Location of Abandoned Wells by Magnetic Surveys: acquisition and interpretation of aeromagnetic data for five test areas

by

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I. INTRODUCTION

The Underground Injection Control Regulations (UIC), issued by the Environmental Protection Agency (EPA), 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 which a search must be made for possible conduits such as abandoned wells from the injection stratum to overlying aquifers containing potable water. 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 are erroneous, or described only in broad terms and many old records are not readily available. Hence there is a need for other means of locating abandoned wells.

In an earlier phase of this study Frischknecht and others (1983) evaluated the use of geophysical methods, particularly magnetic and electrical techniques, for locating abandoned wells containing steel casing. The first step in the study of magnetic methods for locating wells was to characterize the magnetic fields of representative well casings. Ground magnetic measurements were made around a number of known wells located near Denver, CO. It was assumed that the field of the casing could be represented as the field of a number of magnetic pole pairs. A non-linear least square curve fitting or inversion program was used to determine the strength and location of a set of pole pairs that produce a field which is a close approximation to the observed field. The parameters determined by this process were then used to calculate the expected fields at various heights above the surface. It was concluded that it should be possible to detect steel casings by means of low-level aeromagnetic surveys. The results of the modeling were used to design aeromagnetic surveys which were carried out in four small areas in Oklahoma and one in Colorado. The primary purpose of this report and of USGS Open File Report 85-614B is to present and to evaluate the results of these airborne surveys. Persons interested in the detailed results for all of the test areas will need to refer to Open-File Report 85-614B as well as to this report. A summary of some of the results has been given by Frischknecht and Raab (1984a, 1984b, 1984c); the latter report, which has been released also by the EPA, contains suggestions for non-specialists regarding use of geophysical methods. All of the work described in this report was sponsored by the Environmental Protection Agency.

Aeromagnetic Surveys

Survey Design

The principal factors which govern the design of an airborne survey for location of steel casings are (1) the variations in the magnitude and shape of the magnetic anomaly with distance from the casing, (2) the instrumental noise of the system, and (3) magnetic anomalies or noise from all sources other than the casing. Time variation in the earth's field could also be a factor but it can essentially be eliminated by not flying during periods of abnormal magnetic activity and by use of a well placed ground monitor.

Extrapolation of ground magnetometer anomalies near casings to predict aeromagnetic results over casings should be fairly reliable. However, except for the results of Frischknecht and others (1983) little published data are available which can be used for prediction of airborne anomalies. Their results indicated that most of the wells they studied could be located by aeromagnetic surveys using reasonable flight heights and line spacings. Generally the wells studied contained at least 200 feet or more of 8 5/8 inch diameter casing. There are, no doubt, abandoned wells, in which only a small length of casing was used or in which the near-surface casing has been removed, that are impossible or economically impractical to locate and such wells were not considered in the survey design.

Instrumental noise is fairly easy to determine although it does depend somewhat on field conditions such as turbulence at the time of the survey. After computer corrections for maneuvers, the instrumental noise in the airborne system used was estimated to be 0.2 gamma (nanotesla).

Noise from cultural features other than casings and from geologic sources is difficult to predict. Injection wells and water wells not related to petroleum production are likely to be found in industrial areas where there are many other sources of cultural noise. Steel objects such as pipelines, tanks, steel buildings and large machinery are associated with petroleum fields and are possible sources of anomalies. Also, many oil fields are found in industrial and moderately populated areas where there are other steel structures. In general, sedimentary rocks in which petroleum is found are very weakly magnetic and the geologic sources of anomalies over petroleum fields are usually the metamorphic and igneous rocks beneath the sediments. The anomalies due to these deep sources have broad wavelengths and gentle gradients. However, locally some sedimentary rocks contain enough magnetite to cause substantial short wavelength magnetic anomalies. In fact, there is evidence that some oil fields are marked by the existence of magnetite or pyrrhotite formed in the near surface rocks by reaction between the rocks and gases or fluids migrating upward from the petroleum deposit (Donovan and others, 1979, Henderson and others, 1984).

Lacking adequate quantitative information on cultural and geologic noise levels it was assumed that a total field anomaly from a casing should have an amplitude of at least one gamma to be recognizable. Based on the group of Colorado wells studied, a flight elevation of 61 meters (200 ft) and a line spacing of 100 meters (328 ft) was chosen. In choosing this line spacing it was assumed that errors in actual spacing would not exceed 24 meters (80 ft).

In selecting the sampling speed of a magnetometer the tradeoff between sensitivity and sampling speed (see table I) must be considered. Original plans were to operate the available magnetometer (Table 1) at a sample rate of 0.73 s., which provides a sensitivity of 0.1 gamma or better. However, this relatively low sample rate tends to introduce errors due to aliasing and does not permit adequate definition of anomaly shape. Therefore a sample rate of 0.40 s., which gives a sensitivity of 0.2 gammas, was chosen for the magnetometer. Other data were sampled at an interval of 0.2S.

Possible use of gradiometers was considered by Frischknecht and others (1983). Instrumental noise levels of about 0.023 gamma/m (0.007 gamma/ft) for the horizontal gradient and 0.0098 gamma/m (.003 gamma/ft) were assumed. It was also assumed that because of other noise the smallest recognizable anomaly

Table I

Instrument	Experimental Conditions	Precision or resolution*	Accuracy
Airborne Magnetometer E.G.&G. Geometrics G-811/813	Sensor not rotating, signal-to-noise >95, sensor free of magnetic inclusions, sensor temp 0-100°C ± 5%	sens / cycl time: 0.05 gamma / 1.1 .1 / 0.73 .2 / 0.48 90% of readings are within ± one increment of above	± 0.5 gamma
Ground Magnetometer E.G.&G. Geometrics G-856	Sensor not moving, low gradient and low electrical interference, signal > 8.0, temp -20 to 50°C	sens = 0.1 gamma noise = ± 0.1 gamma internal time - 1 sec	1 gamma 5 sec/month drift
Vertical Gyro Lear Siegler 7000 E	proper installation -54 to 71° C	null 30' of arc	Maximum error in pickoff = 40' of arc
Synchro to DC converter Computer Conversions Corp SL0214L	25°C, ± 10% amplitude & frequency variations and ± 5% power supply variations	infinite (0.044° as recorded)	±15' of arc + 0.4'/°C
Compass System King KCS 55A	proper installation, after warmup	resolution .0878°	2° of arc
Navigation System Motorola MiniRanger III	proper installation, system calibrated, normal atmospheric conditions, unobstructed line-of-sight to transponders	1 meter resolution both ranges	3 meters or better

Table 1 (continued)

Data Processor for Motorola Mini-Ranger	proper installation, Mini-Ranger III operating as above	1 meter resolution	For best geometry 1.4X range error; for worst geometry 4.0X range error in worst direction
Radio Altimeter Sperry Stars AA-200	Proper installation, pitch ±20°, roll ±30°, flat terrain, -15° to 55°C	infinite resolution (0.61 ft as recorded)	0-100'--±3' 100-500'--±3% 500-2500'--±4%
Barometric Altitude Transducer Rosemont model 1241 M3B1	proper installation, -55 to 70°C	infinite resolution (4.88 ft as recorded)	relative ±6.25' at sea level
Indicated Airspeed Transducer Rosemont model 1221 D1A1 SCZ	proper installation, -55 to 71°C, 40-110 knots indicated airspeed	infinite resolution (.033 knot as recorded ±0.25 knot)	Operating accuracy ±2.5 knot
Data Acquisition System Sonatek SOS 1200	Properly installed, 0 - 50°C	A-D conversions 12 bit ± 2 bit in least	Linearity ±.024% of full scale significant bit, quantizing error Internal Clock±.012% of F.S. clock 1 sec.drift 0.006%/day
Tracking Camera Automax G-2	Properly installed, Level flight at 150' above ground	Essentially infinite, ground coverage 165 ft.	Alinement with airframe ±1° location of a small point ±2 meters or better

would be five times the instrumental noise level. Under these assumptions gradiometer measurements would have to be made on a closer line spacing than total field measurements to locate small casing anomalies. However, it should be noted that gradiometer systems measure total fields as well as gradients so that, in any case, a gradiometer system would provide more information than a total field system, although at a greater cost. Also, gradient measurements would be useful in discriminating against long wavelength anomalies produced by geologic sources.

Airborne system used

The aircraft used was a Fairchild Porter. This single turbine engine STOL aircraft can be operated at speeds of 100 knots or less. Its high rate of climb, low stalling speeds and reliability of the turbine engine make it more suitable than most fixed wing aircraft for extremely low level surveys. Geophysical and auxiliary navigation and equipment are listed in table I.

Rotation of the sensor and magnetic fields of the aircraft represent sources of noise and error in the airborne measurements. Ferromagnetic parts of the aircraft are sources of both induced and permanent magnetic fields. Electrical circuits in the aircraft constitute current loops which are sources of both alternating and DC fields. Rotation of the skin and frame of the aircraft relative to the earth's magnetic field induces transient eddy currents in those structures which are sources of transient magnetic fields.

The magnetometer sensor is placed at the end of a tail boom or stinger in order to remove it as far as possible from the fields of the aircraft and yet have it rigidly coupled to the aircraft so that its motions are known. The following measures have reduced the magnetic fields of the aircraft at the sensor: (1) some of the ferromagnetic parts of the aircraft have been replaced with non-magnetic stainless steel or other non-magnetic parts; (2) other parts are regularly demagnetized using a degaussing coil; (3) two wire circuits rather than a single wire with airframe return are used in all long circuits carrying appreciable DC current.

Most of the remaining field of the aircraft at the sensor is compensated. DC currents are driven through a three axis coil placed about 37 inches ahead of the sensor in the tail boom to cancel the permanent field. Small permalloy strips are placed near the sensor to cancel the effects of induced magnetization; the fields from these strips vary in the same way as the field from the aircraft, as the attitude of the aircraft changes. The proper currents in the compensation coils and the placement and length of the permalloy strips are determined empirically through flight tests. Closed wire loops can be placed near total intensity fluxgate sensors to compensate for eddy current fields but this is not practical for proton magnetometers due to the degradation of the signal-to-noise ratio from electrical losses in the compensation loops.

Two different measures of the residual field of the aircraft are commonly used, heading effect and maneuver noise. Heading effect is the variation of observed field with slow changes in heading or azimuth of the aircraft when it is in level flight. Maneuver noise is the variation of the magnetometer readings in a constant earth's field when the attitude of the aircraft is changed from the horizontal (pitch or roll maneuvers) or the heading is rapidly changed (yaw maneuver). Heading effect is independent of eddy currents but rapid maneuver noise is dependent on both eddy currents and uncompensated fields of permanent and induced origin. Rotation of the sensor causes small changes in the signal of a proton magnetometer and constitutes an additional source of noise.

Before correction, heading error was roughly 1/2 gamma for the work described here. Noise due to slow maneuvers was about the same. The chief source of high frequency noise is from eddy currents induced by turbulence and aircraft maneuvers and, in some cases, it was higher than one gamma. To provide information for identification and removal of maneuver noise, roll and pitch signals from a vertical gyro and yaw signals from a fluxgate compass are recorded.

In locating well casings, accurate positioning of the aircraft along the flight path and accurate recording of the position are necessary. In general, positioning the aircraft visually or by Dopplar radar are not adequate, and recovery of the flight path by a tracking camera or by recording the Doppler results is generally not adequate, although in some areas there may be enough landmarks for visual navigation and for recovery of the flight path using a tracking camera.

To provide adequate information for pilot guidance and flight path recovery, a microwave navigation system which determines position by trilateration was used. To use this system, transponders are placed at either end of a known baseline. The range to each of these transponders is measured by a transceiver in the aircraft and the two range numbers are recorded directly in digital form by the data acquisition system. Using the known transponder locations and measured ranges, an on-board data processor determines the position of the aircraft in the local coordinate system. The position of the aircraft relative to pre-programmed flight lines is also determined and displayed on indicators in the cockpit for pilot guidance. If the transmission path is interrupted by an obstacle or another factor prevents determination of valid range information a warning light comes on in the cockpit and a flag message is recorded. To achieve uninterrupted transmission paths the transponders were placed at the top of 10 m (30 ft) masts on top of hills or high points and the receiving antenna was placed on a long rod which was extended about 3 feet beneath the aircraft while flying.

The accuracy of actual locations depends on the accuracy of the transponder locations, the accuracy of the range information, and the geometry of the triangle. Information is most accurate when the angle of intersection of the range lines is 90^{o}. For this angle, the maximum error is 1.4 times the range error. To avoid large errors, the angle of intersection was kept between 30^{o} and 150^{o}, in which case the maximum error is four times the range error in one direction and much less in the other direction. The accuracy of horizontal locations also depends on knowledge of the aircraft height relative to the transponders. However, the terrain in the test areas was flat enough that this factor was not a significant source of error. Transponder locations were surveyed relative to each other and to prominent landmarks using a laser ranging theodolite.

Height of the aircraft above ground is measured with a radar altimeter. The output is displayed for pilot guidance and recorded as well. Also recorded, were outputs from a barometric or pressure altimeter and an indicated airspeed transducer. This information is often useful in processing conventional aeromagnetic data but was not important for this project.

A 35 mm tracking camera was used to take overlapping frames of the flight path. For this project the photographic information was used primarily to check the accuracy of the microwave navigation system at selected points and to tie photographically determined well locations to the flight path.

The primary data acquisition system records data on 1/2 inch tape; the recorder has a read head which permits verification of the data recorded on tape. Information from the magnetometer, the microwave navigation system, and the system clock is entered directly in digital form. Analog data are entered through a multiplexer and A-D converter. A strip chart recorder is used to monitor the output of the magnetometer and some of the microwave navigation data were printed on the terminal used to control this system. Fiducial marks on the strip chart and frame numbers on the tracking camera film are controlled by the digital acquisition system.

Field Procedures

The aeromagnetic test area near Denver (figure 1) is part of the area in which ground magnetometer measurements were made (Frischknecht, et. al., 1983). Four test areas near Oklahoma City (figure 2) were selected by the University of Oklahoma (Fairchild and others, 1983, Fairchild, 1984). The Oklahoma areas selected had 14 or more wells in each section, as determined from records of the Oklahoma Corporation Commission, and are predominantly rural in nature. Information on the size and amount of casing in the holes and the names and addresses of landowners was provided. The four areas were inspected to determine the locations of dwellings and livestock which should be avoided by the aircraft and the locations of towers and other features which might be a hazard to the aircraft. Large parts of three of the original four areas (Horseshoe Lake, Moore, Oklahoma City) were excluded from the survey area, primarily because of the presence of dwellings.

Tentative sites for the microwave transponders were selected from a study of USGS topographic maps. The sites were selected to be on tops of hills to provide line-of-sight transmission paths to the aircraft and they were located so that the angle of intersection of the range lines to the aircraft was between 30^{o} and 150^{o}. Next, the landowners of the tentative sites and landowners who control access to the sites were contacted in person or by telephone to obtain permission to temporarily place a transponder on their property. After permission had been obtained, the actual sites were inspected to make certain that there were no unusual problems such as nearby powerlines or livestock which might damage the masts or guy ropes. Tentative sites within the survey area for the base station magnetometer were selected during these inspection trips. In general, landowners were cooperative and willing to allow temporary placement of the transponders and magnetometer. In one instance it was necessary to pay a landowner a nominal sum for use of his land. In another instance it was necessary to place the site in a pasture where the equipment had to be protected from cattle. The greatest problem in this process was contacting the landowners and, in many cases, the person leasing the land.

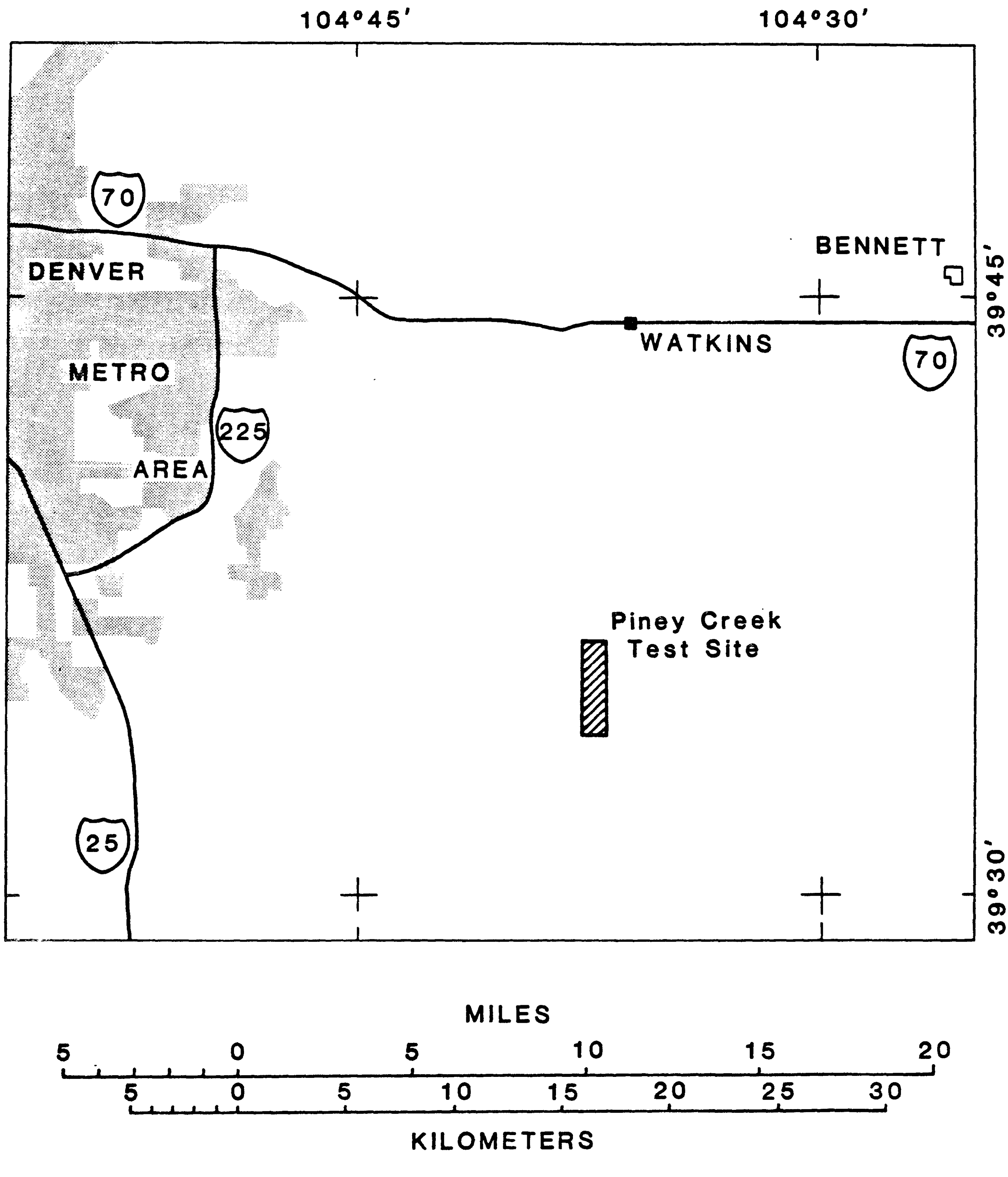

Figure 1. Location of Piney Creek, CO test site.

