Bulletin of the
Association of Engineering Geologists
Vol. XXVII. No. I. 1990
pp. 37-50

Magnetometer and Gradiometer Surveys for Detection of Underground Storage Tanks

CHARLES M. SCHLINGER
Department of Geology and Geophysics, University of Utah, Salt Lake City, UT 84112

ABSTRACT

In recent years there has been a surge of interest in methods for rapid and reliable detection and location of underground storage tanks and other cultural features related to hazardous substances in the subsurface. In the United States much of the motivation comes from recent environmental protection legislation that regulates underground storage tanks, including both existing and new installations. U.S. regulatory matters aside, ground-water contamination is a problem that knows no national borders; remediation of sites where hazardous substances can invade or have invaded ground-water supplies is a global concern. Detection and location of underground steel storage tanks can be readily accomplished using magnetometer and magnetic gradiometer surveys, which arc a passive variety of remote sensing. This paper presents investigations at two sites at Hill Air Force Base, northern Utah. In each case, magnetometer and gradiometer data have proven to be valuable for assessing the possibilities of existence and location of buried underground storage tanks. Relevant magnetic-field principles are reviewed and methods of data acquisition, reduction, analysis and interpretation are described.

INTRODUCTION

There are numerous sites, under both private and public jurisdiction, throughout the world where hazardous chemical materials arc thought to exist at depth in the soil, however, the existence and specific locations of these materials arc in fact not at all well known. Of pressing concern in the United States is the integrity of the subsurface containers of such material; more specifically, the location and evaluation of underground storage tanks (UST) and remediation of leaking tanks. Some of the underground tanks arc in use; others arc not. Both old and newer tanks present in the subsurface pose an environmental problem in the form of hazardous substances leaking into ground-water supplies. For the purposes of ground water protection it is imperative for both the public and private sector to locate existing tanks, evaluate their condition, and if necessary, remove or replace them. New regulations from the United States Government (Code of Federal Regulations, 1988) stipulate conditions for construction and condition of underground storage tanks used for substances regulated by the U.S. Federal government.

An easily-used and interpretable method for rapid location of underground storage tanks is needed. Magnetic surveys fill that need. Magnetic methods have a history of application in mineral, geothermal, and hydrocarbon exploration, archeology, and a variety of other areas. Here I review the application of magnetometer and magnetic gradiometer surveys to the location of lost or imprecisely located underground steel storage tanks. The gradiometer, an instrument that is an adaptation of the conventional magnetometer, gives the gradient of the magnetic field. The gradient is especially useful for detecting objects buried at shallow depth (the gradient is the quantity measured by magnetic locators used in land surveying). In addition to the application discussed in this paper, magnetic surveys have broad general application in passive surface searches for buried cultural objects, or searches for areas of prior human disturbance.

The study presented in this paper was developed for several reasons. In the first place, the Environmental Management Directorate at Hill Air Force Base, northern Utah, responsible for the sites discussed here, wished to see whether or not magnetic methods have any demonstrable utility for environmental and engineering site investigations. Secondly, the study was conducted to investigate advantages and disadvantages of magnetometers over magnetic gradiometers for these sorts of investigations, and to highlight problems that might be addressed by future research involving magnetic surveys of high-resolution and high-data-density. It is worth noting that the application of magnetic surveys described herein was not to definitively identify underground storage tanks using magnetic methods. The purpose was to narrow down the range of sites for excavation, rather than pursue a course of random excavation, or worse yet, a course of no action, due to a lack of information.

The following results are from a recent investigation of underground storage tanks at two sites at Hill Air Force Base. Hill Field, as it is known, lies on the Quaternary Weber Canyon Delta Formation, which consists of interbedded silt, sand, gravel and clay lenses.

PRINCIPLES

For the purposes of an engineering or environmental surface site investigation, the objective of a magnetic survey is to detect, by means of surface measurements, variations in the magnetic properties, or magnetization, of the subsurface. These variations in subsurface magnetization commonly arise due to geological structure, such as a pegmatite vein or basaltic dike in granite, a fault in bedrock, or hydrothermal alteration. They can also arise from prior human disturbance of alluvium or soil, from the presence of magnetic objects in the subsurface, such as a steel underground storage tank, and in the same instance, from the presence of a nonmagnetic void in the subsurface, such as fiberglass storage tanks, if the surrounding soil materials are magnetic. The presence of a lateral variation in magnetic properties due to an object or void in the subsurface gives rise to a lateral variation in the magnetic field at the surface of the earth, above the object. The variations in the magnetic field arise either because the object has a large magnetic field of its own that adds to the background magnetic field, or, alternatively, in the case of a void at depth, because the absence of alluvial material in the void gives rise to a local reduction in the magnetic field. Note that the fluid in an underground storage tank does not directly give rise to a magnetic signal; it is the absence of alluvium or the presence of highly magnetic material that gives rise to the signal that we seek to measure at the surface. Values of the magnetic field above or below expected background values are known as anomalous values. Collectively these anomalous values define the spatial variations in the field that we measure, and constitute magnetic anomalies. Mapping magnetic anomalies on the surface allows us to infer the presence or absence of magnetic material in the subsurface.

The successful completion of magnetic surveys for any site investigation requires that a number of distinct operations be carried out at each site. The first entails magnetic field measurements along profiles (or a grid) in the field area. Both accurate and precise measurements of the magnetic field strength are required. Field strength is the magnitude of the geomagnetic field, and therefore is a scalar quantity; it is commonly referred to as the 'total field.' The total field is the most commonly and easily measured quantity in surface magnetic surveys. Proton precession instrumentation is commonly used for such measurements. In addition, instruments arc available that can simultaneously provide measurements both of the field strength and of the vertical component of its spatial gradient (the 'gradient').

The earth's magnetic field varies not only with spatial position but with time also; consequently, the second operation of importance is measurement of the time (diurnal) variation of the geomagnetic field at a fixed point at the site. The time variation, once quantitatively documented, can be factored into the data reduction procedure. The location where diurnal variation is established is often referred to as a base station. Measurements at the base station made at time intervals from 5 to 30 minutes are commonly acceptable, depending on the rate of the diurnal variation. Importantly, one must also record the times at which data arc acquired by the other "roving" magnetometer(s) used to establish the spatial variation of the magnetic field.

