EVALUATION OF AN IMPROVED PROTON MAGNETOMETER AT PREHISTORIC TOWN CREEK, NORTH CAROLINA

by

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MARSHALL DONNIE GRAHAM. Evaluation of an Improved Proton Magnetometer at Prehistoric Town Creek, North Carolina (Under the direction of Dr. Donald Brockington.)

Field work was undertaken at Town Creek Indian Mound State Historic Site, with its purpose the evaluation of an improved proton magnetometer designed specifically for archaeological field usage and its intent the demonstration of the instrumentation's value as an aid to site appraisal. The experimental magnetometer demonstrated field resolution and repeatability of 0.5 gamma in an ambient field of 55,000 gammas, it was stable and reliable in use, and it proved in all respects to be suitable for its intended purpose. Surveys were made of four ten-foot squares using the instrument, and the magnetic contours derived from its readings were mapped prior to analysis of plots previously made by Dr. Joffre Coe of the exposed but unexcavated subsoil features. Comparison of the feature plots with the magnetic contours due to the reburied features demonstrated that most of the major and many of the minor features would have been found had digging been undertaken in the detected magnetically anomalous areas. Many of the smaller features failed to register magnetically, either being camouflaged by close proximity to other archaeological features, by an apparent low susceptibility enhancement of features on the site, or by influences of the site's geology. Despite these effects it is concluded that the improved magnetometer is potentially of great value for appraisal of prehistoric sites in the southeastern United States.

PREFACE

The increasing number of publications devoted to archaeological application of methods and instruments adapted from the physical disciplines witnesses both to the maturation of archaeology as a science and to the need for continuing interdisciplinary exchange of ideas so that process is enhanced. In this spirit, then, this thesis addresses the archaeological problem of site appraisal through the geophysical technique of magnetic anomaly detection; it has as its purpose the evaluation of an improved proton magnetometer designed specifically for archaeological field usage and as its intent the demonstration of the instrumentation's value as an aid to site appraisal.

The interdisciplinary foundations of this thesis pose a paradoxical requirement difficult to meet in its actual writing: That results from research in both terrestial magnetism and instrumentation for measurement of its characteristics be presented in such a way as to not overshadow the basic anthropological application. This dilemma has been approached by providing the necessary technical information as appendices, rather than incorporating it into the body of the thesis. Thus, Appendix I explains terminology used in describing mechanisms and properties important to discussion of magnetic materials. Since the relatively small man-made magnetic anomalies of archaeological interest are superimposed on the ambient terrestial field, Appendix II provides a description of the terrestial magnetic environment. As introduction to a functional description of proton-magnetometric instrumentation, Appendices III and IV survey available magnetometers from the view of their potential application in archaeological site appraisal. Throughout this thesis no attempt has been made to cite comprehensively; rather only those sources are cited which are either especially helpful or unusually well-referenced. It is hoped that the balance so struck will lead to the more-detailed treatment that may be desired.

More so than normally, this thesis would not have been completed but for help given freely by many people. Dr. Donald Brockington encouraged my entry into this area of archaeological research and has shared his knowledge and time most unselfishly. Dr. Joffre Coe opened the resources of the Research Laboratories of Anthropology to me and gave unrestricted access to Town Creek and to field notes related to it. Dr. Richard Yarnell extended interest and encouragement, and Mr. Gary Stone provided discussion patient beyond the duties of friendship.

The staff at Town Creek Indian Mound State Historic Site was extremely helpful, and Mr. Jack Wilson's aid with the field work was most professional. Ms. Debra Smith patiently typed and corrected the manuscript, and Mr. Steve Caparella solved circuit problems. Understanding given by a special friend, Ms. Martha Graham, was an important asset.

Magnetic maps of the United States were located and loaned by Ms. Marie Hastie of the Weston Observatory, Weston, Massachusetts, and magnetic data for the survey date were supplied by Ms. Beverly Campbell of the Fredericksburg (Virginia) Magnetic Observatory. Dr. Paul Serson provided publications by his Division of Geomagnetism, Canadian Department of Energy, Mines and Resources.

Development of the experimental instrumentation was considerably eased by help from several companies. Mr. Bruce Aldridge of Texas Instruments, Inc., supplied the TIL-306 and TIL-308 displays used in the magnetometer and data systems, respectively. Mr. Kenneth Gannor of Weston Instruments, Inc., provided the M-1220 digital panel meter used in early experimental equipment, while Mr. Everett Hanlon of Reliability, Inc., contributed the V-PAC power converters and Mr. Gene Welch of International Crystal Manufacturing Co., Inc., the OE-10 clock oscillator used in developing the magnetometer.

I would like to thank each of the above-named people.

Unusual support and understanding was given by many persons within the Coulter organization but particularly by Mr. Wallace Coulter, by Mr. Joseph Emkjer, and by the people of Coulter Biomedical Research Corporation. To them this thesis is dedicated.

Don. Graham

1978

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EVALUATION OF AN IMPROVED PROTON MAGNETOMETER AT PREHISTORIC TOWN CREEK, NORTH CAROLINA

Chapter I
INTRODUCTION

The professional archaeologist, faced with increasing site destruction resulting from farming, mining, and construction activities but curtailed by limited funding in his ability to respond to it, must often wish for a means of appraising the relative merit of several sites as he attempts to select from the many known to him the few he will be able to excavate. His quandary becomes particularly acute when the sites lie within the bounds of major earth-moving operations: Schedules for such projects are commonly established without consulting the archaeologist responsible for the affected area, so that he may be faced with the necessity for quickly selecting those sites whose destruction represents the greatest archaeological loss. Whether priorities for selection be based on the need to locate sites promising to yield data related to specific cultural or historical problems or on the necessity to select those sites promising to yield the maximum information for his investment, some *a priori* knowledge of the extent and content of available sites may determine the difference between an unsatisfactory excavation and one that, for similar expenditures in energy and money, salvages the desired archaeological data.

Traditionally, test pits and trenches have been widely used in an attempt to gain this *a priori* insight before undertaking a full-scale excavation, but the sampling vagaries inherent in this approach may combine to give a totally erroneous impression of a site's character, especially with regard to the type, number, and spatial distribution of features buried within it. Additionally, the extent of a site, and the work and methods required to excavate it, may not be reliably indicated through routine test pitting or trenching, further emphasizing the desirability of a rapid means for site appraisal.

With realistic restrictions on non-archaeological variables, the geophysical techniques of soil resistivity measurement and magnetometry

have seen effective and increasing use among European archaeologists as an aid in evaluating buried features on sites, but their acceptance by American archaeologists has been less enthusiastic. Either technique can, under ideal conditions, detect features as small as post molds, and either may allow many subsurface features of a whole site to be located and plotted in the time a test pit could be properly excavated. Since neither technique will detect buried artifacts (except in the special case of certain metallic objects), they may not be helpful in choosing sites for study of a problem related to material culture; but selection of sites suitable for study of burial practices, pottery-firing methods, house structure, fortifications or ceremonial complexes, or of sites potentially yielding maximum information for expended time and money, may be greatly aided through their use.

Both techniques depend on detection of anomalies induced by human activities in a semi-infinite volume conductor assumed to be otherwise homogeneous but because of the physical principles upon which their operation is based, each provides a different representation of those anomalies. Resistivity surveying depends on the fact that once the original subsoil of a site is disturbed, the fill which finds its way back into the disturbance will differ in content and compaction, and hence in permeability to mineral-carrying ground water, from the surrounding undisturbed earth. Permeability to circulating ground water within the disturbance may be either greater than or less than in the subsoil, depending on what fills it: If the removed soil were returned to the pit or ditch, permeability would increase, but it would decrease if a rock or brick wall or foundation were buried during the refilling. In normal climatic conditions these differences result in a parallel increase or decrease in the electrical conductivity of the disturbance, relative to original subsoil, and so can be detected as resistance variations between electrodes inserted into the earth near the disturbance. The magnitude of the resistance variation is determined by the differential conductivity of the feature and subsoil, the extent and depth of the feature, and the spacing, penetration and diameter of the sensing electrodes; this dependence on electrode geometry and soil contact requires practically that the electrodes be carefully driven into the soil to a constant depth and at a regular spacing along the line of site

traversal and has led to the use of more than two electrodes in attempts to minimize soil-electrode interface effects on the data. Still, it is not difficult to illustrate why features can occur but not be detected.

Because soil in a feature is more permeable to water circulation than is the surrounding earth, periods of dryness cause it to lose water more quickly, causing conductivity decreases that effectively remove the feature; continued drying may then later result in the feature reappearing, but as an area of anomalously low, rather than high, conductivity. If the feature contained a mixture of soil and rock or brick, it might be detectable due to the (normally) higher soil conductivity or due to the lower conductivity of the rock or brick; but if the first is cancelled by the second, the feature will go undetected. This may naturally occur on rocky soils where, besides the difficulty of satisfactorily driving the electrodes, random variations in conductivity due to the rock may mask those due to archaeological features; other geological structures may have an opposite effect, leading one to interpret clay or soil pockets in a rocky subsoil, or an underground spring or water table, as archaeological features. And finally, prehistoric hearths, usually detectable due to reduced permeability beneath the fire-hardened hearth center, may be masked by collection of rain water in that same baked center. AITKEN (1974) discusses the method in detail.

Magnetometers may also detect features of all types mentioned above, but the response is due to alternations in the earth's local magnetic field, either through changes in the ease with which the soil can be magnetized under influence of the earth's magnetic field or by acquired magnetism, rather than by conductivity differences. Mechanisms responsible for these effects are discussed in Appendix II; here it is merely noted that pits, ditches, walls, foundations, roads and similar features alluded to in connection with resistivity measurements are most commonly apparent to the magnetometer because of differences in the feature's susceptibility to magnetization, while features such as kilns, hearths, large objects of fired clay and rocks which have been heated *in situ* provide a stronger anomaly due to their acquired magnetism. Since igneous and some metamorphic rocks fall naturally into this last class, archaeological features on sites underlain by them will often be masked by their high acquired magnetism; natural deposits of iron oxides may

have a similar effect, but due to their relative ease of magnetization. With exception of buried rock of some sedimentary types and air-filled voids, most archaeological features tend to appear as an increase in local field strength; again, a feature containing a mixture of igneous and sedimentary rubble may not be detected due to the average magnetic character of its fill being not unlike that of the surrounding subsoil. Man-made magnetic anomalies of no archaeological significance usually result from nearby power lines or substations, metal buildings or fences, or ground currents due to heavy electrical machinery; and natural events such as sunspot activity may also cause unreliable data, but the effect of these can often be reduced by instrumentation design or analysis techniques. AITKEN (1974) also discusses these points.

The first step in appraising a site by either magnetometry or resistivity measurement is the establishment of fixed datum points and a grid of standard size. The site is then initially surveyed at low resolution to detect anomalies and then these examined at higher resolution to delineate their extent. Once the cause of any suspicious anomalies is determined, the archaeologist has left a plot of subsurface features which indicate by their number and distribution the site's extent; its character may be indicated by patterns among the individual anomalies. Although some information as to the nature of an individual anomaly is given by its strength, extent and shape, there is no way of unambiguously interpreting a given anomaly. Given this fact, it can be seen that site appraisal cannot remove the need for excavation, but can be a valuable aid in site selection (CLARK, 1975).

The relative advantages of the two appraisal techniques, magnetometry and resistivity measurement, may be summarized as follows: Magnetometers allow the rapid survey of an area, while resistivity instrumentation lends itself to incrementated, straight-line traverses, usually with less resolution than is possible with magnetic equipment; magnetometers are not affected by soil moisture content but are sensitive to certain igneous geological structures, while resistivity equipment may be useless where high water tables persist but is unaffected by most geologic formations other than near-surface soil pockets in rocky subsoil, near-surface streams, or inhomogeneous topsoil; magnetic surveying is usually able to locate isolated, and often small, features such as refuse pits,

burials, larger post molds, iron items and baked clay hearths, kilns and artifacts, while resistivity surveying is more suited to detection of ditches, historic buildings and stone structures. It can also be used close to power installations or metal structures which would limit or prevent the application of magnetometers, and the instrumentation is less complex and costly than is a magnetometer. However, appraising an overgrown site is much slower and more tedious than with the magnetometer, due to the necessity for driving the electrodes into the ground in a fairly critical pattern and the need to keep the several cables disentangled; difficulty in driving the electrodes may make use of resistivity equipment on a rocky site frustrating if not impossible.

The characteristics of the two techniques are to a certain extent complementary, although each is potentially capable of detecting the same features as the other; both should be considered as valuable additions to the professional archaeologist's more customary methods, since more information of greater dependability can be acquired through a combined survey than through use of either technique alone. However, in this thesis only magnetometric instrumentation is considered, its operational characteristics more nearly suiting it to rapid field usage, particularly in areas under permanent vegetation; and an experimental proton magnetometer based on an improved design is evaluated, with the intention being demonstration of its value as an aid to site appraisal.

That the evaluation be realistic was the primary concern underlying the selection of prehistoric Town Creek for the field trials. While many sites both pristine and reburied are known, Town Creek (perhaps uniquely) offers a controlled experiment avoiding problems inherent to either a site whose plan is unknown or one whose plan is available but whose magnetic characteristics may have been altered during excavation and reburial. Since the 1930s Dr. Joffre Coe, Director of the Research Laboratories of Anthropology, University of North Carolina at Chapel Hill, has removed the plow zone from parts of Town Creek, recorded the features in its clay subsoil and reburied them under the stripped plow zone without excavating them. Comparison of Dr. Coe's feature maps from his field notes with interpretations of magnetic determinations made before the notes were seen was felt to define a sufficient evaluation. Because Town Creek is representative in many germane aspects,

and because underlying geology of the area is similar to that at many other sites in the southeastern United States, favorable results at Town Creek should augur well for the general value of the experimental instrumentation as an aid to site appraisal. The following Chapter describes the site, the field work done there, and the results obtained, while the third Chapter summarizes the findings and conclusions.

Chapter II
FIELD WORK AT TOWN CREEK

Located on approximately fifty acres of land near the confluence of Little River and Town Creek in southern Montgomery County, North Carolina (35.18°N, 79.9°W), Town Creek Indian Mound lies in the border zone between the coastal plain and piedmont sections of the state and consequently is furnished with a reliable supply of water due to the river drainage between the two areas. A favorable climate, an abundance of natural resources, and the lack of natural barriers to movement resulted in the Uwharrie peoples' occupation of the area prior to 1400 AD, but by the mid-fifteenth century an invading Muskogean-speaking, Creek derivative people advanced from the south. These invaders built villages throughout the Pee Dee river system and for two hundred years held them against attack, until weakened by continuous warfare they relinquished their land to its former occupants and returned to the south. The site and its occupational sequence are more fully described in the site Guidebook, published by the North Carolina Department of Cultural Resources, and by GRAHAM (1973) in her study of the dentition of both peoples.

The invaders brought with them to Town Creek the Lamar form of the Mississippian cultural tradition, a tradition which guided them to build their round, bark-covered houses within stockaded enclosures furnished with watchtowers at the entrance. Although only the priests or caretakers lived within, a similar enclosure surrounded the ceremonial center where activities, especially religious, involving all villages were held and where certain of the dead were buried. As reconstructed by Dr. Joffre L. Coe, Director of the Research Laboratories of Anthropology, University of North Carolina at Chapel Hill, through excavation and analysis spanning some thirty-five years, the ceremonial center at Town Creek was in keeping with this tradition (Fig. 1).

Running westward from the Little River a high log palisade, interwoven with branches and daubed with clay, encircled a large mound, a

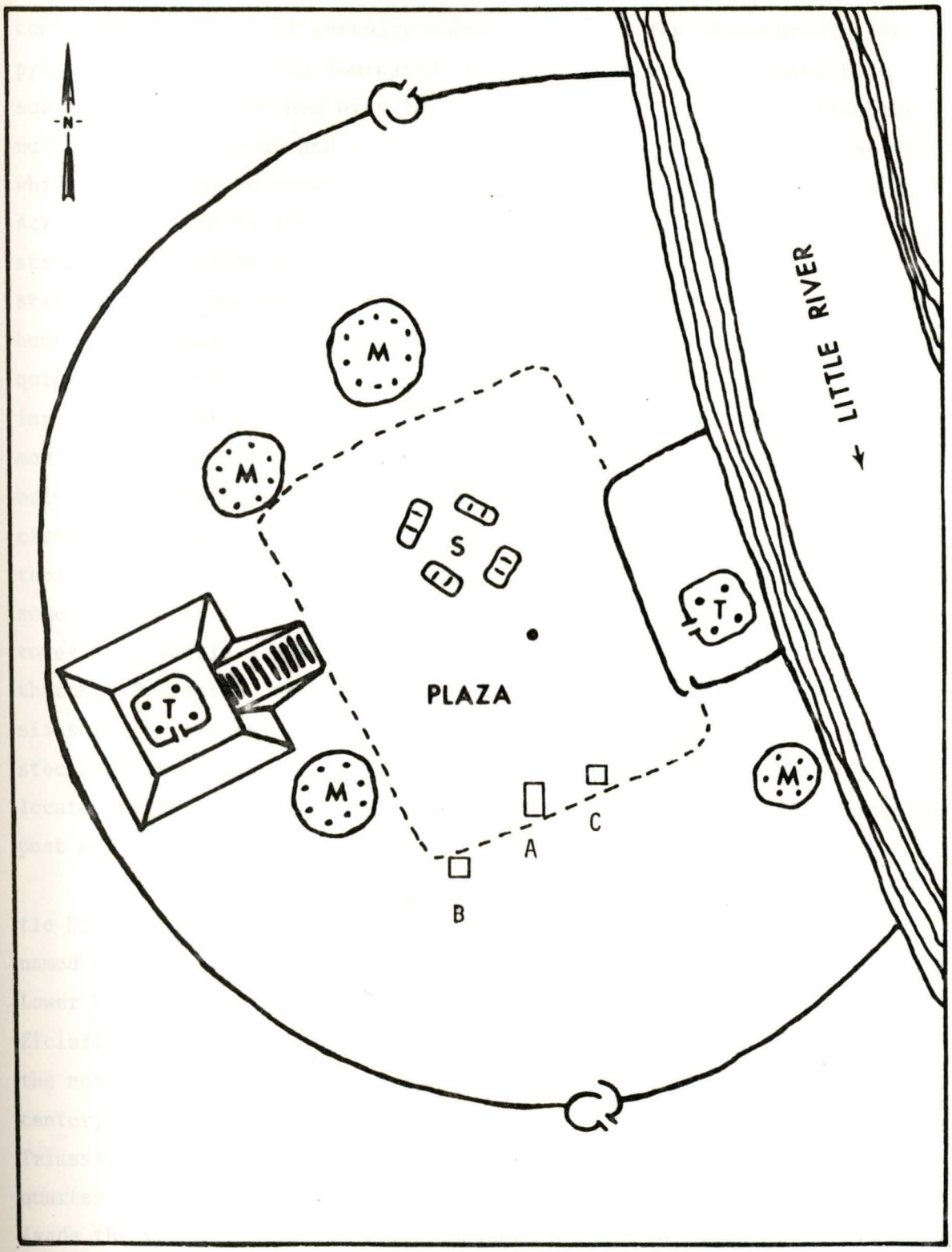


Figure 1. The Town Creek ceremonial center; survey areas are indicated by A, B, and C. (M indicates a mortuary, T a temple, and S the Square Ground; adapted from GRAHAM, 1973.)

central plaza, several mortuary complexes, and a few structures. The pyramidal earthen mound dominated the center; it was surmounted by a square structure reached by a log-paved dirt ramp approaching from the northeast. The mound and apparent temple were but the last of a series which began with an earth-covered ceremonial lodge at the plaza level. Across the plaza to the east of the mound stood a second, stockaded structure, possibly a priest's house. On the plaza between these two structures lay the Square Ground, reverenced by the Pee Dee tribe as the home of its soul. Facing the square were four open-fronted sheds equipped with three rows of seats where the men of the tribe sat according to social status to discuss tribal affairs and hold religious ceremonies. To the side stood a fifth shed, possibly used for storage; the only other structures within the palisade were the mortuaries, built as circular houses in several locations around the plaza. In the floors of these the dead were buried, the adults in cane or bark -lined pits and some infants in large pottery urns, ceremonially "killed". All structures were wattle-and-daub over pole frameworks and were roofed with thatch. Presently, the reconstructed Town Creek ceremonial center consists of the truncated pyramidal mound topped by a square temple, the stockaded-structure across the plaza to the east, and one mortuary house located to the northeast of the mound; a stockade wall rebuilt using the post molds of the original surrounds the center.

