LOCATION OF ABANDONED WELLS WITH GEOPHYSICAL METHODS

by

F. C. Frischknecht
P. V. Raab
U.S. Geological Survey
Geological Division
Denver, CO 80225

Interagency Agreement No. DW 149 30473-01-0

Project Officer

Jeff van Ee
Aquatic and Subsurface Monitoring Branch
Environmental Monitoring Systems Laboratory
Las Vegas, NV 89114

This study was conducted in cooperation with the U.S. Geological Survey, Department of Interior

ENVIRONMENTAL MONITORING SYSTEMS LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
LAS VEGAS, NEVADA 89114

NOTICE

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency under interagency agreement number DW 149 30473-01-0 to the U.S. Geological Survey, it has been subjected to the Agency's peer and administrative review, and it has been approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

PREFACE

The Environmental Monitoring Systems Laboratory of the U.S. Environmental Protection Agency (EPA) provided funding for the research on geophysical methods described in this report. The cooperative effort between EPA and the U.S. Geological Survey (USGS) is part of a larger effort to provide local, state, and Federal agencies with guidance methodologies to determine if abandoned wells exist in an area where the underground injection of wastes is contemplated. Besides geophysical surveys, record-searches, as conducted by the University of Oklahoma, and photographic searches have proven to be useful in locating abandoned wells.

This summary of the geophysical studies and the results was written for persons who are not familiar with the terminology and methodology of geophysics. The reader who is interested in more technical details, including all of the results, may refer to the USGS open-file reports that are listed among the references.

ABSTRACT

Abandoned wells are sometimes an important element in the contamination of fresh underground water supplies. If a well is not properly plugged and the casing is leaky, it may serve as a conduit for brines or other pollutants to reach a fresh water aquifer. This study was made to determine the feasibility of using geophysical methods to locate abandoned wells which contain steel casing. Preliminary considerations indicated that magnetic and, perhaps, electrical methods should be useful.

Detailed measurements of the Earth's magnetic field in the vicinity of a number of wells showed large disturbances or anomalies in the field. Using a mathematical model developed to represent the effect of a steel casing, it was possible to predict from ground magnetic measurements the anomalies which would be observed by a magnetometer placed in an aircraft. Although magnetic anomalies caused by a casing diminish rapidly as the height is increased, it appeared that wells could be detected from a low flying aircraft.

From the model study, a survey was designed with an aircraft height of 60 m and a spacing between flight lines, or tracks, of 100 m. Aeromagnetic surveys were made over one test area in Colorado and four test areas in Oklahoma where there are many known wells. Supplemental information was obtained with a ground magnetometer. The aeromagnetic results agreed well with those obtained by a records search and by interpretation of aerial photographs. These methods are complementary in that each provides information which the others do not.

Most wells in Oklahoma produced anomalies with magnitudes far exceeding the threshold for recognition. In a few cases the anomalies were small; but, with careful analysis, most of them were recognized. When wells occurred in close proximity, it was difficult to determine how many there were from the aeromagnetic results. Anomalies due to other manmade features, such as pipelines and transmission line towers, were a minor problem in interpreting the aeromagnetic results. In the Colorado test area, sharp anomalies resulting from variations in the magnetization of near-surface sedimentary rocks caused difficulty in interpretation of the aeromagnetic results. However, questions in interpretation were resolved by selective ground magnetometer measurements. Overall it was estimated that 95-98 percent of the wells in the areas surveyed were detected. Thus, the results of the study show that the magnetic method is an effective means of locating abandoned wells. However, most agencies or organizations which have the responsibility for finding wells will require technical assistance in designing and carrying out magnetic surveys.

Electrical methods which were tested were the dipole-dipole resistivity/induced polarization (IP), self-potential, and loop-loop electromagnetic methods. Substantial self-potential anomalies were observed over some but not

all wells. The results of a few resistivity/IP and electromagnetic tests did not indicate the presence of wells. There are some other potentially useful electrical methods which were not tested. However, it appears that electrical methods have only limited uses in locating abandoned wells. Unless more promising electrical results become available, use of only the magnetic method is recommended.

CONTENTS

FIGURES

INTRODUCTION

The Underground Injection Control (UIC) regulations promulgated by the Environmental Protection Agency regulate injection wells for the protection of actual or potential underground sources of drinking water as required by the Safe Drinking Water Act. One provision of the UIC regulations establishes a radius of review around proposed new injection wells, based on the hydrogeologic properties of the subsurface. Within this radius a search must be made for possible conduits, such as abandoned wells, from the injection stratum to overlying aquifers containing potable water.

It was estimated in 1979 that there were some 500,000 municipal, industrial, commercial, agricultural and domestic wells injecting fluids below the surface, and that at least 5,000 new injection wells were being constructed each year (Federal Register, 1979). Due to differential pressures, dormant or abandoned wells sometimes serve as conduits between aquifers containing brine or other pollutants and fresh water aquifers. Location of such existing wells is an important task; it was estimated in 1979 that there were as many as 1,800,000 producing, dormant, and abandoned wells in the United States (Federal Register, 1979). The problem presented by abandoned or unknown wells is especially acute in petroleum producing regions where the total number of wells may reach densities as high as 2,000 per square mile. Particularly in the early days of petroleum production, the locations of wells were not always recorded. Some recorded locations were erroneous, or described only in broad terms, and many old records are not readily available.

Geophysical methods originally developed for resource exploration may be useful in locating abandoned wells. The "classical" methods of exploration geophysics are (1) the seismic method, depending on the propagation of mechanical or seismic waves through the Earth; (2) the gravity method, depending on changes in the force of gravity due to variations in density from region to region; (3) the magnetic method, depending on disturbances in the magnetic field of the Earth caused by magnetic materials; and (4) electrical methods, depending on the the electrical resistivity and other electrical properties of the Earth. The objectives of this research were to study the feasibility of locating wells using geophysical methods and to test and demonstrate the most promising methods.

Throughout the history of petroleum production, steel casings and other steel pipes have been used in almost all petroleum wells; and, until recently, steel casings were used in most drilled water wells. A steel casing causes a relatively large disturbance, which may persist to distances of a few hundred feet from the end of the casing, in the magnetic field of the Earth. Instruments called magnetometers, which measure magnetic fields, can be used to locate the magnetic disturbances or "anomalies" caused by steel casings.

Magnetometers can be operated in low-flying aircraft, thereby offering a rapid means for magnetic surveys of large areas. Although a type of simple handheld magnetometer is sometimes used by construction and maintenance personnel to locate iron and steel pipes, apparently magnetometers have not been systematically used for location of wells.

Steel casings are very good conductors of electricity, relative to the surrounding Earth, and electrochemical reactions may take place between a buried steel object and the Earth. Therefore, some of the electrical methods of exploration geophysics may be useful in locating steel casings. However, in some instances, all or part of the casing and other pipe has been removed from abandoned wells; neither the magnetic nor electrical method would be useful in locating uncased drill holes.

The change in gravity due to the presence of a cased or uncased hole is too small to warrant considering the use of gravity techniques. Seismic methods might be of some use, but the range of detection would be rather short and the method is costly to employ. Remote sensing methods which employ microwave, infrared, or other high frequency electromagnetic radiation may be useful, theoretically, in detecting disturbances of the soil which mark a well site, but were deemed to have little chance for success in practice. Due to these considerations, it appeared that the magnetic and electrical methods were the only ones likely to be effective in the location of casings, and it was decided that primary emphasis should be placed on magnetic methods.

In the first phase of this study, Frischknecht and others (1983) developed a simple mathematical model for the magnetic field of a casing. To apply this model to specific casings, the magnetic parameters of the casing must be determined experimentally. Magnetic parameters for a number of nonproducing or dry wells near Denver, Colorado, were determined from measurements made with a ground-based magnetometer. The model was then used to predict the results which would be obtained with a magnetometer placed in a low-flying aircraft. Since results of this study indicated that it was feasible to locate casings from airborne measurements, the parameters of an airborne survey were designed (Frischknecht and others, 1983).

In the second phase of the study (Frischknecht, and others, 1984), aeromagnetic surveys of a small test area near Denver and four small areas near Oklahoma City, Oklahoma, were made. The test areas near Oklahoma City were selected by the University of Oklahoma (Fairchild and others, 1983). Ground magnetic measurements were made at many localities to aid in the evaluation of the aeromagnetic data. The data were processed and evaluated to arrive at conclusions and recommendations for the use of the magnetic method.

The use of electrical methods was considered and self-potential and inductive electromagnetic methods were tested (Frischknecht and others, 1983). During the second phase of the study, the dipole-dipole resistivity/IP method was tested near one casing (Washburne, 1984).

CONCLUSIONS AND RECOMMENDATIONS

The results of this study show that steel well casings generally produce large and distinctive magnetic anomalies. Although these anomalies diminish rapidly with distance from the wells, modeling indicated that wells could be detected by magnetometer measurements made on the ground or from low-flying aircraft. The results of aeromagnetic surveys in Oklahoma agreed well with those obtained by interpretation of aerial photographs and by a search of available records. Since these other methods are not completely reliable, there is no way of knowing exactly how many wells there are in the test areas, but it was estimated that 95-98 percent of them were detected by the aeromagnetic survey. Although the location of abandoned wells is basically a new application for the magnetic method, this study demonstrates that ground and airborne magnetic surveys are effective for this purpose.

Some of the advantages of the magnetic method in locating casings are:

1) The method can be readily used to accurately locate buried casings where there has been no surface evidence of the well for many years.

2) By use of an aircraft, large areas can be surveyed rapidly without need for access to the property.

3) With the use of a ground magnetometer, the horizontal position of a casing can be located within one or two meters and the results are immediately available.

Some of the disadvantages of magnetic methods and problems in their use are:

1) Wells which do not contain near-surface casing or other pipes cannot be detected at all, and it may be impractical to locate wells containing only a small amount of casing due to the large number of close-spaced measurements which is then required.

2) The magnetic method may be relatively costly compared with other methods, particularly if the areas are small and few in number.

3) In some areas, magnetic disturbances due to manmade objects, such as pipelines and steel buildings or anomalies due to naturally occurring magnetic minerals in near-surface rocks, interfere with the recognition of anomalies caused by casings.

4) Most commerical and public institutions which have a need to search for abandoned wells will, at least initially, require technical assistance from outside their organizations.

Theory suggests that it may be possible to detect steel casings with electrical methods of geophysical exploration. There are many reports of distortion of resistivity/IP measurements caused by wells. However, the results of one resistivity/IP test made as part of this study did not indicate the well. Some casings produced substantial electrical self-potential anomalies; but, most did not. Two standard electromagnetic methods which were tested did not yield useful results. While more study is needed to completely evaluate the use of all electrical methods in locating wells, it appears that electrical methods are generally less effective and more costly than magnetic methods.

The results of this study do not indicate that further research is required before the magnetic method should be applied in the search for abandoned wells. Most of the questions that can be addressed in a modest research effort have been answered. In considering the application of the magnetic method in the search for abandoned wells in a new area, the most important questions are: (1) what size magnetic anomalies are the casings likely to produce, and (2) how much magnetic interference will there be from other manmade sources and from natural sources? These questions can never be completely answered, since each new area will be somewhat different than those already investigated. However, we believe that our test areas in Colorado and Oklahoma are representative of conditions in many oil fields, and that our results can be used in planning and conducting work in other areas.

The results of any new surveys designed to locate wells could be valuable guides to further work, and they should be published as soon as possible. After experience has been gained in a number of new areas, it would be very worthwhile to carefully evaluate the effectiveness of the magnetic method, compared with other approaches, and to identify continuing problems in the application of the magnetic method. Such a review might lead to new recommendations on how to best use the method, and it might lead to recommendations for further study of particular problems or techniques.

The results of this study indicate that it is very useful to employ three methods: records-search, photointerpretation, and magnetic surveys, in locating wells. All three methods are recommended for use in new areas. However, since each method has deficiencies, there is the possibility that in particular areas one or more of the methods will not be applicable. Also, in some areas, it is likely that wells can be located by use of only one or two methods.

There are a number of different circumstances in which the use of magnetic methods to locate wells should be considered. Sometimes there are requirements to physically locate buried wells which are known from records; ground magnetic methods are most useful for this purpose. Regulations require a search for abandoned wells within a certain radius, sometimes specified to be 1/4 mile, of proposed new injection wells (Federal Register, 1979). Ground or airborne magnetic methods might be used for this purpose; but, if a search is to be made around the location of several proposed injection wells in the same general area, airborne methods will probably be least expensive. Finally, an agency or firm may have a need to search for wells over large areas to find potential sites for injection wells which are the prescribed distance from any abandoned wells.

PRINCIPLES OF MAGNETIC AND ELECTRICAL METHODS

MAGNETIC FIELDS

The Earth possesses a magnetic field which has roughly the same form as that which would result from a large bar magnet placed near the Earth's center. Both the intensity and direction of the Earth's magnetic field vary with location. Such a field that possesses a direction as well as intensity is called a vector field. The Earth's field is customarily described in terms of three quantities: declination, inclination or dip, and intensity or "total field." Declination is the difference between true or geographic north and the direction in which the needle of a magnetic compass points. Inclination is the difference between the direction of the field and the horizontal plane. Intensity is a measure of the strength of the field or the force which it exerts on magnetic objects. Declination and inclination are measured in degrees, and intensity is expressed in gammas (1 gamma = 10^{-5} oersted) or in S.I. units as nanoteslas. Numerically, the gamma and the nanotesla are the same; the former unit is still used by most geophysicists. Over the coterminous United States, average values of declination, inclination, and intensity vary systematically between about 20° west of north to 20° east of north, 52° to 76° from the horizontal plane, and 48,000 to 60,000 gammas, respectively (Fabiano, and others, 1983). Locally, the values of the field may fall far outside these ranges.

The interaction between the Earth's field and changing amounts of radiation from the sun causes the intensity and direction of the field to vary with time. Of most concern in magnetic surveying are a more or less regular daily variation of the field and irregular changes which take place over time periods varying from a few minutes to hours during "magnetic storms." In making magnetic surveys, it is generally necessary to monitor these time variations and to remove their effect from survey data.

MAGNETIC PROPERTIES OF MATERIALS

Magnetization is a phenomenon which some materials exhibit that causes objects made of the material to behave as magnets. For purposes of this report, two kinds of magnetization should be recognized: induced magnetization and permanent or remanent magnetization. Induced magnetization in a material depends on the intensity and direction of the surrounding or inducing magnetic fields; in our case, this is the Earth's field. If the Earth's field is removed by placing the material inside a magnetic shield, the induced magnetization in the object becomes zero. The degree to which a material is magnetized by an inducing field depends on a parameter called magnetic susceptibility. Permanent or remanent magnetization is the property of some materials such as those used in household magnets, that causes them to retain magnetization in the absence of a magnetic field. Permanent magnetization in an object depends on the original inducing field and a material property called coercive force. The total magnetization of an object is the sum of the induced and permanent magnetization.

The magnetic field near a magnetized object is the sum of the local field due to the object and the Earth's field. It is sometimes convenient to think of these fields in terms of imaginary lines along the direction of the field. In Figure 1, the Earth's field locally is shown by a set of nearly parallel lines whereas the field of the magnetized object is shown by a set of curved lines. In summing the two fields, their directions as well as intensities must be considered. Thus, the total field near a magnetized object may be greater or less than the Earth's field.

