# 8

# Geophysical Surveying of Archaeological Sites

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ABSTRACT

*In this chapter the two most commonly applied geophysical methods for assessing archaeological sites are described in detail. Magnetic surveying responds to contrasts in the magnetic properties of soils, which can be brought about by, among other causes, human activities such as burning, by humic decomposition, by compaction, and by the introduction of structures. Resistivity surveying responds to differences* in *the electrical conductivity of soils, which can be brought about by, among other causes, alterations of the natural soil profile through the construction of mounds or ditches, by compaction, or by the introduction of structures. Magnetic surveying is independent of soil moisture but will not respond if a structure is composed of the same magnetic material as the surrounding soil. Resistivity surveying is strongly dependent on soil moisture and on the contrast in porosity between a structure and its surrounding matrix.*

*Magnetic surveying is faster and easier to interpret but cannot easily be carried out near interfering magnetic sources, such as modern buildings or power lines. Resistivity surveying is slower and somewhat more difficult to interpret but is free from the interference of nearby buildings and power lines.*

*Like all remote sensing methods, those described here are nondestructive and are considerably more economical than test excavations, if they are properly conducted. A geophysical survey carefidly coordinated with an archaeological program can provide valuable information for the planning and execution of that program, as the examples given for both techniques demonstrate.*

The last 25 years have seen many applications of geophysical survey techniques in archaeological site surveying. The methods usually emerged from small-scale field experiments by physicists and geophysicists; they were then applied primarily by European archaeologists. In the last decade, however, there has been a growing awareness among American archaeologists of tile value of geophysio methods in site location and mapping.

The various geophysical techniques for• gathering information about subsurface features all depend, in one way or another, on differences in electric magnetic, or elastic (seismic) properties of rocks and sediments. The technique may be classified as passive or active. In the first category, existing force fields a measured directly without instrumentally generated signals and the results are interpreted in terms of subsurface features perturbing the field. Magnetic thermal, and gravity measurements fall in this category. In the second or active category, instrumentally generated signals pass through the subsurface and are then detected and recorded. Seismic techniques, electromagnetic technique (including use oldie simple metal detector, the pulsed-induction metal detector and the soil conductivity meter), earth resistivity measurements, and the recently developed ground-penetrating radar are all active devices. This chapter will deal with one technique in each category: magnetic and earth resistivity surveying. For summaries of most geophysical methods see Aitken (1974) or Ti (1972).

## MAGNETIC SURVEYING

### SUMMARY OF METHOD

Magnetic surveying (or prospecting), as practiced on archaeological sites, con lists of measuring the magnitude of the earth's magnetic field at each point on grid established over the site. Variations in the magnetic properties of the subsurface material (sediments, rocks, or artificial materials such as brick) can produce an observable variation (anomaly) in the measured magnetic field. Anomalies may he caused by artificial structures such as walls, ditches, foundations, fire hearths, pits, or even an area of more intensive habitation. The task of interpretation—to separate the results of human activity from geological variations in subsurface materials—is guided by knowledge of the physics of so magnetization and by the manipulating and displaying of the data in various ways so as to reveal significant patterns. At any site, successful application of the method depends on the magnetic properties of the local subsurface, the external and nature of the human activity, the burial depths of artificial and natural features, and, filially, the care taken in field measurement and analysis.

### HISTORICAL DEVELOPMENT

For several decades geophysicists have used magnetic surveying In the search for minerals, but until 20 years ago the instruments available were not sufficiently sensitive for archaeological applications. The development of the proton magnetometer provided just the needed sensitivity. Belshe (1957) seems to have been the first to experiment with a proton magnetometer in an archaeological context. He was followed by Aitken, Webster, and Rees (1958), and soon the Oxford University group under Aitken was obtaining results of archaeological usefulness. Subsequently, groups developed in Germany (Scollar, 1961), Italy (Lerici, 1961; Linington, 1964), and France (Hesse, 1962). The literature in this field is now fairly extensive. Reports of technical aspects, until recently, have been concentrated in four journals: *Archaeometry, Prospezioni Archeologiche, Revue darchëometrie* and *Archaeo-Physika.* The literature on applications is scattered throughout a number of geophysical and archaeological journals; extensive references may be found in Aitken (1974) and Tite (1972).

In the United States, an early practitioner of magnetic surveying was the NIASCA group at the University Museum, University of Pennsylvania, under Rainey (Rainey and Ralph, 1966) and Ralph (1964; Ralph, Morrison, and O'Brien, 1968). Their applications for the most part were in the Old World, as was the survey work by Rapp and Henrickson (in McDonald and Rapp, 1972). To our knowledge the first recorded application on this continent was at Angel Mounds by Black and Johnston (1962). Subsequent applications in this hemisphere are documented in Ezell et al. (1965), Morrison, Clewlow, and I leizer (1970), Greiner and Coe (1972), Arnold (1974), Nashold (1977), and von Frese (1978). The MASCA group has conducted some magnetic surveys in the eastern United States (Bevan, 1975).

The present writers recently started magnetic surveying on sites in the Central Plains (Weymouth, 1976) and, in conjunction with the Midwest Archaeological Center (National Park Service) and other agencies, have surveyed or analyzed data from surveys covering approximately 33 hectares in about 10 states and a few sites outside the hemisphere (Weymouth and Nickel, 1977; Weymouth, 1979; Bleed et al., 1980).

In the last few years several groups and individuals throughout the United States have started using magnetic surveying on sites. In one case a group from Michigan State University has covered a fairly large area (Mason, 1981).

### THEORY

The magnetic field at any point on the earth can be defined, for our purposes, as the direction taken by a compass needle freely suspended there. The direction can be specified in terms of *declination,* the angle between true north and the horizontal component of the earth's field, and inclination (or *dip),* the angle between horizontal and the direction of the total field. The field strength or magnitude is proportional to the maximum torque exerted on the compass needle by the field. In this chapter the unit of magnetic field strength used is the *gamma* (1 gamma is also equal to 1 nanotesla, the SI unit). The earth's magnetic field in the United States varies from roughly 49,5(X) to 59,500 gamma, and its inclination varies from 60° to 75° below the horizontal.

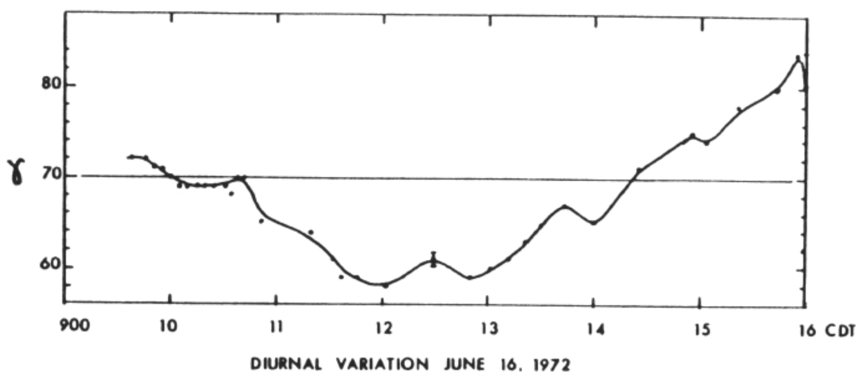


**Fig. 8.1.** Typical diurnal variation recorded by a stationary proton magnetometer.

Another aspect of the magnetic field with which we must be concerned is its variation with time. In a regular diurnal variation the magnitude decreases during the middle of the day by approximately 20 or 30 gamma from higher morning and evening values (fig. 8.1). During magnetic storms larger variations occur over time periods of a few hours to days.

### *Magnetic Properties of Soils*

In the presence of a magnetic field, material such as soils, rocks, and ferrous objects can become magnetized. Such a magnetization is said to be *induced.* In addition to induced magnetization-, which vanishes when the applied field is removed, some materials exhibit *remanent* magnetization, magnetization that persists in the absence of an applied field. Baked clays and some rocks retain a thermoremanent magnetization after being heated to several hundred degrees centigrade and then cooled in a magnetic field. Remanent magnetization can also arise from chemical change or from the settling of small particles in a magnetic field (see pp. 240-43).

A range of time responses exists between the extremes of permanent magnetization and the very rapid component of induced magnetization. Because the time response depends on particle sizes in the soil, parts of soils can become magnetized very rapidly while other parts change their magnetization very slowly. (This phenomenon of *viscous magnetization* is explained in detail on pp. 243, 245.)

The compounds in soils which are important in causing magnetization are hematite (*a*— $Fe_2 0_3$), magnetite ($Fe_3 0_4$) and maghemite $Fe90_3$). The hitter two compounds are much more strongly magnetic than the first, their saturation magnetization being approximately 200 times that of hematite. Since soils contain a few to several percent iron oxides, these compounds and their



conversion from one form to another are the significant factors of soil magnetization. Two measures of the response of a material to magnetization are its *magnetic susceptibility,* which is the ratio of magnetization (dipole strength per unit volume) to magnetic field strength, and its *specific susceptibility* (dipole strength per unit mass per unit field). This latter quantity is measured in emu per grain. (For definitions of units see Aitken, 1974:140.)

Typical values for specific susceptibility are as follows (all in units of 10' einu/g).

| | |
|---|---|
| Limestone, some unbaked clays | 10 |
| Subsoils | 50-100 |
| Topsoils | 100-1,000 |
| heated soils, fired clays | 1,000-2,500 |

Natural and anthropogenic activities can cause a conversion from hematite to magnetite or maghemite, thus resulting in a greater susceptibility. Such conversion processes, explored by Le Borgne (1955, 1960), occur when hematite is reduced to magnetite either during heating, as in a hearth, or during anaerobic decomposition in humic soil. Consequently, topsoils usually have a higher susceptibility than subsoils and hearths, while burned houses and trash pits may be even more magnetic. For a complete discussion on various aspects of soil magnetization relating to magnetic surveying of archaeological sites, see Graham and Scollar (1976).

### *Measurement of the Magnetic Field*

The three instruments primarily used for archaeological surveys are the proton free-precession magnetometer, the fluxgate magnetometer, and the cesium or rubidium magnetometer. The proton magnetometer is the least expensive and by far the most widely used. Its sensor consists of a coil surrounded by a hydrogen-rich liquid (water or kerosene). A polarization current through the coil creates in the liquid a magnetic field many times more intense than the earth's. This field partially polarizes the hydrogen's nuclear protons, which are spinning magnetic dipoles. The polarization current is then quenched and the protons precess (gyrate) in the field of the earth. For the few seconds that the protons precess coherently, a voltage is induced in the coil. This voltage is amplified, the frequency measured, and the results displayed in gammas. In older commercial units the total cycle time may be 7 seconds, but this can be shortened to 3 or 4 seconds with no loss of sensitivity; the normal sensitivity is 1 gamma, which can be increased to 0.25 gamma in the usual portable models. Commercial units arc now available with cycle times of 1.5 seconds and sensitivities to 0.1 gamma.

The fluxgate magnetometer measures the component of the vector field along the axis of a coil and is thus strongly direction-dependent. This disadvantage can be overcome by combining two instruments as a *gradiometer,* which is direction-independent. A gradiometer measures the magnetic gradient or difference in magnetic field at the two sensors. The requirement for parallel alignment of the detector units is stringent; therefore, the cost of a differential fluxgate magnetometer is high.

In cesium or rubidium magnetometers atomic electrons of these two elements (in a vaporized state) replace the nuclear protons of the proton magnetometer; otherwise the operational principles are comparable. Both fluxgate and cesium or rubidium magnetometers have a high sensitivity and also provide continuous measurements of the field, but their costs are greater than that of a proton magnetometer.

*Anomalies Produced by Local Features*

An isolated magnetic feature (termed a *source)* whose dimensions arc small compared with the sensor distance produces the simplest, so-called dipole anomaly. A *normal dipole anomaly* results from induced magnetization (such as in a small pit), where polarization will be in the same direction as the earth's field. However, dike magnetization is permanent (such as in a piece of iron, a burned rock, or a fire hearth), the polarization may be in a different direction than that of the earth's field and the resulting anomaly is termed a *nonnormal dipole anomaly.*

The total magnetic field in the neighborhood of a normal dipole anomaly is the combination (vector sum) of the uniform, downward-pointing field of the earth and a weak, dipole field from the source feature. The profile of magnetic values measured along a south-north line is represented in figure 8.2. Three characteristics of this anomaly type may be noted:

I. The maximum intensity of the magnetic profile is displaced to the south of the source by about one-third the source–sensor distance.

2. The full width of the profile at half maximum is about equal to the source–sensor distance.

3. The negative region, due to the source dipole field opposing the earth's field, is about 10 percent of the maximum intensity. As in the first characteristic, this is true at midlatitudes.

Deviations of a magnetic anomaly from these characteristics imply a nonnormal dipole—that is, a source with permanent magnetization. Long, narrow pieces of iron or burned rocks in particular produce anomaly profiles with large deviations from those of normal dipole anomalies. Thus, if the minimum is not north of the maximum, or if the minimum deviates appreciably in magnitude from 10 percent of the maximum, one can conclude that the source is not a feature resulting from induced magnetization.

The magnitude of the anomaly depends strongly on the source–sensor distance, decreasing proportionally with the inverse (Witte cube of that distance. The magnitude also depends on source volume, *V,* and magnetic susceptibility contrast, *k.* For further discussion see Breiner (1973), Tite (1972), Aitken (1974), or Weymouth (1976).