In its course southward through central North Carolina, the Little River drains an appreciable portion of the Carolina Slate Belt, so-named because of its underlying bedded argillites (volcanic slates) of Lower Paleozoic or Precambrian origins (STUCKEY and CONRAD, 1958); surficially, these argillites are apparent approximately one-half mile to the northeast of the Town Creek ceremonial center. In the area of the center, the Little River has cut its present bed into a broad deposit of Triassic alluvium (approximately 40 feet deep at the present well, one quarter mile north of the palisade wall). Between the well and the palisade the westward-flowing river encountered and exposed a Triassic dike and was deflected southwest along this diabase form, now visible as a line of spheroidally weathered boulders and clays in the stream bed below the palisaded structure. The center faces eastward toward this dike, falling within 300 feet of it for most of the site's extent; it stands

on a bluff approximately 25 feet above the stream bed, at an elevation above sea level of 215 feet. The bluff itself results from differential erosion of the Triassic alluvium and falls quickly to the south and west but only slightly to the north, where traces of a former river course may be found in swampy alluvial deposits between the palisade wall and the visitor's center. Evidence for differential erosion, particularly in the southeastern corner of the palisaded area, can be found in the relatively greater concentration of mineral nodules in the alluvial clay forming the subsoil (Dr. Joffre Coe, personnal communication).

Although detailed aeromagnetic data are available for a large area just northwest of the site (HENDERSON and GILBERT, 1966), little similar data could be located for the area of interest. However, values for the terrestrial field parameters (Appendix II, Section II.1) can be estimated from magnetic maps for the continental United States, and such are summarized in Table 1; of note here is the value for F, the total-field intensity. Additional magnetic information resulted from an aerial survey of the central Appalachian Triassic Basin done under contract to ERDA by GEODATA INTERNATIONAL, INC. (1975); flight-line 16 passed just north of the Town Creek center at an altitude of 450 feet, and the flight data-log shows a total-field intensity of 54,430 gammas over the site area, with variations of ±150 gammas within 5 miles along the flight path. Indeed, increased variability in the aerial magnetic data is apparent for the entire width of the Triassic alluvium through which the Little River winds.

The subsoil at the Town Creek site consists of alluvial (rather than residual) clays but the basic underlying geology is similar to that at many other prehistoric sites in the southeastern United States. More importantly, Town Creek ceremonial center offers a unique opportunity to conduct controlled evaluations of appraisal instrumentation: Since the 1930s Dr. Joffre Coe has recorded subsoil features over large areas of the site and reburied them under the removed plow zone without excavating them, and certain of these areas have remained undisturbed since. The areas allow one to avoid problems found with excavated and refilled features, while offering the advantages of a known plan for evaluation of experimental instrumentation or data. When magnetometric instrumentation is being considered, the Town Creek center offers the additional

TABLE 1

VALUES OF MAGNETIC PARAMETERS AT TOWN CREEK, NORTH CAROLINA (1975 Epoch)

Parameter	Value	Annual Variation	Source*
F, Total Intensity	54,500γ	-65γ	MAP I-915
I, Inclination	66.3°	-5.8'	MAP I-912
Z, Vertical Intensity	49,900γ	-97γ	MAP I-914
H, Horizontal Intensity	21,800γ	+58γ	MAP I-913
D, Declination	4.3°W	6.4'W	MAP I-911

* Maps are available from: Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, Virginia 22022.

advantage of few interference sources: Vehicular traffic cannot pass sufficiently close as to pose serious problems, and the only power or water lines, or massive iron objects, on the site are those related to environmental control in the reconstructed mortuary house sited in the northern part of the palisaded area. (The permanent grid system is marked out with iron rods driven on 100-foot centers.) For these reasons, the Town Creek site was chosen for evaluation of an improved proton-precession magnetometer designed specifically for use in archaeological site appraisal.

2.1 Instrumentation and Field Methods

The purpose of the field work at Town Creek ceremonial center was twofold: To evaluate in a realistic archaeological setting a preliminary version of a new proton-precession magnetometer incorporating several design improvements, and if possible to demonstrate its value as an aid in archaeological site appraisal. The instrumentation and field methods used in the evaluation will now be described.

Instrumentation. Since the first instrument description (WATERS and FRANCIS, 1958) and the archaeological field application by AITKEN (1958, 1959), the proton-precession magnetometer has become the most commonly used surveying instrumentation (Appendix IV), this despite some application of the magnetic field-balance (GRAMLEY, 1970), the fluxgate (ALLDRED and AITKEN, 1966; CLARK, 1975; CLARK and HADDON-REECE, 1972-73; PHILPOT, 1972-73), and cesium and rubidium resonance (BREINER, 1965; BREINER and COE, 1972; MORRISON *et al.*, 1970; RALPH, 1964; RAINEY and RALPH, 1966; RALPH *et al.*, 1968; STANLEY and GREEN, 1976) magnetometers. Background information on operational principles, advantages and disadvantages, and comparative merits of the various magnetometers is given in Appendices III and IV; these and the excellent summaries by AITKEN (1970, 1974) should be consulted for details. Here it will only be noted that proton magnetometric instrumentation measures the absolute field intensity, is orientation insensitive, has sub-gamma sensitivity, and requires no mechanical operating parts; its main disadvantage is its need to polarize the proton sample and to time-average the precession signal, so that its output data is discrete rather than continuous. Once operating, the instrumentation has proven to be rugged and reliable; in available forms it has required initialization to individual sites and

has been relatively expensive (Appendix IV). These considerations, and recent developments in coherent receiver design and large-scale integrated circuitry, led to the design of an instrument responding to the requirements of archaeological field usage (Appendix II, Section II.3) and incorporating current technology. The basic design follows that of standard instrumentation (WATERS and FRANCIS, 1958; AITKEN, 1974), but avoids through autoranging much of the initialization requirement while providing at low cost the capabilities of:

1) Measuring with 0.1 gamma sensitivity over the range of 45,000 to 65,000 gammas;
2) Reducing overall sensitivity by varying either the time base or signal averaging period to accomodate unusual field conditions;
3) Operating in absolute, variometric, or gradiometric modes, and of easily changing operational modes if field conditions so warrant; and
4) Displaying direct-reading, decimal intensity data to the operator while simultaneously supplying four-line binary-coded decimal output suitable for direct recording as raw point data or for input to microprocessor-based data processing prior to recording.

In the preliminary version field-tested at Town Creek, all these features were provided, although the instrument was only operated in the absolute mode and its output was manually recorded. Laboratory work has verified the expected operation of variometric and gradiometric modes and has produced the expected data output.

The prototype instrumentation consists of a sensor head connected to an electronics package by shielded coaxial cable; power was supplied by a pair of 12-volt motorcycle storage batteries located remotely and connected to the electronics package by 16-gauge wire. The 14 ampere-hour batteries are larger than necessary, capable of providing more than three days field operation between charges, but were selected for the evaluation to rule out any effects of low supply voltage.

The sensor head (HALL, 1962) consists of 965 turns of 40-gauge copper wire wound around a 250 ml polyethylene bottle filled with distilled water through which nitrogen had been bubbled for 30 minutes;

resistance of the winding was 10 Ohms, limiting the polarizing current to approximately 1.25 Amperes. The coil was screened with aluminum foil, to guard against interference and nonterrestial rapid field variations; it was connected to the electronics package with 25 feet of RG58/U cable, the shield of which was connected to the aluminum screen. During the field work the sensor head was mounted 8.4 inches above the lower end of a wooden staff held vertically by an assistant.

The electronics package contains a low-noise, high-gain amplifier (BORDONI and PALLOTINO, 1977) to increase the low level of the sensor's proton-precession signal to one suitable for counting; a phase-locked frequency multiplier (YAMAMOTO and MORI, 1978) to implement counting directly in gammas; and the frequency counting circuitry, including sequencing and data conversion, display, and output circuits. The sequencing circuits include a second phase-lock loop (GARDNER, 1966) operating as a swept-frequency, search-and-acquire coherent receiver (BLANCHARD, 1976) to provide automatic adaptation to local field intensities through autoranging of the magnetometer input and band-pass filters. Solid-state switching of the sensor between its polarizing and precession modes (HARKNETT, 1969) and for data subtraction (SCOLLAR and LANDER, 1974) in the variometric and gradiometric operational modes is also provided by the sequencing circuitry. The resulting instrument requires only that the operator turn on the power and verify initialization at the start of the work on a new site, and then press a button when the sensor head is in position for data-taking. The rest of the operational cycle is automatically sequenced, including the output of data, and the instrument indicates readiness for a new operational cycle by blanking its data display after one-half second. (A detailed description of the magnetometer circuitry will be published elsewhere.)

Implemented with commercial CMOS integrated circuits, the electronics occupy six small (3" x 4") printed circuit boards and cost approximately $300 for the components. For the field tests the electronics were housed in a large (6" x 8" x 16") aluminum box for ease of access; the finished form could be less than one-quarter this volume.

Field Methods. The squares to be surveyed were selected by Dr. Joffre Coe from an area whose features he had previously plotted and reburied; on 3 October 1978 he reviewed the field plots for these squares

with Mr. Jack Wilson who is familiar with the site and who had agreed to assist with the field work. (My first indication of the site's true subsoil complexity was to come on the following day, as I watched the slide presentation at the visitor's center.)

On 4 October the -100L100 and -200L100 markers were located and a north-south baseline established between them; the two trial squares (-170L80 and -160L80), for which plots were supplied Mr. Wilson by Dr. Coe, were surveyed in and scanned with a commercial beat frequency metal detector (SCOLLAR, 1962) to locate any surficial iron. (Although no distinct indications of metal objects were obtained, other than over grid markers, diffuse indications of metal were noted in several areas; apparently due to the uneven distribution of mineral nodules and oxides in the soil, similar diffuse areas were noted in all areas surveyed. Curiously, magnetometer data usually, but not always, showed greater intensities over such areas.)

In setting up the magnetometer it was found that the batteries powering the accessory oscilloscope needed charging, that the magnetometer had internal damage as a result of airline handling, and that the proton-precession signal damped out more quickly than expected, possibly due to the heavy content of magnesium nodules and oxides in the soil (Dr. Joffre Coe, personnal communication). Consequently, no attempt was made to collect data, the remaining daylight being used instead to examine the site and its setting.

On returning to the site 5 October with fully operational equipment, comparative data were first taken over a 10-foot square 100 feet due south of the well house (Fig. 2). Six readings were taken at each corner and the center of the square, six additional readings at each of three points in a traverse of the utility trench were taken, and six further readings returning to the starting points of both the square and traverse were obtained; converted to absolute field intensities, the ten adjusted data sets and their statistics are listed in Table 2, where alphabetical order indicates the temporal sequence in which the data were taken. These data were intended to demonstrate data scatter, instrument repeatability, and instrument sensitivity to a known source of interference; they will be discussed in a later section.

In all the field work, survey data were taken as follows: The

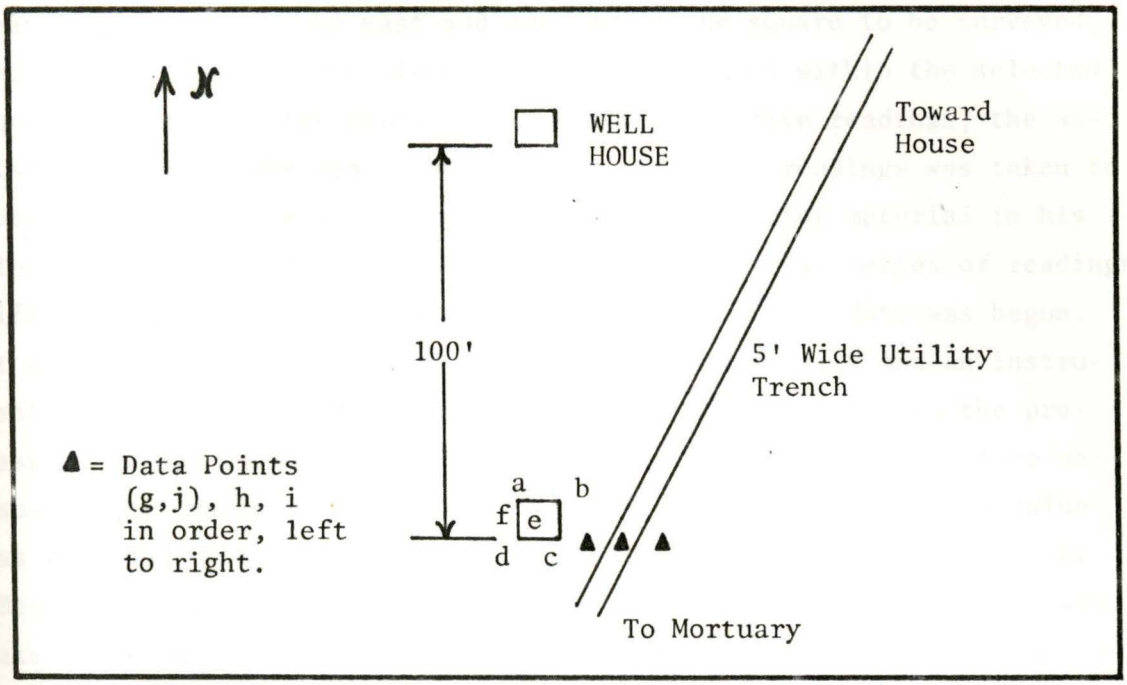


Figure 2. Location of off-site data points. Letters indicate temporal sequence in which data was taken and correspond to the columns in Table 2, below.

TABLE 2

ABSOLUTE INTENSITY VALUES FOR DATA POINTS OF FIG. 2

(To convert to total terrestial field, add 54,800 gammas. The first row of statistics presents the average field at each data point; the second, the absolute standard deviation; and the last, the t-value.)

a	b	c	d	e	f	g	h	i	j
27.8	31.4	37.9	33.1	30.0	27.4	28.0	66.5	34.3	61.5
28.9	32.1	40.5	31.5	30.6	28.8	60.1	50.8	42.6	57.5
28.8	31.8	37.1	32.1	29.9	27.9	54.0	237.6	41.5	59.5
28.4	30.9	37.9	33.0	29.9	28.5	50.1	40.9	47.1	52.9
29.1	31.1	36.5	32.5	30.4	27.5	51.1	218.9	45.6	55.9
28.1	30.8	39.1	32.4	30.8	28.0	59.0	162.9	39.0	50.4
Statistics:									
28.5	31.3	38.2	32.4	30.3	28.0	55.4	129.4	42.4	56.3
0.51	0.53	1.44	0.58	0.40	0.55	4.26	88.3	3.53	4.14
2.551	0.567	4.267	0.708	1.277	2.905	---	---	---	---

magnetometer electronics package and accessory equipment were placed at least eight feet to the east and outside of the square to be surveyed, and the sensor staff was placed flat on the ground within the selected square. Following the recording of a series of five readings, the assistant stood by the sensor and another series of readings was taken to determine whether he was carrying any iron-containing material in his clothing or on his person; if the averages of the two series of readings differed by less than one gamma, collection of survey data was begun. At each data point the sensor staff was held vertically and an instrument polarize-read-display cycle was initiated, during which the precession signal was monitored on the accessory oscilloscope. If no unusual signal variations or damping were observed, the displayed value was recorded by hand while the assistant moved to the next data point. (Because the coax cable can generate microphonics when moved, care was taken to insure that the assistant and cable were stationary before initiating the instrument cycle.) Adjusted data appear in Appendix V.

The data points were located by placing wooden stakes at one-foot intervals along two opposing sides of a given 10 foot square. (Care was taken to use only nail-free wooden stakes or aluminum gutter spikes for all stakes, corner markers, and indicators.) A nylon cord marked at one-foot intervals was stretched between two other stakes which were successively moved from one to the next pair of marker stakes; at each position data for the 11 points making up that traverse were recorded. To check data repeatability, remeasurement at a traverse center point was periodically done, and all first traverses of a new square were taken as the average of five readings at each data point. For the first three 10 x 10 squares surveyed, the traverses all ran south to north, while in the last square they ran west to east.

As sketched in Fig. 1, the survey squares themselves are located south of the game pole, along the periphery of the former plaza area; again alphabetical sequence indicates survey order. Area A is the trial area for which plots of subsurface features were supplied Mr. Wilson by Dr. Coe; plots were provided on the suggestion of Dr. Donald Brockington as a means of evaluating experimental results to see whether extensive data-taking were warranted. Area A includes the two squares -160L80 and -170L80, data being taken at a sensor height of 8.4 inches and

an interval of one foot, between 8:45 and 10:45 AM. The south-north traverse along the L89 line was taken as the reference traverse for the area; the average of 5 readings at each of its 21 points was recorded.

It was intended to compare the resulting field data with the feature plots of the trial area to verify the location of detected anomalies before moving to a four-square test area, but inspection of the data showed sizeable magnetic variations of unexpected randomness, few of which could be clearly correlated with plotted features. Selected data points were remeasured and repeatability determinations made, with standard deviations in resulting data of 0.4 to 0.6 gamma. It was decided to try an area of less subsurface complexity, and a single square at B (-200L130) was suggested by Mr. Wilson, who had plotted it in a previous summer and who knew it contained only a few isolated post molds. This square was surveyed between 12:15 and 1:15 PM, using the L140 line as the reference south-north traverse for which an average of 5 readings was recorded; the adjusted data appear in Table E, Appendix V.

Since a field inspection of the data from this square showed appreciable but smaller variation than obtained from the first two squares, the variation was accepted as being a real result of site conditions, and attention was turned to the test area at C. A 10 x 20 foot area (squares -140L50 and -150L50) suggested to Mr. Wilson by Dr. Coe was surveyed in and traverses started at 2:00 PM, with the west-east traverse along the -150 line serving as the 5-reading reference. Unfortunately, at 2:40 PM a thunderstorm began, and although the major electrical activity was at some distance from the site, the recorded data became increasingly erratic, requiring careful monitoring to contain variability. As a consequence, surveying was halted without completing square -140L50, and only data for square -150L50 is given in Appendix V.

By 4:15 PM the storm had receded and the equipment was taken back to area B for a re-recording of the L140 traverse, as a check on the day's diurnal activity. These data are discussed in Appendix V.

2.2 Survey Results

Because the operational simplicity of the experimental instrumentation was obtained at the expense of considerable sophistication, complexity, and possible instability in its circuitry, and because its

sensitivity prohibits full operational testing in the laboratory, the field work described above was planned to provide data characterizing the new design as well as to yield insight into its archaeological usefulness, and the results will be presented in that order.

Characterization of Instrumentation. In the field, instrumentation operation was reliable and trouble-free, with no symptoms of circuit instability or sensitivity to field conditions. Initialization only required reducing signal-averaging period from 0.5 to 0.4 seconds to account for unexpectedly heavy signal damping over the site. (This required that the indicated intensity be multiplied by 1.25 to convert to absolute field intensity; had the damping been anticipated, the multiplication could have been done internally.) Autoranging readily accomodated intensity variations between the survey areas.

Summarized in Table 2, adjusted data taken near the well north of the palisade demonstrate both the absolute accuracy and repeatability of the instrumentation. As noted in Table 1, in 1975 total intensity for the Town Creek site was approximately 54,500 gammas, subject to a secular decrease of 65 gammas/year: this figure closely coincides with the value 54,430 gammas recorded in the 1975 aeromagnetic survey by Geodata International, Inc. Thus, the current total intensity at the site should be about 54,400 gammas; field data averaging 54,832.1 (±3.41) gammas were obtained for the square of Fig. 2 (points a to f). Of the 432-gamma discrepency, 320 gammas can be demonstrated to originate in the quartz crystal used in the time-base oscillator: Its actual oscillation frequency is 999,162 Hertz, rather than its stated nominal value of 1.0×10^6 Hertz. The remaining 112-gamma error can be attributed to map errors, particularly so in view of the ±150 gamma variation shown in the aeromagnetic flight-log over the Triassic Basin. Even though absolute calibration of the crystal is in error, its stability does meet the specified value of three parts in 10^5; consequently magnetometer stability would also be of that level. If necessary, the absolute error could be easily eliminated through use of another crystal.

Although the frequency-counting circuitry and low-noise preamplifier give a calculated resolution of 0.1 gamma, examination of the data standard deviations listed in Table 2 shows a practical resolution of about 0.5 gamma in an interference-free area. In fact if only data

from the square are considered, including data from point c where interference has caused both the mean and variance of the data to increase, the average standard deviation is 0.69 (±0.42) gamma; if point c is eliminated, the average standard deviation is 0.51 (±0.076) gamma. The effects of interference were further checked by traversing the utility trench to the reconstructed mortuary (data points g, h, i, and j). The trench is about two feet in depth and contains both active and inactive power lines and a 3/4" diameter iron pipe; it runs in a 5-foot wide exploratory trench dug to undisturbed subsoil. Averaged data taken across the trench show a sharp (100 gamma) anomaly but the individual data show both increased intensity and variability, peaking over the trench. It is suspected that the intensity increase is due to the iron pipe, while the increased variability originates in electrical interference from the power line. At a distance of 8 feet both effects were greatly reduced, and at 15 feet the intensity was only 6.1 gamma above the average for the square; the standard deviation of the data went from ±88.3 gammas over the trench to ±1.44 gammas at 15 feet.

