreme northwestern corner of the pit where no boundary line is shown. Refuse completely fills this pit to within a few feet of the surface. The refuse over the pavement in the western portion of the pit extends from near surface to a depth of 60 ft. The depth of refuse in the east-west trending portion of the pit with sloping sides formed from spoil approaches a maximum of 60 ft while the depth of refuse in the southeastern portion is less than 40 ft. The magnetic map, therefore, appears to reflect many of the geometric details of the original pit.

Comparison of EM and Magnetometer Results

Clearly the magnetometer has defined the refuse more accurately than the EM, both qualitatively and quantitatively. The two areas beyond the pits in figure 6 which could easily be

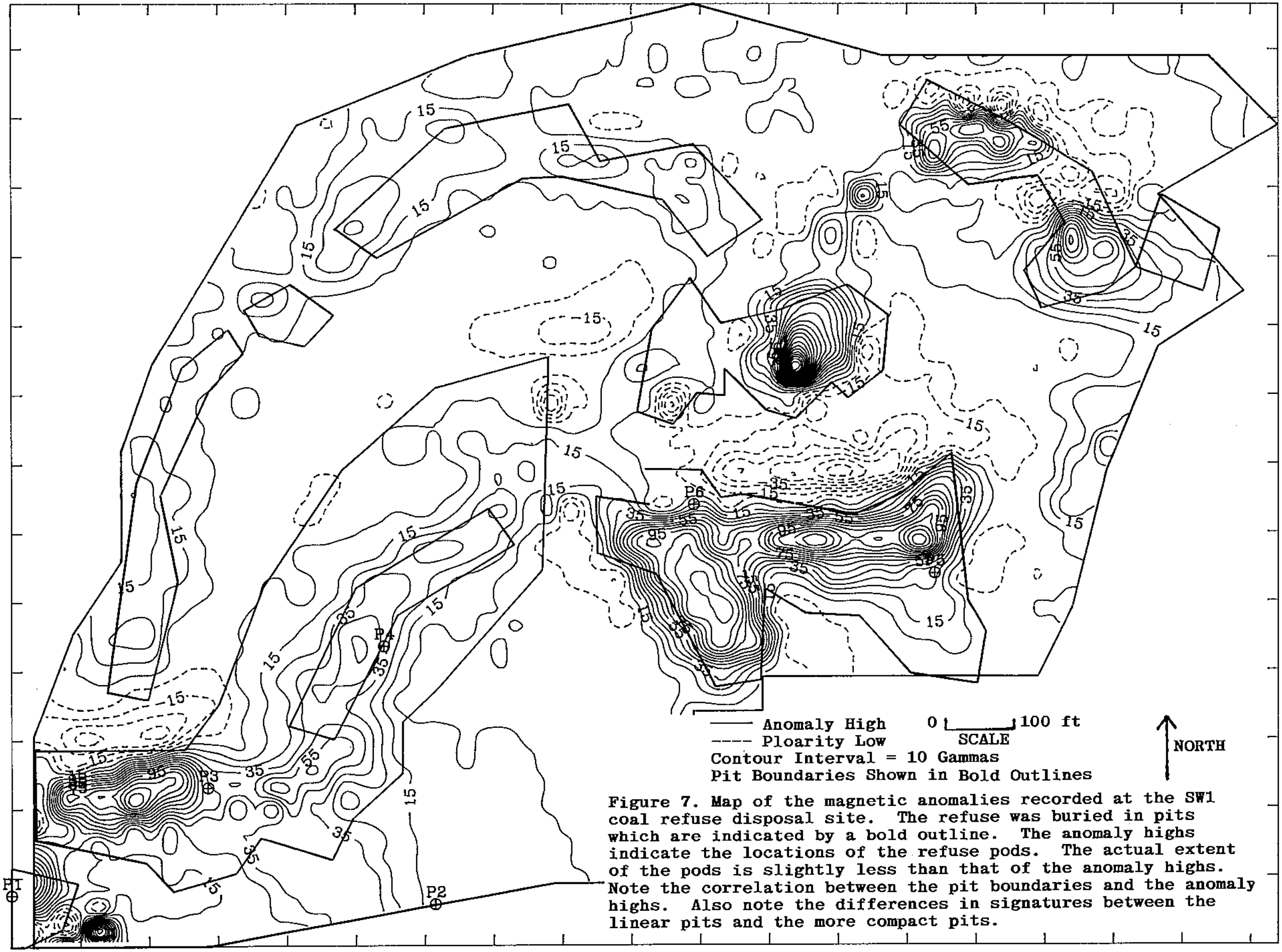


Figure 7. Map of the magnetic anomalies recorded at the SW1 coal refuse disposal site. The refuse was buried in pits which are indicated by a bold outline. The anomaly highs indicate the locations of the refuse pods. The actual extent of the pods is slightly less than that of the anomaly highs. Note the correlation between the pit boundaries and the anomaly highs. Also note the differences in signatures between the linear pits and the more compact pits.

