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GEOPHYSICAL METHODS FOR LOCATING ABANDONED WELLS

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PREFACE

The U.S. Environmental Protection Agency's (EPA) Environmental Monitoring Systems Laboratory in Las Vegas has provided the funding for the research effort described in the report. The mathematical model described in this report of a magnetic anomaly for a steel-cased well indicates that an airborne magnetic survey can theoretically locate abandoned wells. The EPA has enlisted the help of the National Center for Groundwater Research at the University of Oklahoma to identify areas around Oklahoma City where high-resolution aerial magnetic surveys may be flown. The Environmental Monitoring Systems Laboratory in Las Vegas has funded the U.S. Geological Survey (USGS) to perform these field studies in 1983, and the results will be presented in a later USGS/EPA report in 1984.

The cooperative effort between the EPA and the USGS is aimed at providing local, state, and Federal agencies with the methodology to determine if abandoned wells exist in an area where the underground injection of wastes is contemplated. Magnetometer surveys will likely be just one of several methods that can be utilized in locating abandoned wells. The record searches conducted by the National Center for Groundwater Research and the historical photographic searches conducted by the EPA's Environmental Photographic Interpretation Center may provide alternative approaches to the problem of locating abandoned wells. An examination of the costs and benefits of the various methods will be available from the EPA in 1984 after the USGS has completed the field studies in Oklahoma.

ABSTRACT

A preliminary study of the feasibility of using geophysical exploration methods to locate abandoned wells containing steel casing indicated that magnetic methods promise to be effective and that some electrical techniques might be useful as auxiliary methods. Ground magnetic measurements made in the vicinity of several known cased wells yielded total field anomalies with peak values ranging from about 1,500 to 6,000 gammas. The anomalies measured on the ground are very narrow and, considering noise due to other cultural and geologic sources, a line spacing on the order of 50 feet (15.2 m) would be necessary to locate all casings in the test area.

The mathematical model used to represent a casing was a set of magnetic pole pairs. By use of a nonlinear least squares curve-fitting (inversion) program, model parameters which characterize each test casing were determined. The position and strength of the uppermost pole was usually well resolved. The parameters of lower poles were not as well resolved but it appears that the results are adequate for predicting the anomalies which would be observed at aircraft altitudes. Modeling based on the parameters determined from the ground data indicates that all of the test casings could be detected by airborne measurements made at heights of 150 to 200 feet (45.7-61.0 m) above the ground, provided lines spaced as closely as 330 feet (100 m) were used and provided noise due to other cultural and geologic sources is not very large. Given the noise levels of currently available equipment and assuming very low magnetic gradients due to geologic sources, the detection range for total field measurements is greater than that for measurements of the horizontal or vertical gradient of the total intensity.

Electrical self-potential anomalies were found to be associated with most of the casings where measurements were made. However, the anomalies tend to be very narrow; and, in several cases, they are comparable in magnitude to other small anomalies which are not directly associated with casings. Measurements made with a terrain conductivity meter and slingram system were negative. However, from other work it is known that electrical resistivity and induced polarization measurements can be influenced significantly by the presence of a casing.

It is concluded that detailed ground magnetic surveys would be effective in locating casings within relatively small areas. It would be very costly to cover large areas with ground surveys, but it appears that airborne surveys may be a cost-effective means of locting wells when the search area is on the order of a few square miles or more. Also, airborne methods could be used in some areas where access to the area on the ground is difficult or impossible.

This report was submitted in partial fulfillment of interagency agreement AD-14-F-2-A092 by U.S. Geological Survey under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from April 1982 to April 1983, and work was completed as of April 1983.

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SECTION 1

INTRODUCTION

The Underground Injection Control Regulations (UIC), issued 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 which a search must be made for possible conduits, such as abandoned injection wells, from the injection stratum to overlying aquifers containing potable water. Geophysical methods originally developed for resource exploration may offer assistance in carrying out these regulations. The U.S. Environmental Protection Agency in an interagency agreement with the U.S. Geological Survey sponsored a preliminary study of the feasibility of using geophysical exploration methods to locate abandoned wells containing steel casing.

It was estimated in 1979 that there were some 500,000 municipal, industrial, commercial, agricultural, and domestic wells in the U.S. injecting fluids below the surface, and that at least 5,000 new injection wells were being constructed each year. Also, due to differential pressures, dormant wells sometimes serve as conduits between aquifers containing brine or other pollutants and fresh water aquifers. Location of 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. 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.

Throughout the history of petroleum production, steel casings have been used in drilling almost all petroleum wells; and, until recently, steel casings were used in most water wells. In some cases, all or part of the casing has been removed from the well. Magnetometer surveys offer a means of locating abandoned wells which contain steel casing near the surface. Magnetometers are used to map perturbations in the Earth's magnetic field such as those caused by buried ferromagnetic objects. A steel casing causes a relatively large disturbance in the magnetic field at distances on the order of tens to hundreds of feet from its end. Magnetometers can be operated in low flying aircraft thereby offering a rapid means for magnetic surveys of large areas.

Steel casings are very good conductors of electricity relative to the surrounding: earth and rocks. Therefore, some of the electrical methods of exploration geophysics show promise of being useful in locating casings. Seismic methods appear to be only very marginally useful. Remote sensing methods which employ microwave, infrared, or other high frequency electromagnetic radiation are likely to be useful in detecting disturbances of the soil which mark a well site.

STUDY OBJECTIVES

The primary objectives of the work described in this report were: 1) to develop a mathematical model and representative parameters from which the magnetic field of a casing can be calculated and 2) to use this model to study the feasibility of using airborne magnetic methods to locate well casings. Secondary objectives were to investigate the feasibility of locating casings by means of ground magnetic surveys, to make a preliminary study of the usefulness of electrical methods, and to provide a brief discussion of the principles of magnetic and electrical methods.

SECTION 2

MAGNETIC METHODS

MAGNETIC FIELD OF THE EARTH

The Earth possesses a magnetic field caused primarily by sources in the core. The form of the field is roughly the same as would be caused by a dipole or bar magnet located near the Earth's center and aligned subparallel to its geographic axis. Near the equator, the magnetic field lines are directed almost horizontally; but, over most of the conterminous United States, the field is inclined at an angle greater than 60° with respect to the horizontal (Fabiano et al., 1983). The direction of the horizontal projection of the field lines (declination) ranges between about 20° east and 20° west of north over most of the conterminous United States. The intensity of the Earth's field is customarily expressed in S.I. units as nanoteslas or in an older unit, the gamma; numerically one gamma (10^{-5} oersted) equals one nanotesla. Except for local perturbations the intensity of the Earth's field varies between about 50,000 and 60,000 gammas over the conterminous states (Fabiano and Peddie, 1981).

Many rocks and minerals are weakly magnetic or magnetized by induction in the Earth's field and cause spatial perturbations or "anomalies" in the Earth's main field. With some notable exceptions (Donovan et al., 1979), sedimentary rocks, which characterize essentially all of the world's oil fields, are usually so weakly magnetized that they can be ignored in ordinary magnetic studies. Man-made objects containing iron or steel are often highly magnetized and locally can cause large anomalies.

The intensity and direction of the Earth's field varies on time scales ranging from thousands of years to a microsecond and shorter times. The very slow or secular variations are due to changes in the core. Variations having periods ranging from tens of years to about one second are caused by processes in the magnetosphere and ionosphere; the ultimate source of these variations is electromagnetic radiation and particles from the sun. At periods corresponding to frequencies between about one hertz and several megahertz, most of the energy comes from lightening strokes.

MAGNETOMETERS

The magnetometer is a sensitive instrument which can be used to map spatial variations in the Earth's magnetic field. Some magnetometers are highly portable instruments which are operated manually. Other instruments are mounted in aircraft or other vehicles and they produce a continuous recording as the vehicle moves. Currently, most measurements are made with one of three types of electronic magnetometers: the fluxgate, the proton precession, and the optically pumped magnetometer. In the fluxgate magnetometer, the magnetic field is sensed by the level of saturation it causes in a strip of special steel. Inherently, the fluxgate magnetometer measures the strength of the component of the field which is parallel to the strip or, so called, fluxgate. However, fluxgate magnetometers have been adapted to measure the total intensity or scalar field by vector summation of the fields measured by three orthogonal sensors or by automatically and continuously orienting a single sensor so that it is always parallel to the field lines. In the proton magnetometer, a magnetic field which is not parallel to the Earth's field is applied to a fluid rich in protons causing them to partly align with this artificial field. When the controlled field is removed, the protons precess toward realignment with the Earth's field at a frequency which depends on the intensity of the Earth's field. By measuring this precession frequency, the total intensity of the field can be determined. The sensor for optically pumped magnetometers includes a cell filled with rubidium or cesium vapor or helium which is "pumped" by a light source; the principles of operation are more complex than for a proton magnetometer. Like the proton magnetometer, the optically pumped magnetometer measures the total intensity of the field.

Total field magnetometers are generally faster and easier to use than component or vector magnetometers; and, except for very special purposes, all airborne surveys and most ground surveys are made with total field instruments. The proton magnetometer is most commonly used. Optically pumped instruments are sometimes used in high resolution airborne measurements and in gradient measurements where high sensitivity and continuous measurements are desired. Currently, the primary use of fluxgate instruments is in measuring components of the Earth's field and in operating in areas of extremely high gradients or electrical noise. Hand-held fluxgate magnetometers are sometimes used for measuring the vertical component of the field. The sensor is oriented by a damped pendulum. Tripod-mounted fluxgate instruments are used for measuring the inclination and declination of the Earth's field. By using this instrument in conjunction with a portable proton magnetometer, the components of the field can be determined.

For some purposes a close approximation of the gradient of the field is determined by measuring the difference in the field between two closely spaced sensors. In principle, the gradient of any component or of the total intensity of the field can be measured in the vertical direction or any horizontal direction. In practice, the quantity measured most commonly is the vertical gradient of the total field.

SURVEY TECHNIQUES

Ground magnetic measurements are usually made with portable instruments at regular intervals along more or less straight and 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 some areas where it is possible to drive off roads.

Most magnetic surveys are done from aircraft. Airborne measurements are made along parallel flight lines which are normally spaced 1/8 mile (0.2 km) to 6 miles (9.7 km) or more apart. 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 surface. Usually the pilot navigates visually to fly along lines drawn on maps or aerial photographs. A tracking camera or a video camera and recorder is used to obtain a continuous visual record of the flight path. The location of the aircraft is plotted at map locations where common points on the map and on the tracking film are recognized; the magnetic data are then adjusted to the flight path by assuming that the speed and direction of the aircraft are constant between identified locations. Errors in location are on the order of several tens of feet at low altitudes 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. Doppler radar, VLF, Loran-C, and inertial navigation systems are sometimes used for pilot guidance or to supplement photographic recovery of the flight path. Their use 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 transponders placed at accurately surveyed sites. Position is then determined by a transceiver and computer on the aircraft which determines the range to each transponder. 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 is usually measured with a radar altimeter.

To make accurate anomaly maps, temporal changes in the Earth's field during the period of the survey must be considered. Normal changes during a day, sometimes called diurnal drift, are a few tens of gammas but changes of hundreds or thousands of gammas may occur over a few hours during magnetic storms. During severe magnetic storms, which occur infrequently, magnetic surveys should not be made. There are a number of methods of correcting surveys for temporal 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. All of the measurements at field stations are then corrected by assuming a linear change of the field 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. Intersections of the regular flight lines with the tie lines are determined and the difference in intensity between the two sets of measurements is calculated. The results are then adjusted by linear interpolation of the data along flight lines between tie lines so that the flight line data fit the tie line data. Sometimes continuously recording magnetometers are used 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 very 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 since, over a large area, temporal variations vary spatially in an unpredictable manner.

Intense fields from man-made electromagnetic sources can be a problem in magnetic surveys. Most magnetometers are designed to operate in fairly intense 60 hertz and radiofrequency fields. However, extremely low frequency fields caused by equipment using direct current or the switching of large alternating currents can be a problem. Pipelines carrying direct current for cathodic protection can be particularly troublesome. With great care, particularly in accurate determination of the flight path, significant airborne anomalies on the order of one gamma or less can be mapped in areas of very gentle magnetic expression. Although some modern ground magnetometers have a sensitivity of 0.1 gamma, sources of cultural and geologic noise usually prevent full use of this sensitivity in ground measurements.

After all corrections have been made, magnetic survey data are usually displayed as individual profiles or as contour maps. Geologic interpretation of magnetic anomalies is carried out by comparison with theoretical anomalies calculated for idealized geologic models, comparison with anomalies over known geologic features, and from constraints provided by other geophysical and geological results in the area. Identification of anomalies caused by cultural features, such as railroads, pipelines, and bridges is commonly made using field observations and maps showing such features. There are no well-established analytical procedures to follow for identification and location of such features. However, in many respects the problem of locating abandoned wells is much simpler than the interpretation of most geologic features. Anomalies due to wells are probably all very similar. Also, the objective is simply to detect the anomaly and to identify its source as being a casing and not to determine additional parameters of the well.

For more information on the principles of the magnetic method and survey techniques, the reader may wish to consult some of the many papers and textbooks (for example, Hood et al., 1979; Nettleton, 1976; Telford et al., 1976; or Parasnis, 1975) on the subject.

SECTION 3

APPLICATION OF MAGNETIC METHODS TO ABANDONED-WELL PROBLEM

MAGNETIC PARAMETERS

The feasibility of locating abandoned wells with magnetic methods might be established empirically by making measurments over known wells using all of the promising airborne and surface techniques. This would be an inefficient approach so a combination of field measurements and numerical modeling are being used to study the general problem. Field surveys provide data from which the magnetic parameters of casings can be determined. Once the parameters are established, numerical modeling provides a relatively fast and inexpensive method for simulating the anomaly for any type of survey. For example, by modeling it is possible to design and evaluate the potential usefulness of an airborne survey in discovering abandoned wells prior to having flown such a survey.

Few measurements of the magnetic fields around well casings have been published. Barret (1931) published some results and referred to other unpublished measurements. Van Weelden (1933) gave an analysis and summary of a number of measurements. Both authors were concerned with the question of whether or not a group of casings could cause the overall magnetic minima which has been observed over a number of oilfields around 1930.

The magnetization of a steel pipe consists of two components, induced and permanent. The induced magnetization depends on the intensity of the Earth's field, the magnetic permeability of the pipe, and the attitude of the pipe with respect to the Earth's field. The permanent magnetization depends on the ability of the pipe to retain a permanent field, and on the magnetic fields and the mechanical and thermal effects to which the pipe has been exposed. Ideally, one might hope to calculate the induced component. However, this calculation is not easy (Lam, 1977) since analytical solutions do not exist and one would have to resort to numerical methods. Furthermore, there is considerable uncertainty in determining the effective magnetic permeability of a steel pipe given the effect of joints, other flaws, and stresses. With these problems in mind, we decided to characterize the magnetization of steel well casings using actual measurements without trying to distinguish between induced and permanent magnetization.

A number of different mathematical models could be used to represent a magnetized casing. The component of magnetization transverse to the pipe could be represented as a line of transverse dipoles. However, considering the relatively small diameter of the pipe, the moment of these dipoles would be very small due to demagnetization. Therefore, the transverse component is of little interest and, for our present purpose, only the magnetization along the axis of the pipe need be considered. This axial magnetization could be represented by a continuous distribution of infinitesimal magnetic dipoles. However, a finite number of dipoles or pole pairs is adequate to represent the field at any appreciable distance from the casing. From the papers by Barret and Van Weelden, it appeared that, to a good first approximation, a casing can be represented by a single pair of poles. This observation plus the simplicity of the model led us to use sets of pole pairs to represent a casing. Barret gave an equation for calculating the pole strength. However, this equation does not account for the demagnetization effect which occurs at surfaces of highly permeable bodies. Van Weelden discussed some of the assumptions which have been made about the location of the poles in a bar of magnetic material and gave an equation for the calculation of the vertical field of a casing using an empirically established constant. Our approach is similar except that we have made the problem more general by the use of computer curve-fitting or inversion methods to determine the model parameters from field data.

MATHEMATICAL MODEL

We will use a right-handed Cartesian coordinate system with the z-axis positive upwards and the x-axis positive south. Definitions of the symbols used are as follows:

B - magnetic field vector,

$\overline{B}_x$, B_y, B_z - magnetic field components,

F - total magnetic field intensity,

H - horizontal magnetic field,

m - monopole strength,

x,y,z - spatial coordinates,

x_i, y_i, z_i - position of a pole m,

r_j ($x-x_i$, $y-y_i$, or $z-z_i$) - j-th component of the vector from pole m_i to the point of observation,

$r = [(x-x_i)^2 + (y-y_i)^2 + (z-z_i)^2]^{1/2}$ - magnitude of the vector from a pole to the point of observation,

β - the angle between the horizontal plane and the casing,

ϕ - the angle between the horizontal projection of the casing and the x-axis; this is the usual ϕ in spherical coordinates,

μ_0 - the magnetic permeability of free space.

The components of the magnetic field and some of the derivatives due to a single pole are:

$$B_x = m \frac{\mu_0}{4\pi} \frac{x-x_i}{r^3}$$

$$B_y = m \frac{\mu_0}{4\pi} \frac{y-y_i}{r^3}$$

$$B_z = m \frac{\mu_0}{4\pi} \frac{z-z_i}{r^3}$$

$$\frac{\partial B_x}{\partial x} = m \frac{\mu_0}{4\pi} \left[\frac{1}{r^3} - \frac{3(x-x_i)^2}{r^5} \right]$$

$$\frac{\partial B_y}{\partial x} = - \frac{3m\mu_0 \,(x-x_i)\,(y-y_i)}{4\pi r^5}$$

$$\frac{\partial B_z}{\partial x} = - \frac{3m\mu_0 \,(x-x_i)\,(z-z_i)}{4\pi r^5}$$

More generally, these expressions can be written as

$$B_j = m \frac{\mu_0}{4\pi} \frac{r_j}{r^3}, \; j=1,2,3, \text{ corresponding to } x,y,z \text{ - components} \qquad (1)$$

$$\frac{\partial B_j}{\partial x_k} = m \frac{\mu_0}{4\pi} \left[\frac{a_{jk}}{r^3} - \frac{3r_j \, r_k}{r^5} \right]; \; j = 1,2,3; \; k = 1,2,3 \qquad (2)$$

where

$a_{jk} = 0$ if $j \neq k$

$a_{jk} = 1$ if $j = k$

The field caused by the second pole of a pair is given by the same expressions using the opposite sign for the pole strength. After summation over all pairs of poles, the horizontal, H, and total, F, fields are given by

$$H = (B_x^2 + B_y^2)^{1/2}$$

$$F = (B_x^2 + B_y^2 + B_z^2)^{1/2} \tag{3}$$

The three spatial derivatives of F are calculated as

$$\frac{\partial F}{\partial x_j} = F^{-1} \sum_{k=1}^{3} B_k \frac{\partial B_k}{\partial x_j}, \; j=1,2,3 \tag{4}$$

The absolute position of one pole in each casing is given by the coordinates (x_i, y_i, z_i). Then all other pole positions in a casing are calculated according to the relation

$$\underline{x}^1 = \underline{x}^0 + \underline{L}\,(\ell, \beta, \phi)$$

where

$\underline{x}^0$ = (x_i, y_i, z_i)

$\underline{x}^1$ = the position of another pole a distance ℓ from the first pole along a casing oriented in the (β, ϕ) direction. The components of $\underline{L}$ (ℓ, β, ϕ) are:

L_x = $\ell \cos \beta \cos \phi$

L_y = $\ell \cos \beta \sin \phi$

L_z = $\ell \sin \beta$

To simulate realistic magnetic data, nonzero values for the Earth's magnetic field components must be entered into the problem. In the forward problem, the components are simply added at each point within the region of interest to the corresponding component of the anomalous field. In the inverse problem, the Earth's field components are treated as parameters to be determined by the nonlinear least squares procedure.

Since the coordinates have been set up in the conventional sense, with the unit vector $\underline{x}$ pointing from north to south, the unit vector $\underline{y}$ pointing from west to east, and the unit vector $\underline{z}$ pointing up, care must be taken when entering geomagnetic values that were specified within the usual geomagnetic coordinate system. The transformation is straightforward:

$$B_x = -X$$

$$B_y = Y$$

$$B_z = -Z$$

where X, Y, and Z are the field values in geomagnetic coordinates. Details of the computer programs developed are given in the appendix.

FIELD MEASUREMENTS

To obtain representative data which could be used for analysis of the detection problem and the design of airborne surveys, measurements were made near a number of wells in two oil fields near Denver. The first field (figure 1) is east of Denver and contains a number of producing, dry, and abandoned wells which were drilled during the 1970's. The contours on figure 1 are values of total intensity with an arbitrary datum subtracted and are taken from an aeromagnetic map (Petty et al., 1966). It should be noted that the oil field is located in a region of fairly gradual magnetic variations. The second field (figure 2) is north of Denver near Boulder and contains many abandoned and a few producing wells. Development of this field began around the turn of the century. Records on the wells are incomplete but the magnetic data are still useful. Relevant information regarding the wells where we have records is summarized in table 1.

In general, measurements were made along four radial lines, originating at each well, in the magnetic north, south, east, and west directions. Measurements were made directly above the well, at 5 feet (1.5 m) from the well and then at 10 foot (3.05 m) intervals out to 100 feet (30.5 m) 20 foot (6.1 m) intervals to 200 feet (61 m) and 50 foot (15.2 m) intervals to a maximum distance of 700-800 feet (213-244 m) along each line. Total magnetic field measurements were made with proton magnetometers, one with a sensitivity of one gamma and another with a sensitivity of 0.1 gamma. Up to four readings were taken at each station. Obviously poor readings were rejected and the remaining were averaged. In general, there was little scatter among readings except very near the well where the magnetic gradient was high. Repeat readings were made at a base station near each well, and the results were used to correct the profile data for diurnal drift. At most sites, a continuous recording proton magnetometer was used to ensure that data were not taken during magnetic storms and to provide additional information for diurnal drift corrections.

The results were all obtained with the sensor placed 8.25 feet (2.51 m) above the Earth's surface. Before making any readings, all visible steel objects such as discarded oil drums, valves, or pipes, were removed from the immediate vicinity of the traverses. In some cases, the traverses were near or over steel objects which were partially buried and could not be readily removed.

TABLE 1. LOCATIONS AND CASING INFORMATION FOR WELLS STUDIED

Well Number	Name	Location	When Drilled	Type and Amount of Casing	Pipe above Ground	Type of Hole
1	V&V Lowrystate 5-25	Sec. 25, T. 5 S., R. 65 W. 500' FWL, 2110' FNL	3/30/78	260' of 8 5/8" at 24 lb/ft 8,450' of 5 1/2" at 15.5 lb/ft	No, cut below ground surface	Abandoned oil well
2	V&V Lowrystate 1-35	Sec. 35, T. 5 S., R. 65 W. 600' FNL, 600' FEL	7/24/72	210' of 8 5/8" at 24 lb/ft 8,562' of 5 1/2" at 15.5 lb/ft	No, cut off below ground surface	Abandoned oil well
3	V&V Lowrystate 5-36	Sec. 36, T. 5 S., R. 65 W. 660' FWL, 1761' FNL	8/16/72	292' of 8 5/8" at 24 lb/ft 8,422' of 5 1/2" at 15.5 lb/ft	No, cut off below ground surface	Abandoned oil well
4	Pennzoil State A #1	Sec. 36, T. 5 S., R. 65 W. 1980' FNL, 660' FNL	9/72	211' of 8 5/8" at 24 lb/ft 8,390' of 5 1/2" at 15.5 lb/ft	Yes, 3' of casing above ground surface	Dry hole
5	Texaco State of Colo. "Y" #1	Sec. 20, T. 5 S., R. 64 W. 650' FSL, 660' FWL	2/17/73	266' of 8 5/8" at 24 lb/ft	Yes, 3' of casing above ground surface	Dry hole
6	Texaco State of Colo. "Z" #1	Sec. 18, T. 5 S., R. 64 W. 660' FNL, 1800' FWL	2/24/74	264' of 8 5/8" at 24 lb/ft 1,583' of 5 1/2" at 15.5 lb/ft starting at 7,000' depth	No, cut off below ground surface	Dry hole
7	Unlimited, Ltd. Mother Goose #1	Sec. 19, T. 5 S., R. 64 W. 660' FSL, 660' FWL	4/17/79	196' of 8 5/8" at 24 lb/ft	No, cut off below ground surface	Dry hole
8	TRI State 9-26	Sec. 26, T. 5 S., R. 65 W. 1980' FSL, 660' FEL	11/16/72	270' of 8 5/8" at 24 lb/ft 6,068' of 5 1/2" at 15.5 lb/ft starting at 1770' depth	Yes, 3' of casing above ground surface	Dry hole
9	Rucky et. al. State 13-21	Sec. 21, T. 5 S., R. 64 W. 690' FSL, 660' FWL	4/14/74	221' of 8 5/8" at 24 lb/ft	No, cut off below ground surface	Dry hole
10	RPC State 7-20	Sec. 20, T. 5 S., R. 64 W. 1980' FNL, 1980' FEL	2/13/79	240' of 8 5/8" at 24 lb/ft	No, cut off below ground surface	Dry hole

(continued)

TABLE 1. (Continued)

Well Number	Name	Location	When Drilled	Type and Amount of Casing	Pipe above Ground	Type of Hole
11	Texaco State of Colo. "V"	Sec. 19, T. 5 S., R. 64 W. 660' FWL, 1980' FNL	10/22/72	267' of 8 5/8" at 24 lb/ft 8,333' of 5 1/2" at 15.5 lb/ft	Yes, 5' of casing above ground surface	Dry hole
12	Boulder Field	Sec. 9, T. 1 N., R. 70 W.	Before 1950?	No well information available	Yes, 2 1/2' of casing above ground surface	Dry hole
13	Boulder Field	Sec. 9, T. 1 N., R. 70 W.	Before 1950?	No well information available	Yes, 2 1/2' of casing above ground surface	Dry hole
14	William Bennett #3	Sec. 33, T. 2 N., R. 70 W. 2050' FNL, 1710' FWL	2/1952	36' of 8 5/8" at 24 lb/ft	Yes, 5" of casing above ground surface	Abandoned oil well
15N	Haystack Dome Oil Co. #1	Sec. 33, T. 2 N., R. 70 W. 648' FNL, 975' FEL	9/1952	200' of 8 5/8" at 32 lb/ft 1000' of 5 7/8" at 26 lb/ft	No, cut off below ground surface	Abandoned oil well
15S	Is approximately 26 ft. south and 4 ft. east of 15 N. Well data is unclear on these two wells. Information on 15 N may apply instead or also to 15 S.					
16	Haystack Dome Oil Co. #16	Sec. 33, T. 2 N., R. 70 W.	11/1951	300' of 10 3/4"	yes, 2' of casing above ground surface	Dry hole?
17	William Bennett #1-x	Sec. 33, T. 2 N., R. 70 W.	11/1962	300' of 8 5/8" at 32 lb/ft	No, cut off below ground surface	Dry hole?

Experimental gradiometer measurements were also made; for this purpose a special nonferrous staff was used to hold two sensors at a fixed separation. A switch between the magnetometer (0.1 gamma sensitivity) and the sensors made it possible to alternate between sensors for successive readings to determine the difference in field between them. Vertical gradient measurements were made at wells number 14 and 16 using a 6.6 foot (2.0 m) separation between sensors with the lower sensor about 4.9 feet (1.5 m) above the ground. Horizontal gradient measurements were made at the same stations with the sensors about 4.9 feet (1.5 m) above the ground and with a horizontal separation of 6.6 feet (2.0 m).

The inclination of the Earth's field was measured at a number of stations near well number 7 using a "D-I" fluxgate magnetometer. The height of the sensor was about 5.0 feet (1.52 m). Declination was not measured due to the time required to establish an accurate azimuth reference. Total field measurements were made at the same stations and heights so that vertical and horizontal components of the field could be calculated.

All of the magnetic data were processed and plotted using a microcomputer and programs which were modified for this purpose.

QUALITATIVE ANALYSIS OF RESULTS

In general, the field results confirm the validity of the mathematical model. All of the known casings produce sharp positive anomalies in the total field indicating that they are magnetized along the axis of the casing, as expected. According to the mathematical model, with directions measured from magnetic north, the east-west profiles over or near a well should be symmetric and the north-south profiles should be asymmetric with a low on the north side. The reason for the asymmetry in the north-south direction is that on the north side, the horizontal field of the upper pole opposes the horizontal component of the Earth's field whereas on the south side these two horizontal fields are additive. Most of the field results (figures 3-38) show this pattern.

The peak amplitude of the total field anomalies ranges from about 1,500 to 6,000 gammas. Since the depth to the upper end of a well casing is unknown, except for those wells which extend above the surface, and since accurate measurements directly over the well are hard to obtain because of the steep gradients present, it is difficult to assess actual variations in magnetization among wells directly from field measurements.

The form of the gradient curves (figures 39-46) is roughly as expected. Profiles of horizontal gradient are asymmetric about the casing. East-west profiles of vertical gradient are symmetric about the casing but north-south profiles of vertical gradient are somewhat asymmetrical due to the asymmetry of total field profiles in this direction.

Unlike the total field, the vertical component of the field is symmetric about the casing in all directions (figures 47-50). The horizontal component is asymmetric in the north-south direction. If half of the anomaly were reversed, the two halves would nearly be mirror images for well number 7. Near the casing, a small anomaly was observed in the east-west profile of the horizontal component. This indicates that the profile was located slightly south of the true east-west line directly over the casing.

At most sites, the main anomaly due to the well is distorted by separate small anomalies which must be due to concealed steel objects. As expected, the gradient measurements are more affected than the total field measurements. These small anomalies seem to be concentrated near the wells as one would expect. K. H. Johnston, et al., (1973) have written a very interesting manual on how to locate abandoned wells using such miscellaneous discarded metal objects as clues. However, they relied on the use of electromagnetic metal detectors and other techniques rather than magnetometers. Given the existing data, none of the anomalies studied by these authors could be mistaken for the anomaly due to the well itself. However, if one were searching for unknown wells for our study areas using a rather loose grid, some of these anomalies would be identified as possibly being caused by casings. Detailed measurements would be required to avoid such aliasing and to permit more positive identification of casing anomalies. The gradual changes in the total field which occur along the profiles away from the wells are probably due mostly to sources in the crystalline basement rocks at considerable depth. Some small changes were observed which may be due to slight magnetization of the near-surface rocks. Gradual variations are not a limitation in the use of ground magnetic surveys because the variations due to extraneous man-made objects are larger. However, variations associated with geologic sources may be a serious source of noise in airborne total field surveys. Such geologic noise is probably a less serious problem in airborne gradient surveys.

For the test areas described, a fairly tight grid would be necessary to make the probability of missing a well very small using ground measurements. Total field measurements made at 25- or 30-foot (7.6-9.1 m) intervals along lines spaced 50 feet apart would probably be adequate for most cases. Even with this type of grid, it would probably be necessary to make a considerable number of other detailed measurements to distinguish between anomalies due to well casings and anomalies due to extraneous sources; however, the latter may serve as a guide to the presence of a nearby well.