As a check on equipment repeatability, the field was remeasured at points a and g; these data appear in Table 2 as columns f and j. In both instances Student-t testing verified the apparent lack of significance in differences of the recorded data. Thus it is concluded that, so long as operation is not attempted in too-close proximity to known sources of interference, the absolute accuracy, resolution, and repeatability of the magnetometric data provided by the experimental instrumentation are satisfactory for successful archaeological field application (Appendix II, Section II.3).

Survey Data. With instrumental variability established, attention can now be directed to the survey data. As noted above, variability in data from all surveyed areas was greater than was desirable and includes temporal components as well as ones originating in geological and archaeological features (Appendix II, Section II.1). Since the temporal variations are of no interest here, the survey data must be adjusted for them. This was done using the data of Table 1 and the assumption that diurnal variation paralleled that at the Fredericksburg (Virginia) Magnetic Observatory, given in Table C, Appendix V. The adjusted data appear in Table 2 and Tables D, E, and F of Appendix V.

Although area A (squares -160L80 and -170L90) was surveyed first, apparently random variability in the recorded intensities led to survey of area B (square -200L130), known to contain only a few post molds, with the intent of establishing magnetic characteristics of the site itself. Adjusted results, given in Table E, Appendix V, have been used to generate a magnetic contour map of the square (Fig. 3). If the damped readings (due to visible iron corner spikes) at points -200L130 and -200L139, -200L140, and -190L140 are ignored, with few exceptions the data show smooth contours typical of geologic effects; range of variation is from 54,942.3 gammas at -200L138 to 54,956.4 gammas at -190L130 diagonally to the northeast, with a mean square intensity of 54,950.35 (±3.24) gammas. Examination of the traverse and line statistics in Table E supports east-west orientation of the contour lines: Line means taken along the east-west lines show a gradual increase south-to-north, from 54,945.14 (±2.12) gammas at -200 to 54,954.75 (±0.88) gammas at -190, whereas the line means taken along the traverse begin at 54,950.22 (±4.11) gammas at L140 and monotonically increase to 54,950.34 (±3.21) gammas after falling smoothly to 54,949.62 (±3.17) gammas at L136. Statistics for the line (mean of means = 54,950.37 ±3.10) and traverse (mean of means = 54,950.34 ±0.80) data reflect the greater south-to-north variability. Superimposed on the geological variation are three exceptions to its smoothness.

The first of these, a 3.8 gamma gradient between -196L138 and -195L138 and peaking at the latter, could be due to a fair-sized post mold since scanning the area within a 2-foot radius of -196L138 with the metal detector resulted in no indication of surficial iron or diffuse oxide concentration; unfortunately interpretation is made difficult by the damped reading obtained at -197L138. The second exception, the area centered on -195L135 and running along the -195 line for a foot either side, is more probably due to a square-center nail, left *in situ* and buried when the square was reburied, than due to an archaeological feature. The final exception is the pair of damped readings at -198L131 and -198L132; here the metal detector indicated an area of diffuse response not typical of a metallic object and hence assumed to be a local concentration of oxides. In all of the square, this was the only area giving such an indication.

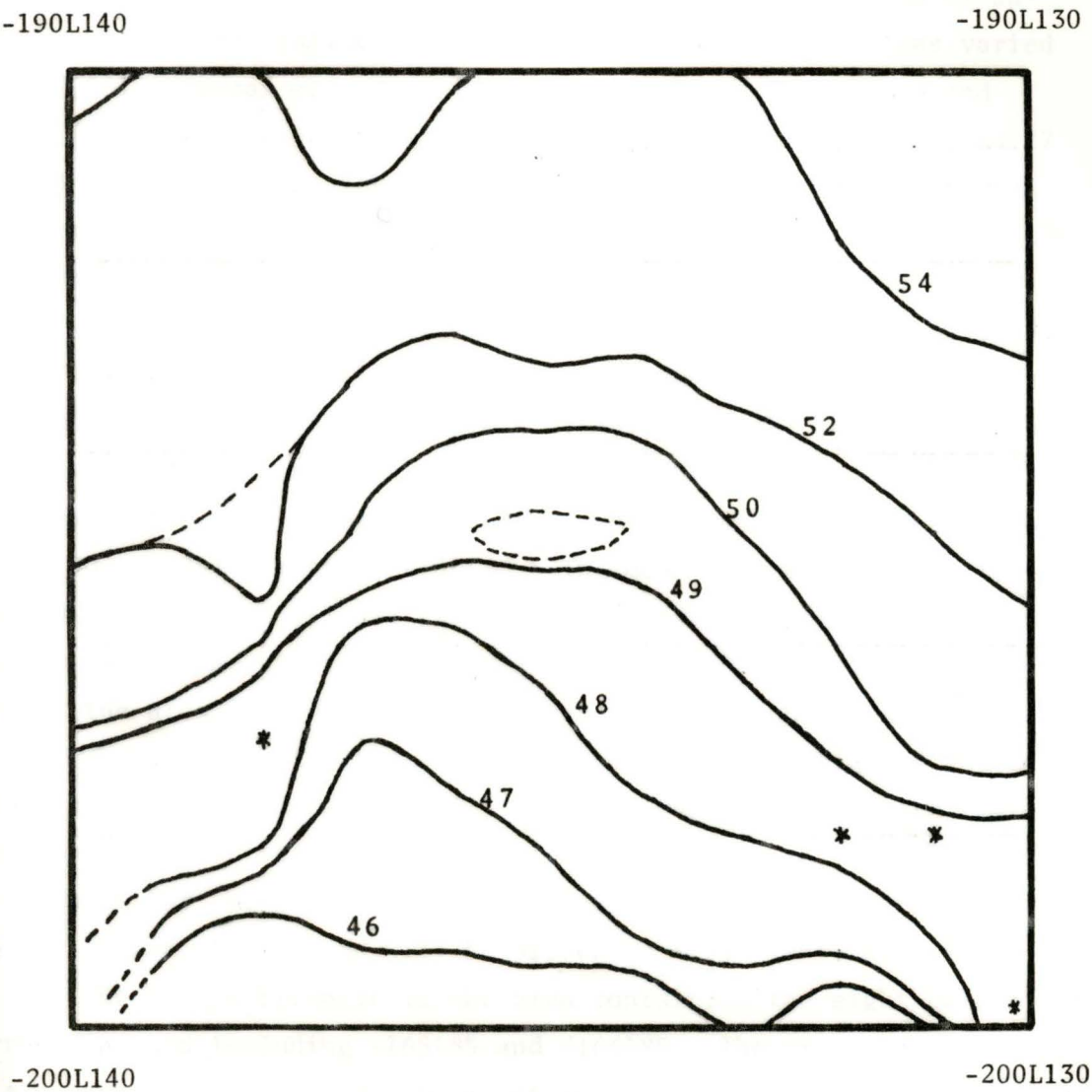


Figure 3. Magnetic contours for area B. Numbers indicate contours in relative magnetic intensity, convertible to absolute intensity by adding 54,900 gammas. * indicates a damped reading; see Table E, Appendix V for numerical data.

Given a sense of the geological contribution to measured intensities, data from area A (Tables D.1 and D.2, Appendix V) can be approached with more confidence. In square -170L80, intensities varied from 54,961.2 gammas at -170L87 to 54,968.2 gammas at -160L90 and 54,967.4 gammas at -160L80, with a mean square intensity of 54,964.27 (±0.45) gammas. Again, the intensity increases regularly but at a lower rate going south-to-north, from 54,962.54 (±0.77) gammas at -170 to 54,965.99 (±1.52) gammas at -160; however, it also increases only slightly less regularly in the west-to-east direction, from 54,963.89 (±2.25) gammas at L90 to 54,965.28 (±1.03) gammas at L80. This trend continues into the adjacent square -160L80, where the south-to-north variation increases the mean intensity to 54,971.70 (±1.42) gammas at -150, while the west-to-east variation causes a further increase, to 54,970.30 (±1.86) gammas at -150L80. The mean square intensity for -160L80 is 54,968.60 (±1.31) gammas. Thus the net increase in intensity to the northeast, first noted in square -200L130, continues through the area included in both squares -170L80 and -160L80.

The contours for the two squares are given in Figs. 4 and 5; both maps show considerable local variation when compared with Fig. 3. The smoothness of the geological contours is broken in several areas in the plot for the combined 10 x 20 area; five areas appear in the map for square -170L80 and will be presented first (Fig. 4).

The most noticeable is the area containing the eight points surrounding and including -165L85 and -164L85. The size and shape of this contour suggest a pit approximately 3 feet in diameter, centered between these two points; the anomaly is too large and uniform to result totally from a square-center nail left in place. To the south of this anomaly, at -170L84, the sudden deviation in the 72-gamma contour suggests the presence of a weak anomaly due to a feature whose approximate diameter is one foot, and a similar comment and conclusion apply to the sudden deviation in the 64-gamma contour around -166L81. A weak anomaly at -169L88 suggests yet another feature of similar size. In the northwest corner of the square, the 66-gamma contour encircles points -162L88, -162L89, and -161L89 and runs into square -160L80 (Fig. 5); geologically it probably should only include -161L89. This impression is confirmed by the 67-gamma contour which

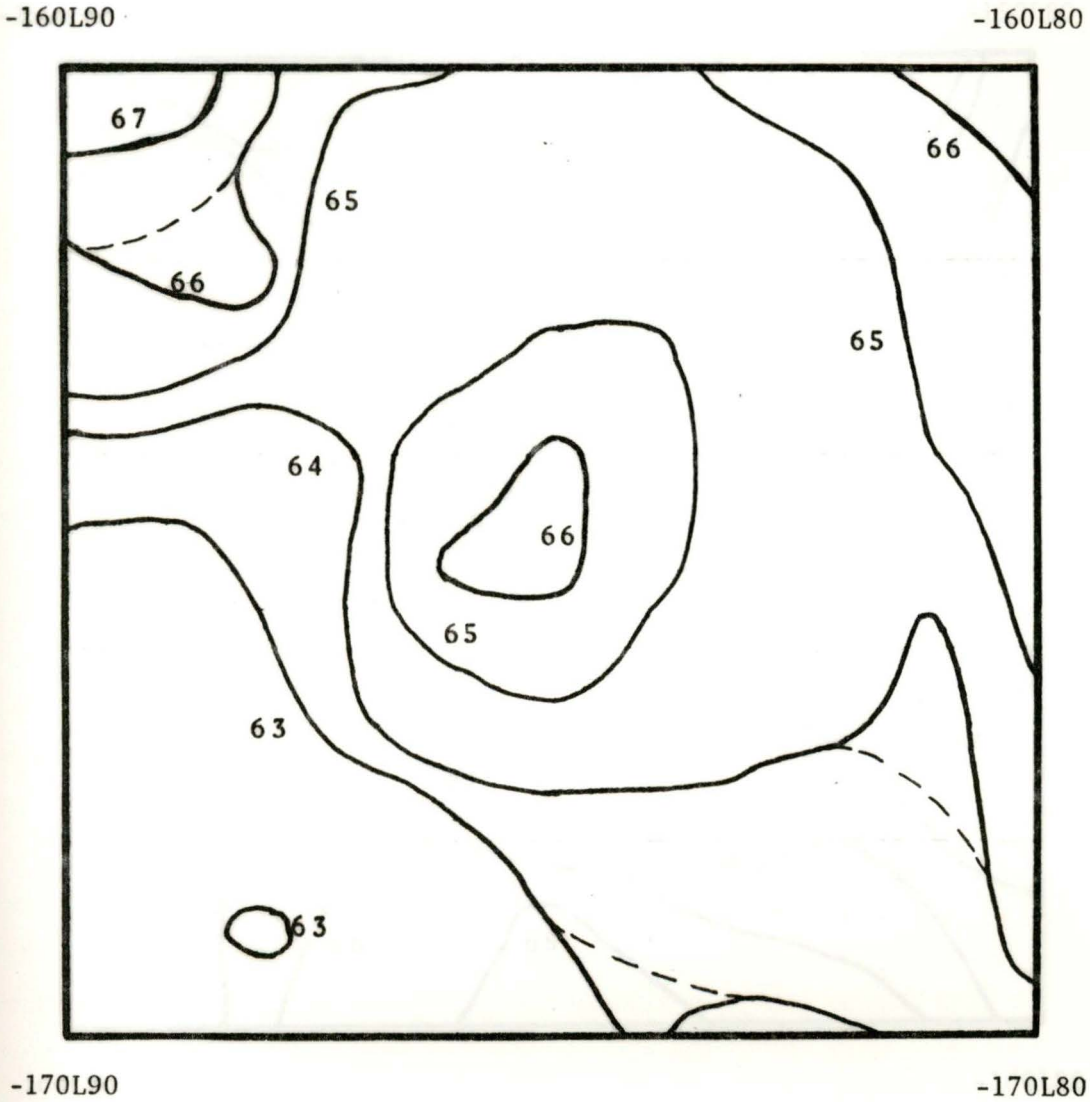


Figure 4. Magnetic contours for area A (square -170L80). Numbers indicate relative magnetic intensity, convertible to absolute intensity by adding 54,900 gammas. * indicates a damped reading; see Table D.1, Appendix V for numerical data.

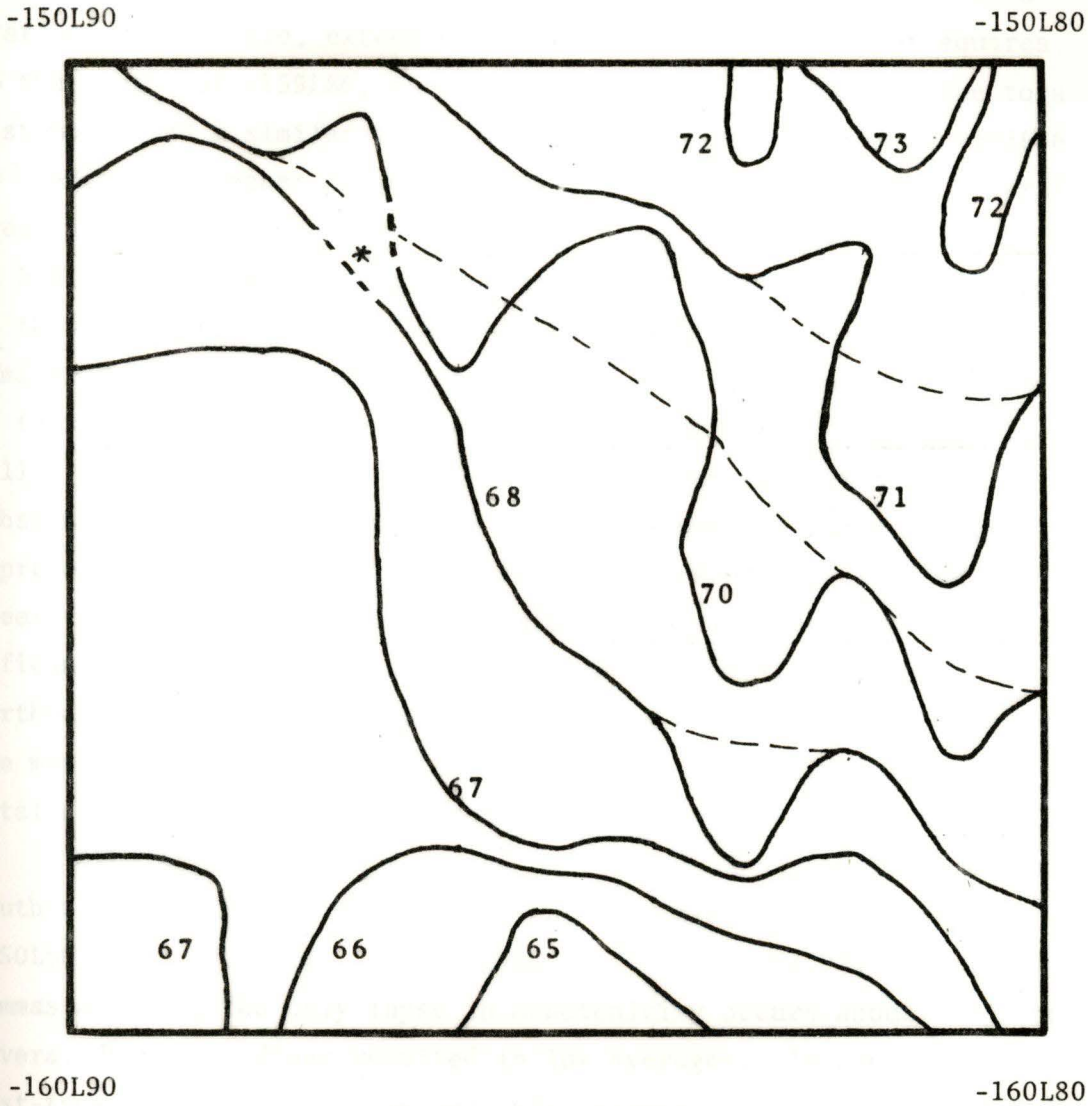


Figure 5. Magnetic contours for area A (square -160L80). Numbers indicate relative magnetic intensity, convertible to absolute intensity by adding 54,900 gammas. * indicates a damped reading; see Table D.2, Appendix V for numerical data.

encircles only four points before disappearing into other squares: -160L89, -160L90, -159L89, and -159L90. This would appear to be a feature of fair size, extending northwestward into adjacent squares. To the south, at -159L86, is a very local anomaly, possibly due to a post mold, and a similar observation and conclusion apply at -153L86 to -152L86. No other anomalies show clearly in -160L80, but several areas are interesting, particularly so along the 70-gamma contour. In addition to the last-mentioned area, four sudden deviations occur in this contour, about -157L81, -156L83, -152L84, and -151L87; and a similar deviation occurs in the 68-gamma contour, around -158L83. Of these, only the last and those around -156L83 and -157L81 could be called features -- unless rock, shell, or other similar oxide-free substances were used to fill the feature, since the other deviations represent lower susceptibility material than would be expected. The sheer tortuosity of the contour indicates possible archaeological significance. The remaining areas, three weak anomalies, appear in the northeast corner of the square and may be features, but scanning with the metal detector indicated one of the areas of diffuse increased metal content, making it difficult to draw a firm conclusion.

The adjusted data for area C (Table F, Appendix V) show the south-to-north increase continuing but more slowly across square -150L50, from 54,972.39 (±1.34) gammas at -150 to 54,974.75 (±2.38) gammas at -140; the only lapse in monotonicity occurs about -143 where several damped readings resulted in low averages. In contrast, the west-to-east variation increases only slightly, from 54,972.80 (±1.76) gammas at L60 to 54,975.23 (±2.05) gammas at L55, before decreasing to 54,971.69 (±5.43) gammas at L50. Mean square intensity reached 54,973.34 (±1.01 gammas).