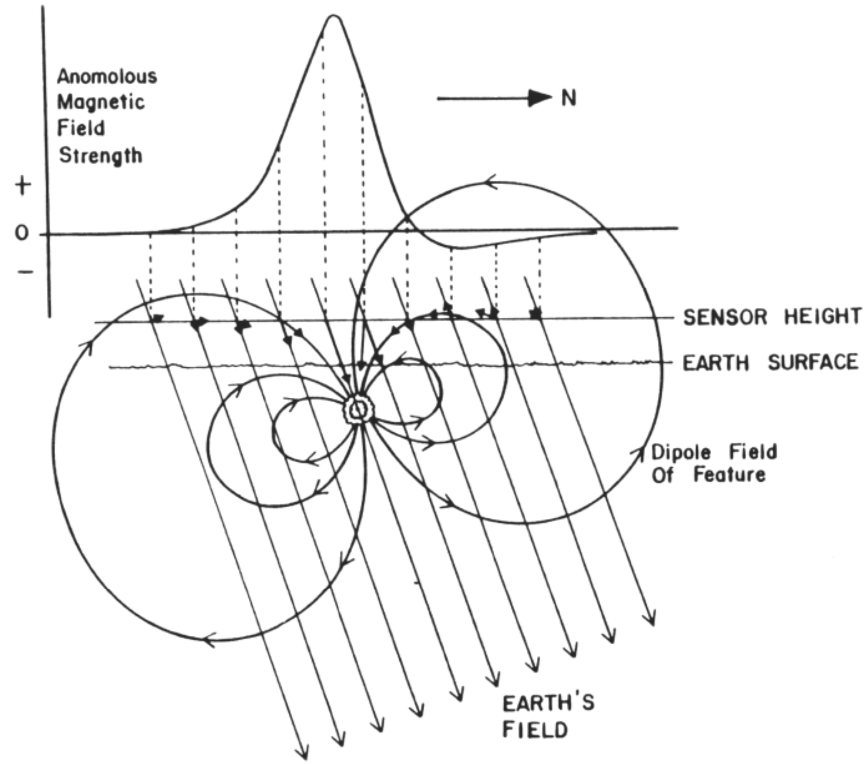


**Fig. 8.2.** Combination of a dipole magnetic field produced by a local source and the magnetic field of the earth. The plot is that of the magnitude of the sum of the two fields as measured by a magnetometer passing over the source.

A filled ditch oriented east-west is like a row of parallel dipoles, with a negative anomaly north of the maximum. For other shapes—ditches, plates, etc.—see Aitken and Alldred (1964), Breiner (1973) or Linington (1972).

APPLICATION OF THE METHOD

The method to be used in surveying a site depends on the information sought. If one wants information on possible linear features, such as ditches or walls of known orientation, or if the location of small features (such as fire hearths) in buildings of presumed location are known approximately, then one or a few magnetometer traverses may suffice. If surveying is done over a short period of time, it is not necessary to use a second or reference magnetometer; plotting profiles of such traverses may be sufficient to reveal the information desired.

If simple traverses do not suffice, then the problem is to seek patterns of anomalies in a two-dimensional mapping of the magnetic field over the site.

Mapping is accomplished by measuring the field on a grid of points over the site. When more than a few minutes are needed to survey the area, some method must be used to correct for the temporal variations of the earth's field. Without such corrections, the resulting magnetic map will be distorted and spurious anomalies will appear, particularly along traverse rows. The basic idea behind all corrections is the assumption that the earth's field changes in time simultaneously everywhere over a region considerably larger than the site being mapped. To carry out the corrections, several approaches can be used.

If only one magnetometer is available, it alone can be used to correct for temporal variations. The operator simply intersperses repeated readings at a single reference station between groups of grid readings—for instance, after each row of points. The reference readings are then plotted against time and a curve drawn through them. In this way reference values corresponding in time to each grid value are estimated and subtracted from the grid values. This procedure, however, can still result in incomplete corrections and spurious anomalies, particularly linear anomalies along traverse lines.

To survey a site properly, particularly if it is more than a few meters in area, two magnetometers in either of two modes must be employed. In the differential mode, one magnetometer is kept at a fixed reference point while the other measures values at the grid points. Because the instruments are operated simultaneously, any difference between the two readings represents the total field magnitude, corrected for time variation, at that point. In the gradiometer mode, two sensors are kept a fixed distance apart-1 in, for instance—in a vertical array. Both magnetometers are again operated simultaneously, and the difference in readings is recorded. These values are *gradient magnitudes,* the vertical spatial change of field magnitude. As in the differential mode, the temporal variations are canceled, but in addition any long-range trends affecting both sensors equally are canceled, whereas local anomalies (which will more strongly affect the lower sensor) will be recorded. The writers prefer the differential mode for any extensive survey.

Before starting the field survey of an extensive archaeological site, all visible geological and archaeological features must be examined. Also, the nature, size, and depth of features, as well as the possible existence of iron artifacts, should be ascertained, as this information will shape the field strategy and aid in the final interpretation of the data. Those conducting the survey should work closely with the archaeologists, so both parties share an understanding of the archaeology of the site and the geophysical method.

Some evaluation of the survey's possible success may be obtained by measuring the magnetic susceptibility of typical soil samples from the site. These samples should be taken at representative stratigraphic levels, as well as inside and outside any archaeological features of the site. By measuring the susceptibility of the samples before and after heating in a reducing atmosphere, it is possible to evaluate expected anomaly sizes and to get some information on the extent of anthropogenic hematite-magnetite conversion.

The size of the survey grid unit is determined by the size of the features



expected. Since the number of magnetic field measurements will be proportional to the square of the grid spacing, this choice is *a* compromise between detail sought and time available. Generally speaking, the grid spacing should be comparable with, or somewhat smaller than, the linear dimensions of expected anomalies. Features of a meter or two in size near the ground surface can be surveyed with a 1-in grid. If the features are deeper, then the spatial extent of the anomalies will be larger (as well as weaker) and a larger grid spacing can be used. On historical sites, linear features such as walls or cellars can be picked up with a larger unit. One approach on large sites is to use a coarse grid (such as 2 in) and then concentrate with a 1- or 1/2-m grid in areas of greater magnetic activity.

In choosing sensor height above the surface, two considerations must be noted. First, since the width of an anomaly increases with the source–sensor distance, a greater sensor height will result in less resolution between anomalies from neighboring sources. An approximate rule is to have the source–sensor distance no greater than the intersource distances that one wishes to resolve. This suggests a source–sensor distance equivalent to or less than the grid spacing.

Second, the sensor height must be selected so as to reduce the relative contributions from surface noise arising from variations in surface-soil magnetization. The noise contribution relative to the signal will decrease with increasing sensor height. Probably the best compromise is to set sensor height at between 40 and 60 cm for a 1-in grid.

A necessity in all archaeological work is the location of some permanent reference points. This is no less true in the case of geophysical surveys. When surveying a site, particularly if it is large, the area should be subdivided into squares or blocks, each of which is treated as a unit. We have found that a block 20 grid units on a side is convenient. This area will have 21 x 21, or 441, grid points and can be surveyed in about 70 to 90 minutes, depending on site conditions. Including the time needed to lay out blocks and set up equipment, it is possible to survey three to five blocks ill a day. If possible, these blocks should be oriented along magnetic north, since this orientation aids in the interpretation of anomalies. For a large site the blocks can be arranged in hectares, five blocks along an edge. The coordinates of grid points in each hectare can be designated *I* north, *J* east, where *I* and *J*) run from I to 101. This is a convenient size array to be handled as a single matrix of values in computer programs.

## OPERATIONAL DETAILS

The following discussion assumes survey operation in the differential mode, with one magnetometer sensor moved from grid point to grid point and one kept stationary for reference readings. We thus speak of moving sensor values, reference sensor values, and their differences.

Our technique for locating the grid points within a block is as follows. Stakes are placed at the four corners of the block and two ropes marked with grid units are placed, one at each end of the block, from stake to stake. Another rope marks the grid points along a traverse row from end rope to end rope. To avoid confusion and aid systematic data recording, all traverses should be conducted in the same direction, either south to north or west to east.

A systematic form for recording data in the field should be carefully planned. The writers use data sheets calling for the following information: site, block, data, grid unit, and names of persons operating the magnetometers. In addition, the height of the sensor and the sensitivity of magnetometers should be noted. Each sheet has space for four rows with 21 grid points and columns for the moving-sensor value, stationary-sensor value, and their difference, the last in case it is desirable to hand-calculate these values. The time of day is recorded at the start of each row. This is desirable if problems of analysis arise and one wishes to reconstruct events at the time; recorded data can also then be correlated with magnetic storm information.

Errors can arise in the hand-recording of data, so it is preferable to machine-record data with a data-collecting circuit connected to the magnetometer. Such a system involves expense and design time but considerably improves reliability.

Before taking measurements, it is important to evaluate the local magnetic environment. Vehicles can produce a shift of roughly 1 gamma at 30 in. Such disturbances are acceptable only if they remain stationary throughout the survey. Larger and closer amounts of iron, if stationary and not too large, can be treated by mathematical filtering techniques applied to the data. Power lines, moving trains, and other nonstationary sources must be avoided.

The person holding the moving sensor must be carefully checked before starting. Steel shoe tips, belt buckles, bank cards with magnetic strips, and even eyelets in hats can cause trouble. Repeated readings should be taken with the person assuming several positions relative to the sensor. Variations in readings should be random and not greater than one or two times the "least count" of the instrument (the smallest possible change in value displayed).

Even if the magnetic field is absolutely stationary in time, a random scatter or noise in reading values of about ±0.5 times the least count will be observed. When two instruments are recorded at the same time and the difference taken, this random scatter becomes -±0.7 times the least count. In actual practice, the reproducibility of difference values (taken by repeated readings at the same grid point, repositioning the sensor each time and calculating the standard deviation) is more like three to five times the least count. This variation in the difference values is a measure of the least amount of noise to be expected. Anomalies smaller than this variation may be lost in this noise unless they are observed on several grid points.

The reference magnetometer should be close enough to the grid points so that communication between the operators is not impaired but not so close that the two sensors interact. Two or 3 in is sufficient. It is important not to locate the reference sensor in a strong magnetic gradient. In such a gradient the instrument can lose sensitivity and give erratic readings. The location should be checked this possibility by taking repeated readings, with the sensor moved slightly between readings. Variations no greater than random noise indicate lack of a gradient.



One final and very important field procedure is the measuring of common rows." Relocating the reference magnetometer between recording two blocks will result in a constant shift in the difference values between the two blocks. This may be corrected by measuring one row common to the two blocks twice, once with each block. The average shift in the differences on the common row is then the correction factor that is added to all the values of one of the blocks to bring them to the same "level" as the other block. If the standard deviation in the distribution of shifts in differences on the common row is greater than 3 to 5 times the least count of the magnetometers, then the correction factor may not be reliable. This can arise by careless positioning of the sensor or by passing over a strong gradient due to an anomaly on the common row. In this latter case small and unavoidable shifts in sensor positions can cause large shifts in recorded values. Either a subset of values on the common row that avoids the anomaly should be used or other common rows should be measured. These problems arc particularly troublesome with matching blocks recorded on several days on a large site.

## INTERPRETATION

The first requirement in the analysis of magnetic data is to produce a matrix of magnetic field values corrected for diurnal variations to be used in all subsequent mapping and profiling. Since the number of values from a site can be quite large, computer processing becomes desirable or even necessary. The following discussion assumes the use of a computer.

Usually, results are presented in various ways so that individual anomalies and patterns of anomalies can be identified. The simplest treatment is to plot profiles along traverse rows, this is useful in seeking linear features of known orientation.

For any more complicated situation it is necessary to examine the areal (two-dimensional) patterns of anomalies. Various forms of magnetic contour maps are generated in which the magnetic field strength is treated as a "height'' on a map of the site. Although simple contour maps can be hand-drawn by recording the magnetic field values on a grid of points and drawing lines of equal magnetic field magnitude through the grid of values, this process can he very tedious and is not likely to be often repeated if the map needs to be redrawn with a different scale or contour interval. Thus it becomes necessary to produce contour maps by a computer.

The most convenient types of computer contour maps are those produced by a line printer. Such maps are quickly generated and easily interpreted because of the visual advantage obtained through use of the shading variations of print characters. They have the disadvantage of relatively low resolution determined by the print character size. In the simplest map type the magnetic field values at the grid points are sorted according to predetermined intervals (usually no more than 10) and print characters of different shades arc printed at the grid points according to these intervals. The result is effective for sites of more than one hectare.

The map next in complexity is based on interpolation between grid points and prints several characters per point. A commercial program package that makes such maps with a wide range of options is SYMAP (1975). A simpler program to obtain some of these same results is described by Davis (1973).

The traditional type of line contour map can be programmed to output on a plotter. Such a map can have much higher resolution but lacks the immediate visual impact of a shaded map. Color contour-mapping equipment is also available, but it is expensive.

## EXAMPLES OF MAGNETOMETER SURVEYS

### *The Knife River Indian Villages National Historic Site*

The objective of this National Park Service project is to assess and develop into a national historic site a collection of Mandan, Hidatsa, and other Native American village sites grouped at the confluence of the Knife and Missouri rivers north of Bismarck, North Dakota (Weymouth and Nickel, 1977). The Midwest Archaeological Center (MWAC) of the National Park Service has been gathering magnetic survey data at Knife River since 1976, with the present writers analyzing them. Two magnetometers in the differential mode have been used to collect data, which since 1978 have been recorded automatically with an electronic data logger.

One of these villages—Big Hidatsa (32M E12), occupied in the late eighteenth and early nineteenth centuries—covers several hectares and is marked today by many depressions left by earth lodges. These show up clearly on the magnetic record, partly due to the, topography, but also due to differences in soil susceptibility inside and outside the lodges: some lodges are visible on the magnetic maps but are not visible in the topography. The most characteristic anomaly of these lodges is their central fire hearths, which lie at depths of 40 to 120 cm below the ground surface and produce anomalies of 20 to 50 gamma. In addition, anomalies associated with smaller interior or exterior fire hearths are visible. Midden areas between houses produce magnetic high regions. These correlations have been established by soil probes and by test excavations.

Figure 8.3 is a grid-point map of data taken over two seasons (1977 and 1978) at Big Hidatsa. Each print character corresponds to data on 1 grid point, with an interval of two grid points between different characters. The map illustrates a way in which one can organize a large survey. Each set of blocks obtained on one day has been balanced against other **sets** by using common rows. Each hectare is handled as a separate matrix in the computer processing.

