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Ground Based Magnetometer Survey of Abandoned Wells at the Rocky Mountain Arsenal – A Case History

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GROUND BASED MAGNETOMETER SURVEY OF ABANDONED WELLS AT THE ROCKY MOUNTAIN ARSENAL - A CASE HISTORY

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ABSTRACT

A program of ground magnetometer surveys was designed and implemented at the U.S. Army Rocky Mountain Arsenal, Denver, Colorado, in an attempt to locate a number of 1940's vintage water wells. These wells were associated with homesteads and farms that occupied the area prior to the construction of the arsenal. The surveys were part of the overall program to properly abandon these farm wells to eliminate potential pathways for the migration of contaminants.

Total field and vertical gradient magnetic data were collected along 14 survey grids encompassing nearly 30 acres of property at a 10' x 10' station/line spacing. Each survey grid was constructed approximately 300' on a side to encompass an area that was reasonably certain to contain the targeted well based on the apparent accuracy of the well location information available in the historic records. In most cases, historic information on the depth extent of well casings, casing diameter or casing thickness was either absent or contradictory, and as a consequence, modeling of expected anomalies for each well target was not performed. However, test surveys were conducted to observe anomalous response characteristics at several known farm wells. These wells, for which information on the depth extent, casing diameter and casing thickness is recorded, all produced sharp, positive anomalies characteristic of monopolar type sources. Amplitudes ranged between 300 and 4000 gammas with half-widths of 20'.

The relatively large database obtained at each survey grid was reduced on a PC and outputted as a contour map which readily permitted an analysis of the relative shape and intensity of anomalies. The data, in most cases, revealed the presence of strong positive anomalies that are easily recognizable from other dipolar features detected at the sites and, based on the test survey results, are interpreted to represent well casings. Follow-up excavation sites were selected accordingly. The cost of the magnetometer/gradiometer surveys at the 10' x 10' spacing, including data reduction and interpretation, was estimated at $1000/acre.

INTRODUCTION

The U.S. Army Rocky Mountain Arsenal (RMA) encompasses a 27 square mile area located approximately 12 miles northeast of Denver, Colorado. RMA was established in 1942 and has been used by government and industry for the manufacturing, testing and packaging of chemical munitions and commercial pesticides. Prior to the construction of the arsenal, land use in the area was primarily agricultural and residential. Approximately 250 water wells used for irrigation, stock watering and domestic use were associated with the various homesteads and farms that occupied the land at this time.

Following the acquisition of the property by the Army in 1942, the homes and farm buildings were demolished and removed. Structures and equipment associated with the wells (such as windmills and pumphouses) were also removed, leaving well casings flush with or cut-off just below grade. During the 46 years since the establishment of RMA, several efforts have been made to inventory the pre-1942 wells. Despite those efforts, the actual field locations of wells became difficult or impossible to re-establish as the areas became overgrown and as property boundaries, roads and other landmarks changed.

Available information indicates that approximately one-half of the wells were greater than 30" in diameter and were probably hand dug. The remainder of the wells were apparently drilled and contain steel casing. Reported well depths range from 15' to 1000'. Shallow wells were installed in unconsolidated alluvial and eolian deposits comprised of dune sand, and sand and gravel outwash containing cobbles, silts and clays and, locally, beds of volcanic ash. The combined thickness of the unconsolidated deposits at RMA ranges from 30' to 130'. Deeper wells penetrate the 250' to 400' thick Late Cretaceous-Early Tertiary Denver Formation sandstone or the underlying 500 to 600' thick Late Cretaceous Arapahoe Formation sandstone. Both the Denver Formation and the Arapahoe Formation are important aquifers in the Denver metropolitan area.

In connection with numerous ongoing pollution abatement/remediation efforts at RMA, a program was recently implemented to locate abandoned wells that lie within areas of contaminated ground water. As part of this program of work, a visual search for the pre-1942 wells was performed during the summer of 1987. Following the visual search it became apparent that some type of remote sensing search method was needed to locate 15 potentially deep (greater than 50' and up to 1000') wells. The individual location of each of the 15 wells *was* constrained to a relatively small area, based on information from old maps and aerial photographs. However, collectively the wells were scattered across nearly the entire arsenal property (Figure 1) occurring in nine different sections that encompassed both developed areas of the facility as well as open land. Information available from historic records concerning the completed depth of the well, the casing type and casing diameter was misleading and contradictory, however, considering the age and approximate depths of the wells it appeared likely that all wells contained metal casing.