Contour lines for square -150L50 (Fig. 6) show the most complexity of any of the surveyed areas, but seem to indicate three large features. The strongest anomaly, of over six gammas, occurs in the area including points -142L54 and -141L53 northwestward into the next square; because of the size and strength of the anomaly, it almost certainly must represent a burial or garbage pit. Similar comments and conclusions also apply to the second-strongest anomaly which includes -149L55 and -149L56 eastward to -145L55 and -145L56. Although an area

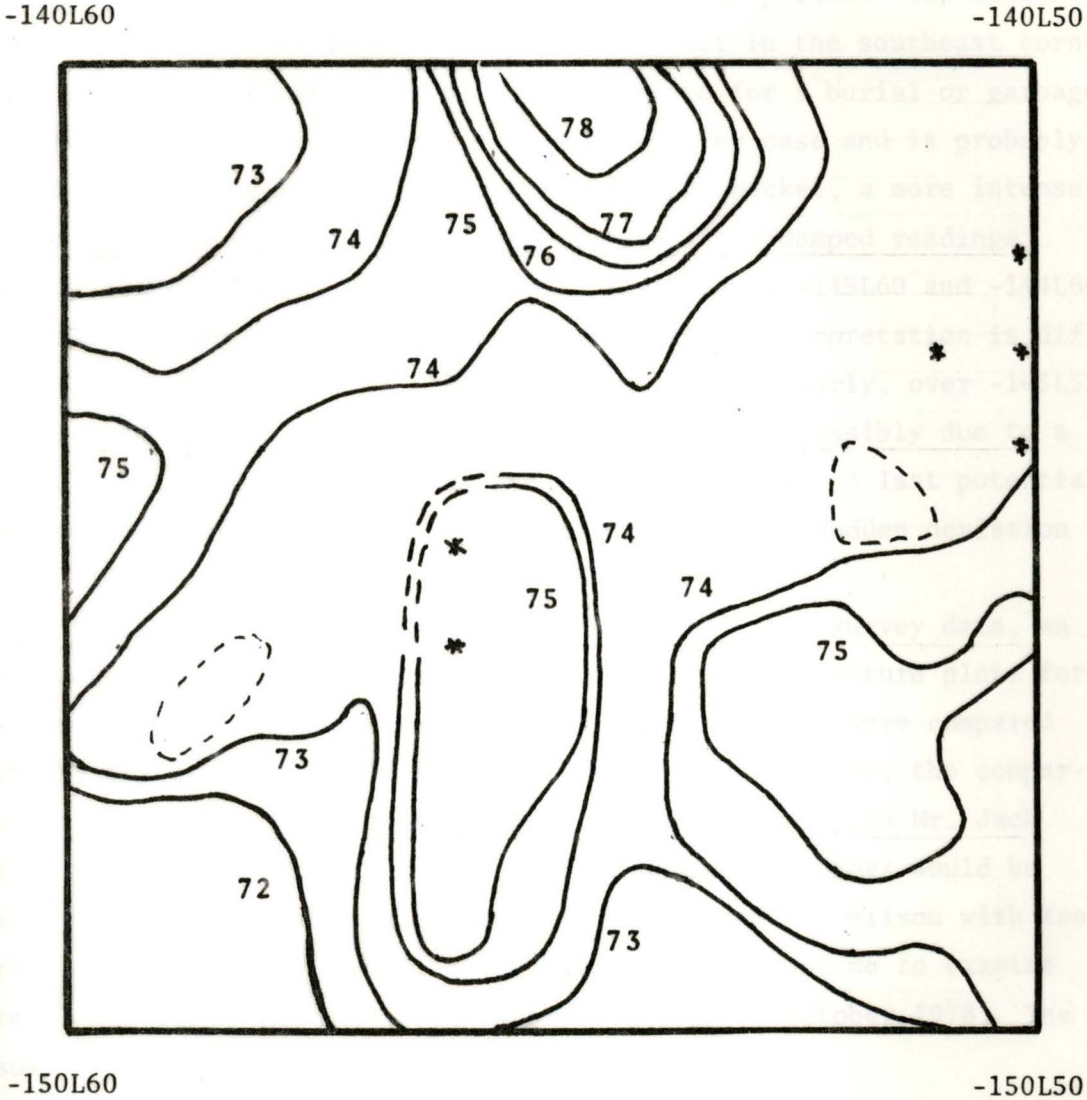


Figure 6. Magnetic contours for area C. Numbers indicate contours in relative magnetic intensity, convertible to absolute intensity by adding 54,900 gammas. * indicates a damped reading; see Table F, Appendix V for numerical data.

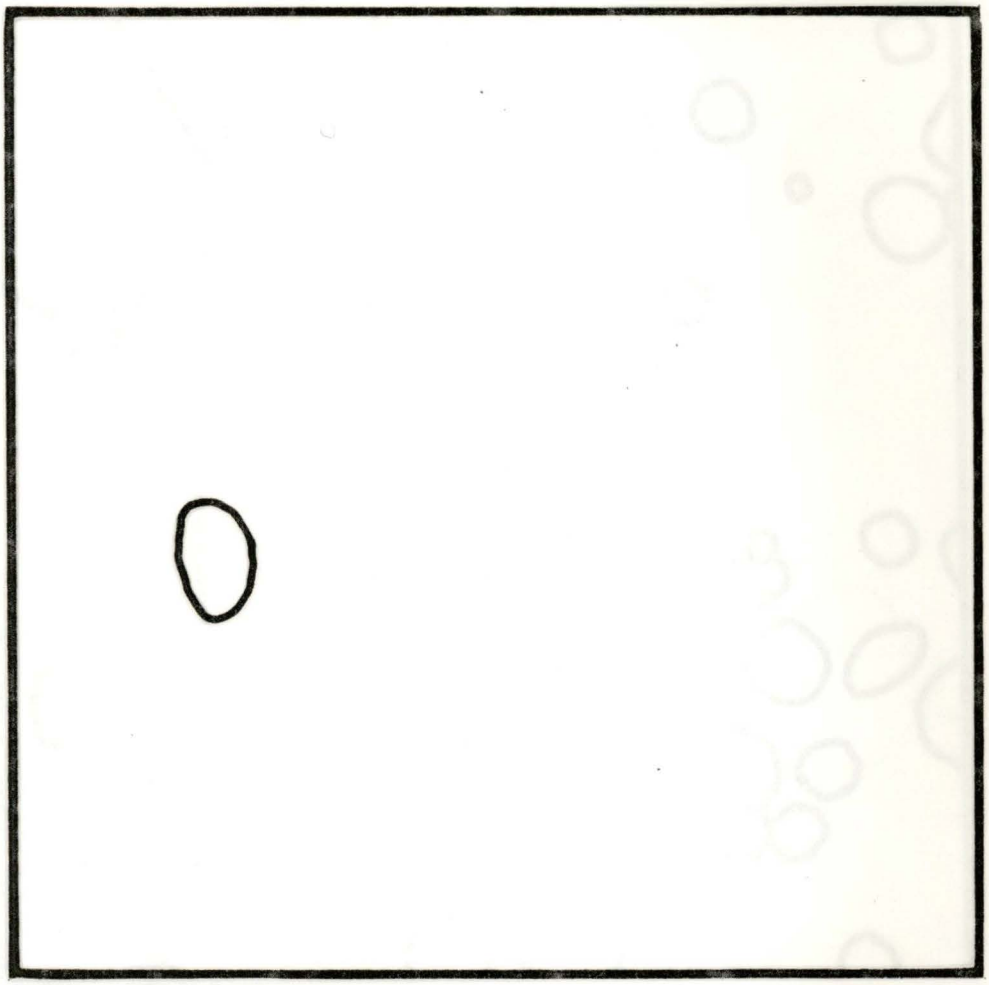
of damped response which overlapped the feature occurred at -146L56 and -145L56, it is likely to have included both these points. The weakest of the three anomalies fills about 6 square feet in the southeast corner of the square; although its size is appropriate for a burial or garbage pit, the anomaly is too weak to make a convincing case and is probably several overlapping post molds or a local oxide pocket, a more intense manifestation of which is the likely source of the damped readings around -143L50. Another weak anomaly appears around -145L60 and -144L60, disappearing into the square to the west so that interpretation is difficult; however it could be a large post mold. Similarly, over -145L52, -145L51, and -145L52 appears a second weak anomaly, possibly due to a post mold but impossible to so state with conviction. A last potential feature, at -147L58 and -147L59, is indicated by the sudden deviation of the 73-gamma contour.

This concludes interpretation of the adjusted survey data, an interpretation completed prior to examination of the feature plots for the three areas. To check these interpretations, they were compared with the feature plots on file in Dr. Joffre Coe's office, the comparisons being made after discussing the interpretations with Mr. Jack Wilson to determine if areas of damped or unusual readings would be likely to contain free iron. Dr. Coe had provided Mr. Wilson with feature plots for areas A and B; these Mr. Wilson allowed me to examine after I had given him the above interpretations 16 October 1978. The results of these comparisons will now be given.

As Fig. 7 shows, the feature plot for area B contains only a single post mold, located at -195.7L137.9; this is roughly 8 inches directly to the south of -195L138 where such a feature was postulated, but near enough that exploratory digging should have found the northern edge of the feature. Mr. Wilson verified the liklihood of a square-center nail being left in place when he recovered the square, leaving the post mold unexcavated.

Figs. 8 and 9 reveal area A to contain many features, only a few of which were resolved with certainty. In the order the presumed features were described, the large feature in the center of square -170L80 is due to the feature of similar size in Fig. 8, centered about 1.5 feet southwest of its apparent location; the shift may be due to

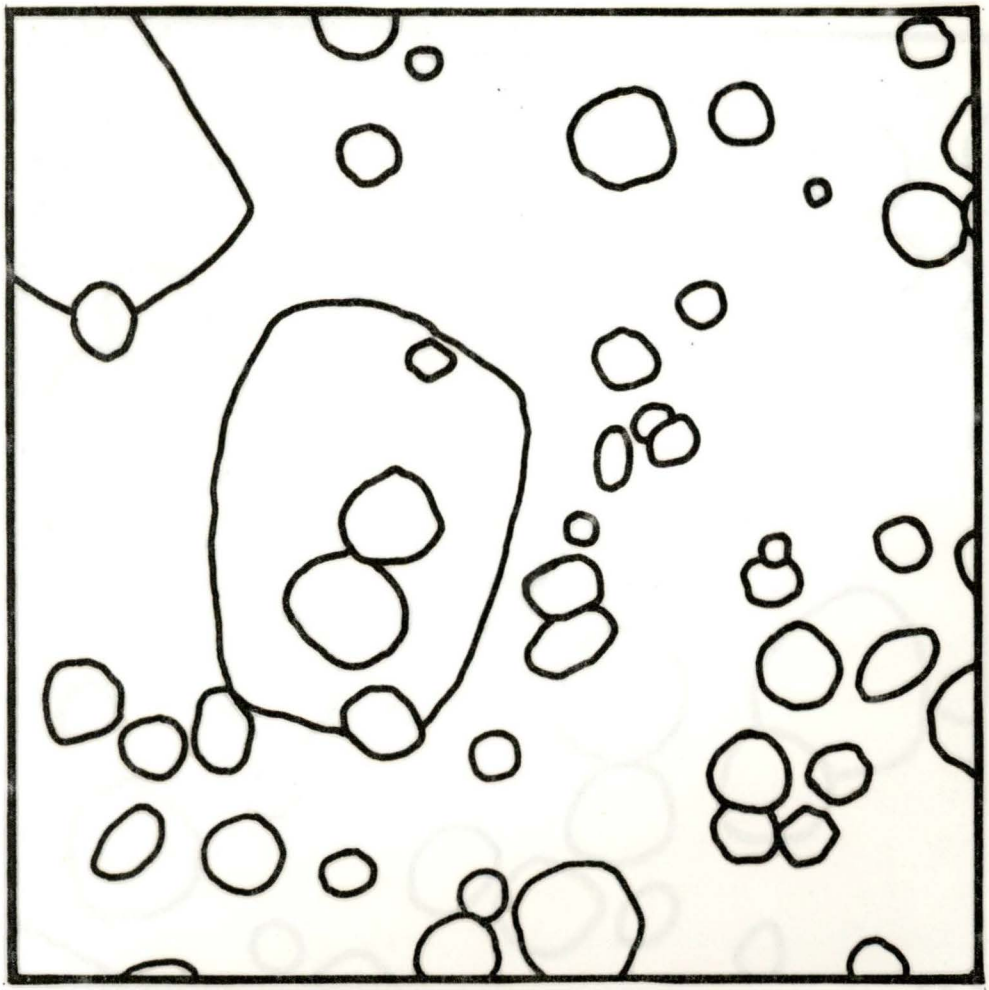
-190L140 -190L130



-200L140 -200L130

Figure 7. Feature plot for area B, courtesy of Mr. Jack Wilson.

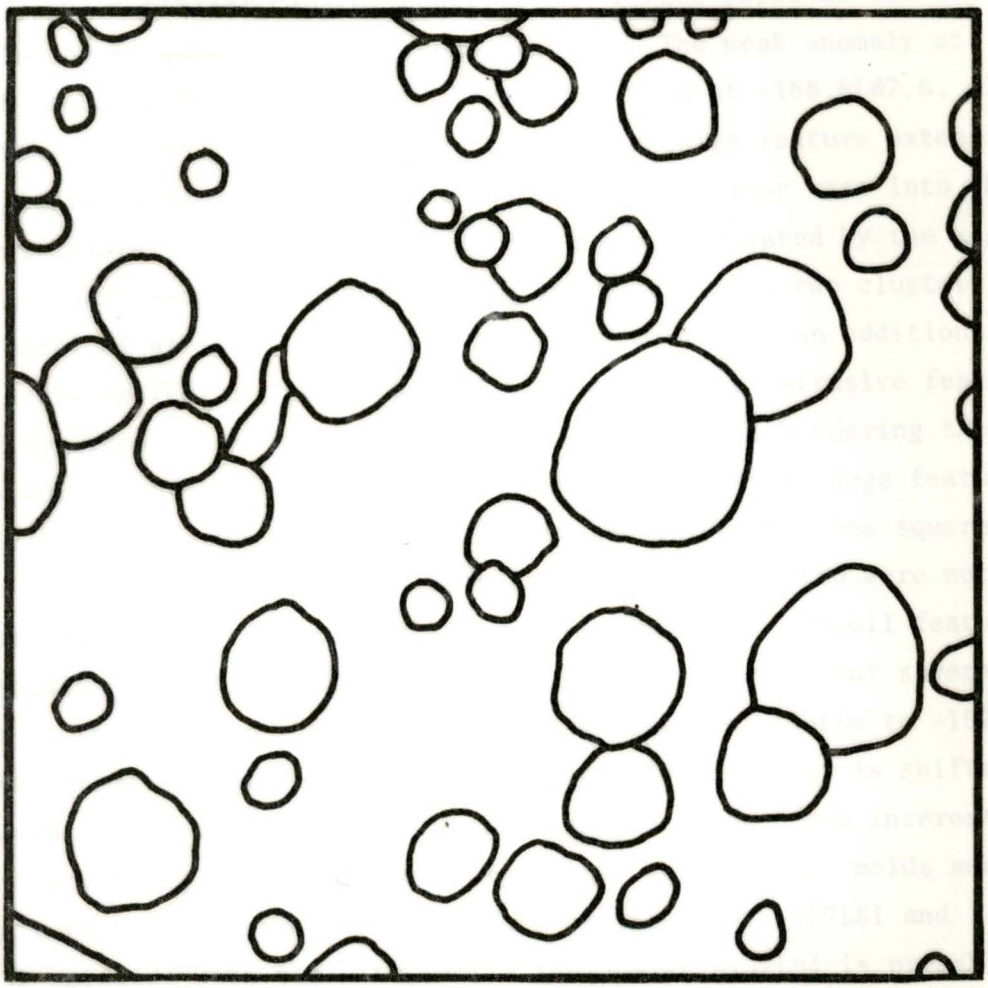
-160L90 -160L80



-170L90 -170L80

Figure 8. Feature plot for area A (square -170L80), courtesy of Mr. Jack Wilson.

-150L90 -150L80



-160L90 -160L80

Figure 9. Feature plot for area A (square -160L80), courtesy of Mr. Jack Wilson.

rock in the intrusive pits or partly the result of a square-center nail. To the south, at -170L85, appears a cluster of three small features which account for the sudden deviation in the 63-gamma contour line at -170L84, and a similar cluster centered on -167L82 explains the deviation in the 64-gamma contour around -166L81. The weak anomaly at -169L88 probably results from the large post mold at -168.6L87.6. In the northwest corner of the square, there is a large feature extending only slightly into square -160L80, but it does continue west into the adjacent squares. Thus, exploratory digging as indicated by the magnetic contours would have located both large features, two clusters for a total of at least eight of the smaller features, an additional small isolated feature (at -168.6L87.6) and the five intrusive features. Except for those at -170L85, all the small post molds bordering the square would have been missed, as would have one fairly large feature at -161.5L83 and several post molds scattered throughout the square.

As Fig. 9 demonstrates, results for square -160L80 were not as impressive, probably because of the complexity of the subsoil features. The anomaly at -159L86 coincides with a large post mold, but several others in the area went undetected. The anomaly at -153L86 to -152L83 probably results from the large feature at -153.5L86, but is shifted northward about one foot. The 70-gamma contour does prove interesting: Along its winding course are two large pits, several post molds and the last feature mentioned above. The deviations at -157L81 and -156L83 coincide with the pits, while the one at -152L84 is probably due to the cluster of post molds there. The last deviation in the 70-gamma contour occurs at -151L87 where there is no feature, but which is just north of a damped reading so that the reading at this point may be artifactual. As noted previously, both this and the deviation at -152L84 represent areas of lower susceptibility, which causes their validity as features to be questioned; for the feature at -152L84 to have unquestionably resulted from the cluster of post molds would require a considerable amount of rock or shell as filling.

Discussed in connection with square -170L80, the anomaly at the western juncture of these two squares extends further into -160L80 than does the large feature there; this may be due to the influence of the relatively large feature centered at -158.5L88.5. In any case

this feature should have been located if exploratory digging had been done based on the contours. However, none of the features in the center part of the western edge, nor in the northeastern corner, showed other than as increased randomness in the recorded readings and so went undetected. Still, four of the largest features were located.

Field notes, provided 18 October by Dr. Coe for square -150L50, show that its northeastern two-thirds lay inside a circular mortuary, the boundary of which was visible in levels 1 and 2 as dark charcoal-flecked midden against the lighter subsoil. Outside the mortuary were only some 20 post molds in level 2, but inside were three post molds and five pits, three of which were circular and centered at -144.5L56, -142.8L55, and -142L57.5 respectively. When the upper two levels were removed, only 11 of the post molds and the two remaining pits, a large oblong one 3.5 feet long at -146L55 to -143L52 and another large one running into square -140L50 at -140L53.4, were found to penetrate into level 3. However, four new pits and several new post molds were found inside the mortuary, together with a few new post molds outside. It is these features which were left unexcavated.

The feature plot of level 3 (Fig. 10) shows the oblong pit of level 2 to have either been a continuation of or overlain a complex of two overlapping pits, which in turn become contiguous with a large pit at -140L53.4. This last was detected as the strongest anomaly found and was interpreted as a burial, as was the weaker anomaly over the pit between -149L55 and -145L55; the pit connecting the two was not detected although the point of contiguity at -143L54 does show as a sharp deviation in the 74-gamma contour of Fig. 6. The large pit centered at -144L57.5 also went unresolved, the deviation in the 73-gamma contour at -147L57 being attributed to a large post mold (if at all a feature); the mottled fill of the intrusive pit may have negated its effects, except in this area. Smaller pits, at -140L68.5 and -143L50, were missed due to damped readings in the area. The weakly anomalous area centered on -147L52 is over a cluster of (four) post molds as predicted, and a single post mold does underlie the weak anomaly at -145L52. The potential feature at -145L60 to -144L60 did not materialize, but two major features were precisely located and a third should have been located if exploratory digging had been done over anomalous readings.

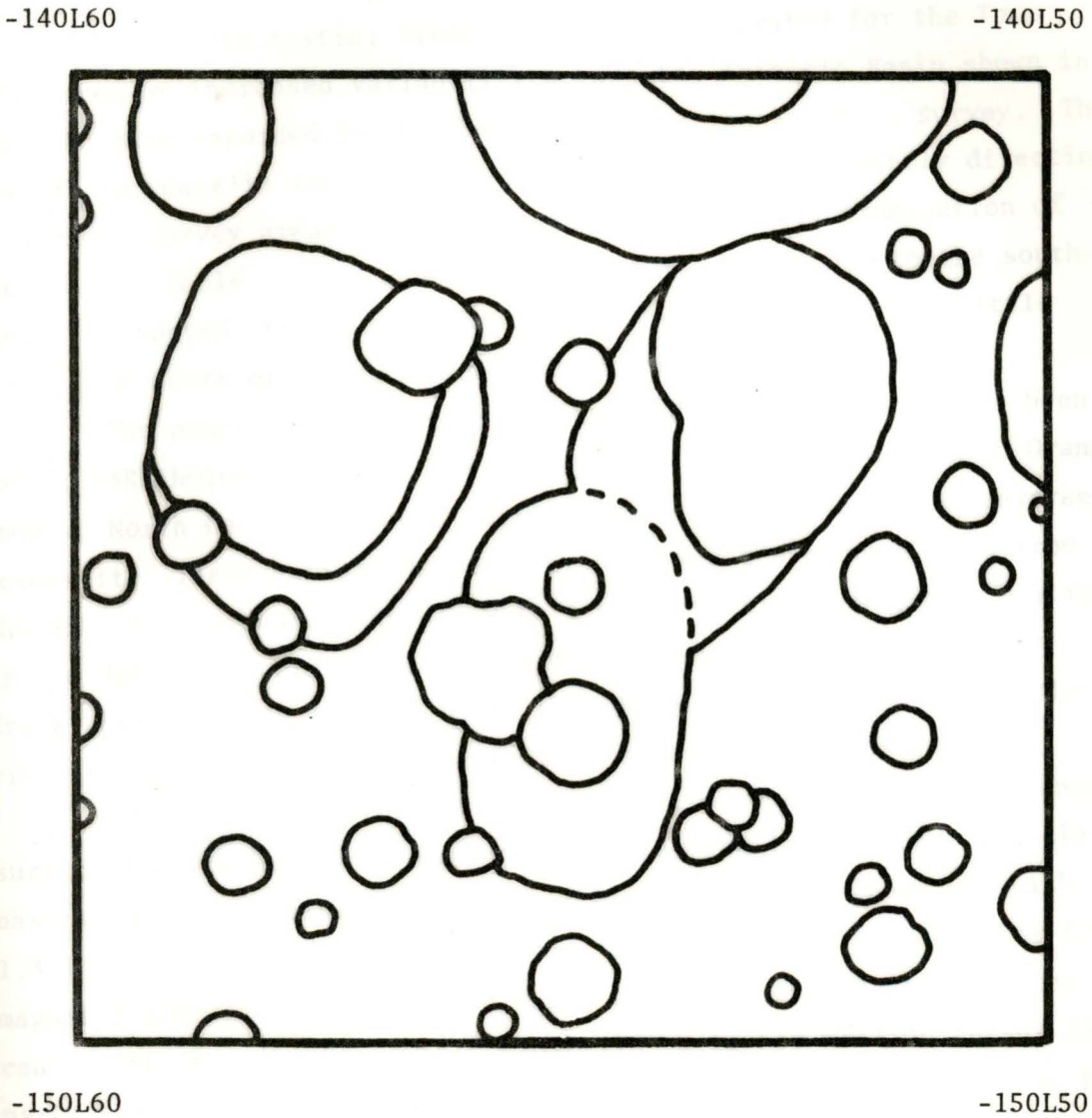


Figure 10. Feature plot for area C, courtesy of Mr. Jack Wilson.

