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Magnetic Surveying for Buried Metallic Objects

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Abstract

Field tests were conducted to determine representative total-intensity magnetic anomalies due to the presence of underground storage tanks and 55-gallon steel drums. Three different drums were suspended from a non-magnetic tripod and the underlying field surveyed with each drum in an upright and a flipped plus rotated orientation. At drum-to-sensor separations of 11 feet, the anomalies had peak values of around 50 gammas and half-widths about equal to the drum-to-sensor separation. Remanent and induced magnetizations were comparable; crushing one of the drums significantly reduced both. A profile over a single underground storage tank had a 1000-gamma anomaly, which was similar to the modeled anomaly due to an infinitely long cylinder horizontally magnetized perpendicular to its axis. A profile over two adjacent tanks had a smooth 350-gamma single-peak anomaly even though models of two tanks produced dual-peaked anomalies. Demagnetization could explain why crushing a drum reduced its induced magnetization and why two adjacent tanks produced a single-peak anomaly.

A 40-acre abandoned landfill was surveyed on a 50- by 100-foot rectangular grid and along several detailed profiles; The observed field had broad positive and negative anomalies that were similar to modeled anomalies due to thickness variations in a layer of uniformly magnetized material. It was not comparable to the anomalies due to induced magnetization in multiple, randomly located, randomly sized, independent spheres, suggesting that demagnetization may have limited the effective susceptibility of the landfill material. A different 6-acre site survey conducted on a 10- by 10-foot grid was analyzed to determine the maximum station spacing and line separation that could have been used. Essentially, all of the anomalies at this site would have been resolved by a survey conducted on a 20- by 20-foot grid and the larger anomalies would have been detected by a 50- by 50-foot grid.

Introduction

Magnetic surveys have traditionally been used by geologists to locate changes in rock type such as might be associated with ore bodies, fault contacts, or igneous intrusives. Another common application is determining the probable depth to basement beneath sedimentary rocks. For these applications, the principal geologic variable is the distribution of ferromagnetic minerals, mainly magnetite, within the earth. The theory and survey procedures are described in a variety of references (e.g., Grant and West 1965, S.E.G. 1966, Parasins 1975, Nettleton 1976, Telford and others 1977, Robinson and Coruh 1988). A particularly concise review of surveying with portable magnetometers is given by Breiner (1973).

Magnetic surveys are used in hazardous waste site investigations to locate 55-gallon drums, underground storage tanks, buried pipes, and the edges of covered landfills. These applications usually involve shallow iron or steel objects, which influence the way the surveys should be conducted and interpreted. Tyagi and others (1983) describe controlled field tests in which single drums and clusters of drums were buried at various depths. The test site was then surveyed with a variety

of geophysical instruments including a total intensity magnetometer. They found the magnetic detection limit for a single drum was 6 to 11 feet below the surface and that the boundaries of a dump site containing steel drums can be easily determined. Gilkeson and others (1986) describe a magnetic survey of a series of landfill trenches that had been used to dispose of steel drums. They found a distinctive pattern of magnetic highs over the trenches and lows over the intertrench corridors. They noted that these signals were similar to the calculated magnetic anomalies due to infinitely long rectangular bodies having dimensions comparable to the trenches and a magnetic susceptibility of $k = 0.1$. As explained later, a susceptibility of this magnitude is expected for a mass containing many disseminated ferrous metal objects. Frischknecht and others (1985) and Jachens and others (1986) describe field tests and models that demonstrate the use of magnetic surveys to locate covered abandoned well casings. This application is important because abandoned wells are potential pathways for the vertical migration of contaminated ground water. They found strong positive anomalies over the wells that closely resemble models of simple magnetic dipoles having the positive pole at the top of

the casing and the negative pole at its base.

In this paper, the theory behind magnetic surveying is briefly reviewed and the field tests conducted to determine the total-intensity magnetic anomalies due to 55-gallon steel drums and underground storage tanks are briefly described. The anomalies due to the three drums tested had peak amplitudes of around 50 gammas and half-widths approximately equal to the 11-foot separation between the drum and the magnetometer sensor. The half-width is the distance between the two sides of an anomaly at intensities of one-half of its peak value. These anomalies were similar to those due to isolated dipoles but in addition to the magnetization induced by the earth's ambient field, both remanent magnetization and demagnetization seemed to affect the signals. Remanent magnetization is a permanent magnetization that is independent of the ambient field. Demagnetization is a limit on the strength of induced magnetization within an object imposed by the internal field due to the object itself. The surveyed anomaly due to one underground storage tank was similar to that due to an infinitely long cylinder magnetized perpendicular to its axis. However, the anomaly due to two adjacent tanks also resembled that of a single body. Again, remanent magnetization and demagnetization are thought to affect these signals. If the results described herein are representative, then the strengths of anomalies due to drums and tanks may depend more on their volume than on their metal content. Also, it may be difficult to infer from the shape of a magnetic anomaly the exact location and nature of the causative body. Demagnetization may also influence the magnetic signals from landfills containing many metal objects. One site survey is described in which the total-intensity field resembled that due to a uniformly magnetized layer of varying thickness but did not resemble that due to an assemblage of magnetically independent objects. One implication is that magnetic surveys may not be able to locate concentrations of metal objects, such as drums, within a landfill. Another is that successful landfill surveys may be conducted on a relatively coarse station grid. The data from a second survey conducted on a 10- by 10-foot square grid were analyzed to determine the maximum station spacing that could have been used. For this particular site, essentially all of the signal would have been resolved with stations on a 20- by 20-foot grid and the stronger anomalies would have been detected on a 50- by 50-foot grid.