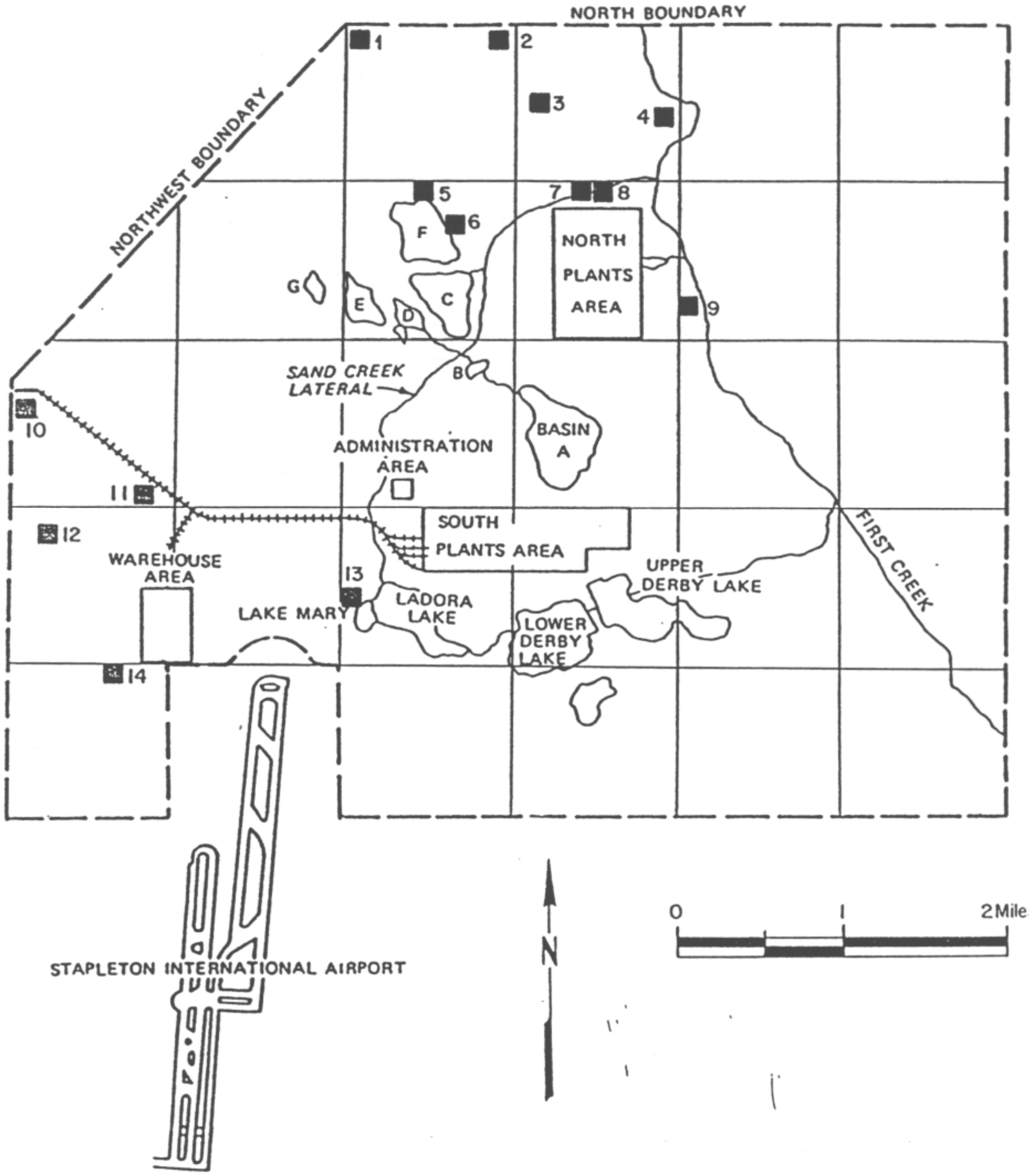


Figure 1 ROCKY MOUNTAIN ARSENAL SITE MAP

MAGNETIC SURVEY

Background

Ground-based magnetometer surveys utilizing a proton precession magnetometer/gradiometer were selected for use over other instrumentation configurations in the search effort based on the following considerations.

- The limited number and widespread location of wells precluded the cost effective use of airborne surveys which would have required follow-up with ground surveys. Relatively tightly constrained well locations, determined from the historic records review and an evaluation of aerial photographs, permitted ground search methods to be employed efficiently within a manageable area of one to three acres.

- Considering the assumption, at least initially, that all wells contained metal casing, it was not necessary to utilize instruments capable of locating uncased wells.

- The association of the wells with homes and farm buildings, and observations made during visual reconnaissance of the search areas suggested that the occurrence of a moderate amount of buried metal debris was likely in the vicinity of the wells. Magnetometers were selected for use over metal detectors because 1) magnetometers are insensitive to nonferrous metals and therefore, effectively screen out "noise" due to nonferrous debris in the search area; and 2) magnetometers are capable of detecting well casings at greater depths and from greater lateral distances, permitting comparatively larger station/line spacings.

- Proton precession type magnetometers are relatively inexpensive, widely available and readily adapted to performing rapid grid-controlled surveys with data output to and processing by microcomputers.

A brief discussion of the theory of magnetic methods and principles of magnetic data interpretation relevant to the application of detecting and discriminating anomalies associated with steel cased wells is presented in the following paragraphs. Overviews of magnetic methods are available in Parasnis (1975), Breiner (1973), and Nettleton (1976).

The direction and magnitude of the geomagnetic field at any point on the earth's surface may be uniquely defined by a total intensity vector, T. Proton precession magnetometers measure the magnitude of T; most commonly in units of gammas. In the vicinity of RMA, the value of T is approximately 54800 gammas.

Local disturbances or magnetic anomalies in the earth's field arise from a local change or contrast in magnetization which occur where concentrations of natural or manmade ferrous material are present. As measured on the magnetometer, these disturbances result in an increase or decrease above background (54800 gammas at RMA) of a few gammas to several thousand gammas. By observing a number of total field measurements along traverses that cross the area of magnetization contrast, the amplitude and shape of the anomaly or "anomaly signature" can be measured and characterized, respectively.

The magnetization contrast of ferrous material is primarily the result of induced magnetization. Induced magnetization is a function of the direction and strength of the surrounding geomagnetic field and the magnetic susceptibility of the material, and can be thought of as originating from a magnet or magnetic dipole created within the material. For a given magnetization, anomaly amplitude is a function of the distance between the object and the magnetometer, and the amount of magnetizable material present.

The anomaly signature (i.e., its symmetry/asymmetry and relative magnitude of positive or negative character) is a function of the orientation of the induced magnetic dipole. Magnetic anomalies exist as arrangements of magnetic dipoles, monopoles (dipoles whose ends are far apart), lines of dipoles or monopoles, or sheet like distributions of dipoles or monopoles. Which arrangement is observed depends on the shape of the object (i.e., equidimensional, elongate, sheetlike, etc.) and on the orientation of the object within the geomagnetic field. The combination of object shape and orientation within the earth's field largely determines the anomaly signature. Magnetic anomalies that result from arrangements of magnetic dipoles generally produce an asymmetrical positive/negative anomaly signature (at inclinations of the total field vector that occur in the continental U.S.) and result from objects that have an equidimensional shape or are equidimensional in cross section in the direction of the total field vector. Anomalies that arise from monopolar sources generally produce a nearly symmetrical positive anomaly signature and result from objects that are elongate in the direction of the total field vector.

It is by understanding the cause of specific anomaly signatures that well casing anomalies can be discriminated from other sources of magnetic anomalies. The magnetic anomalies that result from well casings can be modeled as a vertical magnetic dipole whose ends are located near the top and bottom of the casing (Barret, 1931; Frischknecht, 1983). In a qualitative sense, the well can be envisioned as a monopolar source because of its elongate shape and its vertical orientation. Frischknecht, et al (1983) and Jachens (1986) have shown, through modeling and field studies, that vertical well casings produce strong positive total field anomalies of several hundreds to several thousands of gammas directly over the casing even at distances of many tens of feet. Barret (1931) indicated that for a fixed magnetometer-casing separation, the anomaly size is primarily a function of the cross-sectional area of metal of the casing. Test surveys conducted at RMA, over known wells similar to those expected to be encountered in the search program, produced anomalies which ranged from 300 to 4000 gammas when measured with a magnetometer to top-of-casing separation of 6'. Observed anomaly half-widths were approximately 20' to 22' along an east - west profile and approximately 18' to 20' in a north-south profile. Results for test surveys conducted over a 24" diameter, 63' deep well and a 4.5" diameter, 500' deep well are shown in Figures 2a-b and 2c-d, respectively.

The strong magnetic anomalies produced by well casings make their detection relatively simple. Moreover, their unique shape permits them to be readily discriminated from other potentially obscuring anomalies such as miscellaneous buried ferrous debris associated with the homes and farm buildings at RMA. This is because, in contrast to abandoned wells, the objects that comprise buried debris tend to be small with respect to their separation from the magnetometer (i.e., equidimensional) and, therefore, comprise dipolar sources. As a result, this debris typically produces asymmetrical positive/negative anomalies in contrast to the characteristic symmetrical positive anomaly signature of wells.

It should be noted that the well casings may have a large permanent magnetization. Permanent magnetization is related to the thermal, mechanical and magnetic history of the object, and is independent of the geomagnetic field. The anomaly measured by the magnetometer expresses only the net effect of induced and permanent magnetization. Although the permanent magnetization of individual well casings that are the target of this search are unknown, they are not thought to have significantly altered the anticipated anomaly signatures described above, based on numerous test surveys over known wells at RMA.