Figure 8.4 is a topographic map of Sakakawea Village (32M E 1 1), another village of the same time period at Knife River. It may be compared with figure 8.5, a SYMAP magnetic map of the same region with a 9-ganuna interval (Weymouth and Nickel, 1977). Figure 8.6 is the southeastern part of this map with a contour interval of 5.6 gamma. The anomalous regions at N21-31, E80-89 is due to a house not visible on the topographic map. Two excavations in

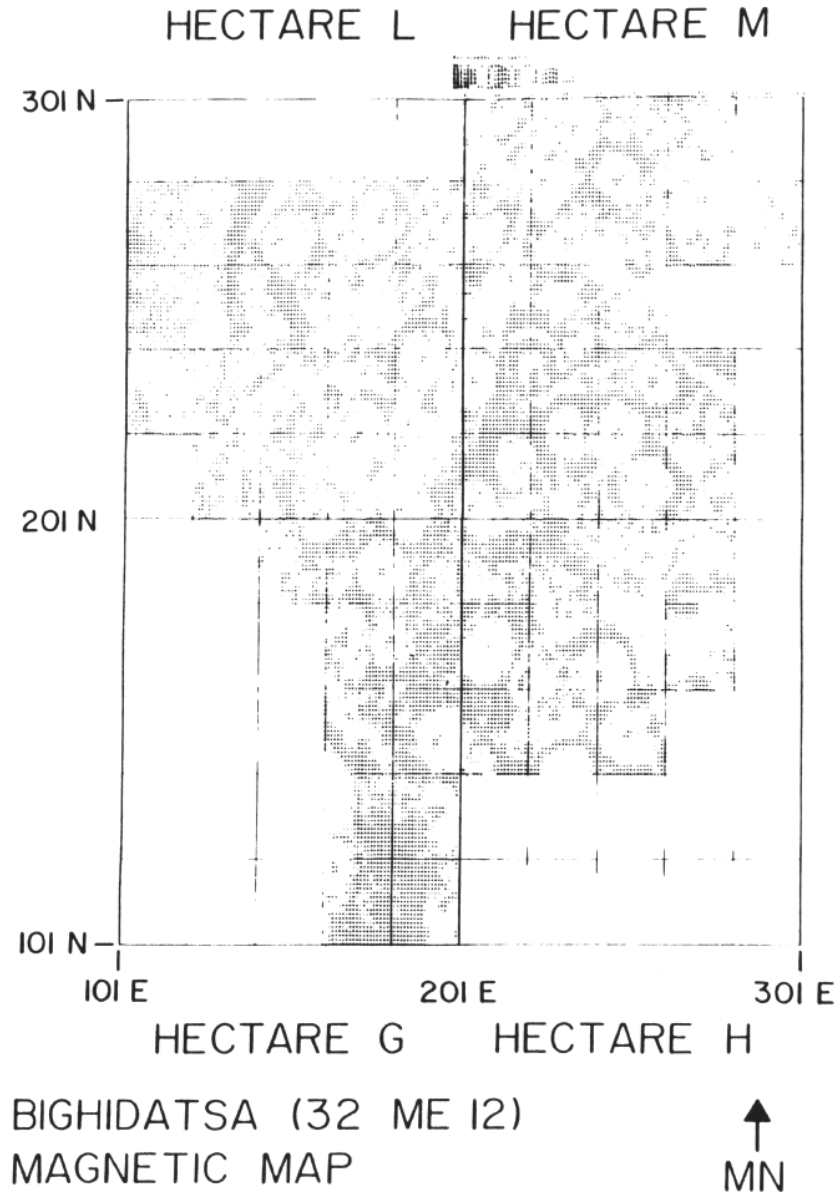


**Fig. 8.3.** Grid-point map (or level map) of parts of 4 hectares of the Big Hidatsa site (32ME12), Knife River Indian Villages National Historic Site. Each print character is at a grid point. Each increment in character darkness represents an increase in two gamma.

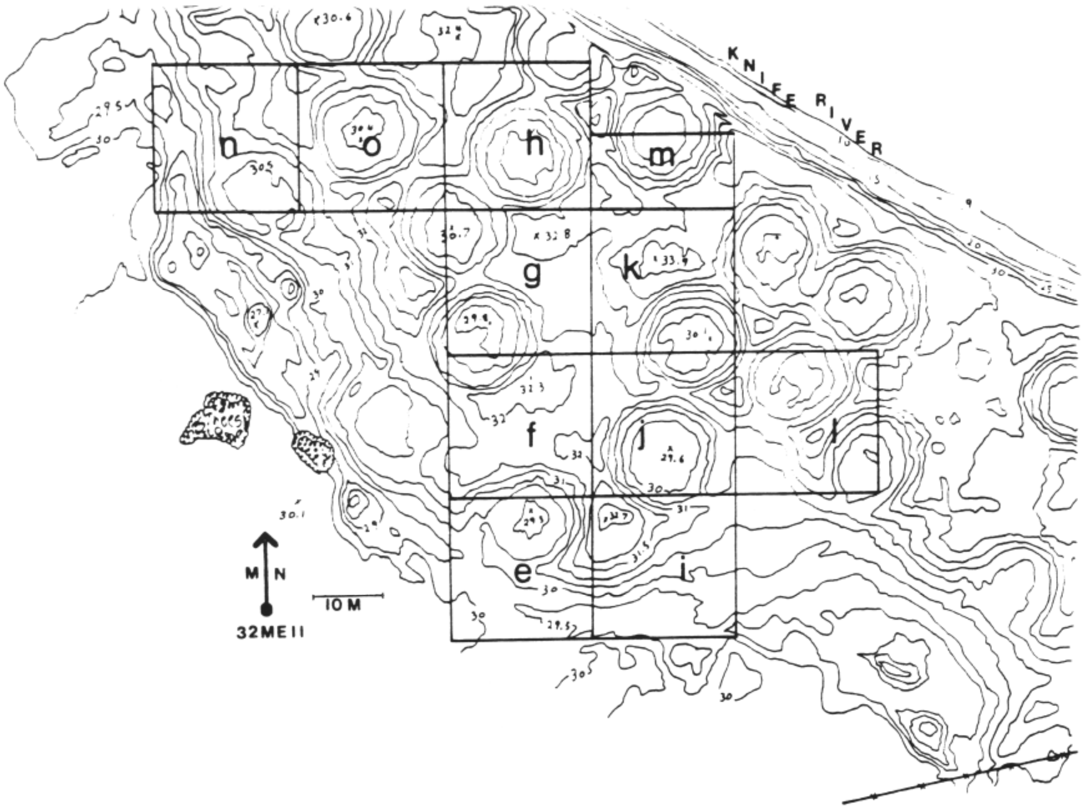


**Fig. 8.4.** Topographic map of Sakakawea Village (32ME11), Knife River Indian Villages National Historic Site; contour interval of 15 cm.

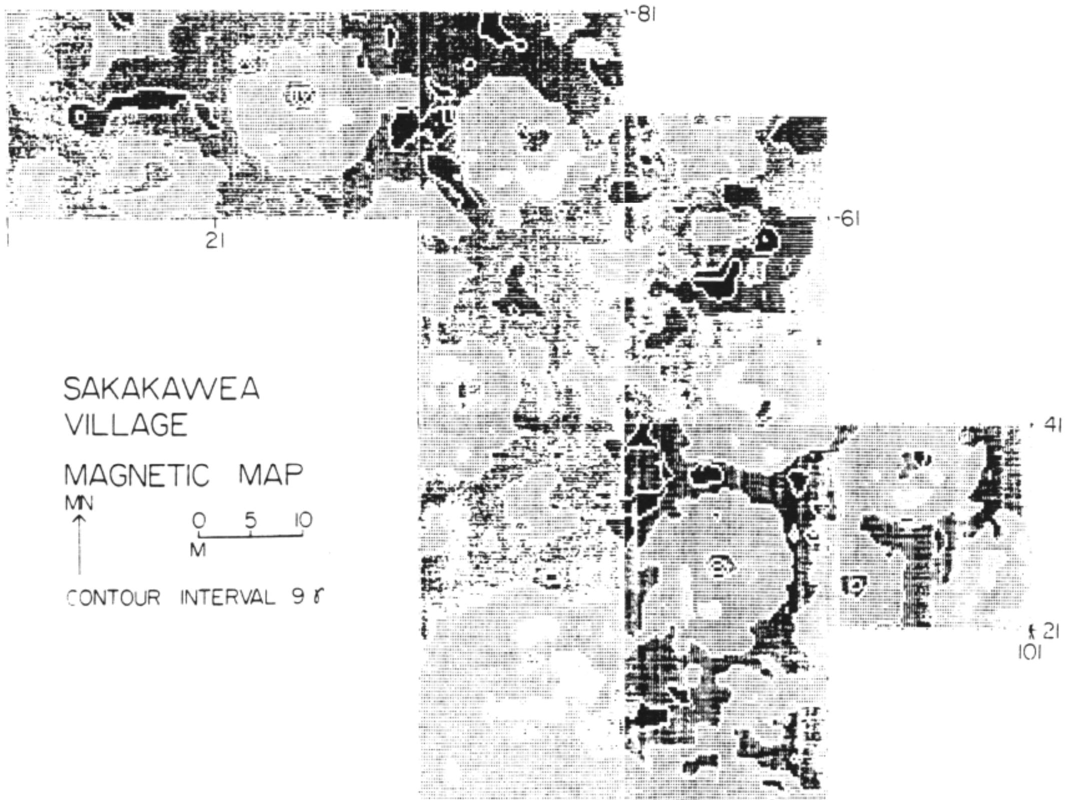


**Fig. 8.5.** Magnetic map of Sakakawea Village (32ME11), Knife River Indian Villages National Historic Site; contour interval of 9 gamma.

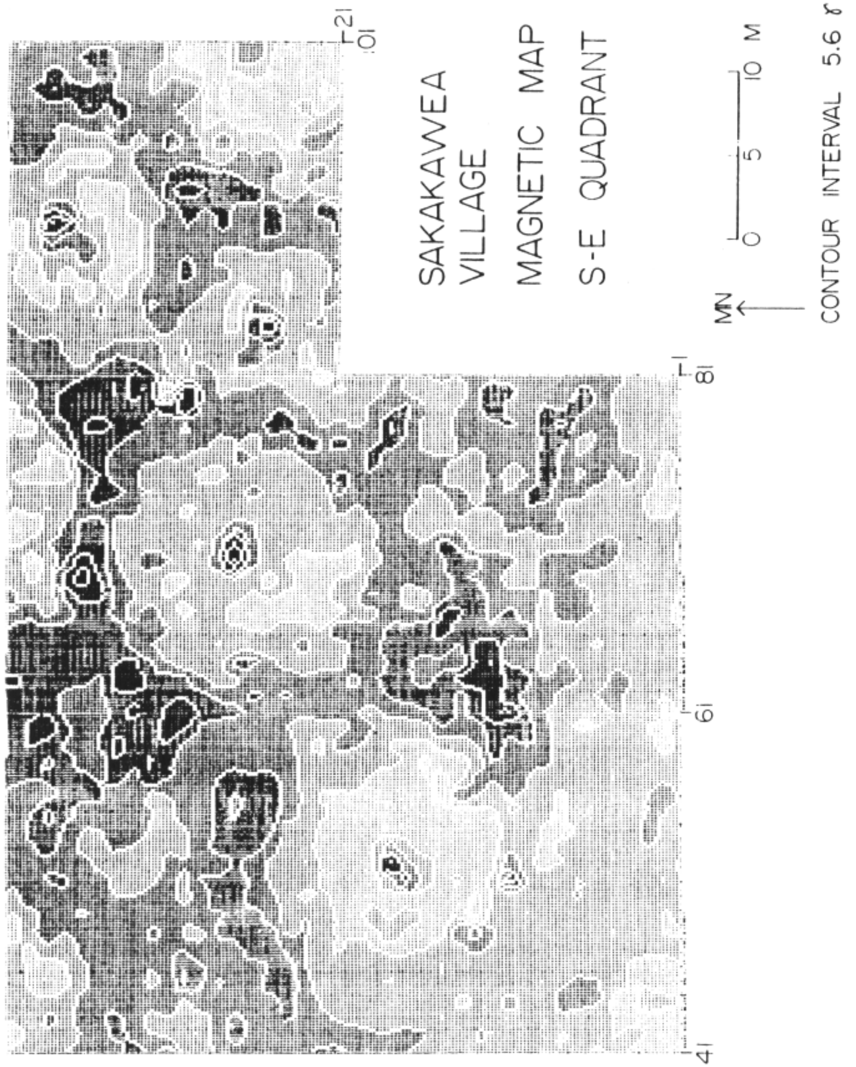


**Fig. 8.6.** Magnetic map of Sakakawea Village, southeast quadrant; contour interval of 5.6 gamma.

this area established that the anomaly at N36, E69 between the houses was caused by an exterior fire hearth about 60 cm in diameter and 40 cm below surface and that the smaller anomaly just to the south inside the house was caused by a group of burned rocks—a presumed sweat lodge.

Figure 8.7 is a magnetic map of house 6 in block 0 in the northwest quadrant, taken with the sensor at our usual height of 60 cm. Figure 8.8 is a map of the same area but based on readings taken with the sensor 120 cm high. Some of the smaller and sharper anomalies produced by near-surface sources disappear in

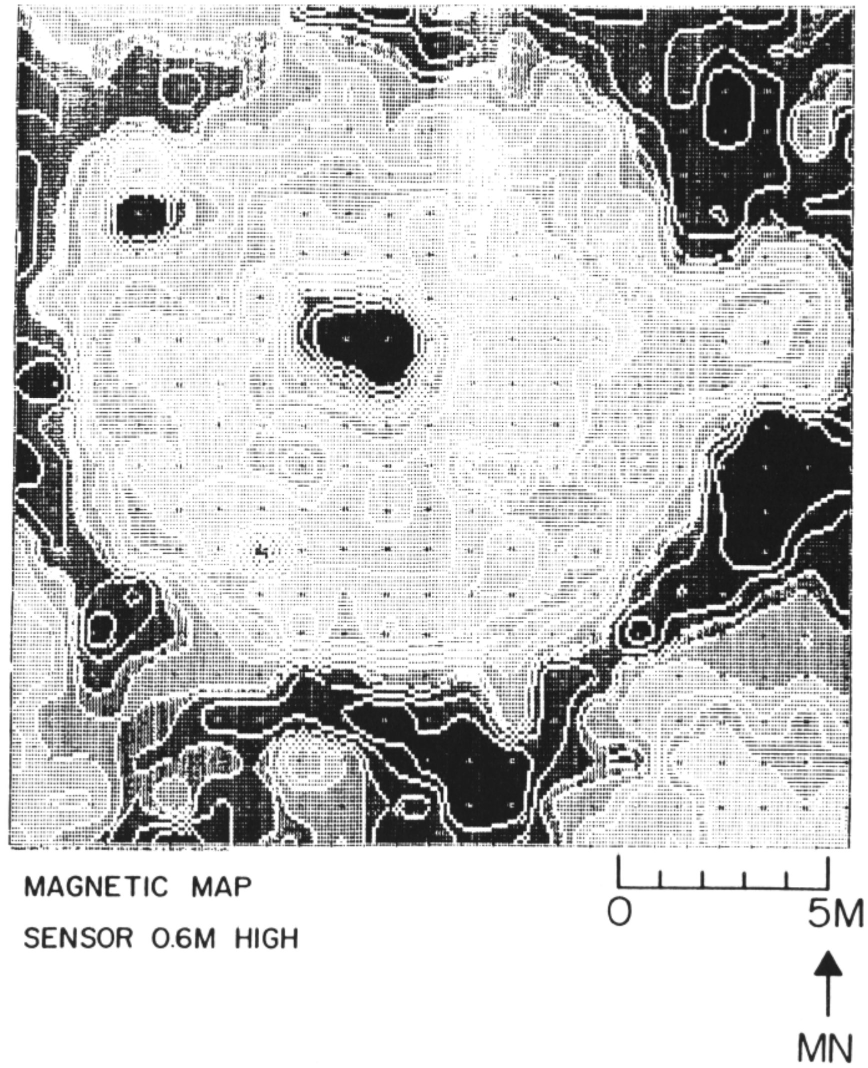


**Fig. 8.7.** Magnetic map, house 6, Sakakawea Village; sensor height of 0.6 m, contour interval of 2 gamma (except at highest and lowest levels).