2.3 Discussion

As discussed in Appendix II, geology is a crucial determinant of the observed terrestial field; this is demonstrated for the Town Creek area by increased variability across the Triassic Basin shown in magnetic data recorded in the Geodata International, Inc., survey. The gradual increase in recorded intensities in the northeasterly direction throughout survey areas at Town Creek has been noted; examination of the data in Table 2 also shows an apparent gradient, but to the southeast. Projected, the two gradients seem to intersect in the Little River just north of the palisaded structure.

The presence of a Triassic diabase dike in this area has been noted; HARRINGTON (1946) in his survey of a similar structure in Orange County, North Carolina, found variations to 1200 gammas in a traverse across it. These variations began gradually a few hundred feet from the dike and increased rapidly with a gradient of a few gammas per foot as the dike was approached. The similar geologic gradient at Town Creek, particularly in area B, is thus likely due to the dike in the river just east of the site, less than some two hundred feet away.

In weathering, the dike may have also contributed to the uneven surficial distribution of magnesium nodules and iron oxides: Its diabase material contains 7.76% iron in various forms as compared with 1.37% for granite and a crustal average of about 6.8%. The other ferromagnetic elements, cobalt and nickel, also are present to a greater concentration than in the Earth's crust (78 parts per million versus 75 parts per million for nickel; 50 parts per million versus 25 parts per million for cobalt) and greatly exceed the concentrations in granite (approximately 2 parts per million for both). The magnesium concentration in diabase is 3.99%, versus 0.24% in granite and a crustal average of 2.09% (HURLBUT and KLEIN, 1977; p. 124). Thus, the observed concentration of magnesium nodules and diffuse metallic response could both originate in weathering of the dike's diabase material. The net result is decreased contrast of the true archaeological features, sometimes to the point of their total obscuration, or damping of the precession signal. The first effect is especially important, due to the observed low soil susceptibility enhancement at Town Creek: The strongest archaeological anomaly found, the large pit at the northern edge of square

-150L50, was only 6 gammas and most were only about two gammas; this contrasts with reported anomalies of 10 to 20 gammas for similar features at Angel Site, for example (JOHNSTON, 1964). Apparently the clay subsoils at Town Creek do not permit full operation of usual enhancement mechanisms (TITE, 1971); the resulting low-strength subsoil features may then be further reduced at the surface by the plow zone which has been relatively homogenized by its removal and replacement, or screened by their close proximity to each other.

The survey was made using the magnetometer in its absolute mode, so that operational stability could be observed; as a result the recorded data reflected both geologic and diurnal effects. Had the instrument been used in its differential mode, both these effects would have been largely negated, obliviating the need to adjust the data for diurnal variation and to consider the absolute geologic profile during its interpretation. In actual field use the differential mode would be employed, making field analysis of the data much more feasible.

Data interpretation might also be eased using an analysis technique applied to spectra; this technique assumes that the data is composed of Gaussian distributions, fitting of which in an iterative manner can describe the set of distributions best fitting the data (ALLEN and McMEEKING, 1978; KINGMA *et al.*, 1976). Since anomalies due to a simple feature approximates a Gaussian in its spacial distribution, the method should yield a more detailed interpretation of the magnetic data than given by the analysis used here. CLARK (1977) has described a computer program for one version of this method. Here, linear interpolation between magnetic intensities at adjacent grid points was used to generate the magnetic contours; the averaging inherent in this approach may have obscured detail which would have been resolved by more sophisticated analytical methods. It should be noted that the binary-coded decimal output of the experimental magnetometer is computer compatible, making such analysis convenient, if desired.

Chapter III
CONCLUSION

The field work at Town Creek was intended to permit evaluation of an experimental proton-precession magnetometer in a realistic archaeological setting typical of prehistoric sites in the southeastern United States. It was also hoped to demonstrate the value of the instrumentation as an aid to appraisal of such sites. Because features in large areas of the Town Creek ceremonial center had been plotted and reburied without excavating them, it was felt that this site offered a unique opportunity to do a controlled evaluation at a remote location offering realism while avoiding many practical problems in data interpretation. Accordingly, the evaluation field work was done there, with two goals envisioned: To define the operational characteristics of the experimental instrumentation, and to deduce as much as possible about the subsoil features of selected squares prior to comparison of the data interpretations with the feature plots.

The instrumentation was found to operate stably and reliably, giving a practical data resolution of ±0.5 gamma in an ambient field of 55,000 gammas. The absolute field was measured to be 54,937.72 (±59.75) gammas averaged over the survey area; known to include a removable 320-gamma error due to time-base inaccuracy, this figure agrees acceptably with available data for the area. Repeatability of experimental data was limited by the geomagnetic environment, rather than by circuitry properties. In all respects the instrumentation design proved acceptable for use in site appraisal.

The areas selected for survey were found to contain a moderate northeasterly gradient, probably due to effects of the Triassic dike just east of the site. Magnesium and iron oxides from the weathering of this diabase structure caused damped readings and loss of the precession signal in some areas and in others gave a false indication of an anomaly. These effects were found to be particularly important,

since the low differential-susceptibility enhancement of the site's features resulted in many smaller features being lost in soil noise due to uneven oxide distribution and close proximity of features. Indeed, conditions at Town Creek combined to make the evaluation most realistic and challenging.

Despite these difficulties originating in the geological and archaeological complexity of the site, positive evidence of the instrumentation's worth was found when the magnetic contours derived from its readings were compared with the feature plots. In square -200L130 the single feature, a post mold approximately one foot in diameter, was predicted within 8 inches of its actual location. In square -170L80, both large pits and at least 14 of the smaller features would have been uncovered by digging at detected anomalies; all the small features bordering the square, several scattered ones, and one fairly large feature would have been missed.

In square -160L80, the heavy distribution of features resulted in poor resolution in two areas of the square, and none of the features present were detected. In fact, only two anomalies were apparent through their intensity; three others, including the two pits, were detectable through deviations in a geological contour rather than as an isolated anomaly. However, this same analytic technique indicated one anomaly where none existed and another which although present, would require rock or other low-susceptibility material as fill in the feature.

Although two large and several smaller features were not resolved in square -150L50, at least one of the large features would have been located had digging been done at the two presumed burial pits, both of which were precisely located. The other unresolved pit would have been discovered had the deviation in the contour line at -147L58 been investigated; apparently pit depth and fill content combined to produce only a very weak anomaly there. Again, although many of the square's post molds were not resolved, a cluster of four was defined and a single isolated one was accurately located. This would indicate that in a less-complex area of the site, it should be able to detect at least the larger post molds with fair certainty; surely isolated pits would contrast strongly.

Throughout the analysis of the field data several assumptions were implicit, the failure to satisfy any of which would cause features to be undetected. It was assumed that the geomagnetic contours were smoothly continuous, that similar features were approximately of uniform depth, and that the plow zone was homogeneous and therefore of uniform magnetic transparency. Obviously, exceptions to each of these occur (and did occur at Town Creek), but the relative success in detecting low-contrast features there argues for their practicality. The assumption most likely to be violated at Town Creek, given the comparatively smooth geologic gradient and homogenization of the plow zone during its removal and replacement, is that of uniform depth of comparable features: Examination of excavated burials shows both extended and shaft-and-chamber graves, with depth from subsoil surface for both types varying from a few inches to a few feet. As an example, in an adjacent square a child was found in a pit whose total depth at excavation was about six inches, and a similar situation may hold for some of the larger unresolved features. Unfortunately, such features will be found on most sites, particularly those under prolonged cultivation as was Town Creek.

The functional characteristics of the experimental magnetometer were not obtained at expense of operational speed, undue operator skill requirements, or cost. In the field work, about two minutes were required to record data from a one-foot increment, ten-foot traverse; practically, more time was spent moving the traverse cord than in recording data. If only a single reading were taken at each point, the 10 x 10 squares could have been surveyed in about one-half hour by using a movable cord grid. Initialization to site conditions is automatic, and component cost is comparatively low.

In conclusion, field evaluation at Town Creek has shown both the suitability and value of the improved magnetometer for use in archaeological site appraisal, this on a prehistoric site which while in many ways typical of others in the southeastern United States, offers particular challenges due to its archaeological and geological complexity. The fact that many of its low-contrast features were found speaks strongly of the magnetometer's general potential, a potential its reliability, simplicity, and speed of operation only accent.

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Appendix I

TERMINOLOGY OF MAGNETISM

Terms indicating various types of magnetic behavior will be defined here based on the manner of coupling which occurs between any unpaired electrons belonging to the material's atoms. Such electrons determine the magnetic properties of the material, including its ease (susceptibility) and retention (remanence) of magnetization under the influence of an external magnetic field. The susceptibility χ of a material can be measured as the ratio of the induced magnetization M to the applied field intensity T; the relative magnetic permeability μ_r of the material is then $\mu_r = \chi + 1$. Any stable magnetization M' remaining on removal of the applied external field is the remanent magnetization of the sample.

If an external magnetic field is applied to a material whose atoms contain no unpaired electrons, constancy of the applied field and of the effective orbital current requires that the orbital path of the electrons precess to maintain a constant level of interaction, but the orbital rotation generates an additional magnetic moment in opposition to the original orbital moment originating in the electronic current, with the result that the applied field effectively reduces the total magnetization within the material ($\chi < 0$). Such materials are said to be diamagnetic and have no remanent magnetic moment, since the precession moment acts to return the orbital path to its original position on removal of the applied field.

If the external magnetic field is applied to a material with an incomplete electronic shell, the orbital precession typical of diamagnetic materials occurs, but there is also a tendency for the field to align the spin magnetizations due to the unpaired electrons parallel to itself, increasing the total internal magnetization ($\chi > 0$). This paramagnetic effect is much stronger than that due to diamagnetism and is also lost on removal of the applied field, due to the randomizing

influences of thermal agitation. Most paramagnetic materials have susceptibilities comparable to those of diamagnetic substances but in a few (iron, nickel, and cobalt), magnetic fields due to the unpaired electrons couple adjacent atoms, causing a spontaneous magnetization without an applied field. (This effect is also temperature-dependent and is lost above the Curie temperature, the material then reverting to a paramagnetic condition.) For these ferromagnetic materials, the coupling mechanism and lattice structure determine magnetic properties.

Strict ferromagnetism occurs in iron, nickel, cobalt and alloys of these metals, in all of which adjacent atoms are directly coupled through interaction of the magnetic fields of the unpaired electrons, giving rise to high spontaneous magnetization whose direction readily aligns with that of any applied field. However, in oxides and other compounds of these metals, coupling occurs through an intermediate atom, and the material's magnetic properties depend on whether adjacent crystal sublattices have unequal or equal numbers of oppositely directed, internal magnetic dipoles. In the first case a net magnetization results and the material is said to be ferrimagnetic, reflecting its weaker magnetization as compared with the strict ferromagnetic materials. Similarly, if adjacent sublattices have equal numbers of oppositely directed dipoles, the antiparallel moments cancel each other and the material is called antiferromagnetic since on a macroscopical scale the ferromagnetic attributes are eliminated; however, such materials usually retain a degree of parasitic ferromagnetism due to imperfections in the lattice or in chemical composition. Thus as Fig. 1 indicates, compounds identical in chemical composition (haematite and maghemite, both Fe_2O_3) may have different magnetic properties: Haematite is antiferromagnetic with parasitic ferromagnetism, but maghemite is ferrimagnetic, with a correspondingly greater susceptibility and remanence.

Thus, while susceptibilities of all paramagnetic materials are greater than zero only those of ferromagnetics are significantly so, and only ferromagnetic materials acquire remanent magnetization. Many mechanisms resulting in permanent magnetization of crystalline ferromagnetics have been described, all depending on a balance between the magnetostatic forces arising in mutual attraction between opposing dipolar fields and the magnetocrystalline forces arising in alignment

of the dipoles into a minimum-energy configuration at the crystal surface. This balance is achieved through formation of magnetic domains, within which the dipoles are aligned but between which their direction gradually reverses to form the so-called Bloch walls. For a system of such domains in the absence of an applied field the minimum-energy configuration exists when the net external field is zero, or when domains orientate themselves so that their unlike poles are as close as possible. In the presence of an applied field, the domains parallel to the field direction expand at the expense of non-aligned domains by the movement of their Bloch walls; ideally, the system should revert to its original configuration upon removal of the external field. Practically, however, the Bloch walls may have passed through energy barriers due to crystalline imperfections and impurities, preventing the magnetostatic forces from returning them to their original positions and causing a remanent magnetization after removal of the external field.

The various types of remanent magnetisms are defined in terms of the predominant physical mechanism whereby the Bloch walls were configured through these internal energy barriers. Thus, the magnetization remaining when a field applied to a ferromagnetic is relaxed is called isothermal remanent magnetism (IRM), since it was acquired at constant temperature; it (or magnetism acquired by any other mechanism) can be gradually relaxed to a new minimum-energy configuration depending on external field conditions by any of several agitating mechanisms which act to randomize primary dipolar orientations, beginning preferentially with the Bloch walls. In the absence of an applied field the resulting domain configuration is such as to minimize the external field due to the dipoles, while in the presence of a second applied field the relaxation of primary dipolar orientations is such that they align with the direction of that field, resulting in the gradual development of a secondary remanent magnetization (SRM). If the source of agitation is mechanical vibration, the resultant SRM is called mechanical remanent magnetization (MRM); if decaying alternating magnetic fields, then anhysteritic remanent magnetization (ARM); if in hydrostatic pressure directly, then pressure remanent magnetization (PRM); and if the source of agitation is thermal, the magnetization is called viscous remanent magnetization (VRM).

The rate at which primary magnetization relaxes or secondary magnetization is acquired is dependent on the intensity of the particular agitations acting on the ferromagnetic and on its magnetostatic and magnetocrystalline forces; the time necessary for the magnetization of a given particle to relax to its thermal equilibrium value and direction is proportional to the anti-log of the ratio of particle volume to ambient temperature. Thus, below a certain particle volume V_B and above a certain temperature T_B, relaxation times are so short that particle magnetization can follow rapid changes in field direction; the sample retains no remanent magnetism and behaves superparamagnetically. At V_B (or T_B) the relaxation time becomes several minutes, and the particle's remanence can be measured; this volume (temperature) is said to be the one at which the magnetization is blocked in the particle. Consequently, two further mechanisms whereby magnetization may be acquired can be defined: Thermo-remanent magnetism (TRM) is acquired by particles larger than domain size which have been cooled from a temperature greater than the material's Curie temperature to less than T_B; conversely, if particle temperature is kept constant and the particle allowed to grow through V_B by crystallization, the blocked-in magnetization is called chemical remanent magnetization (CRM). Although the igneous origin of many rocks accounts for their primary TRM, exsolution of their iron-titanium oxides often results in a stable CRM in these rocks, as well as in the metamorphic ones. However, the predominate mode of magnetization in sedimentary rocks arises in the deposition from water of detrital particles eroded from older formations and containing primary magnetization; these tend to settle so that they align with the ambient field, giving rise to detrital remanent magnetization (DRM). In a given sample, the natural remanent magnetization may have been altered by any of the mechanisms producing SRM; study of these magnetic puzzles is the basis of palaeomagnetics.

Appendix II
GEOMAGNETIC BACKGROUND

The local characteristics of the terrestial magnetic field are crucially important in archaeological applications of magnetometry, since their spatial and temporal variations often mask the comparatively smaller effects of man-made magnetic anomalies. Because performance of practical instrumentation beyond the limits imposed by local field conditions is pointless, the characteristics of terrestial fields and of man's magnetic artifacts are summarized as background for evaluation of magnetometric methodology.

II.1 Terrestial Magnetism

Magnetic fields exist wherever electric charges are in motion, whether on a macro scale as when electric current flows in a conductor, or on an atomic scale as when electrons orbit or spin in a nuclear shell. Because both the magnitude of charge and its direction of motion are determinable, the resulting magnetic field at any point in space about a moving charge has a defined direction and intensity, measured in gammas (γ). NUSSBAUM (1966) gives a review.

The terrestial magnetic field is thought to originate within the Earth's molten core as a result of circulating electric currents (BUSSE, 1978); at the Earth's surface these are apparent as a non-uniform field of total intensity F = 60,000 gammas at the two magnetic poles, where field lines enter (73°N, 100°W) or exit (68°S, 143°E) at 90° inclination to the local horizontal, and as an intensity F = 30,000 gammas near the Earth's magnetic equator, where the inclination is zero. At 45°N, where F = 45,000 gammas, the resulting gradient in the terrestial magnetic intensity is 20 gammas/kilometer in altitude and 5 gammas/kilometer in latitude (TARLING, 1971; pp. 93-98). At any point on the Earth's surface, the horizontal component of total intensity is given by H = F(cos I), while the vertical component is simply Z = F(sin I), where I is the

angle of magnetic inclination.

Non-antipodal and eccentric, the Earth's field can none-the-less be modelled as though some 80 percent results from a single geocentric dipole of magnetic moment 8 X 10^{30} ergs in magnitude, inclined at an angle of 11.5° to the Earth's rotational axis and positioned so that its axis intersects the Earth's surface at two geomagnetic poles (78.5°N, 69.1°W and 78.5°S, 110.9°E). Thought to originate in influences of the mantle-core topography on fluid motions in the liquid core, the residual non-dipolar field demonstrates some eight asymmetrically distributed regions of continental dimensions which vary by as much as 15,000 gammas above or below the field intensities predicted by the inclined dipole model (CREER *et al.*, 1973). It is these large-scale nonuniformities, particularly intense in the southern hemisphere, that are primarily responsible for the varying divergences of magnetic from true north, depending on the observer's location on the Earth's surface. Thus, the horizontal field component H, to which a compass responds, may be further resolved into a component directed to the north, N = H(cos D), and an equatorial component, E = H(sin D), directed either easterly or westerly; here D is the observed angular divergence, or declination, between the directions of H and geographical north. The total terrestial field at any observation point is uniquely described by any triplet of these intensities and directions, summarized in Table A for the continental United States; detailed maps are available.

The dipolar field has apparently maintained a nearly constant orientation for at least the past million years, but its magnetic polarity has been shown to have reversed many times, with reversal intervals spanning the range of 10^4 to 10^7 years. The intensity of the dipolar field itself varies, presently decreasing at a fairly uniform rate of 5 percent per century from a peak value 1500 years ago of 12 X 10^{30} ergs, a value to which it had increased from 4 X 10^{30} ergs some 5500 years ago (THOMPSON, 1974). In addition, the non-dipolar field shows a persistent, rotation-dependent drift to the west of 0.2° longitude per year. The combined effect of these variations is the observed secular variation in the geomagnetic field parameters, summarized for the continental United States in Table 1. Yet, these variations account for only 25 percent of the total time-varying field.

TABLE A

RANGES OF MAGNETIC VALUES FOR THE CONTINENTAL UNITED STATES (1975 Epoch)

Parameter	Range	Annual Variation	Source*
F, Total Intensity	48,200 to 60,500γ	-93 to +15γ	MAP I-915
I, Inclination	55.0 to 76.3°	-7.3 to -0.5'	MAP I-912
Z, Vertical Intensity	39,500 to 58,800γ	-120 to +3γ	MAP I-914
H, Horizontal Intensity	14,200 to 27,600γ	-17 to +100γ	MAP I-913
D, Declination	21°W to 22.3°E	-8.5'W to +2.3'W	MAP I-911

* Maps are available from: Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, Virginia 22022.