Field Survey

The relative location of the 14 survey grids at RMA are shown in Figure 1. Each survey grid was constructed approximately 300' on a side to encompass an approximately two acre area that was reasonably certain to include the targeted well. These grid dimensions were selected based on the apparent accuracy of the well location information available in the historic records. The survey grids were all surveyed at a 10' x 10' station/line spacing and were oriented north-south. This spacing was selected because of the very narrow width of the anomalies (half-widths of approximately 20') observed in the test surveys (Figure 2). Although station/line spacings of 20' may have been sufficient to insure detection of a well anomaly, it was felt that it would not always provide sufficient resolution of the anomaly shape to permit an evaluation of the likely source of the anomaly (ie, well casing or buried metal debris) without follow-up. This was considered particularly important in view of the uncertainty of the casing diameter and depth of the target wells. If the line/station spacing were to be reduced, the results of the test surveys indicate that east-west station spacings could be reduced more than north-south spacings because of slightly greater half-widths in an east-west direction.

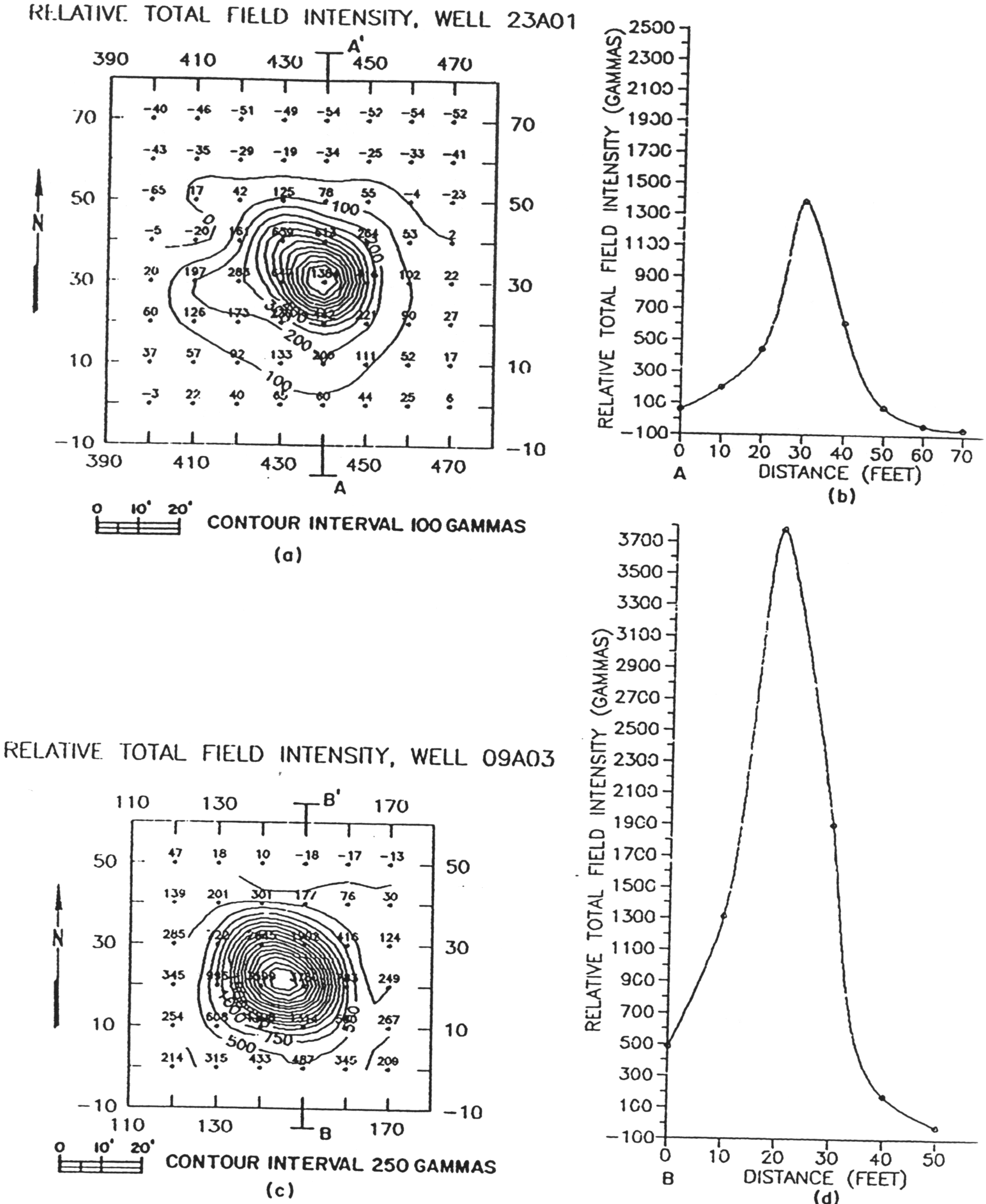


Figure 2 TEST SURVEY DATA; (a) AND (b) PLAN AND PROFILE TOTAL FIELD DATA RESPECTIVELY FOR WELL 23A01 – 1/8" THICK, 24" DIAMETER GALVANIZED STEEL CASING, REPORTED DEPTH 63'; (c) AND (d) PLAN AND PROFILE TOTAL FIELD DATA RESPECTIVELY FOR WELL 09A03 – 1/8" THICK, 4 1/2 DIAMETER STEEL CASING, REPORTED DEPTH 500'.

An EDA Instruments Omni IV proton precession magnetometer/gradiometer was used to perform the surveys. The nominal resolution of the instrument is a few gammas. Although the accuracy of proton precession instruments can be impaired if high magnetic gradients are encountered, in practice this did not present a problem considering that the objective of the survey was simply to detect the presence of a well rather than to determine specific parameters of the well. The Omni IV permitted simultaneous measurement of the vertical magnetic gradient and total field readings by employing a dual sensor arrangement with a sensor separation of 0.5 meters. The vertical gradient is the change in the total field intensity per unit distance in a vertical direction. Gradient measurements were made because gradient anomalies tend to resolve overlapping total field anomalies into their individual constituents and thereby increase resolution of near surface anomalies. Moreover, the gradient data can be achieved with no additional expense or survey time with a dual sensor arrangement.

Each survey was performed in a tie-line fashion (Breiner, 1973) which permitted total field data to be corrected for diurnal variations. Total field and gradient measurements obtained during each survey were stored in the instrument's computer memory and downloaded to a PC computer at the end of each day. The computer and commercially available software were then used to prepare computer generated contour maps of both data sets. The contour maps facilitated a rapid comparison and evaluation of anomaly signatures which was particularly useful in areas where numerous and overlapping anomalies were observed. In this way, well casing anomalies were identified and targeted for excavation follow-up. On flat, open terrain a two person crew could layout the 300' x 300' survey grid, complete the collection of all readings along the grid, download the data and output a contour map in one day.

RESULTS

Observations made at five of the 14 survey sites (grids 1, 3, 9, 13 and 14, Figure 1) are presented and discussed below. Contoured total magnetic field data and selected gradient data are shown in Figures 3 through 10. Field conditions and background magnetic noise environments encountered at these grids are representative of the range of those at all 14 sites.