Keeping tally of the geomagnetic diurnal variations brings up an important consideration. Electric power lines can create problems in magnetic surveys because the current flow gives rise to an alternating magnetic field, which interferes with sensor operation—especially problematic for proton precession magnetometers. Because of this it is difficult and often impossible to carry out a magnetic survey in the vicinity of electrical power lines. The problem is not limited to high-tension AC and DC lines; innocuous-looking rural lines can be a source of grief. While it is not reasonable to offer a safe distance that can be used in a general situation, repeatability of the measurements is usually a sure sign that power lines arc not a problem. In areas where power lines arc present, fluxgate magnetometers (discussed below) offer a decided advantage in that the sensor is not overwhelmed by 60 Hz alternating current

The third important step is assigning all observations unique locations in space. Accurate and precise measurements of the magnetic field and gradient must be spatially located. From an operational point of view this is essential for producing reliable contour maps, or for comparison of individual profiles that cross an area of interest. From an interpretational and applications point of view, if we wish to actually locate and recover a tank or some other source buried in the subsurface, the accuracy of our measurement locations becomes important. In terms of practice, the effort required to locate observations with an error of 0.2-0.3 m is minimal. Achieving this end entails some land surveying, which can be accomplished by means of a variety of procedures, varying in complexity from measuring with a tape, to using a total-station electronic theodolite with electronic distance meter (EDM).

Magnetic Quantities and Units

Before discussing the magnetic surveys acquired at our field sites, a brief review of magnetic quantities and units will be of use. When working with magnetic fields in free space, i.e., above the ground surface, we need to distinguish between cgs (centimeter-gram-second) and mks (meter-kilogram-second) or SI units. In the cgs system of electromagnetic units (cmu), used in applied geophysics for many years, magnetic fields in free space can be referred to in terms of the induction, B, or the field intensity H. That is, in free space = B and H arc vector fields, with magnitude B and H. In the cgs cmu system B has units of Gauss (G) and H has units of Oersted (Oe). Dimensionally, the units of these two quantities are equivalent. For example, the geomagnetic field has an average magnitude at the earth's surface of about 0.5 Oe, or 0.5 G. For practical reasons, workers in geophysics use a unit known as the gamma (γ). 1 γ = 10^{-5}0e = 10^{-5} G. The magnetometers commonly used in applied geophysics have sensitivities of 0.1 to 1.0 γ. Anomalies in the geomagnetic field commonly range from 10's to 1,000's of γ, depending on the depth and size of the source and its intensity of magnetization.

Turning to the SI (System Internationale), applied geophysicists commonly use B, rather than H, to describe magnetic fields in free space. Contrary to the cgs cmu system, in the SI, B is not the same as H in free space; neither do they have the same units. The unit of B in the SI is the Tesla; units of 10^{-9} Tesla are used in practice. These units arc called nanoTesla, or simply nT. Fortunately, a 1 nT field is equivalent to a 1 γ field. Since the geophysical community is moving towards exclusive use of SI magnetic units, their use is increasingly common. All field strength values arc reported in nT; all spatial gradients of the field arc reported in nT/m.

Instrumentation

As mentioned above, proton precession magnetometers arc commonly used in geophysical applications. The principles of operation of these devices arc discussed in some detail by Telford and others (1976), Griffiths and King (1981), Dobrin and Savit (1988). and Robinson and Coruh (1988). The proton precession magnetometer is based on a transducer that converts the earth's field strength into an alternating voltage, which has a frequency proportional to the field strength. From a classical physics point of view the working of a proton precession magnetometer can be understood as follows. Within the sensor, a relatively large magnetic field produced by electric current in a coil aligns the nuclear magnetic moments of hydrogen nuclei (protons).present in a hydrocarbon-rich fluid (e.g., white gas). The current is turned off and an induced emf (electromotive force) is generated within the same coil due to Larmor precession by the magnetic moments of protons. The frequency of precession and consequently the frequency of the induced emf is proportional to the earth's field (about which the magnetic moments arc "precessing") strength.

In addition to proton precession instruments there arc a number of other instruments that can be used for magnetic surveys. In efforts to accurately record the spatial variations of the field strength or gradient, continuous-reading vertical component fluxgate magnetometers and gradiometers (Clark, 1986), offer an alternative to the discrete sampling inherent in the proton-precession magnetometer (and its more sensitive and more expensive cousin, the optically-pumped magnetometer). As mentioned above, the fluxgate sensor is insensitive to 60 Hz "noise" associated with power lines. Overhauser effect magnetometers (Dobrin and Savit, 1988), based on the principle of nuclear magnetic resonance (NMR), are available for high-precision (~0.001 nT = 1 picoTesla) high-sampling (~ 10 samples per second) applications, however, at this time such instruments are built to customer specification and are used primarily for military applications. Given its precision and sampling rate, the Overhauser-effect magnetometer may have great future potential in geophysical applications. While the continuous reading nature of fluxgate magnetometers gives them an advantage over proton precession and optically-pumped instruments, the mechanical and electronic calibration of fluxgate magnetometers and gradiometers is much more critical, because each fluxgate sensor does not give an absolute reading, but has a continuously adjustable baseline—a problem for gradient measurements, in which the readings of two carefully aligned sensors must be differenced. In spite of these difficulties, fluxgate gradiometers, while not in wide use have proven advantage over other magnetometers in some circumstances.

The spatial gradient of the magnetic field is obtained by using two magnetometers in tandem. The most common configuration has one magnetometer vertically above the other, with a separation ranging from 0.5 to 1 m. The vertical component of the spatial gradient, or simply the gradient, is obtained by differencing two simultaneous measurements of B and dividing by the sensor separation. Clearly, this is an approximation of the gradient, due to the finite separation of the sensors. For example, given a point dipole source (which is equivalent to a uniformly magnetized spherical distribution of a magnetic medium) at mid-latitude, buried at 2 m depth, this approximation, obtained with two sensors 1.75 and 2.25 m above the surface, is within 2 percent of the actual vertical gradient at 2.0 m. The deeper the source (e.g., a storage tank) the more closely does the calculated gradient approximate the actual gradient.

Characteristic Signals

From magnetic field theory (Grant and West, 1965) the magnetic field due either to a point (dipole) source, or a three-dimensional (3D) finite volume of magnetized material, decays in proportion to r^{-3} as we move away from the source; r is the separation between the source and the magnetometer. The gradient of the field, on the other hand, decays in proportion to r^{-4}. By means of Fourier transform it is possible to show that a signal proportional to r^{-4} (the gradient of the field) has more power at higher spatial frequencies, relative to a signal proportional to r^{-3} (the field itself). Consequently, the magnetic gradient signal due to a given 3D source is more limited in spatial extent, compared to the field itself. This will be evident in the magnetometer and gradiometer survey data discussed below.

The field strength and gradient of an ideal source at middle magnetic latitudes, near the magnetic equator, and at high-latitudes (near the magnetic pole) are given in Figure 1. An additional consideration from the r-dependence of each quantity is that the gradient decays much faster than the field as we move away from the source. Therefore, the deeper a given 3D source, the less manifestation it will have in gradient measurements as compared to measurements of the magnetic field. Both the gradient measurements and the field measurements have their merits, depending on the source depth and extent at depth, and the variety of sources present at a site. Finally, whereas it is possible in principle, using Fourier analysis, to obtain the field from the gradient and vice versa, for the purposes of our application it is easier to measure and record both simultaneously.