While the time-varying components responsible for secular variation have been linked to internal currents originating in movement of the Earth's molten core, the rapid variations making up the remainder are extraterrestial in origin, arising in ionospheric currents connected with solar activity. Interacting with the terrestial field, these ionospheric currents produce about one-third of their intensity effects indirectly through eddy currents induced in the Earth's mantle. Although these disturbances tend to be localized to regions a few hundreds of kilometers in extent, the direct effects may be worldwide and span a broad frequency spectrum, with periods ranging from a year to a few milliseconds. The most important of these disturbances include the diurnal alternation, magnetic storms, and micropulsations (CAMPBELL, 1976).

Effects of the diurnal alternation are repetitive, the field intensity decreasing from its sunrise value to a minimum at noon and increasing during the afternoon and night; the variational amplitude is seasonal, ranging from ± 2 gammas in January to ± 25 gammas in June. At any location, intensity changes may amount to a few gammas per minute during summer. Field direction is also affected, but variations in both intensity and direction are too irregular to be modelled as periodic. Correlated with the eleven-year sunspot cycle, magnetic storms produce intensity variations of 500 to 1500 gammas; the next maximum in sunspot activity will occur in 1980. Micropulsations usually appear as random bursts with a peak amplitude of a few gammas, increasing with period.

In the outermost layers of the mantle itself, several mechansisms affecting the chemical state and spatial distribution of iron-titanium oxides can operate to cause local magnetic anomalies of several hundred gammas in the global field. Averaging 6.8 percent of the Earth's crust, with much higher concentrations in many scattered ore deposits of appreciable extent, these oxides are present to varying degrees in rocks and soils of all types, making important the mechanisms whereby they are formed and magnetized. (Terminology of magnetism is defined in Appendix I; see also TARLING (1971), pp. 5-54.)

In rocks these iron-titanium oxides appear as complex crystalline particles which, although they differ chemically only in the ratios of constituent iron, titanium and oxygen, differ markedly in their magnetic properties. While the rock is still molten, particles form in basic

igneous rocks that cover the complete solid-solution series between the cubics, magnetite (Fe_3O_4) and ulvospinel (Fe_2TiO_4), with corresponding magnetic properties ranging from stable ferrimagnetism to low-temperature antiferromagnetism as the rare ulvospinel composition is approached; however, in oxygen-rich igneous rocks, particles form which cover the entire solid-solution ilmenohaematite series between the rhombohedrals, haematite (αFe_2O_3) and ilmenite ($FeTiO_3$), both of which are basically antiferromagnetic, although haematite possesses a persistent parasitic ferromagnetism. On rapid cooling, the titanomagnetite series tends toward magnetite as the final composition; while intermediate compositions initially exist in slowly cooled rocks, they usually exsolve from the solid solution to yield intergrown crystals of magnetite and ulvospinel along certain crystallographic planes of the original titanomagnetite particle. By contrast, the intermediate ilmenohaematite compositions almost always exsolve into intergrown haematite-ilmenite crystal complexes, irrespective of cooling rates. In silica-rich igneous rocks, particles sometimes form which have a composition lying between the titanomagnetites and ilmenohaematites, or titanomagnetites may later react with oxygen carried by residual liquids to produce a similar composition, as when magnetite (Fe_3O_4) is oxidized at low temperatures to yield maghemite (γFe_2O_3). These between-series compositions generally exsolve, usually into the cubic magnetite or into the rhombohedral ilmenite, it being impossible for a continuum of solid solutions to exist between the two crystal structures.

Once cooled, some igneous rocks have been converted to metamorphic ones by exposure to elevated temperatures and pressures, and although all iron-titanium oxides are present in the result, the uncertainties of the transition preclude generalizations about their specific occurences. If secondary stresses are extreme, unmixed compositions may remix into solid solutions, to undergo various transformations and exsolutions demanded by the chemical environment and cooling rates; if, however, temperatures increase only slightly, then exsolution of the original solid solutions is usually increased, possibly accompanied by oxidation or reduction of the exsolution product. In both metamorphic and igneous rocks, ilmenite may oxidize through weathering into pseudo-brookite (Fe_2TiO_5), rutile (TiO_2) or other complex iron-titanium oxides, while most other iron

bearing minerals oxidize to haematite. Of these last magnetic minerals, iron sulfides (pyrrhotite) are the only ones common enough to be considered; these occur occasionally in basic igneous rocks and have magnetic properites ranging from antiferromagnetic to ferrimagnetic, depending on sulphur content. The most common form, pyrite (FeS_2), is nonmagnetic at normal temperatures.

While the above geophysical mechanisms determine the chemical state of iron-titanium oxides, deposition of wind or water -detrited particles affects their spatial distribution (STANLEY, 1975). Derived from pre-existing rocks, these detrital particles include ones of the iron-titanium oxides varying in size from clays (<0.002mm) through silts (0.002 to 0.05mm) to sands (0.05 to 2mm) and spanning the entire spectrum of ferromagnetic behavior from superparamagnetism to multi-domained remanency. In the process of being consolidated in a siliceous or calcareous matrix to form sedimentary rocks, the iron oxides further oxidize into clay particles and iron hydroxides (MATTHEWS, 1976); of these most are nonmagnetic, but goethite ($\gamma Fe{\cdot}OH$) is antiferromagnetic, with parasitic ferromagnetism. As sedimentation continues, so does hydration of haematite, until the weight of the accumulating overburden consolidates the lower sediment, drying out the clays and iron hydroxides, with the latter reverting to haematite. Concurrently, silica and carbonates crystallize to cement the drying sediment into a consolidated rock containing haematite as the predominant iron oxide. Lacustrine muds exemplify the complexity of such diagenic processes (DIDYK, *et al.*, 1978).

Mixed with humus from decaying organic material, similar iron-titanium oxide particles occur in unconsolidated form as soils (BEAR, 1958). In soils from igneous formations particles of both the ferrimagnetic titanomagnetites and antiferromagnetic haematite, as well as of the non-magnetic silicates, may be transferred directly into the soil where the oxides may have strong effects on its magnetic properties, whereas the silicates must first be broken down and converted into oxides. A similar situation obtains for soils based on metamorphic rocks, except that the ratio of magnetite to haematite tends to shift toward haematite, with addition of goethite on weathering substrates; this trend continues for the sedimentary rocks, where haematite dominates but goethite increases in wet sediments. In deposits of all origins,

especially those through which oxygen-rich water circulates, maghemite may also occur but in lesser quantities.

Thus while many iron-bearing minerals occur in the Earth's mantle, only magnetite, haematite and maghemite are sufficiently common to cause local alteration in the terrestial field; their chemical relationships are summarized in Fig. A. Of these oxides, both magnetite (Fe_3O_4) and maghemite (γFe_2O_3) are ferrimagnetic, with magnetic susceptibilities many times greater than haematite (αFe_2O_3) which though imperfectly antiferromagnetic still possesses a susceptibility greater than the surrounding matrix. Consequently, because of their greater ease and retention of magnetization under the influence of the terrestial field, deposits of these oxides can cause appreciable magnetic anomalies, permitting their location via geomagnetic prospecting techniques. The origin of their increased susceptibility and remanence lies in unpaired outer electrons of the iron-titanium atoms (Appendix I), and several mechanisms can result in acquired remanent magnetization (Appendix I; TARLING, 1971).

In rocks the iron-titanium oxides appear as heterogeneous crystalline particles dispersed through the paramagnetic matrix; of these particles only about 5 percent contribute to the remanence of a sample. While the rock is molten, these ferromagnetic particles behave paramagnetically until the magma temperature falls to their Curie temperature (generally between 400 and 600°C), where spontaneous magnetization due to electron coupling between adjacent iron-titanium atoms results in the particle becoming superparamagnetic. In this state, magnetization intensity is that of typical ferromagnetics, but its direction readily follows that of an applied field as is typical of paramagnetics; as a result the particle's magnetization is parallel to the terrestial field. At a characteristic temperature, generally about 50°C below the Curie temperature for particles of domain size, the direction of the magnetization acquired due to the terrestial field is "blocked" in, and the particle retains a fixed thermoremanent magnetization (TRM) which decays with a relaxation time of a few minutes. Further cooling results in decreased agitation of the dipolar alignments, with a corresponding increase in relaxation time until it is comparable to geologic times; magnetization acquired near the blocking temperature then becomes stable. The above applies to outer surfaces and exposed edges of igneous

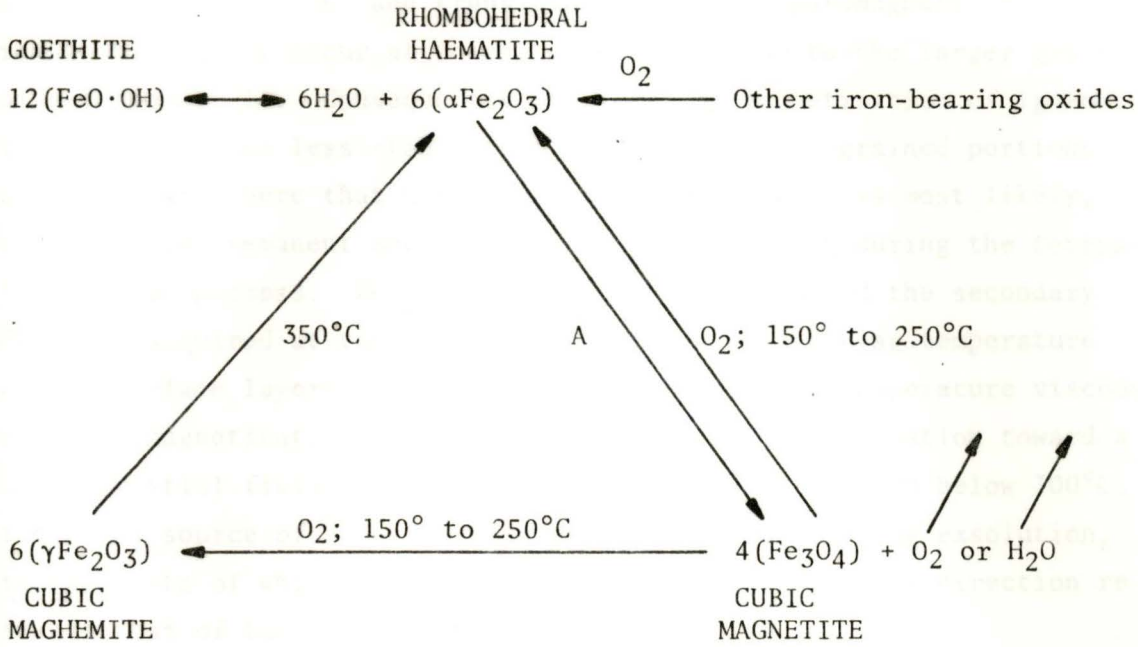

Figure A. Relationships among the common iron oxides. Antiferromagnetic haematite, oxidation product of most iron-bearing minerals, can be reversibly hydrated into antiferromagnetic goethite; or it may be anaerobically reduced to ferrimagnetic magnetite (A) by heating, with liberation of oxygen, or by low-temperature reaction with H^+, with formation of water. Cubic magnetite can be oxidized at low temperatures into either the compositionally identical oxides, rhombohedral haematite (given magnetite crystals larger than a micron, containing lattice imperfections or admixed haematite), or ferrimagnetic cubic maghemite (given chemically and structurally pure submicron crystals of magnetite). Thus, alternate reduction-oxidation conditions operating on haematite can produce first magnetite, and then metastable maghemite, which can be reconverted to haematite by heating above 350°C (SHIVE and DIEHL, 1977; STACEY and BANERJEE, 1974, pp. 25-40). Note that both goethite and haematite possess parasitic ferromagnetism.

masses, since here cooling is most rapid and fine grains result; in the interior of the rock cooling is slower, with attendant growth of large multi-domained grains, and transitions from superparamagnetic to ferromagnetic states occur at lower temperatures due to the larger grain size (Appendix I). Consequently the interior magnetization of igneous rocks tends to be less stable than that of its fine-grained portions, and it is also here that high-temperature exsolution is most likely, with chemical remanent magnetization (CRM) resulting during the recrystallization process. Because both the primary TRM and the secondary CRM were acquired at temperatures less than the blocking temperature of the surface layers, both may be replaced by high-temperature viscous remanent magnetization (VRM) as a result of domain relaxation toward a new terrestial field direction. Once the rock has cooled below 300°C, the major source of secondary magnetization is continuing exsolution, the products of which acquire a low-temperature CRM whose direction reflects that of the then-prevailing terrestial field.

The elevated pressures and temperatures responsible for the conversion of igneous into metamorphic rocks are also sufficiently extreme as to obliterate most of any primary magnetization acquired during their original cooling. Although the low-level PRM resulting from the hydrostatic pressure of overlying formations is lost when the rock is exposed, magnetic anisotropy may result from plastic deformation of the matrix or crystallization of dissolved minerals under pressure, and the detailed magnetic record often becomes complex. However, temperatures of a few hundred degrees usually accompany deep burial, and a (perhaps anisotropic) high-temperature VRM tends to be the dominant remanence in metamorphic rocks, but CRM as a result of exsolution and breakdown of certain iron-bearing silicates may alter this once cooling to about 300°C has occurred, as in the case of the original igneous rocks.

Eroded from the pre-existing igneous or metamorphic rocks, the magnetized particles forming sedimentary rocks orient themselves with the prevailing magnetic field as they are deposited; the tendency is toward preservation of such alignment during sedimentation, particularly if the water content of the sediment is initially high, and detrital remanent magnetism (DRM) results in the consolidating sediment. Although both the composition of an individual particle and its primary

magnetization depend on its source, the many chemical processes to which it is exposed during compaction usually result in the remanence of the consolidated sediment becoming chemical in origin.

In soils, randomizing influences interfere with extensive, long-term orientation of the magnetized particles, and a varying weak addition to the local terrestial field tends to be the net effect. However, under certain conditions secondary TRM and CRM may result from man's activities. The wide distribution of magnetic particles in soils makes these processes important in both archaeomagnetics (AITKEN, 1974; pp. 135-186) and site appraisal by magnetometry.

(Uncommon, but important because of the local intensity of the anomalies they produce, are ferromagnetic substances such as free iron or iron-nickel alloys. Large amounts of these materials occur naturally in extraterrestial rocks and meteorites, which acquire a viscous magnetization parallel to the local Earth's field because of their high saturation magnetization (SUGIURA, 1977; STACEY and BANERJEE, 1974, pp. 170-175). Similarly, strong secondary isothermal remanent magnetization may result from lightning strikes to exposed rock outcrops.)

Thus, of the several mechanisms capable of producing stable remanency, geologic sequences involving thermal, chemical and detrital processes account for most natural rock magnetism. The direction of the acquired magnetization reflects that of the prevailing terrestial field as the individual oxide particles cooled through their blocking temperature, grew through their blocking volume, or were deposited from suspension. Effects of rapid variations in terrestial field direction are averaged out since cooling of magma takes several years (and sedimentation several centuries), but such periods are short compared with secular variation, leaving it as the predominant time-varying influence on the direction of remanency. Analysis of past terrestial field behavior through study of such recorded ancient field directions is the basis of palaeomagnetics (TARLING, 1971; THOMPSON, 1974); the importance of thermal, chemical and detrital remanent magnetism in these studies has led to careful examination of the underlying mechanisms (STACEY and BANERJEE, 1974; pp. 105-135). Since thermoremanency accounts for the primary magnetization of all igneous rocks and is very stable, it has received particular attention (DAY, 1977).

II.2 Man's Magnetic Artifacts

In rocks ferromagnetic particles are tightly bound in an extensive paramagnetic matrix whose physical properties act to shield the particles from the magnetic effects of most human activities (nuclear explosions being notable exceptions). Such is not the case when similar particles occur in soils. Of a size compatible with their erosion from the parent formation by wind or water, randomly dispersed among other particles of many origins and chemical compositions, mixed with materials of organic origin, and alternately heated and cooled or wetted and dried by the weather, free ferromagnetic particles undergo many natural processes which cause significant enhancement of their susceptibility over that of the parent rock. Man's activities may either locally augment such processes, or they may affect particle remanency, as when soils are modified by heating to temperatures above the Curie temperature of the particles. And while they may not affect the magnetic status of oxide particles, magnetic fields associated with power and communications systems may appreciably alter the local terrestial field, as may effects of buildings, fences and other items containing large amounts of iron or iron-nickel alloys. These magnetic artifacts appear superimposed on the local terrestial field.

The magnetic susceptibility of refilled excavations has been noted to be greater than that of the subsoil into which they have been dug, while the susceptibility of features such as roads derived from consolidated subsoil material has been generally found to be less than that of surrounding subsoil. According to LE BORGNE (1965), in agricultural soils this susceptibility enhancement may result by two different mechanisms, both involving *in situ* reduction of antiferromagnetic materials such as haematite or goethite to ferrimagnetic magnetite, followed by a reoxidation to the more-strongly ferrimagnetic maghemite (Fig. A). By the first hypothesis, reduction results from anaerobic decay of organic material in the soil during wet periods, with reoxidation occuring during subsequent drying. By the second, burning of the organic material provides both the temperature increase and reducing atmosphere needed for the reduction of magnetic particles in the soil underlying the fire; air entering the soil during its cooling would permit their reoxidation. Work related to the experimental verification and archaeological

implications of these mechanisms has been reported by TITE and MULLINS (1971), TITE (1972), and LONGWORTH and TITE (1977) and has been reviewed by MULLINS (1977); these summary comments are drawn from these papers.

TITE (1972) has published concentration data for convertible iron oxides in soils derived from the various geological strata; this shows an approximate range of 0.02 to 20 percent by weight. Noting that conversion to strongly ferrimagnetic forms ranges between 0.10 to 0.35 (and is typically 0.25 of the convertible oxides) permits estimation of the corresponding soil susceptibilities. Because the conditions necessary to experimentally verify Le Borgne's first mechanism are very difficult to provide in a laboratory setting, no direct demonstration of its validity has been reported, but indirect evidence in its support is found in the exceptionally high oxide conversions in soils from areas whose climate would favor its operation. Thus, LONGWORTH and TITE (1977) report for certain Italian soils susceptibility enhancement exceeding that obtained in similar soils via the heating mechanism and speculate that analysis of Mössbauer spectra might establish which of the two mechanisms resulted in conversion of a given maghemite sample. Such analysis has shown that the antiferromagnetic component of agricultural soils is goethite rather than haematite as Le Borgne had suggested, that the ferrimagnetic component is indeed impure maghemite as was supposed, and that the antiferromagnetic component converted to maghemite on heating in nitrogen-then-air at temperatures of 450°C or greater. The results depended on the organic material in the soil sample, its oxide concentration and the heating history, but in all respects they were consistent with observed susceptibility enhancement occuring through the heating mechanism (TITE and MULLINS, 1971). The number of fires to which the sample had been exposed was indicated as being the most important single parameter.

Both the fermentation and heating mechanisms would more effectively enhance soil susceptibility if high levels of organic material were present in the topsoil. For this reason those features containing large amounts of humus, as graves, trash pits, post or tree -molds, or privy pits, show magnetically to best advantage, while ditches (which are often refilled almost immediately or soon silt in with the relatively sterile soil which was excavated from them) may show only a weak susceptibility increase. In heavily overgrown sites increased permeability

to ground water in the disturbed filling may result in differential deposition of micro-organisms and decaying vegetation, sometimes permitting detection of ditches in wooded sites although similar ditches in open sites would go unnoticed. Regardless of the mechanism responsible, the resulting susceptibility anomalies range upward to a few hundred gammas for a large pit in a favorable environment; more typically anomalies of at most a few tens of gammas are encountered. TITE (1972) lists data for idealized pits a meter in diameter, buried m meters in subsoil and covered by h meters of topsoil: For a differential susceptibility of 10^{-4}emu/g and m = 0.3, at a sensor height of 0.3 meter the anomaly intensity is 5.8, 2.6, 1.4 and 0.8 gammas for h = 0.3, 0.6, 0.9 and 1.2, respectively; values for m = 1.0 are 10.3, 5.2, 2.9 and 1.8 gammas; values for other differential susceptibilities can be linearly scaled from those given. Thus, a pit with a differential susceptibility of 10^{-3}emu/g at a depth of a meter would give anomalies of 103, 52, 29 and 18 gammas. These values illustrate well the impact on detectability of susceptibility differences between the feature and fill.

Intrusion of original subsoil material or sedimentary rocks into topsoil results in similar anomaly intensities, but of opposite sign since these materials normally have lower susceptibilties than the topsoil they displace. Thus, buried walls, foundations, or roads appear magnetically as features whose field is less than the surrounding terrain. A similar situation arises in the case of a buried chamber, whose void will show as a relatively lower field intensity due to the zero susceptibility of air. AITKEN (1974) gives additional details.