Grid 1 is located at the edge of an open field in the northwest corner of RMA (Figure 1) and encompasses an approximately 350' x 400' area. A powerline and major underground gas line lie 50' to the north of the northern boundary of the survey area but did not adversely affect the results of the survey. The remainder of the area is undeveloped. In the majority of the southeastern portion of the grid, no total field or gradient anomalies were detected. A number of total field anomalies were detected in the 130' x 150' northwestern corner of the survey area which is shown in Figure 3. The negative total field anomaly in the north-eastern corner of this area can be attributed to a signpost (Figure 3), however, there was no other material on the surface to correlate with the anomalies to the south. The southern trend of total field anomalies between

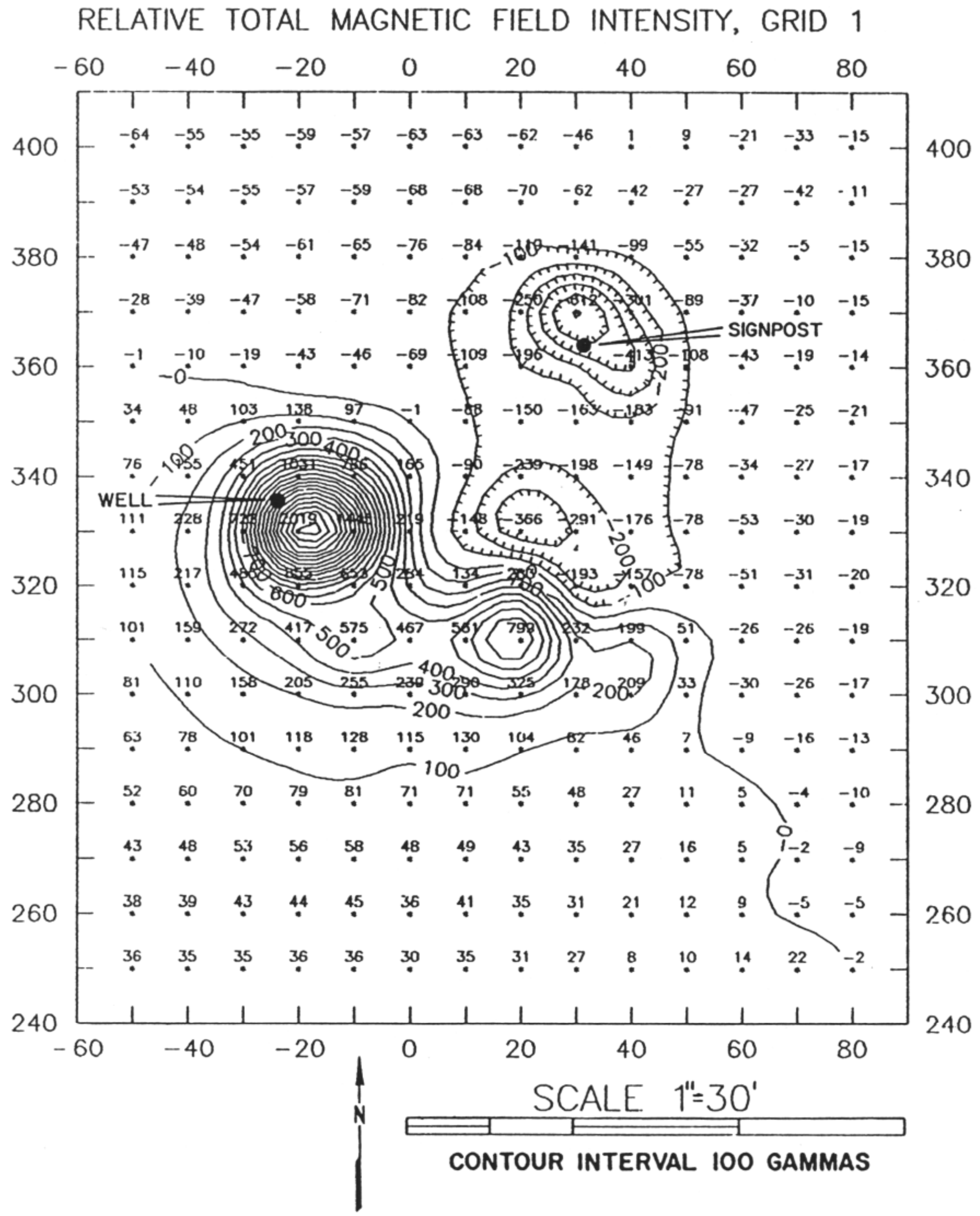

RELATIVE TOTAL MAGNETIC FIELD INTENSITY, GRID 1
WELL
SIGNPOST
N
SCALE 1"=30'
CONTOUR INTERVAL 100 GAMMAS

Figure 3

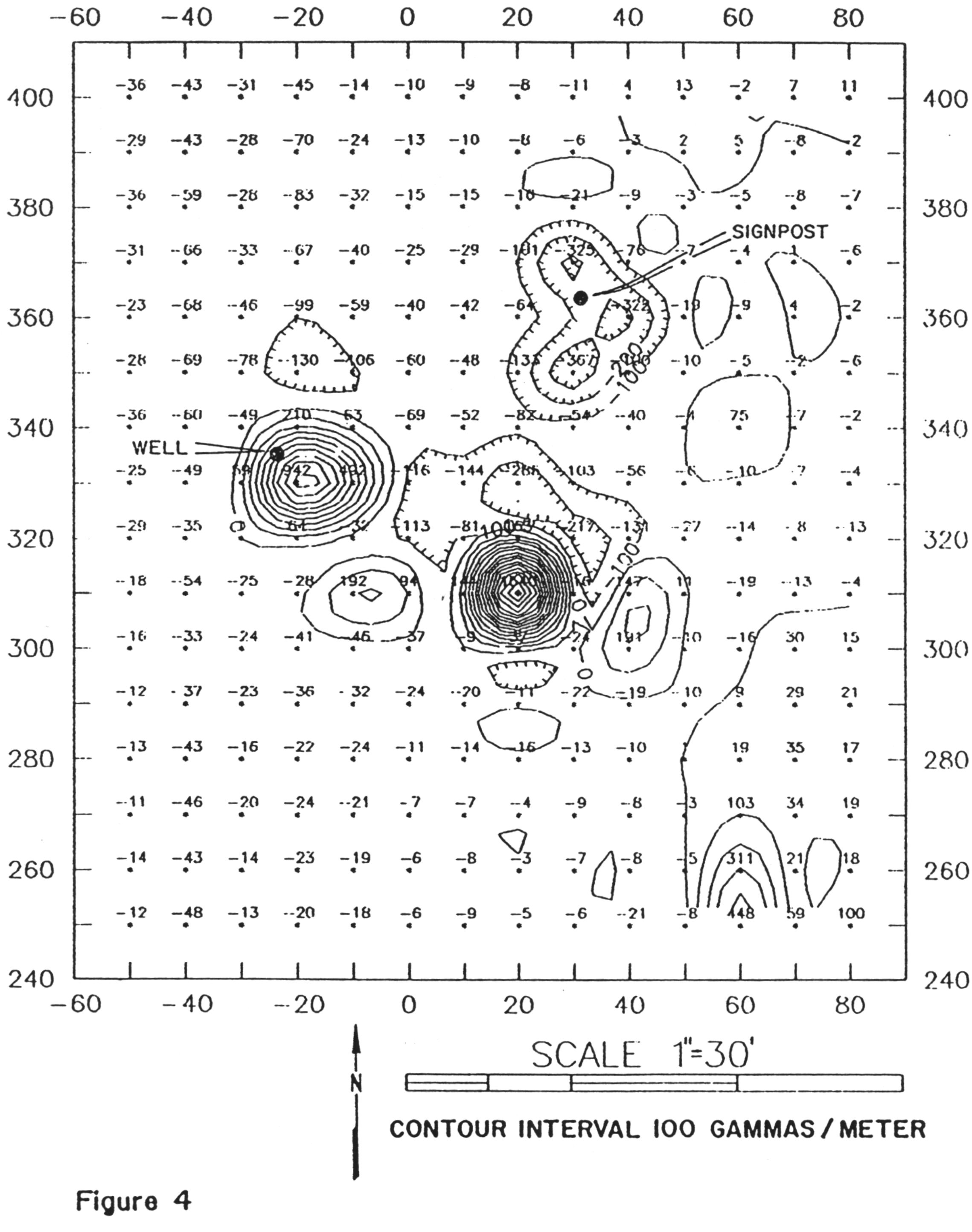
positions 290N and 350N, (Figure 3) appeared to be caused by a strong dipolar source to the east and a strong monopolar source to the west with probably some smaller dipolar features in between. The vertical gradient data shown in Figure 4 better identifies the locations of individual features. Based on criteria presented above, the location of the strong positive anomaly (approximately 2000 gammas at 25E, 335N) was excavated and a 6" diameter well was uncovered approximately 3.5' below the surface. The reported total depth of this well is 460'.