METHODS

Magnetic surveys at the two sites at Hill Air Force Base were conducted on the 10th and 11th of October, 1988. In addition to measuring the magnetic field on the surface at these sites, we measured the rate of change of the field with elevation—the vertical magnetic gradient.

The magnetic and land survey data were acquired in about 12 hr, spread over two days. This was in spite of the fact that the crew members were not familiar with the equipment, which did not influ-

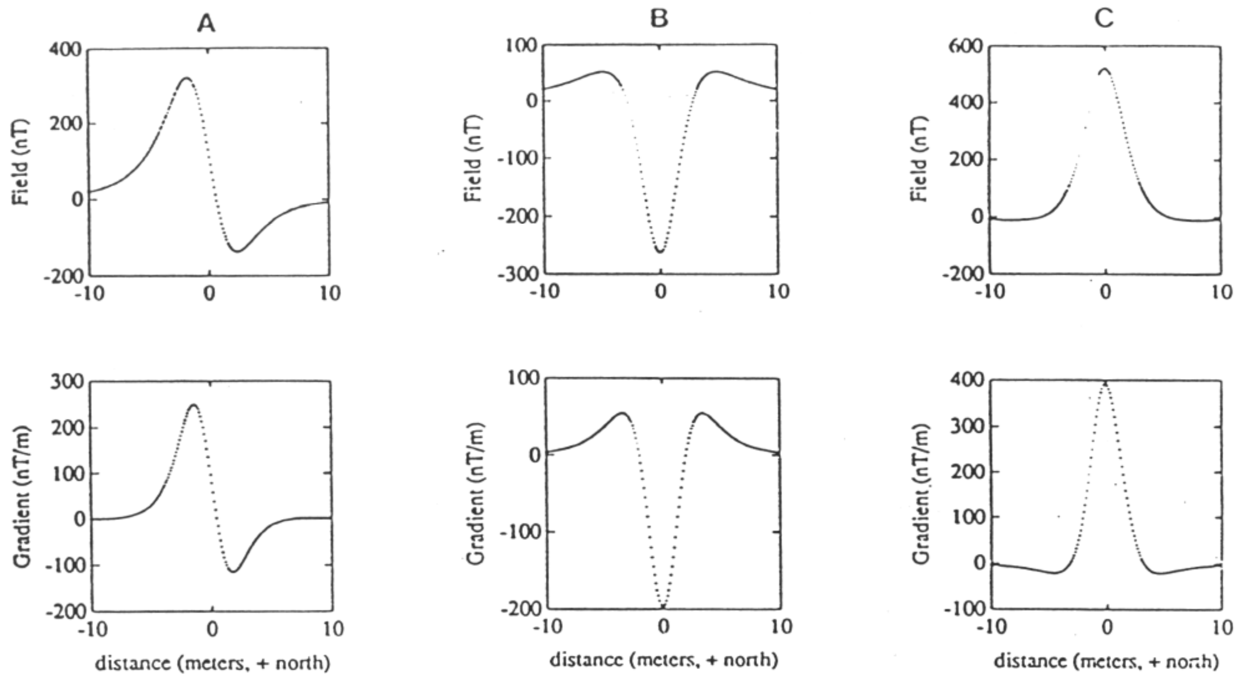

Figure 1. Field strength and gradient for a dipole source (i.e., a sphere uniformly magnetized by the geomagnetic field) as a function of horizontal distance along the earth's surface (south is negative, north is positive). The source has a horizontal coordinate of 0 m. Depth of source burial is 2 m; the field and the gradient are measured at a point 2 m above the ground surface (the vertical coordinate, z, is taken as positive down). A) Source located at mid-latitude (magnetic declination of 0; magnetic inclination of 45°). B) Source located near equator (magnetic declination of 0; magnetic inclination of 0°). C) Source located near pole (magnetic declination of 0; magnetic inclination of 90°). Note that the anomalies in the field strength and the gradient are symmetric with respect to the source location at the equator and pole, but opposite in sign. At mid-latitude, the anomalies are asymmetric features and the maximum is not located over the source, but is displaced a few meters to the south. For all three situations, the gradient varies more abruptly with horizontal distance than the field strength does.

ence our results. A single experienced person and an inexperienced assistant could easily conduct the magnetic and land survey operations. A data logger on the theodolite/EDM and an automated base station magnetometer (to record the time variation of the field) would have eliminated the need for any manual data entry into the computer. Data reduction, checking, analysis and plotting took a day's time, and could be done in half the time by automating and concatenating the separate steps into one. On the other hand, stepping through the process and checking the data at each stage has its benefits.

Acquisition of Magnetic Data

There were no problematic power lines in the vicinity of our sites, and consequently we used proton precession total field magnetometers. An EDA Omni Plus magnetometer/gradiometer was used as the “roving” magnetometer. This instrument combines two proton-precession magnetometer sensors and electronics package, and yields both total magnetic field strength and vertical magnetic field gradient measurements. The sensors arc mounted vertically on a light-weight non-magnetic pole, 2 to 3 m above the ground. The instrument used for our surveys was configured with a sensor spacing of 0.5 m. The measurements of the field strength and its vertical gradient, along with the time of measurement are recorded in instrument memory.

A Geometries model 816 proton precession magnetometer was used for tracking the diurnal variation, with measurements made manually about every five minutes. The magnetometers used for the project arc factory calibrated although we did check them against one another to make sure that their readings of the field at a specific but arbitrary point in space were in agreement. At the end of each day's survey, the magnetometer/gradiometer was connected to a PC-type computer, into which its data were transferred.

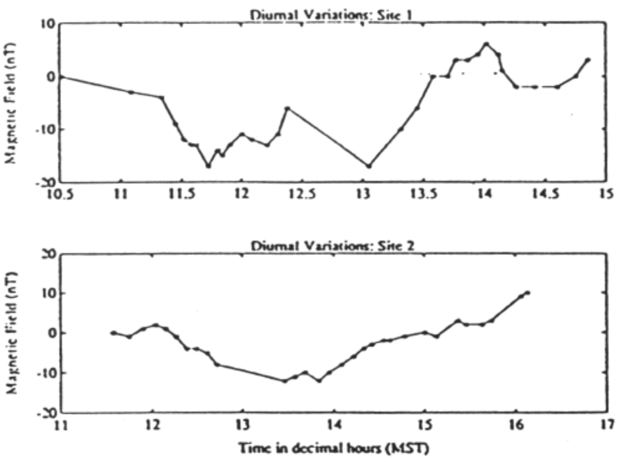

Figure 2. Diurnal variations for surveys at Sites 1 and 2. Time is given as decimal hours (Mountain Standard Time). The first reading of each day has been subtracted from subsequent readings of that day in order to obtain the relative time variations.