Most iron and steel objects exhibit some degree of both kinds of magnetization. A few naturally occurring minerals, such as the iron oxide magnetite, can be magnetized. Rocks containing even a small percentage of these minerals are weakly magnetic and variations in the distribution of magnetic rocks cause perturbations or anomalies in the Earth's field. Most oil or gas fields are found in regions where the near-surface rocks are sedimentary. Generally, sedimentary rocks are only very weakly magnetic, but there are notable exceptions to this rule (Donovan, and others, 1979). Igneous and metamorphic rocks, which occur beneath sedimentary rocks and, in many regions, at the surface, are often sources of substantial magnetic anomalies. Magnetic surveys are useful in exploration for mineral deposits and in studies of subsurface geology. But, in using magnetic methods to locate casings, anomalies due to rocks are a source of interference.

MAGNETOMETERS

The magnetometer is a sensitive instrument which can be used to map variations in the Earth's magnetic field. Some magnetometers are highly portable instruments which are operated manually. Other magnetometers are designed to be mounted in aircraft or other vehicles, and more or less continuous recordings are made as the vehicle moves. Some magnetometers measure the directions of the field and others measure the intensity of the field in a particular direction such as the vertical direction. The intensity of the field along a particular direction is usually called the "component" of the field in that direction. The component of a field in the direction perpendicular to the direction of the field is zero, and the component in the direction parallel to the field is the maximum value, or total intensity, of the field. Measurement of the direction or of a component of the field is generally either very time consuming or inaccurate or both. Most magnetic surveys are made with instruments which measure only the total intensity. Currently, the proton precession magnetometer is most commonly used for total intensity measurements. It consists of a sensor containing a coil of wire immersed in a fluid rich in protons and a separate box containing electronic circuits and a display. The protons in the fluid collectively wobble like spinning tops at a rate which depends on the intensity of the magnetic field. By measuring the rate of wobble, the intensity of the field is determined. Use of a portable proton magnetometer in the field is illustrated in Figure 2.

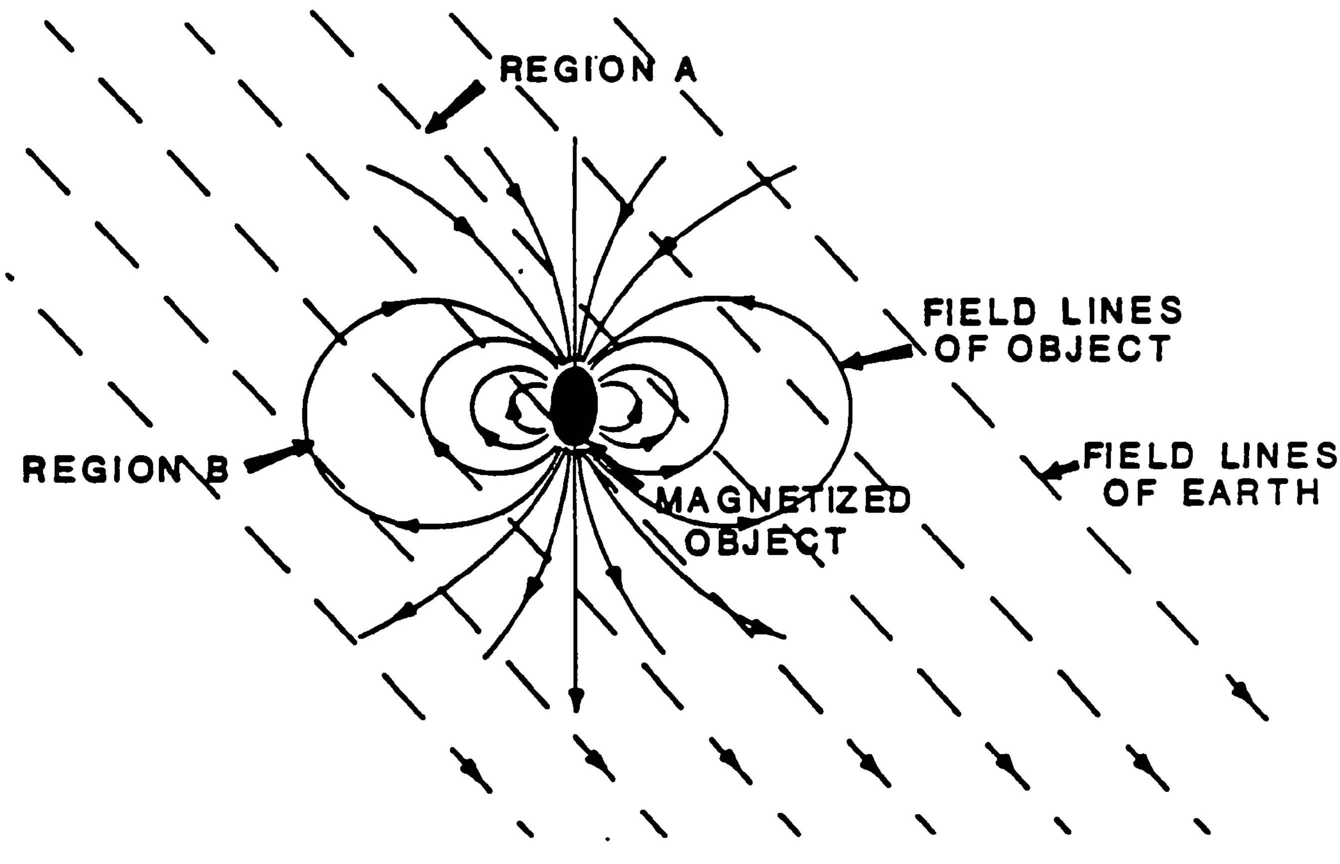

Figure 1. Sketch of magnetic field lines for a magnetized object and their interaction with the Earth's magnetic field lines. The two fields directly reinforce each other in regions such as A, and they oppose each other in regions such as B.

Figure 2. Portable proton magnetometer in use in Colorado.

The proton magnetometer cannot provide continuous measurements. However, in airborne operation, it can sample once or twice a second or faster, depending on its sensitivity. Nominal sensitivity of a proton magnetometer is about one gamma. Some handheld units have a sensitivity of only 10 gammas; other more expensive systems have a sensitivity of 0.1 gamma or greater. Ground magnetometer measurements are recorded in a notebook by the operator or, with newer instruments, directly in a solid state memory. Airborne magnetometer readings are usually recorded on magnetic tape.

For special purposes, changes in the field or "magnetic gradients" are sometimes measured. In practical terms, the gradient is the difference in the field measured at two points divided by the distance between the points. The gradient of a component of the field can be determined, but most often the gradient of the total intensity is measured. Typically, a gradiometer consists of two proton magnetometer sensors and an electronic instrument which measures the field at both sensors and the difference in fields between the sensors. The sensors can be placed one above the other to measure the vertical gradient or at the same height to measure the horizontal gradient in the direction of the line joining the two sensors. Compared with total intensity measurements, gradient measurements provide better resolution of nearby sources, and they are insensitive to time variations in the field.

MAGNETIC SURVEY PROCEDURES AND DATA PROCESSING

Ground magnetic measurements are usually made with portable instruments at regular intervals along straight parallel lines which cover the survey area. Often the interval between measurement locations (stations) along the lines is less than the spacing between lines. Ordinary land surveying methods are used to establish stations at which measurements are made; high accuracy is not usually required. Continuously recording instruments are sometimes mounted on trucks (Hildenbrand, 1982); measurements can be made along road networks and in areas where it is possible to drive off roads.

Most magnetic surveys are done from aircraft. Airborne measurements are made along parallel flight lines that, for geologic investigations, are normally spaced 0.2 km (1/8 mile) to 9.7 km (6 miles) or more apart.[1] For some purposes, aeromagnetic surveys are made at a fixed altitude above sea level; for other purposes they are flown at a fixed height above the ground. The pilot may navigate visually to fly along lines drawn on maps or aerial photographs or some type of electronic navigation system may be used for guidance. A tracking camera or a video camera and recorder are commonly used to obtain a continuous visual record of the flight path. In data processing, the location of the aircraft is plotted at locations where common points on the base map and on the tracking film are recognized; the locations for each measured value of the field are then adjusted to the flight path by assuming that the speed and direction of the aircraft were constant between identified locations. Errors

---

[1]English units or mixed English and S.I. units were used in making field surveys reported here and, where appropriate, quantities are given in both sets of units.

in location are on the order of several tens of feet at low altitues and several hundreds of feet or more at high altitude. Where flights are over featureless terrain or water, the flight path cannot be recovered at all using the photographic method and electronic navigation systems such as Doppler radar, VLF, Loran-C, or inertial navigation must be used for both pilot guidance and recovery of the flight path. Use of these systems improves the accuracy of the flight path determination, but in general, does not provide the degree of accuracy needed for purposes such as the location of abandoned wells. Microwave navigation systems can provide locations accurate to several meters or better. These systems employ two or more radio transmitter-receivers (transponders) placed at accurately surveyed sites. A transmitter-receiver and computer on the aircraft measures the distance or range to each transponder and then computes the position of the aircraft. The chief disadvantage of these systems is that a line-of-site path between the aircraft and at least two transponders is required at all times. Height of the aircraft above ground is usually measured with a device called a radar altimeter. This instrument functions by measuring the time between transmission of a pulse and its reception after being reflected from the ground.

To make accurate anomaly maps, changes with time in the Earth's field during the period of the survey must be considered. During severe magnetic storms, which occur infrequently, magnetic surveys should not be made. Normal changes during the day, sometimes called diurnal drift, are a few tens of gammas and can be accounted for in processing the data. There are a number of methods of correcting surveys for time variations. For ground surveys, one method is to establish a base or reference station in the survey area and to repeat measurements at this base at frequent intervals. Measurements at field stations are then corrected by assuming that the field changed at a constant rate over the survey area during the time interval between repeat base station readings. This method works well, provided the field is relatively "quiet." In airborne surveying, the traditional method is to fly "tie" lines across the rows of parallel flight lines during a quiet period. The points or intersections at which the regular flight lines cross tie lines are determined and the differences in intensity between the two sets of measurements at these points are calculated. The flight line data are then adjusted to fit the tie line data by assuming that the field changed at a constant rate between the intersections. Usually, continuously recording magnetometers are employed at fixed base sites to monitor temporal changes. If time is accurately recorded at both base site and field location, the field data can be corrected by subtraction of the variations at the base site. This method works well for surveys of small areas, provided the base site is in or near the area. It does not work well for surveys of large areas having dimensions on the order of tens of kilometers since, over large areas, variations of the field with time are not uniform.

After all corrections are made, magnetic survey data are usually displayed in the form of isopleths. Such a map shows lines of constant magnetic intensity in the same way that a topographic map shows lines of constant elevation. Survey data are also presented in the form of profiles in which the magnetic intensity is plotted against a distance along the flight line. Various mathematical operations are sometimes used to enhance certain features in the data and suppress others. Geologic interpretation of magnetic anomalies is carried out by comparison of the actual results with theoretical results calculated for idealized geologic models and by comparison of the results with anomalies over known geologic features. Identification of anomalies caused by steel casings is generally quite easy since the anomalies have a characteristic shape. However, the problem becomes difficult when the anomaly due to the casing is weak and there are stronger nearby anomalies caused by other cultural and geologic sources.

For further information on the principles of the magnetic method and survey techniques, the reader may wish to consult some of the many papers and textbooks on the subject. The pamphlet by Breiner (1973) is a good introduction to the subject. The textbooks by Nettleton (1976), Parasnis (1975), and Telford and others (1976) give good treatments of the subject without being highly mathematical. For a review of more recent developments, including the use of gradiometers, the reader might wish to consult the papers by Hood and others (1979), and Emerson and others (1979).

ELECTRICAL PROPERTIES OF MATERIALS

Soils and rocks can conduct electricity, although not as easily as metals such as steel. The intrinsic property of materials which determines the degree of difficulty of driving electrical currents through the material is called resistivity and is measured in the unit, ohm-meter. The resistivity of most rocks is in the range of 1-10,000 ohm-m. In contrast, the resistivity of steel is typically less than 0.000001 ohm-m. The flow of constant or direct current through the Earth depends only on the resistivity. The flow of time-varying or alternating current depends on other properties as well, including the dielectric constant, which determines the way a material behaves in the presence of electrical charges, and the magnetic susceptibility, which was discussed previously in the section on magnetic properties. In practice, the influence of magnetic susceptibility on the flow of alternating currents in the Earth is usually negligible. Also, at the frequencies which are ordinarily employed in geophysical exploration, the influence of the dielectric constant is negligible for most Earth materials. However, some Earth materials, when excited by very low frequency alternating currents, become electrically "polarized." As a result, the resistance of the ground, or more properly the "impedance" of the ground, varies with frequency. Strong polarization effects are often observed when electrical currents flow between metallic objects and the Earth.

Electrochemical reactions between metallic objects and surrounding rocks and soil generate electrical forces, called electrical potentials, which drive electrical currents through the Earth. These self-potentials or spontaneous potentials change only very slowly with time. A number of other processes, such as the flow of ground water, can also generate self-potentials, voltages, and currents.

ELECTRICAL METHODS

Five electrical methods, which may be of some interest in location of steel casings, are resistivity, low frequency electromagnetic, ground penetrating radar, self-potential, and induced polarization. In the resistivity method, electrical connections are made to the ground through use of metal stakes or other devices called electrodes. An extremely low frequency electrical current is driven through the Earth using two electrodes, and the resultant difference in electrical potential or voltage, which is established between points on the surface of the Earth, is measured, usually by use of two other electrodes. By taking the current and electrodes spacings into account, the results are commonly expressed as "apparent resistivity" in ohm-m. The apparent resistivity would be the same as the true or intrinsic resistivity if the Earth were homogeneous. To make a resistivity map, the array of electrodes is moved about the area of interest.

In the low frequency electromagnetic method, the source of energy is a current flowing through a loop of wire or a current flowing through a length of wire connected or grounded to the Earth through an electrode at either end. The current in the wire causes a magnetic field about the wire which alternates at the same rate as the current. Associated with this magnetic field is an electric field that, when it passes through conductive materials such as the Earth, causes or induces an electrical current to flow in the material. These electrical currents flowing in the material produce a "secondary" magnetic field which perturbs the original or "primary" field. When a grounded wire is used, there is also a magnetic field associated with the current that is directly injected into the Earth. The induced current in the Earth and its secondary magnetic field depend on the resistivity of the Earth. An induction coil or other special type of magnetometer is used to measure components of the alternating magnetic field. The results of the measurements are usually expressed as the ratio of the secondary field to the primary field and sometimes the apparent resistivity is also computed.

From theoretical considerations and experience, we expect electromagnetic methods using only a loop or induction source to be effective in the location of horizontal pipelines and similar features and to be ineffective in the location of vertical pipes. Methods which use grounded wires as sources are expected to be much more effective in location of vertical pipes. At very close range, currents induced directly in a casing or other metal object can be detected with "metal detectors" (Johnston and others, 1973). However, at long range the only hope for detection of a casing is to observe the distortion caused by the casing in the normal flow of current in the Earth.

In the ground penetrating radar method, a very high frequency electromagnetic wave is radiated into the ground. When the wave encounters the boundary of a region where the velocity with which the wave propagates changes, some of the energy is reflected to the surface where it is detected. If the velocity of propagation is determined from other measurements, the depth of the reflector beneath the surface can be computed from the difference between the time when the transmitted wave left the antenna and the time when the reflected signal was received. To map an area, the antenna is moved along the surface while the system is operating; a display is thus obtained which resembles a cross section of the Earth. The method is effective only when the resistivity of the rocks is relatively high; it is not likely to be useful in most oil fields where near surface rocks are sedimentary and have low resistivities. The method might be useful in locating wells in igneous and metamorphic rocks and in glacial deposits.