Grid 14 is located in a cottonwood grove that identifies the location of an old homesite in otherwise open grassland near the southwestern corner of RMA. The western half of a 300' x 400' survey area was magnetically featureless, however, a number of anomalies were observed in the eastern half which is shown in Figures 5 and 6. A hand dug well and a rubbish pile containing metal debris were observed in the east-central and southeast total field portion of this area, respectively; a moderate amplitude positive/negative total field anomaly is associated with the rubbish pile (Figure 5). A very strong positive anomaly (approximately 7000 gammas) was identified at grid position 335E, 165N. Again, the vertical gradient data (Figure 6) provides greater spatial resolution of the anomalies. It is interesting to note that during the visual search of this area, which took place in the summer of 1987, the presence of buried metal was detected at these coordinates with a small hand-held scanning fluxgate gradiometer that was used to supplement the visual search. Excavations that were performed prior to initiation of this program of work revealed a 3" diameter pipeline. However, following the resurvey of the area with the proton precession magnetometer and with the advantage of being able to characterize the anomaly signature from contoured data, it became apparent that the pipeline could not explain the size of the observed anomaly. Re-excavation at this position resulted in the location of a 6" diameter well approximately 3.5' below the surface. The reported total depth of this well is 900'.

Grid 9 is similarly located near a cottonwood grove in open grasslan in the north-central part of RMA (Figure 1). Total field data for the central portion of the grid, where the only anomalies were located, are presented in Figure 7. A relatively small (approximately 150 gammas) but distinctly positive anomaly was observed at position 150E, 150N Excavation at this site to a depth of approximately 14' failed to reveal well. However, effectively no metal was encountered during the excavation and a resurvey of the area indicates that the anomaly is still present. I view of these conditions, it is possible that the upper portion of well casing was removed from the well and the present top-of-casing is below 14'. The total depth for this well is unknown.

Grid 3 is located in the northern part of RMA in open grassland with r landmarks identifying previous development in the area. A single, positive 2000 gamma anomaly was crossed in the first line of the survey an subsequently defined by surveying along five additional lines (Figure 8) Excavation at grid position 10E, 190N, revealed a 30" diameter well at 10 below the surface. The reported total depth of this well is 450'.

VERTICAL MAGNETIC GRADIENT, GRID 1



SCALE 1"=30'