Theory

The Geomagnetic Environment

The signals in a magnetic survey are partially the result of, and strongly influenced by, the ambient magnetic field of the earth. As a first approximation this geomagnetic field resembles that due to a single axial dipole whose negative or south magnetic pole is toward the geographic north pole. The strength of this field varies from 60,000 gammas near the poles, where it plunges vertically into the ground, to 25,000 gammas near the equator where it parallels the earth's surface. In any particular region the ambient field is described

by its intensity, inclination (or angle to the horizontal), and declination (or angle to geographic north). Breiner (1973) includes large-scale maps of these parameters for the continental United States. Fabino and others (1979) give more detailed maps.

The geomagnetic field is not constant both in the sense of diurnal variations of several tens of gammas and occasional periods of rapid, irregular, transient variations (magnetic storms). The diurnal variations can be removed from survey data by drift corrections based on either regular base station ties or the record from a fixed base-station magnetometer. Magnetic storms vary in intensity and can make surveying impractical. The Space Environment Services Division of the National Oceanic and Atmospheric Administration provides recorded information on the current level of these fluctuations (telephone number (303) 497-3235) and a forecast of the projected level for the next five days (telephone number (303) 497-3171). It is normally desirable to know the condition of the earth's field during each day of a field survey.

Magnetic Anomalies

Following Telford and others (1976, p. 111, Equation 3.11), the magnetic field at an external point (f , due to a magnetized body can be expressed as:

$$\vec{F}(\vec{r}_o) = \vec{\nabla} \int \int \int_{\text{volume}} \vec{M}(\vec{r}) \cdot \vec{\nabla} \frac{1}{|\vec{r} - \vec{r}_o|} dV(\vec{r})$$

where: \vec{r} is a position vector within the body,
 $\vec{\nabla}$ is the gradient operator,
 $|\vec{r} - \vec{r}_o|$ is the distance between the external point and position within the body,
 \cdot indicates the vector dot product, and
 $\vec{M}(\vec{r})$ is the net magnetization per unit volume.

The net magnetization is the vector sum of induced plus remanent magnetizations. Remanent magnetization is a permanent magnetic moment per unit volume and induced magnetization is temporary magnetization that disappears if the material is not in a magnetic field. Generally, the induced magnetization is parallel with and proportional to the inducing field. Algorithms for calculating the magnetic fields due to uniformly magnetized, simple geometric shapes are given in several texts (e.g., Grant and West 1965, Nettleton 1976, Telford and others 1976, Robinson and Coruh 1988).

Magnetic fields are vectors and magnetometers measure some attribute of this vector field. Proton precession magnetometers measure the maximum intensity (or total length of the vector) and flux gate magnetometers measure the intensity in a particular direction (or vector component). When used with dual sensors, magnetometers also measure the gradient of the attribute; usually in the vertical direction.

The net magnetic field to which the magnetometer responds is the vector sum of the field due to local magnetized materials and the ambient field of the earth. Figure 1 shows the total intensity field due to a simple magnetic dipole, the ambient field of the earth, and the total-intensity anomaly that would be detected during

a survey. In this case, the magnetization of the object is parallel to the ambient field (induced magnetization). There is a magnetic low to the north of the center of the body and a larger high to the south.

Effective Susceptibility

Magnetic susceptibility, k , is the dimensionless proportionality constant relating induced magnetization within a body to the inducing field. In general, the inducing field is the vector sum of both the earth's ambient field and the field due to the object itself. This feedback is referred to as demagnetization and is expressed as a reduction in the effective susceptibility of the object:

$$k_{\text{eff}} = \frac{k_{\text{mat}}}{1 + \lambda k_{\text{mat}}}$$

where: k_{mat} is the material susceptibility, and λ is the demagnetization factor. Grant and West (1965) describe the physical basis for demagnetization and the derivation of this relation.

Demagnetization factors are dependent on both the shape of the object and its orientation to the ambient field. For a sphere $\lambda = \frac{4}{3} \pi$; normal to the axis of the cylinder $\lambda = 2 \pi$; and normal to a flat sheet $\lambda = 4 \pi$ (Strangway 1967). Figure 2 shows the resulting relations between effective and material susceptibility for these simple shapes and orientations. Note that for material susceptibility less than about $k = 0.05$, the effective and material susceptibilities are approximately equal. Most rock units have susceptibilities less than this, therefore, demagnetization does not usually affect the interpretation of geologic surveys. However, ferrous metals have susceptibilities of tens or hundreds, therefore, the effective susceptibility of ferrous metal objects, like steel drums, is limited by demagnetization to a few tenths. If the ferrous metal content of a landfill is several percent of the volume, then the effective susceptibility of landfill material would also be limited. In this case, local concentrations of metal within the landfill would not be expected to significantly increase the local effective susceptibility.

Demagnetization also limits the applicability of the algorithms used to calculate the magnetic effects of simple models. These algorithms usually assume that magnetization is uniform throughout the material, a condition not realized if the field due to the body itself is irregular. For hazardous waste site investigations there is a need to develop magnetic modeling techniques that accommodate demagnetization phenomena. Until this is accomplished, magnetic models of ferrous metal objects (including the models in this report) should be interpreted cautiously.