Location of Measurements

Each measurement was located by means of land-surveying methods. For the sites described here, our magnetic readings were obtained along parallel or nearly-parallel lines laid out on the ground. The estimated precision for locations is ~0.1 m. The endpoints of each line were located by surveying with a total station theodolite with EDM, and the locations of equally-spaced intermediate points of measurement along each line were located by interpolation. Locations of cultural features such as lamp posts, boundary or cadestral monuments, building corners, etc., were also determined. Additionally, the locations of known magnetic objects, such as road signs, parked trucks, trailers, and other cultural objects located on the site or adjacent to it were surveyed. If simple square or rectangular areas are selected for investigation, a surveying scheme that locates only two corners of the grid, and takes advantage of a grid laid out with cord would considerably simplify the land surveying operation and subsequent survey data reduction.

After entry into a computer the survey data were reduced using software previously developed for other projects. All x-y locations arc cast in arbitrary local x-y coordinate systems for each field site. No nearby control points were available for easy merger of these local coordinate systems with Utah State Plane or Universal Transverse Mercator coordinate systems.

Magnetometer Data Reduction

Diurnal variations of the geomagnetic field as recorded manually with the base station magnetometer for each day's work (data for Site 1 and Site 2 were acquired on separate days) are shown in Figure 2. The maximum variations are generally less than about 30 nT. This magnitude of variation, seen by both the base station and the roving magnetometers, is small compared to the observed spatial variations, which are on the order of 100's to 1,000's of nT, nonetheless, each day's magnetic observations were corrected by removing these diurnal variations, both positive and negative. Linear interpolation was used to estimate the variation at times intermediate to the observation times (every 5 minutes). Cubic spline interpolation can also be used, however, an unconstrained application of splines can cause interpolation problems due to oscillations of the interpolating cubic polynomial(s). In applications where the anomalies in field strength are on the order of a few hundred or few tens of nT, sampling of the diurnal variations needs to be done more frequently, e.g., every minute. Diurnal corrections are not applied to the gradiometer data because each of the two magnetometer sensors used for calculating the gradient see essentially the same diurnal variation. This underscores an obvious advantage of gradient measurements—the diurnal variation need not be established.

Once diurnal corrections were applied to the magnetic field observations, anomalies were calculated by subtracting a value appropriate for the background field 2t each site. The background value at each site was determined in a purely qualitative fashion by visual inspection of contour maps of the field strength, and was taken as the average value of the field intensity in areas of the site where the field showed minimal spatial variability. These values are: 54,000 nT for Site 1, area A; 54,450 nT for Site 1, area B; 54,400 nT for Site 2. Removing the background value from observations at each site yields magnetic anomalies, which must be interpreted. A similar procedure could be applied in the case of the gradiometer data, but in areas with large gradients (Sites 1 and 2) this is unnecessary. Finally, data files of x-y-field strength or x-y-gradient were prepared for each site. These data were then gridded and contoured. It is worthwhile to keep in mind that gridding and contouring arc themselves filtering operations that can either degrade or enhance the signals present in the raw numerical data.

Presentation of Data

The locations of measurements of magnetic field and gradient for Areas A and B of Site I are given in Figure 3, along with the locations of several ref-

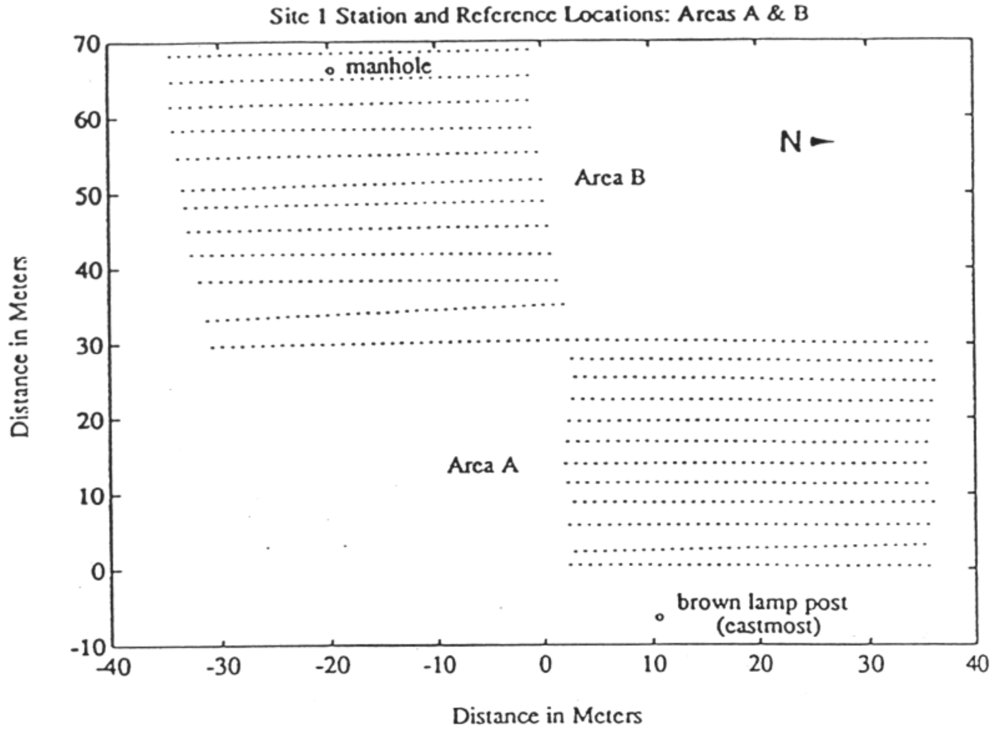

Figure 3. Location of magnetometer and gradiometer observations and selected reference points for Site 1 surveys. The solid dots mark the locations of the observations.

erence points. Figures 4A and 5A are contour maps of anomalies in the magnetic field strength for these Areas A and B. Figures 4B and 5B are contour maps of the vertical gradient of the field strength in these same areas. Figure 6 shows the locations of magnetic field and gradient observations for Site 2, along with locations of reference points. Figure 7A is a contour map of anomalies in the magnetic field strength for Site 2 and Figure 7B is a contour map of the gradient at this site.

DISCUSSION AND INTERPRETATION

A detailed discussion of anomalies in the field strength and the vertical gradient of the field strength for each survey will be illustrative of qualitative interpretational procedures for anomalies caused by underground storage tanks and other cultural features.