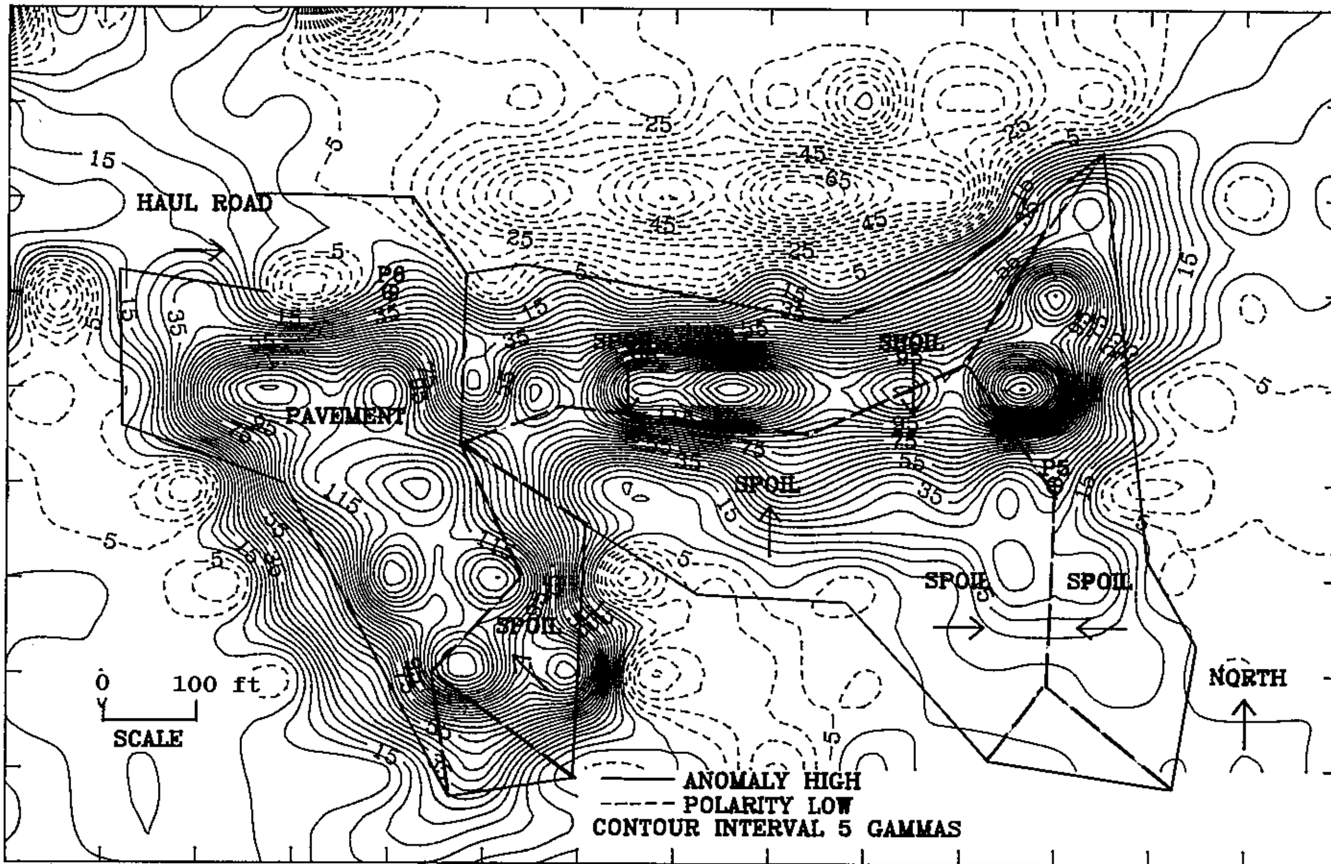


Figure 8. A enlargement of the pit located in the southeastern portion of SW1, figure 7, showing the correspondence between the magnetic contours and the pit geometry. The pit boundary is indicated by a solid bold line; the bottom of the pit is indicated by a bold dashed line. Prior to refuse disposal the coal pavement was exposed in the western portion of the pit and the western highwall was vertical. The central and eastern portions of the pit are formed by spoil piles joining in the center of the pit at the bottom.

interpreted as refuse using EM disappear when the magnetometer is used. EM could define the refuse more clearly had additional traverses been completed using different intercoil spacings and vertical as well as horizontal coplanar configurations. However, I was able to collect seven times as many data points with the magnetometer per man-hour of effort than with EM. Furthermore, one traverse is all that is needed with the magnetometer for quantitative interpretations, as opposed to two or four with EM. Thus, for good quantitative EM data it would be necessary to spend 28 man days in the field compared with one with the magnetometer. DC electrical resistivity profiling could have been used to provide electrical information similar to EM; note, however, that this technique is some three to six times more time consuming than EM (Ladwig 1982).

On the basis of theory, EM techniques must be expected to do poorly over magnetic targets. The apparent conductivity as measured by the electromagnetic terrain conductivity meter is defined as

$$\sigma_a = \frac{4}{w\mu_o s^2}\frac{H_s}{H_p}$$

where H_s = secondary magnetic field at the receiver coil
H_p = primary magnetic field at the receiver coil
$w = 2\pi f$
μ_o = permeability of free space
σ = ground conductivity (mho/m)
s = intercoil spacing (m)
f = frequency (Hz) (McNeill 1980)