CONTOUR INTERVAL 100 GAMMAS/METER

Figure 4

RELATIVE TOTAL MAGNETIC FIELD INTENSITY, GRID 14

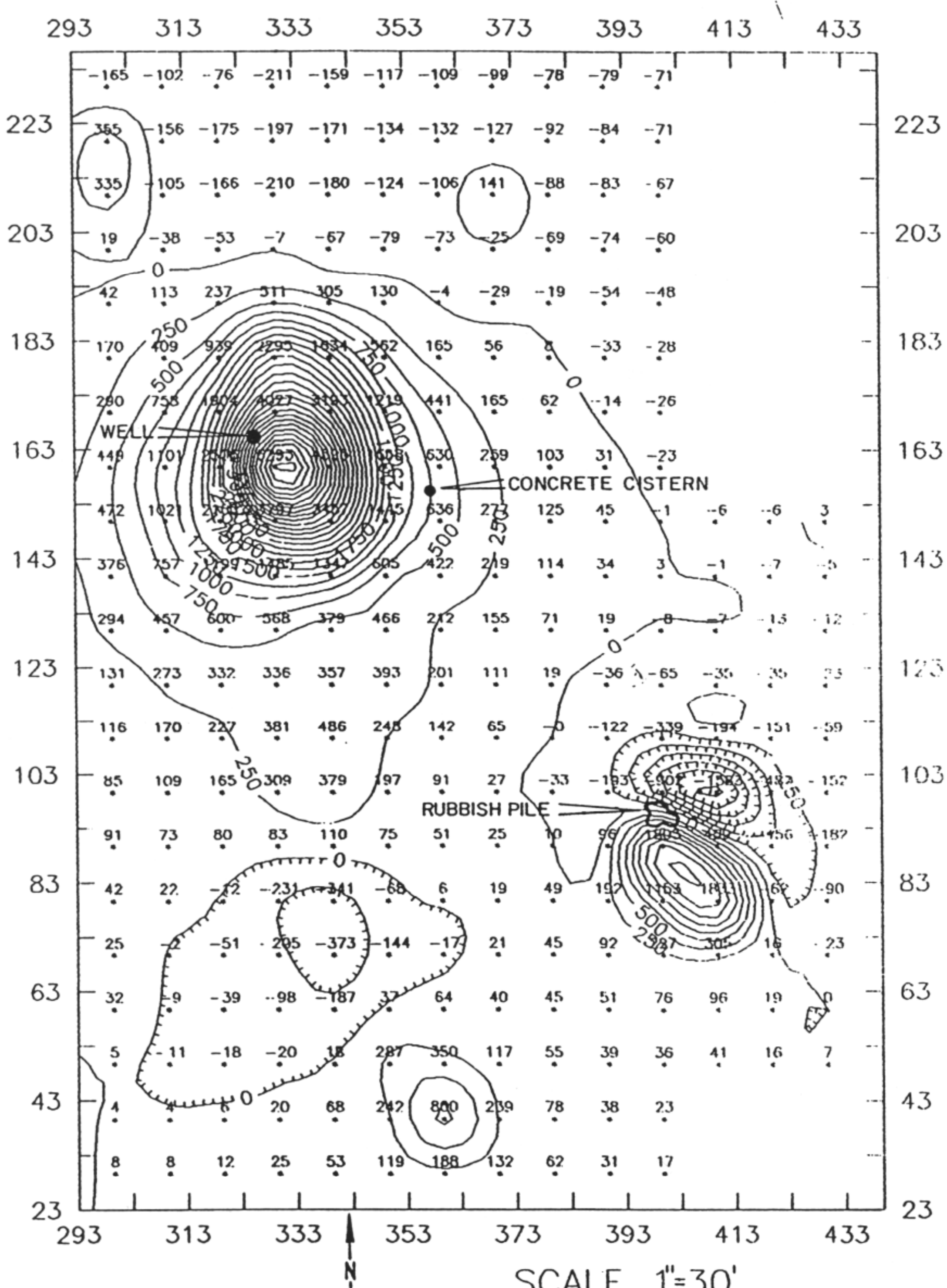


Figure 5

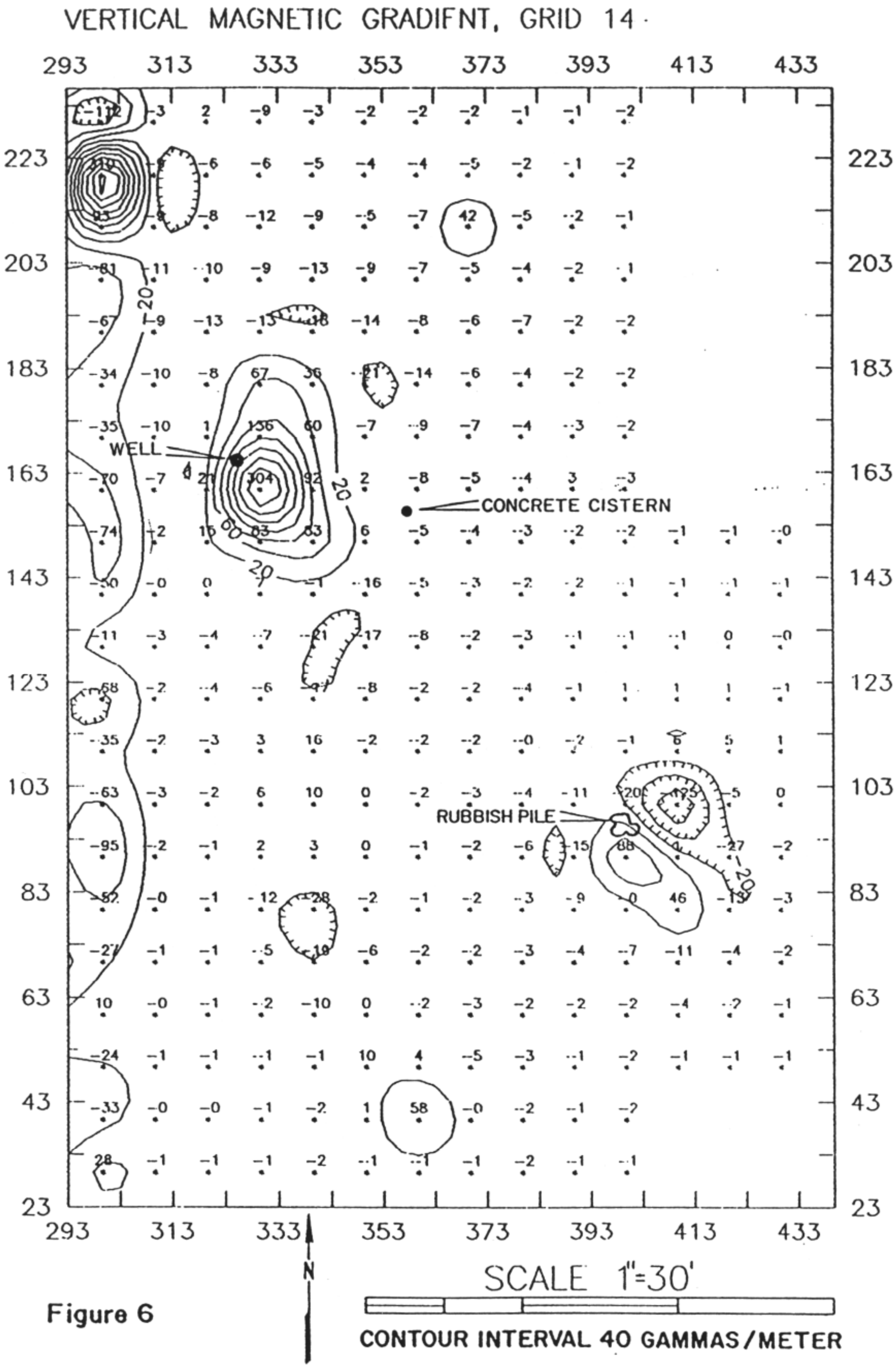

VERTICAL MAGNETIC GRADIENT, GRID 14
WELL
CONCRETE CISTERN
RUBBISH PILE
N
SCALE 1"=30'
CONTOUR INTERVAL 40 GAMMAS/METER

Figure 6

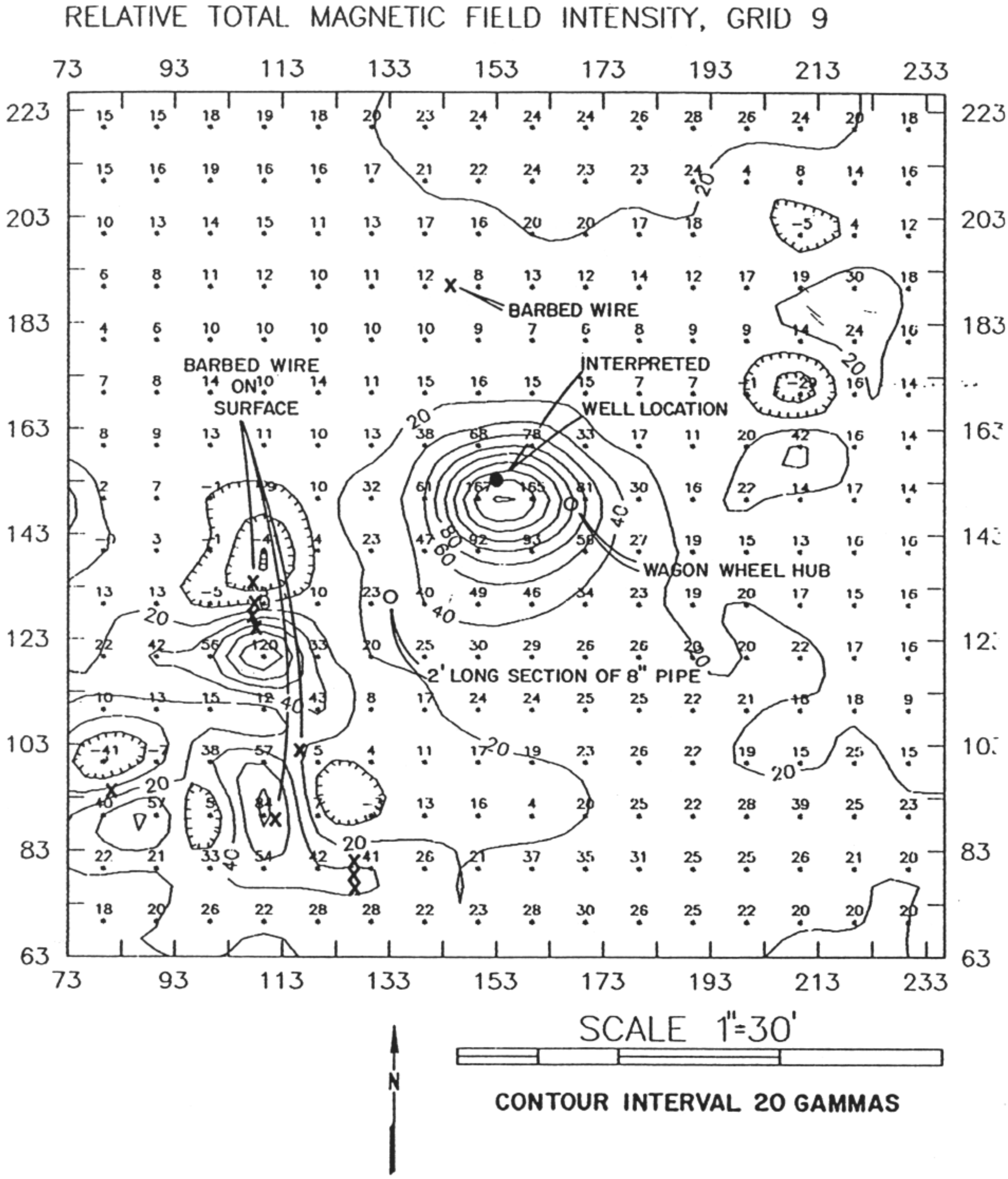

RELATIVE TOTAL MAGNETIC FIELD INTENSITY, GRID 9