The basis of the self-potential (SP) method is measurement of spontaneous electrical potentials. The equipment consists of two non polarizable electrodes, connecting wires and a sensitive voltmeter which presents a very high resistance to the electrodes. Measurements of the electrical potential are made with respect to an arbitrary fixed point in the survey area.

In the induced polarization (IP) method, very low frequency alternating or time-varying current is driven through the Earth using two electrodes. Potential differences are measured with two other electrodes as in resistivity measurements. Usually, the "dipole-dipole" electrode configuration is employed and resistivity measurements are made in conjunction with the IP measurements. In one variant of the IP method the quantity measured is the apparent resistivity at two or more frequencies. In other variations, the degree to which the Earth becomes electrically charged (chargeability) or equivalent quantities are measured. Rocks containing metallic minerals and some types of clay are highly polarizable. Buried metallic objects often give large IP responses when one or more of the electrodes is nearby (Nelson, 1977, Holladay and West, 1984).

For further information in the principles of electrical methods, the reader may wish to consult the general textbooks by Parasnis (1975) and Telford and others (1976). For more detailed information, the reader can consult the textbooks by Keller and Frischknecht (1966) and Wait (1982) or many other books and papers which deal with this subject.

GROUND MAGNETIC MEASUREMENTS

In the first part of this study, ground magnetic measurements were made near a number of known wells to obtain data that were used to evaluate the use of both ground and airborne magnetic methods in locating wells. Later, additional ground magnetic measurements were made to help evaluate the results of the airborne surveys. The first measurements were made near a number of wells in two oil fields in Colorado. One of the fields is east of Denver and includes the area later used for an aeromagnetic test (Figure 3). This field contains a number of producing and dry wells drilled during the 1970's. The second field is north of Denver near Boulder (Frischknecht and others, 1983) and contains many abandoned and a few producing wells.

To obtain data for use in analysis and modelling, measurements were generally made along radial lines or traverses in the magnetic north, south, east, and west directions with the well at the center. The total intensity of the field was determined using proton magnetometers with the sensor placed on a staff 2.4 m (8.0 ft) above the surface of the ground. Repeat readings were made at a base station, and the results were used to correct the data for diurnal drift. At most well sites a recording proton magnetometer was operated to monitor the diurnal drift. Before making readings, all visible steel trash such as oil drums, valves, and pipes was removed from the immediate vicinity of the traverses. Some of the traverses were over buried or partly buried steel trash which could not be readily removed. In the immediate vicinity of some of the wells the magnetic gradients were so large the proton magnetometers were not capable of making reliable measurements, but the loss of this data was generally not a serious problem. In addition to the total intensity measurements, vertical and horizontal gradients of the intensity and the inclination of the field were measured at a number of wells in both Colorado test areas. Initial processing and plotting of data were done on a desk top computer, and then the data were transferred to a larger computer for further analysis.

In evaluating airborne surveys, the ground magnetometer was used to quickly determine the sources of aeromagnetic anomalies. Aerial photographs and maps were used to locate the site of the anomaly on the ground. Measurements were then made on a very rough grid established by pacing. Readings were taken every 6-10 m (20-30 ft) but generally were not recorded. Usually it required only a few minutes to find the casing, if it existed, or a little longer to rule out the existence of a casing if none was found. When a casing was found, a few readings directly over or near the well were generally recorded.

This summary report includes only a few examples of the data which were collected and analyzed; the complete set of data is contained in the reports by Frischknecht and others (1983, 1984). An example of ground magnetometer data near well No. 4, in the Piney Creek, Colorado, area (Figure 3) is shown in Figures 4 and 5. The circles indicate the measured values of the intensity, F, of the field and the solid line is calculated from a theoretical model described in the next section. As predicted by theory, the experimental results show that north-south profiles over a well are asymmetrical; the peak value of the field is a little south of the well and then it drops to slightly less than its normal value in a small region north of the well. East-west profiles are symmetric except for disturbances due to sources other than the well. Well No. 4 produced one of the largest ground and airborne anomalies in the Piney Creek area. A small disturbance, which is due to an unknown object, occurs about 20 m (60 ft) east of the well (Figure 4).

As another example, data for PIW well No. 17 in the Horseshoe Lake, Oklahoma, area (Figure 6) are shown in Figures 7 and 8. The anomaly is much smaller in amplitude and narrower than in the previous example. The airborne anomaly is only about one gamma for well No. 17, which is near the threshold of detection. A secondary feature, perhaps caused by a buried piece of pipe, occurs at about 20 m (70 ft) along the east-west traverse (Figure 8).

The anomalies illustrated in Figures 4 and 5 and 7 and 8 diminish rapidly with distance from the well. To be certain of locating a well with a ground magnetometer, the distance interval between measurements must be small. From study of the results in Colorado, Frischknecht and others (1983) suggested that a suitable grid for locating wells with a total intensity ground magnetometer should consist of stations spaced at 10-m (30 ft) intervals along traverse lines spaced 16-m (50 ft) apart. The results did not indicate that gradient measurements would be more useful than total intensity measurements.

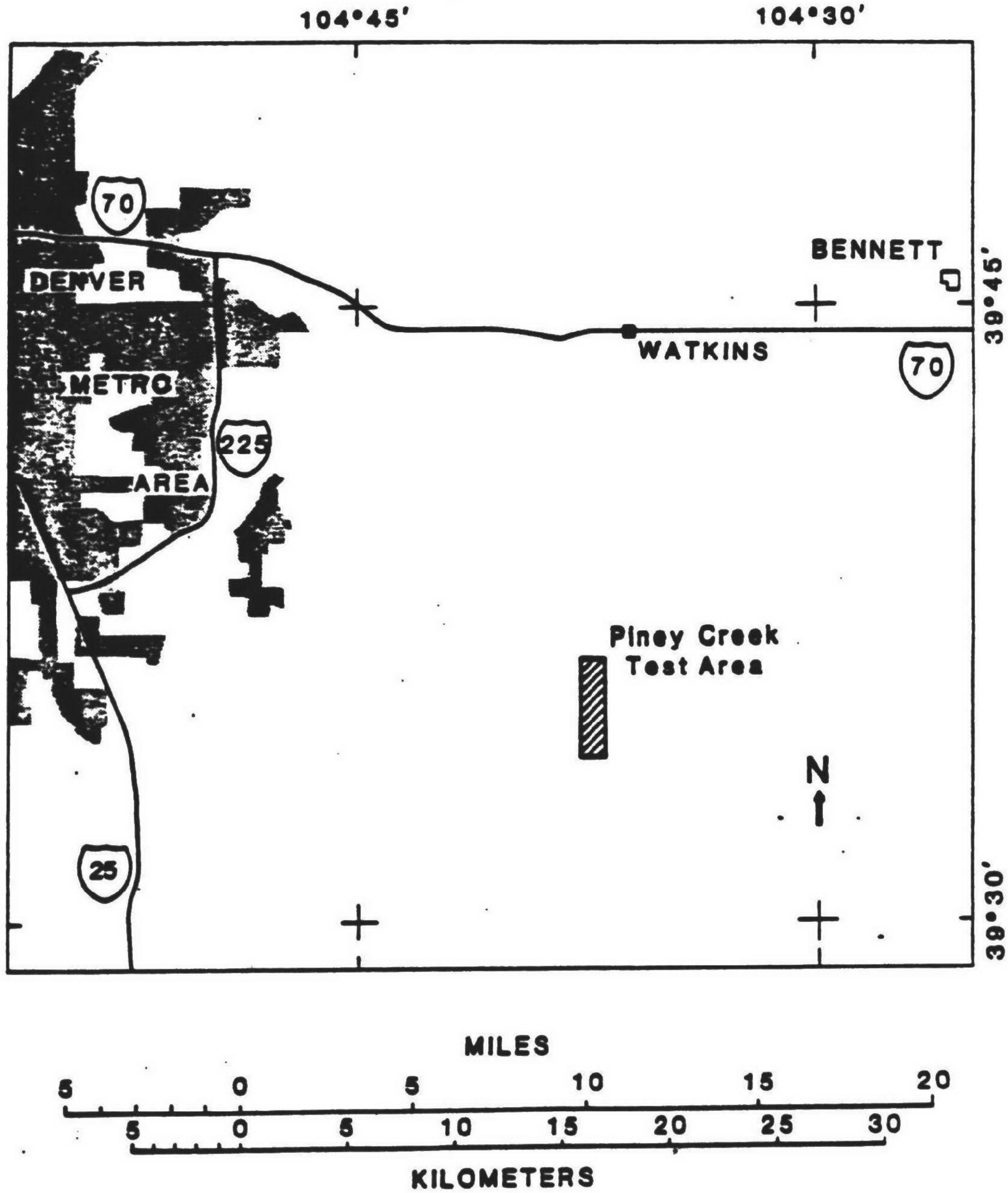

Figure 3. Location of the Piney Creek test area.

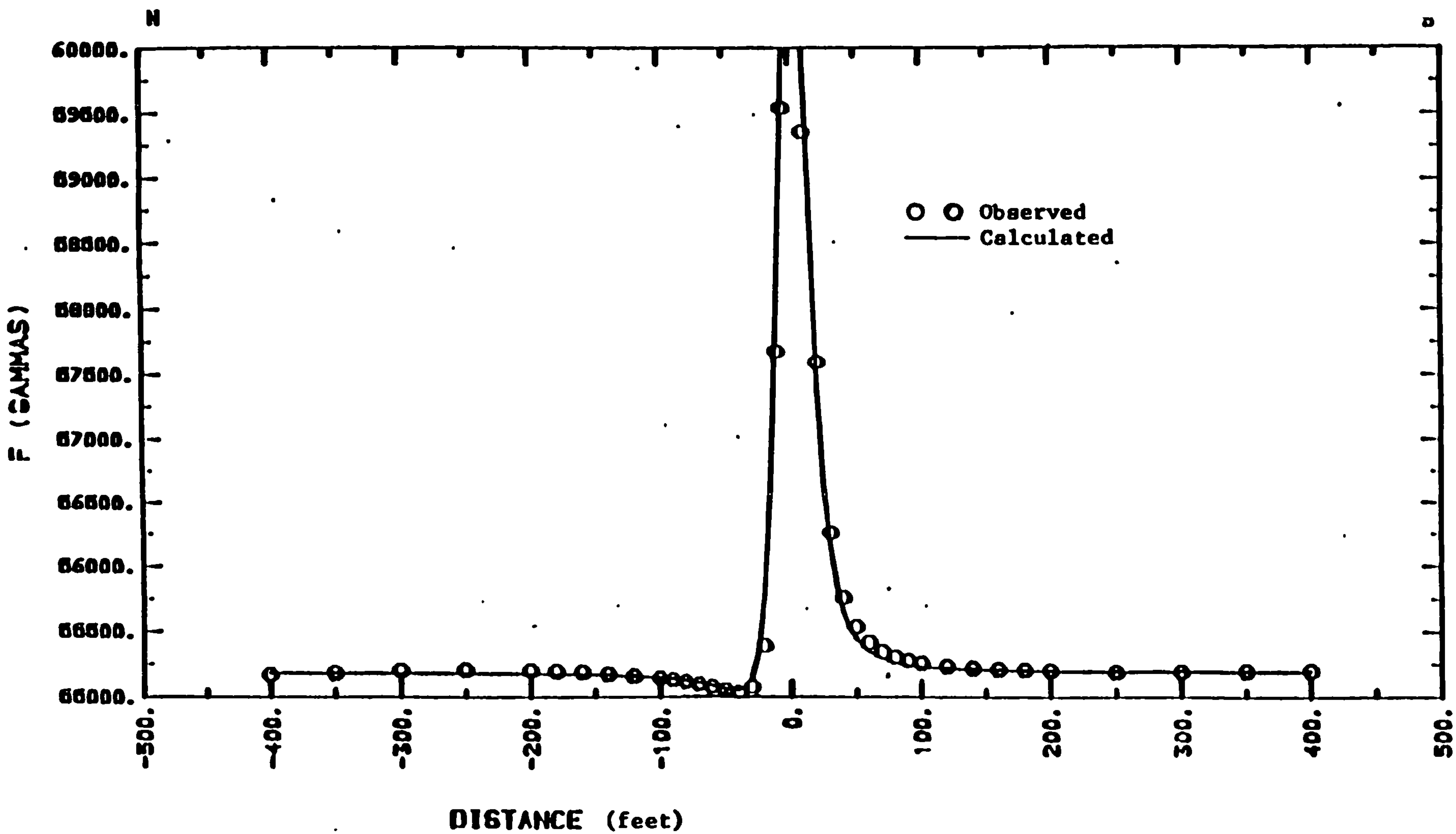

Figure 4. North-south ground magnetic profile over well no. 4.

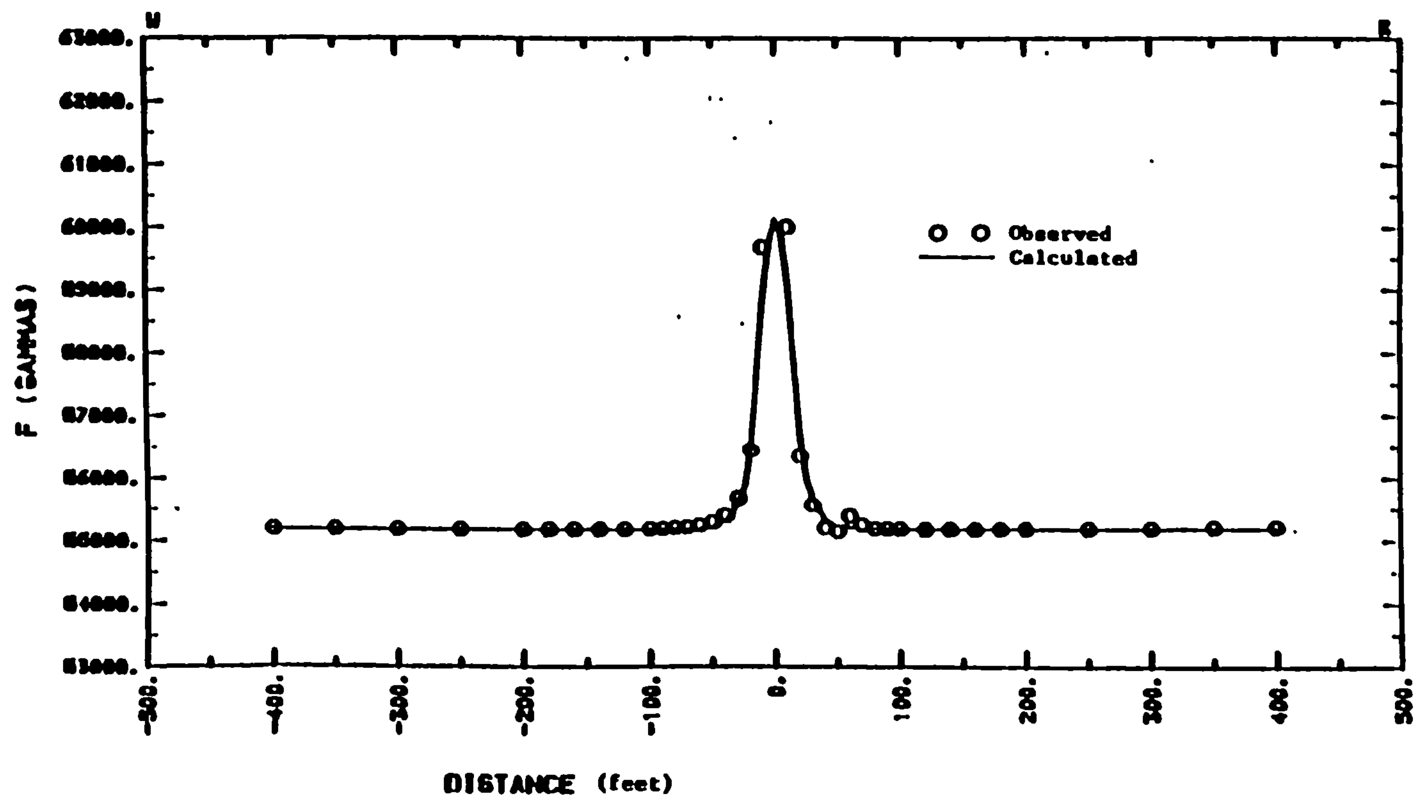

Figure 5. East-west ground magnetic profile over well No. 4.