One feature of most magnetic surveys, including the ones discussed here, is that we sample at discrete points, rather than continuously. Furthermore, magnetic data arc commonly acquired in profile form and this can have an effect on the contour maps. The effect is readily apparent for data sets that exhibit large variations over short distances on the ground, e.g., the gradient maps (Figures 4B, 5B, and 7B). For example, in Figure 4B, the contour lines show more curvature near the lines along which data (locations marked by dots) were acquired. From a logistical point of view, it is unreasonable to acquire a high-density two-dimensional data set, because of time considerations and because it is superfluous. Instead, we acquire data in profiles, with a small sample spacing along the profiles and a larger sample spacing between the profiles (Figures 3 and 6). If one has an idea of the strike direction of the object(s) of interest then the profiles can be aligned at right angles to the strike. It is worthwhile to remember that a number of minor features in the contour maps of the data are a manifestation of 1) discrete rather than continuous sampling, or 2) anisotropy in the spatial density of data.

Spatial aliasing (Figure 8) along the profiles is not a problem because the sample spacing (spacing between points of measurement) was small compared to the expected spatial wavelength of the magnetic field strength and gradient signals due to a storage tank. Conceivably there is a potential for some aliasing as far as sampling perpendicular to the profile lines is concerned, but experience tells us that this is not a serious problem. When looking for the relatively high-frequency (short spatial wavelength)

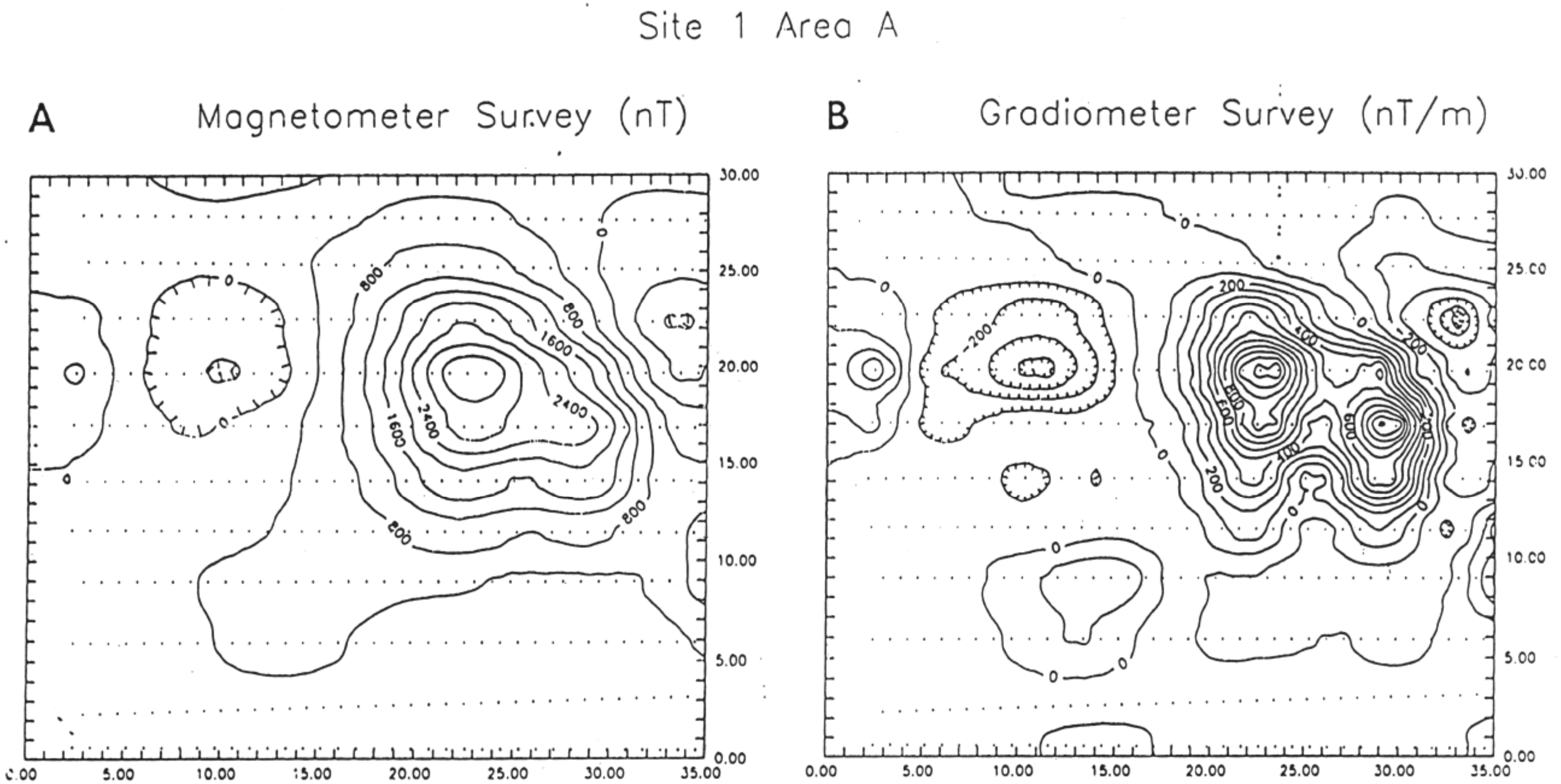

Figure 4. A) Contour map of anomalies in the earth's magnetic field strength for Area A of Site 1. Contour interval: 400 nT. B) Contour map of the vertical gradient of the earth's magnetic field strength for this site. Contour interval: 100 nT/m. The solid dots mark the locations of the observations. Horizontal distances are given in meters.