Field Tests

55-Gallon Drums

The objectives of these tests were to establish the magnetic signal of a 55-gallon steel drum and to compare this result with analytical models. A secondary objective was to determine the extent to which demagnetization limits the effective susceptibility of a steel drum.

A 60- by 60-foot test site was laid out in a flat empty

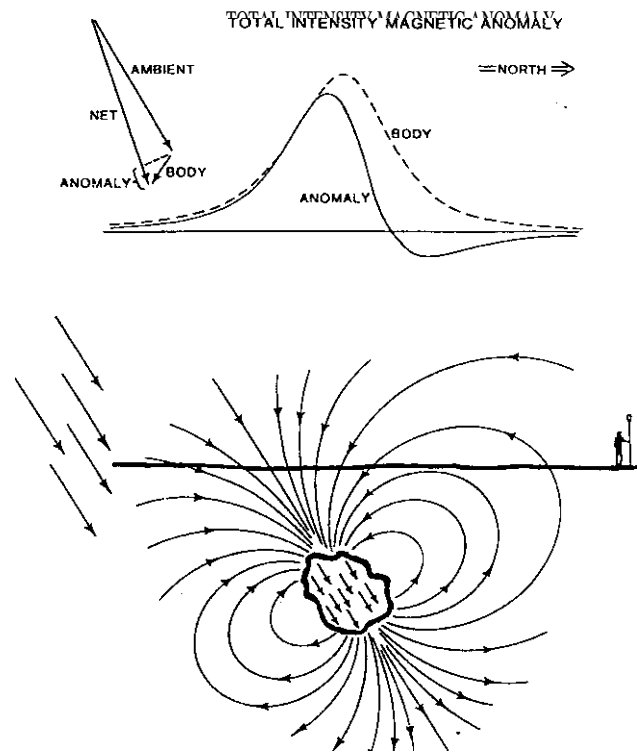


Figure L Magnetic effect of an isolated body magnetized in the direction of the earth's ambient field. The measured total magnetic intensity is the vector sum of the ambient field plus the field due to the body:

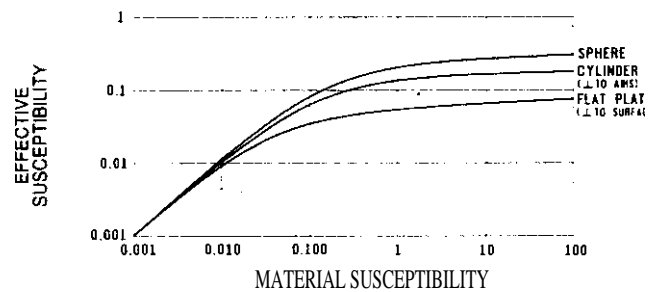


Figure 2. Effective vs. material susceptibility for several simple shapes and orientations. Demagnetization limits the effective susceptibility to a few tenths regardless of the susceptibility of the material (from Strangway 1967, p. 455).

field and a nearby base station was selected. Survey stations were at 3-foot intervals along north-south lines, spaced 6 feet apart (231 stations). In the center of the site a non-magnetic (PVC pipe) tripod was constructed from which the drums were suspended. The drums were 19 feet above ground level; therefore, with the 8-foot sensor height of the magnetometer, the signals were similar to those from drums buried at 3 feet (Figure 3). Running the surveys beneath, instead of over, the objects reversed the signals through an east-west line. This resulted in a reversal of the positions of the positive peak and related trough.

The site was first surveyed with an empty tripod to establish a baseline, which was removed from all subsequent surveys. For each survey, the ends of the north-south lines were first read and linearly drift-corrected to the base station and then the individual stations were read and linearly drift-corrected to the line ends. All data were relative to the first reading at the base station

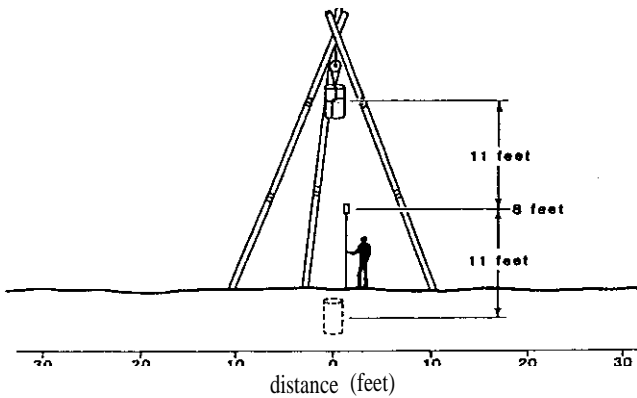


Figure 3. Test apparatus used to simulate the magnetic response of a buried 55-gallon steel drum. The anomaly due to the suspended drum is similar to that of a buried drum except that the positions of the high and low are reversed.

and all were gathered with a total intensity proton-precession magnetometer (Geometrics Model 856). Figure 4 is a perspective diagram of a representative anomaly. The anomaly has a peak amplitude near 50 gammas, and has a half-width about equal to the drum-to-sensor separation (11 feet). It is less than 5 gammas at twice the separation.

Tests were run with three different drums. For each drum, the field beneath the drum was surveyed, the drum was flipped and rotated to reverse the direction of the remanent magnetization, and the new field was surveyed. Along the north-south center line, the average of the two fields is attributable to induced magnetization and one-half their difference is attributable to remanent magnetization. For two of the three drums tested, the anomaly due to remanent magnetization was comparable to that due to induced magnetization. For the third drum, it was 40 percent as large.