From the limited number of measurments made, it appears that in locating wells there is no advantage in measuring gradients. In some cases, the width of the zone where the anomaly is large enough to be easily recognized is larger for gradient than for total field measurements; and, in some cases, it is smaller. However, there is a small zone near the center of gradient anomalies where the sign of the anomaly changes or is near zero. Considering the fact that a grid point could fall in this zone, the grid for ground gradient measurements should be even finer than the grid for total field measurements.

From a theoretical standpoint, there are advantages in measuring components of the field, particularly if the objective is to determine the parameters of casings. However, from a practical standpoint, it is more cost-effective to measure the total field on a fine grid than to measure vertical and horizontal components on a somewhat coarser grid. Consideration might be given to measuring the vertical component only using a self leveling fluxgate magnetometer.

INVERSION OF FIELD DATA

Using the pole pair model and the nonlinear least squares fitting programs described in appendix I, parameters for all of the wells listed in table 1 were found. Profiles comparing the actual data (circles) with the computed data (solid line) are shown in figures 51-86 and the pole parameters which were found are listed in table 2. For several wells, very good computer fits were obtained using only a single pole pair. For other wells a somewhat better fit was obtained using two pole pairs rather than one to represent the casing. Models with two or more separate sets of poles (casings) were used to fit some of the data where the anomaly due to the casing is distorted by anomalies from other sources.

To make the nonlinear least squares algorithm function properly for this kind of data, the "tuning" parameter, V(42), was set equal to zero. Also it was usually necessary to constrain or to fix at 90° the angle β which gives the inclination of the well from the horizontal. This is not an unreasonable constraint because wells are not likely to deviate much from vertical in the upper few hundred feet where both poles are usually found. In models where two casings were assumed, β was not set 90° for the second casing; in some cases β was found to be near zero for the second source, indicating that it is a nearly horizontal length of pipe or similar object.

The components of the Earth's field are unknown parameters in the program. However, Y was set to zero since measurements were along lines approximately parallel or perpendicular to the horizontal component of the Earth's field. Values of X and Z appropriate to the area were entered as starting values. In some cases, the values of X and Z determined by computer fitting seemed satisfactory in that their ratio deviated little from the initial values assumed. However, in other cases, their ratio changed enough so that the inclination of the field was changed by a few degrees. Although inclination was measured at only one site, we know that, except locally near a well, inclination is unlikely to change much over the study areas. Consequently, for wells where the initial computed inclination varied by more than about 0.5° from the regional values, the regional total field was obtained from a good fit to the flanks of the profile with X and Z free to vary. Then X and Z, as computed from this total field and the regional value for the inclination, were fixed in obtaining the final solution.

In general, the depth to the upper pole and the separation between pole pairs was not constrained. However, the separation was fixed or bounded in a few cases where the depth to the second pole exceeded the known depth to the bottom of the casing or where the sign of ℓ was negative thereby placing an apparent pole in the air. For secondary sources, ℓ was allowed to be negative.

It must be noted that distances can be given in either feet or meters in the program provided proper numerical values for the pole strength, m, are used. Field measurements were made in feet and were used as such in the inversion program. The pole strengths given here are in hybrid units; they must be divided by 1076.4 to obtain the results in SI units. If distances are entered in meters, the pole strengths must be divided by 100 to obtain SI units.

TABLE 2. PARAMETERS FOUND BY INVERSION

Well	θ_1	ϕ_1	m_1	x_1	y_1	z_1	l_1	m_2	$z_{1,2}$	$l_{1,2}$	θ_2	ϕ_2	m_3	x_2	y_2	z_2	l_2	X_0	Y_0	Z_0
				Casing 1										Casing 2						
1	90.0	0.0	-711731	-0.2	-4.1	-21.2	533.7											-21202	0	-50943
2	90.0	0.0	-1161479	0.0	-0.3	-15.8	150.0				2.5	266.7	-55995	12.3	137.2	-11.9	48.3	-21320	0	-50921
3	90.0	0.0	-346310	0.0	0.0	-14.5	77.1				330.4	2.8	-47308	0.0	0.3	-7.0	-21.0	-21551	0	-50805
4	90.0	0.0	-2156930	0.2	0.4	-18.2	12.3	-1010510	2.5	979.2								-21324	0	-50902
5	90.0	0.0	-311960	-0.6	-0.1	-6.3	263.6											-21331	0	-50928
6	90.0	0.0	-606597	-3.0	0.8	-12.6	123.0											-21316	0	-50591
7	90.0	0.0	-447745	-1.1	0.0	-11.2	183.7	-577302	11.4	158.0								-21290	0	-50900
8	92.8	112.7	-915074	2.0	0.7	-7.4	172.5				140.9	0.0	1316479	3.2	-0.9	-8.7	8.1	-20006	0	-51136
9	91.6	348.9	-1159134	3.3	-9.9	-16.5	100.0				50.4	32.5	129129	7.9	11.6	-27.9	-26.8	-21335	0	-50940
10	90.0	0.0	-1026136	-5.2	1.9	-13.3	101.7											-21333	0	-50931
11	90.0	0.0	-600918	-0.9	-0.1	-12.3	214.8				15.7	30.4	300496	-88.1	4.6	-12.4	4.5	-21318	0	-50897
12	90.0	85.2	-2307078	0.0	0.0	-17.6	10.1				0.0	301.7	-198466	-189.0	-0.2	-18.4	26.9	-21374	0	-51028
13	90.0	0.0	-410423	0.0	0.9	-14.1	100.0				4.1	13.2	-260482	2.6	0.0	-9.3	-27.7	-21505	0	-50931
14	90.0	0.0	-461299	-3.9	2.2	-10.2	30.4				280.4	315.1	-500398	7.3	-9.0	-7.1	-26.9	-21036	0	-51159
16	90.0	0.0	-1471700	2.7	0.0	-17.1	200.0											-20597	0	-51357
17	93.9	304.5	-1704016	-6.5	5.1	-19.9	99.8											-21366	0	-51011

Joint Inversion

Well	θ_1	ϕ_1	m_1	x_1	y_1	z_1	l_1	m_2	$z_{1,2}$	$l_{1,2}$	θ_2	ϕ_2	m_3	x_2	y_2	z_2	l_2	X_0	Y_0	Z_0
				Casing 1										Casing 3						
15& 6																				
15&	90.0	0.0	-1451898	-1.0	4.3	-15.4	454.7				87.9	93.8	-290472	62.1	1.4	-2.0	5.0	-21364	0	-51006
				Casing 2										Casing 4						
	80.6	104.3	-807166	28.1	-1.5	-12.8	612.9				225.3	167.2	-427036	-150.7	-8.4	-3.9	-16.7			

Although measurements were made to distances of 700 (213 m) or 800 (244 m) feet from the well along most lines, data beyond 400 feet (122 m) from the wells were not used in inversion. The use of data from greater distances does not add significant information and, if noisy, can degradate the inversion process.

Visual inspection of figures 51-86 indicates that the casing anomalies can be fit quite well using the pole-pair model. Attempts to fit other anomalies due to other miscellaneous sources were often fairly successful; for example, consider the east-west profile for well number 2 or the north-south profile for well number 11. However, no attempt was made to fit all of the distortions of the casing anomaly or all of the separate small anomalies. Wells number 15 N and number 15 S are extreme examples in which the north-south profiles show much distortion of the main casing anomalies and the east-west profiles are almost undistorted.

Although the visual correspondence between the observed and model data is good, the question naturally arises as to how well the parameters are actually resolved. In nonlinear least squares curve fitting, estimates of the errors in the parameters are obtained using linear statistics. Such estimates can be very useful if employed with caution; the numbers can be used to compare the relative errors among the parameters but a single error estimate is not necessarily very accurate. In the version of the NLSOL program used in this study (Anderson, 1982), a correlation matrix as well as estimates for the parameters are computed provided the covariance matrix is positively definite. It must be noted that the occurrence of a nonpositive definite covariance matrix does not imply that the parameters are not well defined.

The data for well number 10 appear to be only slightly affected by sources other than the casing. The estimated errors in the parameters are quite small (table 3); the largest percent error (15.47) is in the determination of ℓ, the separation between poles. The data for well number 14 contain a much larger amount of noise due to sources other than the casing. The estimated errors (table 4) are much larger than those for well number 10. For example, the error in ℓ for the first pole pair is 60.5% even though ℓ is much smaller for well number 14 than for well number 10 and consequently should, from this standpoint, be better resolved. Also, the root mean square (rms) error between observed and calculated curves is larger for well number 14 than for well number 10.

Study of the correlation matrix can provide useful information on the relationships between parameters. For example, if two parameters are highly correlated it is difficult to obtain accurate independent estimates of both parameters. Usually, the correlation between parameters 3 and 6 is high; this is because these are the two most important parameters in determining the magnitude of the anomaly. For instance, if in fitting the data, the depth to the first pole is changed to provide a better fit to the shape of the curve, then the pole strength must change to keep the magnitude of the anomaly correct.

Another way of assessing how well parameters are resolved is to compare the results of unconstrained inversions with results obtained in which one or more parameters are fixed. The data for well number 6 (Table 5) were inverted

TABLE 3. STATISTICAL INFORMATION FOR INVERSION OF DATA FOR WELL NO. 10

** RMSERR= 0.32637577E+02

CORRELATION MATRIX

3	0.1000E+01						
4	0.3653E+00	0.1000E+01					
5	0.3019E-01	0.1469E-02	0.1000E+01				
6	0.9527E+00	0.2452E+00	0.8846E-01	0.1000E+01			
7	0.7709E+00	0.5273E+00	0.5961E-01	0.6840E+00	0.1000E+01		
8	0.2135E+00	0.0710E+00	0.3728E-02	0.7702E-01	0.2445E-01	0.1000E+01	
10	-0.2606E+00	-0.0712E+00	-0.3338E-02	-0.7372E-01	-0.1420E-01	-0.9999E+00	0.1000E+01

	**PARM_SOL.	STD_ERROR	REL_ERROR	% ERROR **	
3	-0.1029E+07	0.2322E+05	-0.2256E-01	-0.2256E+01	----- m_1 = pole strength
4	-0.5249E+01	0.1257E+00	-0.2395E-01	-0.2395E+01	----- x = coordinate of casing
5	0.1075E+01	0.6609E-01	0.3524E-01	0.3524E+01	----- y = coordinate of casing
6	-0.1334E+02	0.2007E+00	-0.1505E-01	-0.1505E+01	----- z_1 = depth to first pole
7	0.1020E+03	0.1575E+02	0.1543E+00	0.1543E+02	----- ℓ = separation between poles
8	-0.2109E+05	0.7090E+03	-0.3608E-01	-0.3600E+01	----- X = north component of earth's field
10	-0.5069E+05	0.3400E+03	-0.6723E-02	-0.6723E+00	----- Z = vertical component of earth's field

TABLE 4. STATISTICAL INFORMATION FOR INVERSION OF DATA FOR WELL NO. 14

** RMSERR= 0.6730371E+02

CORRELATION MATRIX

3	0.1000E+01													
4	-0.7167E+00	0.1000E+01												
5	0.0574E+00	-0.8466E+00	0.1000E+01											
6	0.9067E+00	-0.7561E+00	0.0623E+00	0.1000E+01										
7	-0.0660E-01	-0.1352E+00	0.6974E-01	0.3602E-03	0.1000E+01									
8	-0.7000E+00	-0.3737E-01	0.8598E-01	-0.1351E+00	0.8045E+00	0.1000E+01								
9	0.5619E+00	-0.7100E+00	0.5645E+00	0.6810E+00	-0.7561E+00	-0.7701E-01	0.1000E+01							
10	-0.1089E-01	0.6671E+00	-0.3775E+00	-0.9671E-01	-0.5100E+00	-0.6679E+00	0.6701E-01	0.1000E+01						
11	-0.7107E+00	0.9495E+00	-0.7312E+00	-0.7569E+00	-0.5996E-02	0.1666E+00	-0.1010E+00	0.7769E-02	0.1000E+01					
12	0.8017E+00	-0.8595E+00	0.9569E+00	0.8771E+00	0.5296E-01	0.8105E-01	0.5605E+00	-0.7070E+00	-0.7690E+00	0.1000E+01				
13	-0.5592E+00	0.8259E+00	-0.0312E+00	-0.5066E+00	-0.2632E+00	-0.2537E+00	-0.1290E+00	0.7555E+00	0.6940E+00	-0.7034E+00	0.1000E+01			
14	0.6017E-02	-0.6507E+00	0.1625E+00	0.9056E-06	0.7477E+00	0.6734E+00	-0.9906E-01	-0.9307E+00	-0.8873E-01	0.7940E+00	-0.7771E+00	0.1000E+01		
15	0.6605E-01	0.4653E+00	-0.2920E-01	-0.1066E-02	-0.7196E+00	0.0760E-01	0.5535E+00	0.3081E+00	0.4977E+00	-0.1016E-01	0.7716E+00	-0.1209E+00	0.1000E+01	
17	-0.4350E-01	-0.4470E+00	0.3217E-01	0.4937E-02	0.2196E+00	-0.8047E-01	-0.5517E+00	-0.3039E+00	-0.4956E+00	0.1326E-01	-0.7736E+00	0.3197E+00	-0.1005E+01	0.1000E+01

	**PARM_SOL.	STD_ERROR	REL_ERROR	% ERROR **		
3	-0.6613E+06	0.1197E+06	-0.2595E+00	-0.2595E+02	m_1	= pole strength of first casing
4	-0.1074E+01	0.9561E+00	-0.2469E+00	-0.2469E+02	x	= coordinate of first casing
5	0.2281E+01	0.9716E+00	0.4395E+00	0.4395E+02	y	= coordinate of first casing
6	-0.1021E+02	0.8043E+01	-0.8046E+00	-0.8046E+02	z_1	= depth to first pole
7	0.3030E+02	0.8010E+02	0.6050E+00	0.6050E+02	ℓ	= separation between poles
8	-0.1309E+01	0.3915E+00	-0.2062E+00	-0.2062E+02	I_2	= inclination of second casing
9	-0.7030E+00	0.9154E+00	-0.1169E+01	-0.1169E+03	φ	= azimuth of second casing
10	-0.5004E+06	0.1262E+06	-0.2102E+00	-0.2102E+02	m_2	= pole strength of second casing
11	0.7117E+01	0.7662E+00	0.1007E+00	0.1007E+02	x	= coordinate of second casing
12	-0.0969E+01	0.1717E+01	-0.1419E+00	-0.1419E+02	y	= coordinate of second casing
13	-0.7115E+01	0.3206E+01	-0.4610E+00	-0.4610E+02	z_1	= depth to first pole
14	-0.2607E+02	0.2232E+02	-0.8106E+00	-0.8106E+02	ℓ	= separation between poles
15	-0.7804E+05	0.8725E+04	-0.1171E+00	-0.1171E+02	H	= north component of earth's field
17	-0.5816E+05	0.1581E+04	-0.2993E-01	-0.2993E+01	z	= vertical component of earth's field

TABLE 5. EFFECT OF FIXING PARAMETERS FOR WELL NUMBER 6

	Uncon-strained	P=73	P=173	Z_1=-14.6	Z_1=10.6	Z_1=10.6
Pole strength	-686,597	-726,640	-673,441	-855,514	528,619	523,895
North coordinate	-2.99	-3.01	-2.99	-3.11	-2.88	-2.88
East coordinate	0.82	.82	.81	.86	.78	.79
Depth to pole	-12.62	-12.94	-12.51	-14.60*	10.60*	10.60*
Separation between poles	122.96	73.00*	173.00*	123.00*	123.00*	86.78
RMS error	21.85	26.18	22.71	68.07	82.61	78.07

* Fixed parameters

with the separation ℓ fixed at 73 feet (22 m) and 173 feet (53 m); ℓ was found to be 123 feet (37 m) when it was unconstrained. From table 4 it is seen that the rms error between observed and calculated data is not much larger for ℓ = 73 feet (22 m) than for ℓ = 123 feet (37 m). However, the rms error is significantly different for ℓ = 73 feet (22 m) than for ℓ = 123 feet (37 m) and visually there is a significant difference in the quality of the fits (figures 62-63 and 85-86). From such studies, one might say that ℓ is resolved with an accuracy of about -10% to 40%. In fixing ℓ at 73 or 173 feet (22 or 53 m), the pole strength changed by a few percent and the depth to the first pole changed slightly. In another experiment, ℓ was fixed at 123 feet (37 m) and the depth Z was fixed at -10.6 and -14.6 feet (-3.2 and -4.5 m). In both cases, the rms error is more than triple that for the unconstrained case; the pole strength changes by about 25% and visually the fit is not very good (figure 87-88). When the depth to the first pole was fixed, but the separation was unconstrained, a slightly better fit was obtained.

It is concluded that, for most of the wells studied, the parameters are sufficiently well resolved to be used in predicting the response of those wells at airborne survey altitudes. Actual variations in parameters between wells probably are greater than the errors in the estimates of the parameters.

All of the casing and other pipe in wells number 1-11 are of the same type. Therefore, one might expect to find for these wells a correlation between the amount of pipe in the hole (table 1) and the pole strength and separation between poles (table 2). However, there is no clear correlation between the amount of pipe and the parameters. It appears that neither the presence of the inner casing nor the variations in length of the surface casing have much affect on the parameters. This suggests that remanent magnetization or other unpredictable parameters are most important in determining the magnetization of a casing.

MODELLING AND DESIGN OF AIRBORNE SURVEYS

Using the parameters listed in table 2, results expected from airborne surveys were calculated for wells number 4, 5, 6 and 12. Well number 4 is one of the most strongly magnetized and well number 5 is one of the most weakly magnetized of those studied. Well number 6 has typical parameters and the field data are relativelly free from noise. The interpreted pole separation for the vertical casing at well number 12 is only 10.1 feet (3.1 m). Results for all of these wells were plotted in profile form, and results for well number 4 were also plotted as contour maps. To generate the contour maps, the field was calculated along many parallel profiles, the minimum value for the data set was subtracted from the data, and $\log_{10}$ of the result was taken to permit display of the flanks of the anomaly without too much crowding of contours near the peak.

Individual contours on figures 89-91 are approximately circular in form; the center of the circle tends to move southward as the circle becomes larger. The small low in the north side of the casing is clearly seen in the results for 150 feet (45.7 m) (figure 89). The principal effect of varying the aircraft altitude is to decrease the peak amplitude and to broaden the anomaly. On the flanks of the curves, the two effects tend to cancel each other. For example, on the maps for altitudes of 200 and 250 feet (61 and 76 m), the contours between 0.3 and 0.6 occur at almost exactly the same points along an east-west line through the well. Similarly, there are regions where contours on the two maps taken along a north-south line through the well are nearly the same value.

From examination of the profiles for well number 4 (figures 92-99), it is apparent that the magnitude of the low on the north side of the well increases relative to the main high as the altitude increases. For an altitude of 200 feet (61 m), the amplitude of the anomaly for well number 4 is about four times as large as the anomaly for well number 5 (figures 100-103) and nearly three times as large as the anomaly for well number 6 (figures 104-106). The shapes of the anomalies are similar except that the low on the north side of the well is not as pronounced for well number 4 as for the other two.

The pole strength for well number 12 is the highest that was determined for any well, but the short spacing between poles causes the anomaly to attenuate rapidly with height (figures 107-110) so that at an altitude of 150 feet (45.7 m) the anomaly is about the same as that for well number 5; and, at greater altitudes, it is smaller. The model parameters for the subsidiary anomaly at well number 12 were included in the airborne modeling. As a result, a small secondary anomaly is observed, particularly in the profiles for altitudes of 100 and 150 feet (30.5 and 45.7 m).

Vertical and horizontal gradients of the total field were calculated to investigate the feasibility of using an airborne gradiometer. The contour map of the vertical gradient over a casing (figure 111) has a similar "Bullseye" to that of the total field (figure 90). A map of the horizontal gradient taken in the north-south direction has a low and a high of nearly the same shape and nearly equal amplitudes (figure 112). A map of the horizontal gradient taken in the east-west direction shows a low and a high (figure 113) which are antisymmetrical about a north-south line through the casing. The width of the vertical gradient anomaly is somewhat less than the total width of the horizontal gradient anomaly.

As expected, the gradient anomalies are much smaller and slightly narrower for well number 5 (figures 121-124) and especially for well number 12 (figures 125-132) than for well number 4 (figures 114-120). The existence of a second small anomaly is apparent in the profile at a 150 foot (45.7 m) altitude for well number 12 but can scarcely be discerned in the profile for a 250 foot (76.2 m) altitude.

To the extent that the wells studies in this report have typical magnetic properties and that the parameters found by inversion are reasonably accurate, the model results discussed above should be very valuable in designing airborne surveys for locating abandoned wells. In designing a survey, one would like to know, in addition to the expected anomalies, the noise level or errors in the magnetic readings and navigation, magnetic variations due to geologic sources and cultural features, and the density of wells in the area to be flown.

By magnetic compensation of the aircraft and by recording and correcting for the motions of the aircraft, the noise level of an airborne system can be reduced to about 0.2 gamma or better for the total field as measured by sensors mounted in wing-tippods or tail stingers. The noise level of the difference in signals between two sensors can be 0.2 gamma or less depending on where the sensors are located. Considering the separations between sensors, noise levels of about 0.007 gamma/feet (0.023 gamma/m) or better in the horizontal direction and 0.003 gamma/feet (0.0098 gamma/m) or better in the vertical direction can be achieved.

An educated guess about anomalies due to geologic sources can be made if surface and subsurface geologic information is available. However, the only way to obtain quantitative information on either geologic or cultural sources is to make magnetic measurements at the study sites.

If the density of wells in an area is very high, it may be difficult to identify individual wells using airborne surveys. Use of a small spacing between lines will of course help to resolve anomalies due to individual wells. Calculations of the total field were made for two identical wells separated by 200, 300, and 400 feet (61.0, 91.5, 122 m). Parameters of the wells were: $m = 1{,}000{,}000$, $z_1 = -20$, $\ell = 100$ and $\beta = 90°$. From the results it is apparent (figures 133-136) that the resolution at altitudes of 150 and 200 feet (47.7 and 61 m) is rather poor. Of course, even if individual peaks due to the two casings are not recognized, the width and shape of the composite anomaly differ from the anomaly caused by a single casing. If, for instance, the density of wells were $2000/mi^2$, as mentioned in the introduction, the average spacing between wells would be only about 118 feet. In such an area, an airborne survey would have to be made at a height of 50 feet (15.2 m) or less with a line spacing on the order of 50 feet (15.2 m) or less to be able to resolve most of the individual anomalies. If the density of wells is extremely high and all wells must be identified and located, it might be much more practical to use ground measurements rather than airborne measurements. Of course, if the density of wells is extremely high, it may not be necessary to identify separately all of the wells in the cluster.

If the density of wells in an area is low, the primary concern in design of an airborne survey is to be sure that one or two of the lines passes near enough to the well that an identifiable anomaly is obtained. The worst case is when adjacent lines intersect either side of an anomaly at the same level of intensity or gradient. In the absence of geologic sources and cultural sources other than casings, one might define an identifiable anomaly to be twice the maximum noise excursions. To illustrate the design of a survey using the results of this study, we will assume that the smallest identifiable total field anomaly is about five times the expected noise level, or one gamma, and that the smallest identifiable gradient is about five times the expected noise level, or 0.03 gamma/foot (0.098 gamma/m) for horizontal gradients and 0.015 gamma/foot (0.049 gamma/m) for vertical gradients. These assumptions allow for the presence of "noise" due to geologic and cultural sources.

Total field anomalies are slightly broader in the east-west direction than in the north-south direction. Also, magnetometer system noise is likely to be slightly less on north-south lines than on east-west lines. Therefore, there is a small advantage in flying total field surveys in a north-south rather than an east-west direction.

To find well number 5 using a total field survey and assuming the worst case, figures 100-103 can be used to estimate that the spacing must be about 480 feet (146 m) for an altitude of 150 or 200 feet (45.7 or 61.0 m). Under the same conditions, the line spacing to find well number 12 would be about 330 feet (101 m) and to find well number 4 it would be about 900 feet (274 m).

Because of the zero line in the horizontal gradients near the well, a single component gradiometer measuring dF/dx along east-west lines or one measuring dF/dy along north-south lines would miss detecting the well if the line passed almost directly over the well. However, commercially used horizontal gradiometer systems measure the intensity and direction of the total horizontal gradient so the zero line in one component would not be a problem for such a system. If two horizontal gradients or the total horizontal gradient are measured, the line spacing can be considerably larger than if only the vertical gradient is measured. To find well number 12 using the vertical gradient, the line spacing must be about 220 feet (67 m) for altitudes of 150 and 200 feet (45.7 or 61.0 m). To find well number 12 using horizontal gradients, a line spacing of about 300 feet (91.3 m) could be used for an altitude of 150 feet (45.7 m) but at an altitude of 200 feet (91 m) the well cannot be detected. Using the vertical gradient, well number 4 can be detected at an altitude of 150 feet (45.7 m) with a line spacing of about 360 feet (109.7 m) or at an altitude of 200 feet (61.0 m) with a line spacing of about 420 feet (128 m). If horizontal gradients are used, the line spacing can be increased to about 590 feet (179.8 m) for altitudes of 150 or 200 feet (45.7 or 61.0 m).

From this discussion, it is apparent that for the assumptions used the line spacing can be somewhat larger for total field than for gradient measurements. It is also apparent that, if the assumptions used are valid, it would be possible to find all of the wells in this study with airborne surveys. Although the actual flight path of the aircraft can be recovered very accurately with a microwave navigation system, there are significant deviations between the desired path and the path the pilot is able to fly. These deviations are estimated to be about ±60 feet (18 m) or less. Consequently, the line spacing should be reduced somewhat from the numbers given in the preceding paragraph. To cover the worst case, the spacing should be decreased by 120 feet (36.6 m). A reduction of 80 feet (24.4 m) is probably reasonable since the probability of maximum deviations occurring in opposite directions at adjacent localities on adjacent lines is small. The line spacing necessary to locate well number 5 is then 400 feet (121.9 m) if total field measurements are made at an altitude of 200 feet (61 m). This spacing is used in making some of the cost estimates in appendix II. It may be unrealistic to plan and conduct surveys to detect all wells, such as number 12, which apparently contains only a very short length of casing.

Measurements of the total field are usually obtained as a byproduct of gradient measurement. Thus, it might be effective in some cases to design a survey based on criteria for a total field survey but to use a gradiometer system. The horizontal gradient information might be very useful in identifying individual wells where several wells occur in a cluster.

RECOMMENDATIONS FOR FURTHER STUDY OF MAGNETIC METHODS

Little further study of the application of the ground magnetic method is needed at this time. However, if the ground method is applied in a routine way, the results should be periodically evaluated to see if changes in procedures or further research is needed. A test and demonstration of airborne methods is needed: 1) to evaluate the modeling described in this report, 2) to discover any unforeseen problems in the application of airborne magnetic methods to this problem, and 3) to evaluate and demonstrate their effectiveness in locating wells. Plans have been made to conduct a pilot airborne total field survey over some of the wells studied in this report and to conduct more extensive tests in areas near Oklahoma City where there are more than 15 known wells per square mile (2.59 km^2). The results of these surveys should be carefully evaluated and reported. Gradients should be calculated from the total field data to help estimate the effectiveness of using airborne gradiometers. Complete evaluation of the airborne results may require a considerable amount of ground magnetic surveying and a careful visual examination of areas. Some of the necessary examination can, no doubt, be done using aerial photographs. In addition to the planned tests, it would be very useful to study proprietory and other aeromagnetic data taken over oil fields to obtain additional information on typical levels for geologic noise.

There are a number of other unanswered questions which have a bearing on the use of geophysics. An estimate needs to be made of the percentage of holes in which all or part of the casing was removed and the importance of such holes in causing pollution should be studied. As additional data are collected, the magnetization parameter of casings should be determined. The results contained in this report may not be typical, and, if so, this additional data may be needed to guide the design of future surveys. The effect of corrosion on the magnetization of old casings should be studied; possibly some wells are no longer detectable because the casings are too corroded.

SECTION 4

ELECTRICAL METHODS AND THEIR APPLICATION

SUMMARY OF ELECTRICAL METHODS

Many different geophysical methods and techniques comprise what are commonly called electrical or electromagnetic methods. Electrical methods often are defined to include only those methods using direct currents; but, within this report, we use the term electrical methods to include geophysical techniques using both stationary electrical fields and time-varying magnetic or electrical fields. These fields may be of natural or man-made origin.

In resistivity methods, electric currents are driven into the ground and the resultant electric field or potential difference between two points is measured. Usually, two electrodes are used for current injection and another two electrodes are used for measuring potential differences. Commonly, the current and potential electrodes are placed in one of several standard configurations or arrays, depending upon survey objectives. The potential difference measured between two electrodes is divided by the current injected into the ground and then multiplied by a geometric factor calculated from the spacing and direction between electrodes. The results are thus expressed in units of resistivity, ohm-meters. This "apparent resistivity" would be equal to the true resistivity of the earth in the vicinity of the electrode array if the earth were homogeneous. The earth is seldom homogeneous so the measured value of apparent resistivity reflects a weighted average of earth resistivities in the vicinity of the array. To map the resistivity of an area, one or more of the electrodes are moved about to enhance or decrease the relative effect from various parts of the electrical section. Basically, two survey schemes are used: in "depth sounding" the spacing between the electrodes is increased while keeping the center of the array fixed; in "horizontal profiling", all of the electrodes are moved while maintaining a constant separation between electrodes. Often depth sounding and horizontal profiling are combined by alternately changing the separation and advancing the array. In interpreting resistivity data, the objective is to define the boundaries between regions of contrasting resistivity and to determine the intrinsic or true resistivity of each region.

The magnetometric resistivity method is a hybrid technique in which the static magnetic field resulting from direct current driven through the ground is measured. With this method, spatial variations in the magnetic field are used to deduce the relative resistivity of various regions of the subsurface. In both resistivity and magnetometric resistivity methods, very low frequency, time-varying currents are used, but the frequency is so low that electromagnetic induction effects are negligible.

A number of earth processes, such as the flow of water through porous media and chemical reactions between bodies such as metallic ores or steel pipes and the surrounding rocks and soil, generate static or very slowly varying currents and electric fields. Such sources are the basis for the self-potential or SP methods. In the SP method, the potential differences between two electrochemically stable electrodes placed at different locations are measured. Usually, one electrode is kept at a fixed position and the other is moved about to explore the region. There is no way to establish the absolute value of the potential at the base electrode so each SP survey has its own base level. The SP method is used for purposes such as studying the flow of ground water and the exploration for metallic ore bodies and sources of geothermal energy. Variations in the resistivity of the earth influence self-potential values, but resistivity cannot be determined directly from SP surveys.

In electromagnetic methods, time-varying magnetic or electric fields or both are measured. The fields may be of man-made or natural origin. Induction coils or sensitive magnetometers are used to measure electromagnetic fields. At low frequencies, two electrodes are used to measure the electrical potential differences which, if the electrode spacing is small, are a good approximation to the electric field.