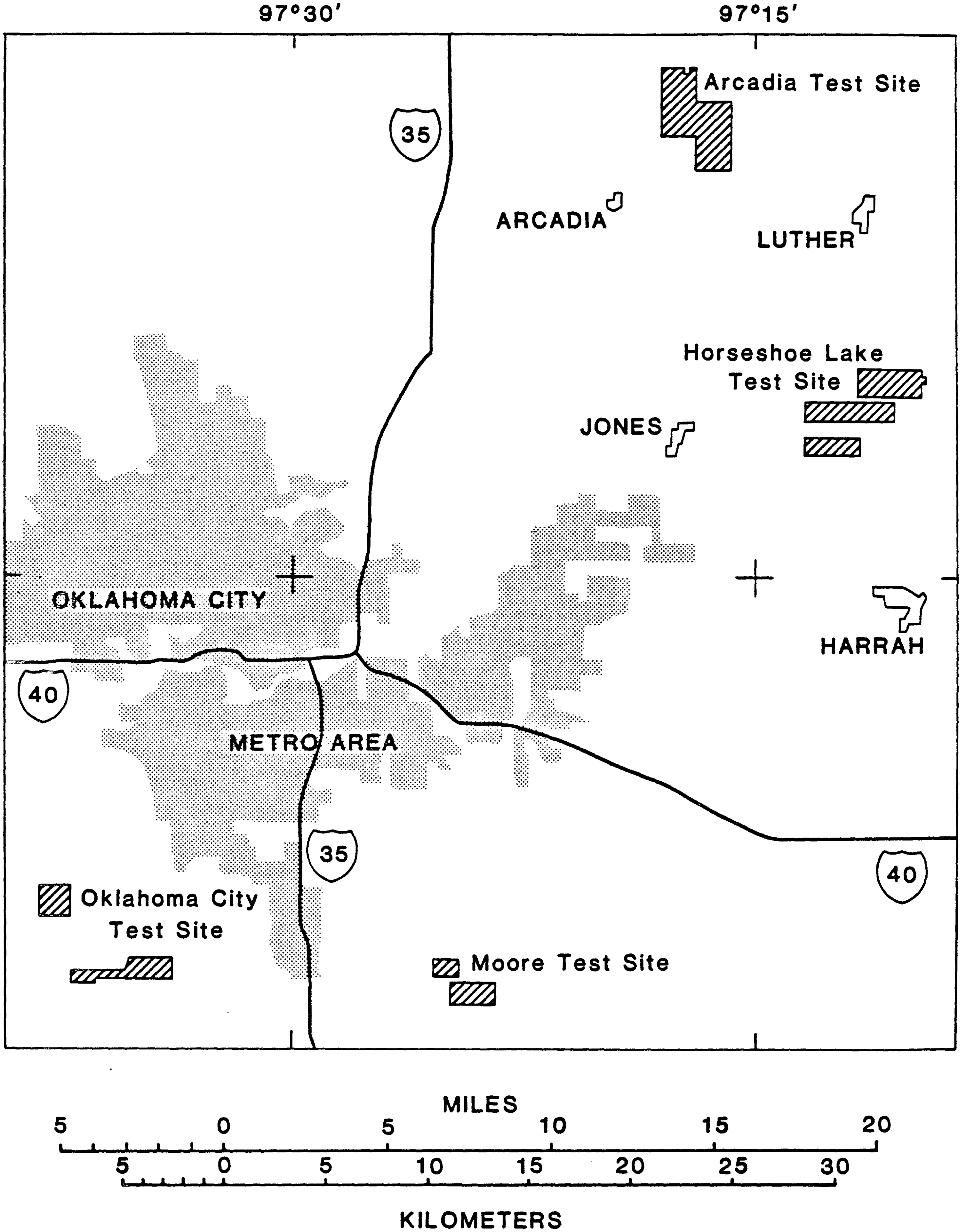

Figure 2. Location of Oklahoma test sites.

Shortly before flight operations began, a surveying crew using a laser ranging theodolite established the distance and direction between transponder sites and established the position of the sites relative to local roads and other cultural features. An effort was made to tie the survey to local bench marks but in the Oklahoma test areas only one of the few available bench marks was found. After completing the land survey for each site, the data were reduced and the grid for the aeromagnetic survey was planned and explained to the flight crew. Each grid contained a line along a road or other easily recognized landmarks. This line was flown at the beginning of the survey at each area to make certain that there were no serious discrepancies between the position as indicated by the navigation system and the position as determined visually. This procedure eliminated the possibility of any major surveying or computational errors.

To avoid excessive turbulence, flights were made either early in the morning or late in the afternoon. The transponders were placed at their sites on the preceding day or on the day of the flight. The base station magnetometer was placed at its site shortly before the flight began. An aircraft to ground radio link was used for coordination between flight and ground crews. In general, each area was completed during one flight although two or three flights were cancelled shortly after they began because of excessive wind or equipment malfunctions. A strip of test film was exposed at the end of each flight and then developed to insure that the tracking camera operated properly. Strip charts and printer output were examined after flights to locate potential problems. Calibration flights were made both in the Denver area and the Oklahoma City area to provide data on the relationship between the magnetometer output and maneuvers. The data were later used in removing maneuver noise from the survey data as described in Appendix I.

Sites for the base magnetometer were selected well away from power lines, roads and other sources of interference or magnetic disturbances. The base magnetometer was set to sample and store the field at a rate of 1 sample/10 sec. After each flight the contents of the magnetometer memory were transferred to a microcomputer and plotted. The clocks in the ground magnetometer and the aircraft data acquisition system were synchronized each day to within about 1 second.

Data Processing

Most of the data processing was done by a contractor, Future Resources Inc. of Lakewood CO. A copy of the report on their work is included in the Appendix. A few clarifications of their report are needed; the data used in preparation of their contour maps were corrected for diurnal variations and heading effect but not for maneuver noise. However, profiles corrected for maneuver noise were supplied. The reduced-scale contour maps included in the body of this report (figures 4 and 9) were plotted by the USGS using the maneuver corrected data supplied by Future Resources. The small differences in maps are primarily due to differences in gridding and plotting programs and not differences in the data. The data taken at multiple elevations in the Piney Creek and Moore test areas (figures 5 and 8) were not corrected for maneuver noise. A constant was subtracted from all of the data sets so the results are a residual field.

Ground Measurements and Modeling

While ground checking airborne results, systematic ground magnetic surveys were made over several wells in the Oklahoma test areas. The data from these surveys were inverted using the program and techniques described by Frischknecht and others (1983); the observed and calculated results are shown in figures A1 - A14 in Appendix 2. In the list of parameters (table A1) we have given all distances in feet and the pole strengths in SI units and in hybrid units. In doing forward calculations, if distances are given in meters, pole strengths must be given in SI units and, if distances are given in feet, pole strengths must be given in hybrid units. For sake of completeness, part of the information on the parameters of wells in Colorado from the report by Frischknecht and others (1983) is included in this report (table A2). Values in hybrid units for pole strength were selected to be a factor of 100 less in table A2 than in the original report (see Frischknecht and others, 1983, page 16). Boardman (1985) has recently published similar results of inversion for a well.

The Oklahoma wells which were studied are not necessarily typical of their fields. Wells 9 and 10 (anomaly 24 and well P 17) in the Horseshoe Lake area produced relatively small anomalies whereas Well 6 (anomaly 21) in the Moore area produced a larger than normal anomaly. Well 10, produced a ground anomaly of only about 1000 gammas, and an airborne profile anomaly of about one gamma, which is the threshold of detectability for the airborne survey. Several of the casing anomalies are distorted by the fields from other pipes or steel objects. Nevertheless, the interpreted parameters for the casing may be fairly accurate.

The inversion program was also used to invert a few airborne profiles over wells. Generally, the casing anomalies in airborne data are superimposed on gradients of geologic origin or on the flanks of anomalies due to other wells or cultural features. Accurate, independent determination of the parameters of the casing is dependent on accurate removal of the gradients or interfering anomalies. However, by assuming that the top of the casing is almost at the surface, useful estimates of pole strength can be obtained from the airborne data.

Aeromagnetic Measurements

Aeromagnetic Profiles

As an example of typical profile data from Oklahoma, part of line 4 for the Arcadia test area (figure 2) is shown in figure 3. The bottom plot, which shows the corrected magnetic field, is "folded", that is, when the trace goes off the top of the plot it re-appears at the bottom. The quantity shown in figure 3 is the actual field less about 53,000 gammas. The trace 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

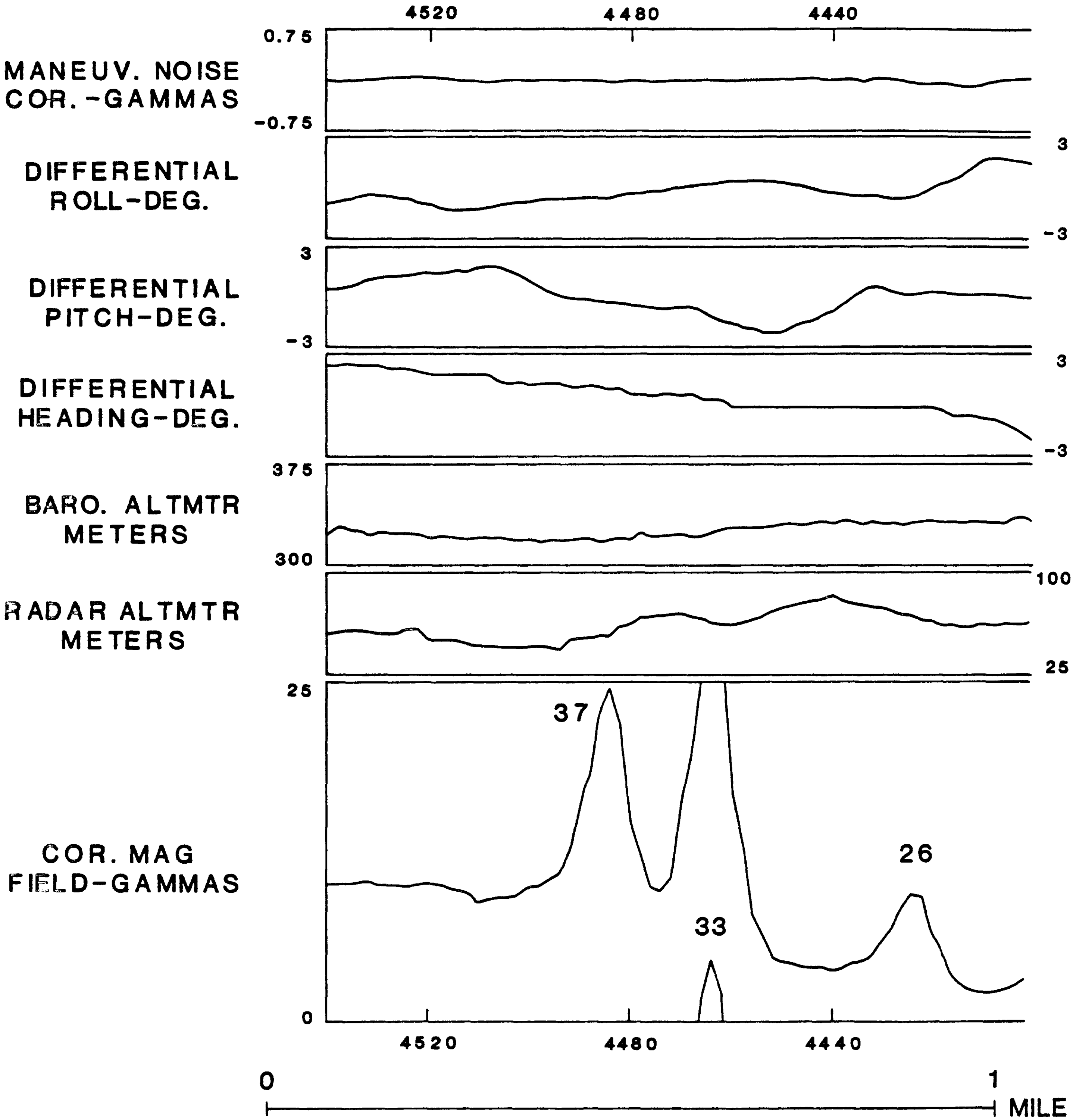

Figure 3. Airborne profile data from Arcadia area. The numbers at top and bottom are identification numbers associated with each reading, and the numbered anomalies correspond with those on Figure 13.

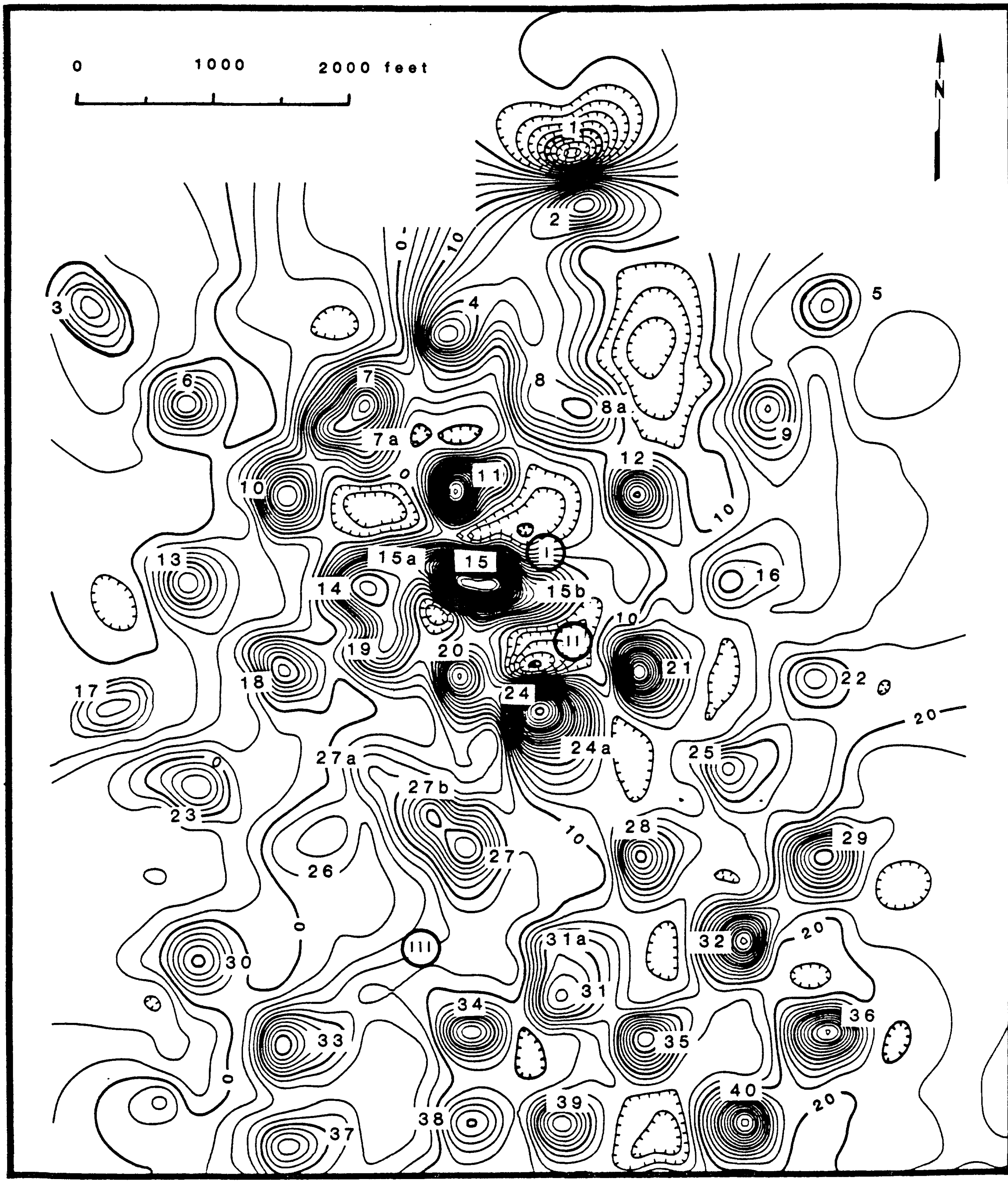

Figure 4. Total intensity contour map for part of Arcadia area.

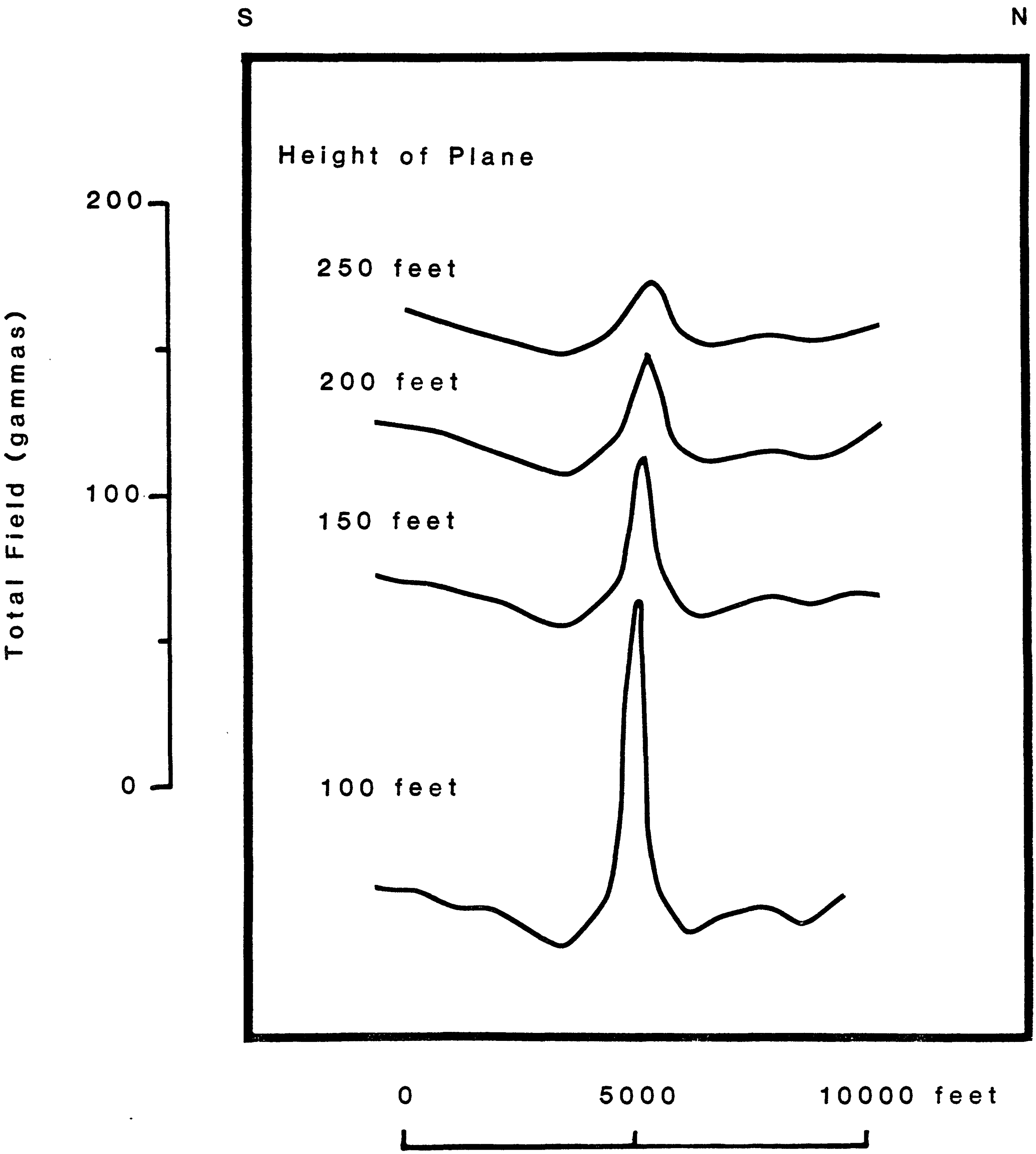

Figure 5. Aeromagnetic profiles for different aircraft heights over well no. 4, Piney Creek area.

anomalies with the same numbers on the magnetic contour map of the area (figure 4). The peaks, which are caused by wells, are superimposed on a small, more or less uniform, decrease in the field from south to north.