The μ in this equation is usually taken as μ_o, the permeability of free space under the assumption of nonmagnetic targets. For a magnetic target, μ is higher than μ_o, so the conductivity the instrument measures comes out lower than the true apparent conductivity. The fact that the target is magnetic actually degrades the EM measurement.

The mapping effort on SW1 clearly demonstrates the effectiveness of mapping refuse buried in pods with singular dimensions in the tens to hundreds of feet. A second site NW1 was mapped to determine the effectiveness of the magnetometer in mapping refuse buried in much smaller, widely scattered pods.

FIELD STUDY AT NW1 SITE

Site Description

In contrast to SW1, refuse disposal operations at NW1 occurred while the site was actively being mined. NW1 is a 40-acre site in Clarion County, Pa. The extreme western portion of the site was mined by a previous operator with perhaps only one or two crop line cuts being taken. The remainder of 40acre site was mined in 1971 and 1972. Reclamation was completed in 1973 (Ladwig 1982). No particular portion of the site was dedicated to refuse disposal; rather the refuse was simply dumped into any working pit that happened to be open at that time. Consequently only one or two truckloads make up the entire refuse pod in most locations. A typical coal dump truck has a capacity of about 25 cu yd. The resultant pods or piles would be no more than about 15-20 ft in the longest dimension.

Conductivity Field Work

A portion of NW1 was mapped in 1982 using EM by Ken Ladwig, formerly with the U.S. Bureau of Mines. Much of the remaining portion was mapped in 1984 using the same technique. The purpose of the mapping was to locate AMD and AMD sources. Buried tipple refuse is suspected as one of those sources. The EM mapping was completed using both 10- and 20-m intercoil separations with both horizontal and vertical coplanar dipole configurations. Readings were taken every 10 m along traverses approximately 25 m apart (Ladwig 1982).