A large variety of electromagnetic techniques exist in which artificial sources are used. One type of source is an insulated loop or coil driven by a harmonic or other time varying current. The time-varying magnetic field induces eddy currents in the earth which have an associated secondary magnetic field. The pattern of eddy currents and the secondary magnetic field are dependent on the resistivity of the earth in the vicinity of the system. For certain applications, time-varying current is driven into the earth using a pair of electrodes. Such a source is more complex than the simple loop; the total current in the earth is a superposition of the "galvanic" current flowing between electrodes, eddy currents induced by the galvanic currents, and eddy currents induced by the current flowing in the wire which feeds the electrodes. Usually, when artificial or controlled sources are employed, one or more components of only the magnetic field are measured. However, in other techniques, both electric and magnetic fields are measured as in the "controlled source" magnetotelluric method. In this latter technique, which employs a grounded wire source, the ratio of the electric field to the orthogonal magnetic field is measured. The results are readily expressed in units of resistivity.

Many electromagnetic surveys are made to locate highly conductive (very low resistivity) regions which could represent metallic ore bodies or other features of interest. In interpreting such surveys, one usually tries to estimate the resistivity of conductive features but not of the region as a whole. Electromagnetic methods are also used for depth sounding. By varying the frequency, the depth of exploration is varied. In interpreting such soundings, the objective is to determine the variation of resistivity with depth.

When current is driven through the earth using electrodes, it has both vertical and horizontal components. The presence of a vertical steel casing can locally cause a large change in the distribution of the vertical currents and corresponding changes in the electric and magnetic fields at the surface. The magnetic field from a loop or other time-varying source causes eddy currents to flow directly in a steel casing. However, the dimensions of the eddy current paths in a casing are so small that the secondary magnetic field associated with these eddy currents cannot be detected at an appreciable distance from the casing. In a horizontally layered earth, loop sources cause eddy currents which flow only in horizontal paths. Horizontal pipelines can significantly influence the distribution of these eddy currents. Thus, loop-loop electromagnetic methods are very sensitive to horizontal pipelines but are relatively insensitive to vertical casings.

The induced polarization or IP method is, in some respects, a hybrid of resistivity and electromagnetic methods, but it depends on the ability of the earth to become electrically polarized. In the IP method, a low frequency sinusoidal or pulse waveform is driven into the ground with electrodes. Usually, the resulting potential difference between the electrodes is measured although in one variation of the technique the magnetic field is measured. If the earth exhibits polarization, the measured apparent resistivity will decrease with frequency and a phase shift between the received voltage and the injected current will occur. Sulfide minerals, graphite, and some clay minerals are sources of polarization. Also, buried metallic objects including vertical casings can locally cause strong IP anomalies. The direct current resistivity is usually obtained as a "byproduct" in making IP surveys. Induced polarization results and their interpretation are often complicated by the fact that the frequencies used are high enough to cause electromagnetic induction so that the effects of the two phenomena are superimposed.

FIELD MEASUREMENTS

Self-potential surveys were made in the vicinity of 11 wells using a fixed base electrode and a roving electrode. The SP nonpolarizing electrodes were of lead-lead chloride construction. Potential differences were measured with a high impedance voltmeter. Distinct and fairly large anomalies were found in the vicinity of four wells, numbers 7, 11, 15 N, and 15 S (figures 140, 142, 144, 145). Small, distinct, short-wavelength anomalies were observed in the immediate vicinity of some of the other wells; for example numbers 14, 16, 17 (figures 143, 146, 147). Small anomalies which appear to be related to the casing were observed for all other wells except number 6; however, many of these anomalies are too small and too similar to other features along the profiles to be diagnostic of a casing. At this time, we have no explanation of why significant anomalies were observed for some of the wells and not the others. The anomalies for wells number 7, 11, 15 S and 15 N are quite narrow, measurements would have to be made on a grid having a spacing of about 10 or 15 feet (3.05 or 4.57 m) in both directions to be reasonably certain of identifying the anomaly. Even then, much additional detailed work would be necessary to identify the anomalies due to wells and those due to other causes.

Electromagnetic measurements were made using two different systems. One system, the EM 31, uses a small transmitting and receiving coil operating at a frequency of about 39 kHz with a loop separation of 12 feet (3.66 m). The instrument is designed so that it measures apparent conductivity (=1/resistivity) directly. Measurements were made over two casings with the coils in line with the traverse and perpendicular to the traverse. No anomalies were observed which could be attributed with certainty to the wells (figures 148 and 149). Other anomalies which are probably due to buried horizontal pipes or cables were observed.

Slingram measurements using a Max-Min II system were made in the vicinity of well number 3 (figures 150 and 151). Slingram systems are similar to the EM 31 except that the loop spacing is much greater, the frequencies used are much lower, and the response is not proportional to earth conductivity. No indication of the well is seen in profiles run with either the horizontal coplaner or vertical coplaner configurations with a loop spacing of 400 feet (121.9 m). The results are typical for flat-lying, conductive, sedimentary rocks and could be inverted to determine the resistivity of the rocks.

RECOMMENDATIONS FOR FURTHER STUDY OF ELECTRICAL METHODS

Neither of the two electromagnetic techniques used, the EM 31 and slingram, are well-suited for the detection of vertical pipe-like bodies. However, it would be worthwhile to experiment with an electromagnetic method using a grounded wire source.

It is known from the work of Holladay and West (1981) and others, that vertical steel casings can cause strong distortion of resistivity and IP measurements when an electrode is in the vicinity of the casing. At high frequencies, some of the distortion may be due to electromagnetic coupling. Due to present interest in the use of IP and resistivity methods in exploration for oil, a considerable amount of proprietary data exist which show these effects and which would have been useful in this study. Further evaluation of any of these data which become available would be worthwhile. However, it must be noted that IP/resistivity surveying is relatively expensive compared with magnetic or SP surveying. Therefore, IP/resistivity might be useful in special circumstances, such as when the upper part of the casing has been removed, but would probably not be economically practical for more routine problems.

SECTION 5

SUMMARY

Initial consideration of the problem of locating abandoned well casings using geophysical exploration methods indicated that magnetic methods would generally be most useful and that some electrical techniques might be useful. Ground magnetic measurements were made over 18 wells in two oil fields near Denver to develop information which could be used in modeling and in the design of magnetic surveys. Anomalies having peak amplitudes ranging from about 1,500 to 6,000 gammas were found over all of the known wells tested. Horizontal and vertical gradients of the total field were measured near some of the wells; the results suggest that gradient measurements are not as useful as total field measurements in the areas tested.

The model chosen to represent a casing is a set of pole pairs. By use of a nonlinear least squares curve-fitting (inversion) program, the strength and locations of sets of pole pairs, which provide a close fit to the observed data, were determined. Using this procedure, the position and strength of the uppermost pole is determined with an accuracy of a few percent, but the error in the position of lower poles may be much greater. The parameters which were determined are adequate for predicting results at airborne altitudes and for other modeling.

Using the parameters determined from the ground measurements, it appears that all of the casings in the test area could be detected from airborne measurements made at altitudes of 150 to 200 feet (45.7 to 61 m) above the surface, provided the flight lines are spaced as close as 330 feet (100 m) and provided noise due to other cultural and geologic features is not too severe. More data over typical oil fields is needed to establish realistic noise levels. If the gradients due to geologic sources are not too high, it appears that the detection range for total field measurements is greater than for gradient measurements, given the instrumental noises of present equipment.

Self-potential anomalies were found to be associated with most of the wells where measurements were made. However, the anomalies tend to be narrow and low in amplitude so it is suggested that use of this method be considered only in cases where magnetic data are inadequate or cannot be acquired.

Test wells were not detected using two loop-loop electromagnetic methods. However, theory suggests that electromagnetic methods using loop sources would not be effective and that only those methods employing grounded wire sources should be used. Theoretical studies and field data, which have been obtained by private contractors and most of which is proprietory, indicate that the resistivity and induced polarization methods are sensitive to the presence of

steel casings. These methods would be much more expensive to use than magnetic methods but might be useful in special circumstances. In particular, the depth range of these methods may be greater than that of magnetic methods in cases where the upper part of a casing has been removed.

SECTION 6

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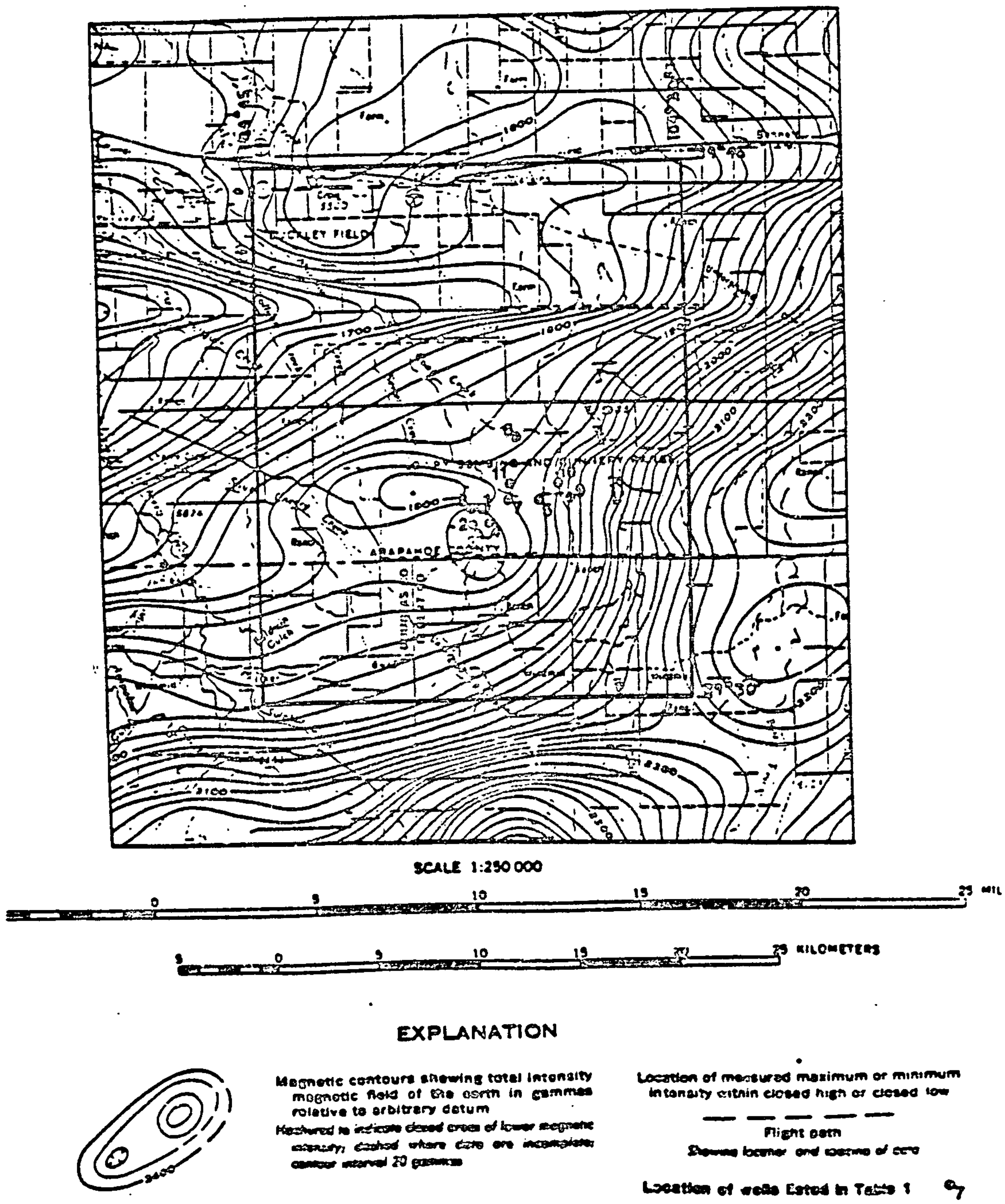


Figure 1. Well locations and aeromagnetic map for test area east of Denver.

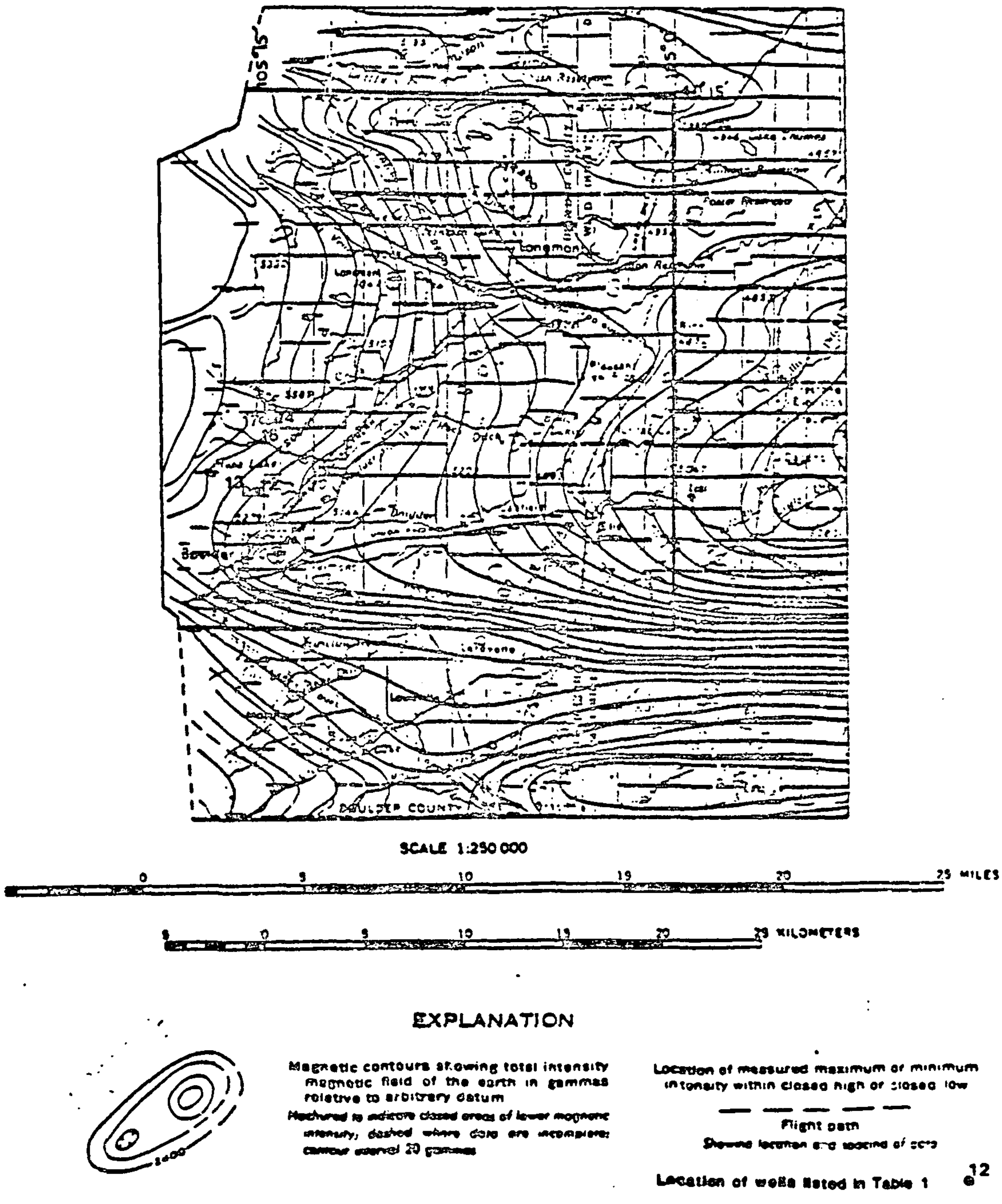


Figure 2. Well locations and aeromagnetic map for test area north of Denver.

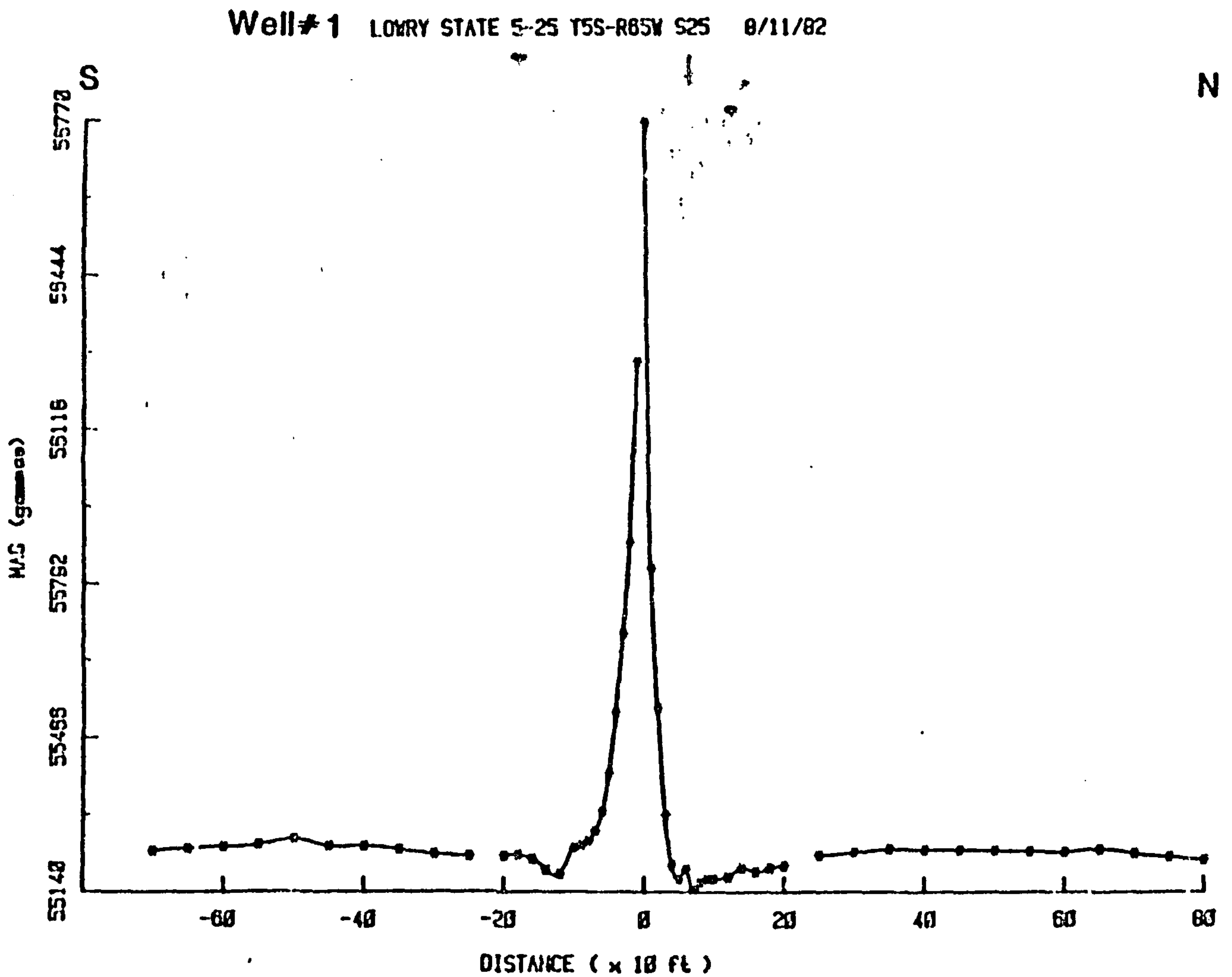


Figure 3. North-south profile of total field over Well Number 1.

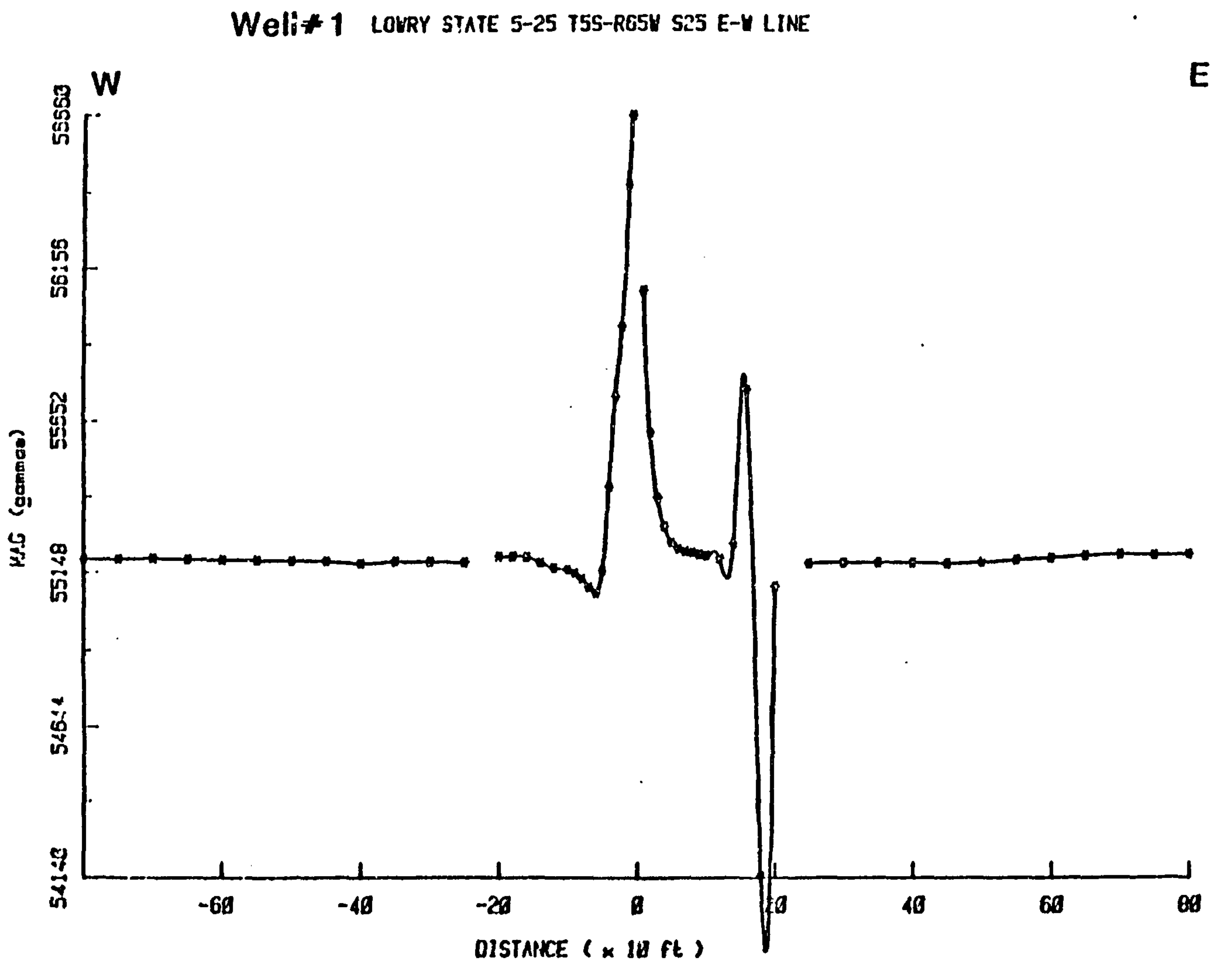


Figure 4. East-west profile of total field over Well Number 1.

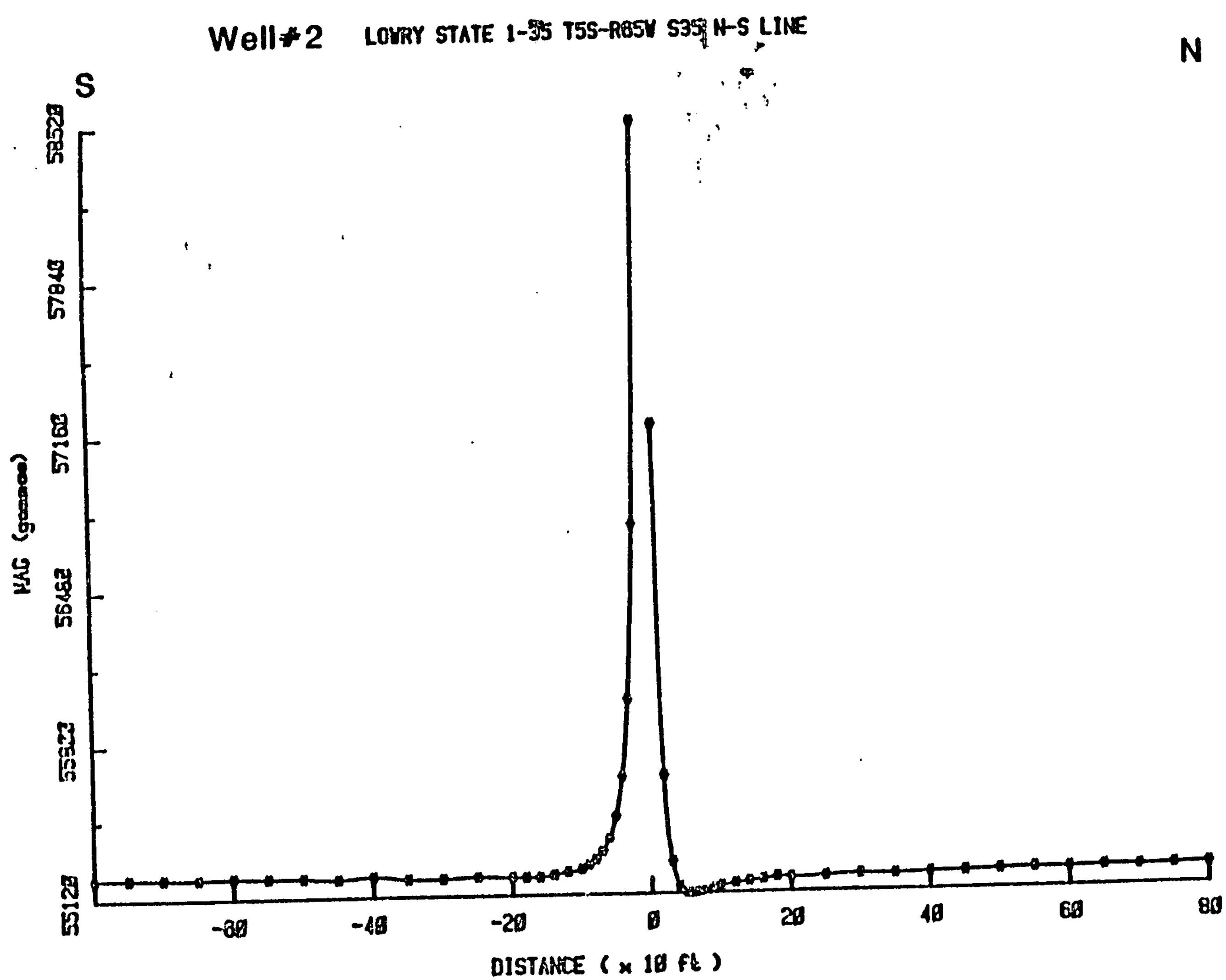


Figure 5. North-south profile of total field over Well Number 2.

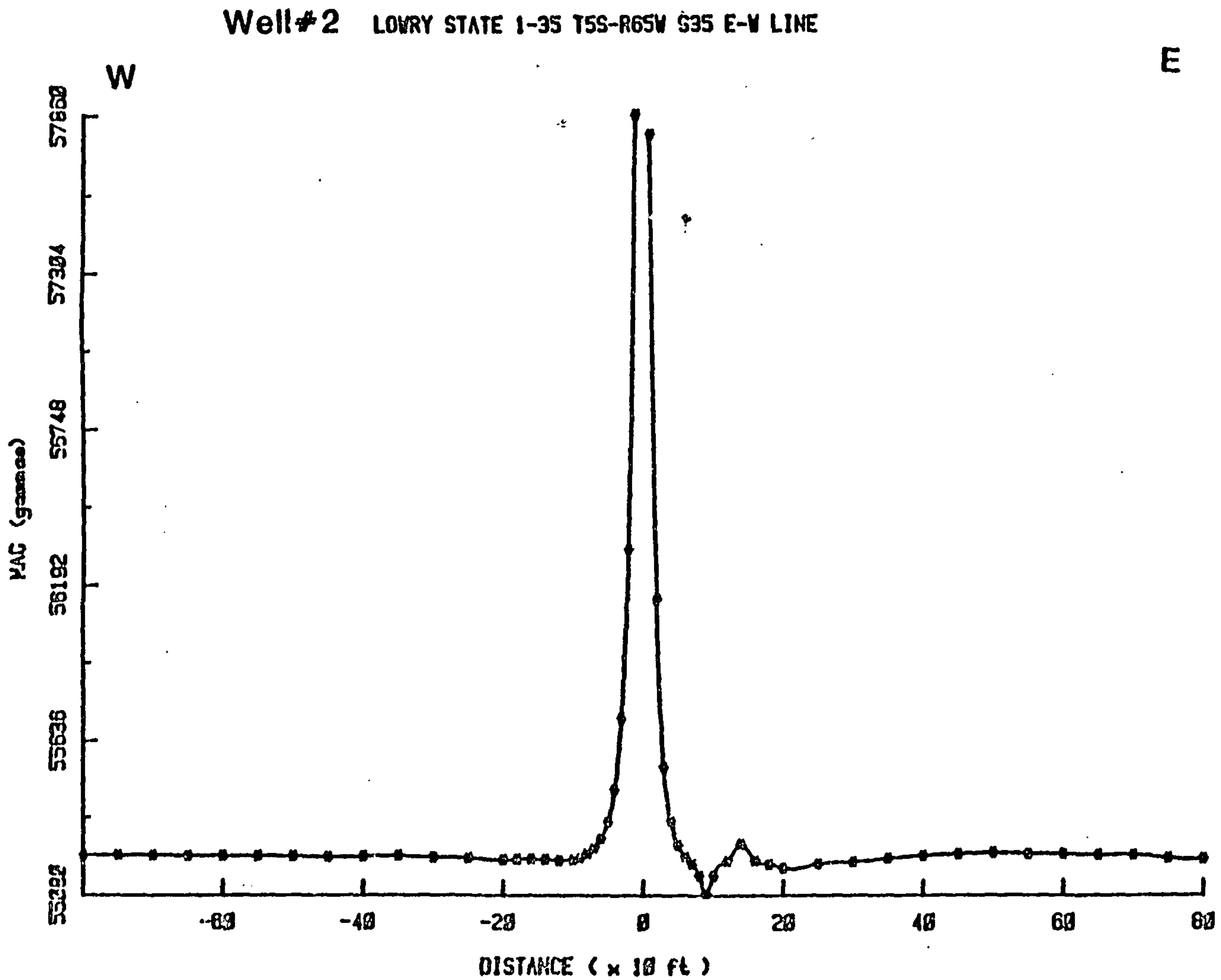


Figure 6. East-west profile of total field over Well Number 2.