Since he first learned to use fire, man has inadvertently heated soils of all types, and the magnetic results are particularly noticeable in areas of long-term habitation, a fact of use in locating new sites. But of all soils the clays are archaeologically the most important. Not only are the clay particles the active soil component in the conversion processes discussed above (LE BORGNE, 1965), they form ceramics when heated to temperatures which exceed the Curie temperatures of the iron oxides (haematite has the greatest, at 675°C). Consequently, the magnetic particles in hearths, kilns, bricks and pots acquire a high temperature thermoremanency during cooling of the ceramic. This TRM is parallel with the direction of the prevailing terrestial field and

although proportional to its intensity, is an order of magnitude larger than the magnetization induced by the field as a result of susceptibility enhancement; both its direction and intensity remain stable over thousands of years despite secular variations in the terrestial field. The similarities between the formative processes and characterisitcs of magnetization in heat-modified clays and in igneous rocks have resulted in the development of an archaeomagnetics (AITKEN, 1974; pp. 135-186) subspeciality within palaeomagnetics (TARLING, 1971; THOMPSON, 1974) which utilizes knowledge of ancient fields derived from datable ceramics to date others of unknown period (DUBOIS and WATANABE, 1965). Detailed analysis of the ancient field recorded in ceramics may also help define brick and pottery firing techniques, locate sources of pottery or bricks, or identify sherds belonging to the same object.

In the field, kilns, hearths, and bricks, pottery, soil baked *in situ* or burnt stones represent in order of decreasing magnetic intensity those features likely to be detected due to their TRM; in favorable circumstances kilns may produce anomalies of a few hundred gammas but a value of 50 to 100 gammas would be more typical (AITKEN, 1961). The other features produce weaker anomalies, of at most a few tens of gammas and usually considerably less than this. Subsurface structures of brick may generate an appreciable anomaly, but the intensity depends on the degree to which orientation of the individual bricks reproduces that during their firing and could be too weak for detection in a given situation. Randomization effects also account for the low-level anomalies found for hearths and baked areas in soils of low clay content. With exception of kilns, then, most features detected due to TRM show anomalies comparable to those resulting from susceptibility enhancement.

The origins and characteristics of rock magnetism were reviewed in Section II.2, where it was noted that TRM was the mechanism whereby igneous rocks acquired their primary (and other rocks some of their secondary) magnetization. This fact limits detection of man-made anomalies over volcanic structures, particularly so if the structure is basaltic (TITE, 1972); site topology may further affect detectability. However, detection of buried walls or foundations constructed from igneous materials may be possible, and statues and columns made from balsalt have been successfully located (MORRISON *et al.*, 1970).

While it is desirable to detect the above magnetic consequences of man's activities, other activities produce local field effects sufficiently strong as to obscure them. Generally these interfering influences take one of two forms, either the presence of free iron or iron-nickel alloys or the presence of electromagnetic fields due to power transmission or communications systems. The most troublesome of these, particularly in agricultural areas, is the presence of surface iron objects.

Present in the form of metallic objects and concentrations of rust, superficial iron litter causes sharp local anomalies, usually indicating both increased and decreased total intensity, which broaden as the depth of the object increases. Bottle caps and nails result in intensities of a few gammas, while differential intensities of more than 10 gammas are common several meters from iron-wire fences and buildings containing iron sheeting; even larger deviations result near transmission line towers, water and gas lines, buildings containing structural steel, and motor vehicles. These last can be especially troublesome on sites near traveled roads and streams, since their motion produces a time-varying effect similar to spatial variations that could be of archaeological interest. For proton magnetometers, iron objects pose an additional problem since their gradient is so large, say 100 gammas/m, that it causes loss of coherency in the active sample, producing a signal decay so rapid that the magnetometer cannot accurately measure the anomaly; the effect can often be used to identify surface iron.

Although the electromagnetic fields due to power transmission and communications systems extend far into space (PARK and HELLIWELL, 1978), their impact arises from the non-linear operation they cause in magnetometer circuitry, rather than from their direct effect on local field intensity. Such time-varying fields are particularly troublesome when their frequency corresponds with a natural resonance in the instrumentation, but design techniques can minimize their disruptive influence. Except for EHT lines, measurements can usually be made to within approximately 50 meters of power transmission lines, but ship-to-shore radio transmissions may affect intensity measurements on sites several miles inland.

II.3 Instrumentational Implications

The origins and characteristics of man's magnetic artifacts, and of the terrestial field upon which these are superimposed, have been reviewed. This discussion will now be summarized to provide a functional specification against which available instrumentation can be evaluated.

Static range. To be of use worldwide, a magnetometer should be capable of responding with suitable sensitivity over the operating range between 30,000 and 62,000 gammas; for use in the continental United States, an operating range of 48,000 to 61,000 gammas is sufficient. Ideally, the operating range could be covered by a single instrument setting, but if this is impractical, appropriate subranges should be easily selectable. Within a given locality, geological and topological effects may combine with features of archaeological importance to cause intensity variations on the order of hundreds of gammas; point-to-point variations may amount to a few tens of gammas. Ideally, the dynamic range should accommodate these point-to-point variations.

Sensitivity. Feature intensity depends on the differential susceptibility between the feature and its surroundings; sensitivity should be as great as possible to permit detection of features refilled with the material excavated from them. However, soil noise resulting from the local random distribution of oxides establishes a practical limit of about 0.1 gamma on useful sensitivity. For this sensitivity to be meaningful, resolution and repeatability should also be about 0.1 gamma. (While absolute accuracy in the intensity measurement is desirable, it is not usually so important as repeatability of readings at any point.)

Dynamic response. Since the object of magnetic mapping is to locate long-term anomalies, dynamic response does not need to be great. Indeed, to limit impact of extraneous electromagnetic fields and micropulsations, response to more than a few Hertz is undesirable, although this conflicts with a broad dynamic range. The sampling period should be as short as is consistent with any need to time-average intensity data and stable to the desired accuracy.

Physical characteristics. Because of field conditions, the instrument should be both light-weight and rugged, should be self contained and low in power requirements, and should be easy to operate in rough terrain. To increase the liklihood of providing useful data under

even adverse field conditions, the instrumentation should be capable of use in modes permitting absolute, difference (variometric), and differential (gradiometric) measurements of the ambient terrestial field. Above all else, it should be reliable and economically viable. Thus, the instrument should be low in initial, operational, and maintanence costs and should not require undue skill or expertise of its operator. To this end, data output compatible with automatic recording equipment should be available, and this data should require as little skilled post recording manipulation as possible. Ideally, data output would be displayed to the operator, prior to its recording as the termination of an automatic operational cycle initiated by the operator once the sensor was in position; this would permit him to concentrate on screening out artifactual readings, rather than on instrument operation. The degree to which these characteristics are realizable will determine to a large extent the acceptance of magnetometric instrumentation as a tool in the professional archaeologist's routine field work.

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Appendix III
INSTRUMENTATION

Since many physical phenomena show a response to magnetic fields, magnetometers based on many techniques have been developed (GERMAIN, 1963; GORDON *et al.*, 1972). Of these many are inherently unsuited to portable use, and geophysical magnetic studies have tended to employ instruments based on magnetic resonance in various elemental species, although more recently fluxgate and superconducting instruments have seen increasing application. The variety of instruments used in archaeological field work is even more restricted, consisting predominantly of resonance devices based on three elements and fluxgate devices (RAINEY and RALPH, 1966). Here magnetometric instrumentation will be surveyed from the perspective of its application in archaeological site appraisal.

III.1 Fluxgate and Superconducting Magnetometers

Although these instruments are based on unrelated physical phenomena, they will be discussed together since they share the need for rather precise alignment with the field whose intensity is to be measured, whereas the resonance devices inherently respond to total rather than component intensity.

Fluxgate magnetometers (GORDON and BROWN, 1972; PRIMDAHL, 1970a). In this technique, the magnetic field causes a highly permeable magnetic alloy coupling primary and secondary coils to saturate; as a result the signal induced in the secondary coil by alternating current flowing in the primary has a frequency twice that of the exciting current and a magnitude proportional to the component of the terrestial field parallel to the axis of the secondary coil (MARSHALL, 1967; GORDON *et al.*, 1965; WEINER, 1969). Design is uncomplicated (TRIGG, *et al.*, 1971; PRIMDAHL, 1970b,c), and the instrumentation is reliable and relatively simple, inexpensive, and rugged. Once set up, it is efficient in use. Ranges

of ± 100 gammas with sensitivities down to fractional-gamma levels are possible; ultimate resolution of the technique is about 0.2 gamma. Dynamic response can be up to 10 Hertz, and readings may be taken continuously. Disadvantages include the orientation sensitivity and a tendency for the saturable core to drift in its offset and permeability. Due to the high directional sensitivity, distortions in the detector support are a common source of drift when the gradiometer connection is used (MORRIS and PEDERSEN, 1961; CLARK and HADDON-REECE, 1972-73; PHILPOT, 1972-73); the detector pair must be carefully matched and kept strictly aligned. In addition to the last two papers, those by CLARK (1975) and ALLDRED and AITKEN (1966) describe archaeological use of gradiometers.

Superconducting magnetometers (CLARK, 1973; GOREE, 1970). If a loop of superconducting material in liquid helium has a link of small cross-sectional area at two points on its circumference, and if parallel currents are caused to flow through both links, relatively small currents can produce critical current densities in the links. If sufficient direct current to bias the loop into superconductivity is passed through the material, the voltage across the loop is a function of the magnetic flux threading its aperture. The voltage is due to circulating currents which oppose changes of magnetic field in the aperture; effectively the current density in the links varies and so affects the material's superconducting properties. As a result the voltage is time-varying, with a periodicity equal to one-half the ratio of Planck's constant to electronic charge. The field can either be determined by perturbing it and counting the number of periodic variations in voltage, or by providing a bucking field which automatically cancels any change in the external field and becomes a direct measure of the external field change (GOREE and FULLER, 1976; GOODMAN *et al.*, 1973; WEBB, 1972; CLARKE, 1970). Despite relatively simple circuitry (FORGACS and WARNICK, 1967; DEAVER and GOREE, 1967), their requirement for a few liters of liquid helium at least every few hours to re-establish cryogenic operating temperatures is a serious disadvantage of these devices, although a superconducting magnetometer (ZIMMERMAN and CAMPBELL, 1975) and conductivity meter (MORRISON *et al.*, 1976) should both have completed field-testing at this writing. Another disadvantage of this type magnetometer is the sensitivity to change in field intensity rather than

to intensity; this increases circuit complexity. Advantages include sensitivity and dynamic characteristics which exceed those of any other magnetometric technique (the unit described by Zimmerman and Campbell demonstrated resolution to 10^{-3} gamma, with potential for improvement to 10^{-4} gamma; linear dynamic range was reported to exceed any other instrument, with a potential response range of 100 Hertz), but these desirable attributes also combine to make the instrument very susceptible to interference from all types of electromagnetic fields. WYNN *et al.* (1975) described a gradiometer version which minimizes the adverse impact of such interference. No description of archaeological application was found; indeed it is likely that due to the logistic problems involved in field operation, little work of interest will be done with this device, although its continuous-reading capability is attractive.

Both the fluxgate and superconducting magnetometers functionally meet requirements for successful use in site appraisal, but both require careful alignment with the field to be measured and both share stability problems due to changes in characteristics of the sensing material. Both provide continuous readings, but the first responds to field intensity and the second to changes in intensity.

III.2 Resonance Magnetometers

As a group, resonance magnetometers depend on alteration of the vibrational characteristics of atomic components under the influence of magnetic fields. The effect was first predicted (BLOCH, 1946), verified (BLOCH *et al.*, 1946), and incorporated into a practical instrument (PACKARD and VARIAN, 1954) for the proton, but similar work has since been done with several other systems including free electrons, elemental helium and mercury, and vapors of at least four of the alkali elements (HARTMAN, 1972). Regardless of the particular system involved, operational principles are similar for all these devices, such differences as exist being traceable to the characteristic vibrational frequency of the active species in a given sensor (SLICHTER, 1963).

If in the presence of the terrestial field the response of such a sensor to a swept-frequency sinusoidal field is observed, it will be noted to peak at a specific frequency which is proportional on the terrestial field intensity. Called the Larmor frequency f_0 of the system,

this frequency depends on the product of total-field intensity T and the invariant gyromagnetic ratio of the sensing material. Thus, the relatively simple measurement of δ_0 yields a determination of field intensity, which for loosely coupled proton and electron systems is inherently calibrated; for gas-phase media, vagaries in sensing the atomic vibrations and in sample containment result in δ_0 being instrument-dependent. Values of γ and δ_0 for several media are summarized in Table B, which also supplies relevant references. GRIVET and MALNAR (1967) give excellent discussion and a comprehensive review of developmental work with resonance systems of all types.

Resonance systems may be operated either discontinuously by initiating oscillation of the active atomic component and measuring δ_0 as the oscillation decays due to losses in the system, or continuously by appropriately supplying external energy at this frequency so that continuous oscillation occurs. The second approach has the advantage of providing continuous field data and can be readily implemented via optical pumping techniques (deZAFRA, 1960) in gas-phase media; although feasible (GRIVET and MALNAR, 1967; SLICHTER, 1963) in proton systems, the necessary circuitry complexity has usually resulted in discontinuous sensing of the free-precession signal. Here the continuously operating systems will be discussed; similar discussion of the discontinuous proton system is given elsewhere.

Although all the gas-phase media listed in Table B have been used in experimental magnetometers, potassium and sodium are unsuited to practical instrumentation (GRIVET and MALNAR, 1967). Of the other media, helium and mercury have seen extensive use in experimental space magnetometers, but only cesium and rubidium have been used in commercial instrumentation. The two isotopes of rubidium noted in the table have both been used in practical devices; they occur naturally in the ratio of a part of ^{85}Rb to four parts ^{87}Rb and give gyromagnetic properties between those of the pure isotopes.

In practical equipment the gas-phase media together with an inert buffer gas is contained in an optical cell through which light from an appropriate source is passed to a photodetector. The source is usually an electrodeless lamp filled with the same active media as the cell, filtered to provide a single spectral line whose energy pumps the

TABLE B

RESONANCE MAGNETOMETRIC SYSTEMS

Active Medium	Gyromagnetic Ratio γ, (sec · gamma)$^{-1}$	Larmor Frequency δ_0, Hertz/gamma	References
Protons	0.267515	4.25763×10^{-2}	DRISCOLL and BENDER, 1958; Appendix IV.
Free Electrons	1.760841×10^{2}	28.02468	TAYLOR *et al.*, 1969; HARTMAN, 1972.
Helium, ^{4}He	1.760771×10^{2}	28.02356	SCHEARER, 1961; KEYSER *et al.*, 1961.
Helium, ^{3}He	0.203795	3.24350×10^{-2}	SCHEARER *et al.*, 1963.
Mercury Vapor	4.7690×10^{-2}	7.59012×10^{-3}	HANUISE, 1970.
Cesium Vapor	21.98290	3.49869	STANLEY *et al.*, 1975; deZAFRA, 1960.
Potassium Vapor			FIRESTER and CARVER, 1967.
^{85}Rubidium Vapor	29.32637	4.66744	BLOOM, 1962; PARSONS and WIATR, 1962.
^{87}Rubidium Vapor	43.95618	6.99585	GRIVET and MALNAR, 1967.
Sodium Vapor			HAWKINS, 1955

sensing media as described by PARSONS and WIATR (1962). As a result the angular momenta of the gas atoms momentarily align themselves along the direction of the excitation beam and then precess at the Larmor precession frequency in the same direction (but with random phase) around the ambient magnetic field. Phase coherence of the atomic precession can be produced, without depumping the sample, by means of a magnetic field rotating at the Larmor frequency about the terrestial field. Coherent precession so resulting throughout the sample volume modulates the excitation-beam intensity and the photodetector output, due to the dependence of optical absorption in the aligned sample upon its orientation with regard to the excitation beam. The photodetector output can then be processed to provide both the magnetic field intensity and the energy fed back to the sample cell to maintain oscillation.

As might be expected from its value of γ_0 (approximately 28 Hertz/gamma) the helium magnetometer offers excellent sensitivity, 0.03 gamma in a response range of 200 gamma for the instrument described by KEYSER *et al.*, (1961), but the 1.4 X 10^6 Hertz output frequency resulting from the terrestial field poses practical stability and measurement problems. Both the cesium and rubidium instruments give output frequencies on the order of 3 X 10^5 Hertz for the Earth's field and for this reason are simpler to design; practical sensitivities of 0.05 gamma are achievable for both media (STANLEY *et al.*, 1975; USHER *et al.*, 1964). Dynamic ranges of several hundred gammas have been demonstrated, and dynamic responses to a few hundred Hertz are attainable. The absolute accuracy of these devices is limited by asymmetry of the optical resonance line related to the Black-Gouldsmit effect (SLICHTER, 1963); as a consequence the Larmor frequencies of the various hyperfine components do not coincide, leading to ambiguity in the field indication of the order of a gamma. A more serious source of error are phase errors between the precession and the derived signal fed back to the sample; these may shift the oscillation frequency sufficiently to cause absolute errors on the order of 10 gamma (USHER and STUART, 1970). However these errors do not affect the repeatability or resolution of a given instrument, both of which can exceed 0.01 gamma; 10^{-4} gamma may be achievable for rubidium (GOREE *et al.*, 1970; GORDON *et al.*, 1972), although the resulting instrument would be extremely fragile.

Although the circuitry for measuring δ_0 is straightforward and reliable (CIARROCCA *et al.*, 1966), the optical cell and associated sensing and driving circuitry tends to be complex and expensive. Consequently, resonance magnetometers themselves are costly, running to several tens of thousands of dollars for complete systems. Although their functional characteristics match well those needed for archaeological site appraisal their economics are a strong deterrent to such use, and both cesium and rubidium instruments have seen fairly limited archaeological application (BREINER, 1965; MORRISON *et al.*, 1970; RAINEY and RALPH, 1966; STANLEY and GREEN, 1976; RALPH *et al.*,1968). This last paper describes use of both cesium and rubidium gradiometers.

In conclusion of this instrumentation survey, several papers comparing different types of magnetometers will be noted. Those by GOREE (1970) and GORDON *et al.* (1972) summarize resolution characteristics of the magnetometers discussed above, plus similar data for magnetometers based on other physical phenomena. ZIMMERMAN and CAMPBELL (1975) provide particularly valuable field comparisons between a superconducting, a fluxgate, and a rubidium magnetometer. RALPH *et al.* (1968) contrast cesium and rubidium devices, and PRIMDAHL (1970c) gives comparative data for a fluxgate and a proton magnetometer. Other studies centered on proton instrumentation are noted elsewhere.

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Appendix IV
PROTON MAGNETOMETERS

Of the many types of resonance magnetometers (HARTMAN, 1972; GRIVET and MALNAR, 1967; SLICHTER, 1963), the free-precession proton instrument has seen widest application in archaeological site appraisal. The principle of nuclear magnetic resonance was anticipated by BLOCH (1946), verified by BLOCK *et al.* (1946) and demonstrated in a practical device by PACKARD and VARIAN (1954), WATERS (1955), and WATERS and PHILLIPS (1956); field trials followed in close order (AITKEN, 1958; 1959). WATERS and FRANCIS (1958) published the first instrument description. Since these origins two decades ago, a voluminous literature describing many instruments and field surveys has accumulated, much of which is accessible through the journals *ARCHAEOMETRY* and *PROSPEZIONI ARCHEOLOGICHE*. This literature will be surveyed, particular emphasis being given that appearing outside these journals, with the intent of identifying the problems and strengths peculiar to proton magnetometry. AITKEN (1974) and BREINER (1973) give excellent introductions to the technique and its archaeological application.

IV.1 Instrumentation

Proton magnetometers are but one type of resonance instrumentation, unique only in the choice of the proton as the entity interacting with the field of interest (GRIVET and MALNAR, 1967; GRIVET *et al.*, 1964). As was indicated in Table B, Appendix III, protons have a gyromagnetic ratio of 0.267515 $(\text{sec}\cdot\text{gamma})^{-1}$ (DRISCOLL and BENDER, 1958), giving a free-precession (Larmor) frequency of 0.0425763 Hertz per gamma; consequently resolution of 0.1 gamma in a total field of 55,000 gammas requires measurement of the precession frequency to 0.00426 Hertz in 2341.70 Hertz, or to 181.8 parts per million. This measurement can in theory be done in a continuously oscillating system, or in a discontinuously oscillating one in which

oscillation is initiated and allowed to decay (GRIVET and MALNAR, 1967; HARTMAN, 1972); practically the measurement accuracy required precludes use of the continuously oscillating instruments for archaeological use, due to the inherent shifting of the precession frequency by the feedback circuitry used to supply system energy losses. Thus the frequency measurement must be done on a signal which exponentially decays from a few microvolts to zero in a few seconds, the exact decay time depending on the liquid used and varying from about 18 seconds for benzene to about 2.5 seconds for water. Since the signal does decay to zero, the oscillation must be restarted for each measurement, or the sample "polarized"; the polarization buildup of oscillation is also exponential and roughly equal to the decay time constant, so the sample liquid is usually chosen to give an acceptable polarization period while giving sufficient time to count the precession signal to suitable accuracy. Water or methyl alcohol is commonly used, the latter being necessary if surveying is intended in sub-freezing temperatures.