Conductivity Survey Results and Interpretation

Figure 9 is typical of the conductivity contour maps produced from NW1. This figure covers the southeastern portion of NW1. Several large, steep

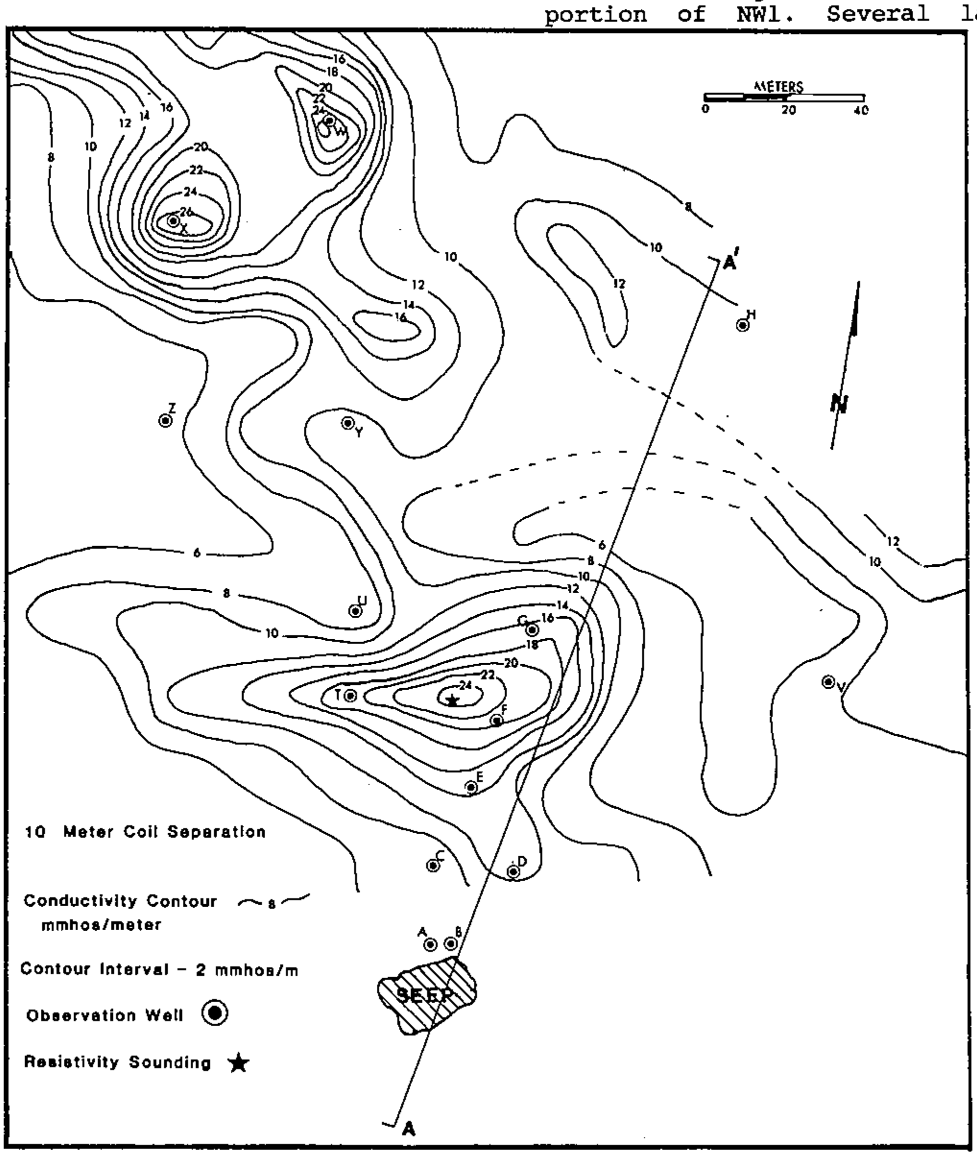


Figure 9. A typical terrain conductivity contour map resulting from Ladwig's work at NW1. The area represented is in the southeastern portion of the site. Conductivity highs represent AMD or AMD sources (Ladwig, 1982)

gradient anomalies were mapped at the site which Ladwig interpreted as signifying AMD or AMD sources. Without drilling, one cannot distinguish between anomalies that reflect AMD and those that reflect refuse. Several confirmation holes were drilled at the locations shown in figure 9. Only 2 holes, X and F, encountered refuse. Ladwig concluded that the anomalies were produced by a combination of both AMD and refuse (Ladwig 1982). In short, the EM work on this site demonstrates the similarity in electrical conductance properties between AMD and refuse as well as the difficulty in identifying either one with confidence.