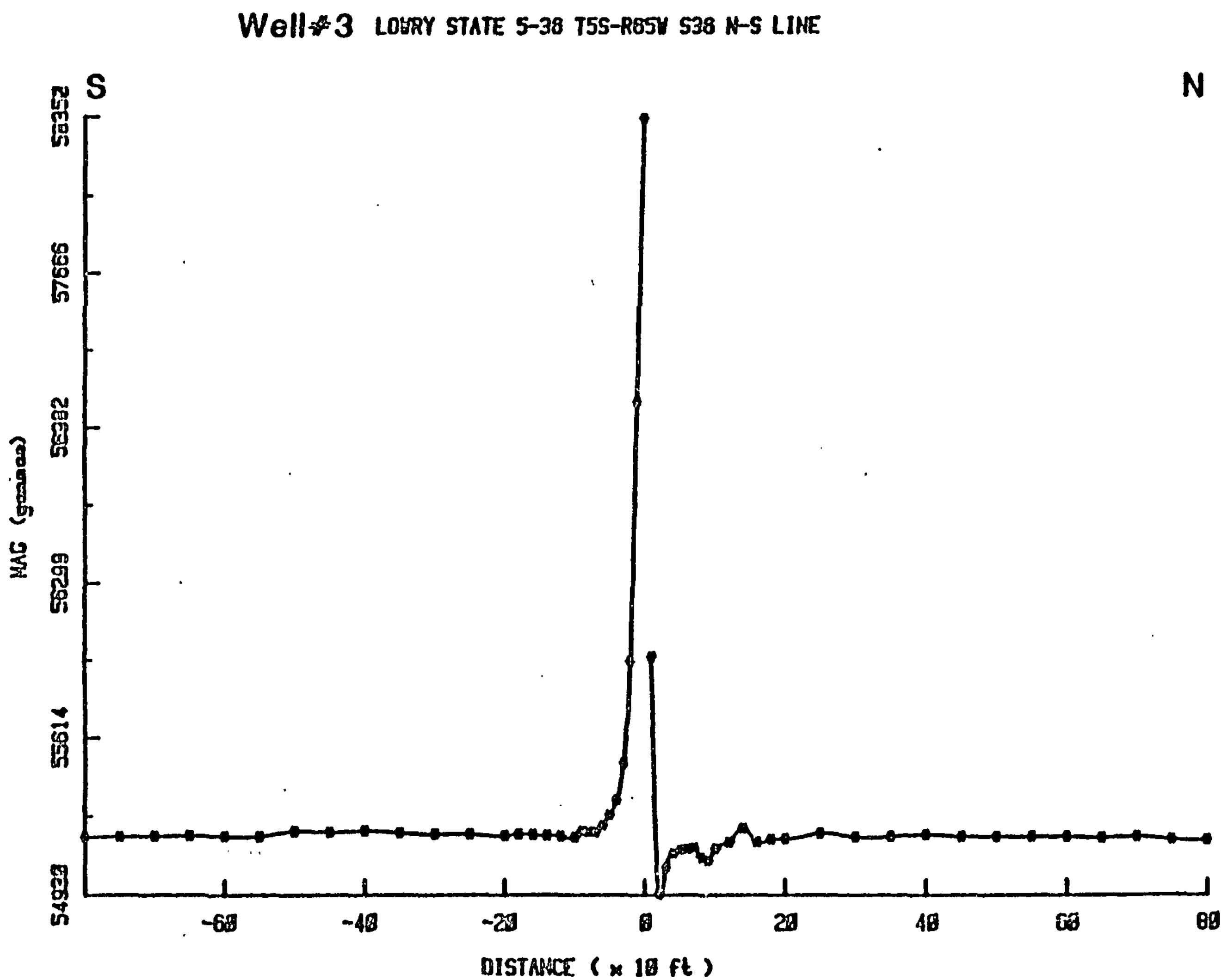


Figure 7. North-south profile of total field over Well Number 3.

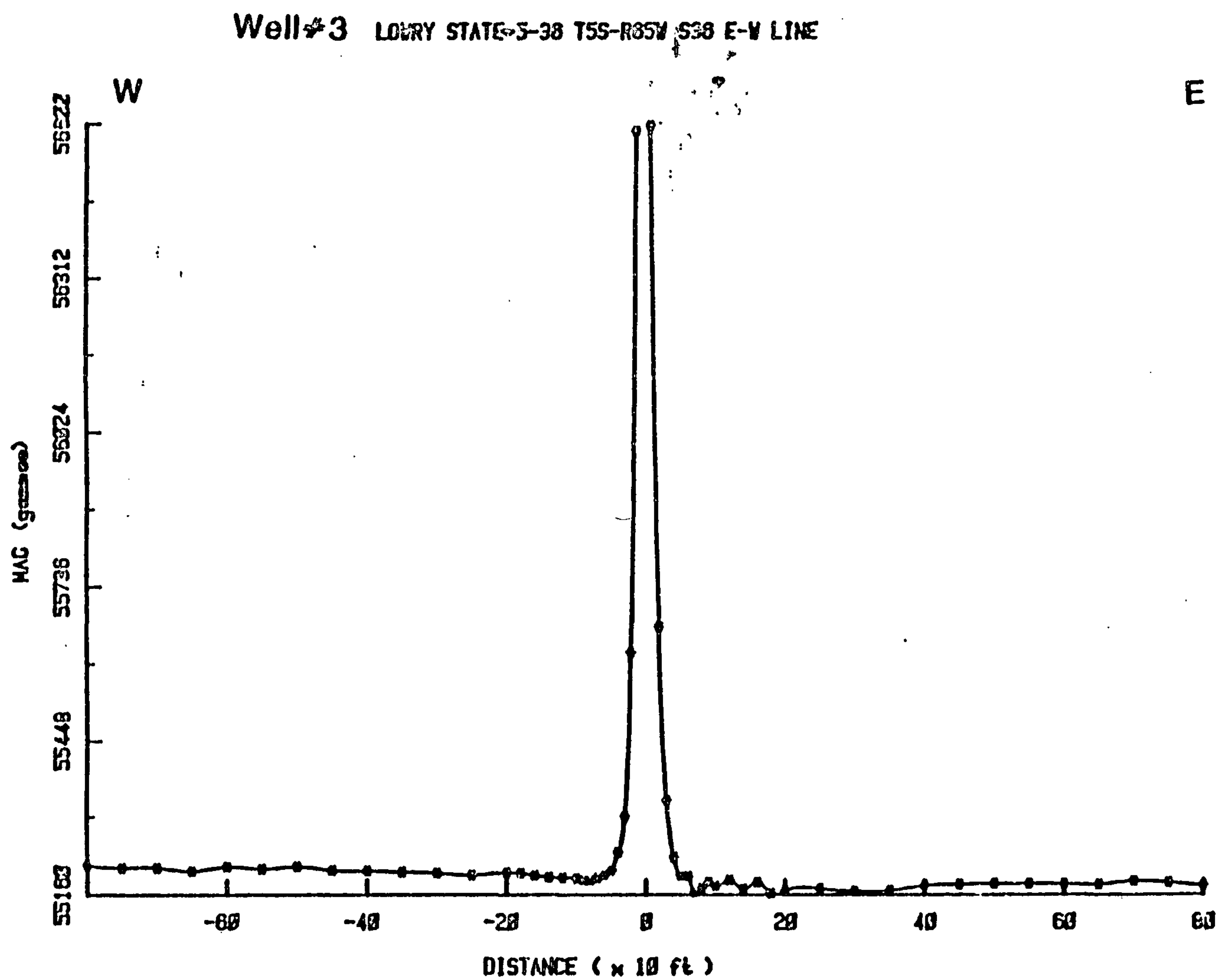


Figure 8. East-west profile of total field over Well Number 3.

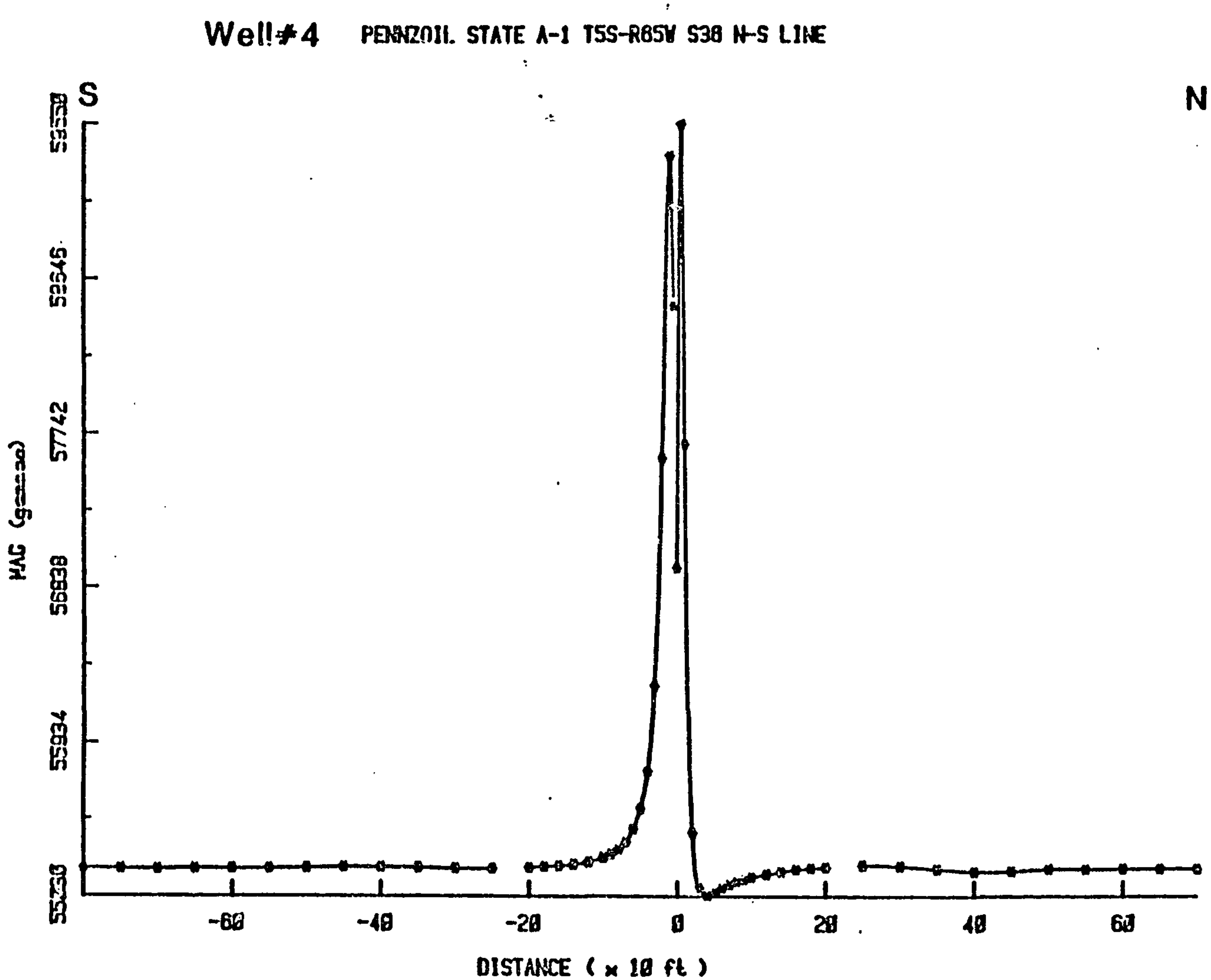


Figure 9. North-south profile of total field over Well Number 4.

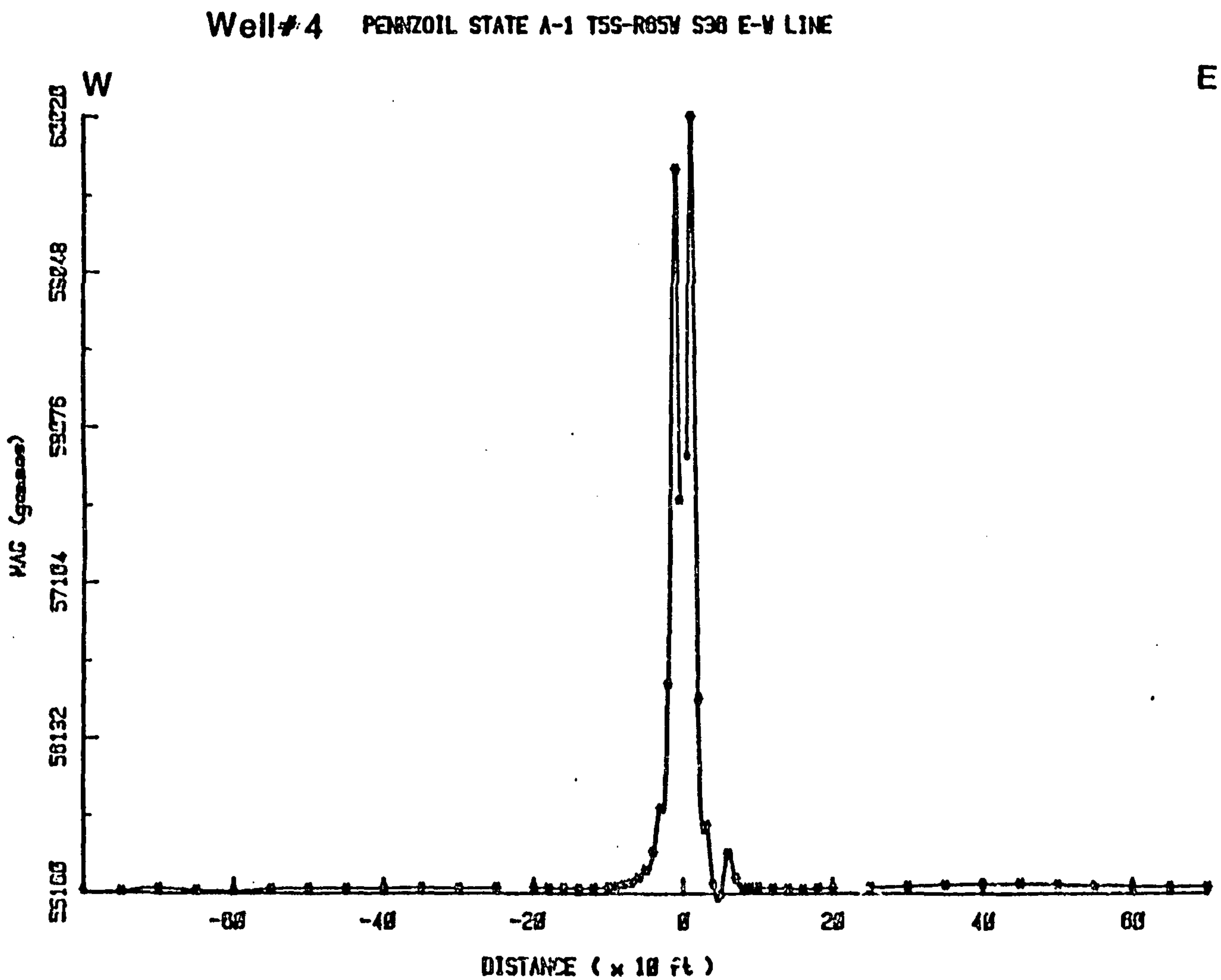


Figure 10. East-west profile of total field over Well Number 4.

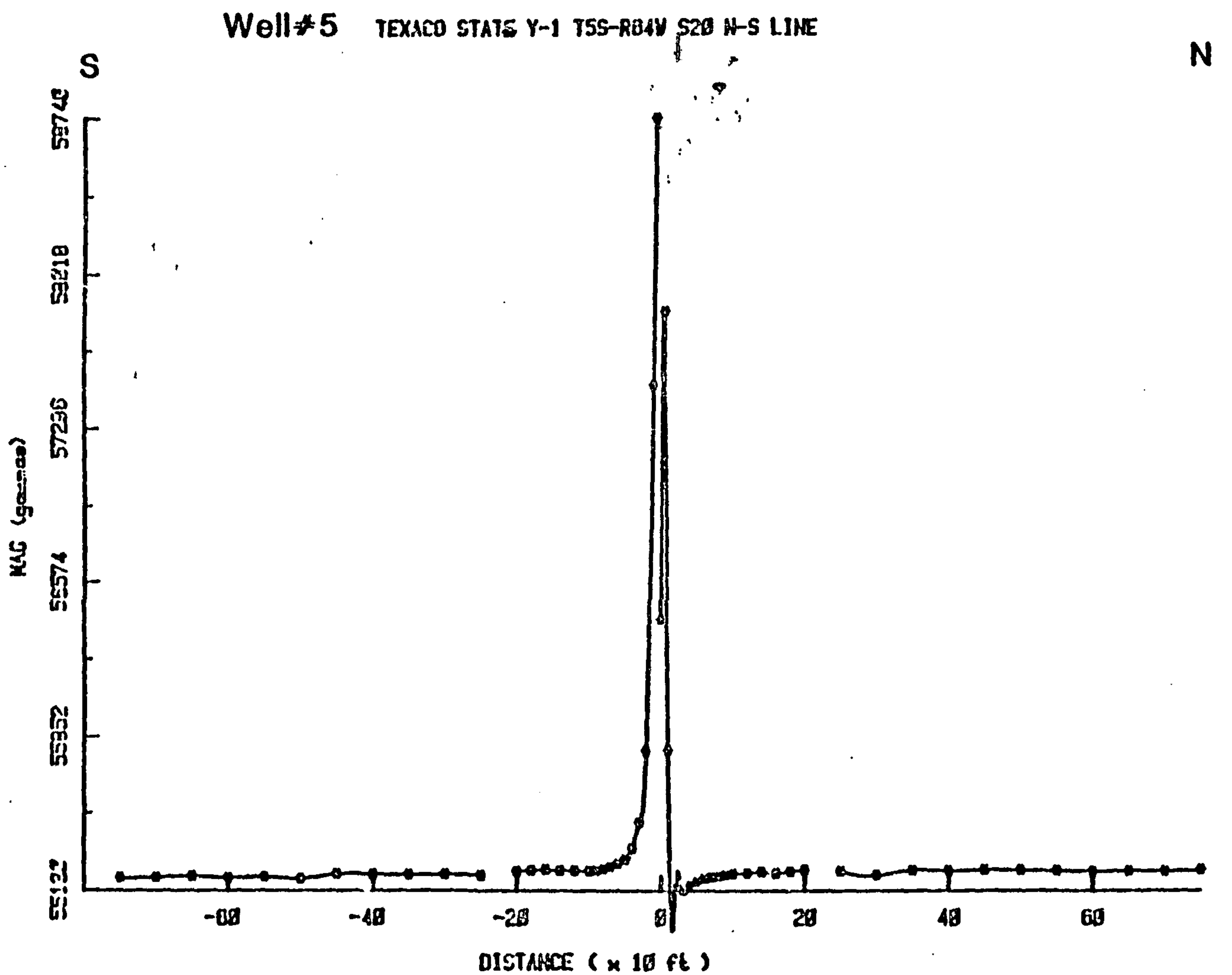


Figure 11. North-south profile of total field over Well Number 5.

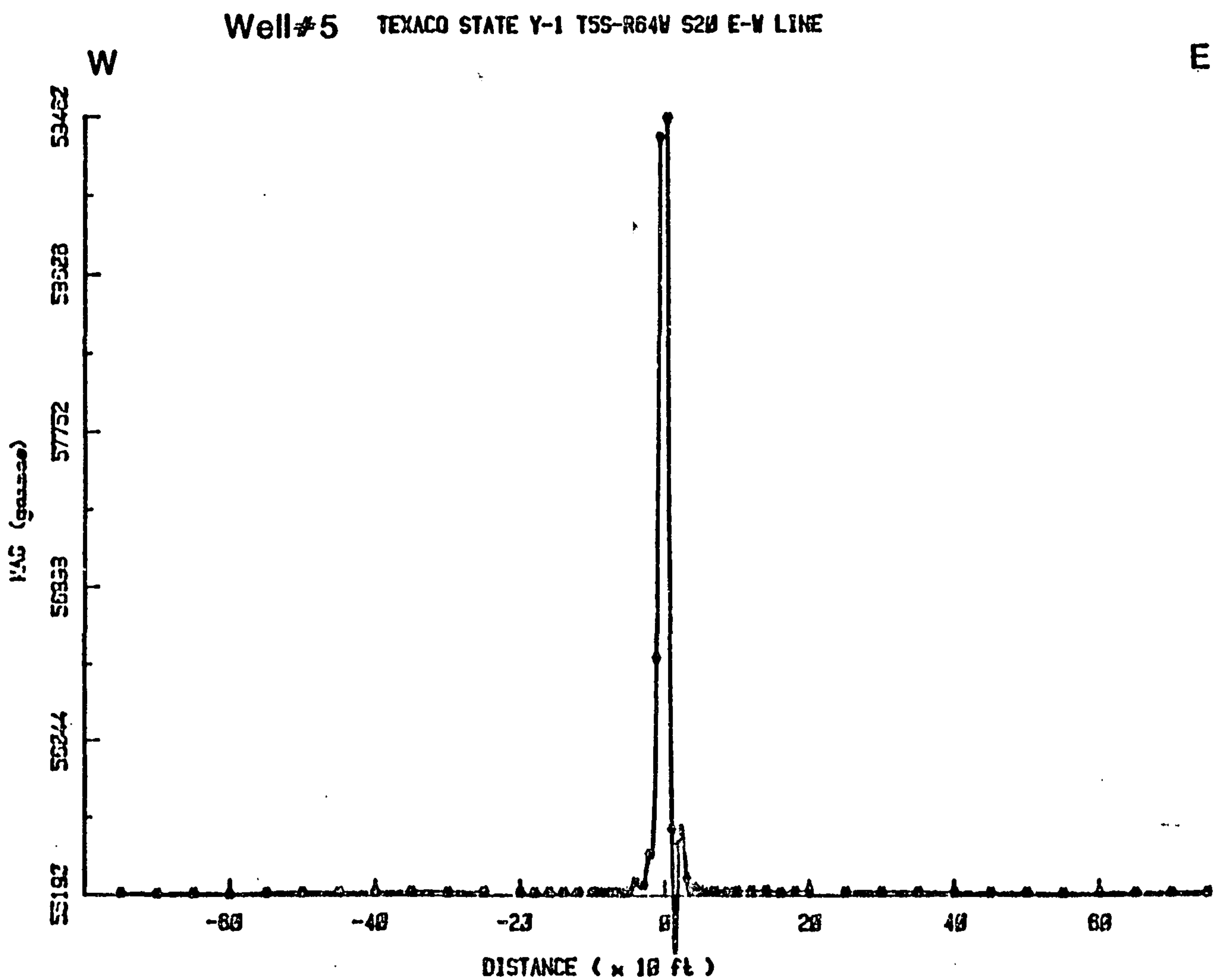


Figure 12. East-west profile of total field over Well Number 5.

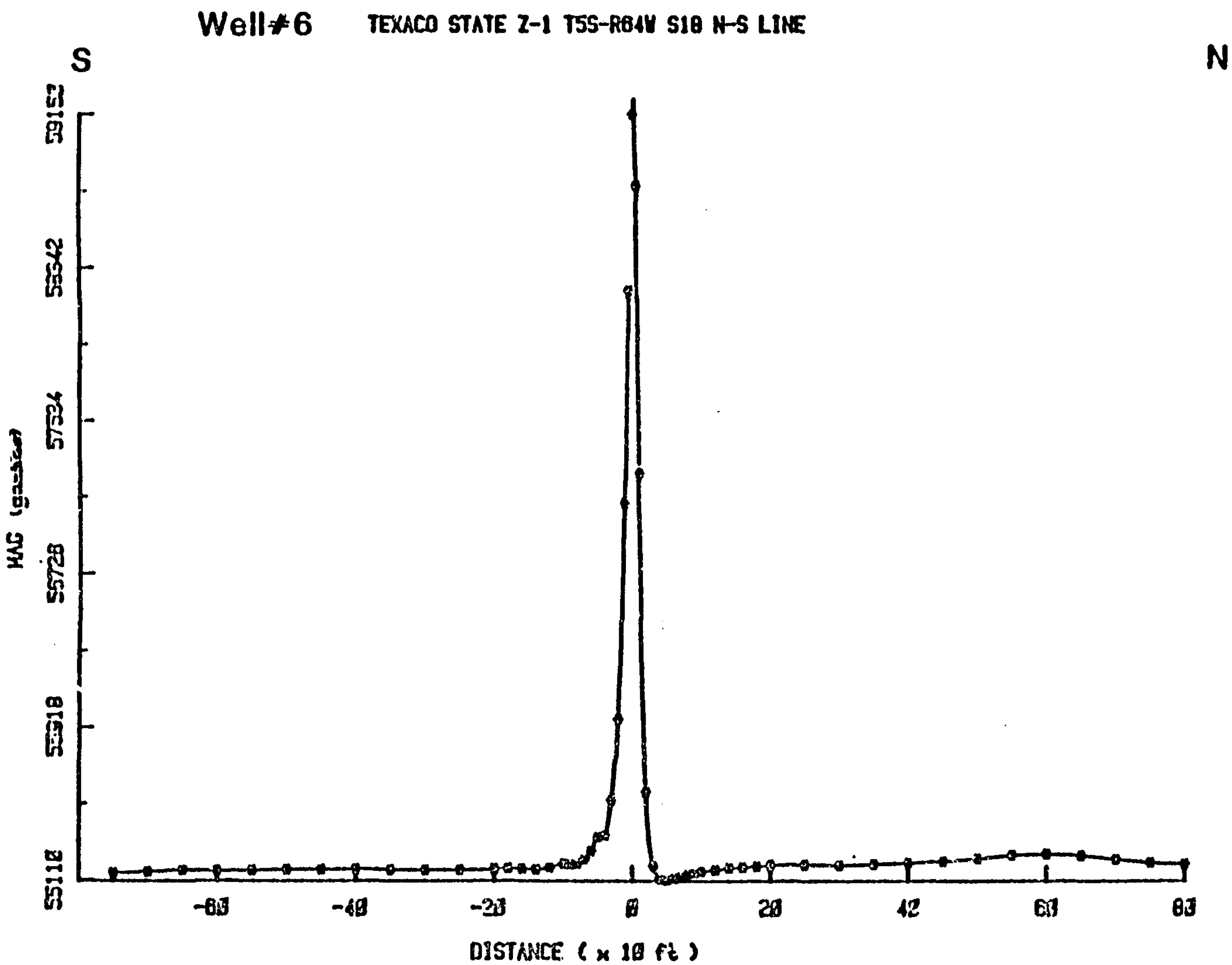


Figure 13. North-south profile of total field over Well Number 6.

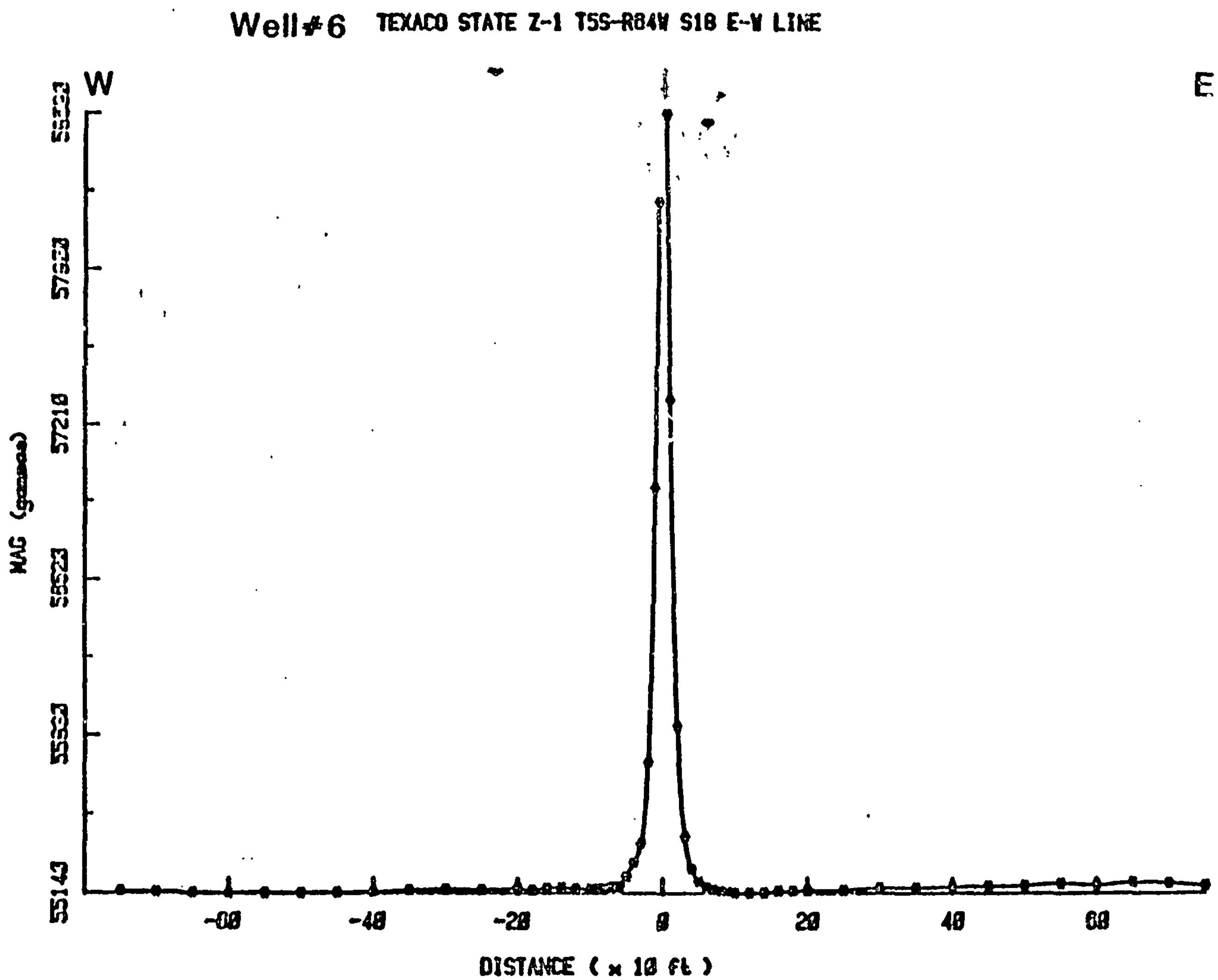


Figure 14. East-west profile of total field over Well Number 6.