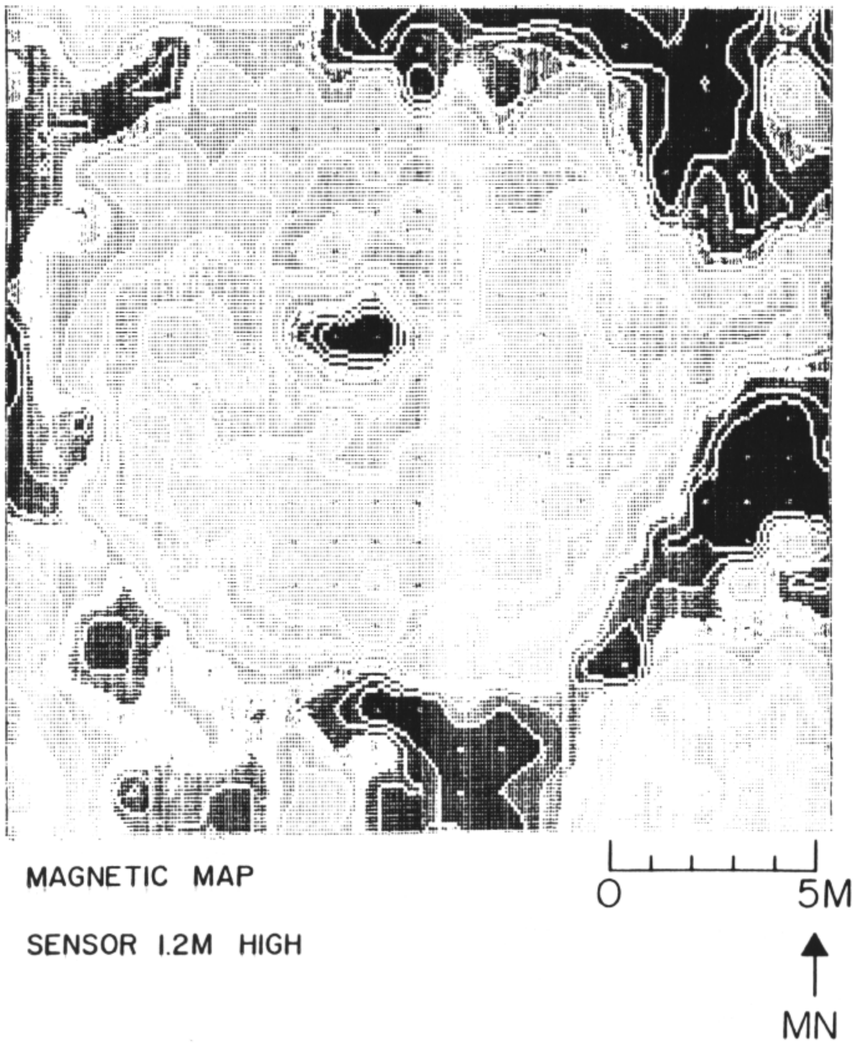


**Fig. 8.8.** Magnetic map, house 6, Sakakawea Village; sensor height of 1.2 m, contour interval of 1 gamma (except at highest and lowest levels).

the second map, while the lire-hearth anomaly produced by a larger and deeper source persists.

*Fort Union National Historic Site*

This site, a trading post in North Dakota from about 1830 to 1865, has undergone considerable excavation. The data for the survey were obtained by the MWAC and analyzed by the present writers.



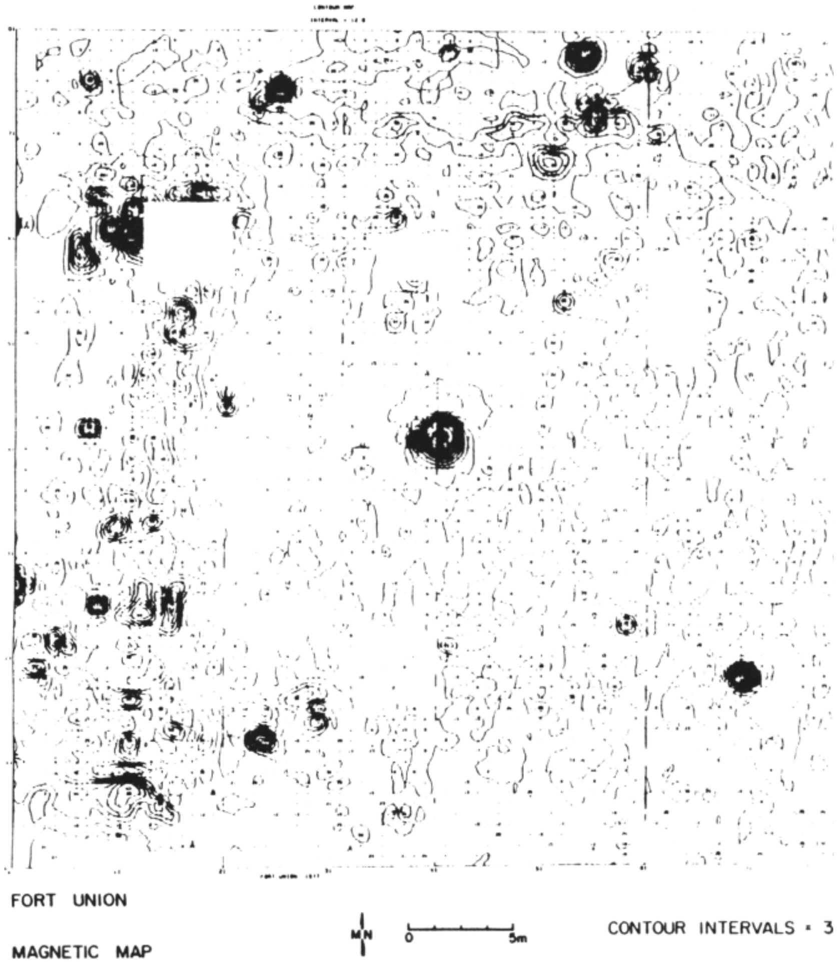


**Fig. 8.9.** Magnetic line contour map, Fort Union National Historic Site; conto interval of 3 gamma.

Figure 8.9 is a line contour of the total survey area. A number of anomalies can be seen, particularly along the position of the western range of houses. Some of these are due to previous excavations and some arise from original wall foundations and fire hearths. The central area, a parade ground, is relatively free of anomalies except for the strong anomaly in the center due to a modern flagpole base. This survey illustrates two points. A strong anomaly at N 19, F.70.5 in the southeast quadrant of the map (see fig. 8.10) was actually located earlier by personnel from MWAC who ran a series of seven 20-m-long traverses using a 1-m grid unit and one magnetometer. On a map of these data (fig. 8. 11) the large

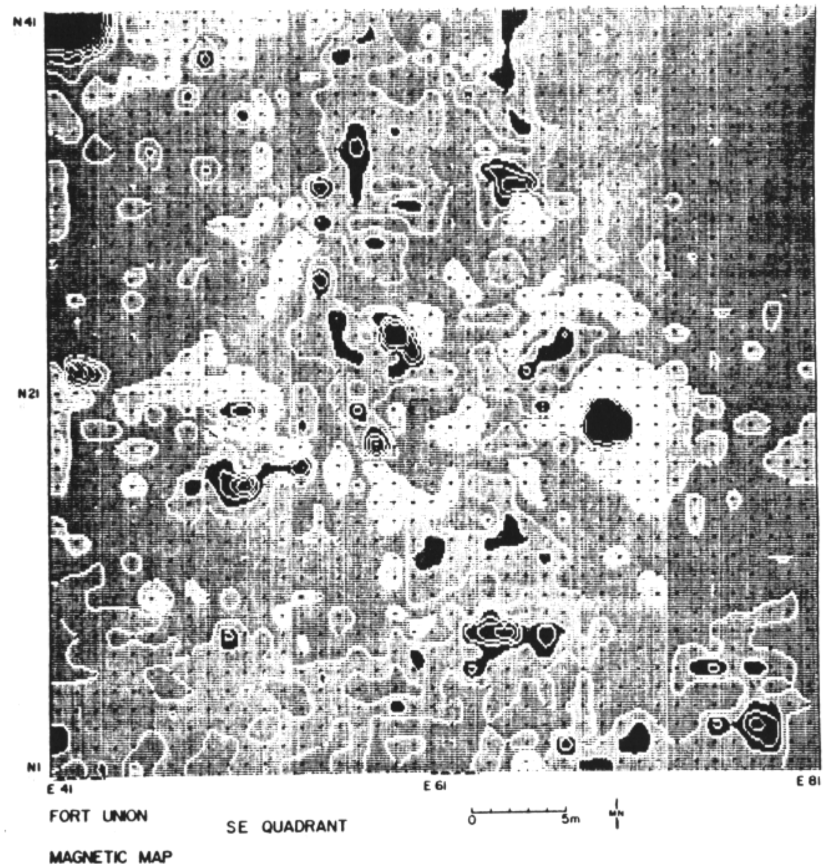


**Fig. 8.10.** Magnetic map of southeast quadrant of Fort Union National Historic Site; contour interval of 5 gamma.

anomaly and a number of smaller anomalies are reproduced. Such an operation is not usually successful on a larger area. Figure 8.12 is a magnetic line contour map resurveyed in part of the southwestern corner using a grid interval of 50 cm. Comparison with figure 8.9 shows several anomalies duplicated, as well as more detail.

### Ward and Guerrier Trading Post

The Ward and Guerrier Trading Post is located adjacent to the Fort Laramie National Historic Site, Wyoming. As part of a program to construct a parking lot and visitors' center, it was necessary to determine the location of die trading post that was known to be in this vicinity around 1858. Excavations in 1963 had

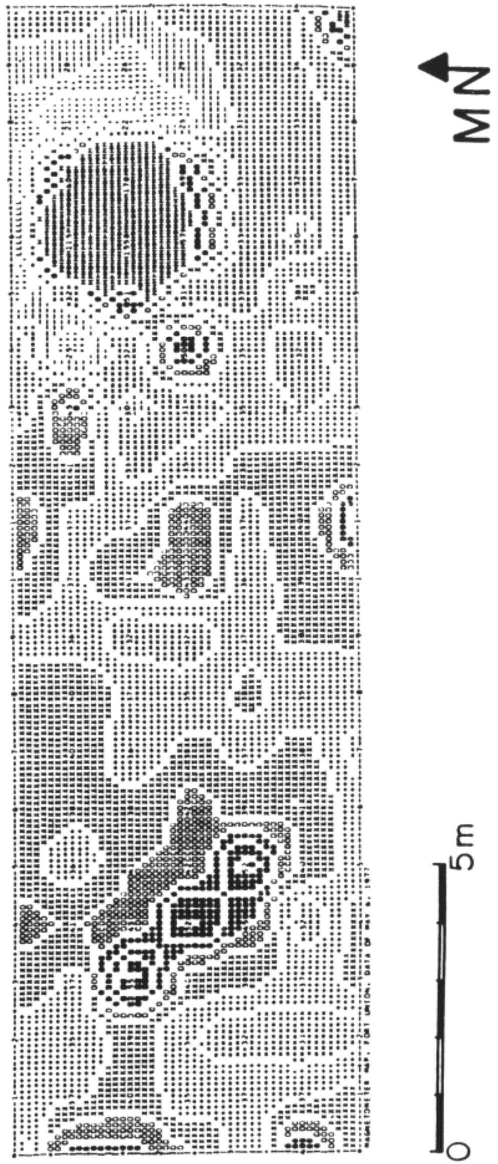


**Fig. 8.11.** Magnetic map produced from 7 east-west traverses in southeast quadrant of Fort Union National Historic Site, no diurnal correction, contour interval of 3.5 gamma.

revealed a small, square Inundation (presumed to be a smithy), several hits and pieces of foundations, a row of portholes, and a sizable trash pit containing iron material that was not removed at that time. The data for the 1963 excavation, however, had been lost and only the approximate position of the site was known. In 1976 the MWAC opened up three excavation units and surveyed the area with two magnetometers, as shown in the magnetic map of figure 8.13 (Weymouth, 1979). Three observations from these excavations and from the survey led to the conclusion that the previous excavations had been found again and determined the position of the main structure of the trading post.

First, the excavation unit and survey information in the easternmost block established this to be the smithy area with the now rediscovered small foundation. Second, the large anomaly at N31, E31 was assumed to be the iron-filled trash pit. Third, a row of sharp anomalies (marked by the dotted line in fig. 8.13) was believed to mark a wall of the main building of the post. The length of this line is approximately 100 feet, which agrees with what is known of the post. This interpretation is further supported by a row of post molds at the end of the line uncovered in the 1963 excavation and indicated in the excavation trench at about N21, E5. Figure 8.14, a 3-1) view of the results, again shows the line of anomalies, the strong anomaly due to the trash pit, and the group of anomalies in the smithy area.

### *The Dolores Archaeological Program*

The final example is drawn from the Dolores Archaeological Program (DAP), a long-term study of the archaeological resources in the Dolores River valley, southwest Colorado, before its inundation by dam construction. As part of the resource assessment a large number of sites, each encompassing two to ten blocks, have undergone magnetic surveying.