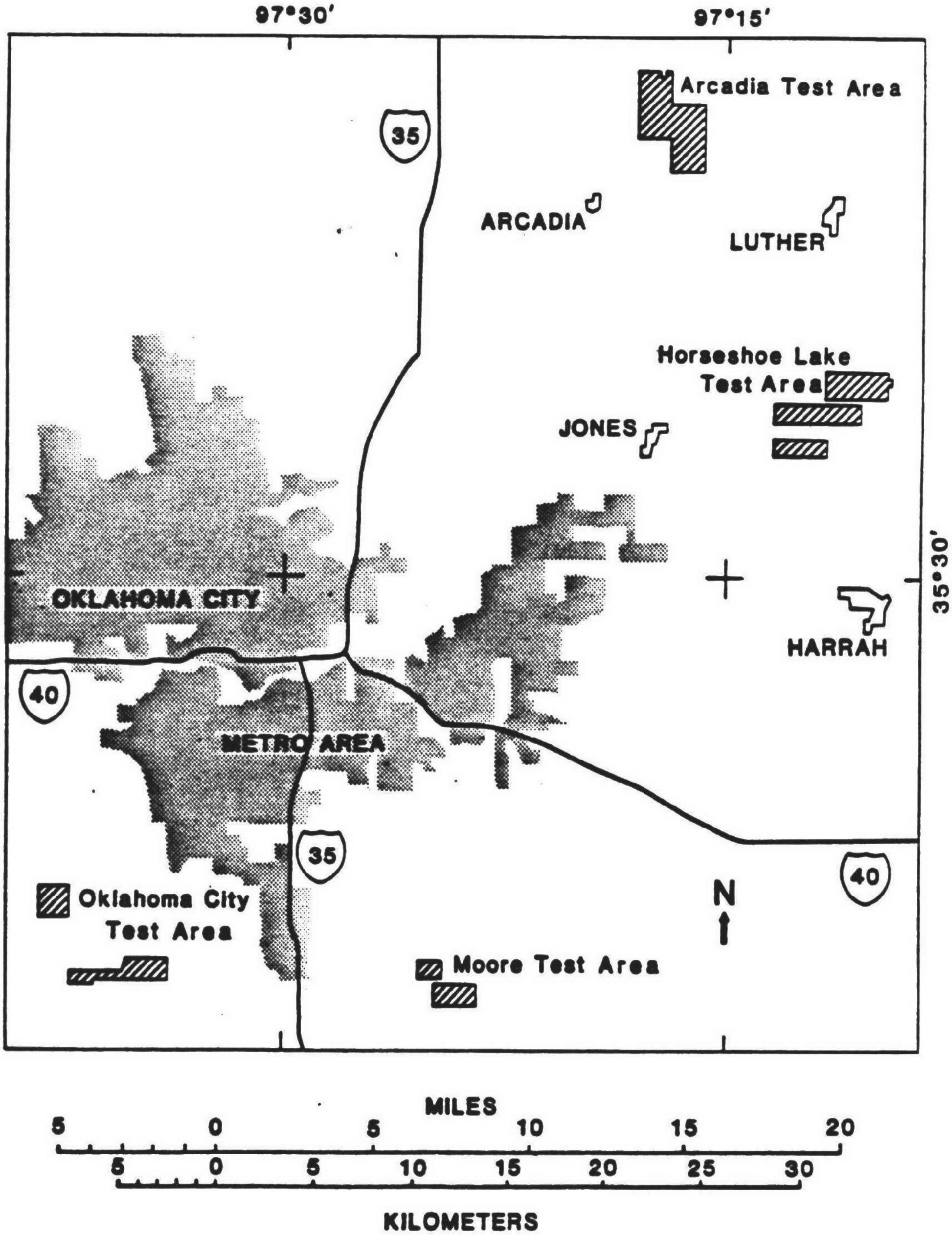

Figure 6. Location of the Oklahoma test area.

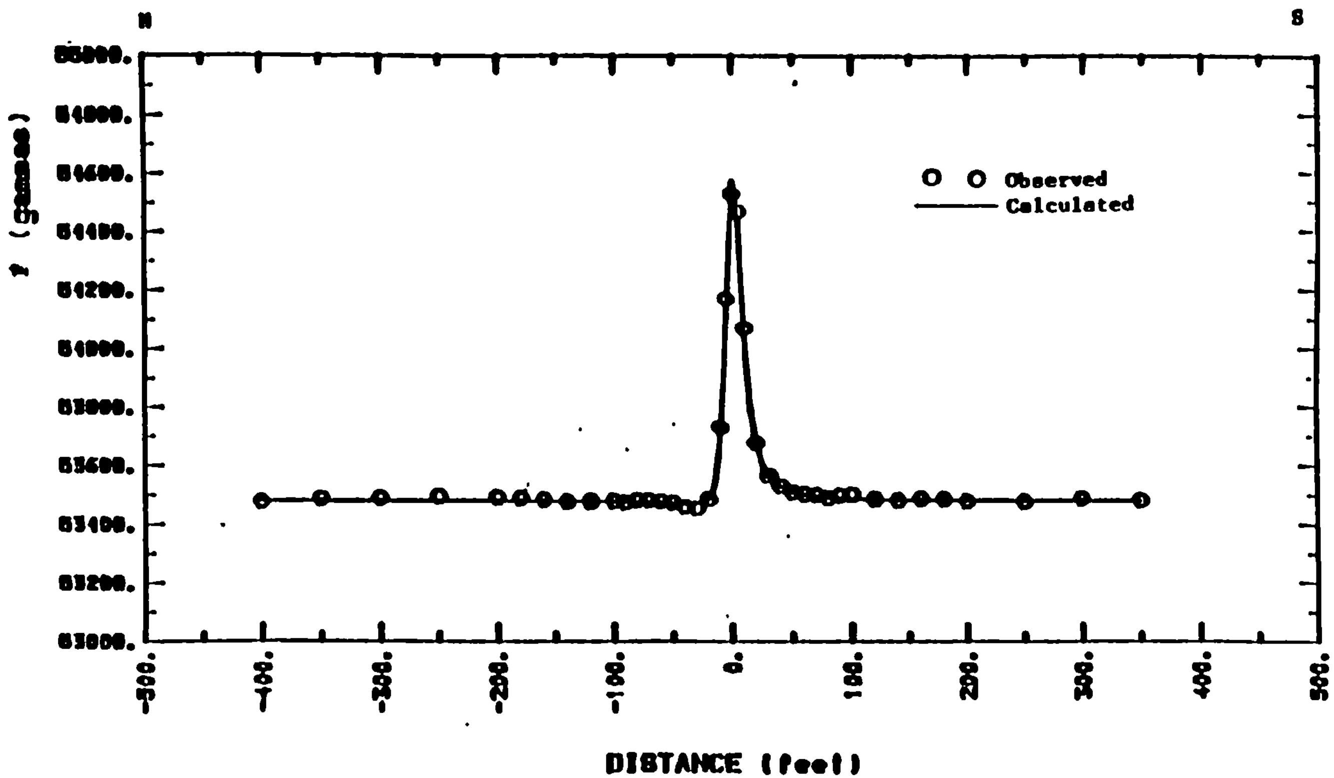

Figure 7. Observed and calculated north-south magnetic profile over well No. 17, Horseshoe Lake test area.

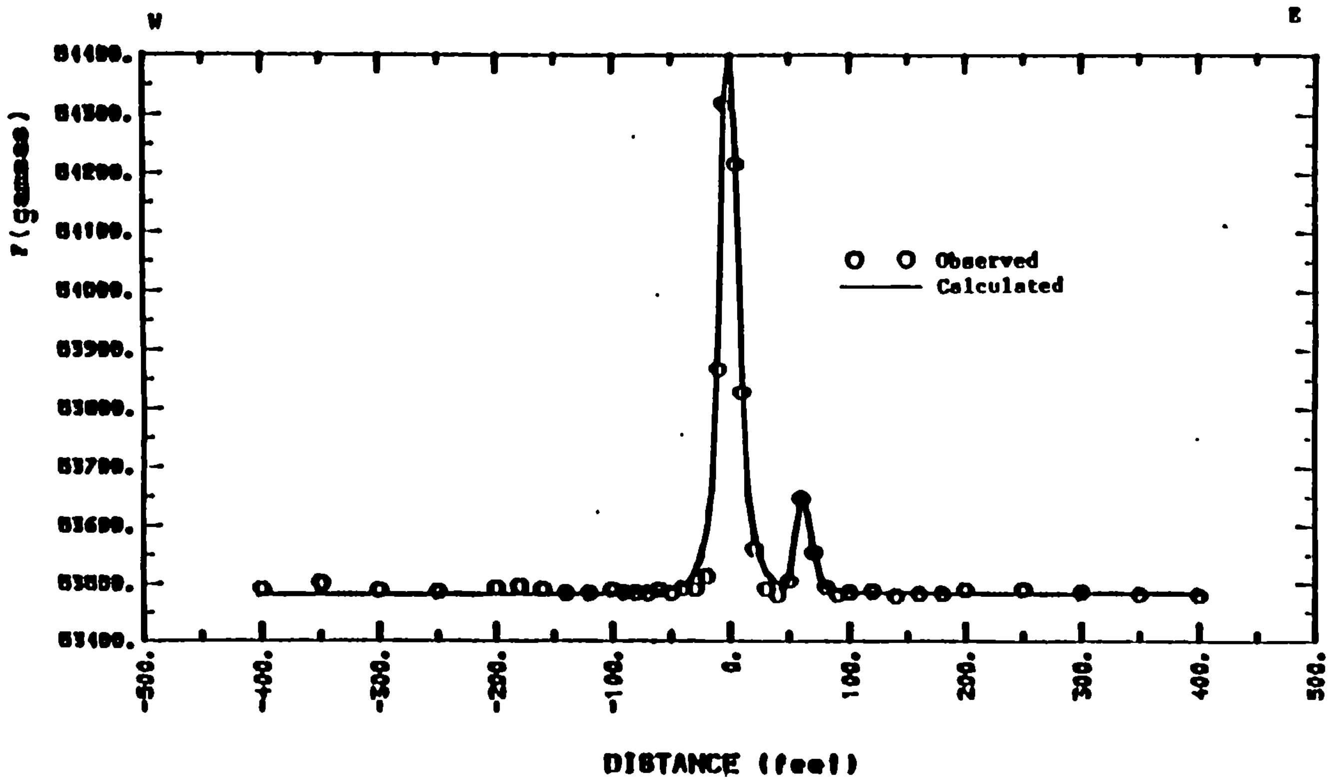

Figure 8. Observed and calculated east-west magnetic profile over well No. 17, Horseshoe Lake test area.

INVERSION OF GROUND MAGNETOMETER RESULTS AND MODELING

There is no simple and direct way to predict the results of airborne surveys from ground results. Also, it is difficult to make a qualitative comparison of the results from different wells if only the magnitude and shape of the anomaly are used. To circumvent some of these problems, a mathematical model of the well was employed. In its most simple form, this model consists of a north and a south magnetic pole separated so that they are approximately at the ends of a casing. Through a process called inversion, sets of magnetic poles which would produce essentially the same anomaly as the one observed were determined; the comparison between the observed data and the calculated data for theoretical models is illstrated in Figures 4 and 5 and 7 and 8. Using the pole strengths and distances found by inversion, it is a simple matter to compute estimates of the airborne results for various wells from their theoretical models.

Estimated airborne anomalies were calculated at various heights and horizontal distances for several Colorado wells. Total intensity as well as horizontal and vertical gradients of the total intensity as well as the total intensity were determined. When viewed in isopleth form, total intensity anomalies are almost circular in shape (Figure 9). To detect such an anomaly, one or more flight lines must pass close enough to the center of the anomaly that a detectable response is observed. The size of the anomaly which can be detected depends on: (1) the sensitivity of the magnetometer used, and (2) anomalies or "noise" due to geologic sources and cultural features other than the target. After considering the sensitivities of existing magnetometer and magnetic gradiometer systems, it appeared that the range over which a casing can be detected is greater for total intensity measurements than for gradient measurements.

From the model studies, it was decided to use a height of 61 m (200 ft) and a spacing between lines of 100 m (328 ft) for the experimental airborne surveys. The use of a greater height and line spacing would have decreased the cost of the surveys but increased the probability of not detecting wells. Use of a substantially smaller height and line spacing is impractical with a fixed wing aircraft.