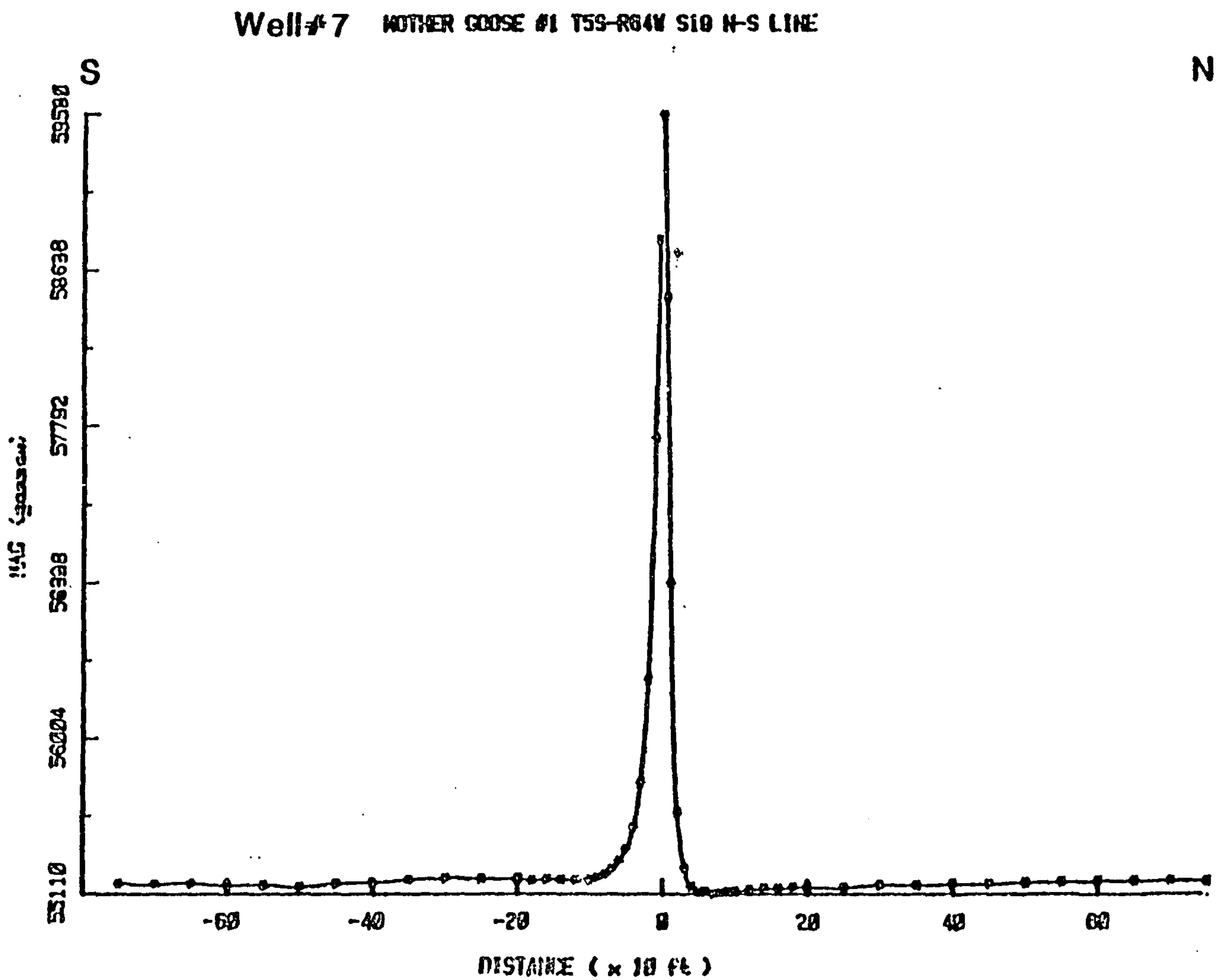


Figure 15. North-south profile of total field over Well Number 7.

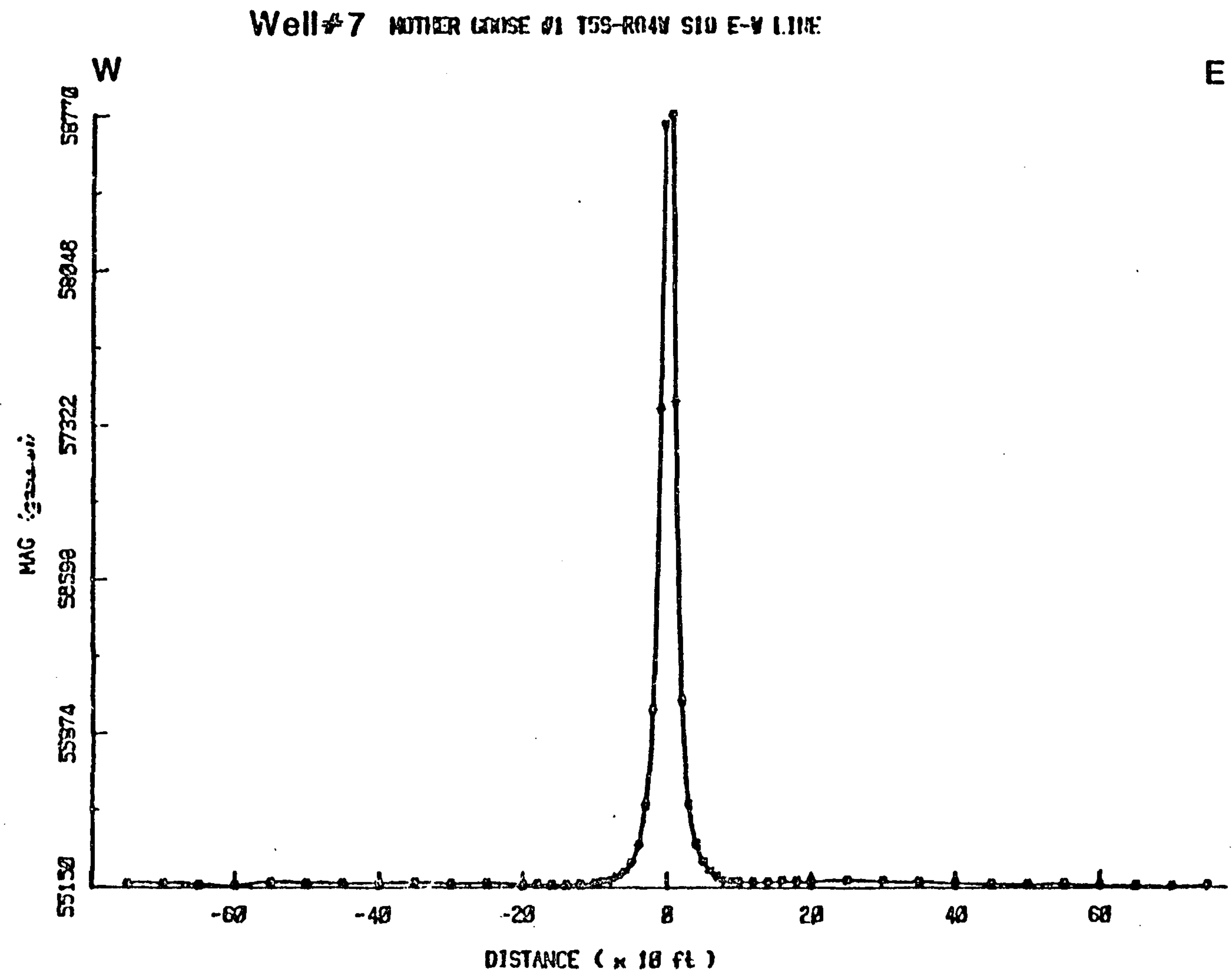


Figure 16. East-west profile of total field over Well Number 7.

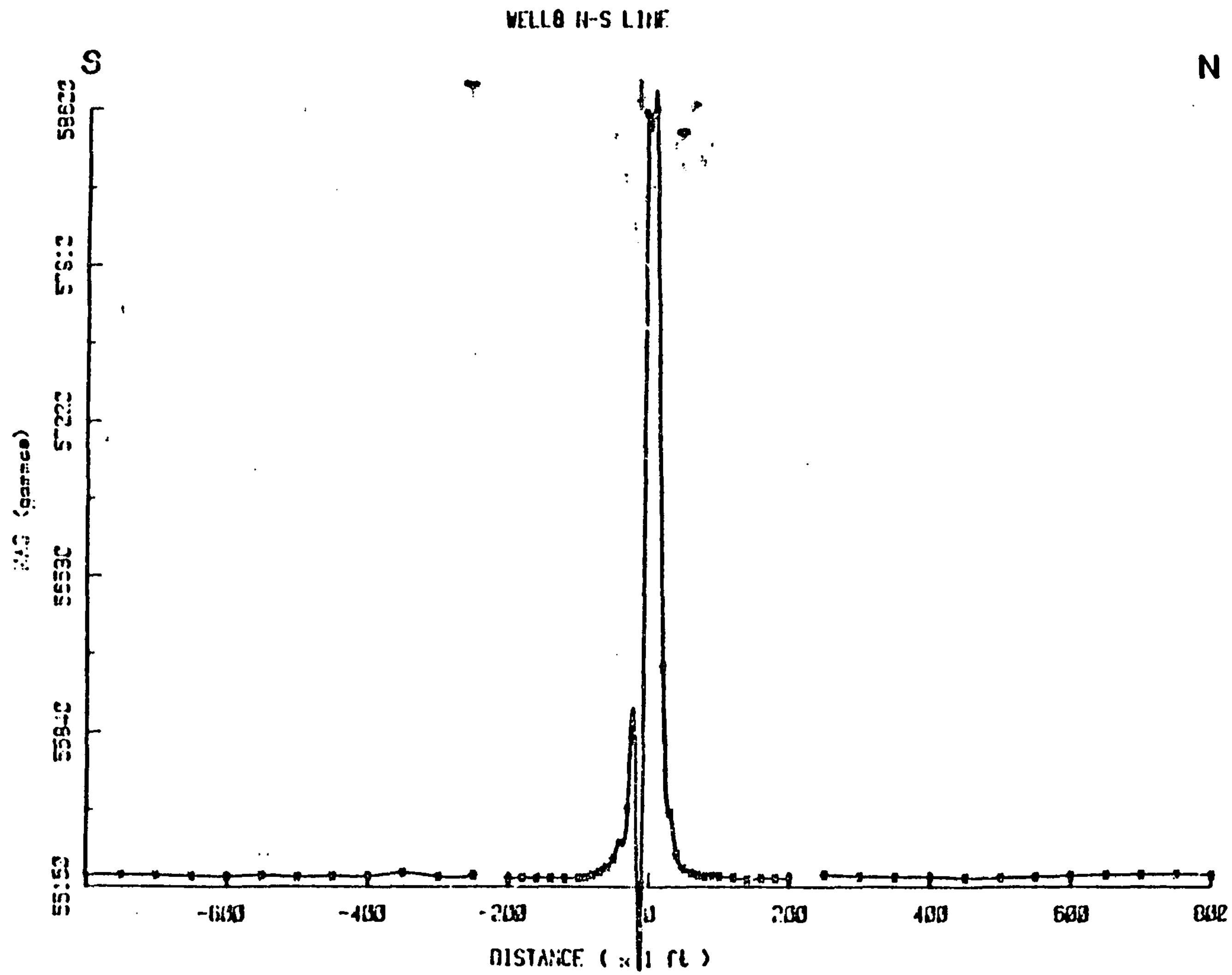


Figure 17. North-south profile of total field over Well Number 8.

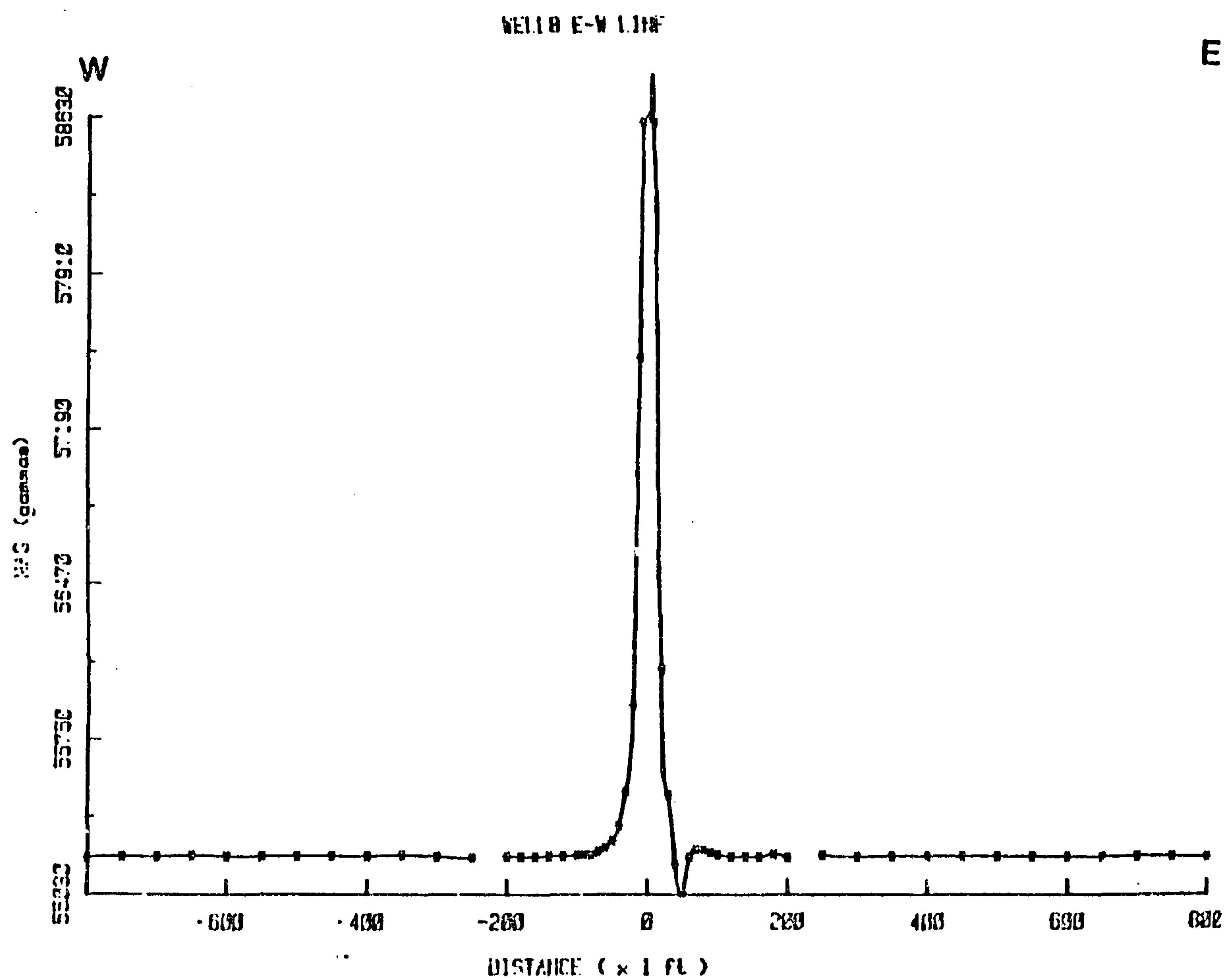


Figure 18. East-west profile of total field over Well Number 8.

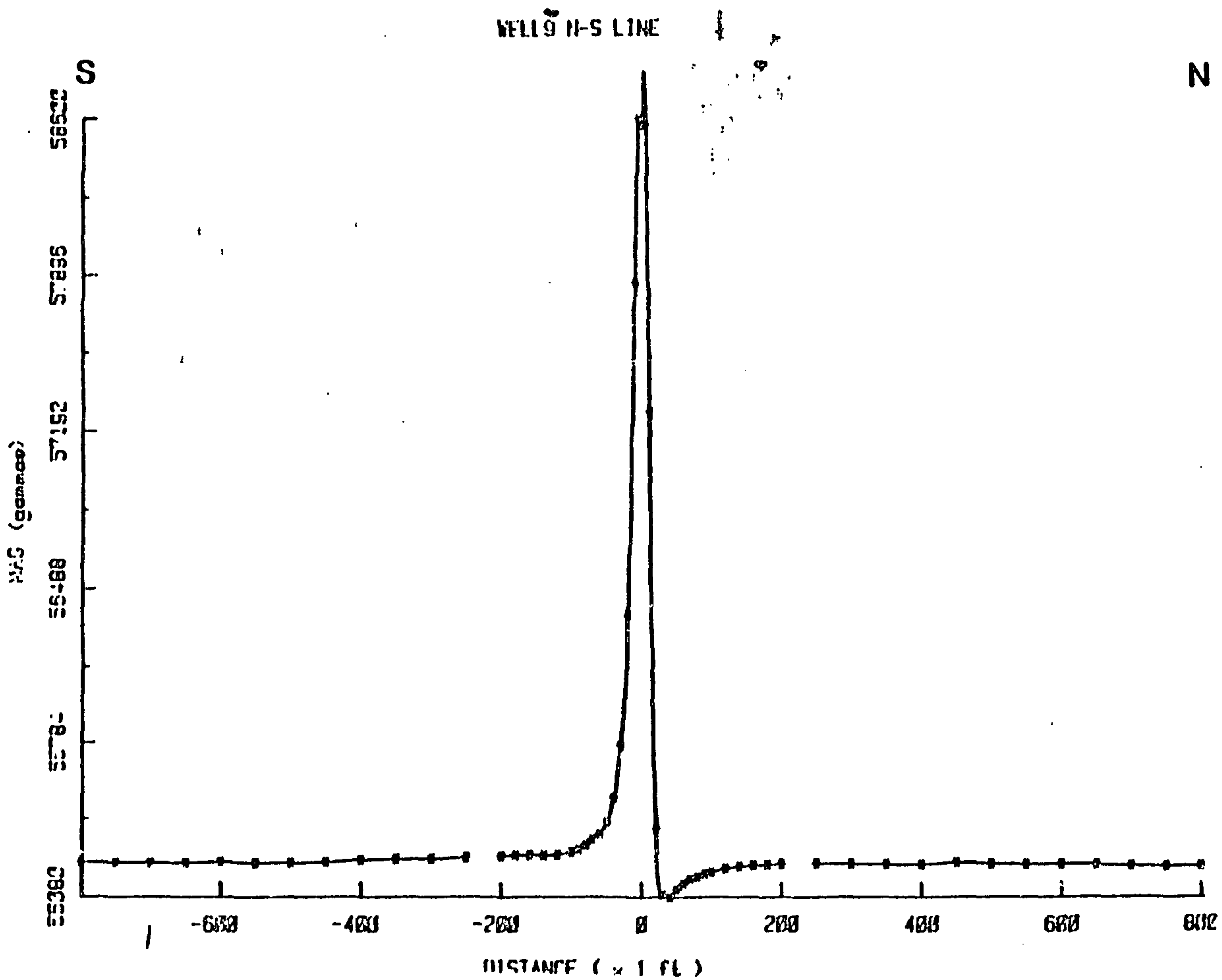


Figure 19. North-south profile of total field over Well Number 9.

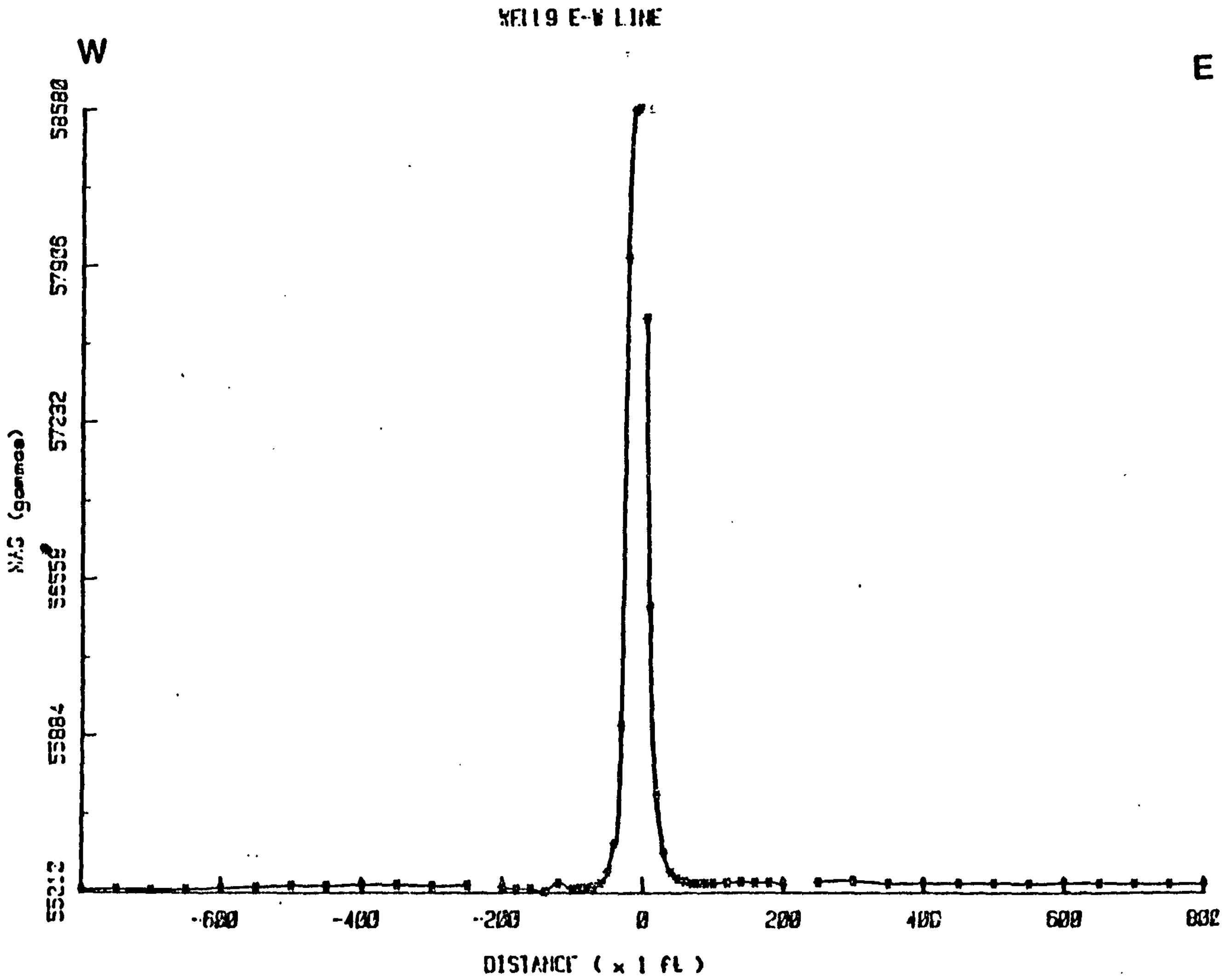


Figure 20. East-west profile of total field over Well Number 9.

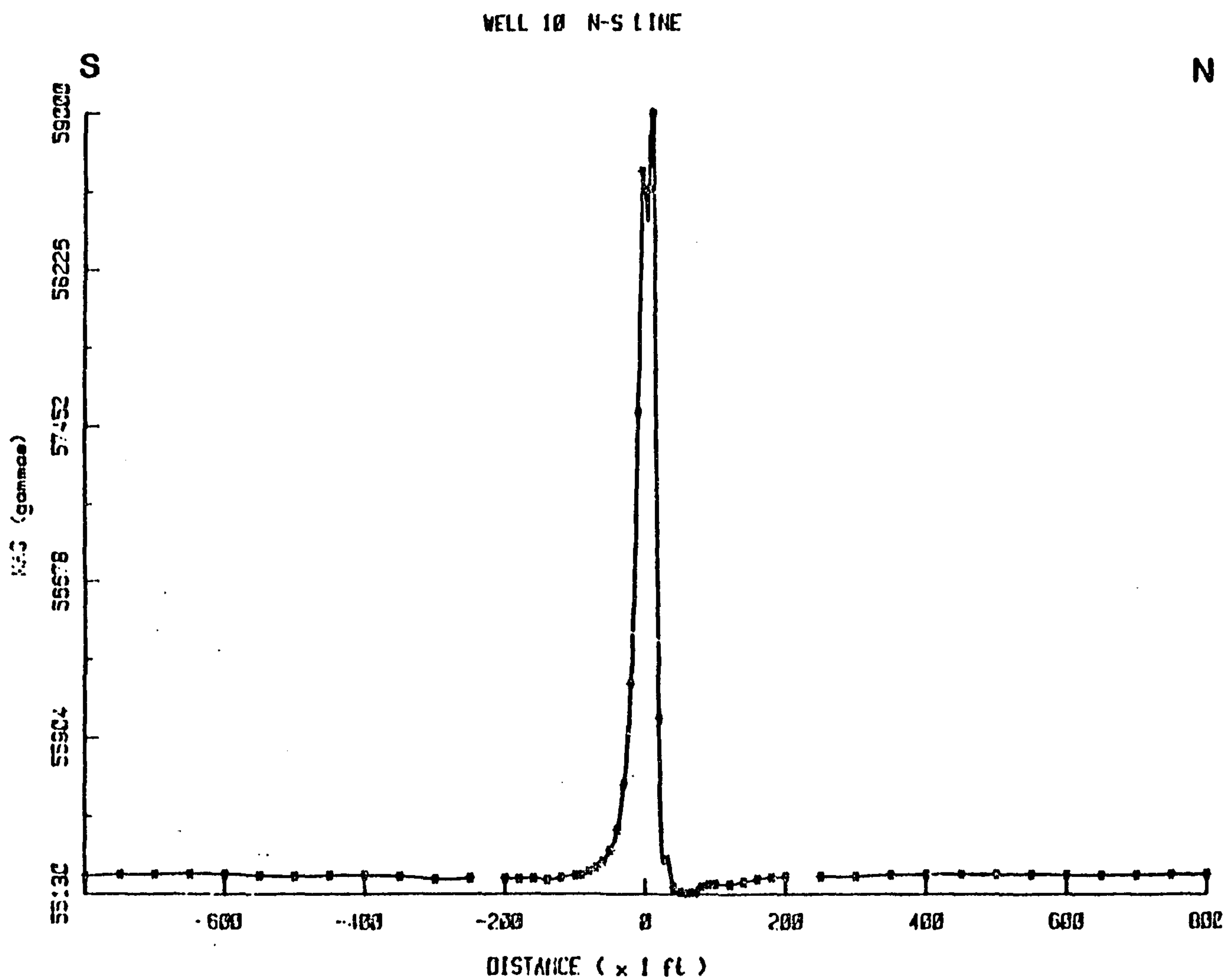


Figure 21. North-south profile of total field over Well Number 10.

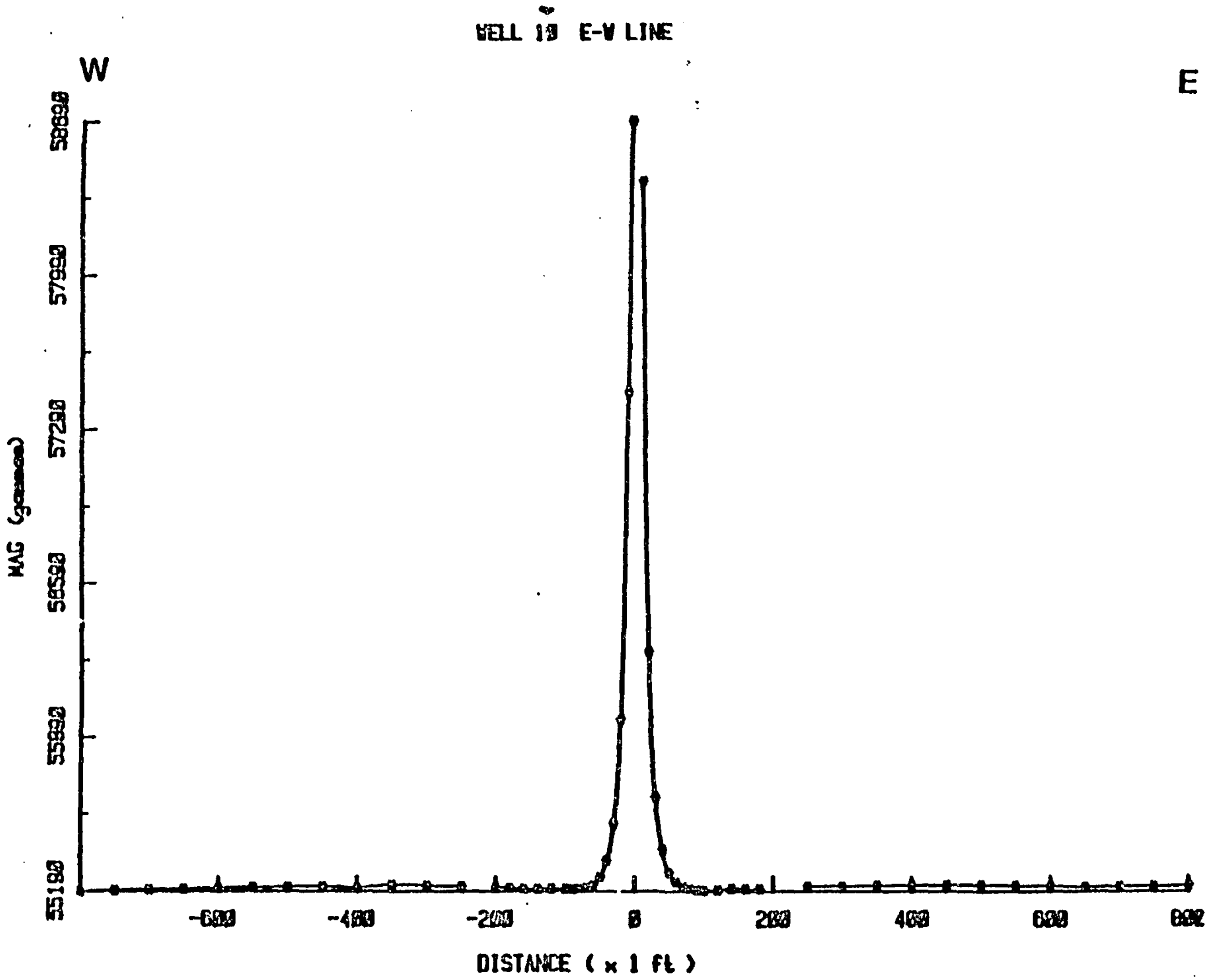


Figure 22. East-west profile of total field over Well Number 10.