Aircraft flights were made over well no. 4 in the Piney Creek, CO test area (figure 1) at nominal heights of 30.5, 45.7, 61 and 76.2 m (100,150,200,250 ft) to determine how the anomaly decreases with height above the ground (figure 5). Earlier, Frischknecht and others (1983) estimated the anomaly at these heights from the ground data for well no. 4 (figures 6 and 7). Well no. 4 is not an ideal selection for this study because its anomaly is distorted by variations in the magnetization of near-surface rocks, making it difficult to estimate the magnitude of the anomaly. However, comparison of the airborne results (figure 5) with calculations based on the parameters obtained from inversion of the ground data indicates that the magnitude of the anomaly was underestimated by about 21% at 29.7 m (100 ft) and by about 23% at 76.2 (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 6 and 7) as well as we would like. In any case we regard the agreement between predicted and actual results as good.

As another example, results taken at altitudes of 45.7 (150 ft) and 76.2 m (250 ft) along part of line 5 in the Moore, Ok area are superimposed without smoothing. Loss of detail as well as amplitude of the anomalies, when the altitude is increased, is apparent (figure 8).

Evaluation of aeromagnetic data

In evaluating airborne surveys aerial photographs and maps were used to locate the site of the anomaly on the ground. Then a ground magnetometer was used to quickly determine the sources of selected aeromagnetic anomalies. Measurements were made on a very rough grid established by pacing. Readings were taken every 20-30 feet but generally 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.

In the Oklahoma areas, the aeromagnetic data were compared with the results of a records search by Fairchild and others (1983) and with an analysis of aerial photography by Stout and Sitton (1983, 1984). In Oklahoma, the records of the Oklahoma Corporation Commission give the locations of wells in terms of the section or fractional part of the section where the well is located. The most specific location is one-sixty-fourth of a section; in a few cases the location may be anywhere within a half-section or a section. Thus it is often difficult to make a one-to-one correlation between wells indicated by the aeromagnetic results and those found by the records search. Locations of wells identified from aerial photography are accurate and it was easy to correlate magnetic anomalies with photographically identified wells (PIW). The next sections describe the results from all five areas in detail. Reduced maps for part of the Arcadia and Piney Creek areas are given in figures 4 and 9. To examine the results for the remainder of these two areas and all of the other three areas, it is necessary to refer to the plates in the companion USGS Open-File Report 85-614B, which show the original results at a scale of 1:6000. For some areas there are slight but

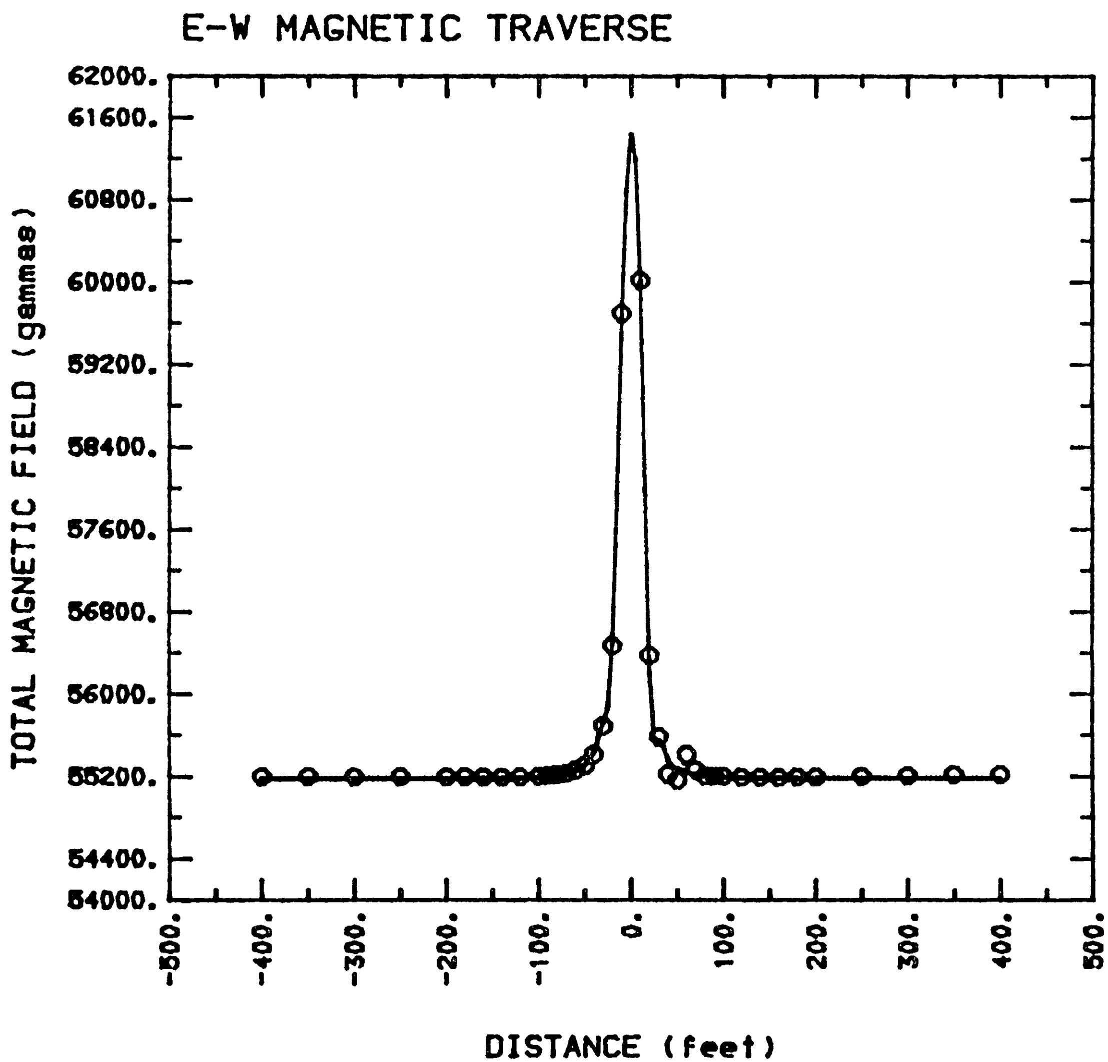

Figure 6. Observed (circles) and calculated (solid line) results for well no. 4, Piney Creek area.

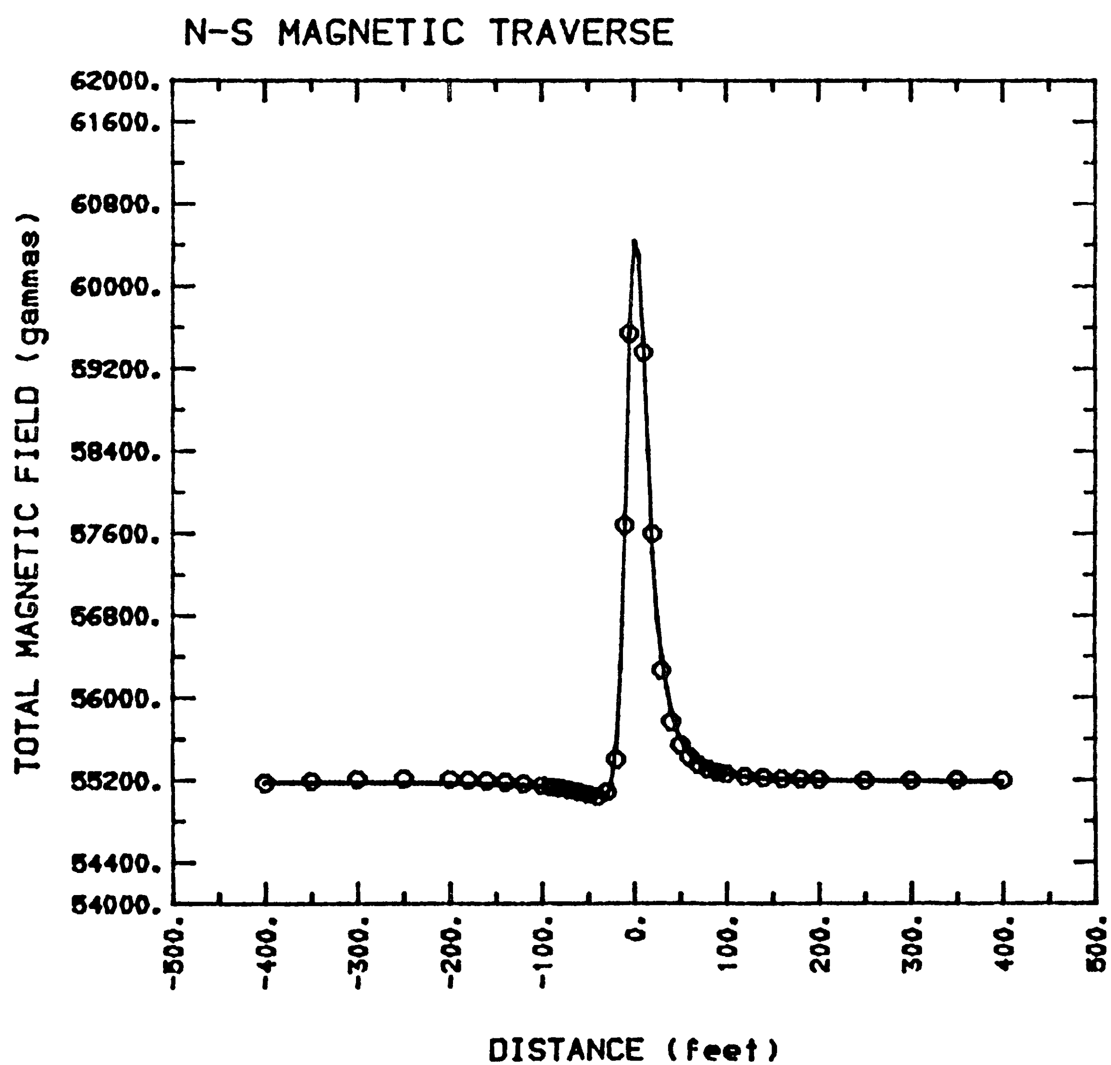

Figure 7. Observed (circles) and calculated (solid line) results for well no. 4, Piney Creek area.

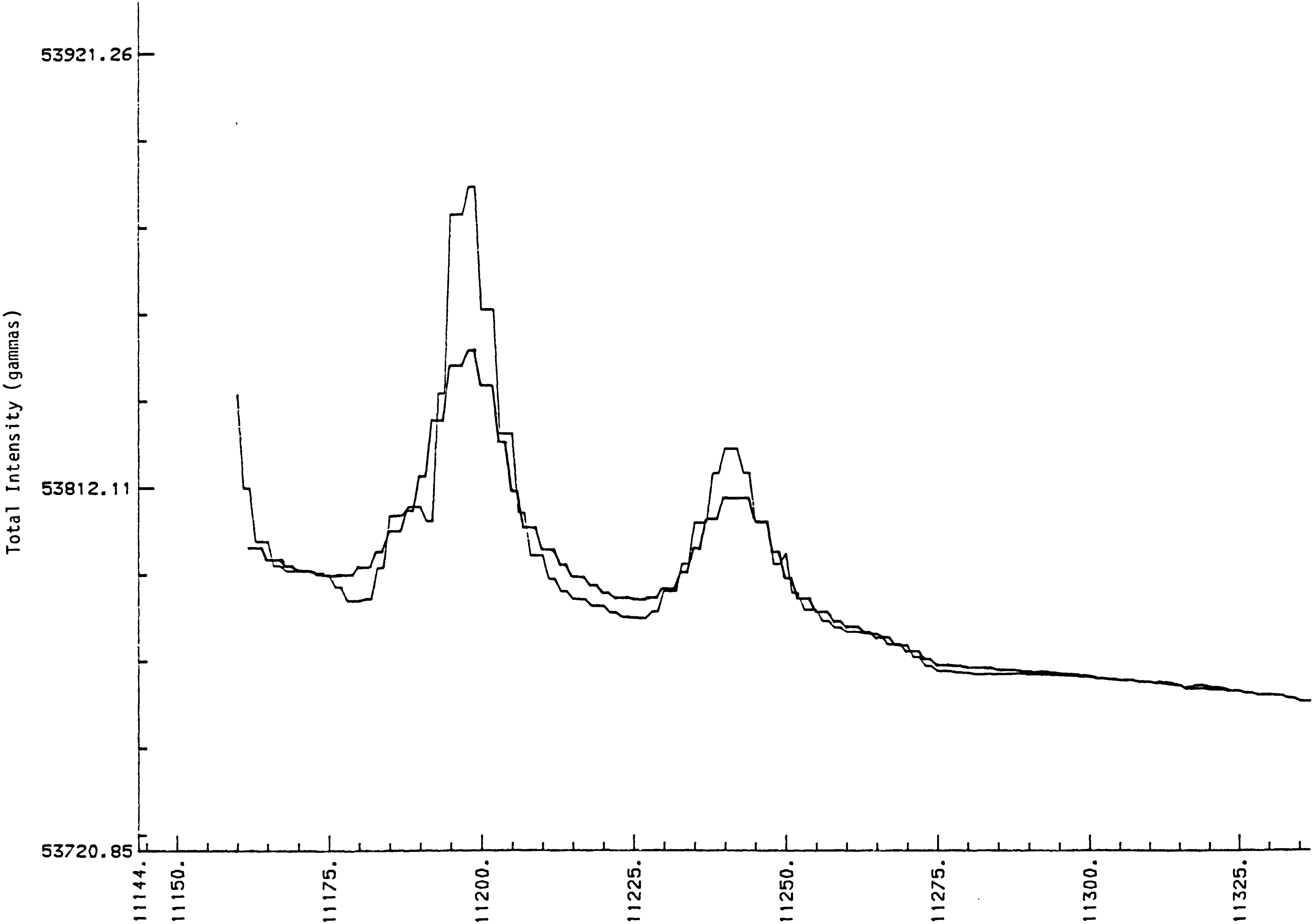

Figure 8. Profile for part of line 5, Moore, OK, at height of 150 and 250 feet.

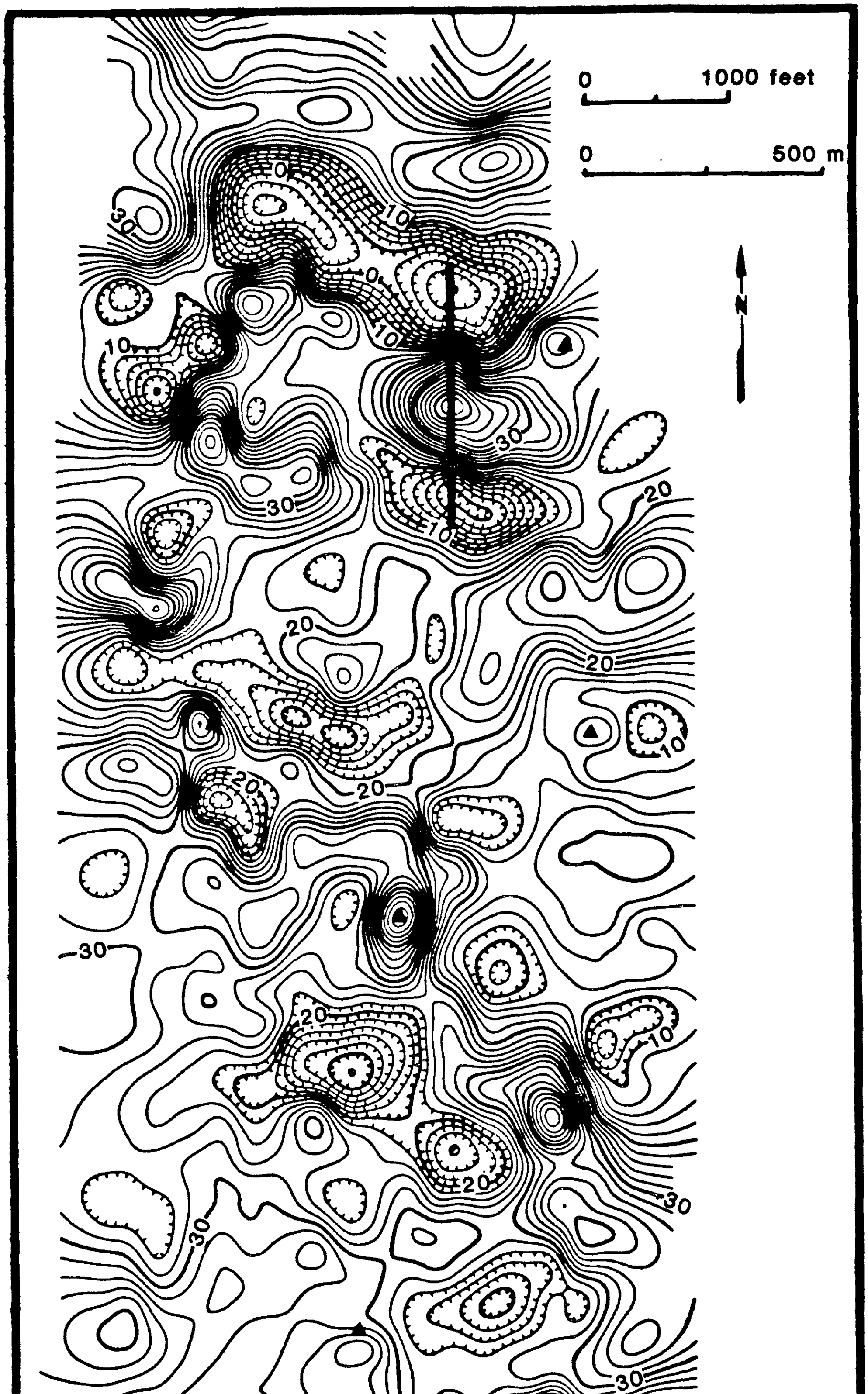

Figure 9. Total intensity contour map for north part of Piney Creek area. Triangles indicate locations of known wells and heavy line indicates location of ground traverse. Contour interval 2 gammas.

consistent offsets between magnetic features and their sources. Apparently these offsets are caused by failure to specify reference coordinates with sufficient accuracy in plotting. The locations of wells identified by photography or information other than magnetics are plotted on the flight line maps. Different symbols are used for abandoned wells (square), probable abandoned wells and dry holes (diamond), possible abandoned wells or dry holes (triangles) and active wells (circles).

Arcadia contour map sheet no. 1

On this sheet (see also figure 4) 40 distinct aeromagnetic features have been labelled. The map is dominated by these features although there is a gentle regional trend with the field 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 chart shows the association of these anomalies with photographically identified wells (PIW) by sheet 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.
8-8a, 21-21a 27, 27a, 27b	Each complex anomaly is associated with two or three PIW's.
3, 17	Outside section where photo interpretation was done; but are probably due to wells.
1, 2	Outside section where photo interpretation was done; probably due to a horizontal pipeline and perhaps a well.
4, 5	Outside section where photo interpretation 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 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 anomaly over I was observed.
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 contour map by gridding and smoothing. The site was not field checked.

Considering only section 3 (see also Figure 4), 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 contours or profile anomalies correlate with 35 original PIW's. There are two other anomalies, 19 and 15b, which are thought, by Stout, to be wells plus 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.

Arcadia contour map, sheet no. 2

On this sheet, 42 aeromagnetic anomalies have been labelled; fewer complex anomalies are observed than on sheet no. 1. There is a gentle regional trend which is east-west in the northern part of the sheet and which changes directions so that it is north-south at the southern end of the sheet.