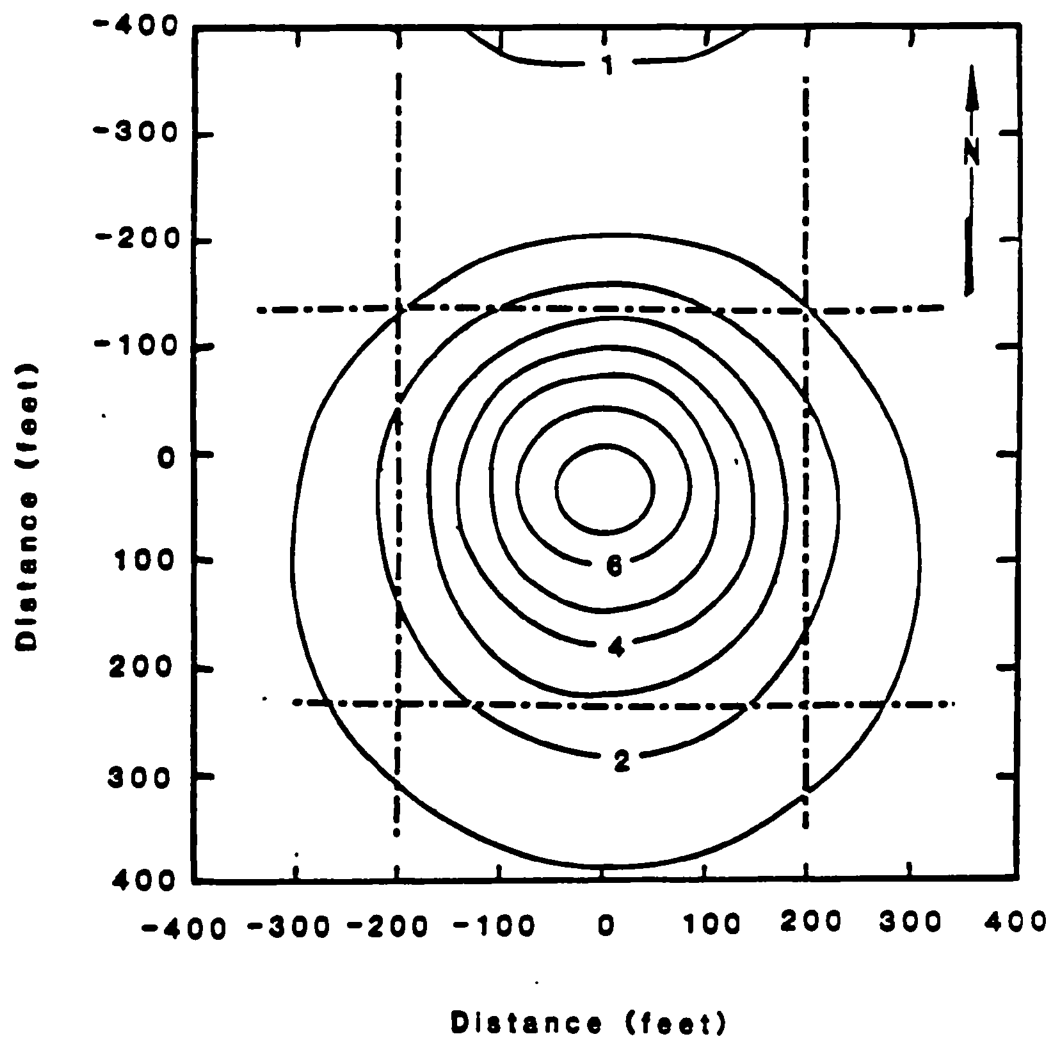

Figure 9. Calculated isopleths of total intensity (gammas) at a height of 200 feet above a well. The lines show spacing of north-south or east-west flight lines necessary to measure a two-gamma anomaly in the worst case.

AIRBORNE MAGNETIC MEASUREMENTS AND RESULTS

Airborne surveys were made in one test area near Denver, Colorado (Figure 3) and in four test areas near Oklahom City, Oklahoma (Figure 6). The aircraft used was a Fairchild Porter (Figure 10) which has a single turbine engine and is designed for short take-offs and landings (STOL). Its high rate of climb, low stalling speed, and the reliability of the turbine engine make this aircraft suitable for very low-level surveying. The main parts of the geophysical system were a high sensitivity proton magnetometer, a microwave navigation system to determine the horizontal position of the aircraft, a radar altimeter to determine the height above ground, and a data acquisition and recording system. Ancillary equipment included sensors for monitoring roll, pitch, and yaw of the aircraft and a 35-mm tracking camera. Since the anomaly from a casing can be very small, high resolution of the field was required. There are many potential sources of noise in making high resolution airborne magnetometer measurements. In particular, some of the component parts of aircraft have both induced and permanent magnetization and when the altitude of the aircraft changes the magnetic field changes at the position of the magnetometer sensor. The sensor was placed at the end of a boom or stinger attached to the tail of the USGS aircraft to remove it as far as possible from the magnetic parts. Various measures were taken to reduce the fields of the aircraft, and compensating fields were introduced to cancel the remaining fields. Nevertheless, a small amount of noise, caused chiefly by electrical currents induced in the airframe (eddy currents) when it rotates in the Earth's field, was introduced into the data. By recording the motions of the aircraft, much of this motion induced noise was later removed through computer processing. Also, there was a slight error termed "heading effect" which depended on the direction of the aircraft and which was a result of imperfect cancellation of the aircraft's field.

The principal concern in setting up the microwave navigation system was to maintain a clear, or line-of-sight, transmission path and suitable angles between the aircraft antenna and the transponders. Topographic maps were used to select tentative transponder sites, preferably in clearings on tops of hills. Final selection of the sites was made after field examination. Contacting and obtaining permission from landowners for temporary use of their land was an important but time-consuming part of this process. Once the sites were selected, land surveys were made to accurately measure the direction and distance between sites and to locate the sites relative to roads and other landmarks. The transponders, which are small, light-weight, battery-powered units, were placed on top of temporary, 9.1 m (30 ft) high, steel masts; in the areas surveyed, this generally placed the transponders above the level of nearby treetops. After completing the surveying for each area, the data were reduced and the grid for the aeromagnetic survey was planned. Each grid contained a flight line along a rural road or other straight-line landmark. This

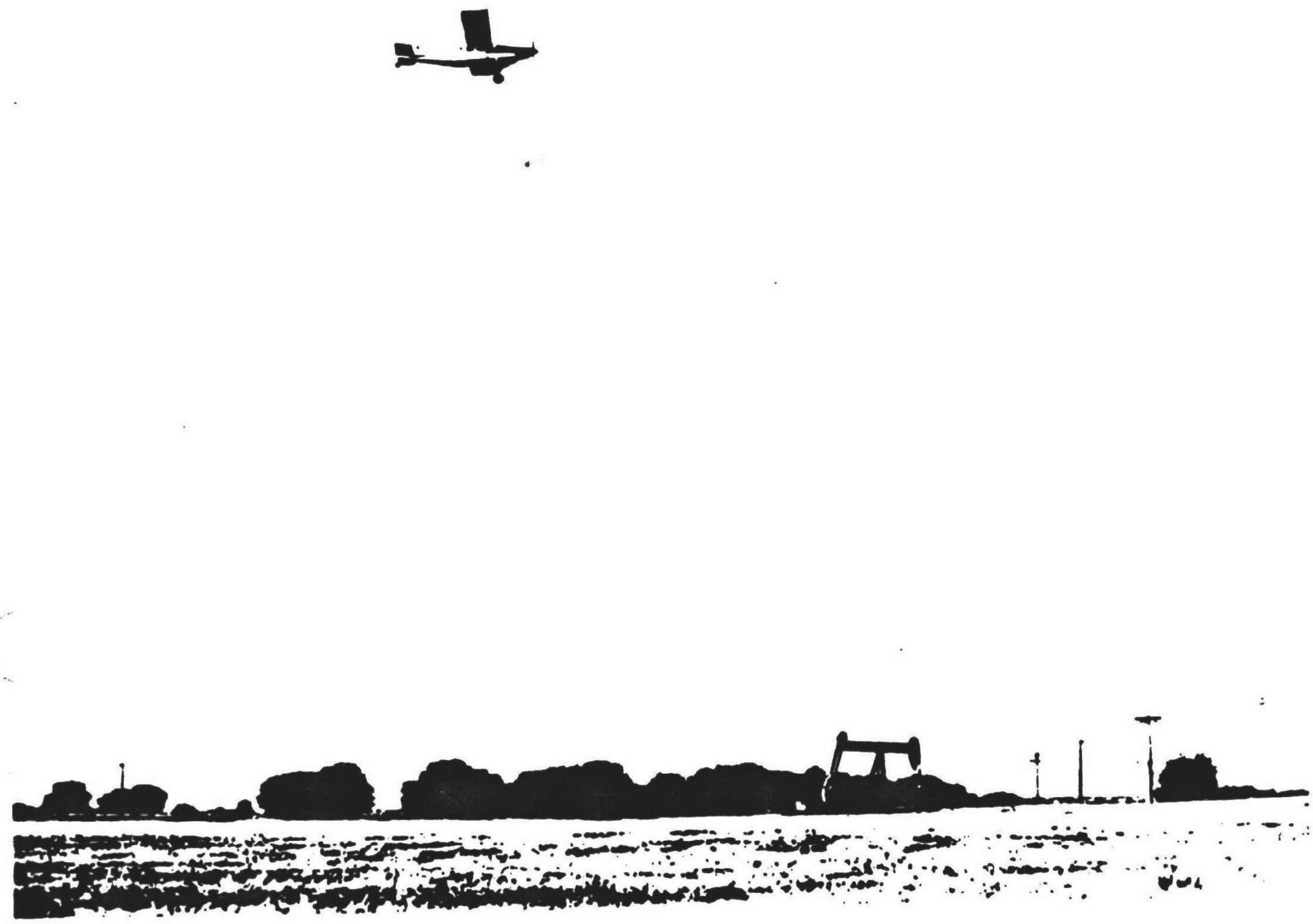

Figure 10. Fairchild Porter aircraft used in this study.

line was flown at the beginning of the survey to make certain there were no serious discrepancies between the aircraft location, as indicated by the navigation system, and the position as determined visually.

To avoid excessive turbulence, flights were made either early in the morning or late in the afternoon. The transponders were placed in operation on the preceding day or on the day of the flight and the base station magnetometer was placed at its site shortly before the flight began. In general, each area was completed during a single flight.

Several weeks before field operations began, the project was discussed with the Federal Aviation Administration's General Aviation District Office in Oklahoma City and a request to make the necessary low-level flights was submitted. Immediately before beginning flight operations, a press release describing the operations was distributed to local newspapers and radio and television stations. The primary reason for the press release at that time was to inform the public of operations by a low-flying aircraft; otherwise, aviation and law enforcement agencies might have been deluged with many reports about a low-flying aircraft.

Most of the data processing was done by a private contractor. The first step was to edit the field tapes to eliminate data taken in turns and other extraneous data. Next, the actual flight path of the aircraft was calculated from the results provided by the microwave navigation system. This was accomplished without any particular difficulty with a relative accuracy estimated at ±5 meters (±16 ft) (Frischknecht, and others, 1984). The results for each line were plotted on a map at a scale of 1:6,000 (1 cm = 60 m).

The magnetic field was corrected for diurnal variations using the tie line method. In making diurnal corrections it was necessary to consider differences in elevation between the tie lines and the traverse lines at their intersections; elevation data were available from the record of radar altimeter output. Corrections for a small amount of heading error were made simultaneously with the diurnal corrections. The average mistie error after the adjustment was 0.2 gammas. Next, the magnetic data were gridded; that is, values of the field were estimated at points spaced about 25 meters apart in both the north-south and east-west directions. The gridded data were used to prepare isopleth maps at a scale of 1:6,000 using an interval between isopleths of two gammas.

Profiles of the data along the flight lines contain much more detail than can be displayed on isopleth maps. Consequently, it was important to remove as much noise as possible from the profile data. Maneuvers were made during a calibration flight at high altitude where the magnetic field changes very gradually with distance. Analysis of this data showed that only roll maneuvers caused significant errors in the magnetometer measurements. A step-by-step procedure was used to find the relationship between roll and the sources of error due to rotation of the sensor and the induced, permanent, and eddy current fields of the aircraft. Once these relationships were established, the information from the roll sensor was used to estimate the maneuver noise. The noise, which was usually less than one gamma, was then subtracted from the magnetometer measurements and the final results, along with auxiliary information, were plotted at a scale of 1:6,000.

As an example of typical profile data from Oklahoma, part of flight line 4 for the Arcadia test area (Figure 11) is shown in Figure 12. The bottom plot, which shows the corrected magnetic field, is "folded"; that is, when the trace goes off the top of the plot it reappears at the bottom. The quantity shown in Figure 12 is the actual field less about 53,000 gammas. The traces for the radar altimeter and the barometric altimeter give the height of the aircraft above ground and above sea level, respectively. The differential roll, pitch, and heading traces give the maneuvers or motions of the aircraft in degrees. The maneuver noise correction was calculated from these maneuvers and has been used to determine the corrected magnetic field. In this example, the maneuver noise is small; in other extreme cases, it exceeds one gamma. The residual noise in the corrected magnetic profile is about 0.2 gamma or less in this example. The magnetic field peaks, numbered 37, 33, and 26, correspond to anomalies with the same numbers on the magnetic isopleth map of the area (Figure 13). The peaks, which are caused by wells, are superimposed on a small, more or less uniform magnetic feature in which the field decreases from south to north.

Aircraft flights were made over well No. 4 in the Piney Creek, Colorado, test area (Figure 14) at nominal heights of 30.5, 45.7, 61 and 76.2 m (100, 150, 200, and 250 ft) to determine how the anomaly weakens with height above the ground (Figure 15). Earlier, Frischknecht and others (1983) estimated the anomaly at these heights from the ground data in Figures 4 and 5. Well No. 4 is not an ideal selection for this study because its anomaly is distorted by variations in the magnetization of nearby rocks making it difficult to estimate the magnitude of the anomaly. However, comparison of Figure 15 with Figures 93-99 in the report by Frischknecht and others (1983) indicates that the magnitude of the anomaly was underestimated by about 21% at 29.7 m (97.5 ft) and by about 23% at 76.2 m (250 ft). Underestimation of the anomaly is not surprising since the calculated results for the model do not fit the shoulders of the observed curve (Figures 4 and 5) as well as is desirable. In any case the agreement between predicted and actual results is good. There are enough other uncertainties in the design of surveys so that an error of 23% in prediction of the size of anomalies is not important.

One of two sheets of the isopleth map for the Arcadia test area (Figure 11) is shown as an example of airborne data where there are many wells (Figure 13). The isopleth interval of the map is 2 gammas; an arbitrary value has been subtracted from the field. On this sheet, 40 distinct aeromagnetic features have been labelled. The map is dominated by these features, although there is a subtle regional trend with the field generally increasing eastward. Some of the anomalies cover a larger area than typical anomalies caused by only one well; these have multiple designations, for example 15, 15a, 15b. The following list shows the association of numbered anomalies with photographically identified wells (PIW's) (Stout and Sitton, 1983) and with the results of ground checking.

Anomaly Number	Association or Probable Source
6, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 23, 25, 26, 28, 29, 30, 32, 33, 34, 35, 36, 38, 39, 40	Associated with one PIW.