BARBED WIRE
BARBED WIRE ON SURFACE
INTERPRETED WELL LOCATION
WAGON WHEEL HUB
2' LONG SECTION OF 8" PIPE
SCALE 1"=30'
N
CONTOUR INTERVAL 20 GAMMAS

Figure 7

RELATIVE TOTAL MAGNETIC FIELD INTENSITY, GRID 3

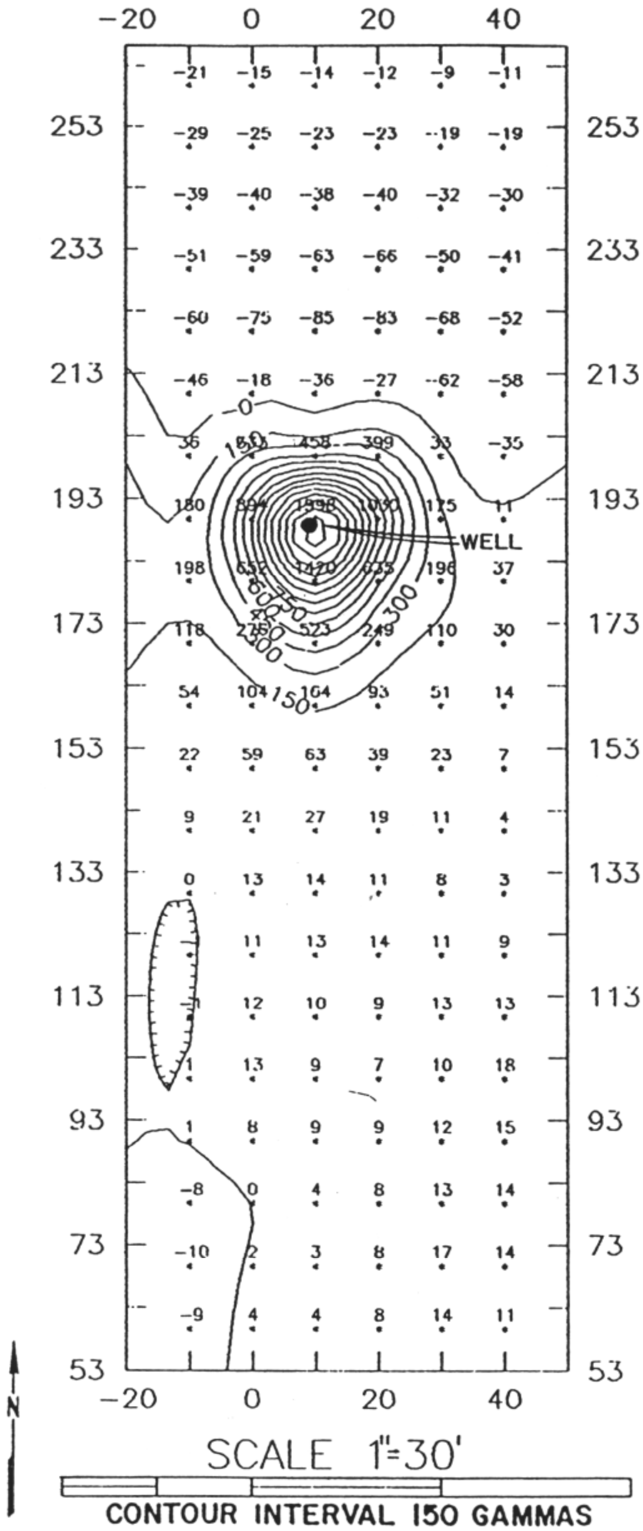


Figure 8

RELATIVE TOTAL MAGNETIC FIELD INTENSITY, GRID 13

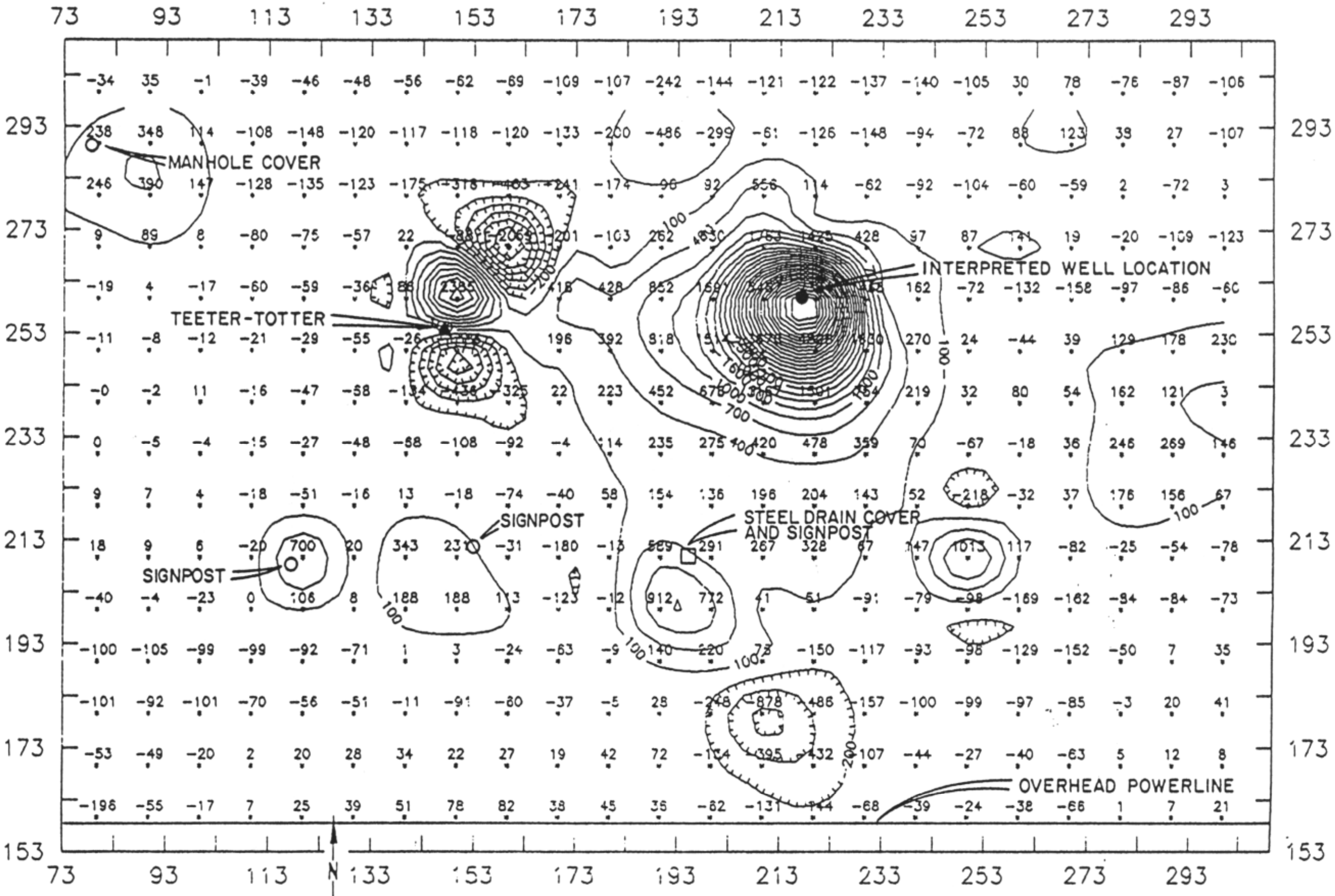


Figure 9

SCALE 1"=30'