The polarization of the sample and sensing of the precession signal is usually accomplished by passing a current of an Ampere or so through a coil of several hundred turns of wire surrounding the proton sample, allowing the sample to polarize, suddenly disrupting the current to the coil, and then connecting the coil to a low-noise, high-gain amplifier to increase the voltage induced in the coil by the protons as they oscillate about the direction of the terrestial field. The output of the amplifier can then be counted by indirect (period) or direct (frequency) counting circuitry. As noted WATERS and FRANCIS (1958) gave the first instrument description; others have described similar (SERSON, 1962a and b; PRIMDAHL, 1970) and improved (FEILD, 1969; HARKNETT, 1969; SARMA and BIDWAS, 1965) equipment, that by Feild preventing total decay of the precession signal by synchronization of the polarization current with the signal.

The voltage induced in the sensing coil is somewhat orientation sensitive (HALL, 1962-63), the largest signal resulting when the coil is oriented to cause polarization in the east-west direction, but a useful signal is obtained for deviations as small as 10° from alignment with the ambient field. However, even the normal low signal level requires that careful attention be paid to reduction of noise (FAINI

and SVELTO, 1962) when designing the sensor head (BECKER, 1967; HALL, 1962), and the self-shielding properties of the toroidal structure can be used to advantage (ACKER, 1971); actual switching of the sensor between polarization and measuring modes can be done with electronic components (HARKNETT, 1969), rather than the mechanical switches or relays used in early instruments. The basic sensor head is rugged, consisting typically of an electrostatically shielded plastic bottle containing water; the coil may be either wound on the outside of the bottle, or immersed in the sample liquid to increase its coupling. As a consequence it has been adapted to aerial use and to sea-going vessels for geophysical prospecting and submarine location (BREINER, 1975); a sea-going head for marine archaeological surveying (GREEN, 1967; HALL, 1966) has been described (GREEN, 1970).

The proton magnetometer can be used in the absolute mode, in which only a single sensor head is used, or in the differential mode if two sensor heads and amplifiers are used. The differential mode can also be simulated by simply subtracting the outputs of two complete instruments (SCOLLAR and LANDER, 1974) and has the advantage of automatically cancelling many first-order effects of diurnal, geologic or solar activity during field work; the exact functional characteristics depend on separation of the two sensors: If one is located at a reference position on the site so that variometric operation results, geologic variation will affect the data to a greater degree than were the two heads mounted on a staff held vertically so that the vertical field gradient was the predominating influence. AITKEN (1960), AITKEN and TITE (1962b), MUDIE (1962) and SCOLLAR (1970) have described differential proton instruments, of which the last is most interesting. Although the absolute mode can be used in archaeological applications (as in this thesis), practically the need to understand field data as it is recorded almost requires that variometric or gradiometric modes be used.

IV.2 Field Surveys

Since AITKEN (1958, 1959) described the first field trials of proton magnetometric instrumentation, additional work has been reported by AITKEN and TITE (1962a) for British hillforts, by LERICI

(1961) on Italian sites, by SCOLLAR (1966) in the Rhineland, and by TITE (1966) near the geomagnetic equator where terrestial fields are weakest; for sites in the United States, EZELL *et al.*, (1965-66) has described work in southern California, and JOHNSTON (1961, 1964, 1965; BLACK and JOHNSTON, 1962) has reported work at Angel Site in Indiana and at Wetherill Mesa. Of more interest here, however, are reports comparing instruments of different types on the same site.

In the setting of a geomagnetic observatory, PRIMDAHL (1970) and PRIMDAHL and DARKER (1971) have examined the stability of a fluxgate magnetometer (WEINER, 1969), using as reference a proton magnetometer because of its inherent calibration. TITE (1961) compared the performance of an absolute proton magnetometer, a proton gradiometer, and a fluxgate gradiometer at the Rainsborough iron-age hillfort and found that while all three gave similar results, the fluxgate was probably capable of the greatest speed of operation due to its lack of a polarization period and its continuous output. The fluxgate's directional sensitivity was found to be of some help in determining the gradient direction. No distinct preference between the two types of instrumentation was stated. RALPH (1964) compared an absolute proton magnetometer with both absolute and differential -connected rubidium units at Sybaris, finding that the greater sensitivity of the absolute rubidium unit could not be meaningfully used. Due to its continuous output signal, surveying speed was about four times greater for the differential rubidium magnetometer than for the proton unit; no conclusion was stated concerning the relative value of the magnetometer data provided by the magnetometers. In a second paper comparing differential cesium and rubidium magnetometers at Sybaris, RALPH *et al.*, (1968) found the cesium unit less sensitive (hence more desirable) to orientation of the sensor element, a fact which was estimated to speed up comparable surveys by 20 per cent. Although no archaeological application of the superconducting magnetometer has been located, ZIMMERMAN (1975) has compared one with both a fluxgate and a rubidium magnetometer for geomagnetic measurements and concluded favorably of its potential, but practically the need for liquid helium is a serious drawback when archaeological field conditions are considered and little use of this instrument is expected.

The major practical drawback to the proton magnetometer, then, is its relatively slow operating speed, due mostly to the polarization period. FEILD (1969) has demonstrated that this fault can be remedied by synchronized polarization, and operational speed of such units is such as to permit a few readings per second in equipment for aerial use. The major advantages of proton instruments include ruggedness and relatively low cost when compared with other types; still the cost of present commercial systems tends to be between $2,500 and $5,000, depending on complexity and sophistication.

(A final note: All magnetometric instrumentation discussed here is sufficiently sensitive as to locate extremely small pieces of free iron. JOHNSTON (1964) found a metal detector a valuable aid in field work, since it enabled him to remove some metallic litter prior to surveying. SCOLLAR (1962) discusses such instrumentation.)

IV.3 Data Handling

Since even a small magnetic survey can produce considerable data, automated methods for recording, processing, and analysis of field data have been pursued, and automatic logging systems described by SCOLLAR (1968) and ANDERSON (1974) are typical of ones developed to increase surveying speed in the field. Once recorded, the dipolar nature of magnetic features makes their interpretation extremely difficult (LILLEY, 1975; SMITH, 1961; JUNG, 1953; GREEN, 1960), a situation complicated by the fact that it is impossible to theoretically describe a unique feature which unquestionably could cause any observed field distribution (ZIDAROV, 1965). Consequently the basic approach to understanding the recorded data is based on study of simple features whose field effects can be calculated, in the hope that similar patterns in field data will represent similar features (REGAN and CAIN, 1975; McAULAY, 1977; AITKEN and ALLDRED, 1964). In view of the many difficulties in data analysis, LININGTON has published an excellent series of papers (1964, 1966, 1974a) describing the use of such simplified anomalies and has extended the approach to include topographic and terrain effects (1974b). The complexity of the mathematical computations involved suit the task to computerization, and many analytic programs have been developed, of which

those by SCOLLAR and KRUCKEBERG (1966) or McAULAY (1977) are good examples. As a result of such studies, diagrams aimed at permitting field evaluation of intensity data have been compiled (ZAGORAC, 1970); these may prove particularly valuable when a new geologic structure is encountered. The complexity of intensity data over superimposed features of whatever origin may be relieved somewhat by varying sensor height above the surface, or by going to the gradiometric mode, but no unambiguous interpretation of the exact size, shape, fill, or depth can be made for any given anomaly.

In summary, while proton magnetometers are inherently unable to provide continuous data and are relatively slow in operation, their low cost, inherent calibration, ruggedness, and reliability once operating outweigh these disadvantages, which can be minimized by proper design and which in any case are not prohibitive ones. The major current, low-cost competitor to the proton instrumentation for archaelogical use is the fluxgate devices which give continuous output, but have drift problems and are direction sensitive. The vapor magnetometers share this direction sensitiveness, are more fragile, and are much more expensive. Properly designed, proton magnetometers should continue to be the most commonly used magnetometric surveying instrumentation for some time.

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Appendix V

ADJUSTED SURVEY DATA

As noted in Appendix II, Section II.1, the Earth's field contains secular and diurnal variations in addition to ones originating in geological and archaeological features. Raw survey intensities were adjusted for secular variation by subtracting the annual variation accumulated since the 1975 base date (approximately 100 gammas, Table 1), and for diurnal variation by assuming that such variation at Town Creek paralleled that at Fredericksburg (Virginia) Magnetic Observatory. The Observatory data for the survey date show the H component undergoing a smooth linear decrease from the 8:30 AM value of 20,397 gammas to a minimum of 20,341 gammas between 11:15 and 12:15 AM, followed by a more erratic increase to 20,402 gammas at 5:00 PM. Localized bursts of activity (amplitudes of ± 4 gammas) occur at 10:10 and 11:15 AM, and 12:45 and around 3:00 PM; thunderstorm activity appears between 2:15 and 3:15 PM as erratic variations of ± 2 gammas or so. The Z component shows a similar profile, decreasing linearly from its 8:30 AM value of 51,594 gammas to 51,574 gammas at 12:45 PM and then increasing again to 51,591 gammas at 5:00 PM.

The continuous recordings were sampled at half-hourly intervals, starting at 8:00 AM and ending with 5:00 PM, and the resultant total intensity F calculated as $F = (H^2 + Z^2)^{\frac{1}{2}}$ for each sample. The results appear in Table C, coded to yield the diurnal variation by subtracting the 1:00 PM value of 55,443 gammas (the absolute terrestial-field intensity at Fredericksburg for that time) from each of the 19 individual values. These data show a total variation of 37 gammas, from 55,479 gammas at 8:30 AM through 55,442 gammas at 12:30 PM and back to 55,479 gammas at 5:00 PM. Since the recorded diurnal (and burst) variations originate in solar activity, parallel changes should have occurred at Town Creek about 10 minutes later, due to coordinate differences between it and the Fredericksburg Observatory.

To check on this assumption, repeat data were taken for the L140 traverse line of area B, the first data set being obtained at 12:15 and the second at 3:45 PM. Statistics for both sets are given in Table E; the difference of the traverse averages was 26.4 gammas, and the mean difference of the paired data was the same, ±1.86 gammas. This difference in the traverse data was highly significant by the t-test for paired data and agreed with the Fredericksburg data to within 5 gammas. Based on the apparent linearity of the Fredericksburg data (Table C), mirror-image linear interpolations about 12:40 PM as a breakpoint were made using the 12:15 and 3:45 PM readings to adjust the data of Table 2 and Tables D, E, and F for diurnal variation.

TABLE C

DIURNAL VARIATION AT FREDERICKSBURG, 5 OCTOBER 1978

(To convert to total terrestial field in gammas, add 55,443. The first row contains hourly values; the second, half-hourly values for the indicated times.)

8:	9:	10:	11:	12:	1:	2:	3:	4:	5:
37.9	28.4	20.8	10.9	2.0	2.9	12.8	21.0	32.0	36.2
36.3	26.1	16.2	8.8	0.0	6.3	15.8	27.5	35.8	

TABLE D.1

ABSOLUTE FIELD INTENSITIES FOR AREA A (SQUARE -170L80)

(To convert to total terrestial field, add 54,900 gammas. All traverses ran south-to-north; beginning time of each traverse is indicated. Data for the L89 traverse are averages of five readings; all others are a single reading.)

Line	L90 9:40	L89 8:45	L88 9:50	L87 10:00	L86 10:10	L85 10:15	L84 10:25	L83 10:30	L82 10:35	L81 10:40	L80 10:45	Line Mean	Line S.D.
-170	61.7	62.4	62.5	61.2	61.7	62.6	63.1	62.7	62.9	63.2	63.9	62.54	0.77
-169	62.4	62.7	63.0	62.8	62.4	62.9	63.0	63.2	63.4	63.7	64.3	63.07	0.56
-168	62.5	62.3	62.7	62.9	62.7	63.3	63.4	63.5	63.0	63.2	64.7	63.11	0.65
-167	61.2	61.9	62.5	63.1	64.7	64.5	64.9	64.1	64.0	63.7	64.0	63.46	1.27
-166	62.6	62.2	62.7	62.6	65.2	65.7	64.8	64.0	64.5	64.1	65.2	63.96	1.25
-165	62.9	62.5	63.9	63.5	66.1	65.9	65.3	64.6	64.6	64.8	65.5	64.51	1.19
-164	63.4	63.6	63.4	64.1	65.9	66.3	65.7	64.7	64.4	65.2	65.7	64.76	1.06
-163	65.7	65.4	64.6	64.7	64.7	65.8	65.4	64.4	64.3	65.4	65.7	65.10	0.56
-162	65.9	66.2	66.4	64.9	64.2	64.5	64.9	64.2	64.4	65.3	65.6	65.14	0.80
-161	66.3	66.7	65.9	64.3	64.8	64.0	64.7	64.6	64.5	65.7	66.1	65.24	0.92
-160	68.2	68.0	67.4	65.2	65.0	64.2	63.9	65.3	65.2	66.1	67.4	65.99	1.52
Mean	63.89	63.99	64.09	63.57	64.31	64.61	64.46	64.12	64.12	64.58	65.28	64.27	0.45
S.D	2.25	2.17	1.74	1.20	1.44	1.31	0.95	0.74	0.73	1.04	1.03	1.33	0.53

TABLE D.2

ABSOLUTE FIELD INTENSITIES FOR AREA A (SQUARE -160L80)

(To convert to total terrestial field, add 54,900 gammas. All traverses ran south-to-north; beginning time of each traverse is indicated. Data for the L89 traverse are averages of five readings; all others are a single reading. * indicates a damped reading.)

Line	L90 9:40	L89 8:45	L88 9:50	L87 10:00	L86 10:10	L85 10:15	L84 10:25	L83 10:30	L82 10:35	L81 10:40	L80 10:45	Line Mean	Line S.D.
-160	68.2	68.0	67.4	65.2	65.0	64.2	63.9	65.3	65.2	66.1	67.4	65.99	1.52
-159	67.3	67.4	66.8	65.0	67.3	64.8	65.4	66.5	66.4	66.9	67.4	66.47	0.97
-158	66.7	66.9	66.4	66.3	66.2	67.1	67.3	68.2	67.5	68.4	68.3	67.21	0.81
-157	66.8	67.2	66.2	66.3	67.4	67.2	67.8	69.4	68.7	70.3	69.6	67.90	1.39
-156	67.0	67.8	67.4	65.7	67.2	68.0	69.0	70.2	69.4	70.7	71.2	68.51	1.73
-155	65.4	66.7	65.2	65.2	67.6	68.2	69.3	70.6	70.8	71.6	70.9	68.32	2.47
-154	66.3	66.9	66.0	66.3	67.9	69.4	68.7	70.5	71.2	71.4	70.7	68.66	2.10
-153	67.2	67.4	67.2	67.4	71.1	69.8	69.3	70.9	70.3	71.8	71.4	69.44	1.83
-152	67.9	67.6	67.9	65.0*	71.5	70.1	69.8	71.6	70.7	72.5	71.6	69.65	2.29
-151	68.2	67.9	70.3	69.7	70.3	71.4	71.3	72.2	71.5	73.1	72.0	70.72	1.63
-150	68.7	70.7	71.4	70.6	71.2	71.9	71.7	72.9	73.3	73.5	72.8	71.70	1.42
Mean	67.25	67.68	67.47	66.61	68.43	68.37	68.50	69.85	69.55	70.57	70.30	68.60	1.31
S.D.	0.96	1.09	1.85	1.91	2.22	2.47	2.32	2.34	2.40	2.45	1.86	2.26	0.71
MEAN	65.57	65.84	65.78	65.09	66.37	66.49	66.48	66.99	66.84	67.58	67.79	66.44	0.83
S.D.	1.73	1.72	1.80	1.60	1.87	1.98	1.77	1.74	1.77	1.88	1.50	1.76	0.13

TABLE E

ABSOLUTE FIELD INTENSITIES FOR AREA B (SQUARE -200L130)

(To convert to total terrestial field, add 54,900 gammas. All traverses ran south-to-north; beginning time of each traverse is indicated. Data for both L140 traverses are averages of five readings; all others are a single reading. The L140 traverse taken at 3:45 PM has not been adjusted for diurnal variation. * indicates a damped reading.)

Line	L140 12:15	L139 12:30	L138 12:35	L137 12:40	L136 12:45	L135 12:50	L134 12:55	L133 1:00	L132 1:05	L131 1:10	L130 1:15	Line Mean	Line S.D.	L140 3:45
-200	42.2*	44.1*	42.3	43.4	44.8	45.9	45.3	46.2	45.8	47.1	49.4*	45.14	2.12	68.3*
-199	43.6*	47.2	45.4	47.1	46.3	46.8	47.3	47.6	47.2	48.3	48.6	46.85	1.39	75.4
-198	47.7	48.4	48.1	47.6	46.7	47.3	47.4	48.1	45.9*	46.5*	48.4	47.46	0.81	73.1
-197	49.0	48.2	46.9*	46.7	47.1	47.6	48.7	47.5	49.1	50.4	50.1	48.30	1.27	71.0
-196	53.3	50.6	49.2	47.7	47.9	48.4	48.6	49.3	50.3	50.4	51.6	49.75	1.70	75.2
-195	52.1	51.7	53.0	49.5	51.4	49.7	50.1	49.7	50.9	51.7	52.3	51.10	1.20	78.6
-194	52.5	53.0	52.6	51.4	50.3	49.3	49.7	51.2	52.1	53.0	52.4	51.59	1.32	83.3
-193	52.1	51.8	52.5	52.8	51.6	52.0	51.9	52.6	51.6	53.9	54.2	52.45	0.88	83.1
-192	52.2	50.6	52.4	53.9	52.5	52.7	52.4	52.3	53.4	54.6	55.1	52.92	1.26	83.4
-191	53.3	52.3	52.9	54.4	53.0	53.4	53.7	53.7	54.5	55.2	54.8	53.75	0.89	85.2
-190	54.4	55.1	53.8	55.2	54.2	53.9	54.3	53.9	54.8	56.1	56.4	54.75	0.88	88.4
Mean	50.22	50.27	49.92	49.70	49.62	49.73	49.95	50.19	50.51	51.56	52.12	50.34	0.80	78.6
S.D.	4.11	3.08	3.81	3.50	3.17	2.84	2.85	2.69	3.21	3.31	2.77	3.21	0.45	6.5

TABLE F

ABSOLUTE FIELD INTENSITIES FOR AREA C (SQUARE -150L50)

(To convert to total terrestial field, add 54,900 gammas. All traverses ran west-to-east; beginning time of each traverse is indicated. Data for the -150 traverse are averages of five readings; all others are a single reading. * indicates a damped reading.)

Line	Time	L60	L59	L58	L57	L56	L55	L54	L53	L52	L51	L50	Mean	S.D.
-150	2:00	70.2	71.1	70.7	72.3	73.7	72.8	71.9	72.7	72.8	73.4	74.7	72.39	1.34
-149	2:15	70.9	72.6	71.8	72.5	76.5	74.3	72.5	72.8	74.8	74.1	74.6	73.40	1.60
-148	2:20	71.2	71.9	72.0	72.6	75.4	74.7	73.9	74.7	75.2	75.3	74.1	73.73	1.53
-147	2:25	72.5	73.6	73.3	72.3	76.3	75.6	73.7	75.8	75.7	75.1	74.5	74.40	1.40
-146	2:30	74.6	73.9	73.8	73.4	67.3*	75.5	73.8	75.4	75.3	74.7	75.2	73.78	2.28
-145	2:35	75.3	74.5	73.2	73.6	65.2*	75.6	72.0	73.1	73.9	73.7	74.9	73.18	2.85
-144	2:40	75.1	74.9	74.0	73.7	73.6	72.2	72.4	73.3	73.8	71.5	68.5*	73.00	1.85
-143	2:45	74.2	73.7	74.3	74.3	74.4	73.8	74.1	73.5	70.9	60.2*	62.4*	71.44	5.13
-142	2:50	72.4	72.5	73.1	74.0	74.3	75.8	76.4	74.2	71.4	70.8	60.5*	72.31	4.27
-141	2:55	72.6	72.1	72.6	73.2	75.5	78.3	77.7	76.3	73.6	71.7	73.5	74.28	2.30
-140	3:00	71.8	72.3	72.5	73.5	76.4	78.9	78.3	75.1	73.6	74.1	75.7	74.75	2.38
Mean		72.80	73.01	72.75	73.22	73.51	75.23	74.25	74.26	73.73	72.24	71.69	73.34	1.01
S.D.		1.76	1.19	1.02	0.70	3.76	2.05	2.25	1.27	1.55	4.26	5.43	2.29	1.52