Anomaly no.	Association or probable cause
1, 2, 4, 5, 6, 9, 10, 11 12a, 14, 15, 16, 17, 18, 19, 20, 21, 23, 24, 25, 28, 29, 36, 37, 38, 39	Associated with one PIW.
30, 31, 33, 34, 35	Associated with large steel towers of power transmission lines — anomaly 34 is probably partly due to a PIW.
32	Probably a well but could be related to transmission line.
22, 27-27a	Outside sections where photo interpretations were made. Aerial photographs indicate there are several buildings in area.
26	Field checked but no typical casing anomaly was found; steel buildings cause large ground magnetic anomalies.
42	Probably a well outside section where photo interpretation was made.
7, 12, 13	Field checked and found casing type anomalies not associated with PIW's.
3, 10a, 28a, 31a	Not field checked but may be wells -- 31a may be related to transmission lines - not identified from photos.
8	Not field checked -- associated with farmyard but there could be a well.
40	Associated with PIW but position does not seem correct perhaps due to mislocation of well and regional gradient which displaces magnetic contours.
41	Associated with locality where very large pipeline crosses top of hill. Vertical component of pipeline probably caused anomaly.

It should be noted that the variations at a height of 2.4 m (8 ft) above straight and level sections of the pipeline causing anomaly number 41 are no more than a few tens of gammas. This is in contrast to large variations observed along pipelines by Atherton and Teitsma (1982).

There are several PIW's which are not associated with very obvious anomalies on the contour map. Field checking and examination of the aeromagnetic profiles yielded the following results:

Well no.	Comments
P1	Associated with a perturbation in contours but there is no closure due to regional gradient and wide spacing between flight lines. The profile for line 6 shows a distinct 4 gamma anomaly near well P1.
P2	The profile for line 16 shows a 4 gamma anomaly. The anomaly on line 17 is probably partly caused by well P2.
P3	Anomalies 18 and 19 are both elongated in the east-west direction due to well 3 but this fact was not recognized in initial examination of the map. Well P3 is associated with a 4 1/2 gamma anomaly on line 16.
P4	There is a nose in the contours but presence of a well is obscured by the regional gradient. Airborne profiles for lines 22 and 23 show 3 and 2 gamma anomalies respectively. Ground measurements show a smaller than typical anomaly.
P5	Contours do not suggest the presence of the well but P5 is associated with a 2 gamma anomaly in the profile for line 26. Ground measurements were not made.
P6	There is a slight suggestion of the well in the contours. Profiles for lines 22 and 23 show 1 and 2.5 gamma anomalies respectively. Ground measurements show the presence of a casing.
P7	The contours do not suggest the presence of well P7. It is associated with a 3 gamma anomaly in the profile for line 26.
P8	Neither the contour map nor the profiles indicate the presence of well P8. If it exists, the anomaly must be very small; on lines 18 and 19 the anomaly if any, is less than one-half gamma.

In section 10, which includes the bottom of sheet 1 and the northwest part of sheet 2, 15 wells were identified from photographs. Easily recognizable contour closures are associated with 12 of these wells and weaker contour disturbances plus distinct profile anomalies correlate with the other three PIW's. The existence of a casing at anomaly 12 was verified by ground measurements, making us fairly certain of the location of at least 16 wells. In addition, it is highly probable that anomaly 37 on sheet 1 and anomaly 3 on sheet 2 represent wells. Anomaly 8 at the farmyard and a nose in the contours south of anomaly 8 on sheet 2 might also represent wells. The record search indicated the existence of 16 wells.

In section 11, in the northwest part of sheet 2, 11 wells were identified from photographs. Easily recognized magnetic closures are associated with each of these wells. Ground checking confirmed the presence of casings at anomalies 7 and 13. The anomaly at 20a may also represent a casing. Thus, 13 wells have been identified with a high degree of certainty and there may be a fourteenth well. The record search indicated that there are 14 wells in section 11. However, one of these wells, located NE NE & SE, section 11, has very little if any magnetic expression. A broad 4 gamma anomaly on line 33 could represent the well.

In section 14, in the southwest part of sheet 2, there are 14 PIW's. Seven of these wells are associated with obvious magnetic contour closures. Minor features in the contours and small, but well defined profile anomalies correlate with 4 other PIW's. Two of the remaining photographically identified wells cause no discernible anomalies in the magnetic profiles and the anomaly of the third well is masked by the anomaly from a nearby transmission line tower. Anomaly 32 is very likely caused by a well and anomalies 28a and 31a may also represent wells. From the two sets of data, we are fairly confident of the existence of 12 wells and the data indicate that there may be as many as 17 wells. The record search indicated that there are 15 wells in section 14.

There are more wells in section 14 which have weak or no magnetic expression than in the other three sections. The reasons for this are not well understood, although some of the wells listed in the records search can be identified with specific magnetic anomalies. The large anomalies, 28 and 29, are caused by wells containing 301 ft (81.7 m) and 390 ft (118.9 m) respectively of 10 3/4 in (27.3 cm) casing. The well which may cause anomaly 31a or 32 has only 80 feet of 10 3/4 in (27.3 cm) casing and well P7 apparently contains only 5 1/2 in (14.0 cm) casing. However, well P5 presumably contains 198 ft (60.4 m) of 10 3/4 in (27.3 cm) casing.

Moore Contour Map

This map displays a number of rather complex features. Many of the wells are close enough together that they produce a composite anomaly. There are few simple anomalies caused by a single well. Also there are a number of features which appear to be caused by sources in the near surface rocks. The gradient west of anomaly 3 is an example of such a feature. Associations of the numbered anomalies with PIW's and ground observations are:

Anomaly no.	Association or probable source
1, 2, 3, 4, 5, 17 18, 21, 25, 28	Contour closures which are apparently associated with a single PIW. Anomalies 1, 5, 21, and 25 were verified on the ground.
6	A PIW causes considerable extension of the anomaly on the north side. Another well found by ground checking causes much of anomaly 6.

7	A PIW causes much of anomaly 7. Two wells found by ground checking cause the westward bulge of anomaly 7 along line 4. One or more unidentified wells probably cause the southeast bulge on anomaly 7.
8, 9, 10	These anomalies are outside sections where photo interpretations were made. Anomalies 8 and 10 are known to be caused by wells and number 9 appears to be caused by a well.
11, 12, 13, 14, 15, 16	These anomalies are part of one large inverted V shaped anomaly which has individual closures or noses. Each of these features is identified with a single PIW except 16 which is identified with two wells. The wells at 12, 14, and 16 were verified by ground measurements.
19, 23, 26	These obvious noses in the contours are associated with PIW's.
22	This anomaly is caused by two PIW's verified by ground checks and one other well identified from ground checks.
27, 29	These are outside sections where photo interpretation was made and do not look like they are caused by wells.

A number of wells which were identified photographically are not clearly associated with features on the contour map.

Well no.	Association or probable source
P1, P2, P6, P7	Wells are within contoured area of map but too far from flight line to be detected.
P3, P5	Ground checking indicated that no casing is present; well 3 is indicated as possible and well 5 as probable.
P4	Ground checking indicates presence of casing. Well is between widely spaced flight lines and the saddle in the contours is probably misplaced westward in region of well due to the source of anomaly 20.

In section 21 there are 18 photographically identified wells; six of these are in the area covered adequately by the aeromagnetic survey and are associated with magnetic anomalies. Three more wells, which were not identified photographically, cause anomalies or bulges in the contours and were verified by ground checking. One or two other wells not identified photographically or during ground checking probably cause the southeast bulge of anomaly 7.

In section 27 there are 20 PIW's; 15 of these are within the area covered by the aeromagnetic survey. Well defined contour closures are associated with 12 of these wells and in some cases, there are two wells associated with a closure. Two of the remaining wells, one probable and one possible, produce no magnetic anomaly. The third well produces an anomaly which is not recognizable in the aeromagnetic data because of a local widening of the line spacing to 160 meters and the presence of strong anomalies due to nearby wells. One well not photographically identified was verified from ground checking at anomaly 27 and, very likely, an unidentified well causes anomaly 20.

In section 28 there are 6 PIW's within the area adequately covered by the aeromagnetic survey. They are all associated with closures or noses in the contours which are fairly easily recognized. No other wells were found in ground checking and there is no strong evidence in the aeromagnetic data for the existence of other wells.

There are some steep gradients in the Moore area which appear to be caused by near surface geologic sources. As an example, results for part of line no. 7, reflown at an altitude of 45.7 m, are shown in figure 10; a sharp 16 gamma change in level occurs between identification numbers 9865 and 9870 west of the anomaly numbered 3. According to the geologic map by Burton and Jacobson (Wood and Burton, 1968) the surface rocks in the area are the Hennessey shale, a deep-red clay shale containing thin beds of sandstone, and the Garber Sandstone and Wellington Formation, a red, massive, fine grained sandstone with lenticular masses of clay. No attempt was made to further identify the sources of the anomalies.

Horseshoe Lake sheet no. 1

This sheet is characterized by generally less complex aeromagnetic features. There is a strong regional trend with the field increasing toward the north.
Superimposed on this trend are a number of anomalies which are characteristic of single wells. Association of the numbered anomalies with PIW's and with ground observations are:

Anomaly no.	Association or probable source
3, 4, 5, 6, 7, 8, 11 12, 13, 14, 15, 16, 17, 18, 19	Contour closures which are apparently caused by a single PIW.
1	Probably due to a pipeline which has a sharp bend at this locality.
2	Ground checking identified the presence of a casing -- there is no visual evidence of a well.
9, 10	Closures likely caused by one well and another cultural feature, or by two wells.

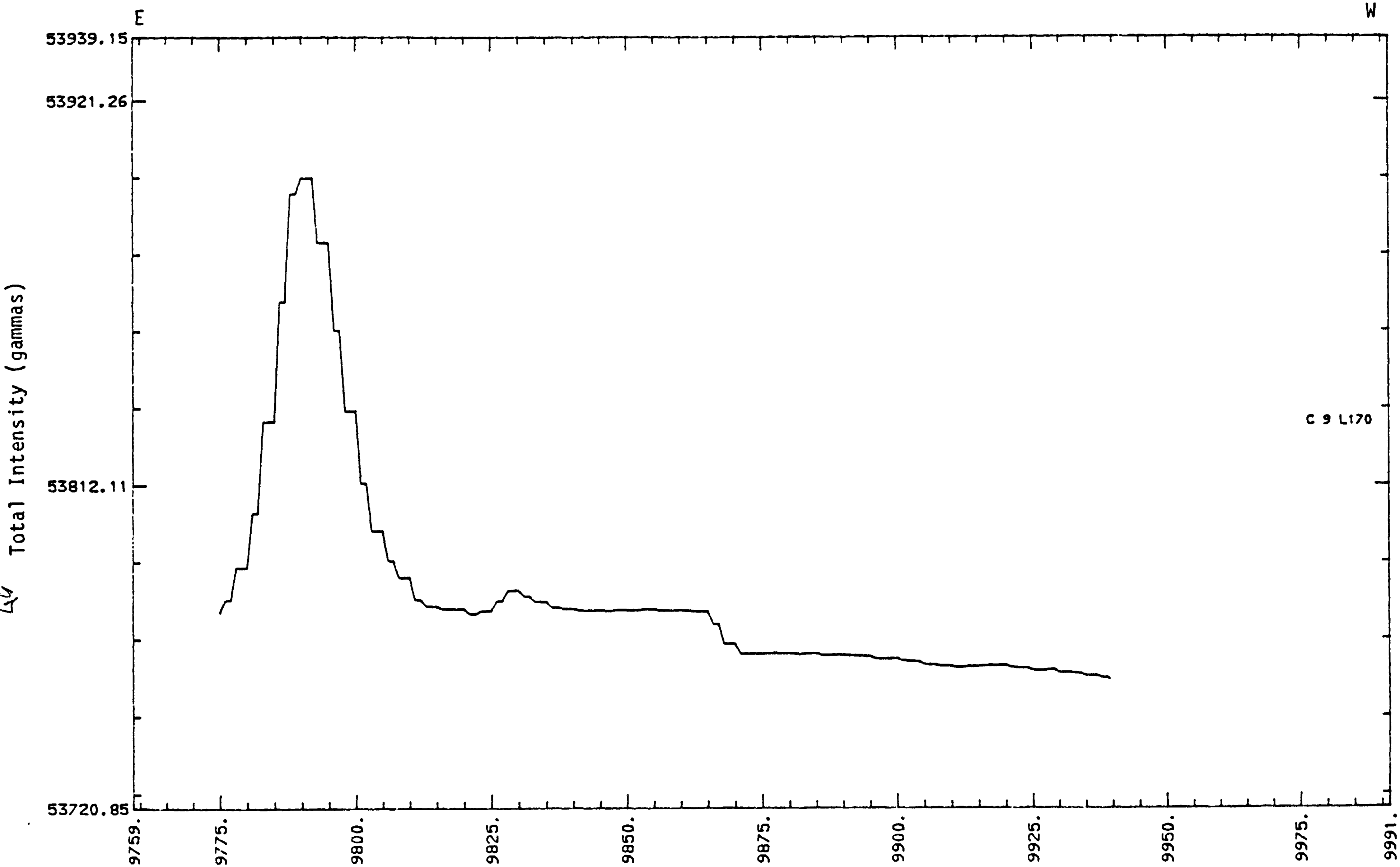

Figure 10. Profile for part of line 7, Moore, OK, at height of 150 feet.

The following PIW's are not associated with contour closures.

Well no.	Association or probable source
P1, P2	Both are associated with noses in the contours and distinct peaks in the aeromagnetic profiles.
P3, P4	No adequate aeromagnetic evidence for either. A weak anomaly due to P3 could be masked by anomaly 18 and the maximum anomaly due to P4 is 1/2 gamma. Ground checking indicated no casing at P3.

The nose in the contours on line 39 north of anomaly 3 suggests the presence of a casing. Noses in the contours on lines 37 and 38, northeast of well P1 may be caused by a well or other cultural features.

m1, m2, m3	Noses in contours and anomalies in profiles which may be due to casings.

Horseshoe Lake sheet no. 2

The regional trend, which is mostly north-south in sheet 1, swings around until it is east-west over most of sheet 2, with the field increasing toward the west. There are more complex anomalies and more weak anomalies on sheet 2 than sheet 1. Association of numbered anomalies with PIW's and ground observations are:

Anomaly no.	Association or probable source
1, 3, 4, 8, 9, 10, 12 15, 16, 17, 18, 19, 20 22, 23, 24, 25, 27, 28 29, 30, 33, 34, 38, 39 40, 41, 42, 44, 45, 46 50, 51, 52, 53, 54	Contour closures which are apparently caused by a single PIW.
7-7a, 14	Contour closure associated with two PIW's,
2, 2a, 5, 5a, 43, 43a, 43b	Contour closures associated with one PIW and one or more non-PIW or other cultural features. A casing was not found at the possible PIW immediately south of 43b.
6, 13, 26, 31, 31a, 32 32a, 34a, 35, 37 47, 48, 49, 55	Contour closure not associated with a P.I.W. Ground checking identified wells at 35, 37, 48, 49, and 55. Tractors and other steel objects were found at 13; a junk yard and probably a well at 26; a farmyard with a waterwell at 31-31a; a water flood well and pipes at 32-32a; and buildings at 47. Anomaly 6 could be associated with a transmission line.

21, 21a, 36	Contour closures outside sections where photo interpretation was done. A casing was found at 36 by ground checking and 21 and 36 are probably caused by wells.

The following PIW's are not associated with contour closures:

Well no.	Association
P1, P2, P3, P4, P5, P6 P7, P8, P9, P10, P11, P12, P14, P15, P16, P18 P19, P20, P21, P22	Associated with obvious noses in contours and peaks on aeromagnetic profiles. Well confirmed at P15.
P13, P17	No obvious nose in contours, but there is a 4 gamma peak in the profile for line 14 at well P13 and a 1 gamma peak on line 8 at well P17; the latter is probably near the threshold of detectability — see the ground measurements which were made (well H.LK 10).

There are a number of other features with a nose or disturbance in the contours and a peak in the profiles where there is no PIW.

Anomaly no.	Association
m3, m6, m7	Probable cause is a well. The contours are misplaced but the profile indicates a well which probably corresponds to the PIW northwest of the anomaly at 2. Anomaly m6 could be due to a transmission line.
m2, m8	No apparent reason for anomaly.
m1, m4, m5, m7	Associated with buildings — perhaps there are water wells.

Two of the negative magnetic anomalies, labelled A and B, were investigated. A is associated with several very long strings of pipe on the surface of the ground and B is associated with a horizontal pipe line which has sections missing.

Table 2 gives a summary of the results obtained from the records search, photo interpretation, and magnetic surveys for Horseshoe Lake sheets 1 and 2. Some of the columns must be used with caution. The sum of the PIW and magnetic anomalies is probably an overestimate of the total number of wells since some of the unchecked magnetic anomalies are probably due to cultural sources other than wells and since some of the possible PIW's may not be actual wells. Since not all PIW's without aeromagnetic expression were ground checked, the numbers in the column for PIW's without ground magnetic anomalies are incomplete.

There is a larger percentage of weak anomalies which did not produce contour closures in the Horseshoe Lake test area than in the other Oklahoma areas. The records search shows that many of these anomalies are due to wells with less than 200 ft (61 m) surface casing, usually 10 3/4" (27.3

cm).However, as in other areas, the correlation between the casing and the anomalies for individual wells is weak.

Oklahoma City sheet no. 1

This sheet is dominated by numerous anomalies characteristic of wells and a number of complex positive and negative anomalies. There is a fairly strong regional gradient trending roughly east-west. Associations of the numbered anomalies with PIW's and ground observations are:

Anomaly no.	Association or probable source
3a, 4, 5, 9a, 11, 12 13, 17, 18, 19, 20a, 23 1, 2, 7, 8, 14, 15, 16 21, 22, 26	Contour closures or prominent parts of closures which are apparently caused by a single PIW. Outside section where photo interpretation was done; some are known to be caused by wells and the rest are probably caused by wells.
3b	Ground checking identified the presence of a casing.
3, 3c, 6, 19a, 20	Probably due to casings but not ground checked.
9, 10, 24	Partly or entirely due to cultural features other than wells; 9 is associated with a pumping station; 24 with farm buildings and at 10, several small separate anomalies, but no exposed pipes, were found.
24a, 25a	Noses in contour closures associated with wells - probably due to farmyard and other features.
27	Outside section where photo interpretation was done - ground checking showed pump.

All the PIW's are associated with a contour closure. There are a few noses in the contours and peaks on the aeromagnetic profiles which may be caused by wells and there are several such features which are probably caused by other cultural sources.

Anomaly no.	Association or probable cause
m1, m2	Noses in contours and peaks in profiles which may be caused by casings. However, other known casing anomalies in this area are larger. Anomaly m1 could be caused by a bridge.

There are 15 PIW's in section 9 and there are magnetic anomalies associated with all of them. The existence of one additional casing was confirmed by ground checking. There are five other anomalies which are likely due to casings and 2 weak anomalies which are typical of casings in other areas. The records search indicated that there are 19 wells in the section. There are several prominent lows which indicate the presence of pipelines; we did not trace the pipelines but we know the location of one pumping station.

Table 2. Summary of results for Horseshoe Lake area

tion	Records search	Total PIW	PIW in surveyed area	PIW with mag anomalies	GCC* with mag anomalies and without PIW	Possible casing anomalies without PIW	Sum possible PIW and probable casing anomalies	PIW with GCNC*
2	19	16	12	12	1	4	21	0
3	13	16	12	10	0	2	18	1 possible
7	20	18	10	10	1	2	21	0
8	27	26	22	22	1	2	29	0
9	18	16	12	12	1	3	20	0
2	14	13	9	8	1	1	15	1 possible
3	14	11	8	8	2	1	14	0

*GCC Ground checked and found casing anomaly.