Magnetometer Field Work

The entire 40-acre site was mapped in July 1987 using a magnetometer. Readings were initially taken on a 25 by 50 ft grid spacing. A contour plot of the readings is presented in figure 10. Due to resolution, only a 10-acre portion of the 40 acres is shown. At this rather coarse spacing, many isolated anomalous readings were observed. Consequently, to get more detail, additional traverse lines were added resulting in over half the site being mapped on a 25 by 25 ft or tighter grid. It should be noted that the area presented in figure 10 is located to the west of that presented in figure 9. Further, EM contours from Ladwig's second effort have been superimposed over figure 10 for comparison and later discussion.

Magnetometer Survey Results and Interpretation

Many anomaly highs and polarity lows are observed in the magnetic anomaly map, figure 10. The positive anomalies are indicated by solid lines; the polarity lows as dashed lines. Both high and low anomalies are shaped like circles or rounded rectangles. Additionally, maximum anomaly amplitudes vary considerably, in part because of the grid spacing used. Most of the piles can be located, but not delineated because only a few data points define each anomaly. If the grid point where the reading is taken does not coincide with the point of maximum amplitude for the pile, readings of a few tens of gammas rather than a few hundred are commonly recorded. Closer grid spacing would be required to better define these anomalies, but wasn't deemed necessary. The 25 by 25 ft grid spacing was sufficient to locate the small isolated refuse piles.

Increased resolution through closer grid spacing is illustrated in figures 11 and 12. The anomaly to be redefined is the one located in the lower left portion of figure 10. The area in figure 11 is the result of mapping on a 25 by 25 ft grid. The appearance is that of a single source with the positive portion of the anomaly (solid lines) on the left and the polarity low (dashed lines) on the right with about a 50 ft separation. The area was remapped on a 5 by 5 ft grid as shown in figure 12. We find there are two sources, each consisting of probably a single truckload of refuse. The anomaly wavelength indicates a lateral dimension of about 15 ft. The steep contour gradient further indicates that the burial depth is shallow. A drill hole located over the anomaly on the right encountered refuse from 12.5 to 27.5 ft.

Additional confirmation of the presence of refuse was made through DC electrical resistivity soundings using the Schlumberger array. Soundings were taken over both positive magnetic anomalies as well as at locations beyond the anomalies. The soundings over the anomalies indicate low resistivity (high conductivity) zones. Soundings taken away from the anomalies indicated uniform, poorly conductive materials both near the surface and at depth. The presence of refuse beneath anomalies was confirmed at several other locations across the site using both air rotary drilling and DC electrical resistivity soundings. In contrast to the EM electrical methods, DC electrical techniques like Schlumberger soundings are not affected by unusual magnetic permeabilities. However, standard interpretation packages for Schlumberger soundings assume infinite flat layers rather than the compact local sources we know to be present here. Hence, at this location the Schlumberger DC results are useful quantitatively, but probably not qualitatively.

The presence of polarity lows of arbitrary amplitudes that are located in an arbitrary direction from the highs, figures 10 and 12, indicate that remanent magnetization resulting from spontaneous combustion is dominant in these source bodies. This further indicates that spontaneous combustion occurred in the refuse before it was trucked onto the site. Several facts need to be recalled: 1) the magnetic fraction of all samples from both NW1 and SW1 was minute, but comparable in volume 2) magnetic combustion particles were predominant at NW1, 3) remanent magnetization, a result of combustion, is often many times stronger than induced magnetization, and 4) if reoriented, remanent magnetization is independent of the local magnetic field. First, the size of refuse piles are orders of magnitude smaller at NW1 than at SW1, yet maximum anomaly amplitudes are twice as great at NW1. This indicates greater magnetic susceptibilities at NW1. Lastly, if induced magnetization were predominant, or if the spontaneous combustion occurred <u>after</u> the refuse had been dumped on the site, all resulting anomalies would be oriented north-south with the polarity lows to the north. Such is not the case here. Polarity lows do not exhibit a