Because most surveys in this program have been followed by excavations or at least blading of the plow zone, it has been possible to obtain rapid checks on the archaeological significance of magnetic anomalies. This has improved our ability to interpret data and make predictions. Following the 1979 season, a study was made of the correlation between predictions made from the magnetic maps and the results of the various excavations. The pit structures and other large architectural features were of sufficient volume and extent to produce anomalies over several meters that could be readily detected; of 26 such "high-priority" anomalies, excavation revealed that 23 were caused by cultural features.

We show as an example of the larger anomalies results from site 5MT2193, surveyed in 1978. Figure 8.15, a magnetic map of this site, shows in the western half two large anomalies that were presumed due to two pit-house structures. These anomalies extend over several meters but have a maximum of only about 15 gamma. Use of quarter-gamma sensitivity here was justified, but a 2-m grid spacing could have been used if only this type of anomaly was being sought.

Upon excavation, the sources of the anomalies were shown to he pit-house structures originally about 1.5 m deep that subsequently were filled in with

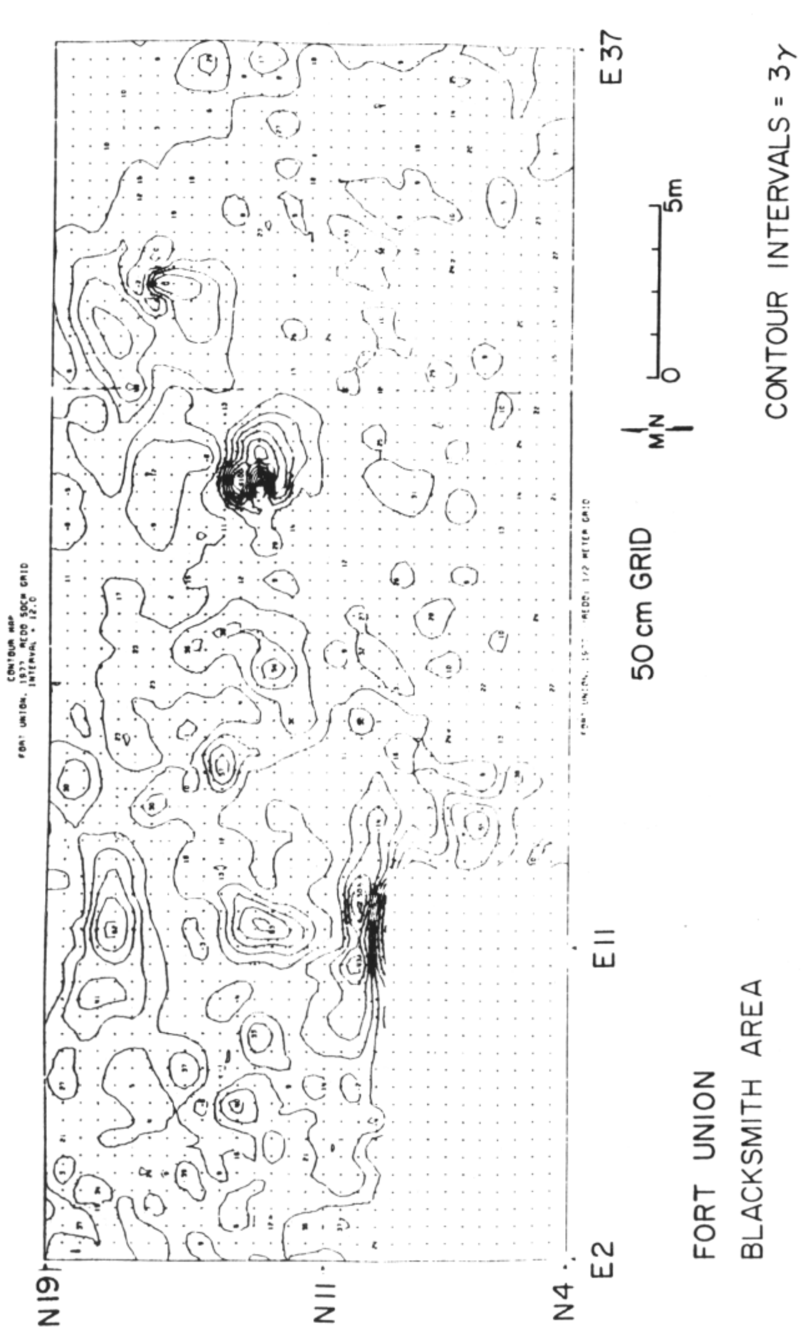


**Fig. 8.12.** Line contour map over blacksmith area, southwest quadrant, Fort Union National Historic Site, using 50-cm grid unit; contour interval of 3 gamma.

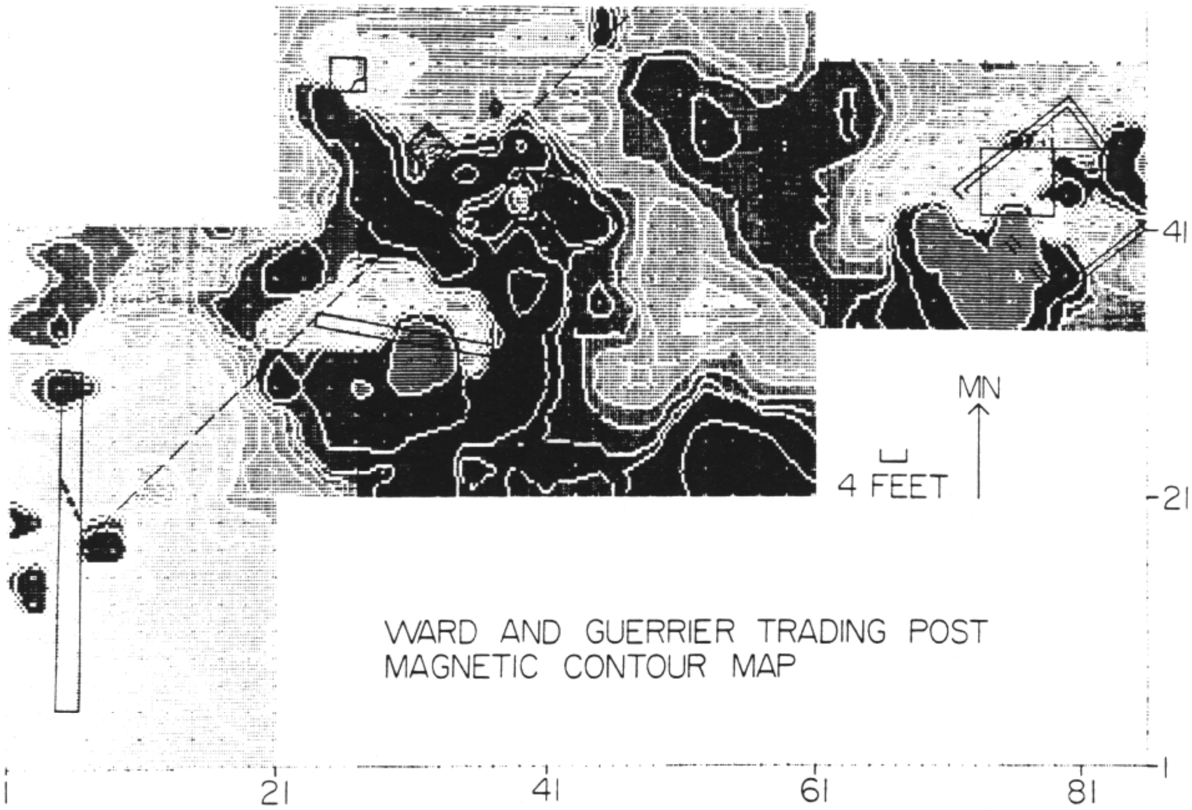


**Fig. 8.13.** Magnetic map of Ward and Guerrier Trading Post, Fort Laramie National Historic Site. Seven 40 ft × 40 ft blocks were surveyed on a 2-ft grid unit.

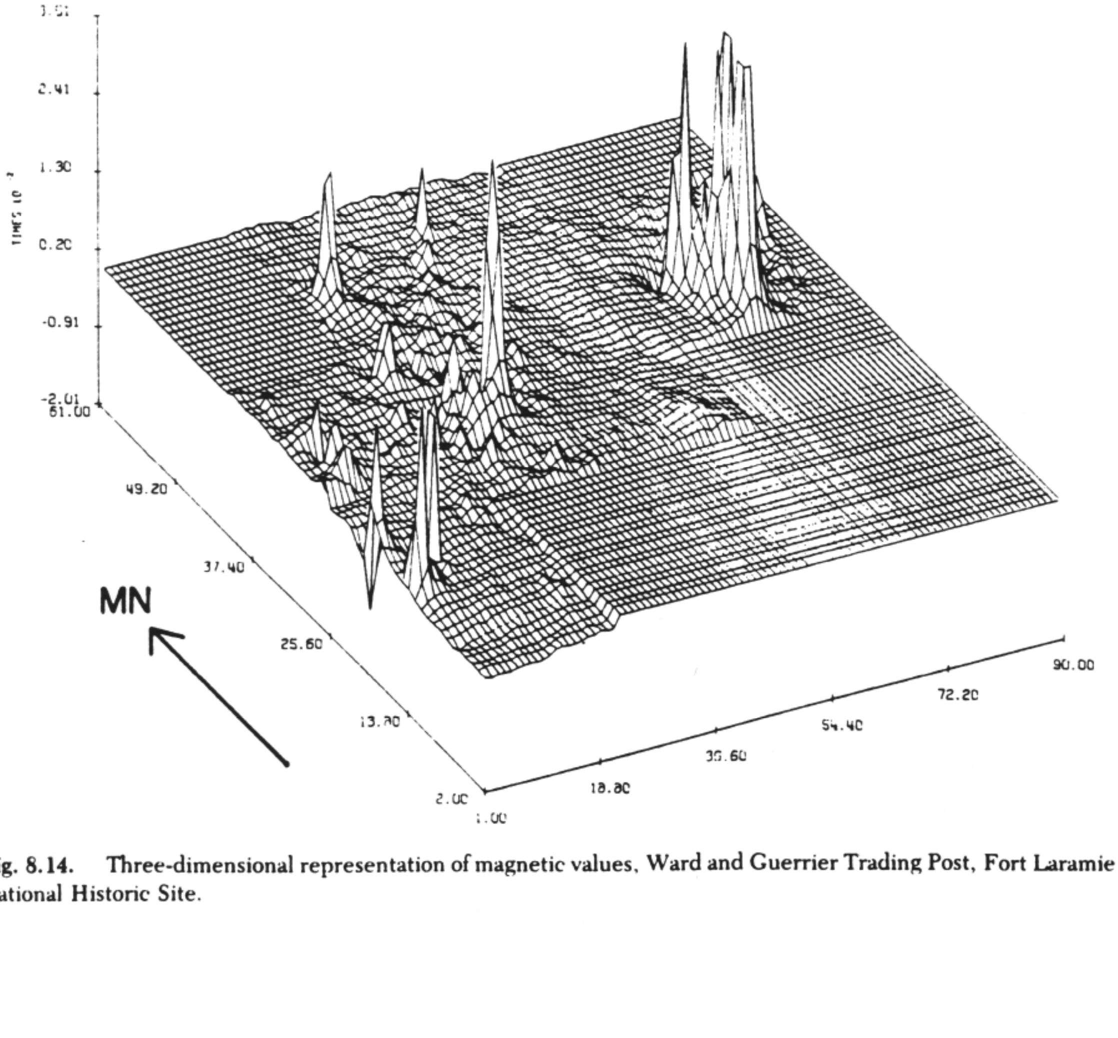


**Fig. 8.14.** Three-dimensional representation of magnetic values, Ward and Guerrier Trading Post, Fort Laramie National Historic Site.