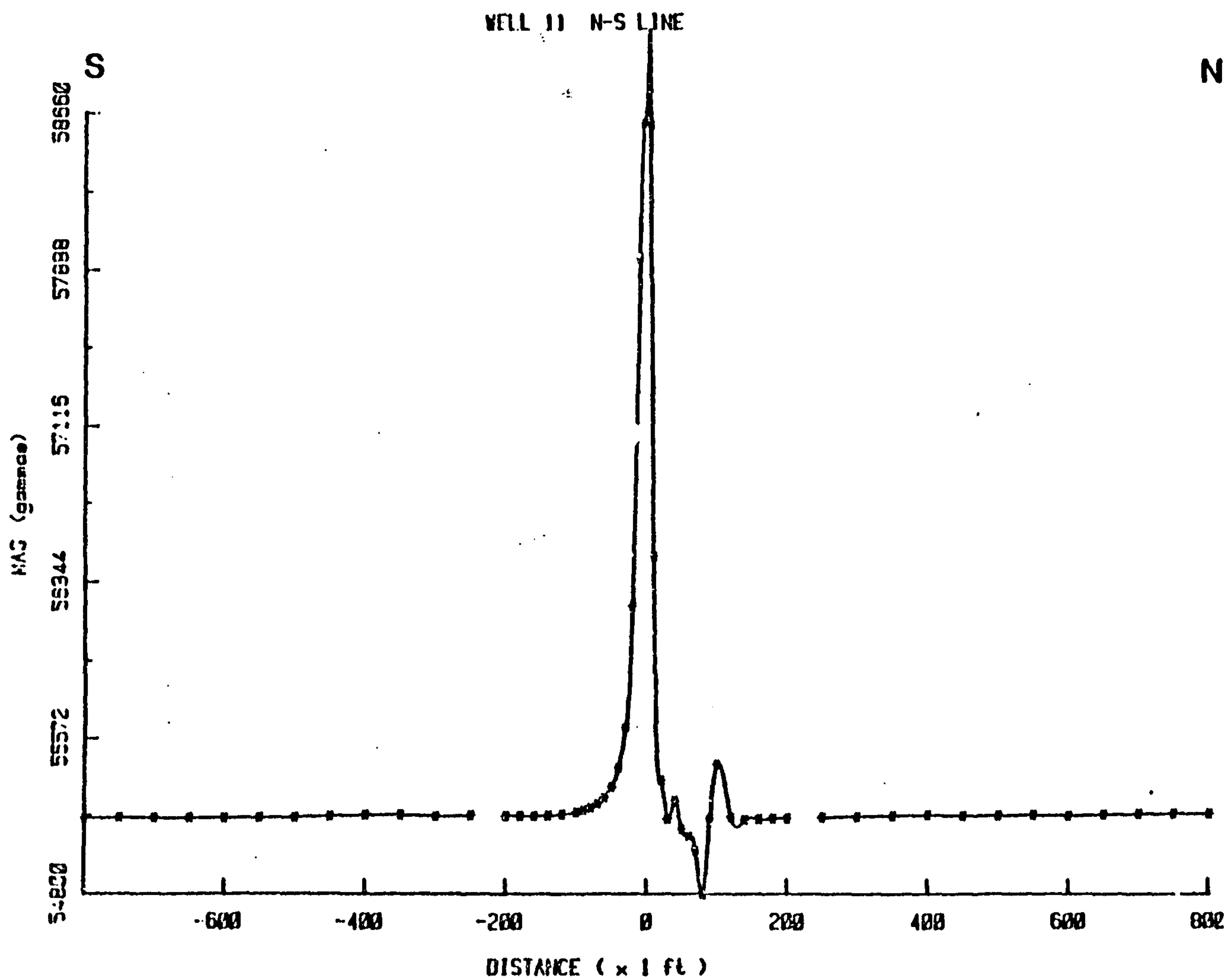


Figure 23. North-south profile of total field over Well Number 11.

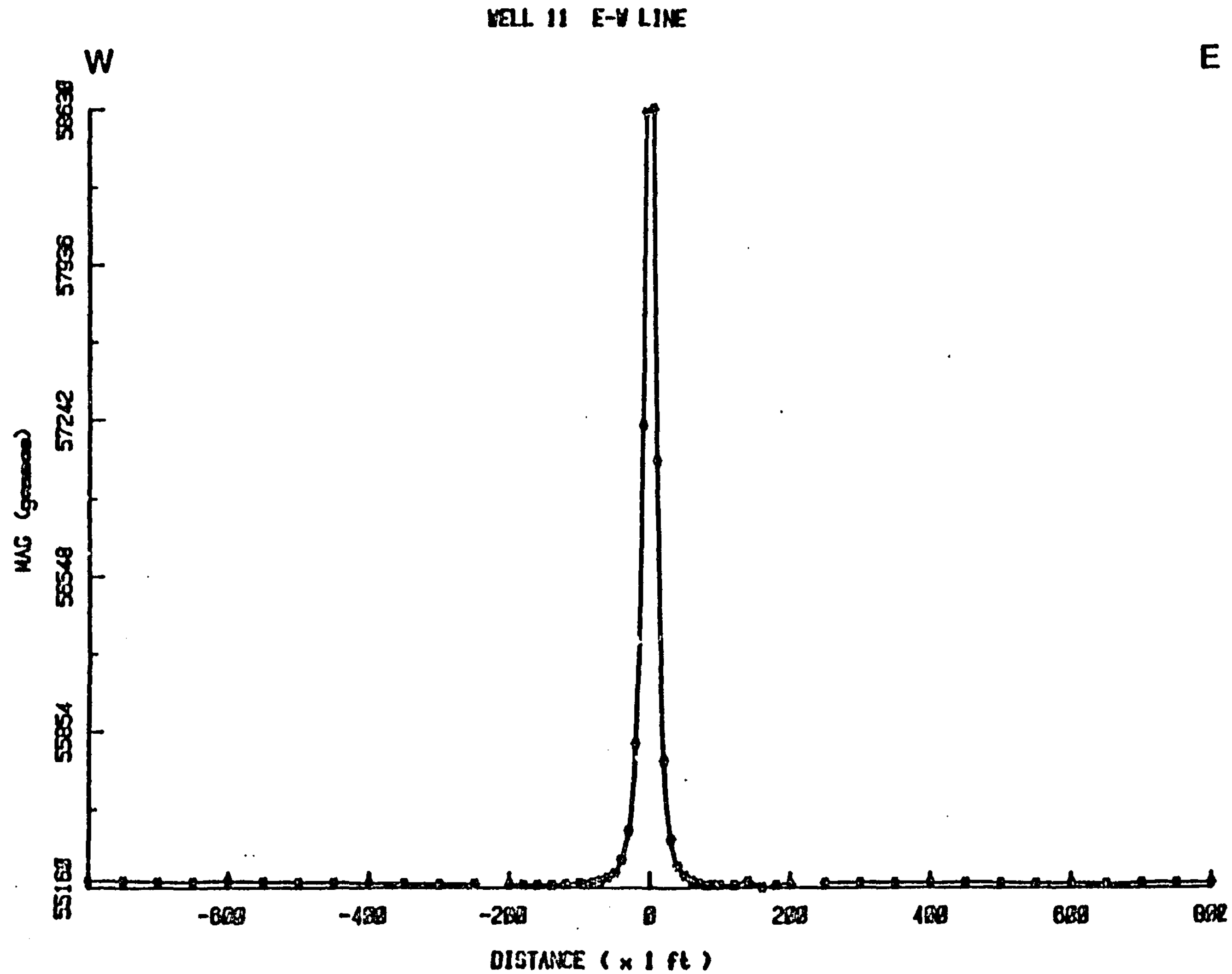


Figure 24. East-west profile of total field over Well Number 11.

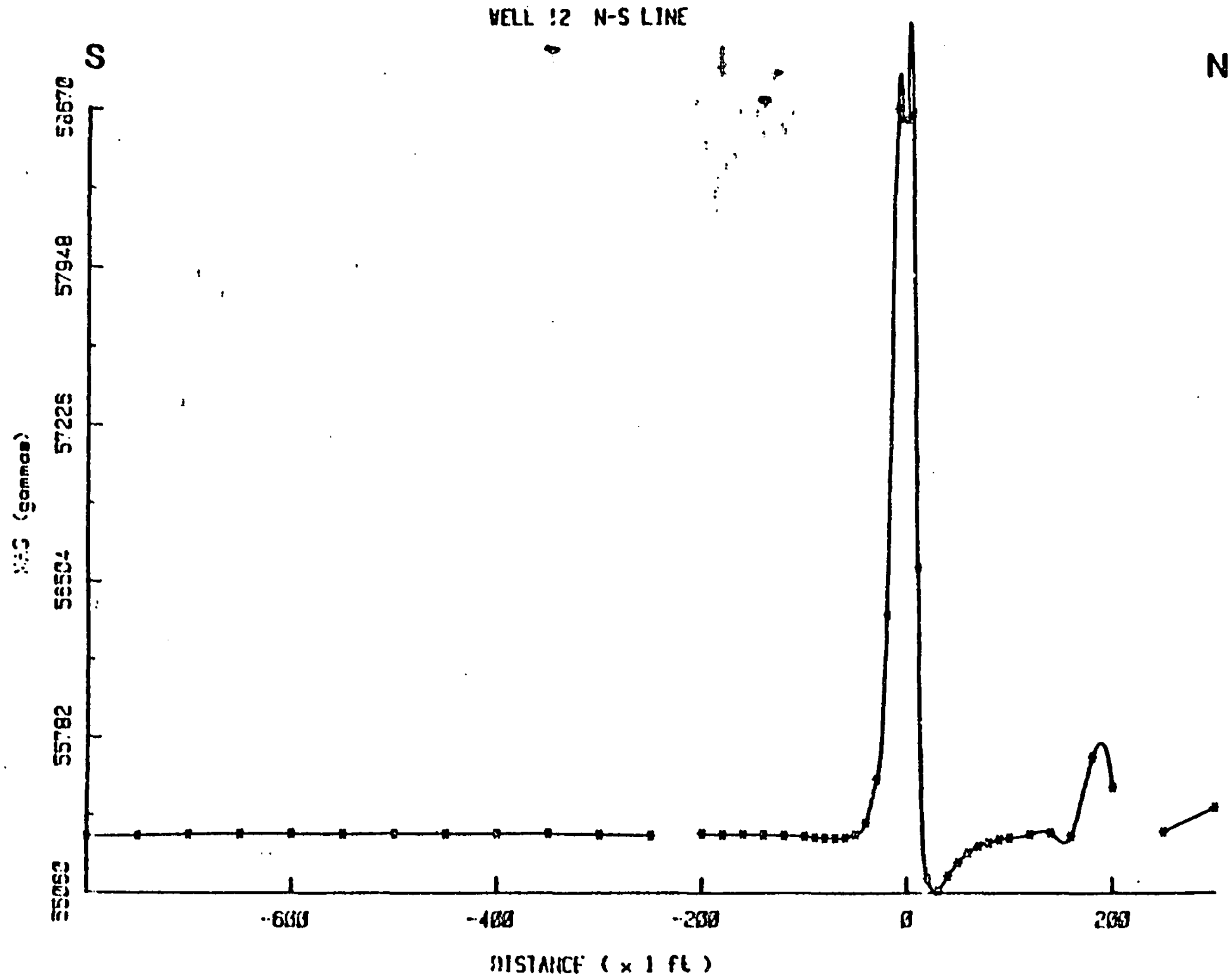


Figure 25. North-south profile of total field over Well Number 12.

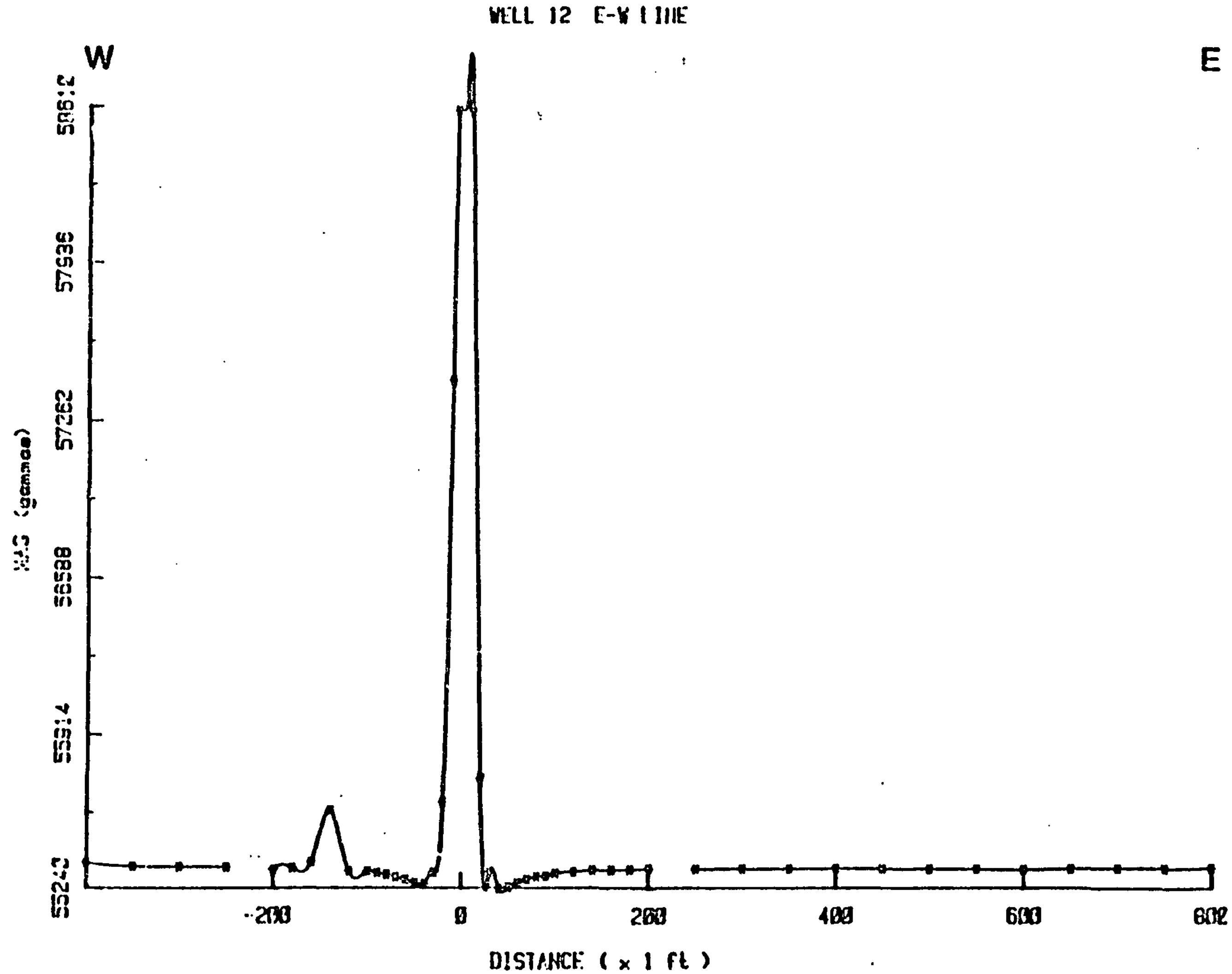


Figure 26. East-west profile of total field over Well Number 12.

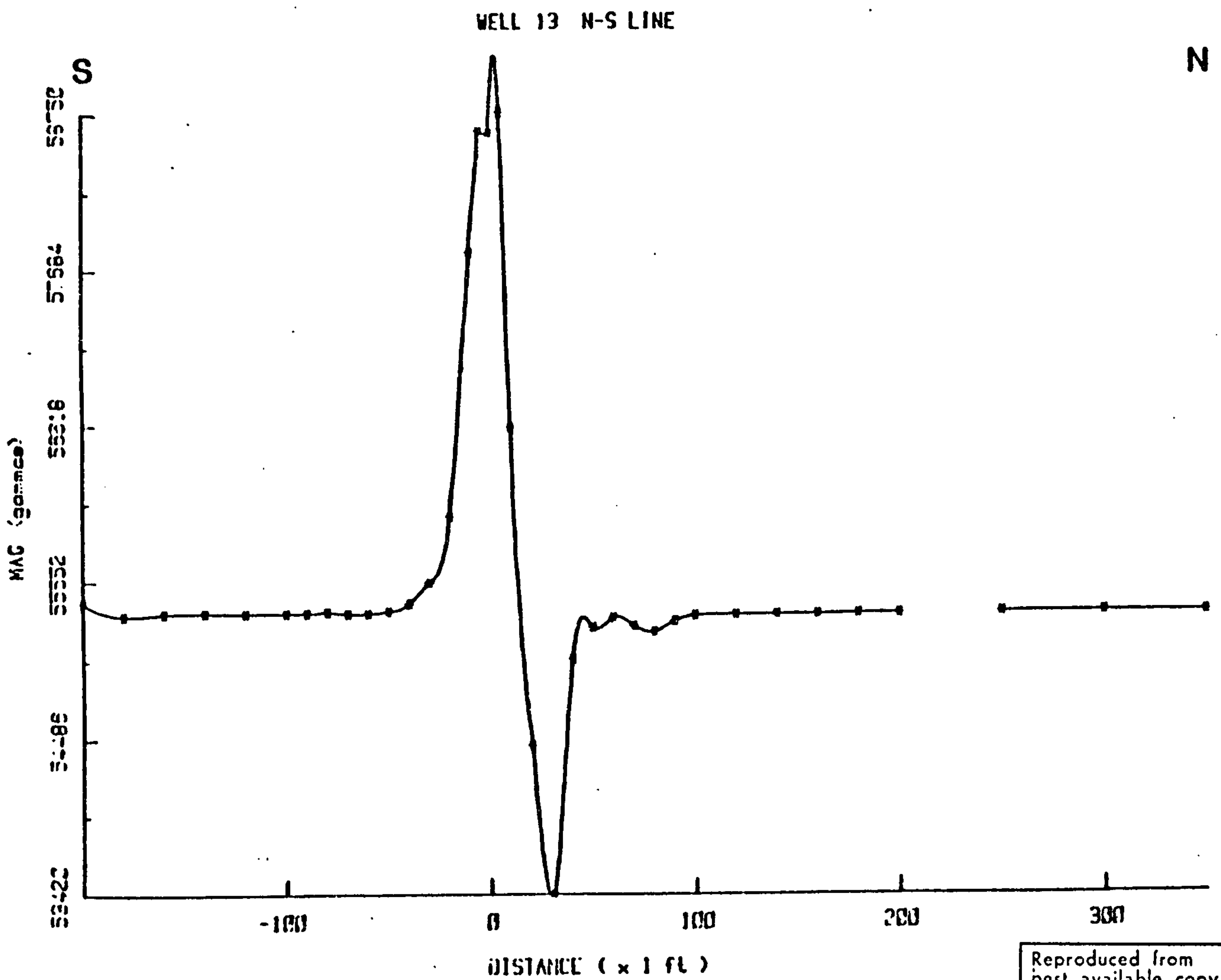


Figure 27. North-south profile of total field over Well Number 13.

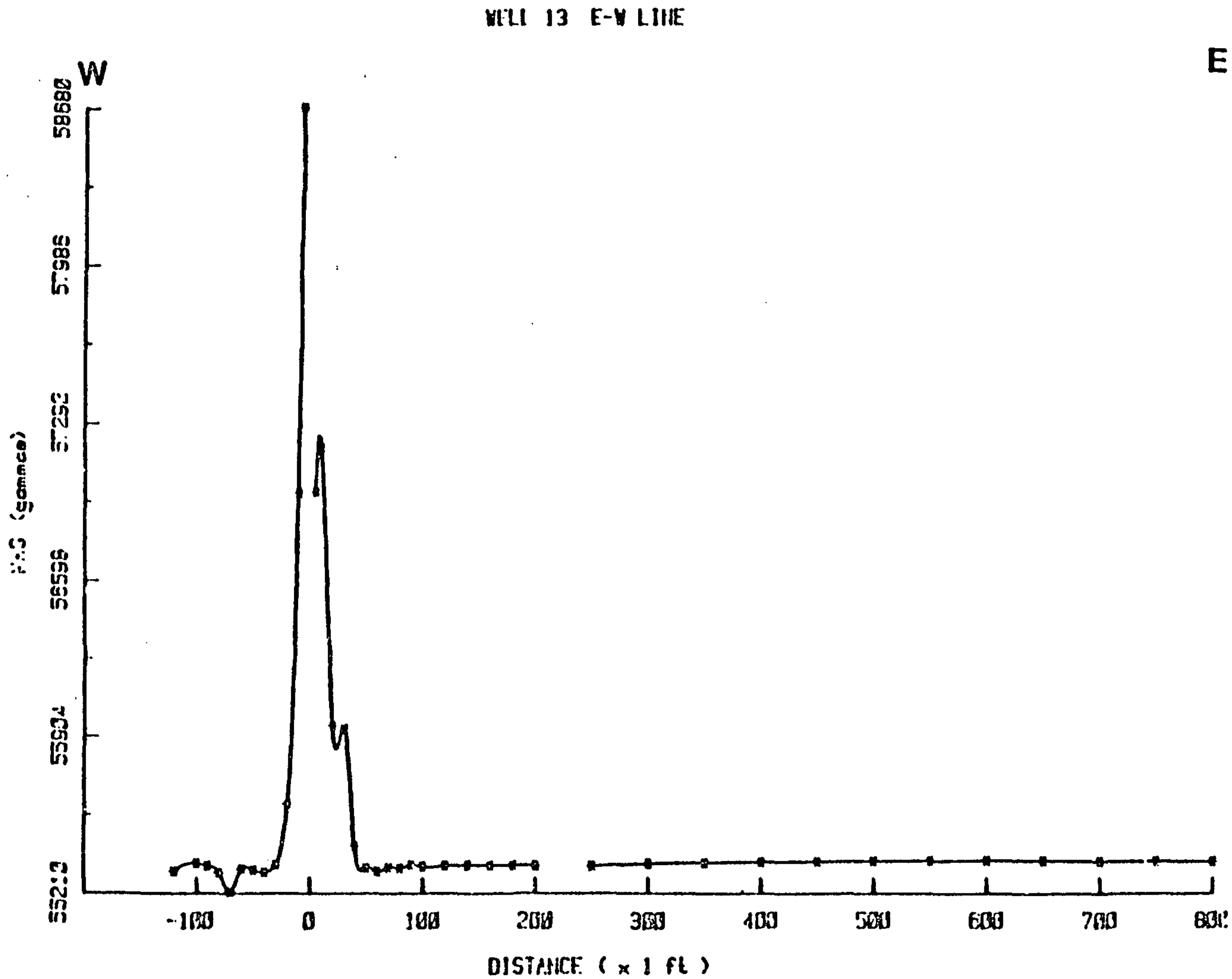


Figure 28. East-west profile of total field over Well Number 13.

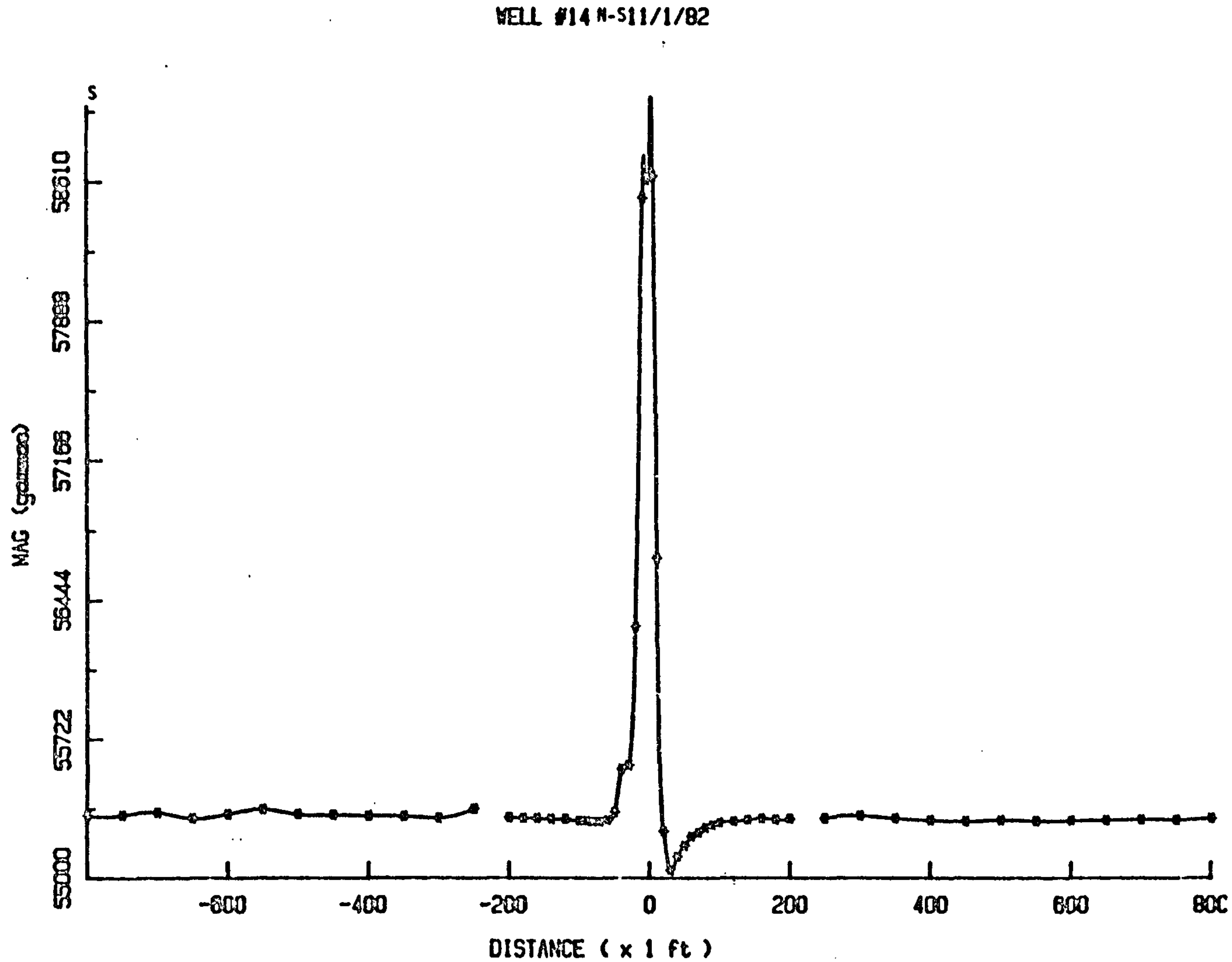


Figure 29. North-south profile of total field over Well Number 14.

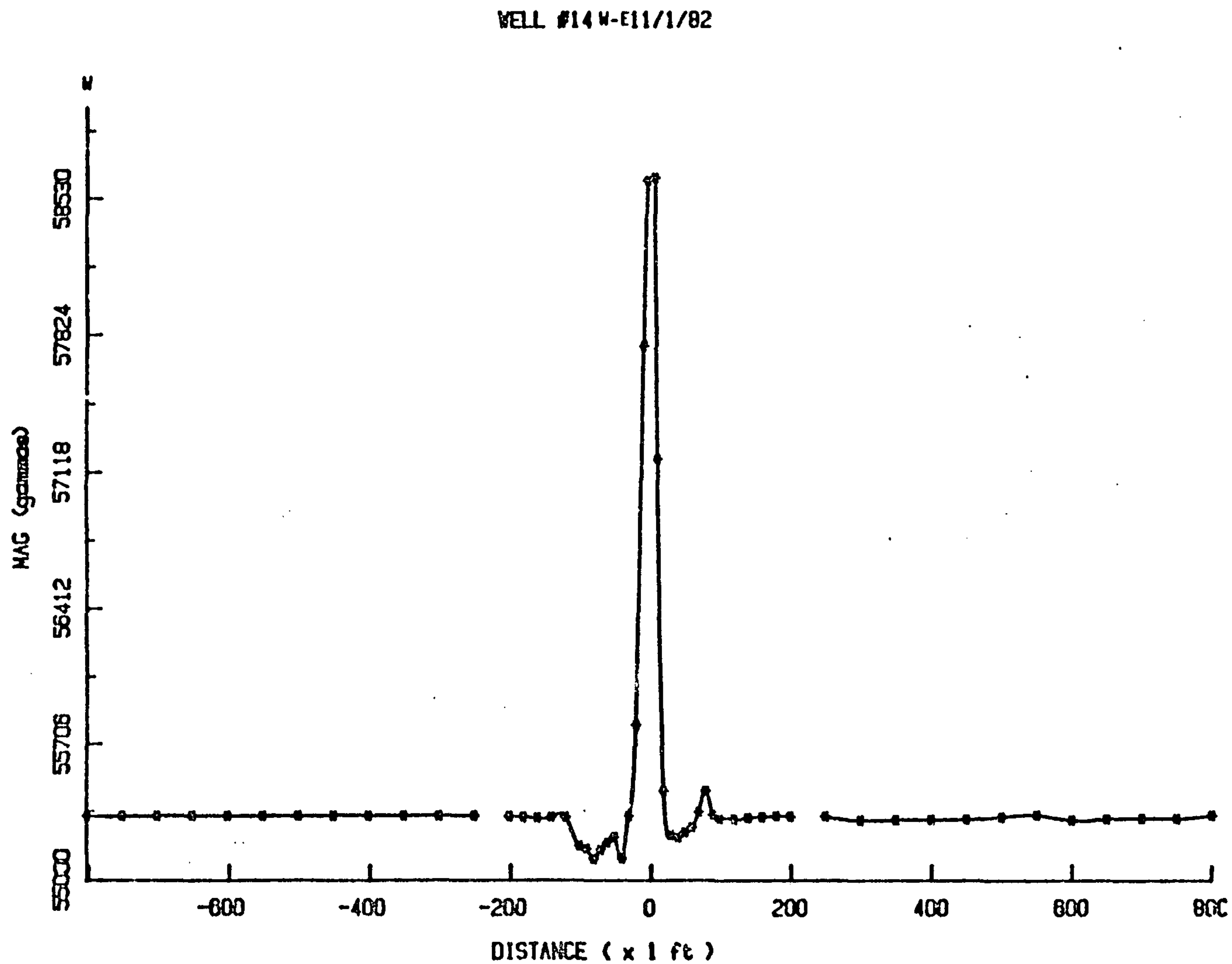


Figure 30. East-west profile of total field over Well Number 14.

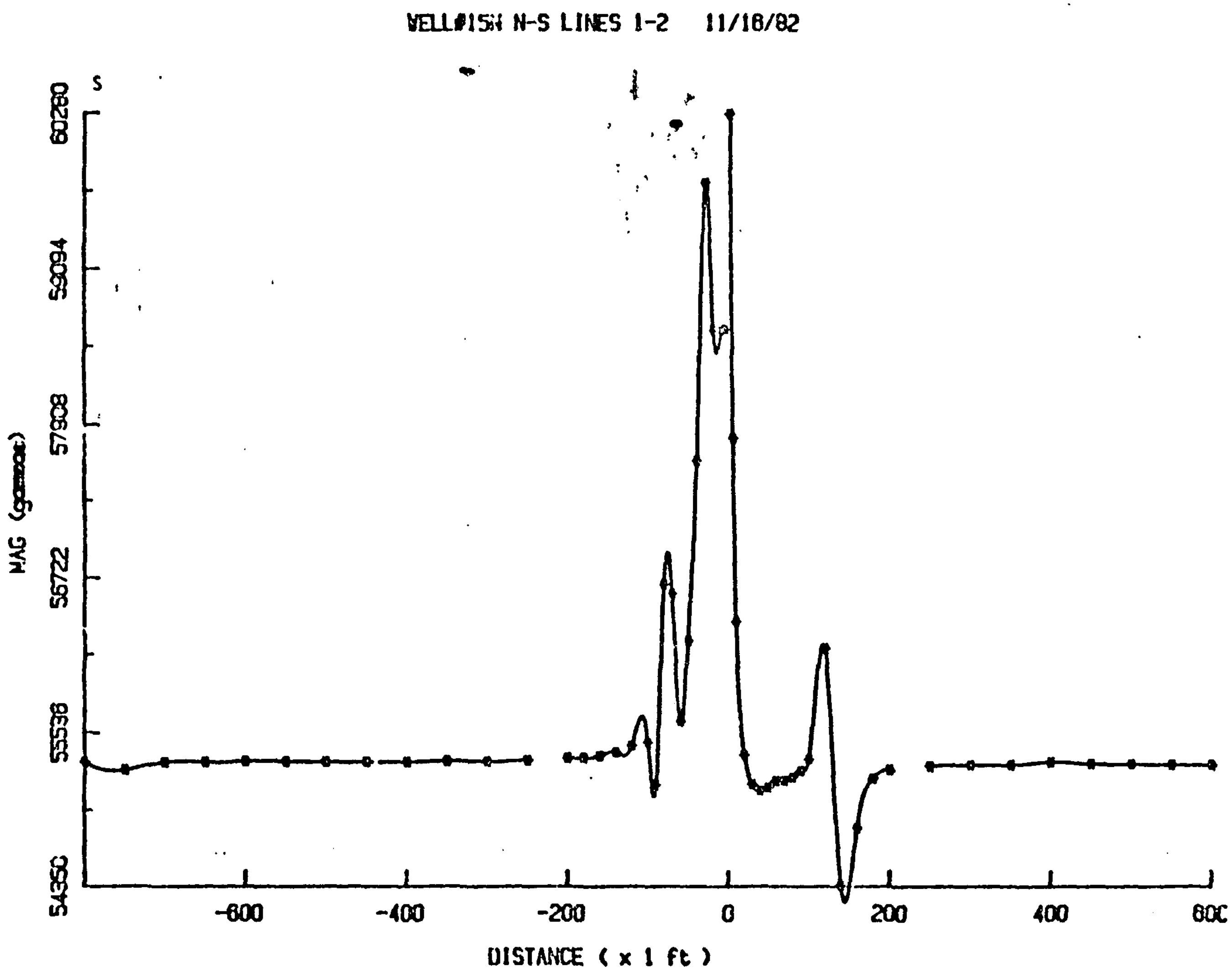


Figure 31. North-south profile of total field over Well Number 15 N.