The third drum was then crushed to a 1.1 cubic foot, drum-shaped mass. This crushed drum was surveyed in both its upright and reversed orientations. Figure 5 shows the observed data along the north-south central profile for both the whole and crushed drums in both of their orientations. In its crushed configuration, the drum showed very little remanent magnetization, possibly because the magnetized sheet metal had been folded over on itself. The anomaly due to induced magnetization was only 30 percent of that of the uncrushed drum even though both configurations contained the same steel.

Modeled profiles of the total intensity anomaly of uniformly magnetized spheres were matched to the induced-magnetization anomalies of both the whole and crushed drums. The sphere volumes were identical to their respective drums. For the whole drum, the modeled sphere had an effective susceptibility of $k = 0.10$, for the crushed drum $k = 0.18$.

Underground Storage Tanks

Magnetic surveys are used to locate underground storage tanks either for their removal or as an aid in positioning boreholes in which leak detectors are to be installed. The following field tests demonstrate the character of the associated total-intensity signals. Again, the data were gathered with a total-field proton-pre-

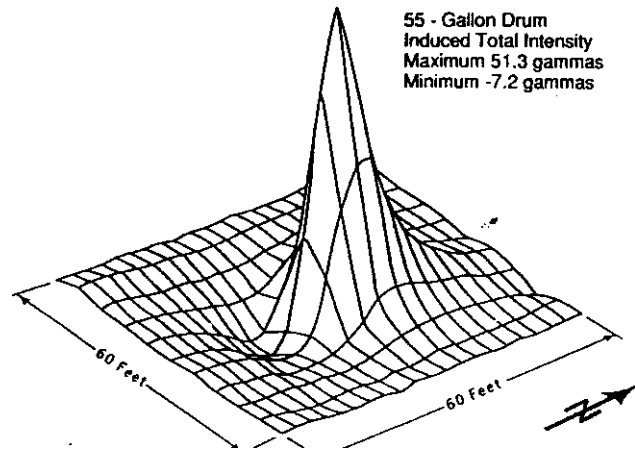


Figure 4. Total intensity anomaly due to induced magnetization in a single 55-gallon drum. The configured surface is one-half the sum of the anomaly due to a drum in its upright orientation plus that due to the same drum in a flipped plus rotated orientation. Survey stations were located at each of the grid intersections.

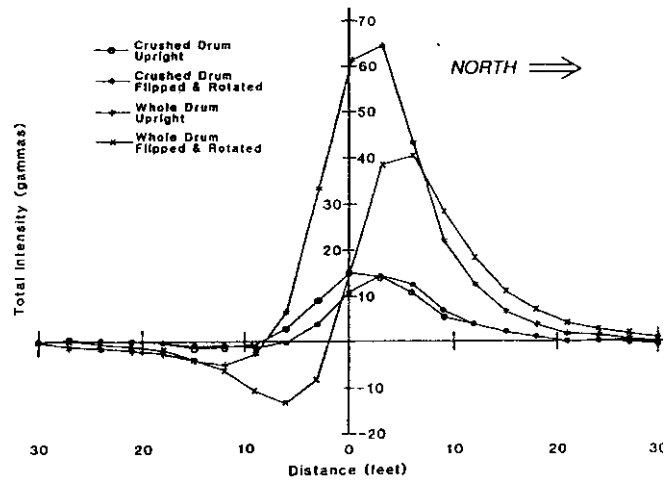


Figure 5. North-south profiles beneath a suspended 55-gallon drum in its upright orientation and its flipped plus rotated orientation. The lower-amplitude profiles are for the same drum after it had been crushed to a 1.1 cubic foot drum-shaped mass.

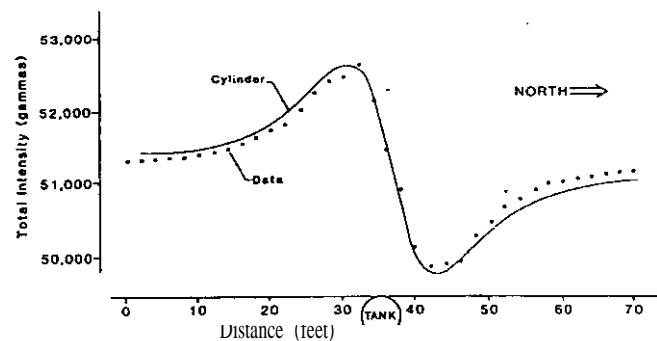


Figure 6. Total-intensity anomaly due to an underground storage tank. The modeled anomaly is that due to an infinitely long cylinder with a horizontal magnetization of 2750 gammas per cubic foot.

sion magnetometer.

The first example is a single tank on a narrow land spit extending from the south shore of Lake Mead, Arizona. The tank had been part of a marine fuel dock until the facility was destroyed by high water and abandoned. There were no remaining buildings, power lines,

pipes or other sources of cultural noise.

Figure 6 is a profile normal to the long axis of this tank along with a matching model based on the actual tank diameter. The model has a uniform horizontal magnetization of 2750 gammas per unit volume. This net magnetization is the vector sum of induced plus remanent magnetization and cannot be resolved without reorienting the tank. One simple possibility is an induced magnetization of 5500 gammas per unit volume ($k = 0.1$) plus an upward remanent magnetization of 4763 gammas per unit volume.