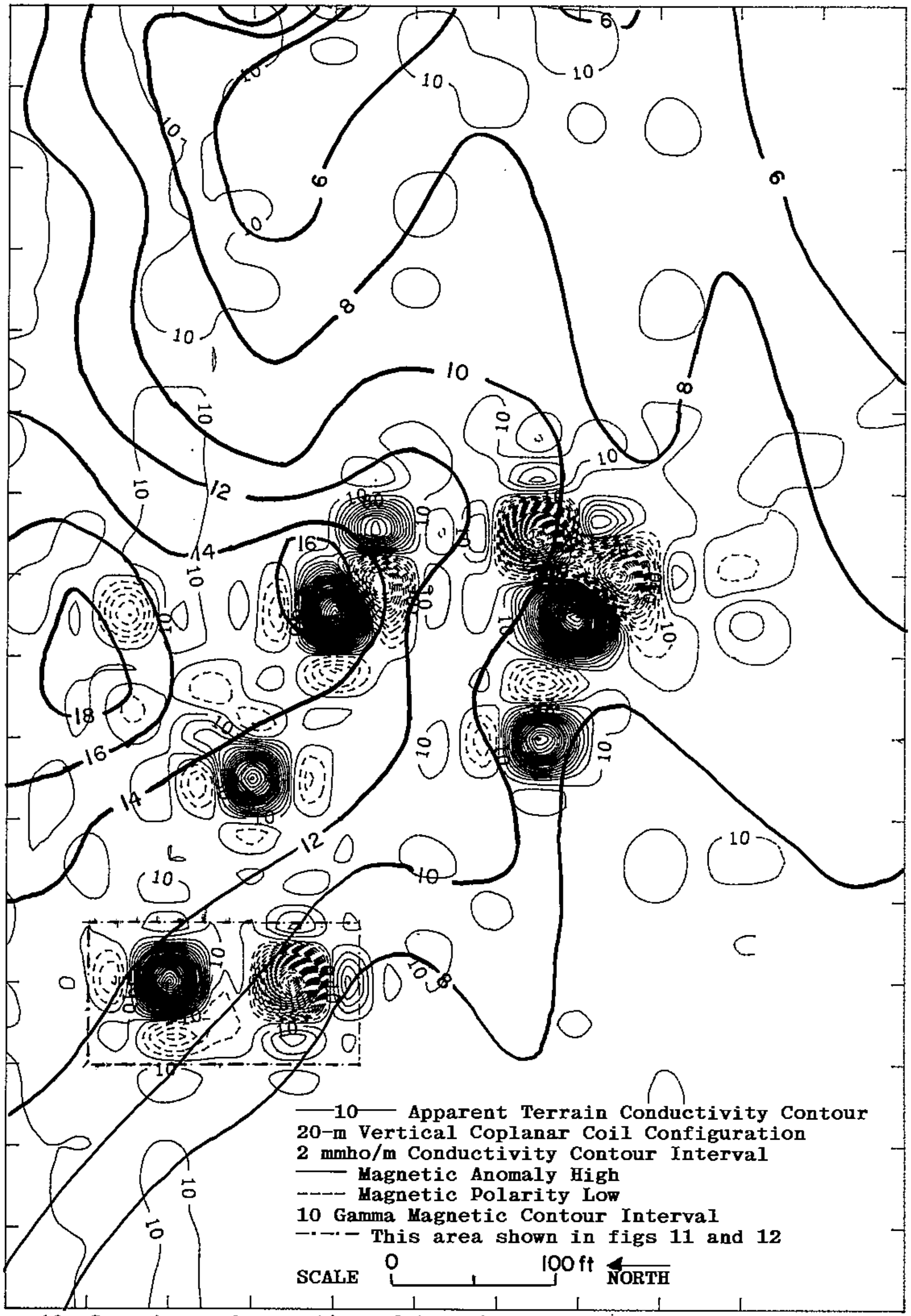


Figure 10. Superimposed magnetic and terrain conductivity maps of the SW 10-acres of NW1 site. Anomaly highs indicate the location of truckload sized pods of refuse buried at the site. Except for a few correspondences, detection of refuse by EM methods were poor. (Conductivity contours from Ladwig, 1984).

uniform north-south alignment. We infer from this that the source bodies came off the dump trucks in fairly large coherent blocks permitting the domains within the magnetic components to remain aligned.