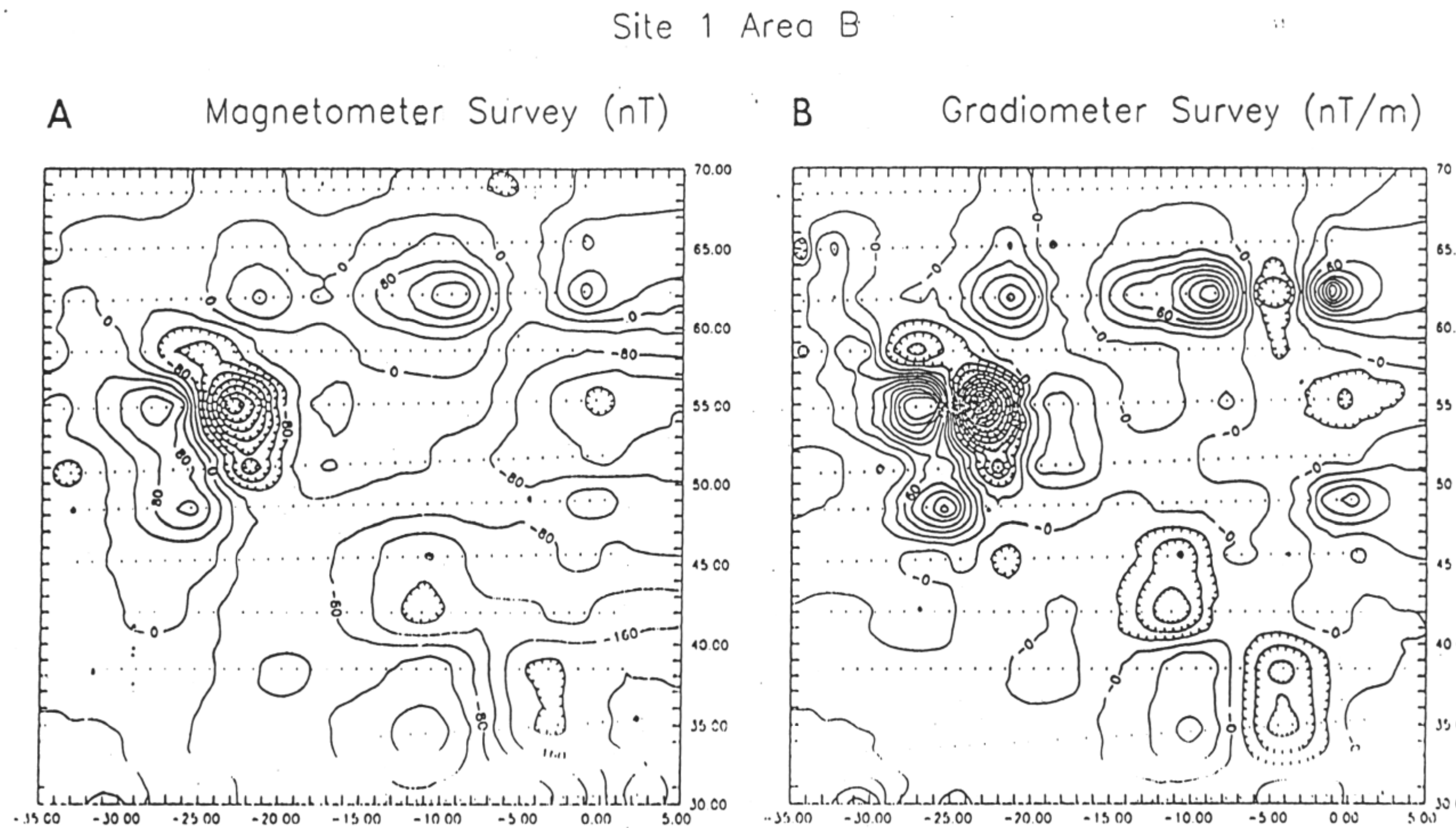

Figure 5. A) Contour map of anomalies in the earth's magnetic field strength for Area B of Site 1. Contour interval: 40 nT. B) Contour map of the vertical gradient of the earth's magnetic field strength for this site. Contour interval: 20 nT/m. The solid dots mark the locations of the observations. Horizontal distances are given in meters.

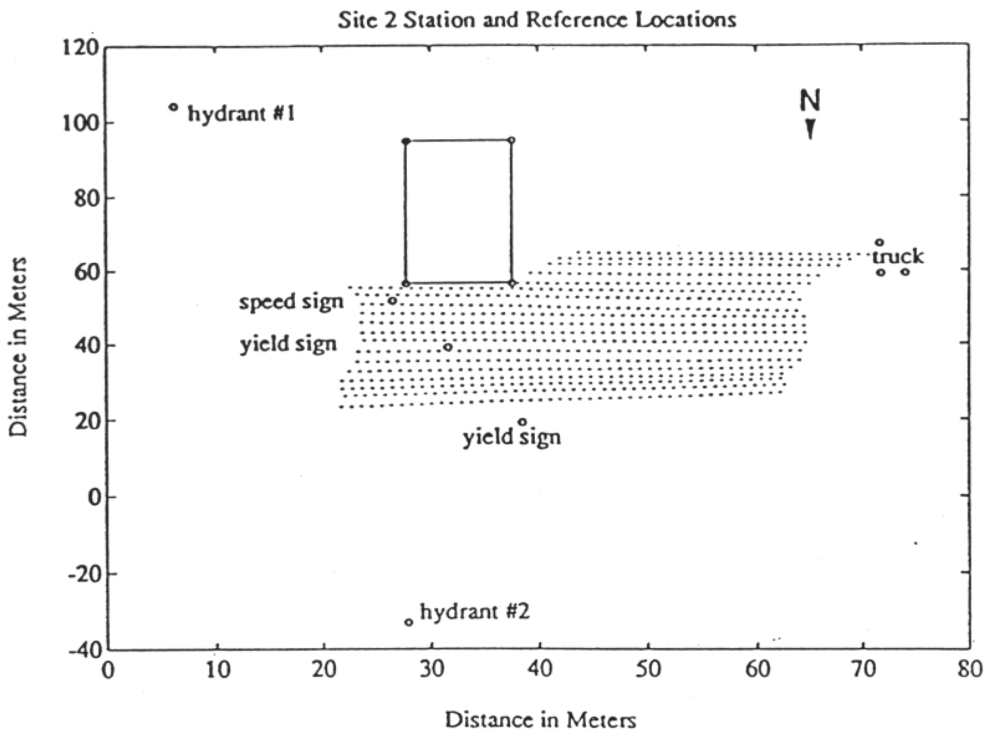

Figure 6. Locations of magnetometer and gradiometer observations and selected reference points for Site 2. The solid dots mark the locations of the observations. Horizontal distances are given in meters. The rectangle marks building 1141.

variations in the gradient, one should generally use a smaller sampling interval than would be used for measurements of the magnetic field strength alone.

Overall then, the contour maps (Figures 4, 5, and 7) offer quite good representations of the magnetic field and its gradient at the earth's surface at each site. A site by site interpretation follows.

Site 1

The area of Site 1 is a paved parking lot with a maintained grassy area adjacent to it. With reference to Figure 3, Area A covers the parking lot and Area B covers a portion of the grassy area. There is thought to be a steel fuel oil storage tank of unknown size and location at the site.