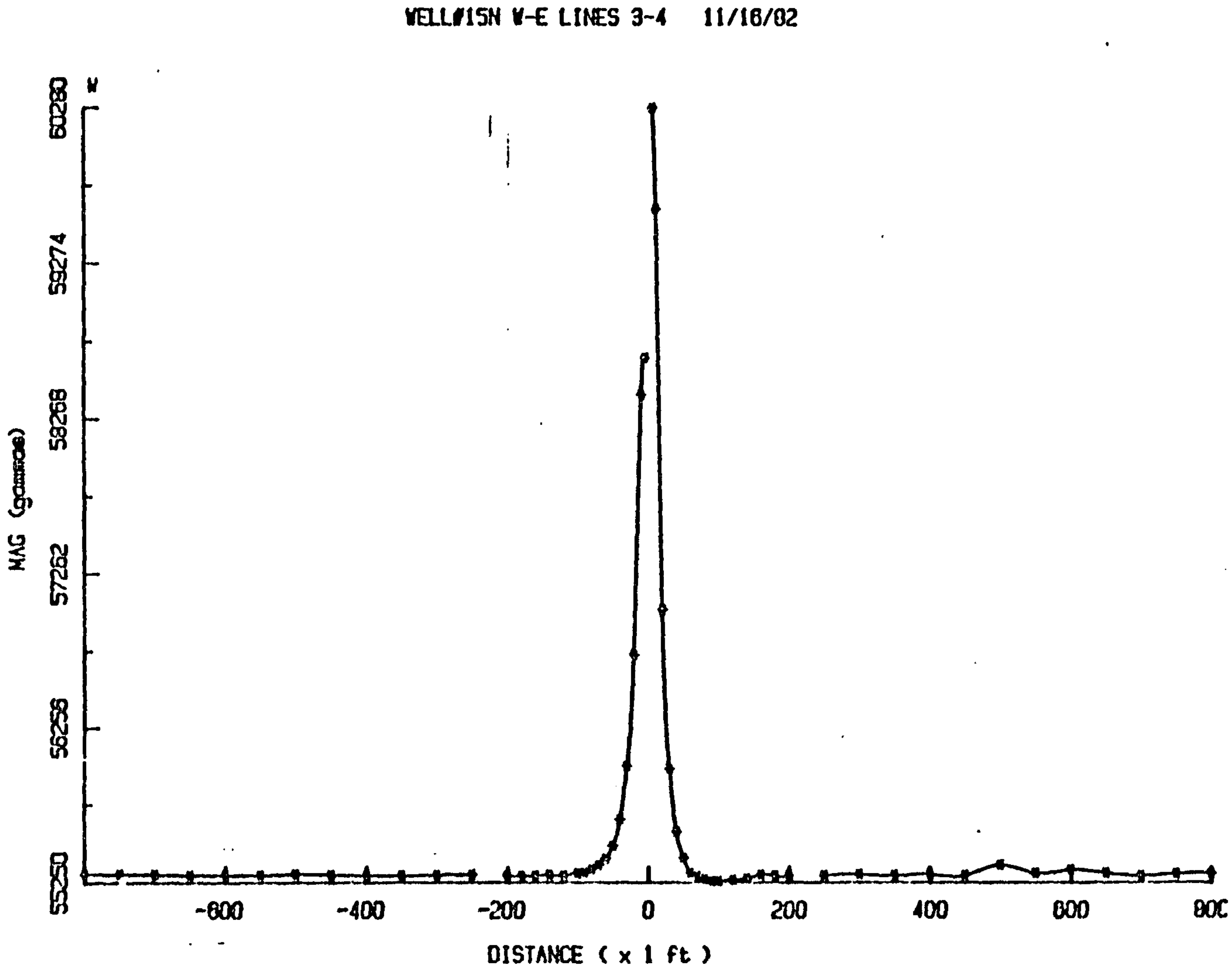


Figure 32. East-west profile of total field over Well Number 15 N.

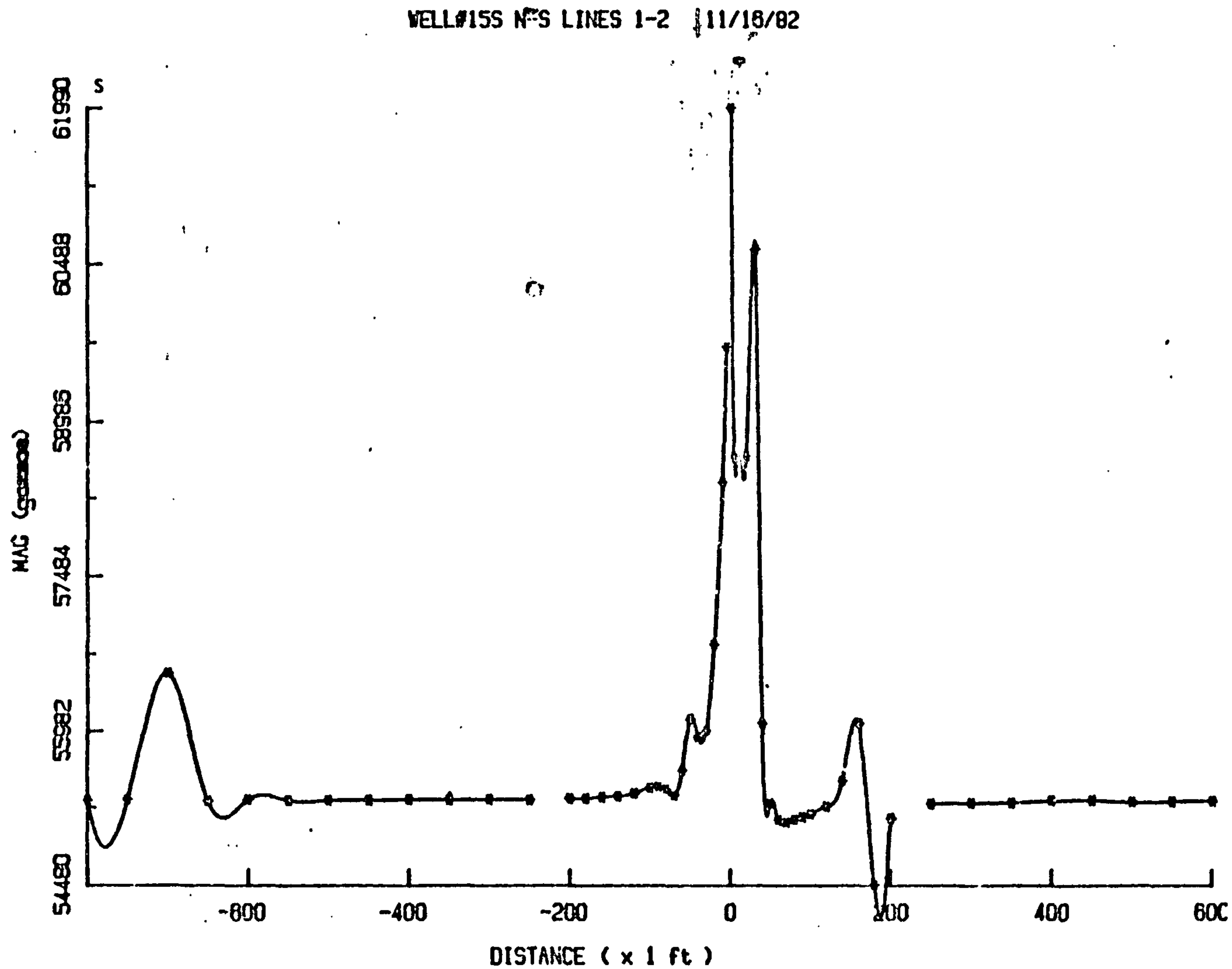


Figure 33. North-south profile of total field over Well Number 15 S.

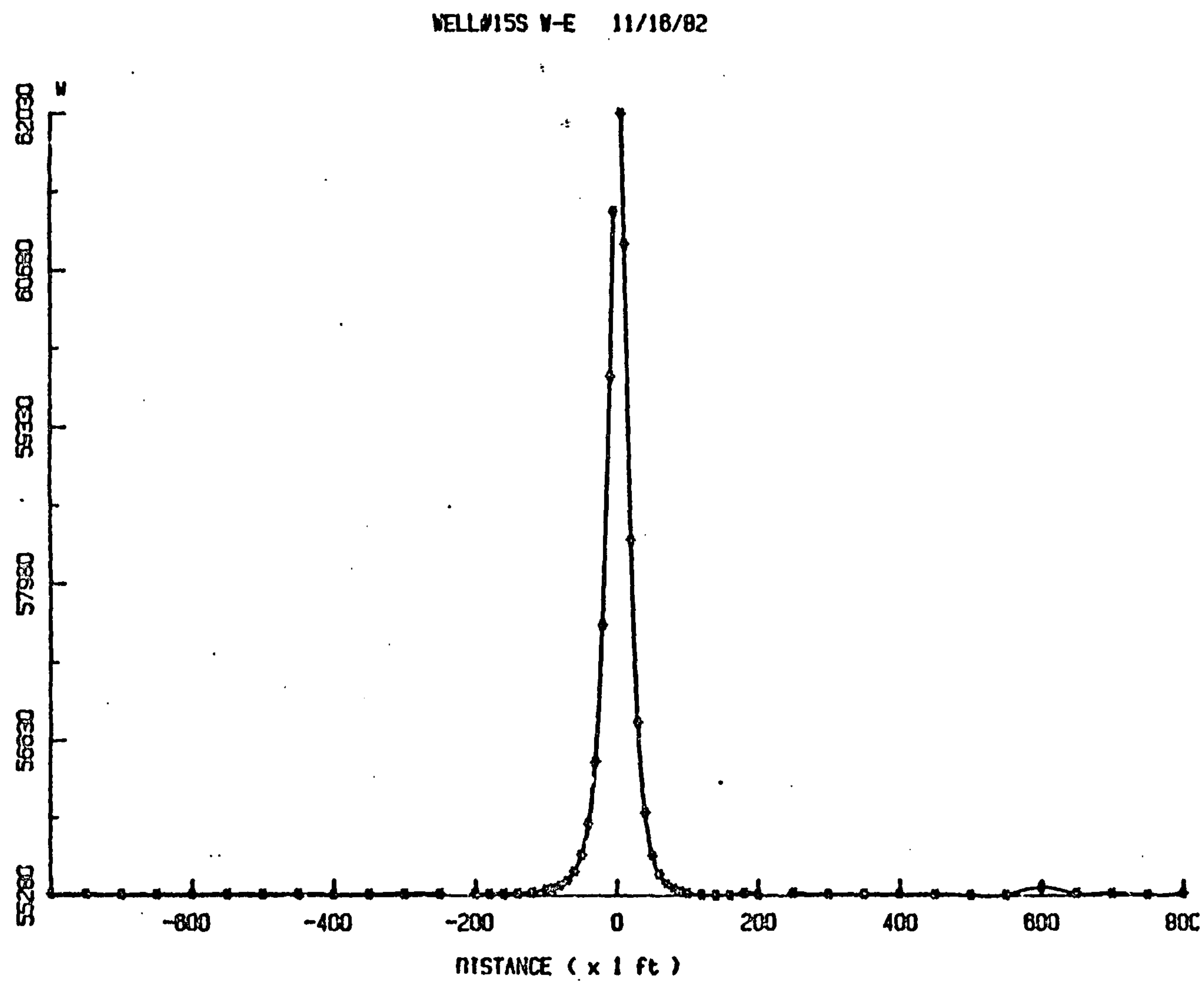


Figure 34. East-west profile of total field over Well Number 15 S.

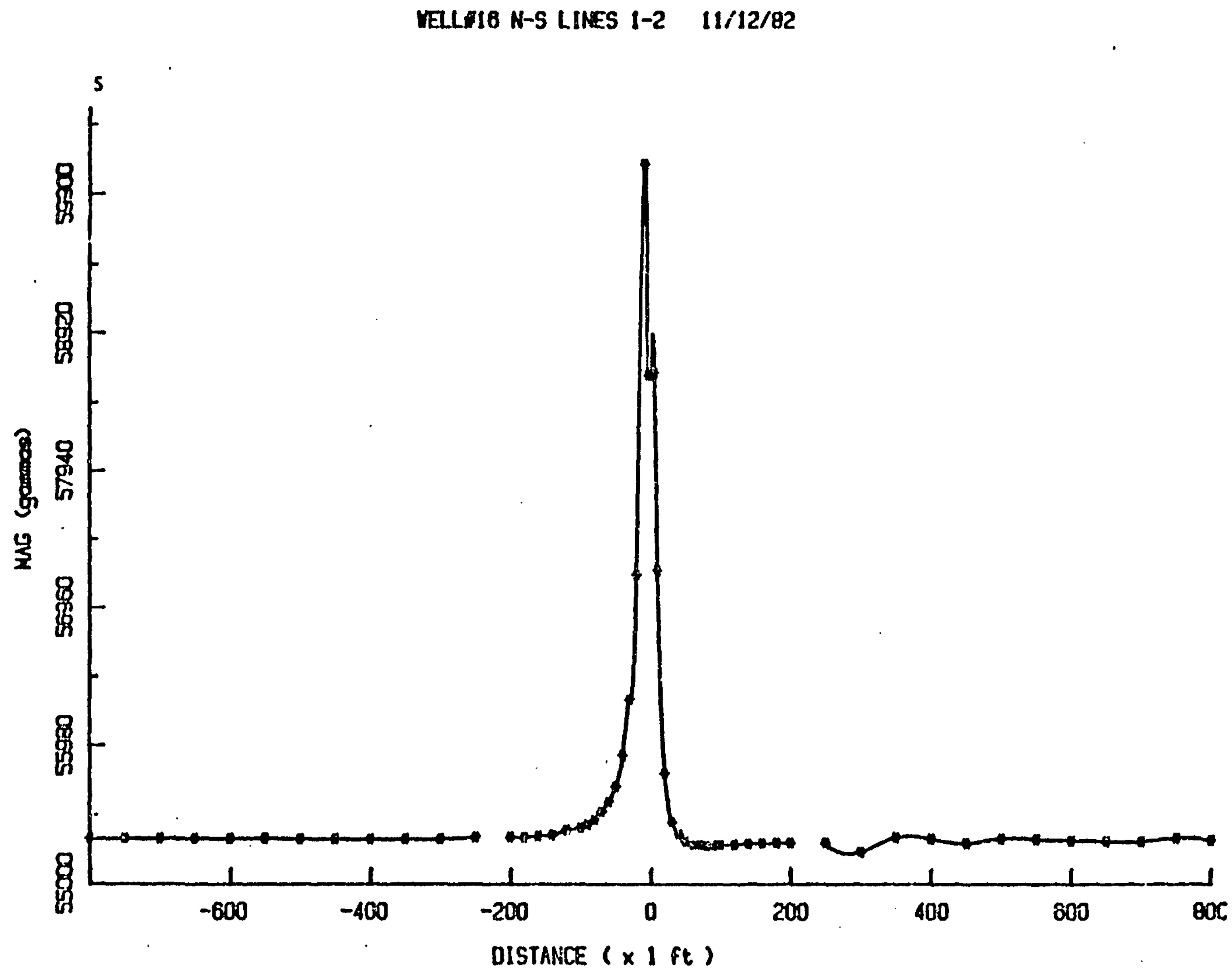


Figure 35. North-south profile of total field over Well Number 16.

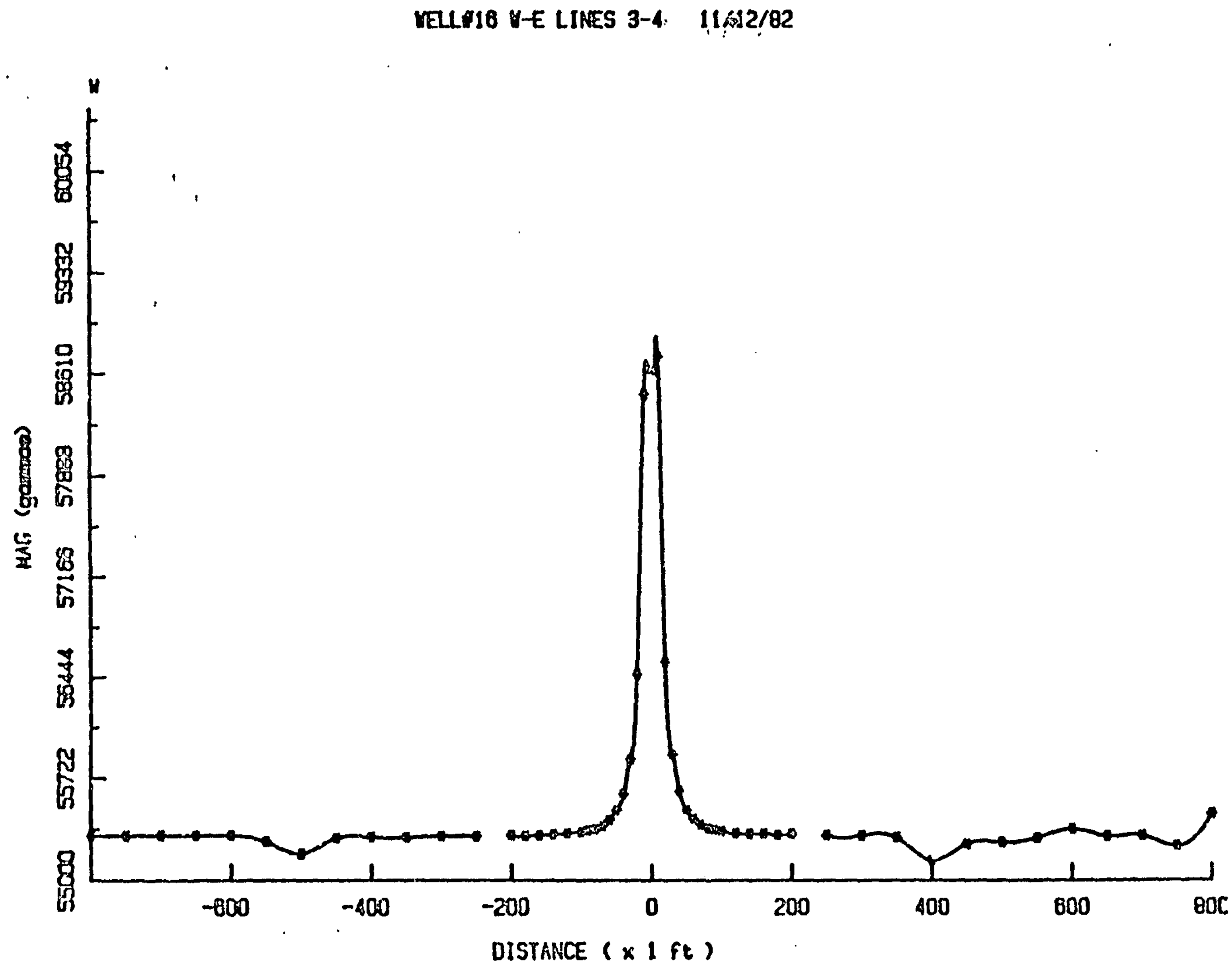


Figure 36. East-west profile of total field over Well Number 16.

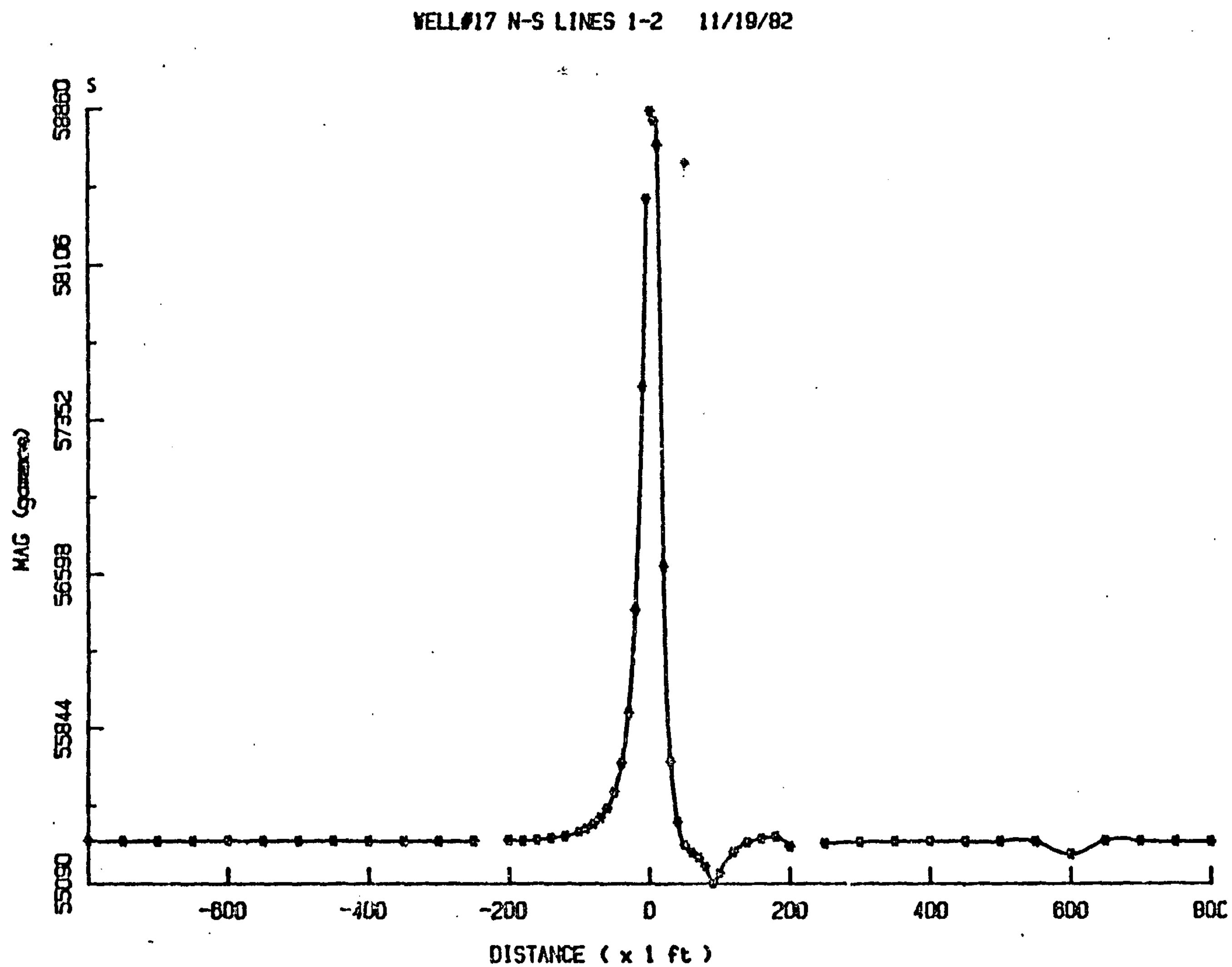


Figure 37. North-south profile of total field over Well Number 17.

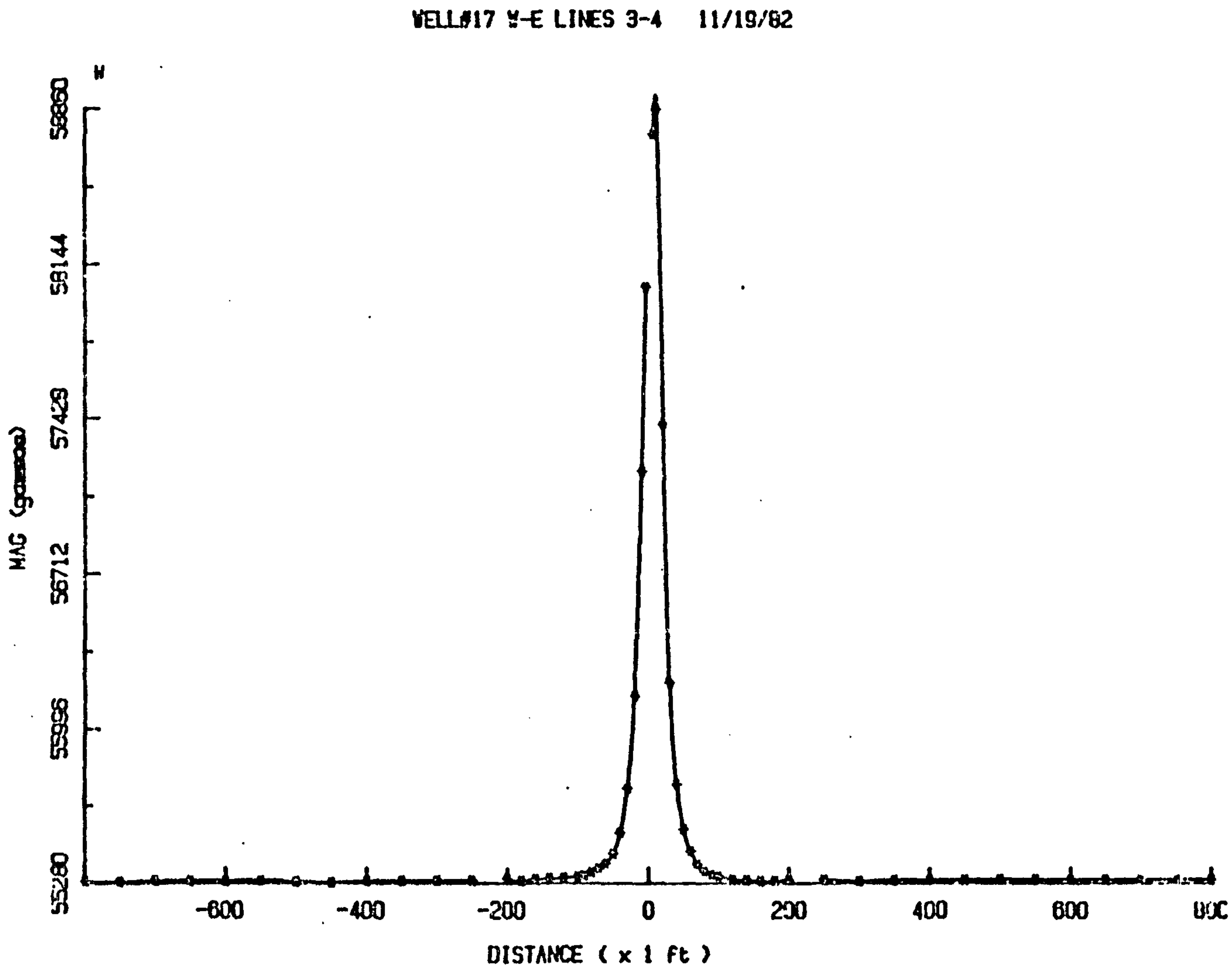


Figure 38. East-west profile of total field over Well Number 17.

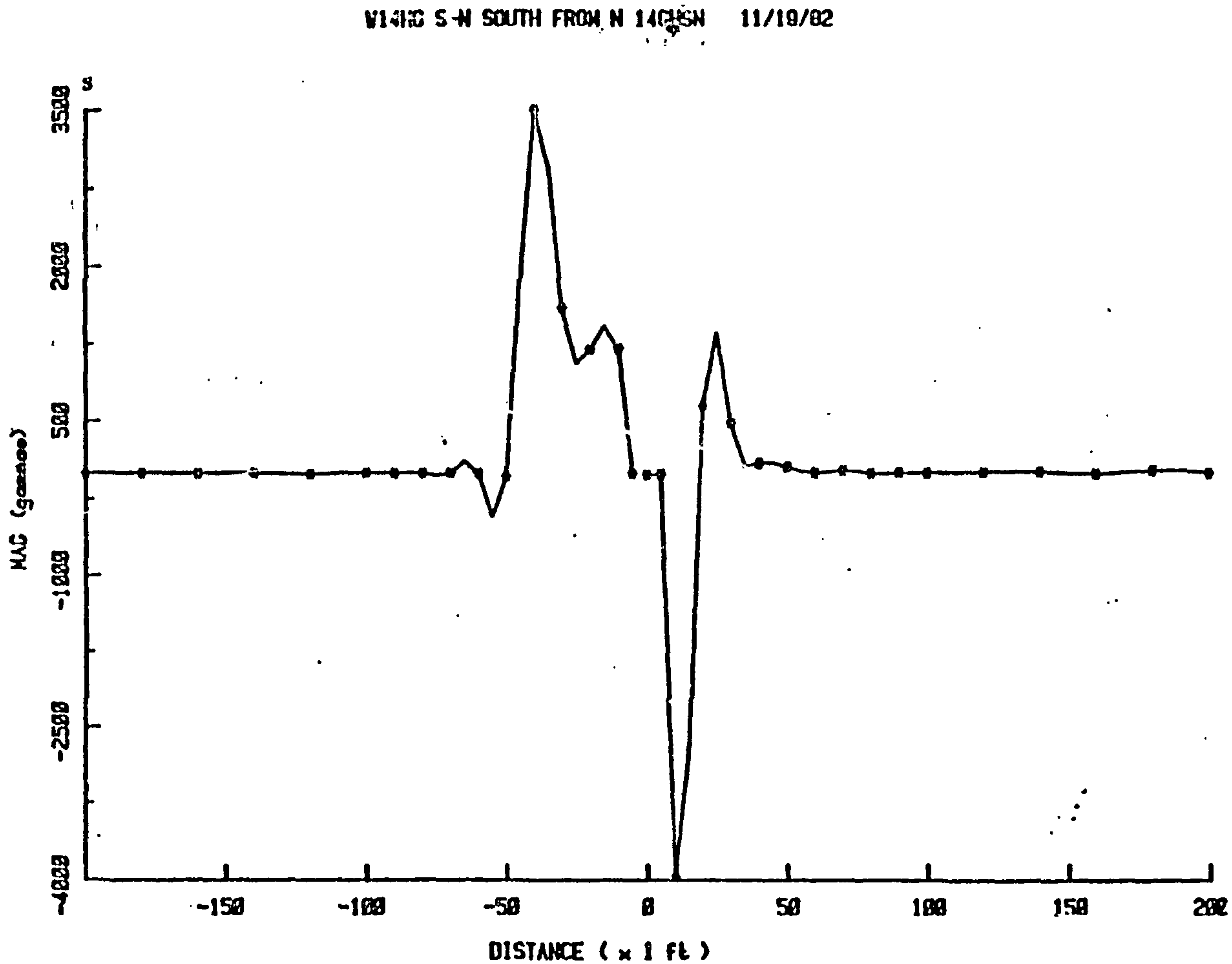


Figure 39. North-south profile of horizontal differences.