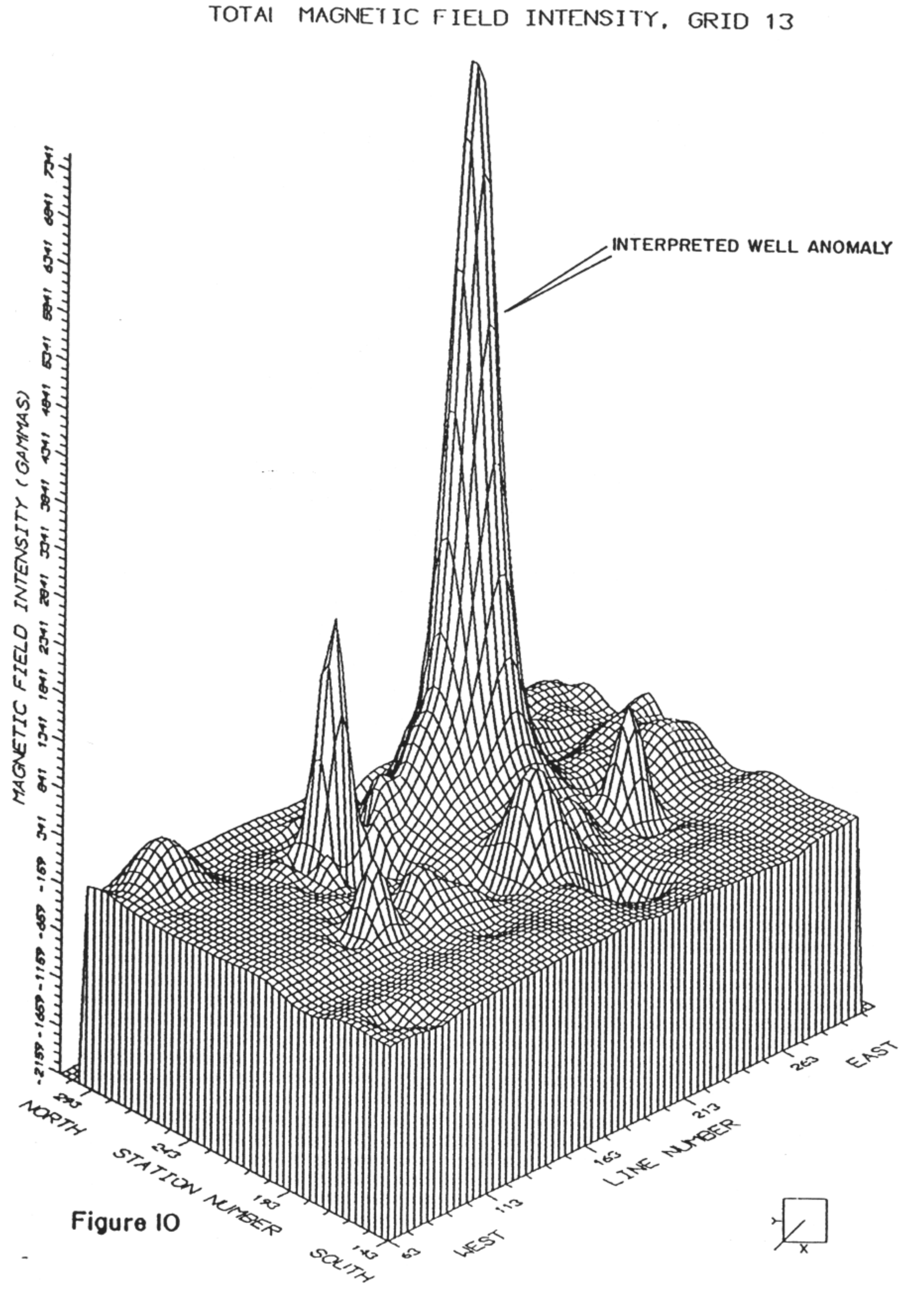

TOTAI MAGNETIC FIELD INTENSITY, GRID 13
INTERPRETED WELL ANOMALY
MAGNETIC FIELD INTENSITY (GAMMAS)
NORTH
STATION NUMBER
SOUTH
WEST
LINE NUMBER
EAST

Figure 10

Grid 13 is located in a developed area of the southwestern part of the RMA facility (Figure 1). Total field data are presented for nearly the entire area surveyed in Figure 9. A swimming pool and commissary lie immediately to the northeast and east of the survey grid, respectively. The survey area is bounded by Lake Mary and an overhead powerline to the south. The total field data in Figure 9 identify a strong positive anomaly (approximately 7000 gammas) amid a number of other anomalies that appear to be related to either dipolar sources or can be correlated to numerous cultural features on the surface. As before, the characteristics of a sharp, strong, positive anomaly suggest the presence of a well casing. These features are recognizable even in an area of rather severe cultural interference as is more effectively demonstrated in a three dimensional ne plot of total field survey data (Figure 10). No excavations have been performed at the location of this anomaly at this time because a routine utility check revealed that the source of the anomaly is located directly adjacent to or beneath a water main.

The locations of anomalies identified at the other 14 survey area were, at the time this article was prepared, in the process of being excavated.

CONCLUSIONS

The success achieved to date in the geophysical program conducted RMA demonstrates the utility of ground based magnetometer surveys locating abandoned water wells of 4 inches in diameter and greater, al cased depths of from 40' to 500', particularly in areas where it may impractical to conduct airborne surveys. The characteristic sharp, strong positive anomaly signatures of well casings readily permit t discrimination of the source of these anomalies from other buried debris that is usually typified by smaller asymmetric positive/negative anomalie Recognition and comparative evaluation of these features is facilitated an evaluation of contoured data which can he rapidly performed on lar databases with PC computers.

Costs for the methodologies employed at RMA, which include t establishment of a survey grid, total field and vertical gradient data collection at 10' x 10' station/line spacings, data reduction, computer contouring, and data interpretation are conservatively estimated $1000/acre.

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BIOGRAPHICAL SKETCH

Brian Martinek received his B.S. in geology in 1978 from Michigan Technological University and his M.S. in 1985 from the Colorado School of Mines. He is currently employed by Geraghty & Miller, Inc., in Denver, Colorado and has diverse interests in geology, geophysics and hydrogeology.