The large positive anomaly in magnetic field strength at Area A of Site I (Figure 4A) is consistent with a three-dimensional magnetic source in the subsurface. The positive nature of the anomaly indicates that the earth's magnetic field is stronger in this part of the area than elsewhere. The amplitude of the anomaly, about 3,500 nT, is very high, and is consistent with a magnetic iron or steel source—presumably an underground storage tank. In fact, results from magnetometer profiles across steel storage tanks of known location (not illustrated) indicate that anomalies of 3,000-5,000 nT can be expected from tanks that hold 1,000-10,000 gallons (4,000- 40,000 liters), buried a meter or so beneath the ground surface. The large anomaly in Area A is broad, which indicates relatively deep burial of a large tank (alternatively, this could indicate numerous smaller sources clustered together). The gradient data (Figure 4B) show two more-localized areas of positive gradient (maximum of about 1,200 nT/m) that can be used to estimate the location of what may be the ends of the tank.

Magnetometer and gradiometer data for Area B of Site I (Figure 5) show much smaller anomalies in the magnetic field and its gradient, compared to Area A. A linear trend of small anomalies in the gradient, located at the top of the contour map in Figure 5B, are thought to be related to a buried 9-cm diameter welded-steel pipeline (abandoned steam line), unrelated to the manhole found in Area B (Figure 3). The manhole is for access to a 15-cm diameter vitreous clay: pipeline, which is presumably nonmagnetic. The manhole and its cast iron cover do not yield much of an anomaly at the ele-

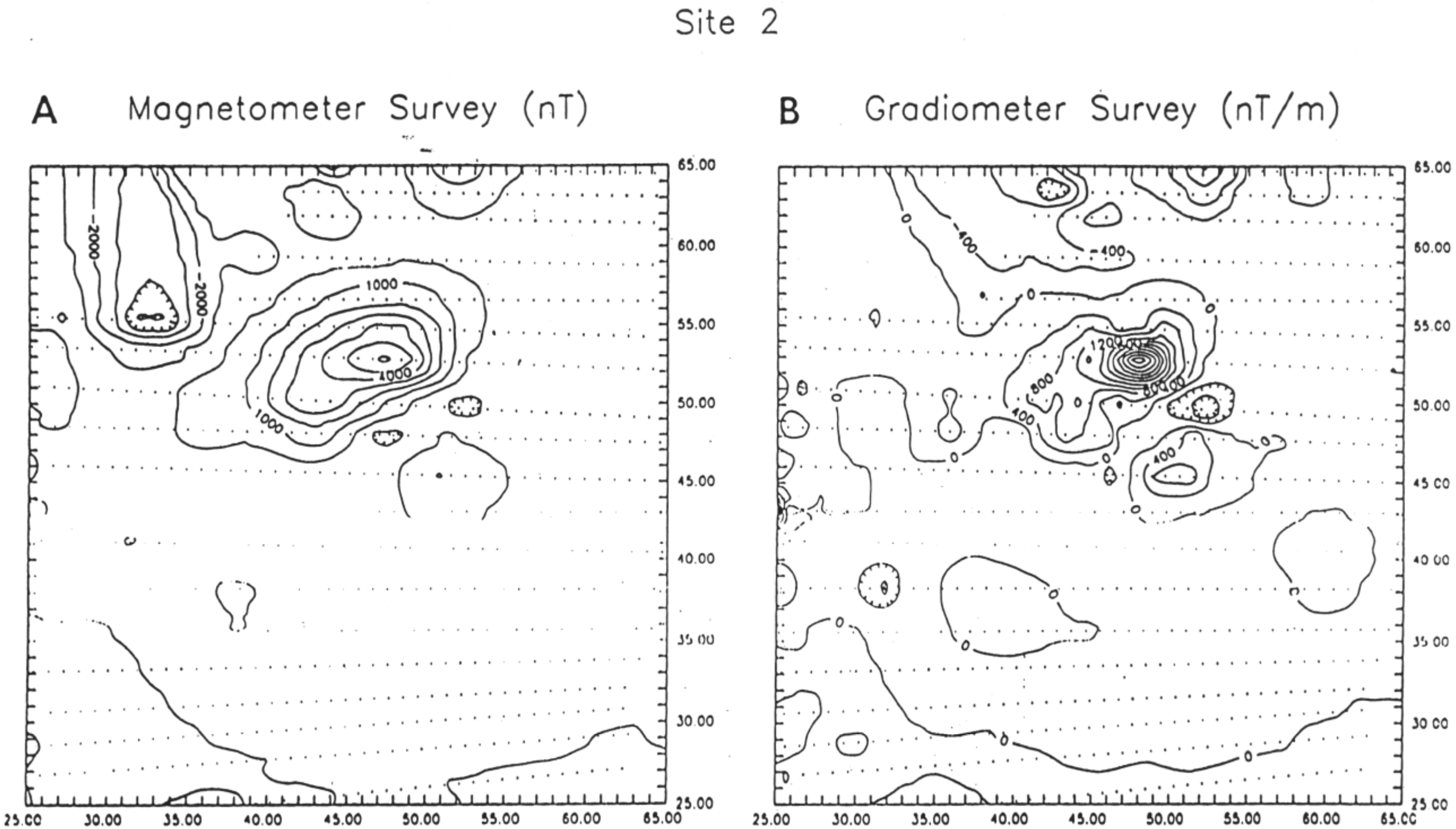

Figure 7. A) Contour map of anomalies in the earth's magnetic field strength for Site 2. Contour interval: 1,000 nT. B) Contour map of the vertical gradient of the earth's magnetic field strength for this site. Contour interval: 400 nT/m. The solid dots mark the locations of the observations. Horizontal distances on the contour maps are given in meters.

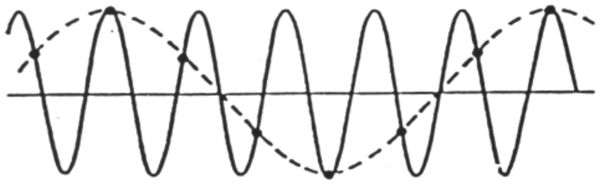

Figure 8. Example of spatial aliasing (from: Anonymous, 1966). The solid line is the signal of interest. The spatial separation of samples (solid dots) is large compared to the wavelength of the signal (solid line), and the signal reconstructed from the samples (dashed line) has a different wavelength than the signal of interest. This highlights the need for the spacing of discrete measurements to be small in comparison to the expected wavelength(s) of the signal that one seeks to observe.

vation of the magnetometer sensor(s)—about 2.5 m above the ground. While I have not investigated this in much detail, from the available literature (Bozorth, 1951; Brandes, 1983), it seems that cast iron is not that strongly magnetized, compared to heavy steel plate steel traditionally used for underground storage tank construction. It is not unlikely that the combination of a large nonmagnetic void (the manhole) and a magnetic disk of cast iron (the cover) yields not much of an anomaly 2.5 m above the structure. There is no doubt that were one to repeat the survey with the gradiometer near ground level, the cover would yield a substantial signal. This underscores an alternative method for doing these types of surveys: bring the magnetometer sensors down close to the ground when looking for weak signals (Clark, 1986), but be ready for extremely high magnetic field and gradient readings when crossing over objects such as manhole covers.