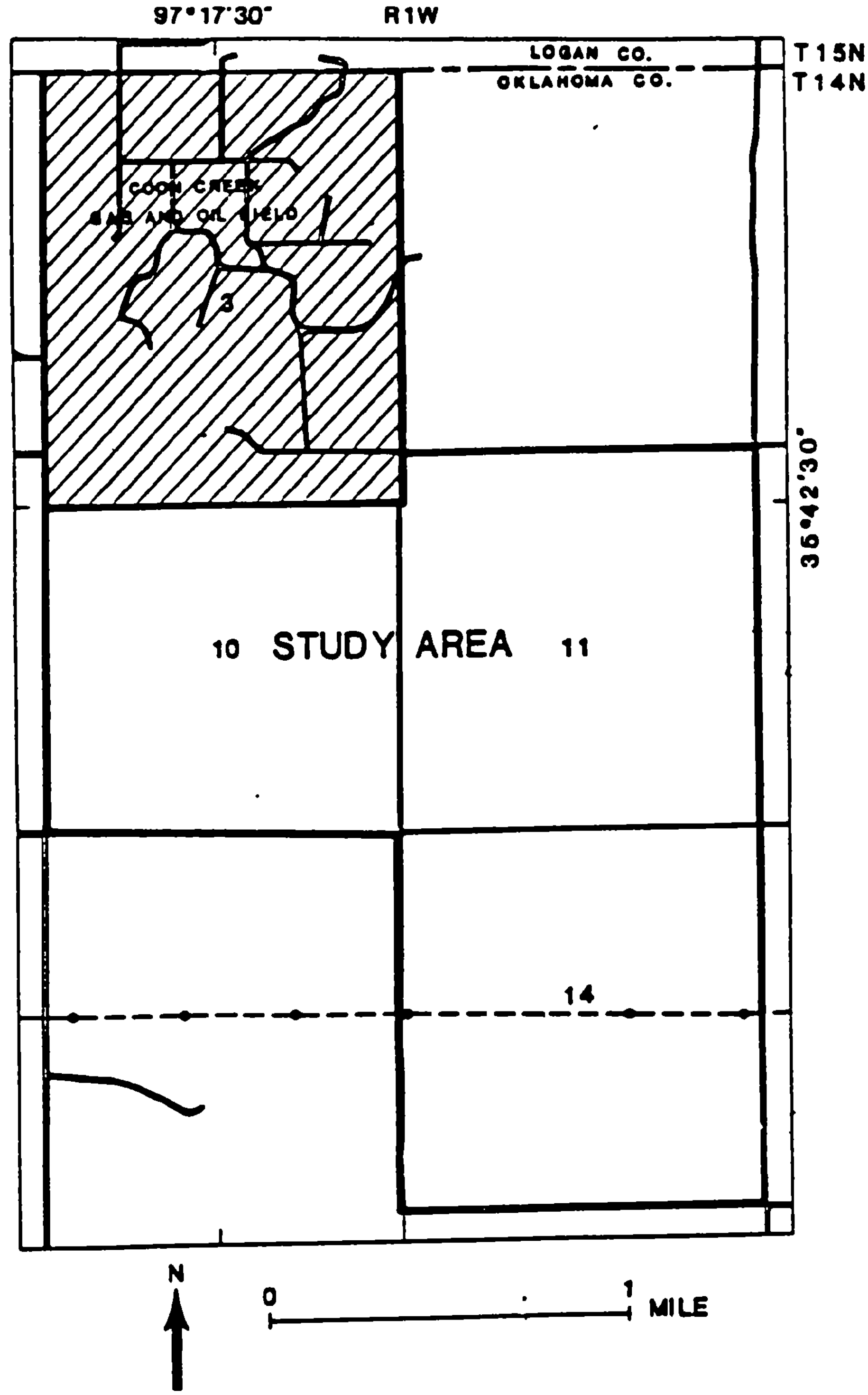

Figure 11. Map of Arcadia, Oklahoma, area, sections 3, 10, 11, and 14. The hachure pattern shows the area included in Figure 13.

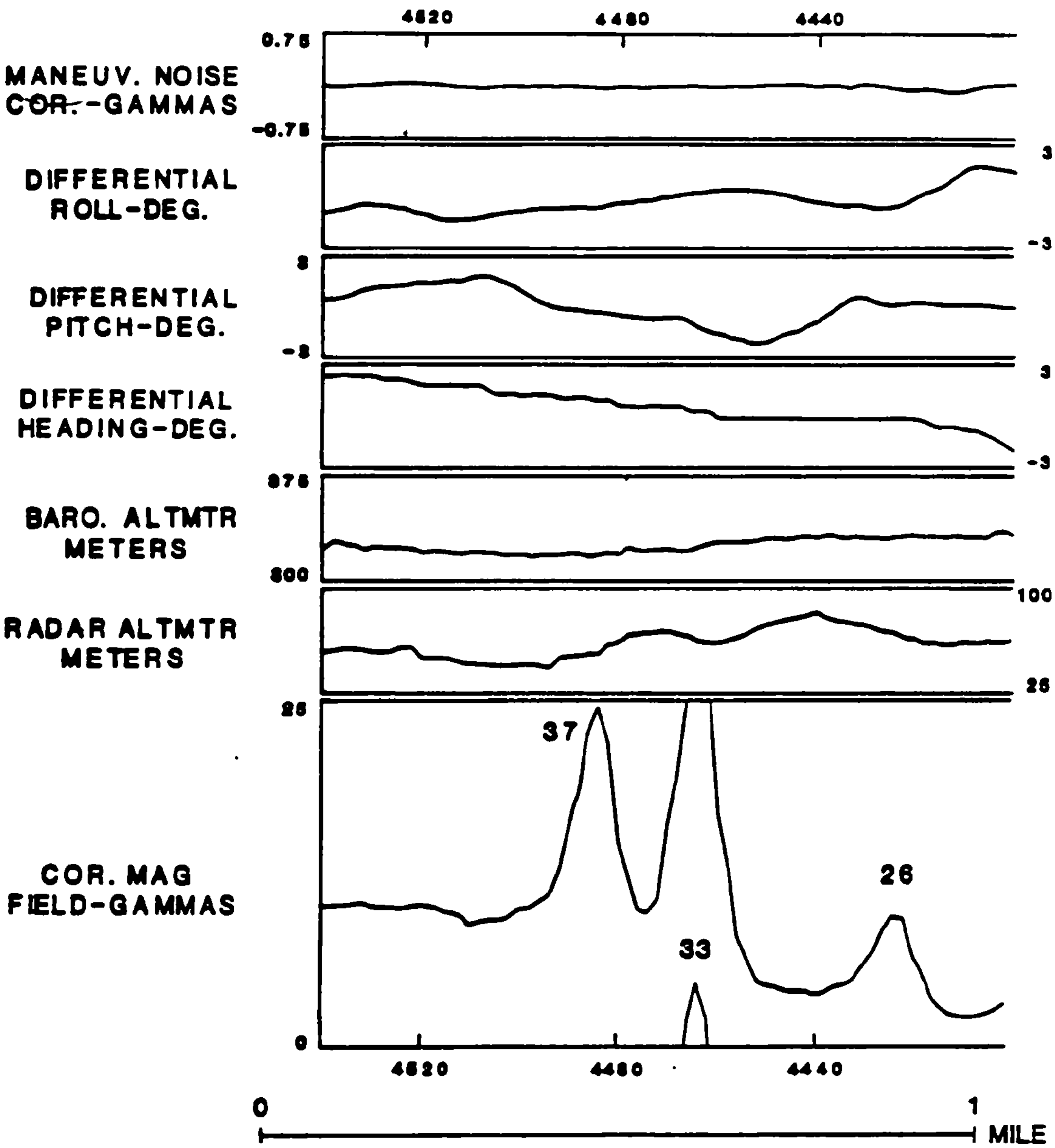

Figure 12. Airborne profile data from Arcadia area. The numbers at top and bottom are identification numbers associated with each reading, and the numbered anomalies correspond with those on Figure 13.

Figure 13. Total intensity gammas isopleth map for part of Arcadia area.

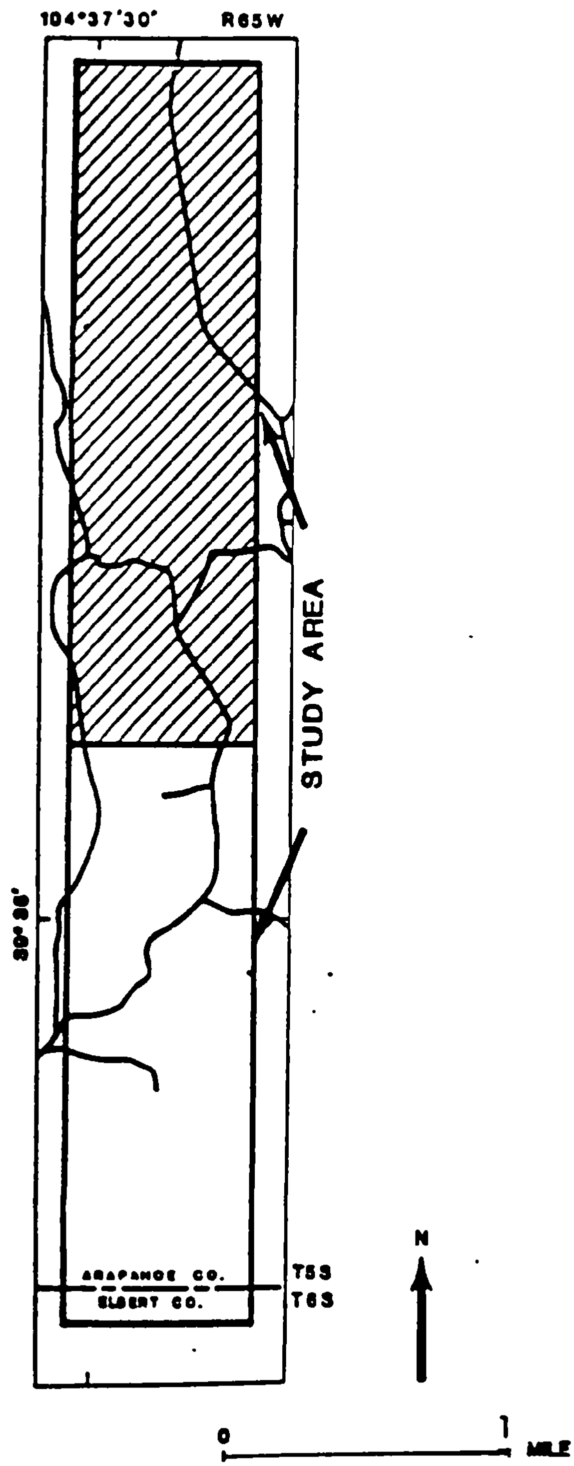

Figure 14. Map of the Piney Creek, Colorado, area. The hachure pattern shows the area included in Figure 16.

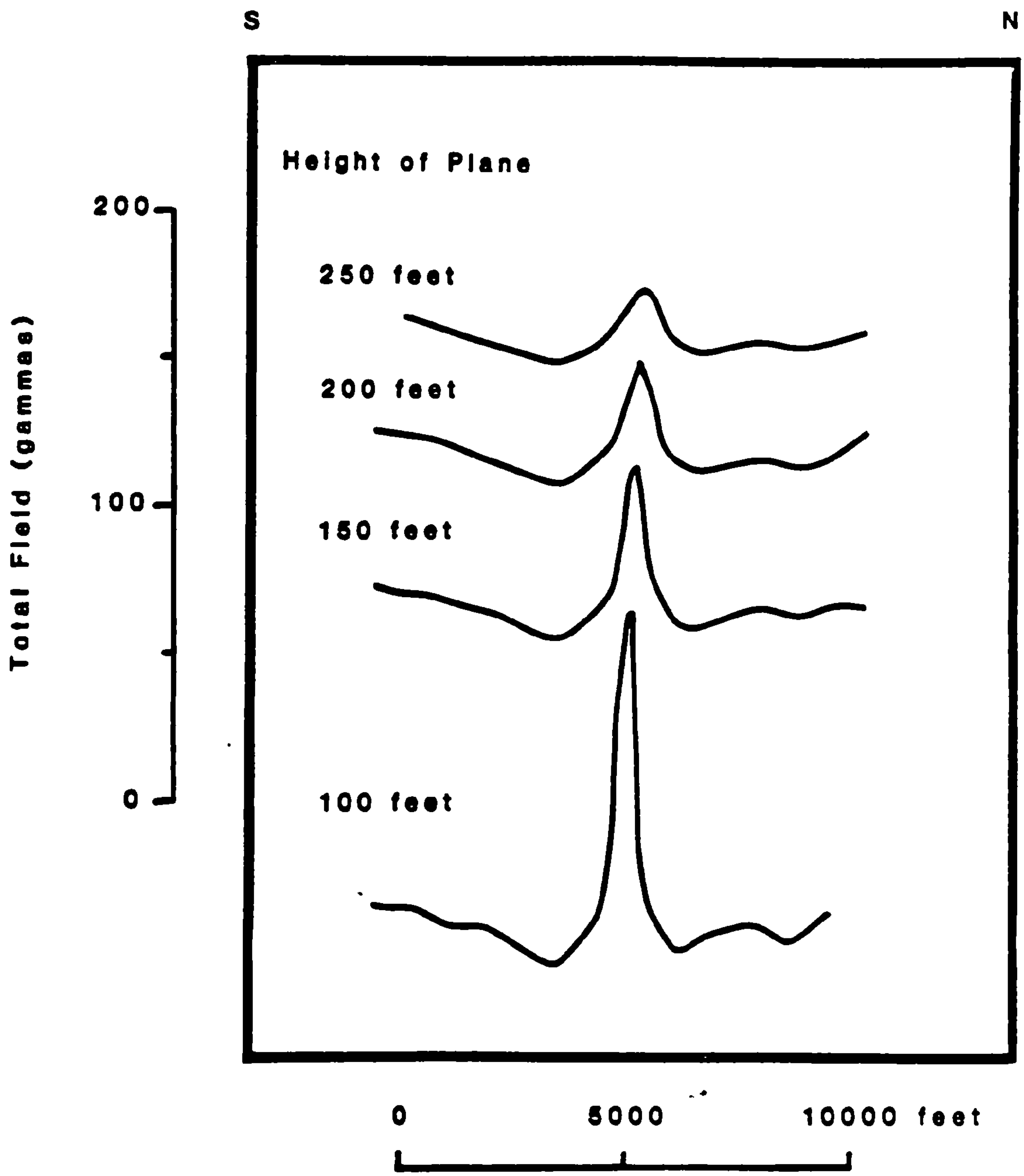

Figure 15. Aeromagnetic profiles for different aircraft heights over well No. 4, Piney Creek area.

Anomaly Number	Association or Probable Source
8-8a, 21-21a, 27, 27a, 27b	Each complex anomaly is associated with two or three PIW's.
3, 17	Outside section where photointerpretation was done; but are probably due to wells.
1, 2	Outside section where photointerpretation was done; probably due to a horizontal pipeline and perhaps a well.
4, 5	Outside section where photointerpretation was done. Anomaly 4 is associated with a well and derrick and 5 is associated with a large pipe of recent origin observed during field check.
24-24a	Anomaly 24a is associated with a PIW and 24 is associated with a feature located during field checking which may be a capped well or the terminous of a pipeline; the characteristics of the anomaly suggest a well.
31-31a	Associated with one PIW, two buildings, and a tank. The anomaly suggests that there might be another well.
19, 37	Apparently caused by wells which were not identified from photos; anomalies were not field checked.
7-7a	Apparently caused by one PIW plus tanks and other facilities.
15-15a-15b	Associated with one PIW and another well and other facilities.

There are three PIW's which are not associated with easily recognizable anomalies; they are labelled with Roman numerals. Field checking and examination of the aeromagnetic profiles yields the following information:

Well No.	Comments
I	Anomaly 15b is too far south to be caused by well I. The profile for flight line 10 shows a change in slope probably due to I but generally the aeromagnetic expression of I is masked by the large anomaly 15-15a. A distinct ground magnetic anomaly over I was observed.

Well No.	Comments
II (identified as a possible well)	Ground checking showed a cleared area and a few pieces of small pipe which produced small anomalies but no anomaly typical of a casing was found. This probably represents a site which was abandoned before a casing was placed.
III	Examination of the aeromagnetic profiles shows distinct anomalies of 5 and 4 gammas on flight lines 6 and 7, respectively; they are no doubt caused by well III but have been suppressed on the isopleth map by gridding and smoothing. The site was not field checked.

Considering only section 3 (Figure 11), which encompasses most of this sheet, 36 wells were identified from photos; one of these sites does not contain a casing. The records search by Fairchild and others (1983) identified 41 wells in section 3; Stout (oral communication, 1984) has interpreted the existence of 37 wells from a comparison of aerial photos and the original records. Magnetic contour or profile anomalies correlate with all 35 original PIW's. There are two other anomalies, 19 and 15b, which are thought, by Stout, to be wells plus two more, 24 and 31a, which may be wells. All wells for which information is available have at least 76 m (250 ft) of surface casing and many have more than 122 m (400 ft). Diameters of the surface casing are 21.9, 24.4, and 32.8 cm (8-5/8, 9-5/8, and 10-3/4 in). Part of the smaller casing, usually 14.0 or 17.8 cm (5-1/2 or 7 in) diameter, has been removed at many of the wells.