The second example is a profile over two adjacent tanks located 22 feet to one side of a large vehicle maintenance garage. Figure 7 shows the observed data, an assumed linear regional, which may be due to the garage, and the residual anomaly along with the profile due to the indicated model. In this case, the entire anomaly might be due to induced magnetization in a single small body that is considerably deeper than the actual tanks. Note that the data did not resolve two tanks even though geometrically correct models of two magnetically independent tanks had dual-peaked anomalies. A possible explanation is that the inducing field within each tank is the sum of the earth's ambient field, the field due to the tank, and the field due to the adjacent tank. The tanks would then not be magnetically independent and the two-tank model would not apply.

Field Surveys

The Landfill

The first example is a survey of a 70-acre covered landfill in south-central Indiana. A 20-acre lake occupies the center of the site and a river flows along the northern and northeastern sides. The landfill had been used to dispose of approximately 40,000 drums of chemical wastes along with a variety of domestic and industrial refuse. The survey was conducted to better define the lateral extent of the landfill and, if possible, to locate clusters of drums.

Two survey methods were used. One was a reconnaissance survey with stations at 50-foot intervals along lines spaced 100 feet apart. The other was a series of more detailed north-south profiles with stations at 10- or 20-foot intervals. Both were conducted with GeoMetrics Model 856 total-intensity magnetometers.

Figure 8 is a contour map of the total intensity data from the reconnaissance survey. The dots are measurement stations and the contour interval is 1000 gammas. At this location, the ambient field is 56,200 gammas and the measured values range from 52,600 to 64,500 gammas, so the anomalous field ranges from 3600 to +8300 gammas. The reconnaissance survey clearly showed areas in the southeast corner and west-central side of the site that are magnetically smooth and are not believed to contain buried debris. The data contoured surprisingly well, considering that drums and metallic debris are exposed on the surface. At the relatively coarse 50- by 100-foot station spacing (necessitated by the size of the site and limited field time) many "single point anomalies" and ambiguities in the contours were anticipated.

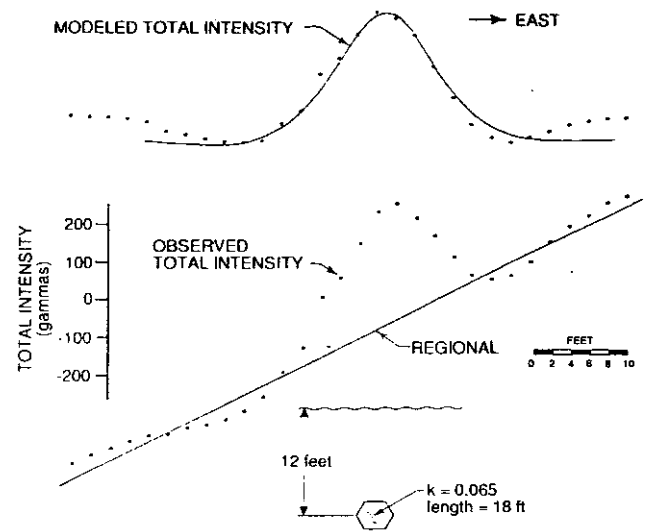


Figure 7. Total-intensity anomaly due to two underground storage tanks. The magnetic data did not resolve the presence of two objects even though calculated models of two near-surface magnetically independent tanks produced dual-peaked anomalies.

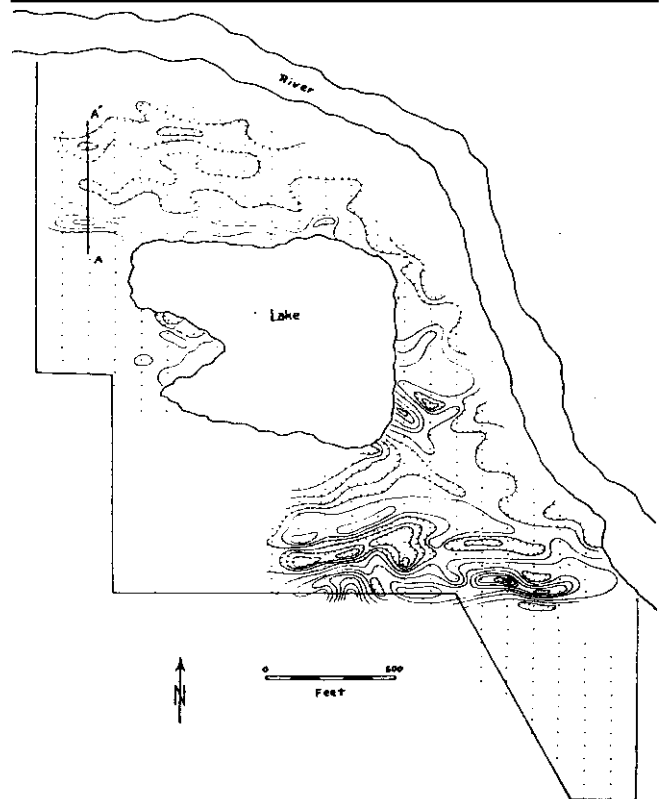


Figure 8. Magnetic total intensity over a covered landfill in south-central Indiana. The contour interval is 1000 gammas and the dots are stations at which data were gathered. Profile A-A' is shown in Figure 9.