*GCNC Ground checked but found no casing anomaly.

Wells in this area typically contain on the order of 1000 ft (305 m) of surface casing.

Oklahoma City sheet no. 2

This sheet is dominated by anomalies characteristic of single wells and a number of complex positive and negative anomalies. The regional gradient is small and not very obvious but there may be some shorter wave length features of geologic origin. Associations of the numbered anomalies with PIW's and ground observations are:

Anomaly no.	Association or probable source
1, 2a, 3, 4, 6, 7, 8, 9 10, 11, 12a, 13, 14, 15, 16, 17, 19, 20, 21, 22 23, 24, 25, 26, 27, 28 30, 31, 32, 33, 34, 35	Contour closures or prominent parts of contour closures which are apparently caused by a single PIW. Ground checking confirmed a casing at 12a.
4a, 8a, 9a, 9b, 11a, 13b 15a, 17a, 19a, 22a, 24a	Extensions of anomalies caused by producing wells. The cause of the extensions is not known but they seem characteristic of this class of wells.
2, 12, 18, 29, 32a	Closure associated with areas where there are farmyards or other buildings, but no PIW's.
5, 7a, 13a, 14a, 16a 29a, 31a, 37	Closures without PIW's and no other obvious causes. Several of these are probably caused by wells.

Anomaly no. 37 is outside the section where photo interpretation was done.

There are a few PIW's where the contour closure is incomplete because the well is too far outside the survey area.

Well no.	Magnetic feature
P1, P2	Partial contour closure.

There is one PIW, no. P3, which is not associated with a magnetic high. It appears that either (1) this well causes a magnetic low or (2) the anomaly due to the well is small and is obscured by the negative anomaly due to some other cultural source; the latter explanation is most probable since no other well studied caused negative anomalies.

There are a few small noses in the contours and features on the profiles which could represent wells but they are probably caused by other sources.

Anomaly no.	Association or probable cause
m1, m2	No obvious possible sources.

There are two large negative anomalies labelled A and B as well as some weaker ones. Anomaly B is associated with a nearby PIW and an industrial yard lot where several drill rigs with horizontal derricks and stacks of drill pipes were stored. Anomaly A is also near an industrial yard lot.

In section 23 there are a total of 16 PIW's, 12 of which are within the area of the aeromagnetic survey. Magnetic highs are associated with 11 of these PIW's and the other one appears to be associated with a magnetic low. There are 6 other magnetic features which could be caused by casings. The records search found 18 wells in section 23. In section 24 there are 15 PIW's, all of which are associated with magnetic anomalies. There are 2 other anomalies, 2 and 18, which are very characteristic of casings but which are near groups of buildings. Anomalies m2 and 16a may be caused by wells or they may be extreme examples of the extensions of anomalies due to producing wells such as 4a, 8a, 9a, and others as noted above. The records search indicates that there are 18 wells in section 24.

Typically, the anomalies in this area are larger than in some of the other areas. Most of the wells in this area contain more than 800 ft (244 m) of 10 3/4 in (27.3 cm) surface casing.

<u>Discussion of results from Oklahoma areas</u>

As a generalization, the density of wells is greater and the anomalies are larger and more uniform in magnitude for the northern part of the Arcadia are than for the rest of the Arcadia area and the Horseshoe Lake area. The regional trend of the earth's field is generally more pronounced in some of the other Oklahoma areas such as Horseshoe Lake, than in the northern part of the Arcadia area. 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 man-made (cultural) sources than Arcadia, sheet 1, but the other Oklahoma areas probably have more such features. In some cases, shape and extent of anomalies were 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.

Considering all four test areas in Oklahoma, there is good agreement between the results from the magnetic surveys and those from photo-interpretation. 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 which are not associated with PIW's and 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	Category 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 the number 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 mistakes in 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 photo-interpretation 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.

Piney Creek

In the Piney Creek area, a primary source of information was a search of the records at the Colorado Oil and Gas Conservation Commission. In some cases it was not certain from the records that holes which had been permitted were actually drilled. The records include the offsets of the hole locations from section boundaries; in some cases there are small discrepancies between the records and actual locations but locations are generally more precise than in Oklahoma. Several wells are indicated on the topographic map; all of these locations were checked. Most correspond to casing anomalies; however, in some cases the ground was disturbed but ground magnetic measurements indicated that there is no casing. Wells with pumps and tanks were identified by direct observation in the field. The locations of known casings are indicated on the flight line maps; their numbers correspond to the numbers on the contour maps of features which were ground checked.

Following are comments regarding the results of ground checking:

Feature	Original well no. (Frischnecht and and others, 1983)	Comments
1		Topographic map indicates well -- ground is smoothed off but there is no evidence of casing.
2		Casing present -- anomaly on aeromagnetic profile is not very diagnostic.
3, 4, 5, 9a		No casing found -- broad magnetic high mapped on ground.
6		Well with tank and pump -- aeromagnetic profile shows very sharp anomaly.
7		Producing well -- aeromagnetic profile shows very sharp 9 gamma anomaly.
8, 9		Casing above surface -- aeromagnetic profile shows sharp peak on broader magnetic high.
10	(1)	Casing present -- aeromagnetic profile shows non-distinctive 6 gamma peak.
11	(8)	Casing above surface -- narrow ground magnetic anomaly --aeromagnetic anomaly is no more than 1/2 gamma.
12		Working well with tanks -- topographic map indicate three wells in this vicinity but ground measurements indicate only one well and a number of horizontal pipelines which terminate.

13		Working well -- large, sharp peak on aeromagnetic profile.
14	(2)	Casing present -- aeromagnetic profile shows isolated 8 gamma anomaly.
15		Topographic map indicates well -- aeromagnetic profile is not diagnostic of well -- ground checking did not locate casing.
16	(4)	Casing above ground -- large sharp aeromagnetic peak
17	(3)	Used as test well for ground measurements --aeromagnetic anomaly is too broad to be diagnostic.
18		Not thoroughly ground checked but no evidence of well — aeromagnetic anomaly is not diagnostic.
19		Casing present -- ground magnetic anomaly is only about 1000 gamma peak and is narrow -- aeromagnetic anomaly, if any, is obscured by steep gradient and is probably less than two gammas.
20		Fairly sharp 7 gamma anomaly on aeromagnetic profile --ground checking located casing not known previously from topographic map or records.

In the Piney Creek Co test area there are 14 wells which are known from ground magnetic measurements or visual evidence; there are two others indicated by records which could not be confirmed (12A, 13A). Two of the known wells did not cause recognizable aeromagnetic anomalies. A weak airborne anomaly from well no. 19 is probably obscured by a strong gradient of geologic origin; there is no apparent reason for the failure to detect well no. 8.

Discussion of sources in Piney Creek area

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. The results of one long ground traverse (figure 9) are shown in figure 11 together with the same profile continued upward to aircraft altitude (Tien Grauch, written communication, 1984). The agreement between the upward continued profile and the airborne results is good; a precise match would not be expected because the anomaly is not two-dimensional. Although the difference between this ground anomaly, due to a geological source and the ground anomaly due to a casing is profound, at an altitude of only 61 m aeromagnetic profiles over the two sources are quite similar.

The sources of the geologic anomalies in the Piney Creek area were not identified. According to Oberhansley (1982) the surface rocks in this area are the upper part of the Dawson Arkose. According to Bryant and others (1981) the surface rocks are lower units in the Dawson. These lower units are primarily arkosic sandstone, claystone, fine grained sandstone, carbonaceous shale and lignite facies probably of Eocene and Paleocene ages. They locally contain tuffite beds and an occurrence of crystal tuff was found immediately east of the area. The tuffite beds are probably the sources of the magnetic anomalies, although one would not normally expect such material to be as highly magnetized as is indicated by the magnetic survey. In any case these rocks are much more magnetic than most other sedimentary rocks.

Summary of Results

Due to the limitations of record searches and other data, 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 photo-interpretation in the Oklahoma areas.

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 length and diameter 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 in some casings may be abnormal due to variations in manufacture or unusual stresses imposed during emplacement, or the casings may have been selectively corroded away. It is worth noting that all of the casings observed were normally polarized with respect to the Earth's field. This direction of polarization is probably acquired during placement of the casing.

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. Removal of a regional field or filtering would probably have made interpretation somewhat easier. We conclude that most wells containing on the order of 60 m (200 ft) or more of 21.0 cm diameter (8 5/8 in.) or larger surface casing can be detected in most environments by airborne measurements. Much smaller amounts of pipe can be found with a ground magnetometer; however, very closely spaced measurements are then required.

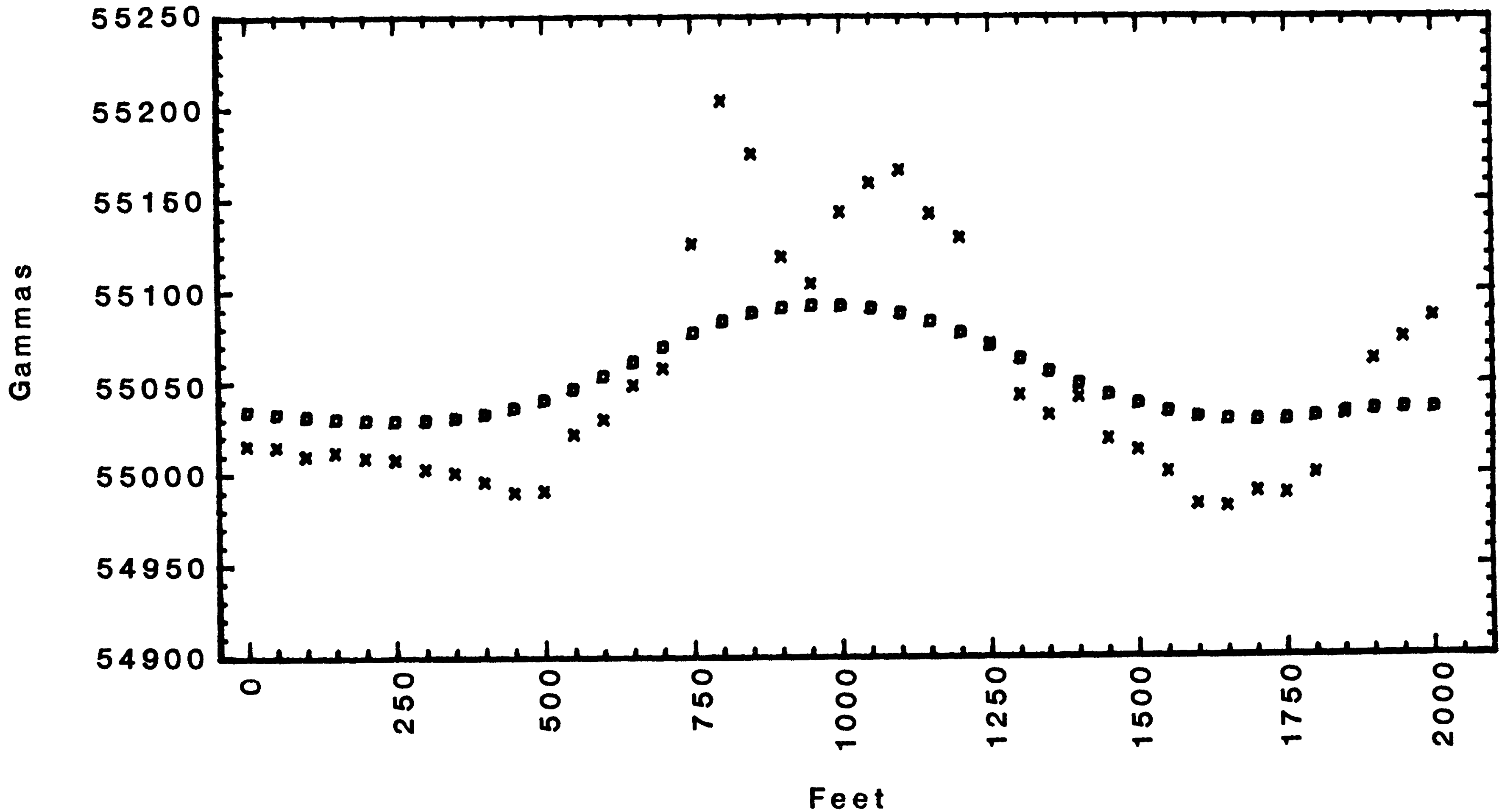

Figure 11. Ground magnetic profile. Stars are observed values -- squares are observed data continued upward to flight elevation (200 ft).

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APPENDIX 1

FINAL REPORT

HIGH SENSITIVITY MAGNETIC

DATA PROCESSING AND PRESENTATION

FOR

HORSESHOE LAKE, OK.
MOORE, OK.
ARCADIA, OK.
OKLAHOMA CITY, OK.
PINEY CREEK, CO.

FEBRUARY, 1984

Submitted to:

U. S. GEOLOGICAL SURVEY
OFFICE OF GEOCHEMISTRY AND GEOPHYSICS
DENVER, CO. 80225

Submitted by:

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INTRODUCTION

A series of high sensitivity magnetometer surveys were conducted by the U.S.G.S. over 5 producing oil fields located in Colorado and Oklahoma. The objectives were to identify magnetic anomalies caused by oil wellheads and casings, and to verify the locations indicated from the aeromagnetic data by comparison of the mapped magnetic data with detailed aerial photography.

This report documents the data processing steps used by Future Resources, Inc. in the preparation of both the aeromagnetic contour maps and the magnetic profiles .

SURVEY AREAS

Four oil fields were surveyed in Oklahoma, all of which were located near Oklahoma City. These fields include Moore, Arcadia, Horseshoe Lake, and Oklahoma City. The fifth field is located in the Denver-Julesburg basin, Colorado. This field is referred to as Piney Creek on the aeromagnetic maps and profiles.

DATA PROCESSING PROCEDURES

Flight Path Recovery

Due to the detailed presentation scale used for the aeromagnetic maps (1:6,000), an automatic navigation system (Motorola Mini-Ranger) was used both to indicate aircraft position to the pilot and for digital flight path recovery. Location data were read from the field tapes as distance from a transponder network located in the survey area. Two transponders were employed at all times. To remove the location ambiguity, an interactive program was designed to enable the computer operator to determine the proper location of the intersecting distance radii.

Flight path positioning is noted on the flight path maps. In addition, every 20th data scan fiducial number is also annotated on the maps. Data scans were maintained at the rate of 1 scan per 0.2 seconds throughout the survey.

Errors in the absolute positioning of traverse lines and tie lines are obvious sources of error in that the location of magnetically anomalous features can be misplaced. The Motorola Mini-Ranger system provided excellent navigational control since the topography was relatively gentle. Relative positioning errors do not exceed +/- 5 meters. Absolute location errors depend upon the accuracy of location of the transponder stations. A tracking camera was also emoloyed in the event of a misregistration of the digital location data. Visual pick points were also annotated by the flight crew. It was not necessary to employ any of these back up navigation aides in compiling the digital location data.

Altitude Recovery

Both barometric and radar altitude data were digitally recorded in the aircraft and are displayed on the profiles. Radar altimeter calibration was performed prior to surveying. Barometric altimeter calibration was accomplished daily by noting the beginning and ending reference sea level pressures at the airport. In addition, a digitally recording thermometer was used to adjust the barometric data using an isothermal atmospheric mode. Due to the diurnal pressure variations during the day, it is expected that the relative barometric altitude error is +/- 20 feet.

Diurnal Compensation

A diurnal monitor was maintained at a fixed base station within the survy area. However, to avoid introducing errors due to uncompensated diurnal variations, an iterative level adjustment program was employed to remove both diurnal and heading effects. Uncompensated diurnal variations are those time varying components of the earth's magnetic field within the survey area which differ from those observed at the fixed base station. Generally, these effects are due to small phase changes of the diurnal field which could be due to source inhomogeneties or induction effects from seep seated geological sources. These effects should be small within an areally limited survey. They can be eliminated by interactive adjustment of the traverse-tieline mistie errors. Adjustments of these mistie errors resulted in a maximum error of 0.40 gammas over all areas, and a mean absolute residual of 0.20 gammas. This residual is easily explained by a combination of maneuver noise, location, and altitude control errors. The ultimate success of the second order diurnal adjustment is related to the relative accuracy of flight path location and altitude control.

Maneuver Noise Compensation

Maneuver noise causes actual magnetic signals due to the motion of a magnetic and conductive airframe within the fixed magnetic field of the earth, and also the effect of this motion on the magnetic sensor element for a proton precession magnetometer sensor.

There are four different sources of maneuver noise in magnetic surveys employing proton precession magnetometer sensors. These are:

1. The permanent magnetism of some of the rigid structural members of the aircraft. As these elements turn with the aircraft maneuvers, a change in the magnetic field will occur. This is referred to as the permanent component.

2. The ferromagnetic material used in the airframe can produce induced magnetic fields by interaction with the earth's field. This induces a magnetic field, the strength of which is determined by the direction of the earth's field

relative to the airframe. This is referred to as the induced component.

3. Electrically conductive structural members of the airframe and the aircraft skin give rise to electrical currents within these members as the aircraft maneuvers. These currents produce a secondary magnetic field. This field is referred to as the "eddy current" component.

4. For the proton precession magnetometer used in the survey, another type of error signal can occur. This is due to the motion of the sensor housing and fluids relative to the protons in precession about the earth's field. This relative motion can change the apparent precession frequency and an apparent, but not real, change in the recorded magnetic field can result. This effect is known as the "platform error" component.

There are 19 coefficients required to completely specify the components of the maneuver noise transfer function. To simplify the problem, the identification and compensation of these maneuver errors were treated as a multi-channel "signal" extraction problem. The "signal" is that component of the observed magnetic field which is highly correlated with the actual maneuver, and the time rate of change of maneuver of the aircraft. A maneuver as recorded on the yaw, pitch, and roll gyros generates magnetic signals at the same frequency as the maneuver together with higher order harmonics of motion. Future Resources employed a multi-channel MESA (Maximum Entropy Spectral Analysis) analysis of the magnetic signal and the amplitude and time rate of change of the motion sensors to calibrate the effective transfer function of the maneuver error. A transfer function was computed and an error correction signal was generated which minimized the coherence between the maneuvers and the corrected magnetic signal. This transfer function was tested both in the calibration area and on the production flights over the Horseshoe Lake area. The maximum coherence between the maneuver signals and the magnetic fields always occurred for the roll component of motion. For this component, the average value of the coherence was 0.24 over Horseshoe Lake.

The first component of maneuver noise to be isolated and removed was the platform motion component. This component was estimated by projecting the angular motion components as detected on the yaw, pitch, and roll sensors onto the axis of the magnetic sensor, and subtracting the effect. To assure that the correct sense of motion was computed, a MESA analysis before and after platform correction was applied to data over the Horseshoe Lake and Piney Creek surveys, to insure that the coherence between the magnetic signal and the projected rotation vector was lowered by subtraction. Next, eddy current effects were eliminated by noting the phase angle as a function of frequency between the platform corrected signal and the yaw, pitch, and roll components. Motion component phase angles at approximately +/- 90 degrees from the platform corrected data which displayed coherencies greater than 0.50 were identified as possible eddy current sources. Only the roll component showed significant coherence with the magnetic field, and a transfer function was computed to remove this effect. It should be noted that a differential coil configuration was installed in the aircraft to monitor eddy current effects. However, its extremely high noise level did not allow its use in the calibration procedures. Finally, the transfer function for the permanent and induced components of differential motion were estimated from MESA analysis of the roll-eddy current corrected signals, and these effects were subtracted from the data.