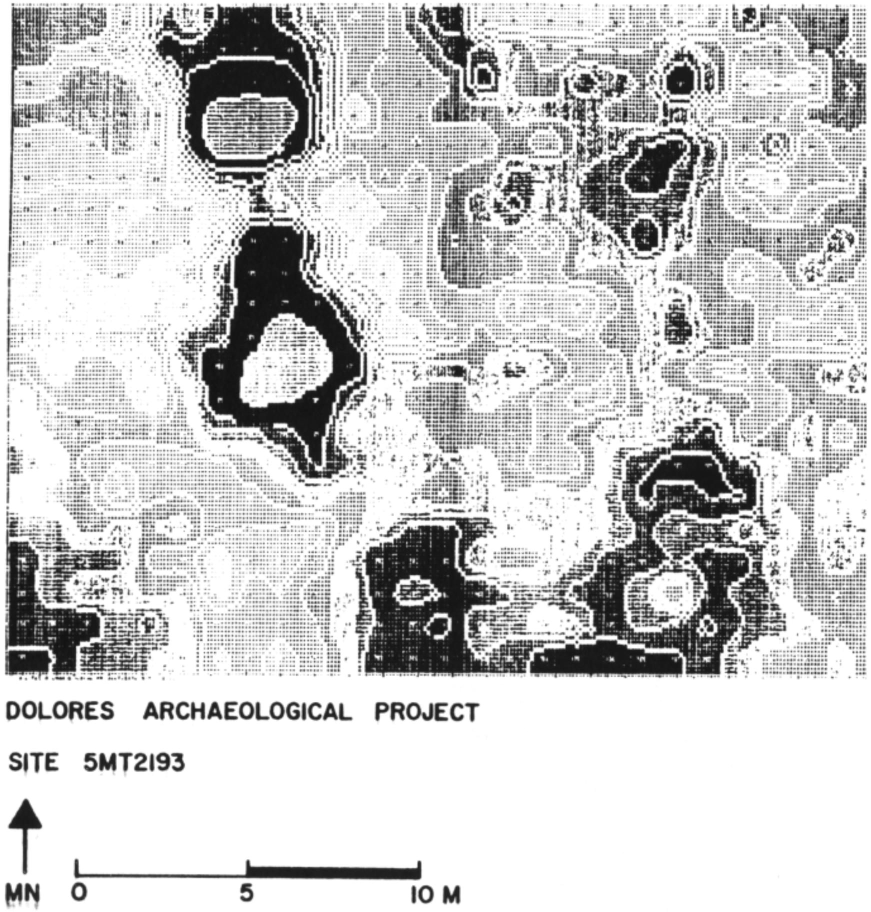


**Fig. 8.15.** Magnetic map of site 5MT2193, Dolores Archaeological Program, contou interval 1 gamma in midrange.

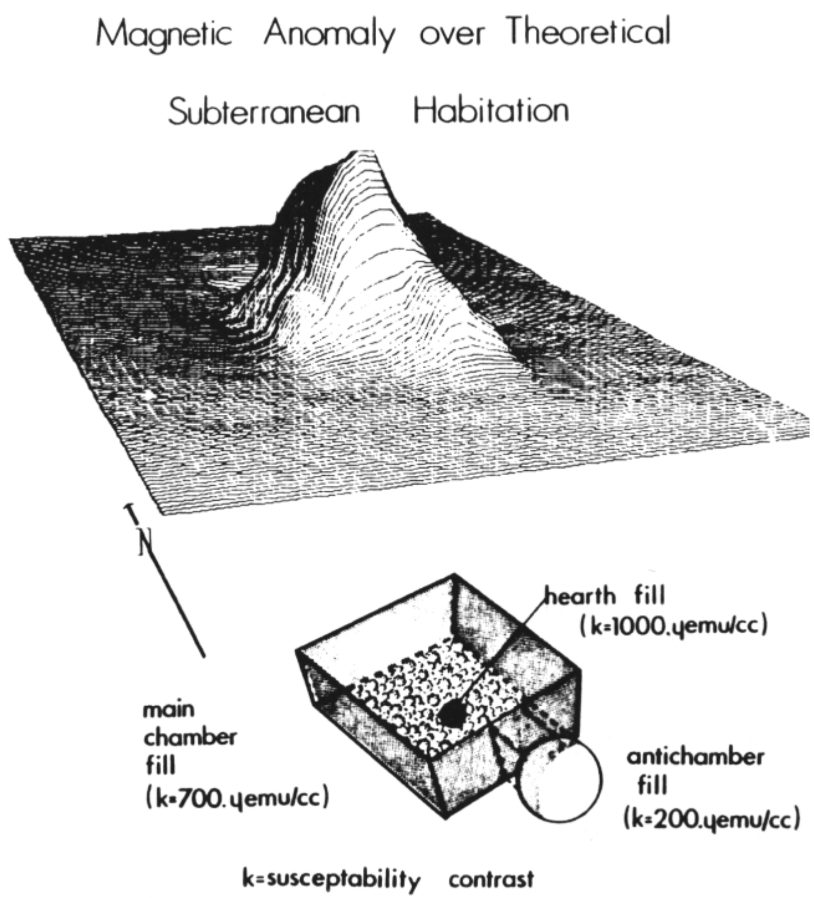


**Fig. 8.16.** Shape of feature and magnetic susceptibility values used to generate a m calculation simulating a magnetic anomaly produced by a pit-house. Upper half of fi shows three-dimensional view of magnetic values produced by calculation.

burned-roof fall and soil. The shapes of the anomalies followed the shapes of the sources fairly faithfully, including the air vent in the southern structure. As a further test of the source-anomaly relation a model calculation was made, representing the southern pit house by a box with a hearth on the floor and a sphere for the air vent to the south. This model is represented in figure 8.16, along with a three-dimensional representation of the magnetic results. The susceptibility values had to be multiplied by four in order to obtain a magnetic map (figure 8.17) comparable with the original map, which was plotted in quarter-gamma units.

## RESISTIVITY SURVEYING

### SUMMARY OF METHOD

Resistivity surveying on archaeological sites indicates spatial differences in sediment moisture: the presence of features, architecture, activity areas, and other archaeological remains can be detected if the amount of moisture they retain is different from that retained by surrounding sediment. Location of these anomalies or contrasts involves careful measurement of the sediment resistivity at

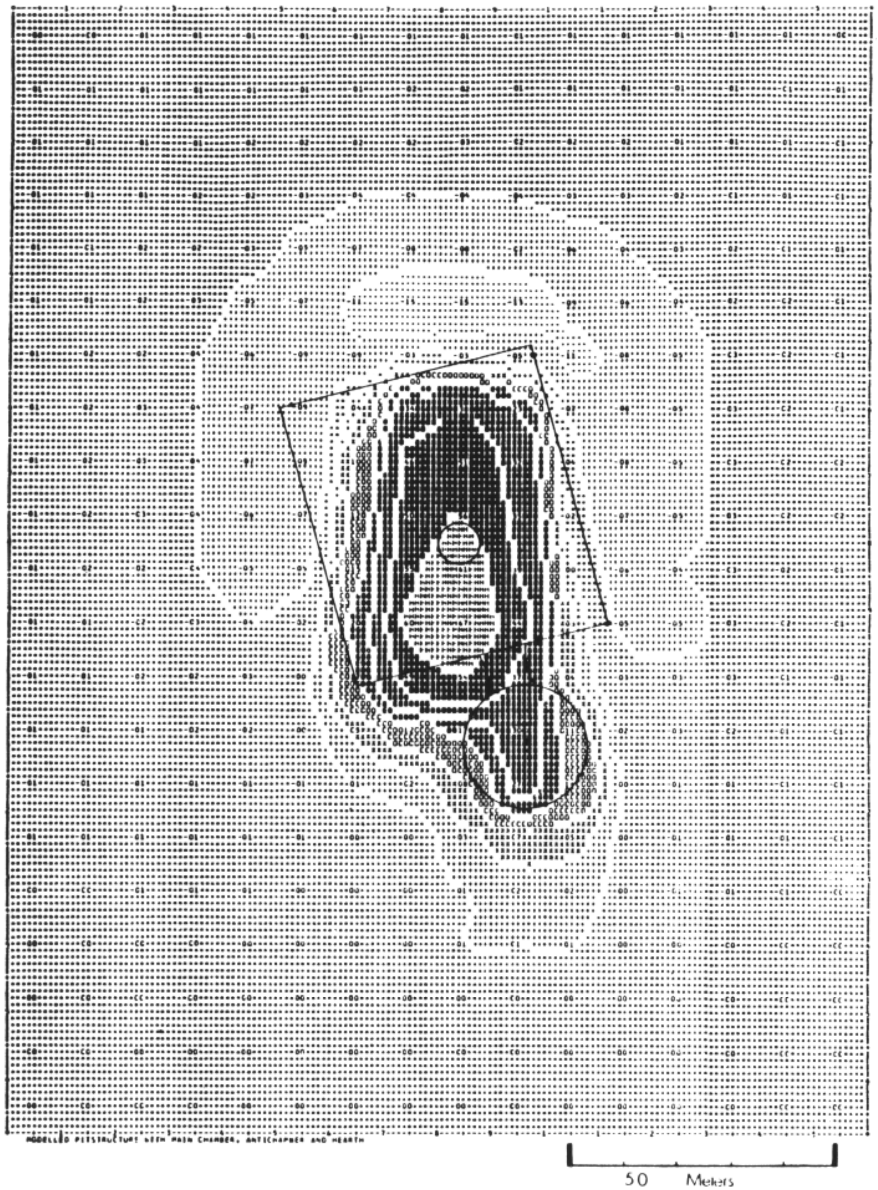


**Fig. 8.17.** Magnetic map produced by model calculation simulating pit-house anomaly. Outline shows the position of the feature below the surface.

discrete points on the surface along traverses or on a grid of points. The collected data are usually displayed as profiles or as electrical-resistivity contour maps. Because of the amount of data involved, a computer is an invaluable assistant. The data are then computer-enhanced (if necessary) and interpreted, and areas of potential archaeological interest are located on the basis of a clear understanding of the principles discussed in the following sections.

## HISTORICAL DEVELOPMENT

Measuring the resistivity of the subsurface has long been used as a method for exploring geologic structure. A practical measuring technique was first introduced by Wenner (1915) and significant improvements were made by Schlumberger (1920). Resistivity measurements are still widely applied in geophysical exploration fir mineral deposits and gravel beds. An early archaeological use of the method was in 1947 by II. Lundberg (De Terra, 1947:162-64), to locate fossil human remains at Tepexplin, Mexico. Since that time resistivity has been utilized successfully by Atkinson (1952), Clark (1969, 1975), Carr (1977), Lithe, Schneider, and Carr (1976), and Ginzburg and Levanon (1977), among others, in a variety of archaeological contexts. For an exhaustive treatment of the historical development of the technique, refer to Van Nostrand and Cook (1966).

## THEORY

In order successfully to conduct and interpret a resistivity survey, a grasp of basic electrical theory is necessary, beginning with the nomenclature. Electric *current* is defined as the rate of flow of charge passing through a cross section of a conducting medium for a specific length of time. To cause charge to flow, a *voltage* (also known as *potential difference,* a measure of the energy used to move the charges) must be applied. When a voltage is applied and a current flows, a *resistance* is encountered to the movement of the charge, which is dependent on the characteristics of the medium in which the charges are moving. These three physical quantities are related by Ohm's law,

$$\text{resistance} = \frac{\text{voltage}}{\text{current}}, \text{ or}$$

$$R = \frac{V}{I}. \tag{1}$$

Resistance is measured on Ohms (SI), voltage in volts (V), and current in amperes (A). In a conductor of length $L$ and cross section area S time voltage difference per unit length can be thought of as the moving force, the current as the quantity that is moved, and the resistance as the opposition encountered by moving the current. From Ohm's law we can develop the concept of *resistivity* by incorporating into equation (1) the geometry of the medium. Resistivity is a more useful quantity than resistance in the examination aim archaeological site since it is specific to the medium and independent of the geometry of the material being surveyed. Resistivity (p) is defined as

$$\rho = \frac{V/L}{J}, \tag{2}$$

where *V/L* is the change of voltage with distance in the direction of current flow and *J* is the current density in the medium in which charge is flowing. The basic unit of resistivity is the ohm-meter or ohm-centimeter (1 Ω-m = 100 Ω-cm). If a specified current is flowing in a known geometrical shape, we can deduce the resistivity of the material, providing the voltage difference is known. The inverse of resistivity (1/p) is known as the *conductivity,* although in the discussion following, we will consider only resistivity. More complete discussions of these concepts are available in most basic physics texts, such as Resnick and Halliday (1966).

*Resitivity Measurements*

The concept of subsurface resistivity measurements can *be* illustrated in an actual field situation. Current is induced in the ground by inserting in the earth two metal probes that are connected to a battery. In this idealized case, distribution of voltage and current in a uniform earth is well understood (a model is shown in fig. 8.18). Also shown are current- and voltage- measuring devices to indicate both the amount of charge flowing between the current probes and the voltage in the area of interest between the two potential or voltage probes.

By calculating the volume affected by the flow of current, we can derive an expression for the average resistivity within the measuring probes:

$$\rho = 2\pi aV/I, \tag{3}$$

which is easily calculated because the distance between the probes *(a)* is known and the current (*I*) and voltage (*V*) are measured quantities. The resistivity is correct only 16r this particular probe configuration (or probe array), as other probe geometries change the volume of earth affected by the current flow. In archaeological applications, the prune concern is not the absolute value of the resistivity at any one point but the change between readings.

We can alter this simple model to illustrate how the current and voltage are affected by some inhomogeneity in the uniform earth—for instance, a trash-filled pit. The voltage and current deviate from the normal pattern and the resistivity measurement of the earth between the two voltage probes changes (fig. 8.19).

If these measurements are continued by moving all four probes from grid point to grid point, we can generate a series of readings indicating the lateral variations in electrical resistivity to a depth approximately equal to the separation between the voltage-measuring probes. By increasing the spacing between the probes for any given survey, one can examine a greater volume (and therefore depth) of material.

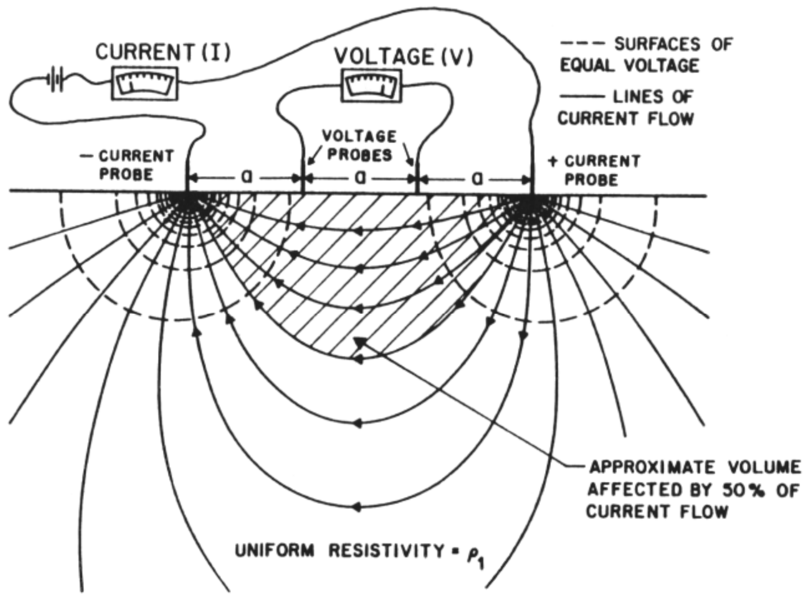


**Fig. 8.18.** Distribution of current and voltage in a homogeneous earth.

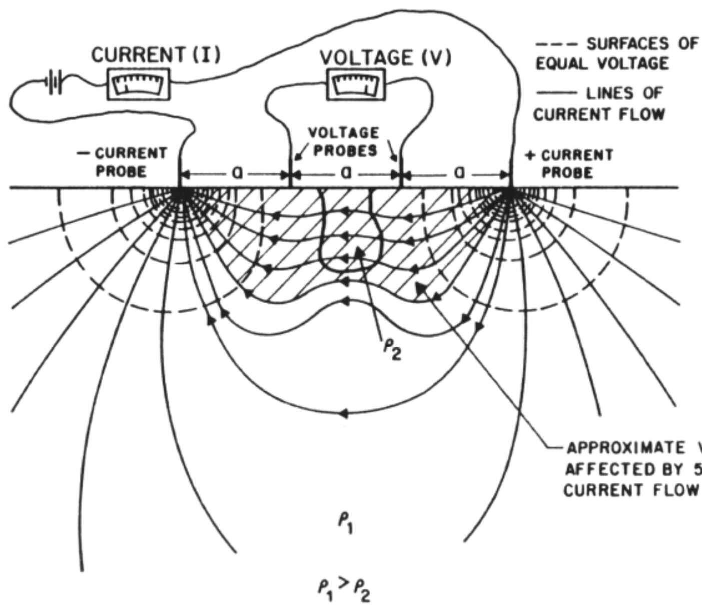


**Fig. 8.19.** Distribution of current and voltage in the presence of a feature with a lowe resistivity than that of the surrounding medium.