Comparison of EM and Magnetometer Results

In figure 10 Ladwig's conductivity contours are superimposed over the magnetometer contours. Only a 10-acre

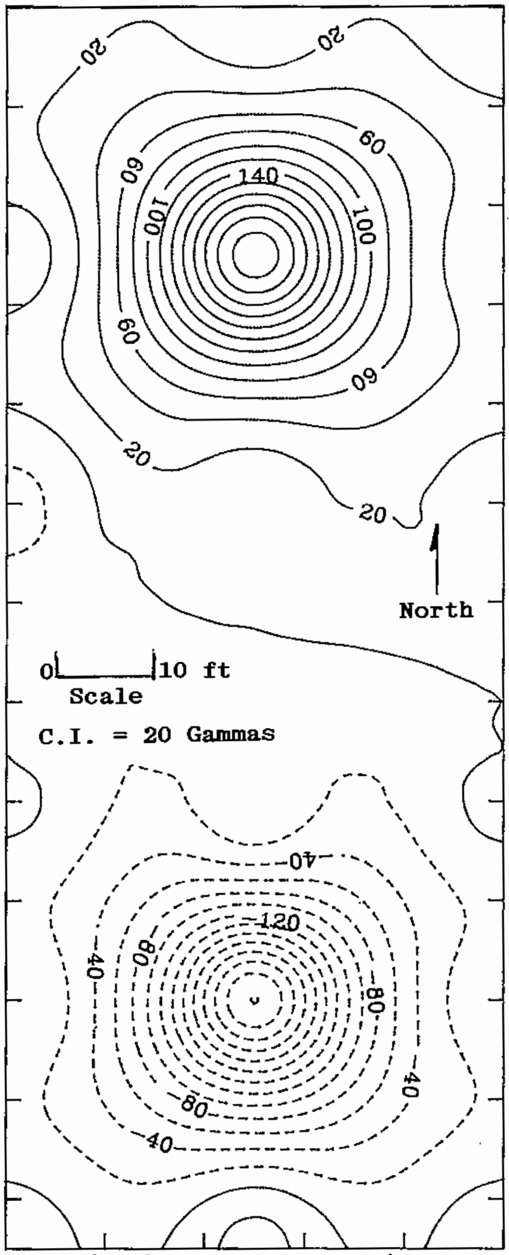


Figure 11. Magnetometer contours resulting from truckload sized pods of refuse mapped on a 25 by 25 ft grid. This appears as a single source body with the anomaly high to the north and the polarity low to the south.