Aeromagnetic Maps

Four steps were involved in the compilation and computer drafting of the aeromagnetic maps presented. These are:

1. Field tape copying and editing.

2. Flight path reconstruction from the Mini-Ranger data.

3. Magnetic data adjustment and error compensation.

4. Gridding and contouring .

The field tape copying and preliminary editing involved converting the raw field data tapes into a format compatible with the Hewlett-Packard 1000 system used in the processing. "Scrubbed" flights were eliminated from the data base, and the tapes were formatted for internal processing.

The flight paths as determined from the Mini-Ranger data were reconstructed from the edited field tapes. Flight path exhibiting severe data drop out were identified. Preliminary flight path maps were generated at scale of 1:24,000 to check for digital navigation errors. The preliminary maps were spot checked against the planned flight directions in order to verify absolute and relative location data. A located data tape was produced for further processing.

The calibration flights, and selected production flights were analyzed by the multi-channel MESA method to determine an appropriate maneuver transfer function. The date were adjusted to compensate for the errors outlined in the previous section. The diurnally compensated, datum adjusted and tied data were corrected for maneuver noise.

The final data were gridded by a minimum curvature spline technique and contoured on a Cal-Comp plotter. Grid intervals for all areas averaged 25 meters in x and y.

Stacked Profiles

Stacked profiles are presented at a scale of 1:6,000. Every 40th fiducial is annotated on the profiles for easy comparison with the aeromagnetic map. The profiles include the following data items:

1. Corrected magnetic data.

2. Maneuver correction signal.

3. Yaw, pitch, and roll signals.

4. Barometric altitude data.

5. Radar altimeter data.

6. Fiducial registration.

Digital tapes include all data displayed on the profiles in addition to the UTM coordinates of all data scans.

Appendix 2

Figures A1 - A14

Tables A1 - A2

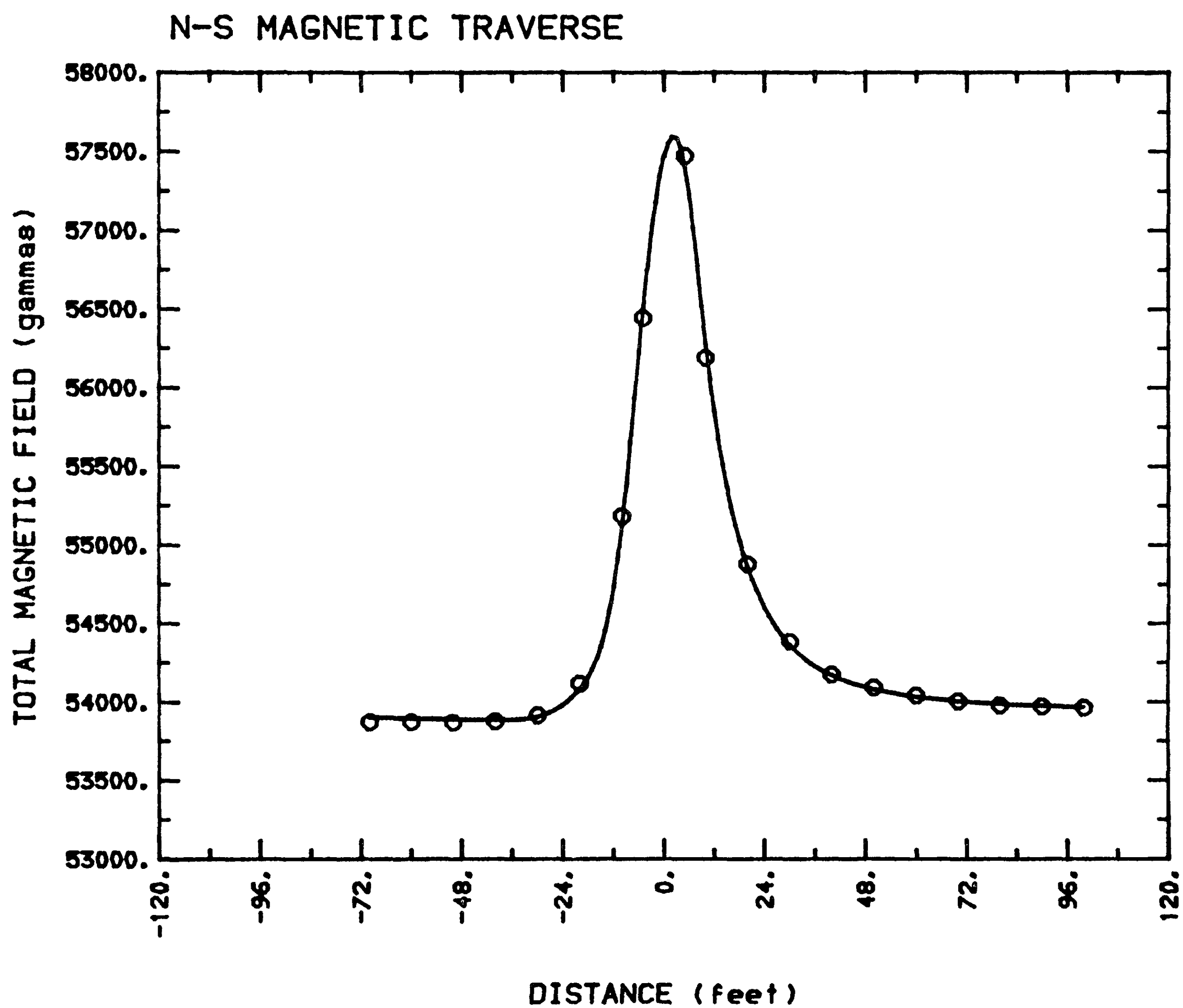

Figure A1. Observed and calculated results for Arcadia well no. 1.

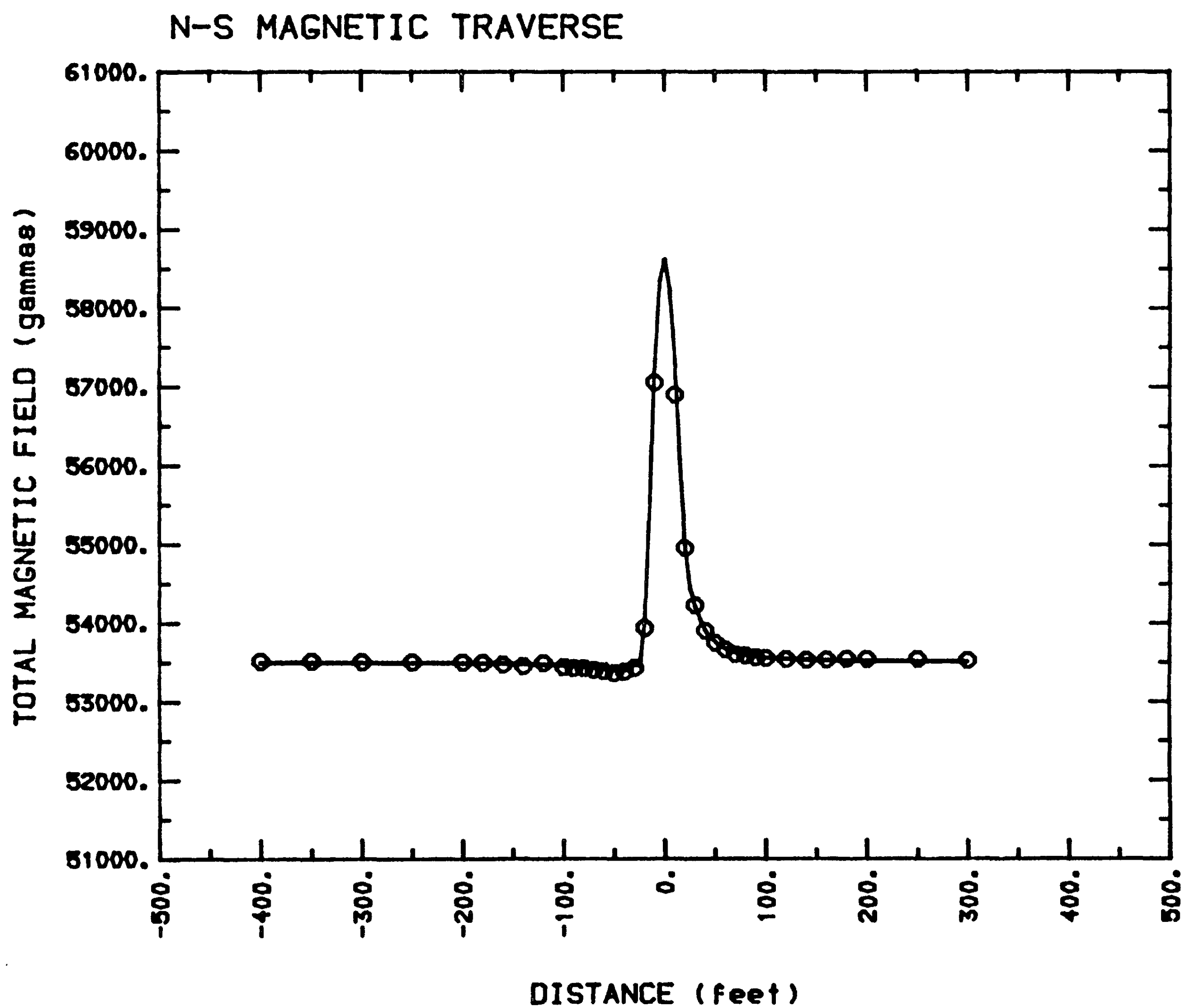

Figure A2. Observed and calculated results for Horseshoe Lake no. 8.

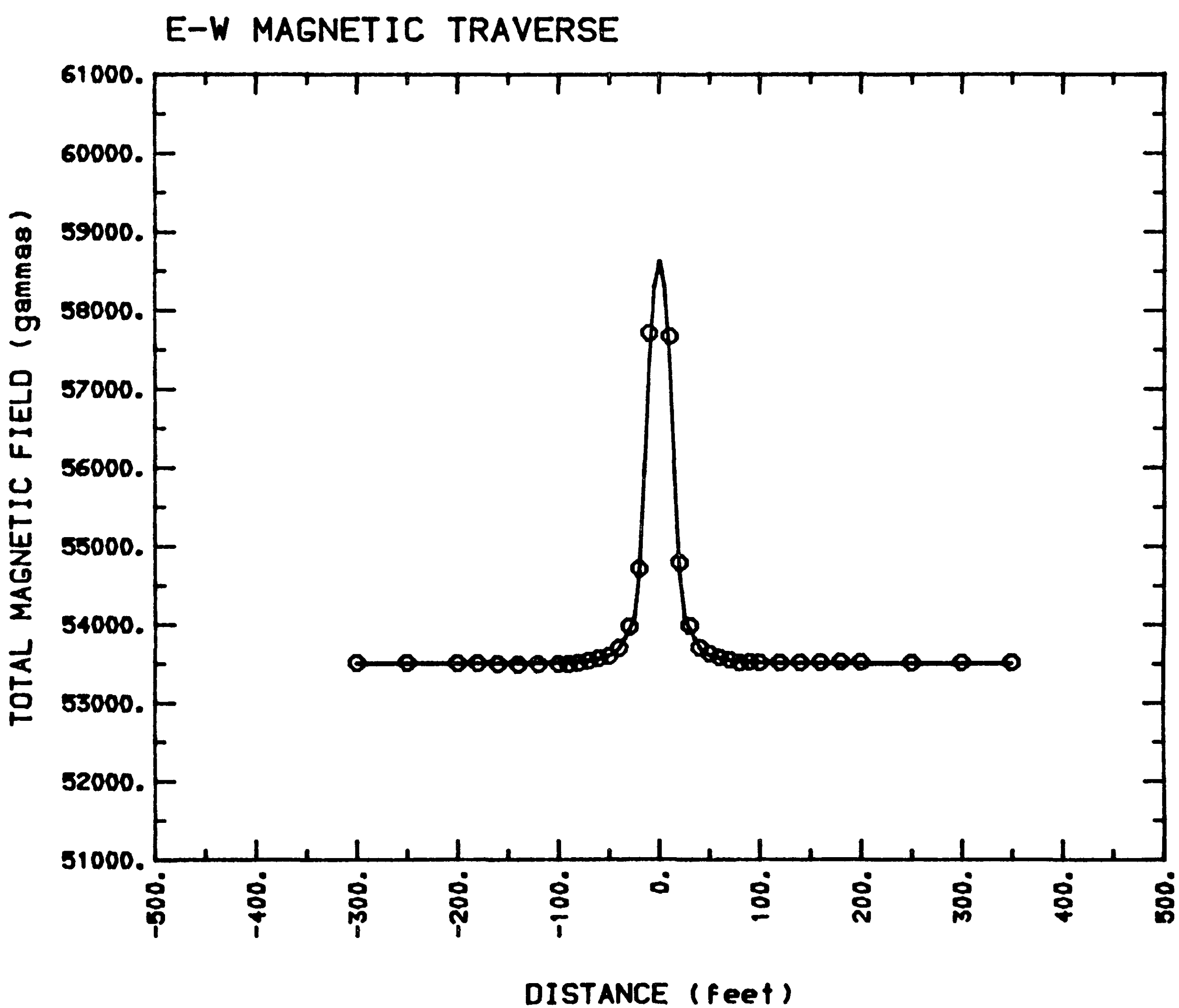

Figure A3. Observed and calculated results for Horseshoe Lake well no. 8.

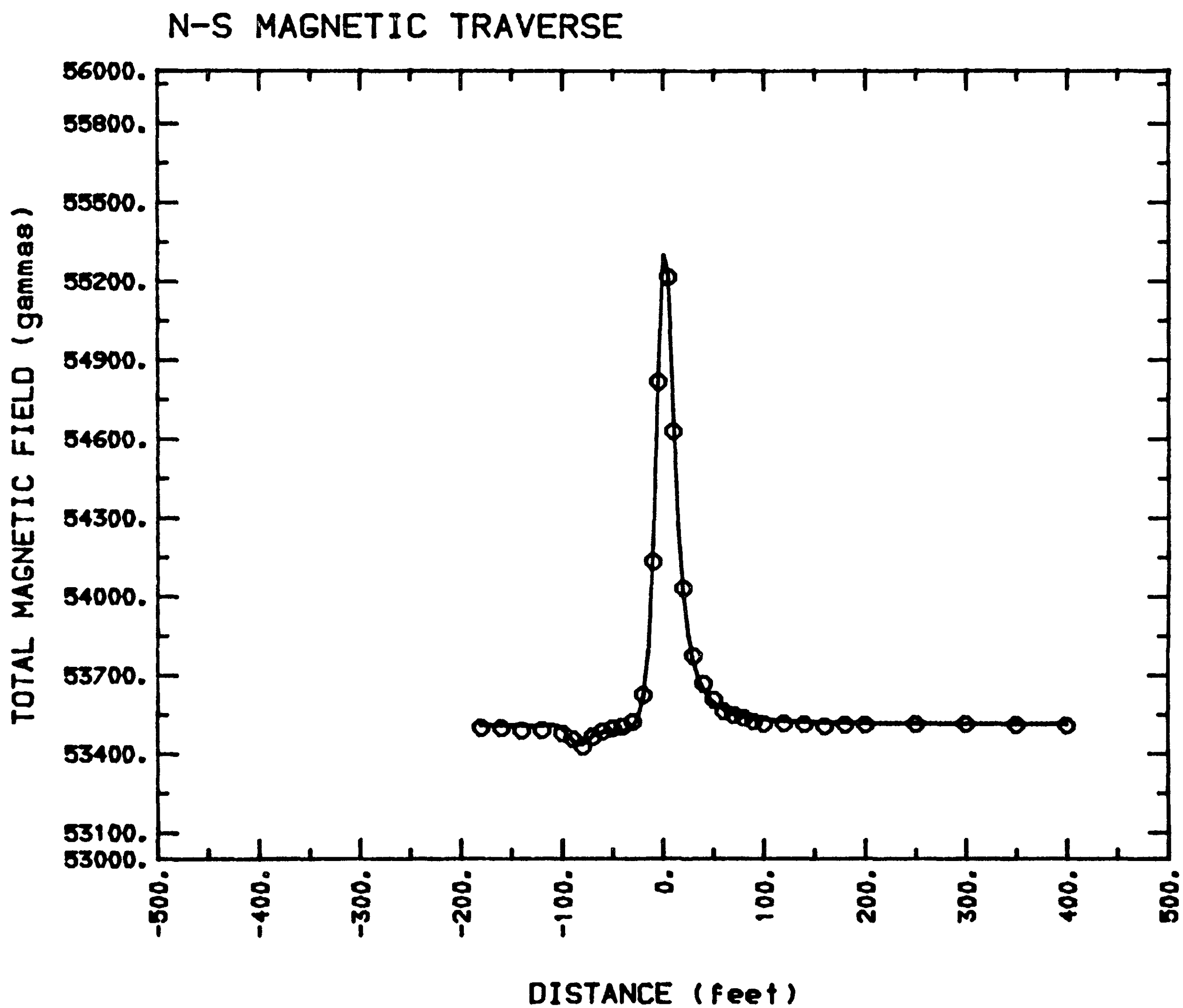

Figure A4. Observed and calculated results for Horseshoe Lake well no. 9.

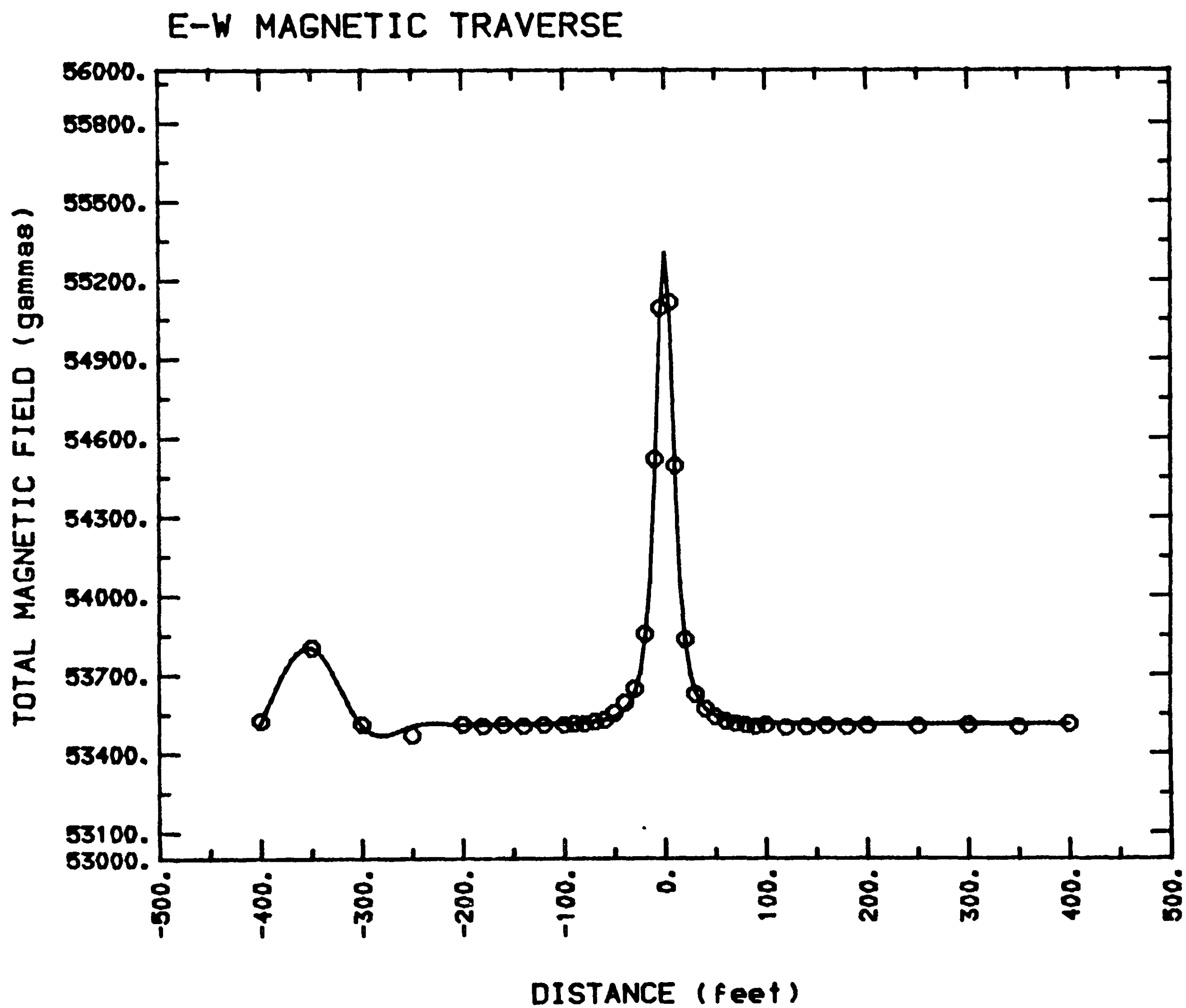

Figure A5. Observed and calculated results for Horseshoe Lake well no.9 .