As a generalization, the density of wells is greater and the anomalies are larger and more uniform in magnitude for this area than for the rest of Arcadia and the Horseshoe Lake area. The regional trend of the Earth's field is generally steeper in some of the other areas such as Horseshoe Lake. In the Moore test area there is evidence for variations in the magnetization of the near surface rocks, but anomalies due to geologic sources are not a serious problem in interpretation of any of the Oklahoma data. The Horseshoe Lake area has fewer anomalies due to manmade (cultural) sources than Arcadia, sheet 1, but the other Oklahoma areas probably have more such features. In some cases shape and extent of anomalies was very helpful in distinguishing between those due to casings and those due to other cultural sources. Probable sources of cultural anomalies, such as transmission line towers, bends in pipelines, and steel buildings were sometimes identified from aerial photographs and topographic maps. When used, ground checks with a magnetometer usually revealed the sources of anomalies; but, in one or two instances, large ground magnetic anomalies from multiple sources such as tanks, pipelines, and steel buildings may have masked a weak anomaly from a casing.

In the Piney Creek, Colorado, test area (Figure 14) there are many sharp anomalies which are due to variations in the magnetization of the near-surface rocks (Figure 16). Some of these anomalies have the same appearance as anomalies caused by casings. Study of the airborne profiles was helpful but not always definitive in determining the source of the anomalies. A considerable amount of ground checking was necessary in this area to distinguish between

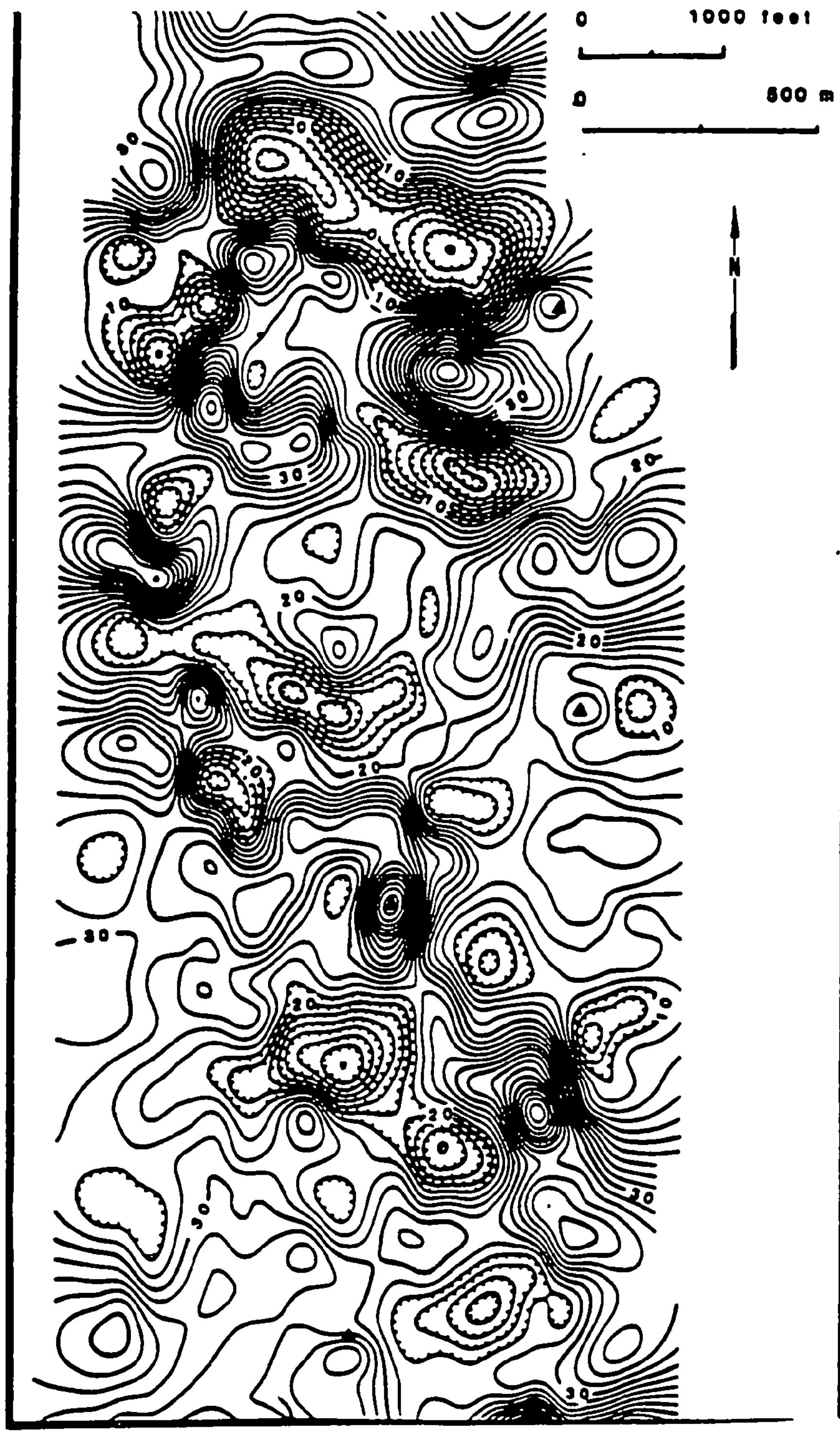

Figure 16. Total intensity gamma isopleth map for part of Piney Creek area. Triangles indicate locations of known wells.

anomalies caused by casings and those caused by geologic sources; the geologic anomalies are not a serious problem in interpreting ground magnetometer results. The airborne method would be somewhat more effective in an area such as this if the flight height and line spacing were decreased.

Considering all four test areas in Oklahoma, there is good agreement between the results from the magnetic surveys and those from photointerpretation. Most PIW's produce aeromagnetic anomalies and most magnetic anomalies which are not due to other obvious cultural sources are associated with PIW's. Following are three categories of exceptions to this generalization:

Category 1: PIW's that are isolated from other wells or other sources of anomalies, and that produce no aeromagnetic anomaly.

Category 2: PIW's which may produce weak anomalies but which are located so close to the source of a strong anomaly that the weak anomaly is masked by the strong anomaly.

Category 3: Aeromagnetic anomalies not associated with PIW's where ground checking has indicated a casing type anomaly and also, in some cases, physical evidence of a well.

A summary of the numbers of these three categories of PIW's and anomalies follows:

Area	Category 1. PIW's Isolated From Other Sources	Category 2. PIW's Near Other Sources	Categroy 3. Casing Type Anomalies Without PIW
Arcadia	2- one was checked and has no ground magnetic anomaly	2	6
Horseshoe Lake	3- two were checked and have no ground magnetic anomaly	2	7
Moore	2- both were checked and have no ground magnetic anomaly	1	4
Oklahoma City	0	1	1

Caution must be used in evaluating the overall significance of category 3 anomalies; there would, no doubt, have been many more had all of the aeromagnetic anomalies been ground checked. However, according to Stout (oral communication, 1983, there is weak or inconclusive evidence in aerial photographs for the existence of wells associated with some of the anomalies in category 3. Most of the PIW's in category 1 were identified as possible wells or dry holes, and some of them probably represent sites which were prepared for drilling but where casing was either never emplaced or has been removed.

In some cases specific PIW's and magnetic anomalies were correlated with particular wells listed in the records search. Generally, there was some difficulty in establishing one-to-one correspondence between the data sets because the locations given in the records are not sufficiently accurate and because of other problems with the records. However, comparisons were made between the total numbers of wells found in each section from the records and the probable number of wells found from photointerpretation and magnetic surveys. With the exception of one section in the Horseshoe Lake area, the number of wells which were photographically identified and which have magnetic anomalies is generally less than the number found from the records. However, in all Oklahoma areas except Moore, the total number of magnetic anomalies which may be caused by casings equals or exceeds the number of wells found from the records.

In the Piney Creek, Colorado, test area there are 17 wells which are known from records or from ground magnetic measurements or visual evidence. Two of these did not cause recognizable aeromagnetic anomalies. A weak anomaly from one of these wells is probably obscured by a strong anomaly of geologic origin; there is no apparent reason for the failure to detect the other well. In the Piney Creek area there are a number of anomalies which look like they could be caused by wells but which are not associated with known wells. Several of these anomalies were ground checked but no casings were found.

Due to the limitations of the other data sets the exact number of wells within the areas covered by the aeromagnetic surveys is unknown. However, from the evidence we concluded:

1. Considering all five test areas, aeromagnetic anomalies are probably associated with 95-98 percent of the wells.

2. More wells were detected by the aeromagnetic surveys than by the initial photointerpretation.

3. More features which are not wells were identified as possibly being wells from the aeromagnetic data than from the photograph evidence.

The anomalies over most wells in the Oklahoma test areas were much larger than required to be easily recognizable; typically, anomalies over the wells in Colorado were smaller. In general, the magnitude of the anomalies depends on the amount and size of the casings, but there are many exceptions to this rule. A few wells in both regions, which according to the records should have enough casing to produce substantial anomalies, produced only weak anomalies. The reasons for this are not known; the records may be inaccurate, the properties of the steel may be different from the norm, or the casings may have been selectively corroded away. Anomalies due to sources in near-surface rocks cause difficulty in interpretation of the Colorado data, but they are only a minor problem in interpretation of the Oklahoma results. Anomalies of cultural origin are present in all test areas, but usually they are easily recognized. We conclude that most wells containing on the order of 60 m (200 ft) or more of

21.9 cm (8-5/8 in) diameter or larger surface casing can be detected by airborne measurements. Much smaller amounts of pipe can be found with a ground magnetometer; however, very closely spaced measurements are then required.

ELECTRICAL MEASUREMENTS AND RESULTS

Electromagnetic measurements using two different instruments with loop sources showed no indication of wells (Frischknecht and others, 1983). Dipole-dipole resistivity/IP measurements made near well No. 2 in the Piney Creek, Colorado, test area showed little indication of the casing (Washburne, J., 1984); this was somewhat surprising since theory (Holladay and West, 1984) and experience in industry indicate that casings often cause resistivity or IP anomalies at distances which may be greater than the detection ranges for ground magnetometer surveys.

SP measurements were made in the vicinity of 11 wells using a fixed base electrode and a roving electrode of lead-lead chloride construction. Distinct and fairly large anomalies were found in the vicinity of four of the wells. Small anomalies were observed in the vicinity of most of the other wells. As an example, the results obtained near well No. 7 in the Piney Creek, Colorado, area are shown in Figure 17. A distinct but rather narrow anomaly occurs directly over the well. However, the profiles show a number of other small anomalies of unknown origin. Such anomalies would cause difficulty in the interpretation of SP results when searching for concealed wells. The SP method might be useful to a limited extent in verification of the presence of suspected wells.

Electrical methods are generally more expensive and more cumbersome to use than magnetic methods. From this limited study of electrical methods it appears that they are not nearly as reliable as magnetic methods in locating casings.

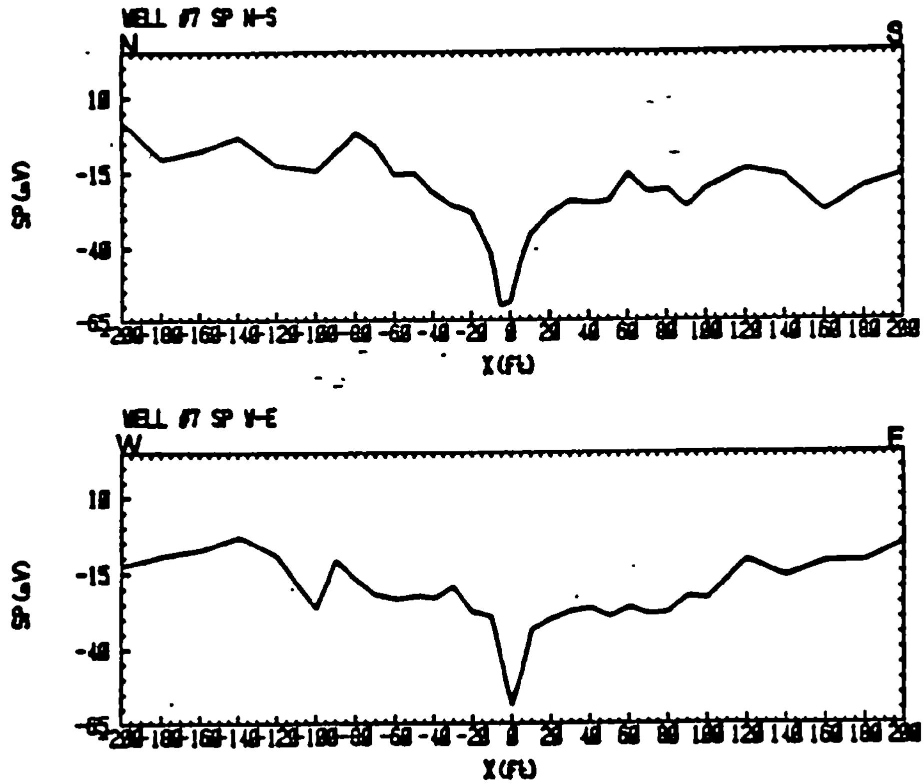

Figure 17. Self-potential profiles over well No. 7, Piney Creek, Colorado, area.

PLANNING AND MANAGEMENT OF GEOPHYSICAL INVESTIGATIONS FOR LOCATING ABONDONED WELLS

The possibility of using geophysical methods should be considered whenever there is a need to search for abandoned wells. Unless the problems are very unusual, the magnetic method is the only geophysical method which should be considered. Depending on the problem, there are several different ways and levels at which magnetic methods should be applied, including:

1. In some cases there may be a need to confirm the existence of a casing or to pinpoint the location of a known but concealed well. If the search area is only a few acres, a casing may be identified and located very accurately by a rapid and inexpensive ground magnetometer survey. An experienced person can make the measurements and interpret the results immediately in the field. Less experienced technicians can make the field measurements and plot the data for later interpretation by an experienced person. An organization which has considerable need for this type of work should probably develop an "in-house" capability.

2. In some cases, such as in searching an area of review around a site for a proposed injection well, it may be appropriate to use the ground magnetometer to systematically search for wells. If access to the property is not a problem, ground surveys generally will be cheaper than airborne surveys for areas of a few square kilometers or less. We recommend that such surveys be designed and progress and results be evaluated by a competent geophysicist or by someone else who has been properly trained and has had experience in doing this kind of work.

3. Airborne magnetic methods are more cost effective than ground magnetic methods for surveys of areas greater than several square kilometers or for surveys of several smaller areas in the same general area. However, if access to the property is difficult or impossible, it may also be worthwhile to use an aircraft for a small area. A specialist should design the survey, monitor data acquisition and processing, and evaluate the interpretation of the results.

To locate or verify the existence of suspected casings, very little equipment is required. A proton magnetometer with a sensitivity of one gamma is adequate; solid state memory is not required because it will not be necessary to record very many readings. If aerial photographs or very detailed maps are not available to locate the site, some sort of surveying aids are necessary. If the site is not far from a known landmark, a compass and a hip (thread) chain or other simple means of measuring distances can be used. If the site is several hundred meters from a known landmark, it may be necessary to use more accurate surveying instruments. The personnel performing the work should have some knowledge of surveying practices and should be experienced in using aerial photographs or surveying equipment, as required. The necessary skills to operate the magnetometer can be learned from reading instrument manuals and textbooks, supplemented by a brief period of working with someone with more formal training and experience.