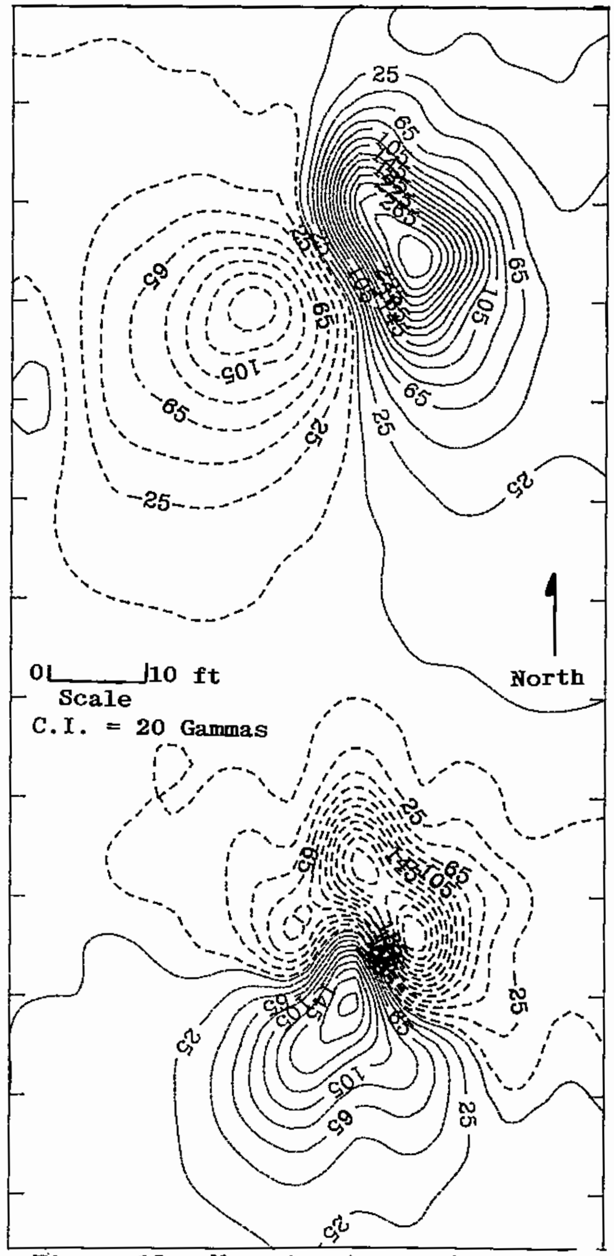


Figure 12. Magnetometer contour map resulting from mapping the area shown in Figure 11 on a 5 by 5 ft grid. Note the increased detail indicating the presence of two anomalies rather than just one.

portion of the 40-acre site is shown. Ladwig found a background conductivity value of 10 mmhos/m or less at this site (Ladwig 1982). An area of values greater than 10 mmhos/m is present in the left-central portion of the figure, implying possible AMD or AMD sources there. Note that several magnetic anomalies interpreted as refuse locations are present in this area. The 16 mmhos/m contour coincides with a magnetic anomaly, but there appears to be few further correspondences between the EM contours and the refuse pile locations as interpreted magnetically. Also, a number of refuse anomalies are mapped using magnetics further to the right where EM values are below 10 mmhos/m. Also the conductivity contours cut across the magnetic anomalies rather than surround them as would be expected.

Additional EM readings at much closer intervals would probably have identified more of the refuse locations. However, it may well be that the EM is more responsive to the AMD than to the refuse at this site, hence the conductivity may be showing an AMD pattern or the locations of nonmagnetic AMD sources.

CONCLUSIONS

The magnetometer's ability to clearly define buried refuse regardless of pod size makes it an effective geophysical tool in locating buried tipple refuse, a potential source of acid mine drainage. The property of remanent magnetism, which is somewhat unique to this particular type of refuse, allows the magnetometer to identify it against a background of mine spoil as well as AMD.

When attempting to map the locations of buried refuse, the magnetometer has many advantages over terrain conductivity. These include:

1) The location of the refuse is not masked by AMD or highly conductive spoil material as it is with EM.
2) Small piles of refuse, no larger than a single truckload are easily detected with the magnetometer.
3) Quantitative as well as qualitative determinations can be made with magnetometer data obtained from a single traverse of the area. A single traverse with EM provides qualitative data but multiple traverses are required before quantitative interpretations are made.
4) An area can be mapped from 7 to 28 times faster with the magnetometer than with EM for an equivalent amount of data.
5) Quantitative interpretations are easier and much quicker with the magnetometer than with EM.

Terrain conductivity has an advantage over the magnetometer, however. EM can detect AMD as well as structural features which the magnetometer cannot.

It was noted earlier that the refuse disposed of at both sites originated from tipples where magnetite was used. The ability of the magnetometer to detect refuse from plants which did not use magnetite is as yet unknown. Indications are, however, that the refuse may still be detected provided some degree of spontaneous combustion has taken place.

Selection of method in a particular investigation should be dictated by the purpose of the study. If refuse is to be mapped for the purpose of reprocessing then the magnetometer should be used. However, if the study is for delineating AMD and its sources, then a combination of both methods is suggested. Even though an area can be mapped more rapidly with the magnetometer, the total field time with either method is insignificant considering the wealth of information which can be collected.

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