The continuity of the contoured field may be due to demagnetization limiting and homogenizing the effective susceptibility of the landfill material. Figure 9 is a north-south profile along line A-A'. Stations are at 10-foot intervals. Also shown is a simple model and modeled field configured to match the larger features in the observed data. The model is an east-west trending, infinitely long polygon with a uniform susceptibility of $k = 0.24$ (the Talwani algorithm, e.g., Grant and West 1965). The horizontal scale is as shown, but there is a 10X vertical exaggeration in the model and its greatest

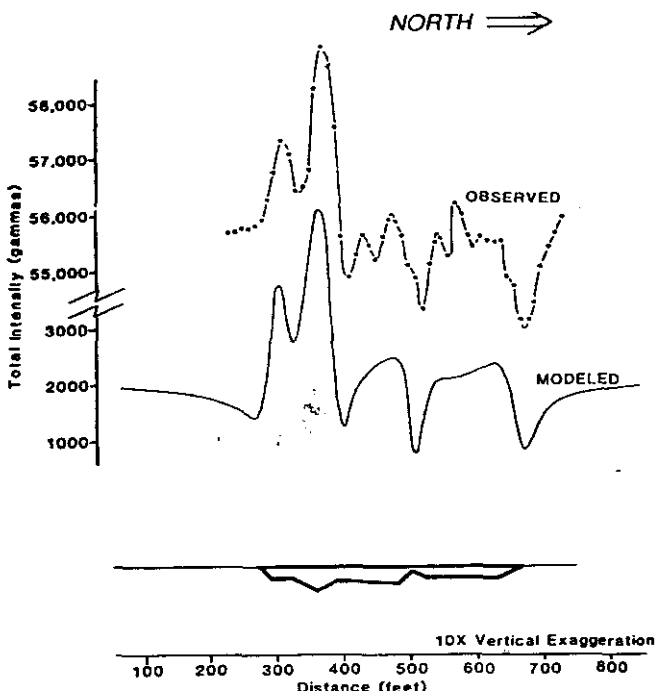


Figure 9. Observed and modeled magnetic total intensity over a covered landfill. The modeled anomalies are due to variations in the configuration of the landfill material.

thickness is only 5 feet. The important point is that the anomalies can be attributed to modest thickness variations in the layer. Comparable results were obtained with models having an irregular upper surface and a flat base. In contrast, Figure 10 shows the effect of induced magnetization in an assemblage of randomly located, randomly sized spheres. This modeled field is predomi-

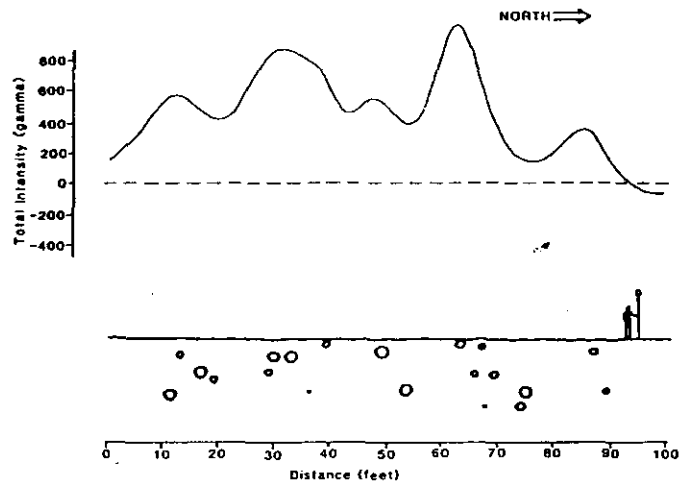


Figure 10. A total-intensity magnetic model of an assemblage of randomly located, randomly sized spheres magnetized in the direction of the earth's field. The modeled field is dominated by a few narrow peaks due to the shallowest objects.

nately positive and dominated by a few high-intensity narrow peaks due to the shallowest objects. The observed field at the landfill had broad anomalies with both positive and negative parts.

The Sludge Ponds

The next example is a survey of some abandoned sludge ponds on a 6-acre site south of Houston, Texas. The ponds had been used to dispose of broken slabs of reinforced concrete and had then been covered with earth. The survey objective was to locate areas where the slabs had been dumped so they could when drilling ground water monitoring wells. It was thought that the steel reinforcing bars in the concrete