To carry out systematic ground surveys on a preplanned grid to detect and locate abandoned wells, the use of a magnetometer with a memory is recommended. This will increase the rate of progress and decrease the likelihood of recording data incorrectly. At a minimum, a suitable interface and a printer or a microcomputer with printer are needed to copy the contents of the magnetometer memory and make a permanent record of the data. Preferably a microcomputer with a disk or tape drive to store the data and a plotter to present the data in graphical form should be used. As in checking sites, if the survey lines are relatively short, they can be established with a compass and hip chain. If the lines are more than a few hundred meters long, it will probably be necessary to use a theodolite or other more accurate means of establishing directions. Persons without previous geophysical experience can be trained to make the measurements and process the data. However, we recommend that a competent geophysicist design the survey, periodically monitor the work, and review the interpretation of the results. There are potential pitfalls and problems, even in "routine" work, and assistance from a geophysicist is likely to increase the cost-effectiveness of the work.

The necessary equipment for airborne surveys is considerably more complex than that required for ground surveys. The aircraft can be either fixed-wing or rotary-wing. Federal Aviation Administration requirements are less stringent for rotary-wing than for fixed-wing aircraft in operating over populated areas. However, hourly costs for operating a small fixed-wing aircraft are usually much less than for operating a rotary-wing aircraft. The magnetometer should have a sensitivity better than one gamma and should take readings at a rate of about two per second or faster. Considerable care must be taken to properly install the magnetometer in the aircraft. If a fixed-wing aircraft is employed, the fields of the aircraft must be properly reduced and compensated and maneuvers should be monitored. If a helicopter is used, the sensor can be towed beneath the aircraft to remove it from the influence of the helicopter.

In terrain where there are many landmarks, it may be possible to navigate a helicopter visually and to recover the flight path adequately with a tracking camera. If there are not enough good landmarks or if a fixed-wing aircraft is used, it will be necessary to use an electronics navigation system for pilot guidance and recovery of the flight path. Under ideal circumstances, this might be a system such as Doppler radar or Loran C, which does not require local transponders; but, in most cases it will probably be advisable to use a microwave, transponder based, system. A radar altimeter is necessary for pilot guidance and to furnish a record of the vertical position of the aircraft. A means for formatting the information from all of the sensors and storing it on magnetic tapes or disks is required and substantial computer capability is necessary to process and display the data after it is collected.

Only well trained and experienced specialists should attempt to carry out aeromagnetic surveys. An experienced interpreter should review the results of the interpretation. In most cases it will be desirable or necessary to ground check some of the aeromagnetic results before a final interpretation is made.

While the results obtained in this study should be useful in planning surveys in other areas, specific information on each new area should be obtained, if possible. The most important questions are:

1. What size anomalies are expected from wells in the area? This question may be answered by making measurements near a few known wells, provided those wells are representative of others in the area. If this is not possible, rough estimates of the expected anomalies can be made from the length and size of the casing in typical wells, provided this information is available from records.

2. Will anomalies due to geologic sources interfere with recognition of anomalies due to casings? This question may be addressed by study of existing geologic and magnetic maps of the area and by making a few ground magnetic traverses.

3. Will anomalies due to cultural sources interfere with interpretation of the results? Most manmade objects which may cause interference can be recognized by inspection of the area from roads or from an aircraft and from a study of aerial photographs and maps.

Selection of persons and organizations to provide needed technical advice and services is critical particularly if airborne surveys are to be made. Surveys which are not adequately designed and carried out will not be effective. On the other hand, a survey can be overdesigned and implemented in such a fashion that, although effective, it costs much more than necessary. Great caution should be exercised in dealing with anyone who is marketing a radically new device or method, particularly if the principles of the device or method must be kept secret.

It is common practice for petroleum and mining companies to obtain needed geophysical data from geophysical contractors and to maintain a staff of geophysicists who design surveys, manage contracts, and interpret the results. Companies who do not have an inhouse staff often rely on consultants or consulting firms for managing their contracts and interpreting survey results. Some geophysical contracting companies have the capability to design surveys and interpret the results as well as to conduct surveys.

Unless the agency or company requiring geophysical services has had previous experience with geophysics, we recommend the use of a consultant, at least initially. The consultant(s) should be trained and experienced in geophysics. Engineers or physicists usually are untrained in geology and they may make mistakes by ignoring geological conditions or by misinterpreting them. Geologists often lack training in geophysics and physics and they may make mistakes regarding physical aspects of the problem. Most geophysicists have had adequate training and experience to deal with any problems encountered in making ground magnetic surveys. However, few geophysicists have had the necessary experience to enable them to critically monitor and evaluate the acquisition and processing of high resolution aeromagnetic data. The qualifications and experience of prospective consultants and contractors should be carefully considered. If possible, evaluations of the contractors' previous performance should be obtained from other clients.

Lists of consultants, consulting companies, service companies, instrument manufacturers, and companies which use geophysical services are published annually in The Geophysical Directory by the Geophysical Directory, Inc., P.O. Box 13508, Houston, Texas 77219, and in The Leading Edge. Advertisements for geophysical services, consultants, and equipment and professional directories are carried in several journals, generally available in technical libraries, including:

Geophysics

The Leading Edge

Geophysical Prospecting

First Break

Mining Engineering

Geotimes

The Departments of Earth science or geology and geophysics at many universities are potential sources of advice and help. Faculty members may be available for consulting; advanced students may be available in the summer to carry out and interpret ground magnetometer surveys.

We suggest that the technical personnel who are responsible for the design and conduct of geophysical surveys and the interpretation of the results should consult the USGS open-file reports by Frischknecht and others (1983, 1984).

Public agencies that have a need to locate wells may, in some cases, be able to obtain help from other public agencies. Several states have agencies concerned with natural resources and geology which have expertise in geophysics. Several Federal agencies, including the U.S. Geological Survey and the Bureau of Mines, have programs in geophysics. In some cases there may be a possibility for cooperative work between agencies.

REFERENCES

Breiner, S., 1973, Applications manual for portable magnetometers: Geometrics, Palo Alto, Ca., 58 p.

Donovan, T. J., R. L. Forgey, and A. A. Roberts, 1979, Aeromagnetic detection of diagenetic magnetite over oil fields: American Association of Pet. Geologist Bull., V. 63, No. 2, p. 245-248.

Emerson, D. W., and others, 1979, Applied interpretation symposium open session: Bull. Aust. Soc. of Expl. Geoph., V. 10, No. 1, p. 120-136.

Fabiano, E. B., N. W. Peddie, D. R. Barraclough, and A. K. Zunde, 1983, International Geomagnetic Reference Field 1980 - Charts and Grid Values (IAGA Bulletin No. 47): U.S. Geological Survey Circular 873, 142 p.

Fairchild, D. M., C. M. Hull, and L. W. Canter, 1983, Selection of flight paths for magnetometer survey of wells: University of Oklahoma, 264 p.

Federal Register, 1979, Proposed Rules--Notices: Federal Register, V. 44, No. 78, p. 23738, 23744, 23746, 23754, 23755.

Frischknecht, F. C., L. Muth, R. Grette, T. Buckley, and B. Kornegay, 1983, Geophysical methods for locating abandoned wells: U.S. Geological Survey Open-File Report No. 83-702, 54 p., 151 figs.

Frischknecht, F. C., P. V. Raab, R. Grette, and J. Meredith, 1984, Aeromagnetic surveys for locating abandoned wells: U.S. Geological Survey unpublished report.

Hildenbrand, T. G., 1982, Models of the southeastern margin of the Mississippi Valley graben near Memphis, Tennessee from interpretation of truck-magnetometer data: Geology, V. 10, p. 476-480.

Holladay, J. S., and G. F. West, 1984, Effect of well casings on surface electrical surveys: Geophysics, V. 49, No. 2, p. 177-188.

Hood, P. J., M. T. Holroyd, and P. H. McGrath, 1979, Magnetic methods applied to base metal exploration: Geol. Sur. of Canada Econ. Geol. Rep. 31, p. 77-104.

Johnston, K. H., H. B. Carroll, R. J. Heemstra, and F. E. Armstrong, 1973, How to find abandoned oil and gas wells: U.S. Bureau of Mines Information Circular 8578, 46 p.

Keller, G. V., and F. C. Frischknecht, 1966, Electrical methods in geophysical prospecting: New York, Pergamon Press, 519 p.

Nelson, P. H., 1977, Induced-polarization effects from grounded structures: Geophysics, V. 42, No. 6, p. 1241-1253.

Nettleton, L. L., 1976, Gravity and magnetics in oil prospecting: New York, McGraw-Hill, 464 p.

Parasnis, D. S., 1975, Mining Geophysics (2nd ed.): New York, Elsevier, 395 p.

Stout, K. and M. Sitton, 1983, Abandoned well study Oklahoma and Cleveland counties Oklahoma: Report no. TS-PIL-83051, U.S. Environmental Protection Agency.

Telford, W. M., L. P. Geldart, R. E. Sheriff, and D. A. Keys, 1976, Applied Geophysics, New York, Cambridge University Press, 860 p.

Time Magazine, 1984, Big stink, scandal over "sniffer planes": Time Magazine, V. 123, No. 5, p. 27.

Wait, J. R., 1982, Geoelectromagnetism, New York, Academic Press, 268 p.

Washburne, J., 1984, Well casing study for U. S. Geological Survey: Phoenix Geophysics unpublished report.

APPENDIX

COSTS FOR GEOPHYSICAL EQUIPMENT AND SERVICES

The cost of the equipment necessary for making ground magnetic surveys is relatively modest whereas a complete airborne system is expensive. The following information was compiled from the winter 1984 price lists of three of several manufacturers of magnetometers; we did not consider all models or the several options that are available in some models. Prices for other equipment are nominal and could vary considerably.

Epuipment	Cost
Proton field magnetometer--1-gamma sensitivity no memory	$3,300-4,000
Proton field magnetometer--0.1-gamma sensitivity and solid state memory (can be used as a base station magnetometer)	$5,100-6,500
Proton field magnetometer and gradiometer with solid state memory	$8,200-8,900
Recording proton base station and airborne magnetometer	$10,500
Airborne magnetometer with 0.2-gamma sensitivity or better at 2 samples per second or faster	$37,000-40,000
Microcomputer and printer for reading out and storing contents of memory magnetometer	$2,500-3,700
Plotter for plotting ground magnetic profiles	$1,100
Compass and hip chain for rough surveying	$280
Microwave navigation system for aircraft	$60,000
Data acquisition and recording system for aircraft	$7,500-40,000
Radar altimeter for aircraft	$10,000
35-mm tracking camera for aircraft	$7,500

Equipment can often be rented at a cost of 10-20% of the purchase price per month. The first-time installation of a system in a fixed-wing aircraft including a tail stinger for the magnetometer sensor but not including equipment listed above will cost $20,000-40,000 or more. A temporary system with the sensor in a towed "bird" can be placed in a helicopter at much lower cost.

It is impossible to provide accurate costs for making magnetic surveys to locate wells because rates of production are likely to vary widely, depending on local conditions. Nevertheless, the following information should be useful in planning.

If accurate surveying is not required and if land access is easy, a crew of two persons can ground check 10-30 sites per day to verify the existence of casings and pinpoint their locations. On a regular grid with a station spacing of 8 meters (26 feet) and using a memory magnetometer, one person can measure about four stations per minute or cover about 1.9 km/hr (6,300 ft/hr). The man hours required for surveying in the grid will be at least equal to those required for making the magnetic measurements. Assuming the spacing between traverses is 16 meters (52.5 ft), a two-man crew could survey and process data along 40-70 kilometers of line (line-km) (24.8-43.5 line-mi) or cover an area of 0.64-1.12 km^2 2 (0.25-0.43 mi^2) per week. Production would be slower if the crew had to spend much time obtaining permission for access to the land or to pinpoint the locations of casings as they are detected. The cost per week including salaries, living expenses away from home, equipment rental or amortization, supplies, and overhead, but not including mobilization to the site, would be on the order of $2,200-3,000 per week. Excluding mobilization or pre-survey expenses such as obtaining aerial photographs, unit costs would be on the order of:

Checking individual sites	$15-60/site
Systematic surveys on a grid	$31-75/line-km $50-121/line-mi $2,000-4,700/$km^2$ $3,100-12,100/$mi^2$

Costs for a routine aeromagnetic survey using small fixed-wing aircraft are on the order of $5.60-9.30/line km ($9-15 line mi), including data processing provided: (1) at least several thousand line-km are flown in one block, (2) the lines are at least 20-30 km long, and (3) Doppler radar and a tracking camera are used for flight path recovery. The costs for similar work done with a rotary-wing aircraft are about $15.50-21.75/line-km ($25-35/line mi). In making such surveys, rates of production during good weather will be roughly 1,000 line-km/day for fixed-wing aircraft and perhaps half as much for rotary wing aircraft. The costs for aeromagnetic surveys designed to locate abandoned wells are much greater.

In surveying the Arcadia test area near Oklahoma City, where the lines were 3.22 km (2 mi) long, the actual time required to do 114 line-km (71 line-mi) with the Fairchild Porter was 1.72 hours so the rate of production was 66.4 line-km/hr (41.3 line-mi/hr). This does not include the time required for the round trip between the airport and the area, which in this case was an additional hour. The rate of production with a rotary-wing aircraft would probably be comparable; it would probably be operated at a lower speed, but the distance flown in turning around between lines would be much less. Precision low-level flying is extremely demanding, and it would be unreasonable to expect a crew to fly survey lines more than about three hours per day.

Following are rough estimates of costs for surveying using a rotary-wing aircraft and assuming that 4 flights of 4 hours total duration are made per week in areas similar to the Arcadia test area.

Helicopter and pilot--16 hours at $500/hr	$ 8,000
Equipment (without microwave navigation system) and crew $10,000/week	$10,000
Data processing and display at $3.00/line-km for 750 line-km/week (466 line-mi) (assuming computer programs already exist)	$ 2,250
Surveying and placement of microwave transponders at $2,500/week	$ 2,500
Total weekly costs	$22,750

There are a number of other fixed costs which must be considered:

Installation and removal of system from aircraft	$11,000
Helicopter standby time during installation and removal of equipment	$ 2,000
Mobilization from helicopter base to and from area, estimated 10 hours at $500/hr	$ 5,000
Rent of microwave navigation system, one month minimum at $5,000/month	$ 5,000
Fixed costs	$23,000

Production is assumed to be 750 line-km or 75 km^2 per week. Using these numbers, a summary for cost of airborne surveys is:

One-week survey from one base	$61/line-km $98 or 100/line-mi $610/km^2 $1,580/mi^2
Four-week survey from one base	$38/line-km $61/line-mi $380/km^2 $984/mi^2

Field costs would be somewhat less if it were not necessary to use a microwave navigation system. Data processing costs would be substantially greater if a tracking camera rather than a navigation system were used for flight path recovery. Field expenses for doing the same amount of work with a fixed-wing aircraft would be considerably less. However, the one-time cost for developing a system such as the one we used is very high and use of a fixed-wing aircraft may be practical only if a large amount of work is required.

The cost of interpreting the results will be highly variable, depending on the number of anomalies in the area and the degree of interference from sources other than wells. In difficult areas a geophysicist may complete interpretation of only a few km^2 per day.