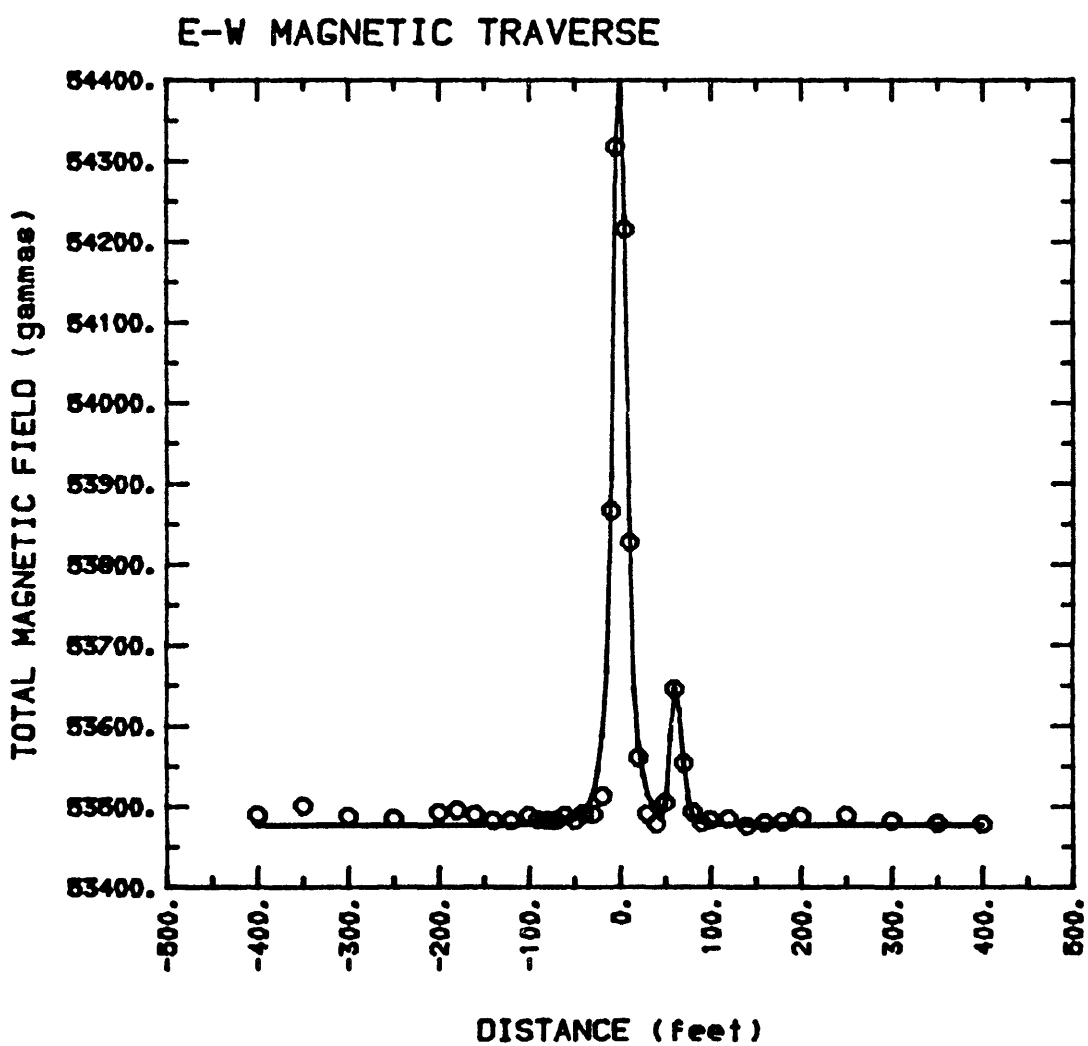

Figure A6. Observed and calculated results for Horseshoe Lake well no. 10.

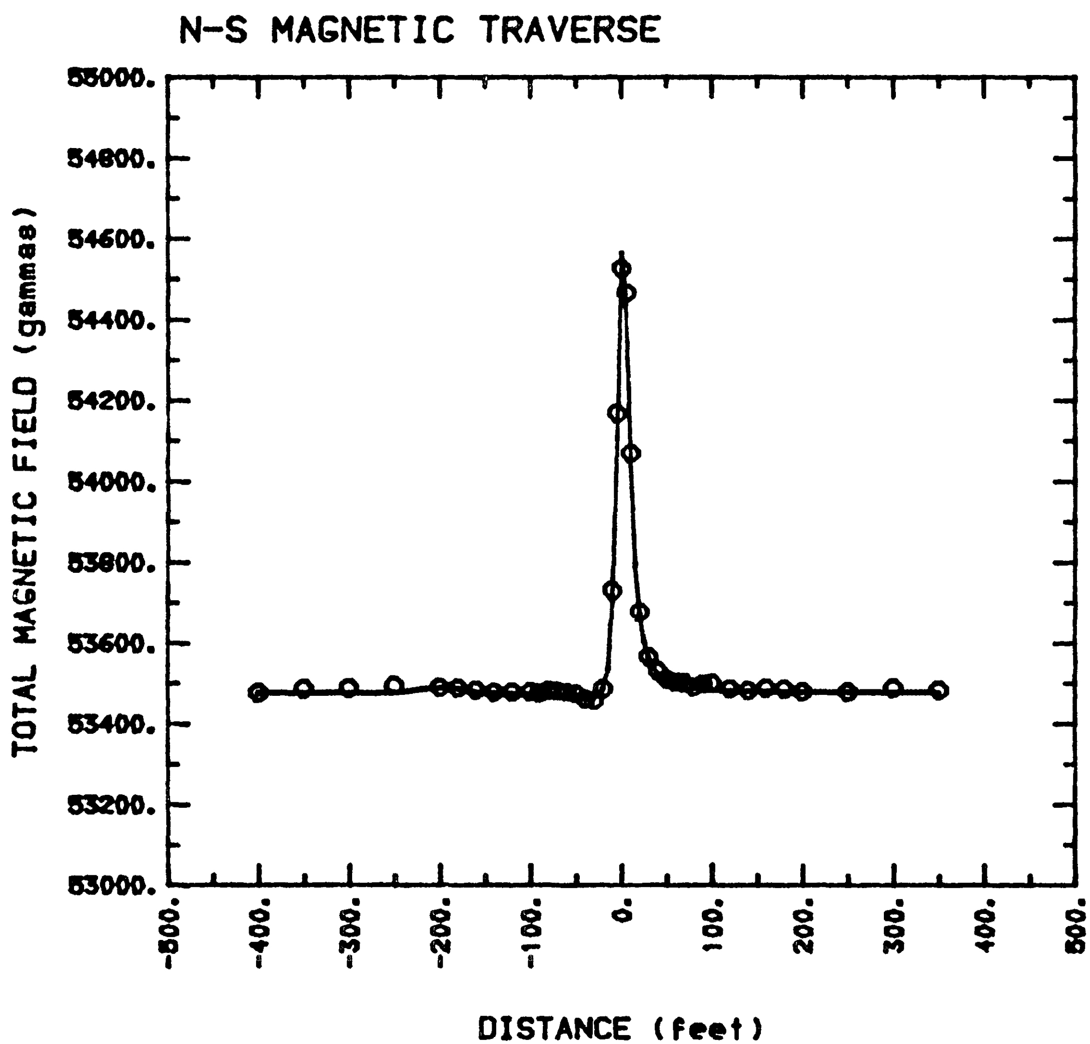

Figure A7. Observed and calculated results for Horseshoe Lake well no. 10.

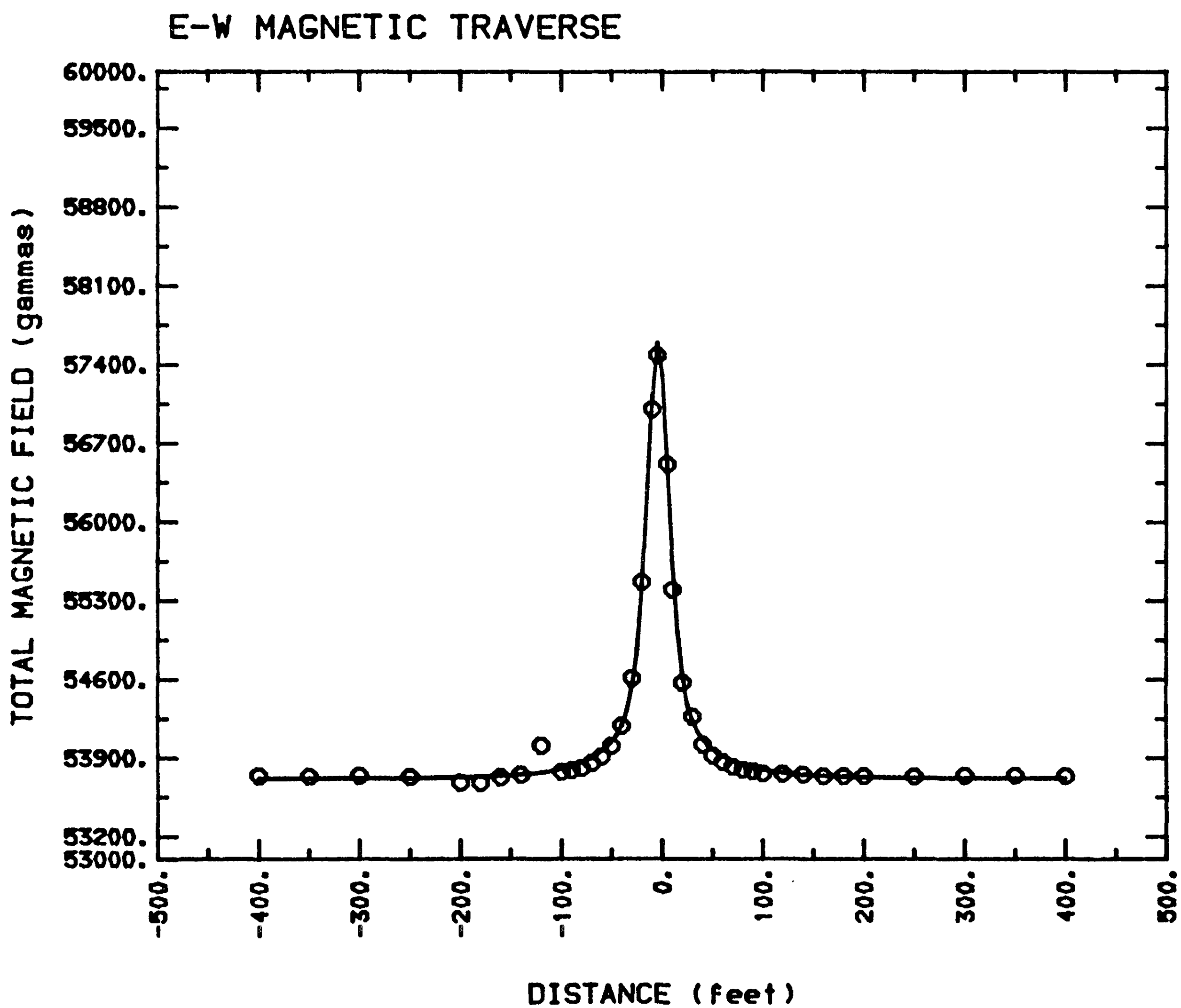

Figure A8. Observed and calculated results for Moore well no. 5.

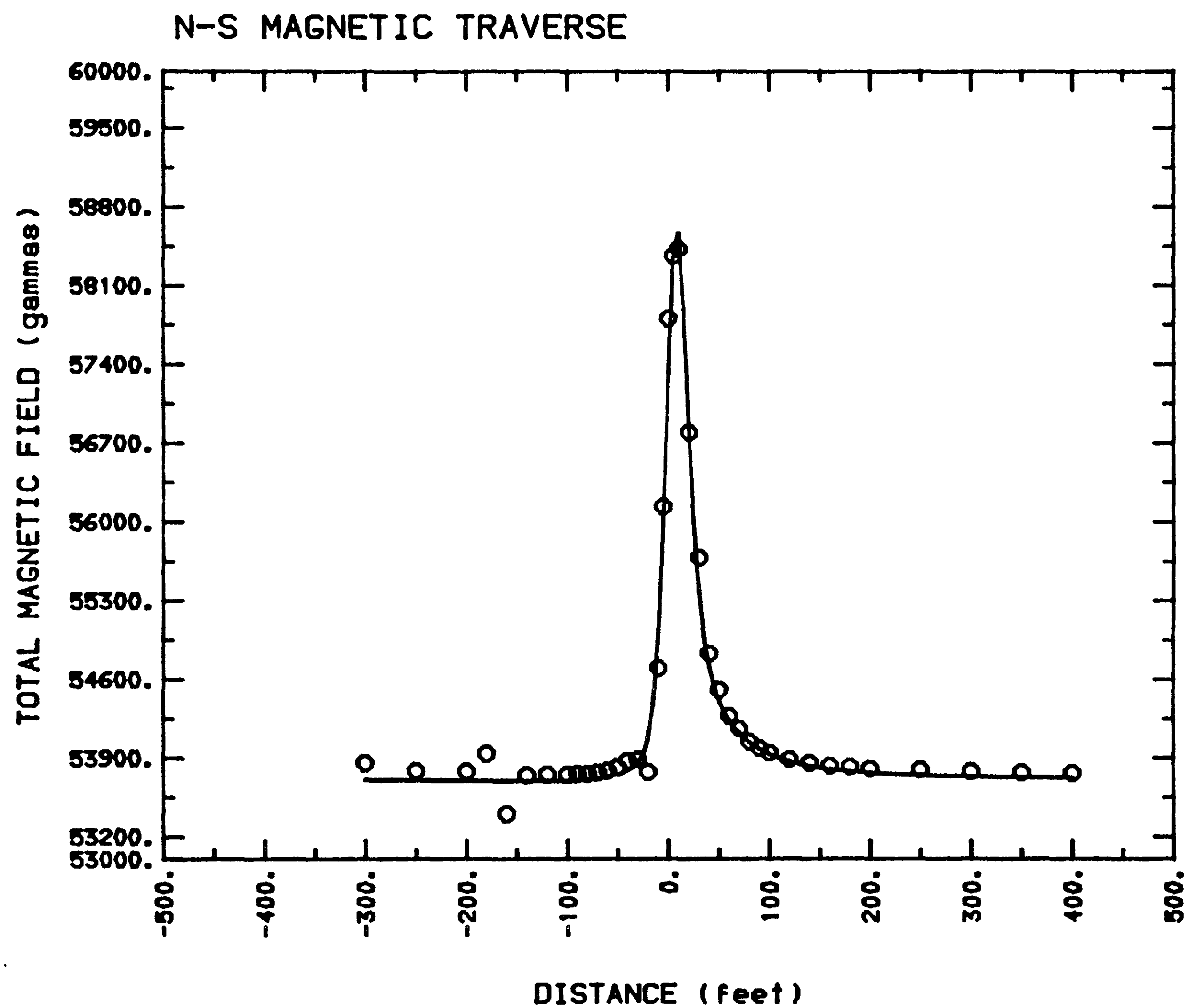

Figure A9. Observed and calculated results for Moore well no. 5.

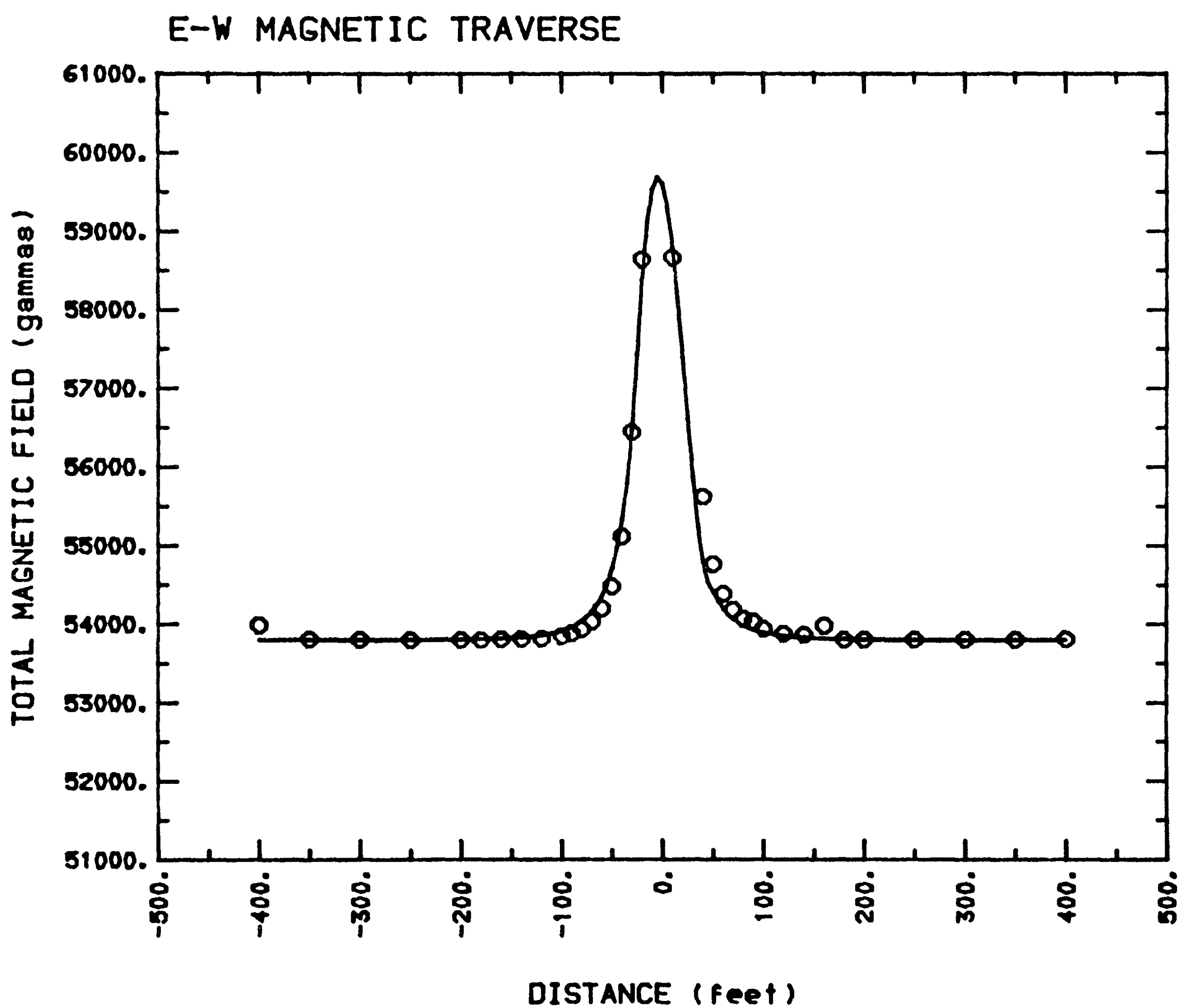

Figure A10. Observed and calculated results for Moore well no. 6.