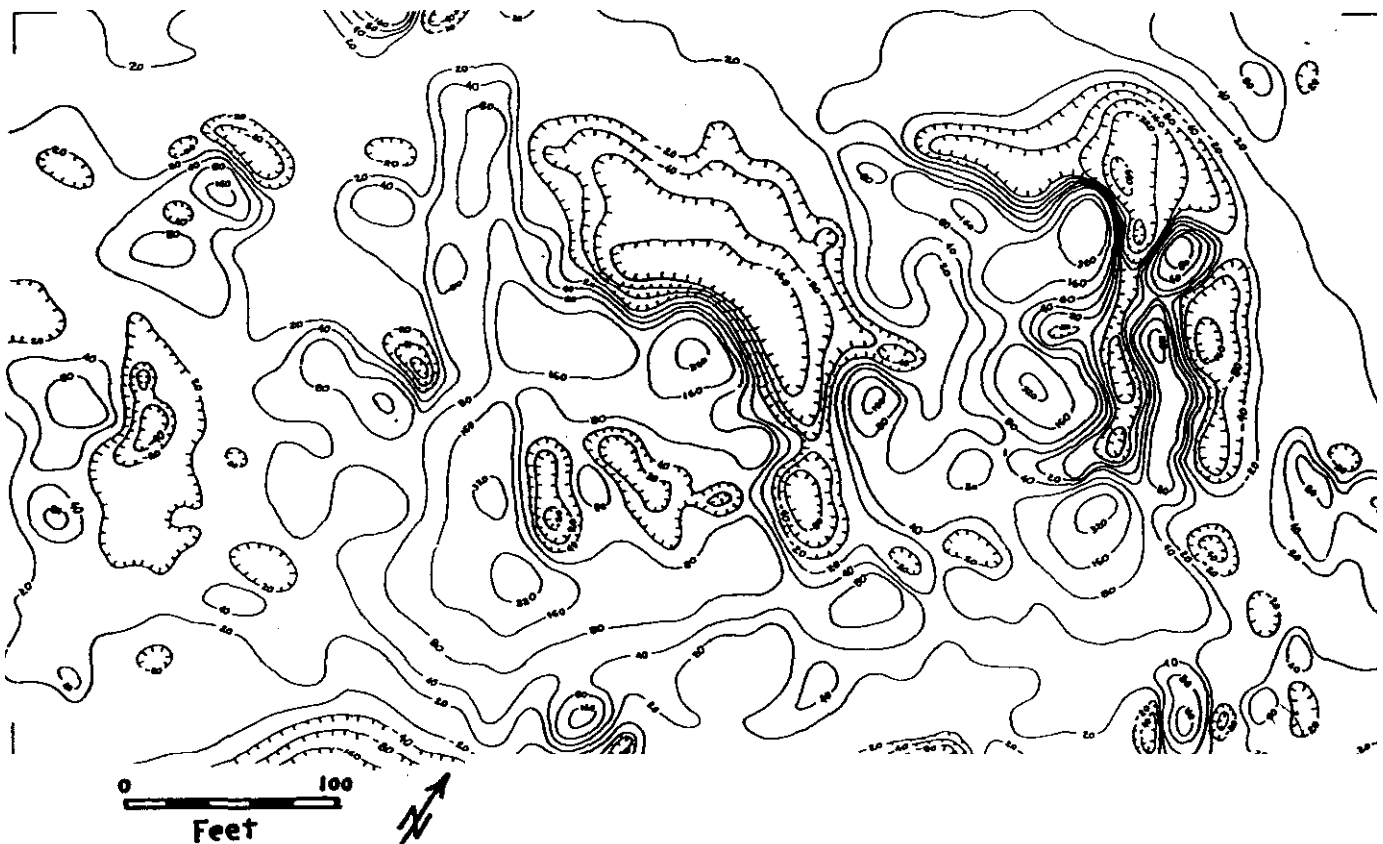


Figure 11. Modeled magnetic total intensity over some abandoned sludge ponds near Houston, Texas. The contours are at $49800 \pm 20, \pm 40, \pm 80, \pm 160, \pm 320, \pm 640$ gammas and stations were on a 10- by 10- foot square grid.

would produce a detectable magnetic anomaly.

This survey was conducted with an OMNI-IV tie-line magnetometer system. Stations were established at 10-foot intervals along lines 10 feet apart and both the total intensity and its vertical gradient were recorded. The OMNI-IV monitors the quality of each reading and the data are reliable except in an 80-foot strip along the eastern side of the site where there is an overhead powerline. In this area about 20 percent of the readings were unreliable and were edited from the data.

Figure 11 is a contour map of the edited total intensity data. Values range from 49,150 to 50,350 gammas. The ambient field at this location is 49,800 gammas so the anomalies range from -650 to +550 gammas. The exponentially spaced contour intervals were used so that both subtle features in the relatively smooth areas and the shapes of the larger anomalies are displayed. This map along with a map of the vertical gradient successfully identified undisturbed areas in which the monitoring wells could be placed.

On Figure 11 there is a tendency for the magnetic highs to be flanked to the north by lows of comparable amplitude. As in the landfill survey, the effect could be modeled as thickness variations in a continuous layer. However, at this site, enough of the slab dumps (and anomalies) are sufficiently isolated to suggest a different interpretation. Figure 12 shows the total intensity anomaly due to a horizontally magnetized slab at a depth of 4 feet. For horizontal magnetization at the latitude of the site, the magnetic highs and lows are of comparable amplitude but for steeply plunging magnetization parallel to the ambient field, the highs are significantly larger than the lows. Demagnetization limits the effective susceptibility perpendicular to the surface of a slab or to the axis of a bar. However, it does not limit the susceptibility parallel to a thin slab or along the axis of a bar. Therefore, for flat-lying reinforced slabs, the horizontal component of induced magnetization is expected to be larger than the vertical component, which is consistent with our model.

Selecting station spacing and line separation involves a tradeoff between survey resolution and the amount of field work. If the distance between measurements is too large, the data will be uncertain by an amount comparable to the amplitude of the narrower anomalies; even if the measurements are precise. (This spatial-aliasing phenomena is similar to the temporal aliasing that occurs when a continuous time signal is digitized.) On the other hand, if the distance between measurements is too small, the time and cost of the survey may be prohibitive. For the survey over the sludge ponds, the relatively short 10- by 10-foot grid was selected because the nature of the signal was not known beforehand and the surveyor wanted to detect all significant anomalies.