ELECTRICAL PROPERTIES OF SOIL SEDIMENTS

In the following paragraphs only sediments on which soil profiles have developed are considered, although resistivity measurements may be made in other sediment types (sand, till, mud) as well. The conduction of current in soils is largely an electrolytic phenomenon—that is, moisture in a soil containing *free* charged particles is responsible for the current flow. The resistance to currents flowing in all soil types depends directly upon the following variables:

1. *Soil moisture content,* which at archaeologically significant depths is usually generated by rainfall, with occasional contributions from areas having high water tables or from nearby streams. In general, soils receiving little rainfall have a high average resistivity and conduct electricity poorly. Seasonal variation in the total amount of rainfall also affects the resistivity (Al Chalabi and Rees, 1962; Clark, 1975). The amount of water that the soil can contain is determined by soil porosity, which exhibits wide spatial variation according to soil type, shape of the constituent grains, and amount of compaction.

2. *Permeability;* although a soil might have a high water content, current cannot flow unless connections exist between its interstitial pores.

3. *Ion content; the* ions responsible for conduction in the soil come from dissolved salts, such as calcium and sodium carbonates. They may be derived from a variety of cultural and noncultural sources: from the soil itself, underlying geologic strata, rainwater, modern agricultural fertilizers, or compounds generated by cultural processes. Figure 8.20 illustrates the pronounced effect of the addition of small amounts of dissolved salts on soil resistivity (Tagg, 1964).

4. *Temperature* affects resistivity, particularly when freezing of the groundwater takes place. Fortunately, most field surveys can be performed when the temperature is above 0°C, where daily variations in temperature are not sufficient to affect the resistivity in an archaeological context.

SOIL RESISTIVITY

The variables outlined above show wide spatial variation depending on climatic, geologic, and edaphic conditions. Consequently, the resistivity of different archaeological sites changes dramatically as well. Typical values of resistivity different soils are given in the following table (Tagg, 1964).

| Type of Soil | Resistivity (Ohm-cm) |
|---|---|
| Loams | 500 – 5,000 |
| Clays | 800 – 5,000 |
| Clay sand and gravel mixture | 4,000 – 25,000 |
| Sand and gravel | 6,000 – 10,000 |
| Slates, shales, sandstone, etc. | 1,000 – 50,000 |
| Crystalline rocks | 20,000 – 1,000,000 |

Similarly, wide variation in resistivity can be encountered on a small scale on an individual site.



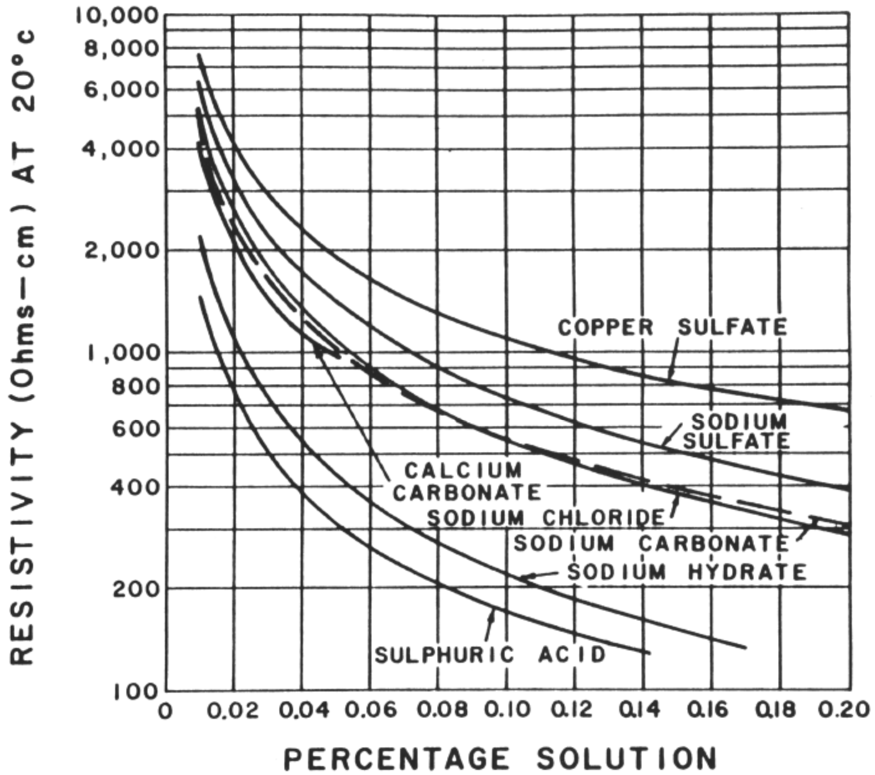


**Fig. 8.20.** Typical resistivity curves of solutions (Tagg, 1964).

Differences in soil moisture, dissolved salts, and like factors also are responsible for producing the *culturally* formed resistivity contrasts that are detected at archaeological sites. Linear features, such as fortification ditches a few meters long, are the most susceptible to detection when the surrounding medium and climatic conditions allow a change in their moisture content. Stone alignments and foundations may exhibit detectable resistivity contrasts because of their marked difference in water retention. I louse floors or other compacted activity areas are visible occasionally due either to decreased porosity or to moisture that has accumulated on their surfaces. Midden areas, which are often high in soluble ions and have a larger volume of interstitial-pore space, can show distinct resistivity contrasts. The resistivity contrast of filled pits, although more subtle than the other, more extensive features, are sometimes discernible.

Although the phenomena responsible for conduction of current in soils and archaeological sites are understood fairly well, one cannot easily predict which archaeological features will be detectable by resistivity surveying or whether the soil noise will confuse or mask cultural resistivity contrasts. Since the state of the physical remains depends on environment and cultural history, a feature which is easily located by resistivity surveying in one area may be imperceptible in another.

## INSTRUMENTATION AND FIELD PROCEDURES

### *Probes*

The probes used for the transfer of current or measurement of voltage usually consist of mild steel rods pointed on one end, with suitable hand holds on the other to facilitate insertion in the soil. Ideally, the probes should act as point sources, but since they must be inserted a finite distance into the ground this is not the case. The actual value of resistivity will change if the insertion depth is varied for one or all of the probes, so steps must be taken to ensure uniformity. This can be accomplished by the use of an adjustable ring on the probe that will arrest insertion at the desired depth. Field conditions usually dictate what is reasonable, although to maintain adequate precision in determining the resistivity the insertion depth should be less than 20 percent of the distance between the nearest adjacent probes (Aitken, 1974; Van Nostrand and Cook, 1966). For a 1-in spacing, the writers have found that insertion to 5-10 cm provides adequate contact in all but the driest soils.

Care must also be taken in situating the probes relative to one another. For example, when using small spacings on the order of 30 cm in a colinear array such as the Wenner or double dipole, errors in the measured resistivity can be as large as 15 percent for the misplacement of a probe by 3 cm (Aitken, 1974). Fortunately, archaeological applications seldom require spacings smaller than 50 cm, as this seems to be the minimum size of detectable features. At 50 cm between probes, one should attempt a positional accuracy of ± 1 cm.

### *Probe Configurations*

For simplicity, only the four-in-line probe configuration, commonly known as the Wenner array, was shown in the previous discussions. In practice, a variety of arrays are effective in an archaeological context, the choice among them depending on the terrain, the size of expected features, and the experience or familiarity of the operator with one array or another. Figure 8.21 shows a plan layout of the more common types. Descriptions of each array follow:

i. The Wenner array is the most often used and has several advantages. It produces the largest percentage change over most lateral soil variations. Most instruments are set up to accommodate this array. With the use of a fifth probe and a rotary switch, the last probe can be deactivated and "leap-frogged" to the front of the array while the instrument operator takes a reading using the other four probes. This allows each additional reading to be taken with the insertion of only one probe instead of moving the entire array. The main disadvantage of the Wenner array is that it tends to produce subsidiary peaking in the data, typified by large excursions in the readings before and after a resistivity contrast occurs.

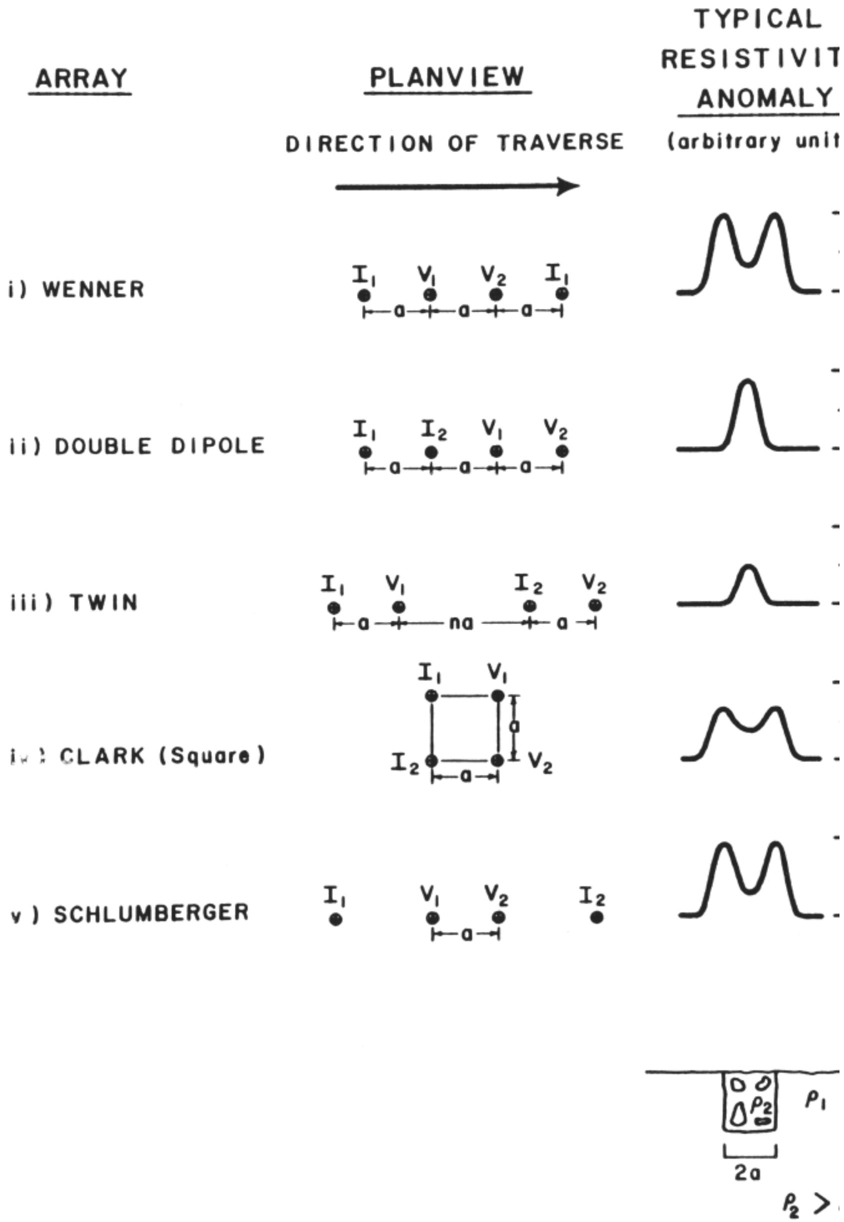


**Fig. 8.21.** Diagram of probe configurations (arrays) commonly used in archaeology w a typical anomaly for each due to an idealized feature.

This gives rise to M- and W-shaped anomalies, as illustrated in figure 8.21i.

ii. The double-dipole array is an attempt to reduce the subsidiary peaking that occurs in the Wenner array while retaining similar sensitivity and mobility. As shown in figure 8.21ii, only a single peak is encountered over a feature of interest, making interpretation of profiles and gridded data less complex (Clark, 1975). A five-probe system can be used in a fashion similar to the Wenner system, thus speeding data collection. The apparent disadvantage of the double-dipole array is the increased fall-off with depth, which means that deeper features contribute less to the readings.

iii. The twin array (fig. 8.21 iii) devised by Aspinall and Lynam (1970) used one fixed current-voltage pair ($I_l$ and $V_l$) that remains fixed throughout the survey while the other pair (/ and V)) is used in the measuring procedure. The motivation for this alteration is economy: the roving pair can 1w mechanically linked together, resulting in the least amount of actual probe movement of any of the configurations. The twin array also has the interpretational advantage of producing single-peak anomalies. Its main disadvantage is reduced sensitivity, producing the least percentage change from background of any of the other arrays. However, in regions where resistivity contrasts are large the twin array is probably the ideal choice. It should be noted that the value of n should always be at least 30 or confusing effects will occur.

iv. The square array designed by Clark (1968) was au attempt to reduce difficulty in the field and in interpretation (fig. 8.21iv). Clark configured the probes in such a way that they can be used as the legs of a table while the instrument and other recording equipment rest on top. This seems like a compact and suitable solution in many instances. Its main disadvantage is the fixed distance between the probes,- usually at a maximum of 1 in, with the effect that the array can be used only in the detection of features that are less than 1 in in depth.

*v.* The Schlumberger array (fig. 8.21 v) is more commonly used in large-scale geophysical applications but has been used successfully in an archaeological context (Rees and Wright, 1969). Its sensitivity is comparable to that of the Wenner array, but subsidiary peaking is again a problem. The distances between $I_l$ and $V_l$ or $I_2$ and $V_2$ should always he much larger than *a.*

Choice of the correct array for any given field situation is not a straightforward procedure. Despite the problems with peaking, the present writers generally use the Wenner array, sometimes verifying a particular anomaly with the double-dipole or the more expeditious twin array, both of which yield single peaks.

*Instrumentation*

In the direct-current cases presented up to this point, a simple ammeter and voltmeter would be adequate to measure the current and voltage needed to calculate the resistivity. In actuality, several problems arise with this method. First, small, chemically derived voltages develop between the probes and the ground, causing measurement errors. Second, probes gradually become polarized during current flow because build-up of charge near the probes alters the measured resistance. Finally, measuring probes can detect small, naturally occurring currents flowing directly through the earth, which introduce discrepancies. All of these error-producing effects can be minimized by using an alternating current with a judiciously chosen frequency, typically between 10 and 500 liz. Most instruments available today are designed in this manner and many are calibrated to read resistivity directly for a specific array.