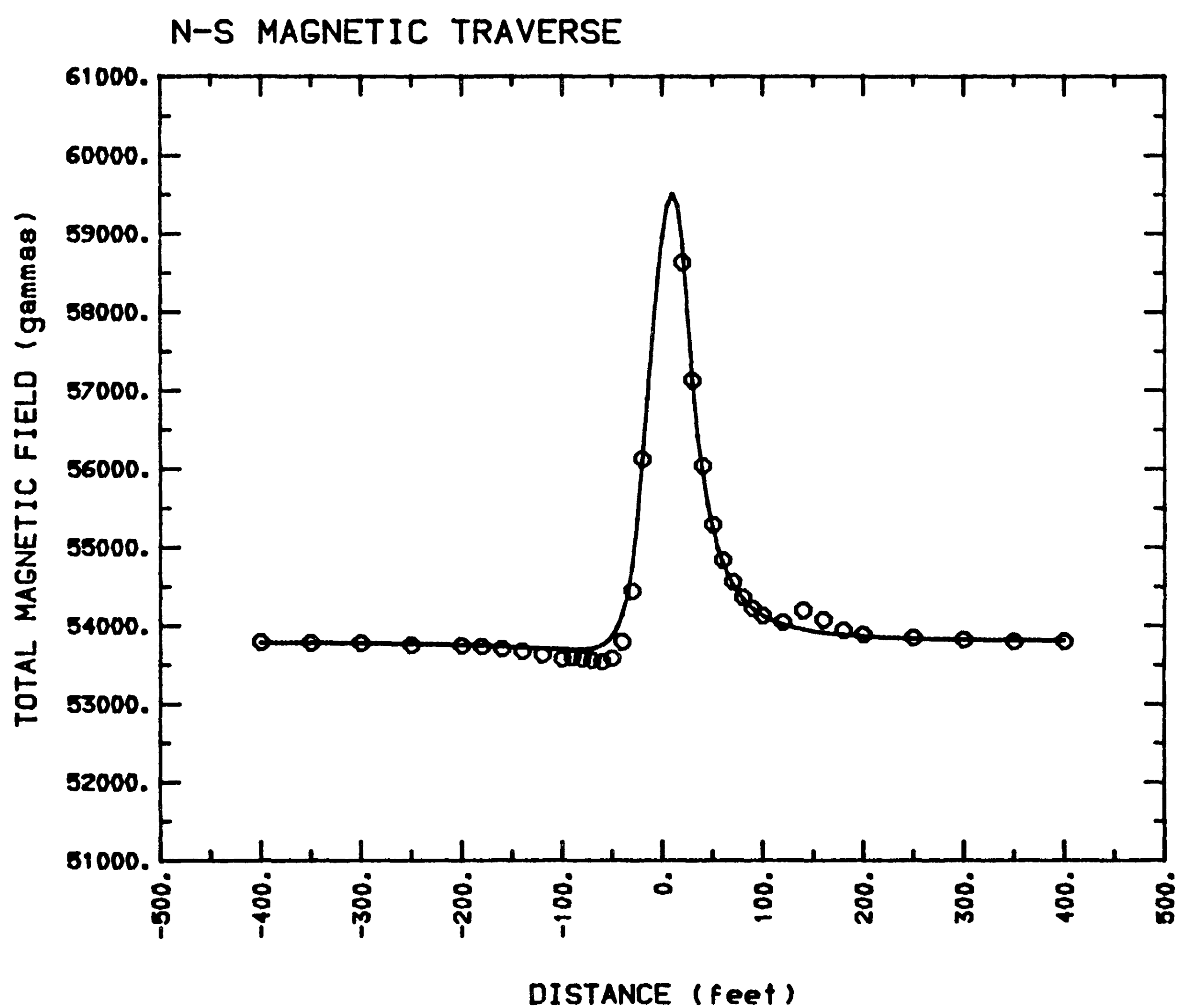

Figure A11. Observed and calculated results for Moore well no. 6.

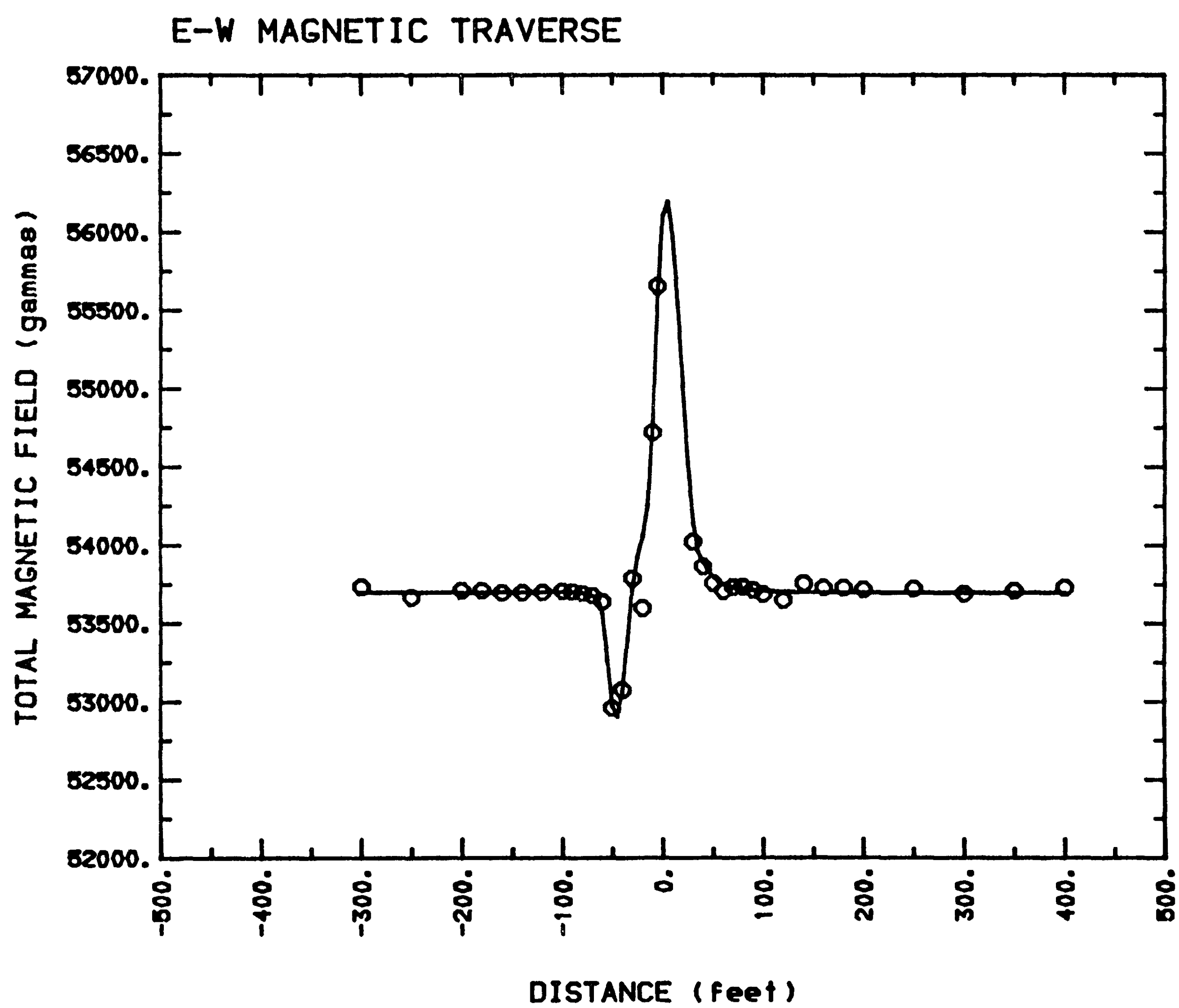

Figure A12. Observed and calculated results for Moore well no. 16.

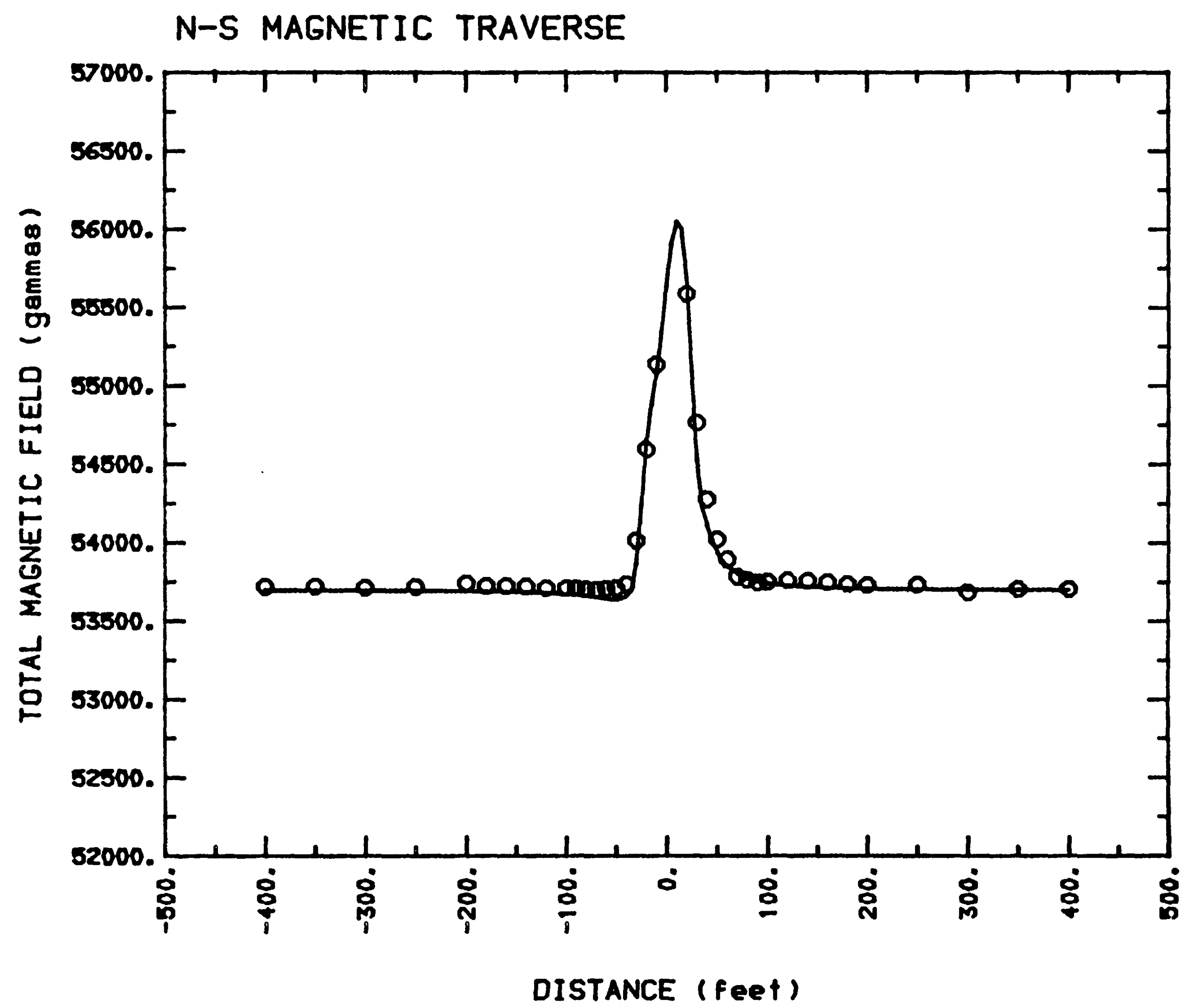

Figure A13. Observed and calculated results for Moore well no. 16.

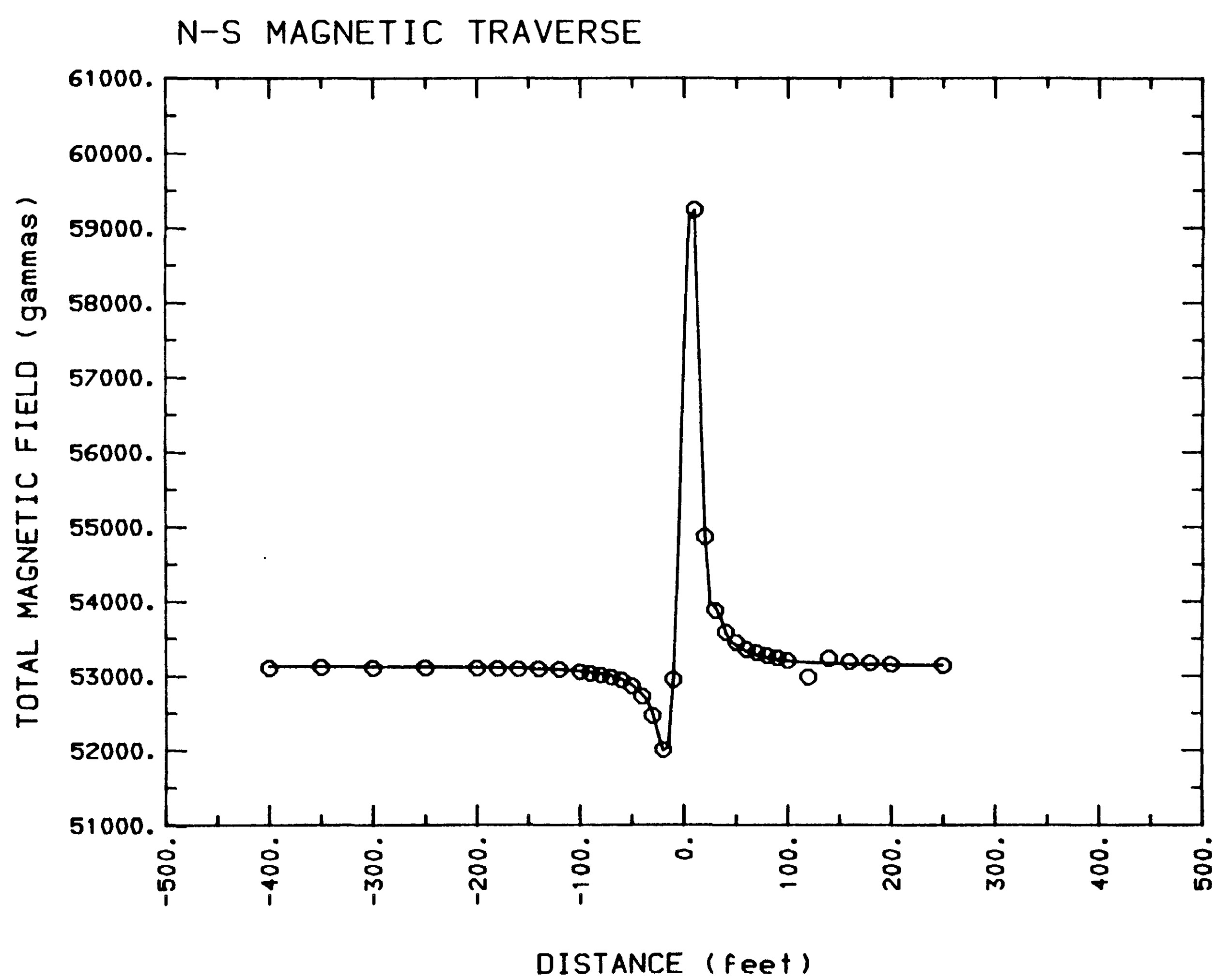

Figure A14. Observed and calculated results for Oklahoma City well no. 12.

Table A1 - Summary of results from wells in Oklahoma

			First Casing											Other Casing					
	Anomaly No.	m_1	m_1					m_2	m_2					m_1	m_2				
well	or PIW No.	SI	hybrid	x	y	z	ℓ	SI	hybrid	z_{12}	$ℓ_2$	β	ϕ	SI	hybrid	x	y	z	ℓ
AR 1	P3	580	6,248	0	0	-12	382												
H. Lk 8	12a	1,134	12,206	-3	0	-12	1,337												
H. Lk 9	24	327	3,524	-1	0	-13	1,112					142	-32	116	1,247	7	-354	-13	93
												97	-3	14	146	86	0	-13	42
H. Lk 10	P17	118	1,268	0	0	-10	617					189	20	9	102	0	63	-6	202
Ok. C 12	15	1,511	16,260	-1	5	-2	378												
M 6	21	5,214	56,121	1	-4	-26	422												
M 5	P4	2,674	28,779	6	4	-19	119	3,183	34,265	39	581								
M 16	19	764	8,227	5	6	-10	3,020												

m = pole strength

x, y, z = position of pole

z_{12} = separation between upper poles of first and second pole pairs

ℓ = separation between pair of poles

β = inclination of casing from horizontal

α = azimuth of casing

Table A2. Summary of Results from wells in Colorado

	*m_1	m_1			m_2	m_2					m_l	m_l					**surface	***inner
	First Casing								Other Casing									
well	SI	hybrid	z_1	ℓ_1	SI	hybrid	z_{12}	ℓ_2	β	ϕ	SI	hybrid	x	y	z	ℓ	casing	casing
1	661	7,117	-21	534													260	8,450
2	1,098	11,820	-16	158					3	267	520	5,600	12	137	-12	48	210	8,562
3	507	5,460	-15	77					350	3	440	4,730	0	0	-7	-21	292	8,422
4	2,006	21,590	-18	12	9,388	10,105	2.5	979.2									211	8,390
5	290	3,120	-6	264													266	
6	638	6,870	-13	123													264	
7	416	4,477	-11	184	5,363	57,300	11.4	158									196	
8	850	9,151	-7	123					141	0	+1,223	+13,163	3	-1	-9	8	270	6,068
9	1,077	11,590	-17	100					50	33	+120	+1,291	8	12	-28	-27	221	
10	953	10,260	-13	102													246	
11	640	6,889	-12	215					16	31	+280	+3,010	-88	5	-12	5	267	8,333
12	2,218	23,880	-18	10					0	302	184	1,985	-189	0	-18	27	?	
13	389	4,184	-14	100					4	13	242	2,605	3	0	-9	28	?	
14	429	4,613	-10	30					280	315	472	5,084	7	-9	-7	-27	36	
16	1,367	14,717	-17	200													300 (10 3/4)	
17	1,503	17,040	-20	100													300 (8 5/8-32 lb/ft.)	
						Joint inversion												
15S&15N	1,349	14,519	-15	455					81	104	750	8,072	28	-2	-13	613	200 (8 5/8-32 lb/ft.),	
									88	94	270	2,907	62	1	-2	5	1000 (5 7/8 - 26 lb/ft.)	
									225	167	397	4,271	-159	-8	-4	-17		

*Poles are negative unless otherwise noted

**Surface casing is 8 5/8" at 24 lb/ft unless otherwise noted

***Inner casing is 5 1/2" at 15.5 lb/ft unless otherwise noted