To determine the maximum distance between stations that would have adequately resolved the field variations, the Fourier transformation was used on the total intensity data and then the resulting amplitude spectra (Figure 13) was smoothed and contoured. This map shows the relative amplitudes of the variations in magnetic total intensity as a function of their widths

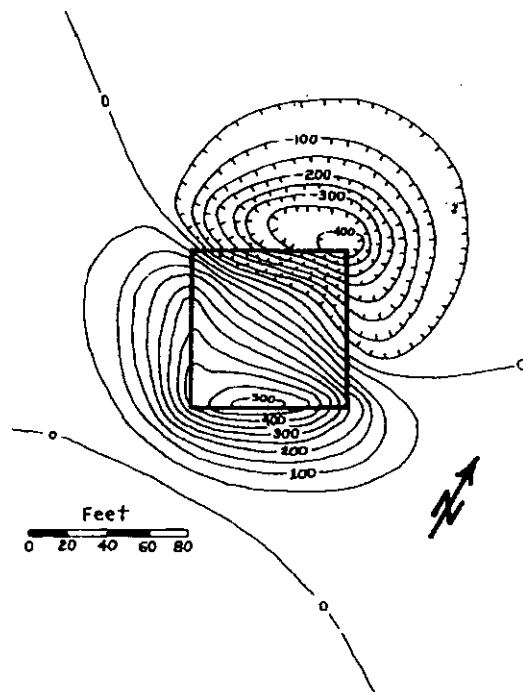


Figure 12. Magnetic total intensity anomaly due to a 80- by 80- by 4-foot thick slab of material with a horizontal northerly magnetization of 1000 gammas per cubic foot. The contour interval is 50 gammas.

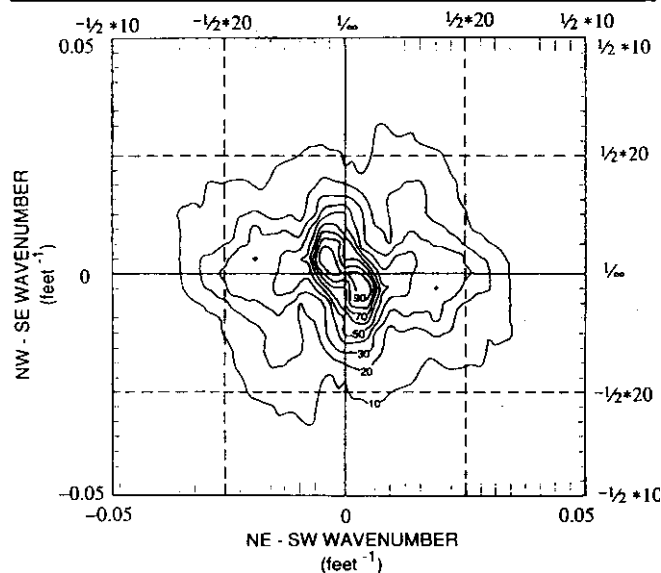


Figure 13. Two-dimensional Fourier transform of the total intensity data in Figure 11. The contoured values are the moduli of the transform after they were smoothed by a nine-point unit matrix. The contour interval is 10 percent of the maximum value.

and orientations. The graph axes are wave number or one-half the reciprocal wavelengths in the ENE-WSW and NNW-SSE directions of the survey grid. The contours are the moduli of the transform (an array of complex numbers) after they had been filtered or averaged with a nine-point unit matrix. The contour interval is 10 percent of the peak filtered value.

Note that almost all of the amplitude spectra are at wavenumbers less than 0.025 ft (0.5/20 ft). This implies that most features would be adequately resolved by a survey conducted on a 20-foot grid, assuming the data were reliable. Some data redundancy is desirable and it is more efficient to make closely spaced readings along

more widely separated lines than it is to make the same number of readings on a square grid. An optimum survey grid at this site might have stations at 10-foot intervals along lines no more than 30 feet apart. Contour maps constructed from alternate stations and lines (a 20- by 20-foot grid) and from every third line (a 10- by 30-foot grid) resolved all of the anomalies on the total-intensity map.

The highest peaks on the amplitude spectra occur at wave numbers near 0.005 ft (0.5/100 feet) and amplitudes are generally less than 50 percent of the peak value at wave numbers greater than about 0.01 ft (0.5/50 ft). This implies that the larger amplitude anomalies would have been detected by a survey on a 50-foot grid. A map constructed from every fifth line and station detected all the major anomalous areas but did not resolve the shapes of the anomalies.

Summary

Magnetic surveys can be an important part of hazardous waste site investigations but the physical principles must be understood before the data are interpreted. In particular, these surveys often involve ferrous metals and effective susceptibility can be limited by demagnetization to a few tenths. The magnetic field variations will then be due to the configuration of the magnetized material rather than to local concentrations of metal.

The detectable anomaly due to an isolated steel drum has a width of about twice the distance between the drum and the magnetometer sensor. A survey to reliably detect single drums would have to be conducted with a station spacing and line separation less than this width. However, if a hazardous waste site contains sufficient disseminated metal for demagnetization to occur, the stronger anomalies can have dimensions comparable to the landfill cells. In this case, relatively coarse station spacings and line separations may be adequate.

Acknowledgments

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Biographical Sketches

Larry Barrows received his M.S. and Ph.D. degrees in geophysics from the Colorado School of Mines in 1973 and 1978, respectively. He has worked as a systems engineer on Skylab remote-sensing experiments and as an exploration geophysicist in frontier areas of Alaska. Since 1979 he has specialized in geophysical surveying for ground water and hazardous waste site investigations, first as the project geophysicist on a radioactive waste disposal program and then as a research scientist for the U.S. EPA. In 1988 he joined Earth Science and Engineering Inc and LaCoste and Romberg Gravity Meters Inc (4807 Spicewood Springs Rd, Bldg. 2, Austin TX 78759). Current projects include using microgravity to detect solution conduits in karst terrains and using seismic groundroll to determine near-surface shear moduli.

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