*Field Procedures*

Lateral variations in soil resistivity are measured by using linear traverses or a regularly spaced grid, the choice depending primarily on required resolution and economy. If the expected archaeological features are ditches or palisades, Or features measuring several meters on a side and lacking interior detail, then traverses are likely the best choice. However, if features on the order of a meter or two in diameter are sought, then more definition can be obtained by measuring with a gridded regular interval. A locational system similar to that described for magnetometer surveying is adequate, providing a nonconductive material, such as dry cloth tapes or ropes, is used.

Establishing the electrical properties of the site before systematic surveying aids in choosing the array and spacing. If the location of any suitable feature is known, a trial traverse can be run using either the Wenner array or the double-dipole or both. The array spacing for this test and the later complete survey should be contrived to allow current flow to encompass as much of the feature as possible. The depth measured by the array is about equal to the distance between the voltage probes. In other words, a volume roughly equal to a hemisphere of diameter *a* is measured. It is permissible to have the probe spacing *at most* equal to the width of the feature, providing its width and depth are roughly the same. A higher degree of confidence in the existence of an anomaly is obtained if three or more readings can be taken over the feature. If its width is greater than its depth, the array spacing should be reduced accordingly. For example, if some horizontal feature, such as a house floor, is encountered at a depth of 30 cm with a width of 4 m and exhibiting a resistivity contrast of 5:1, the following anomalies (expressed in arbitrary units depending on soils) would be

| Probe Separation (m) | Strength of Anomaly (arbitrary units) | Percentage of Maximum Possible Anomaly |
|---|---|---|
| 0.3 | 3.75 | 94% |
| 0.5 | 3.40 | 85% |
| 1.0 | 2.70 | 67.5% |
| 1.5 | 1.80 | 45% |

The test traverse should be extended 10 or 15 in on either side of a prospective feature to ascertain ground-noise conditions. It is often advantageous to traverse a nearby area devoid of cultural features to determine what natural resistivity variation one might encounter. If the overall noise level appears high compared with the anomaly produced by the feature, it is probably best to continue using the double-dipole or Wenner array; if significant change is detected, one might choose the Clark or the twin array to speed data collection. The choice of the array is usually made on the basis of the operator's experience and familiarity with an array and the affinity of the instrument used to one probe configuration or the other. When little is known about the geometry of the features on a site, a probe spacing of I in using the Wenner or the double-dipole array is a judicious choice.

If traverses are used for field measurement, they should extend well away from the region of archaeological interest so that additional background information can he determined. If a survey takes place over an extended time and periodic rainfall occurs, steps should be taken to adjust the traverses relative to one another to correct for the increased soil moisture. This can be accomplished by running a common traverse before and after a rainfall and musing the average difference as a constant for adjusting subsequent measurements.

Where the ground is level, easily penetrated, and clear of excessive vegetation, the writers have taken between live and seven readings per minute or, considering the repositioning of measuring ropes involved, 150 to 190 readings per hour. When a I -m grid spacing is used, an area of about 1,000-1,200 $m^2$ can be covered in a day, although such large surveys are arduous. Hard ground slows the work, as the probes must be pounded to ensure proper contact.

Field notes should be maintained with observations on variations in soil type, ease or difficulty in probe insertion, change in the density of vegetation, and noticeable topographic features. These factors affect the resistivity and can often be of valuable assistance during interpretation. A log of the rainfall for the period of the fieldwork is also a valuable aid, since large amounts of rain can drastically affect the magnitude and even the polarity of resistivity anomalies (Clark, 1975; AI Chalabi and Bees, 1962).

Several simple field techniques can be used to distinguish more readily the resistivity anomalies due to background variation in areas where noise from surrounding soil is high. When the validity of a reading is suspect, the traverse should be rerun for verification. With a simple alteration, instruments can quickly read both the double-dipole and Wenner arrays at a single station without repositioning the probes. In agricultural regions where cultivation has truncated features, the confusing effects of disturbed topsoil caul be reduced and the relative contribution from features increased by using the Barnes Layer Method (Barnes, 1952, 1954; Carr, 1977, 1982). By running two or three traverses over the area of interest and using increased probe spacings for each traverse, sets of data are generated that encompass greater soil depths. These data sets can be treated to reduce contributions from specific layers to enhance resistivity contrasts from cultural features or to reduce noise from topsoils.



## INTERPRETATION

Once data are collected, they are processed and displayed in a manner that will enhance the resistivity contrasts. Little alteration of data is needed before preliminary display, since many instruments produce readings that are already converted to resistivity and some compensate for the array being used. The only other preliminary processing that might be necessary is the addition of an empirical climatic factor, used to compensate for rainfall during a lengthy survey.

Because individual traverses are utilized more often in resistivity than magnetic surveying, profiling the data tends to be a more common display technique. Profiles can be plotted readily by hand and on occasion should be done in the field, *in* order to check noise levels or the feasibility of a particular array or spacing. For large surveys, where an appreciable amount of data is collected, a computer is a necessity.

Where data have been collected on a grid system, contour plotting yields better resolution and more information. In these instances computer maps such as SYMAP or line contours can be used.

Because the signal-to-noise ratio is difficult to quantify in resistivity surveying, in archaeological contexts the data are interpreted qualitatively. Essentially two types of noise are involved: *correlated noise,* caused by the contributions from natural soil variation, and *uncorrelated noise,* the sum of instrument variation, difference in probe spacing and depth, and the occasional poor contact of a probe with the ground. Both sources of noise are sufficient to mask contrasts from archaeological features, so steps should be taken to recognize and to minimize their occurrence.

Correlated noise from natural soil variations can be as large or larger than the signal and in these instances can be distinguished only when the noise signature has a different shape that that of the signal. Traverse data from an area lacking buried cultural remains as the best preliminary clue to recognizing correlated noise. If no specific correlated-noise anomalies are recognizable from natural soil variation, then the standard deviation of all the readings on the test traverse provides a reasonable background level above which to look for cultural anomalies.

Uncorrelated noise levels can be minimized by field procedures. If a measurement on a traverse is greater than the preceding one by a predetermined amount (usually the standard deviation of the test traverse), then the probe contacts should be checked and the reading retaken. Recognition of both correlated and uncorrelated noise can be aided by the use of alternate probe configurations.

Figure 8.21 shows typical anomalies for features similar to pits or ditches. Anomalies are similar in shape for most other archaeological features of that size, but the responses will vary in magnitude. The feature in figure 8.21 has a higher resistivity than the surrounding media such that $\rho_2/\rho_1 > 1$. The anomalies would be inverted if the resistivity of the feature were lower (i.e., $p_2$/p, < I). Resistivity contrasts between larger features may be manifest as an average change in the measurements, rather than as an individual, symmetrical anomaly. If the resistivity contrast is large, subsidiary peaking may he present at the boundary. Models of features have been used to aid in interpretation, but the mathematical calculation for the expected anomalies quickly becomes formidable, even for simple geometric shapes (Cook and Van Nostrand, 1954; Grant and West, 1965; Telford et al., 1976).

## EXAMPLES

The following examples are all drawn from a survey at the Knife River Indian Village National Historical Site in the vicinity of Sakakawea Village (32ME11). The survey was undertaken in cooperation with the Midwest Archaeological Center, National Park Service, to assess the potential responses of experimental features and to examine what cultural areas were amenable to detection using resistivity.

### *Sterile Region*

On the periphery of the village an imitation "cache pit" was excavated and refilled with moistened earth. Profiles across this anomaly using the Wenner and the twin array are shown in figure 8.22. The Wenner array produces the classic W-shaped anomaly, whereas the twin array produces a narrower, single peak. The magnitude of the twin anomaly is uncharacteristically large; it would normally be quite a bit less than the magnitude of the Wenner anomaly.

### *Suspected Palisade*

To test for the existence of a fortification ditch inferred by the presence of a

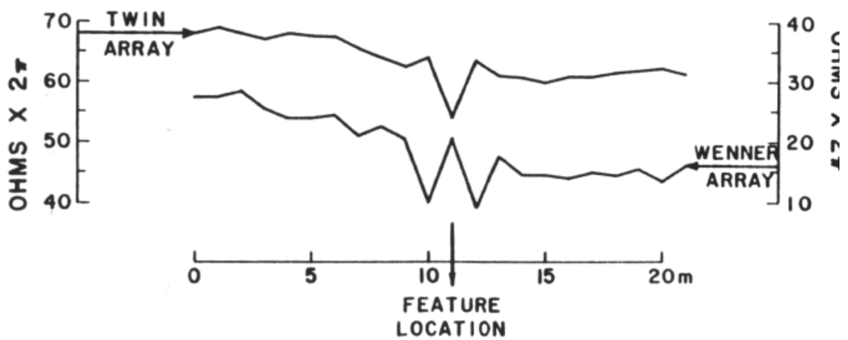


**Fig. 8.22.** Resistivity anomalies over earth-filled pit produced by the Wenner and tw arrays.



visible difference in soil in the river bank where the site is partially truncated, several radial traverses were run from the center of the village across the surrounding depression. The first traverse, which is located north of the area of figure 8.4, is shown in figure 8.23. When a marked area of low resistivity was encountered using probes spaced 1.0 in apart, the traverse was rerun with a spacing of 1.5 m, which shows a reduced contrast. From this we can infer that the source is of limited depth, probably no more than 1 in. Because the other traverses revealed no anomalous responses in this region, it is likely that the source of this anomaly is localized, indicating no detectable fortification ditch.

### *House* 6

Using a sample spacing of 1 m, we collected two matrices of data over house 6 (block 0, fig. 8.4) by running traverses first eat to west and then north to south. This method provides more information on the geometry of features and assures more accuracy in each reading. In figure 8.24 the average of the two profiles is displayed, a technique that reduces contributions from subsidiary peaking for features of certain geometries and reflects some of the larger trends on the site. In the center of the map is an oblong region of lower resistivity corresponding to the center of the depression (see fig. 8.4). We can infer a region of higher moisture and likely a reduced amount of compaction from this data. Surrounding this central low region is a ring of higher resistivity that appears to lie well within the depression. This area is apparently more compact, thus having a reduced moisture content and a higher resistivity. A particularly notable portion of the high ring is a crescent-shaped anomaly on the southeast edge. Wilson (1934) mentions that livestock were kept in the interior of lodges and penned close to the walls. It is conceivable that this high anomaly defines the boundaries of a horse corral or other area of excessive traffic.

The midden region surrounding the depression has mostly a low resistivity due to the reduced compaction and higher ion content. It is interesting to

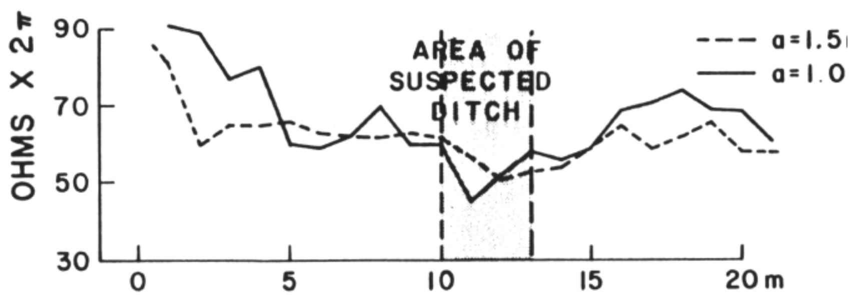


**Fig. 8.23.** Resistivity profiles across a suspected ditch using the Wenner array; wi spacing set at $a$ = 1.0 m and $a$ = 1.5 m.

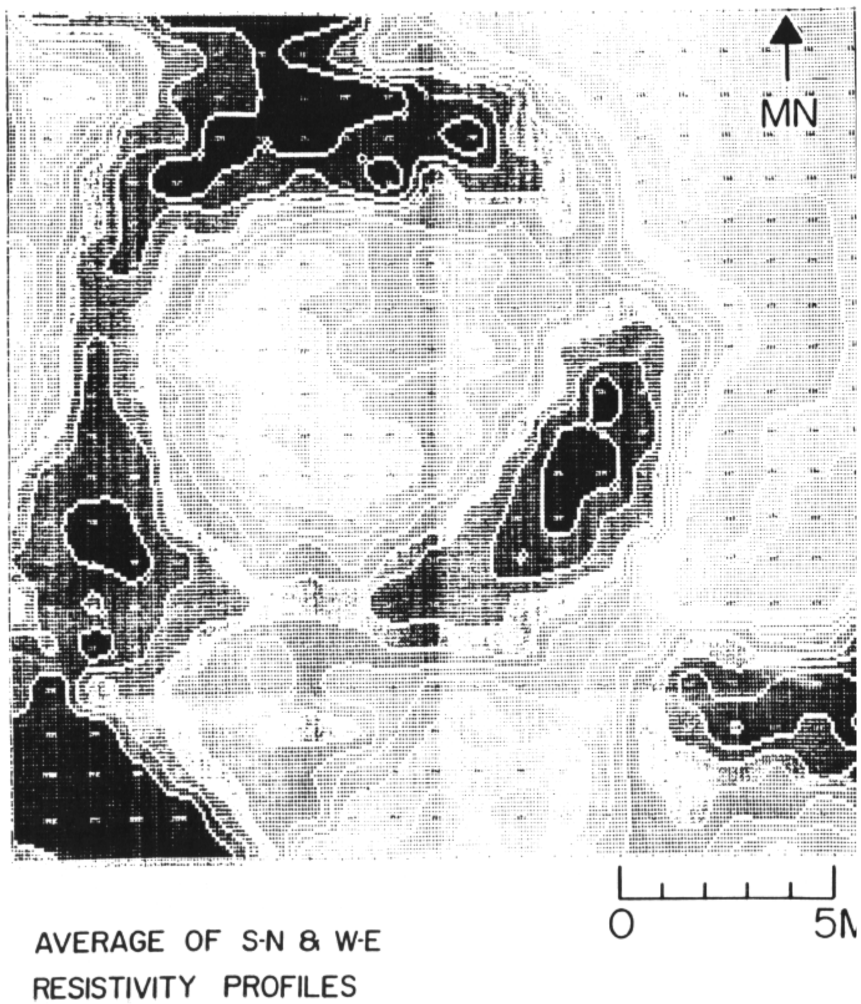


**Fig. 8.24. SYMAP contour map of the average of north-south and east-west profile over house 6, Sakakawea Village.**

compare figure 8.24 with figure 8.7, which shows the magnetic field over this same house. The general outline of the lodge is present in both, but each method shows distinctly different properties of the same area.

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