The main anomaly in magnetic field strength, located in the left-central region of Figure 5A, is a negative anomaly (the field strength here is weaker than that in the surrounding area) of low magnitude, about 320 nT above background. The shape of this anomaly is consistent with either a void in weakly magnetic soil (which describes the soil at the site fairly well), or remnant magnetization. While the amplitude of the anomaly is rather low for the steel underground storage tank thought to possibly exist in the subsurface of this area, the anomaly is larger and more localized than what one would expect for a fiberglass or unreinforced concrete tank. The negative sign could indicate remnant magnetization of iron. The spatial extent of the anomaly is limited, indicating either shallow depth of burial or small source dimension.

Collectively, the amplitude, negative sign of the largest anomaly in the area, spatially-limited nature of anomalies in the area, and, the occurrence of small anomalies along a linear trend, suggest cultural features other than a "generic" steel underground storage tank in Area B. One of the difficulties of interpreting anomalies due to cultural features at many sites, including this one is that recordkeeping has not always been given the priority that we would like it to have had.

Site 2

The area of Site 2 is a gravel lot adjacent to a utility building, which is indicated in outline on Figure 6. There was thought to be a steel gasoline storage tank of unknown size and location at the site.

Locations of data points and of reference points for the magnetic survey at Site 2 are given in Figure 6. Anomalies in the magnetic field strength (Figure 7A) and the gradient (Figure 7B) need to be interpreted in the light of known cultural features (Figure 6). When interpreting these data, one must keep in mind that selection of contour interval is a filtering process; e.g., an interval of 1,000 nT (Figure 7A) will exclude isolated anomalies with amplitudes less than about 1,000 nT. Looking first at the anomalies in magnetic field strength (Figure 7A), one large central positive anomaly is clearly evident, with an amplitude of almost 6,000 nT —a likely signal from a large buried steel object, presumably an underground storage tank. To the left of this anomaly is a smaller negative anomaly. However, a check of Figure 6 reveals that this anomaly is related to the northern edge of building 1141, and is therefore not of interest for the purposes of this study. The contour map of anomalies in the gradient (Figure 7B) shows a large anomaly, with an amplitude of almost 4,000 nT/m, at the same central location. This anomaly in the gradient has more-limited area extent than the anomaly in field strength and clearly marks the likely location of the underground storage tank thought to exist in the area. Interestingly enough, the gradient data do not show a signal from the northern edge of building 1141, pointing out another advantage of the gradiometer. The gradient data probably do not show this feature because the source within the building was probably at the same vertical level as the sensors, rather than in the ground. The line of small anomalies on the left edge of the gradient map (Figure 7B) arc thought to be related to a utility line in the subsurface—possibly a steel water line connecting the fire hydrants marked in Figure 6. The anomalies it the top of Figure 7A and

7B can be related to trailers and trucks parked at the edge of the site.

A few final comments on interpretation arc warranted. In magnetic interpretation modeling commonly is used to determine geometric and physical characteristics of the source(s). Reasonable objectives of modeling might be to estimate the depth of burial or to determine the amplitudes and shapes of anomalies that can be expected from various sources with simple geometry, or, the effects of latitude (Figure 1). Interpretation of data by means of simple modeling entails either a qualitative or a quantitative comparison of the observed data with the magnetic field or gradient due to ideal objects, such as a cylindrical shell with a specific radius, thickness, length, depth of burial and magnetization. Sophisticated modeling, either in the forward or inverse sense (Telford et al., 1976; Griffiths and King, 1981; Dobrin and Savit, 1988; and Robinson and Coruh, 1988) commonly requires greater expenditure of time, and may be of limited value for site investigations of the type described here. This is especially true for steel and cast iron sources, because the magnetization of objects such as fabricated steel underground storage tanks is likely to be heterogeneous, and it may depend greatly on the level of remnant magnetization; point to point variations in the direction of magnetization, which are not known a priori, cannot be reasonably established from observations of the field or its gradient.

In contrast to steel tanks, fiberglass or unreinforced concrete tanks can be expected to produce small signals of only 10 to 20 nT (40,000 liter tank buried 1 m deep) provided that the surrounding alluvium is weakly magnetic (susceptibility of 10-3 dimensionless SI units). If detected, these signals can be readily modeled, because for such tanks, the source of the magnetic anomaly is the void itself, and for this class of tanks the void has ideal geometry and magnetization for modeling (e.g., a uniform cylinder, the magnetic field or gradient of which can be calculated). However, the detection of signals due to fiberglass or concrete tanks would certainly require high-precision work with careful analysis (including filtering of the data) and interpretation. Contamination of the signal by cultural features present at the site may be problematic. In any case, a sensor near ground level, closer to the source, will enhance the signal.

A final precaution centers on the non-uniqueness inherent in magnetic interpretation. While one certainly can evaluate the intensity, polarity and size of an anomaly using surface measurements, and make an interpretation in terms of what the source actually is, using some a priori knowledge of what the possible sources are (as in the interpretations made in this study), determination of source geometry (depth of burial, shape) is a problem with an inherently nonunique solution. Working to limit the possible solutions is a worthwhile endeavor and reaching this goal invariably entails bringing a suitable number of 'constraints to bear on the interpretation problem. In the case of underground storage tanks, a knowledge of tank materials, sizes, depths of burial commonly used, and known cultural features in the area (e.g., buried utility lines) may well constrain the interpretation to the point where the family of solutions is manageable.

EXCAVATION

Based on the magnetometer and gradiometer results (Figure 7) an excavation at Site 2 began on the 20th of November 1989. Excavation was started at the center of large anomaly in the vertical gradient (Figure 7B). Buried 1 m beneath the surface was a steel underground storage tank that contained approximately 42,000 liters (11,000 gallons) of a mixture that was predominately water, with a layer of oil on top. As of November 22 plans were being made for drainage and transfer of this liquid to a treatment facility, to be followed by removal attic tank.

CONCLUSIONS

1. Magnetometers and magnetic gradiometers offer excellent potential for location of underground storage tanks and other buried cultural features of interest for site investigations that focus on hazardous materials. The methods could be useful in other types of investigations as well. These magnetic surveys can be applied even in areas where known cultural features arc abundant.

2. Measurements of the magnetic field strength and its vertical gradient arc easily obtained with commercially available instrumentation. Precise horizontal location of measurements is critical if interpretable results arc desired.

3. Measurements of magnetic field strength often complement gradient measurements. Since both can be acquired at the same time, with no additional effort, the added constraints on interpretation warrant the use of both for many site investigations.