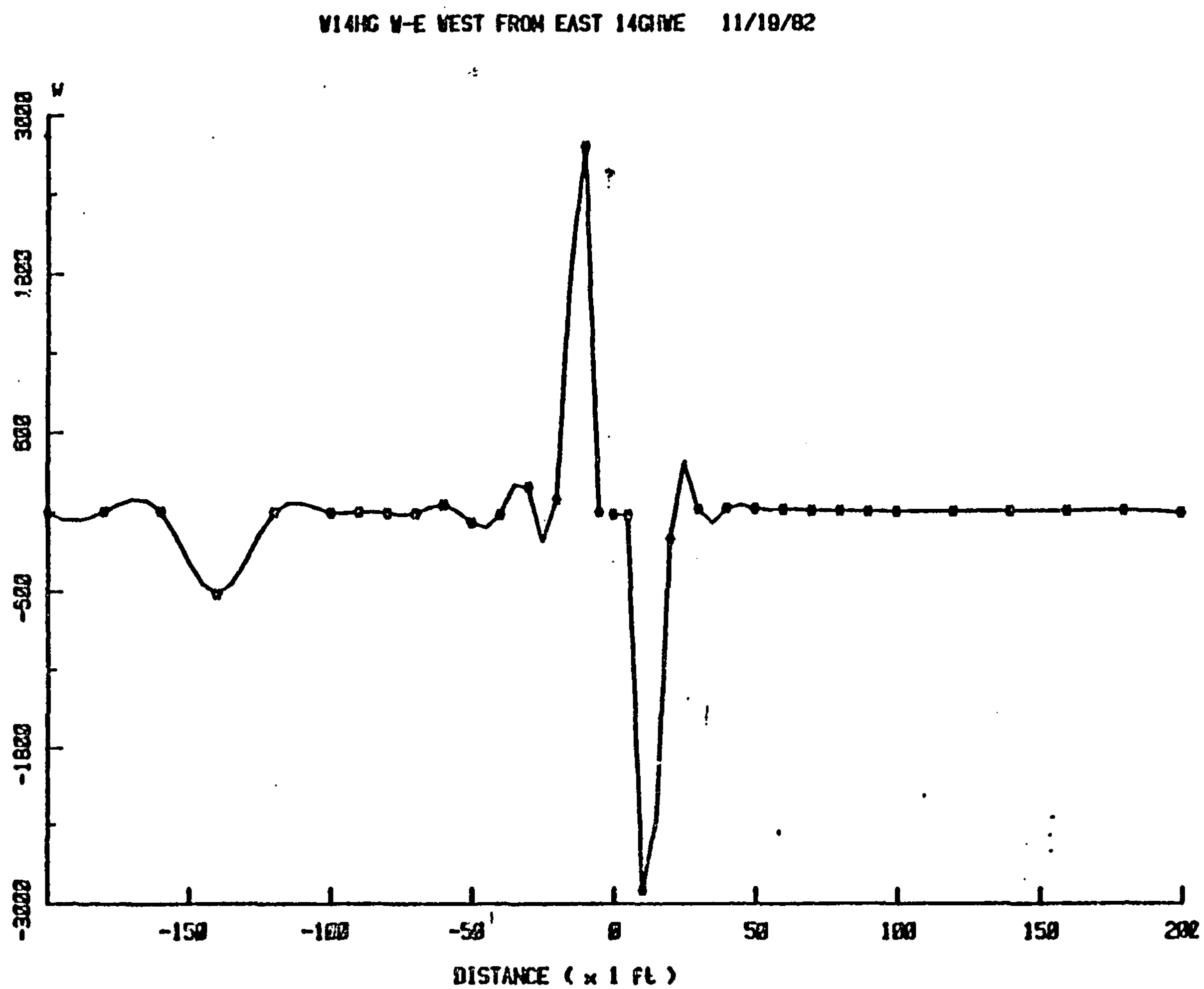


Figure 40. East-west profile of horizontal differences.

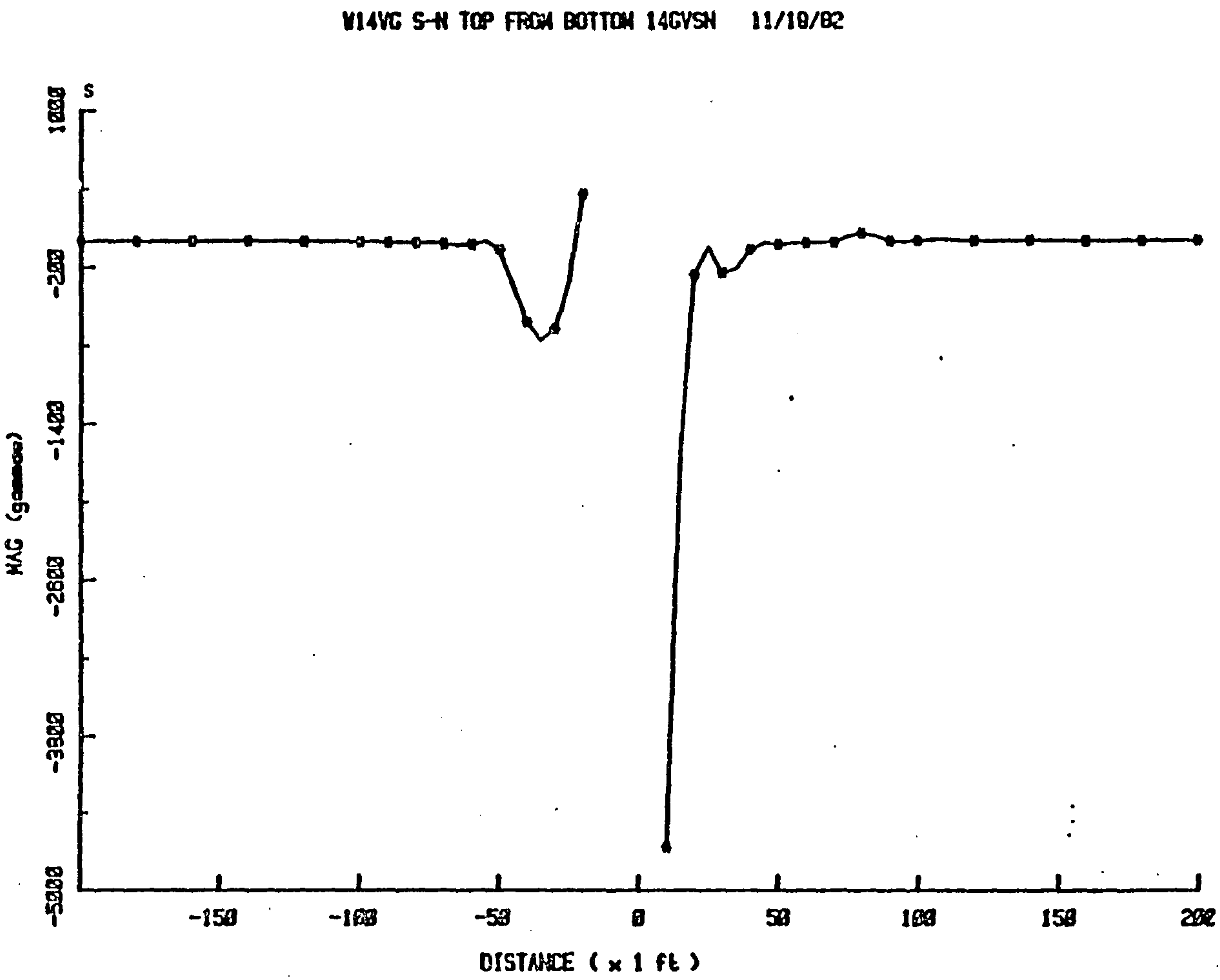


Figure 41. North-south profile of vertical differences.

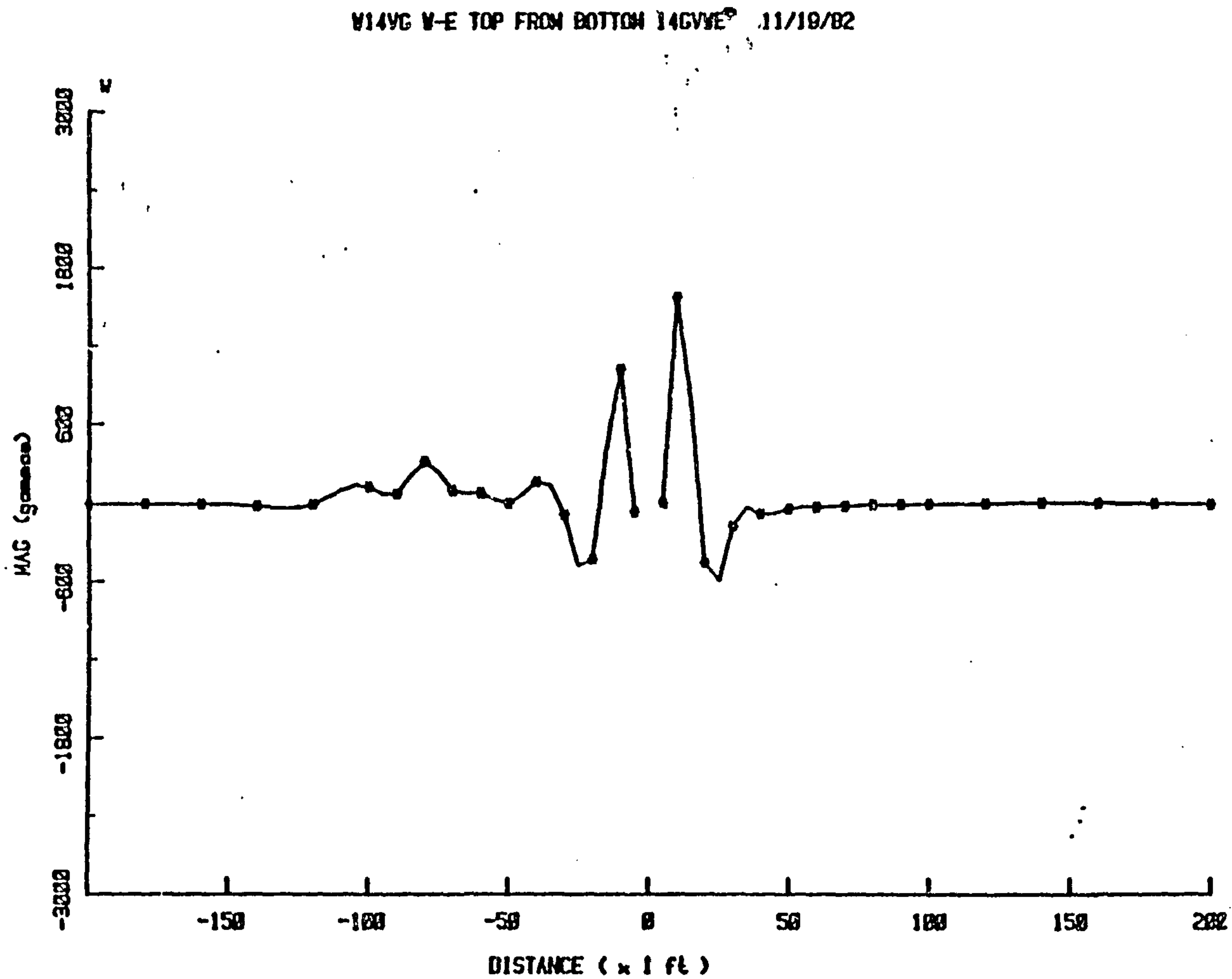


Figure 42. East-west profile of horizontal differences.

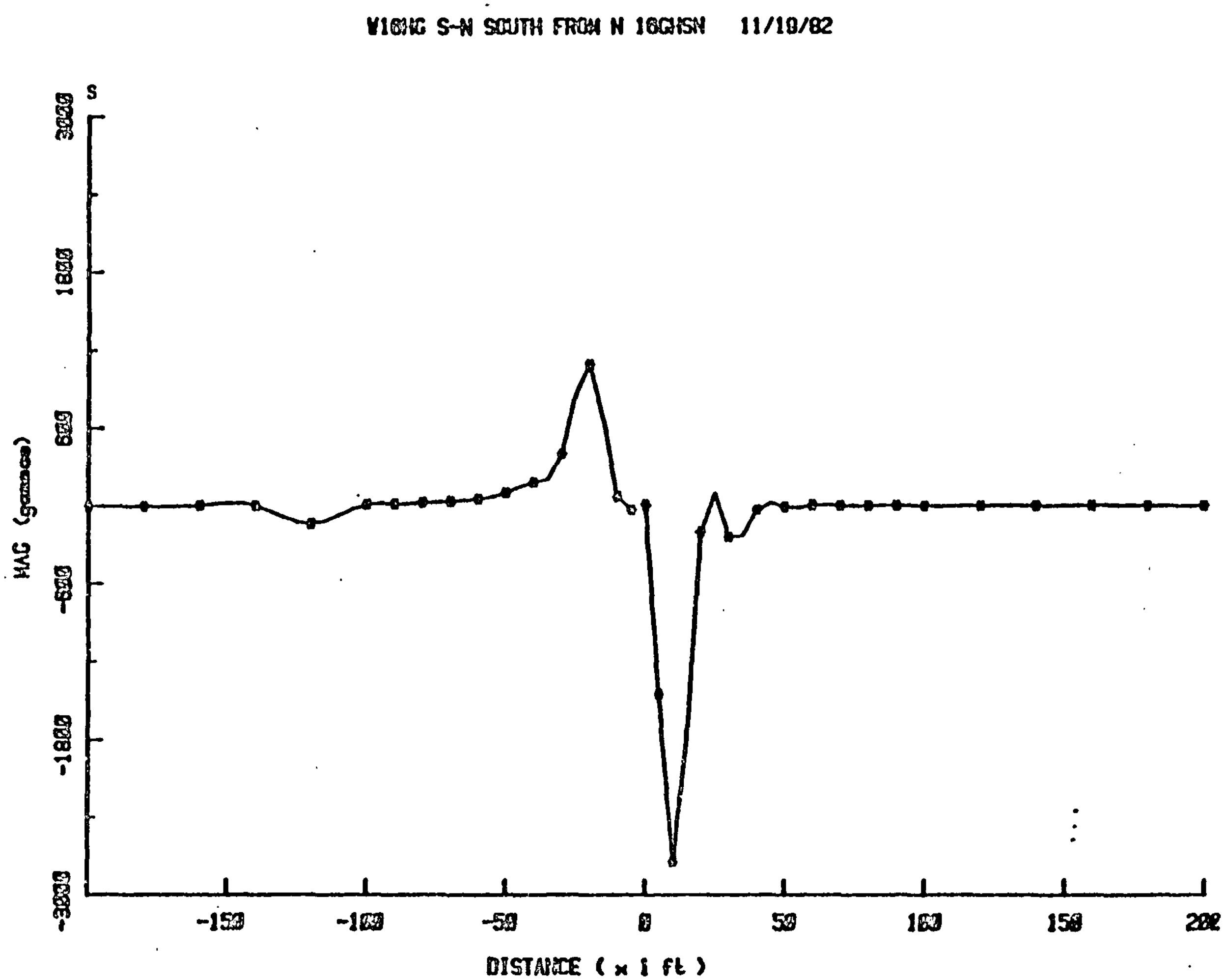


Figure 43. North-south profile of horizontal differences.

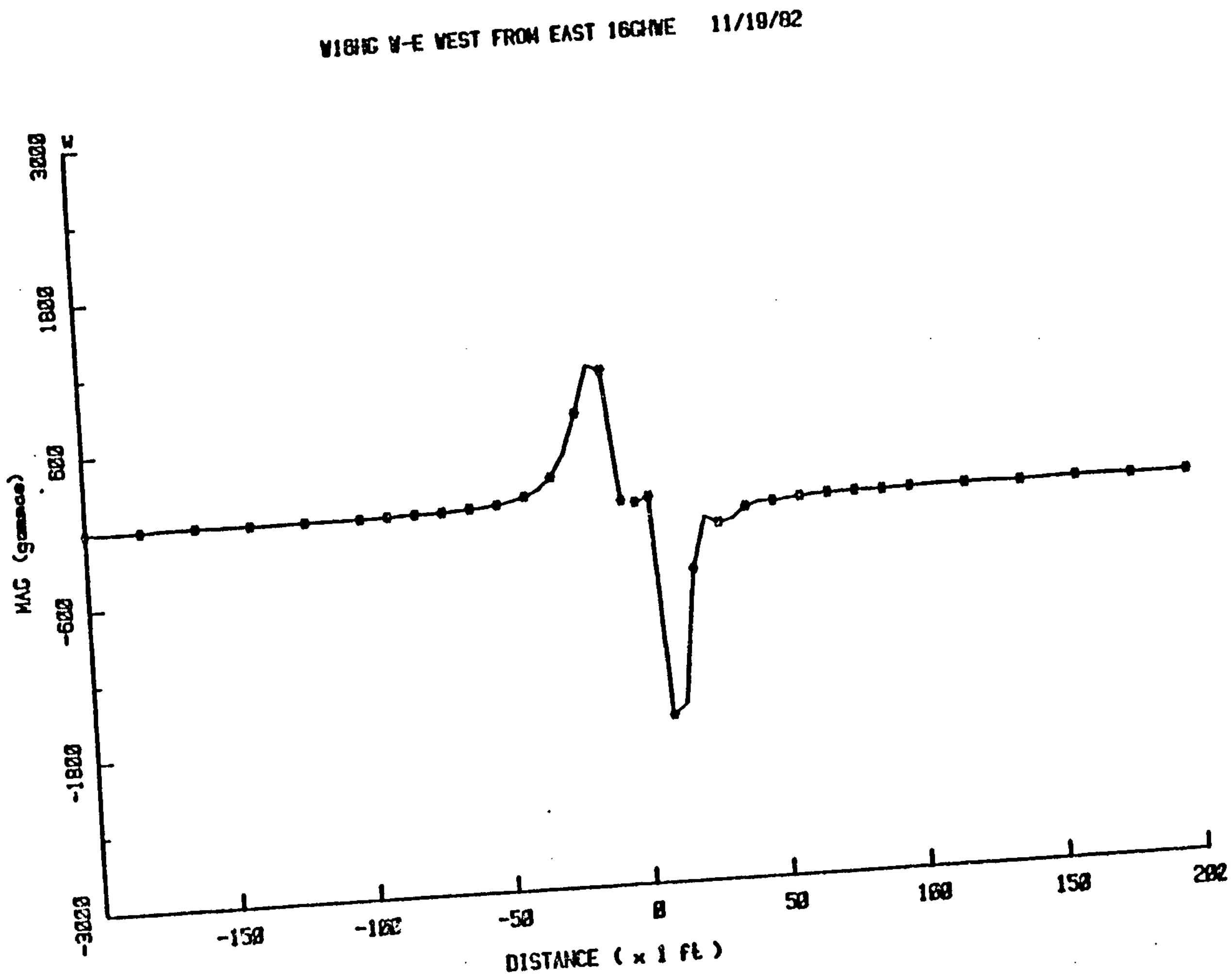


Figure 44. East-west profile of horizontal differences.

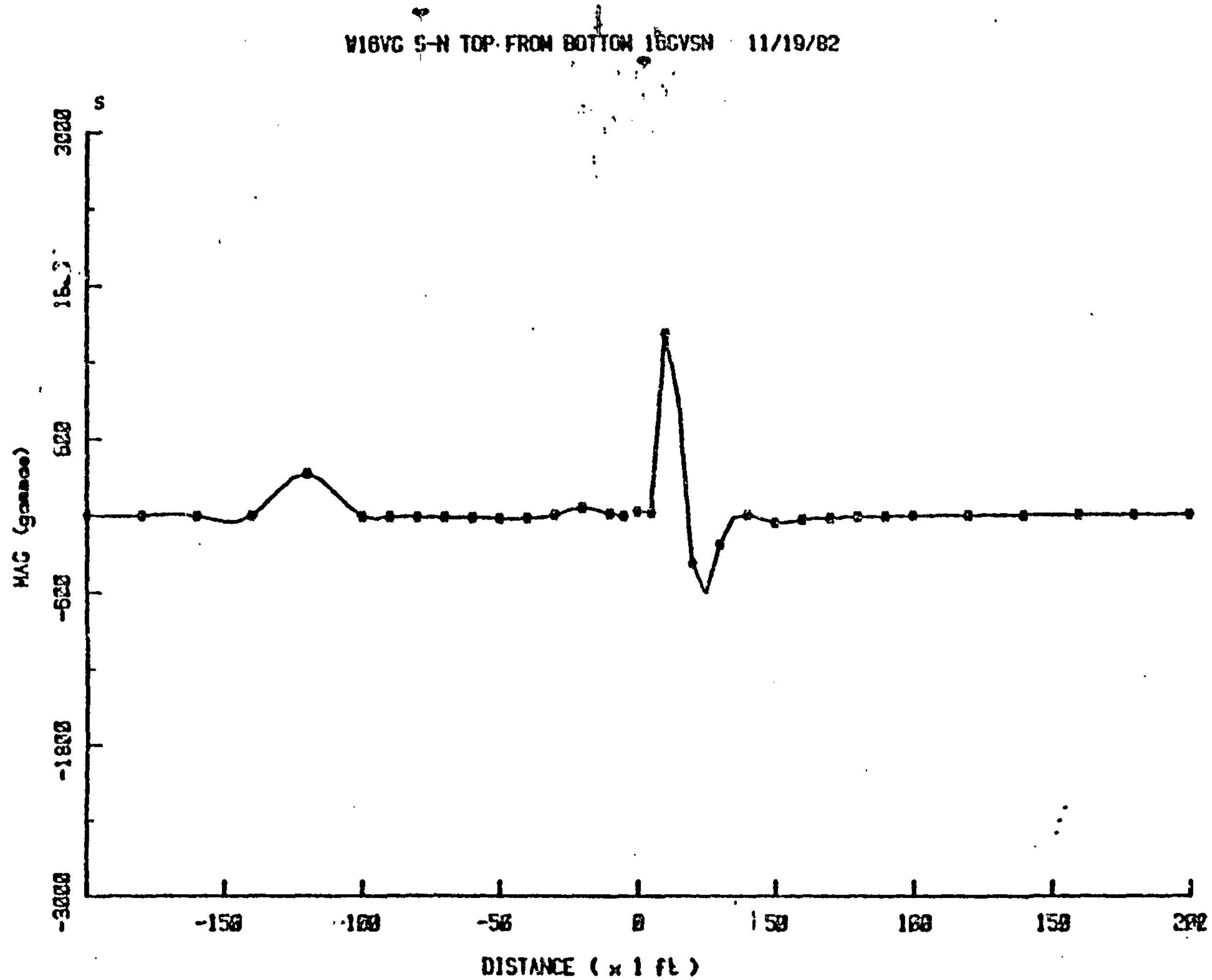
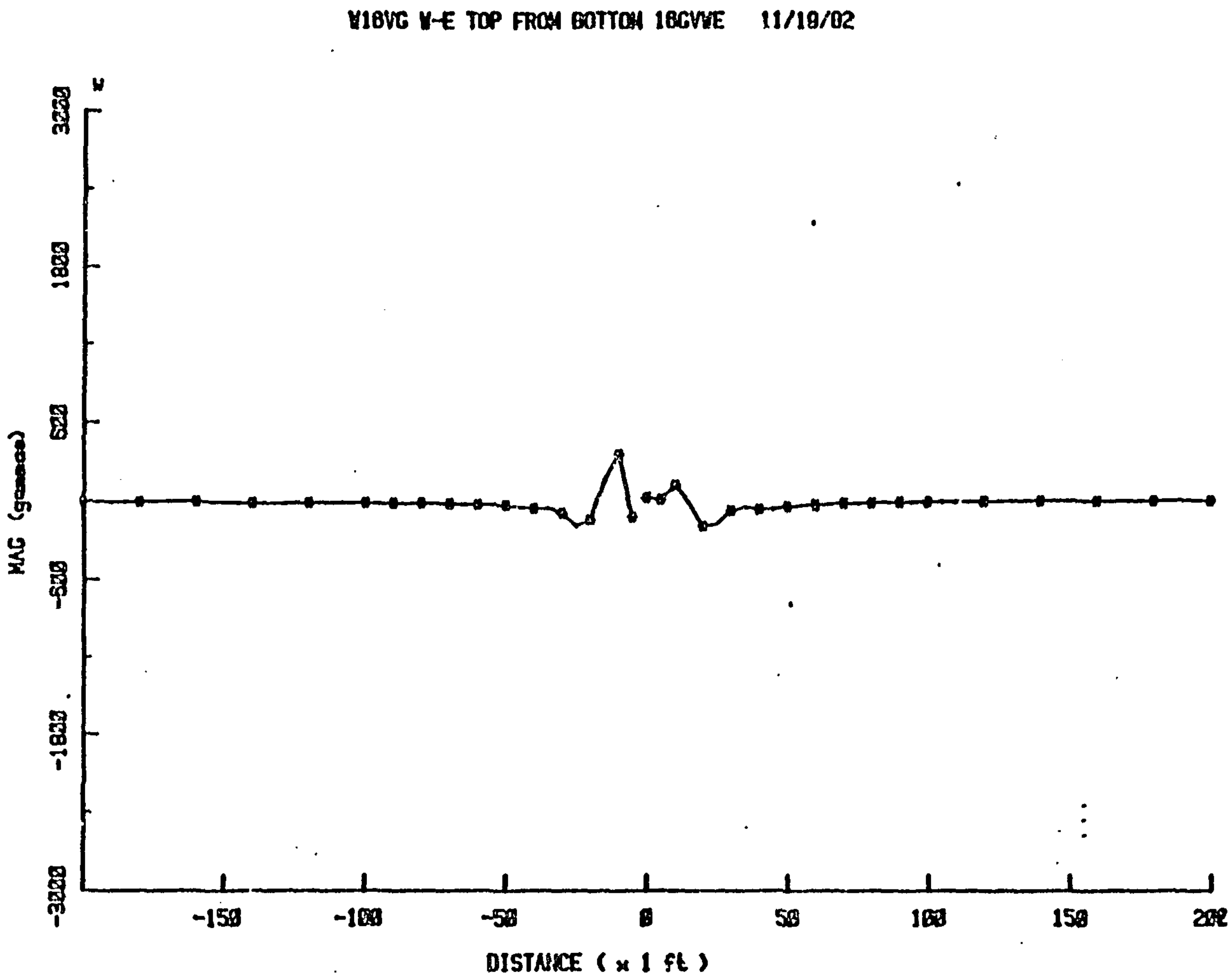


Figure 45. North-south profile of vertical differences.



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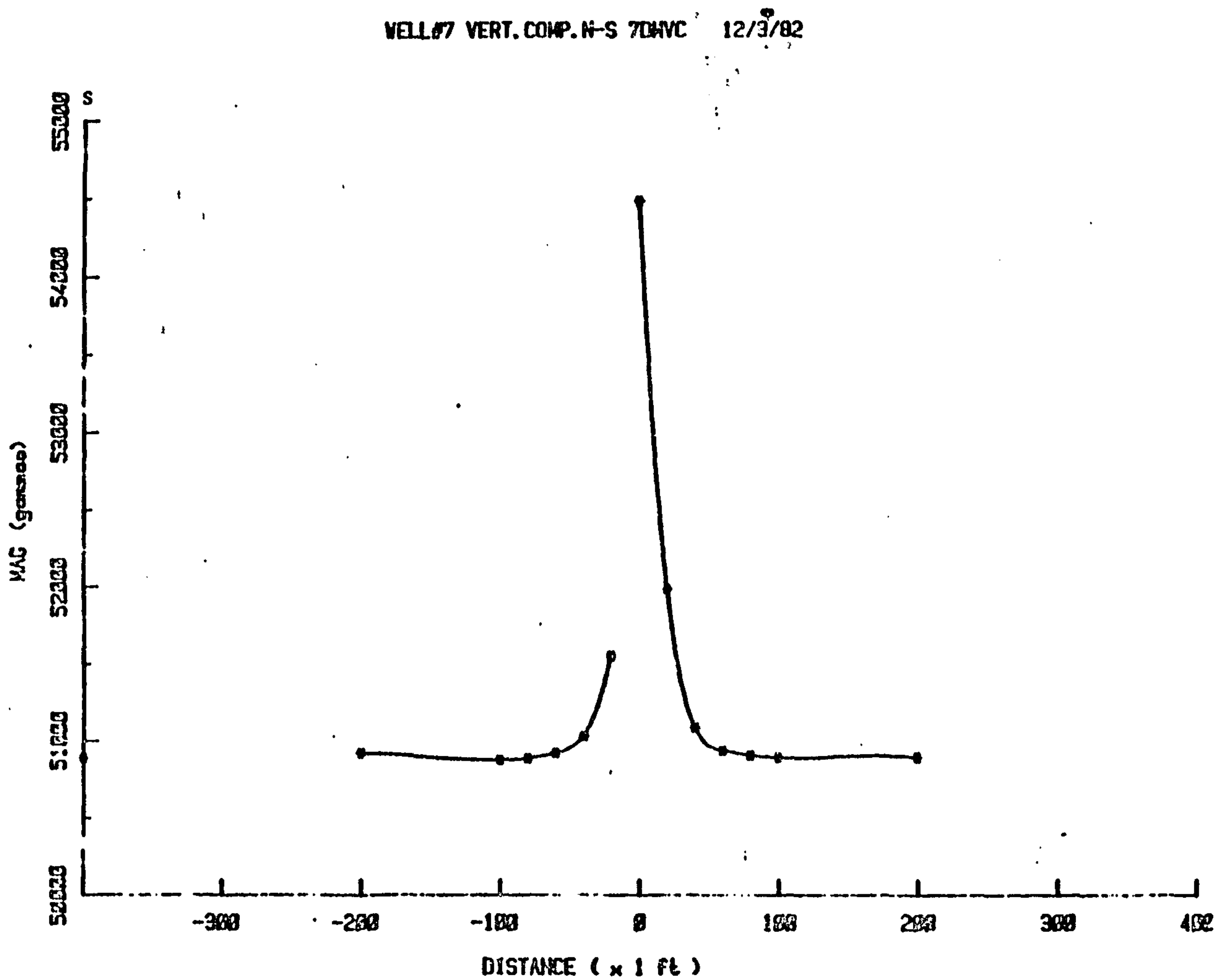


Figure 47. North-south profile of vertical component.

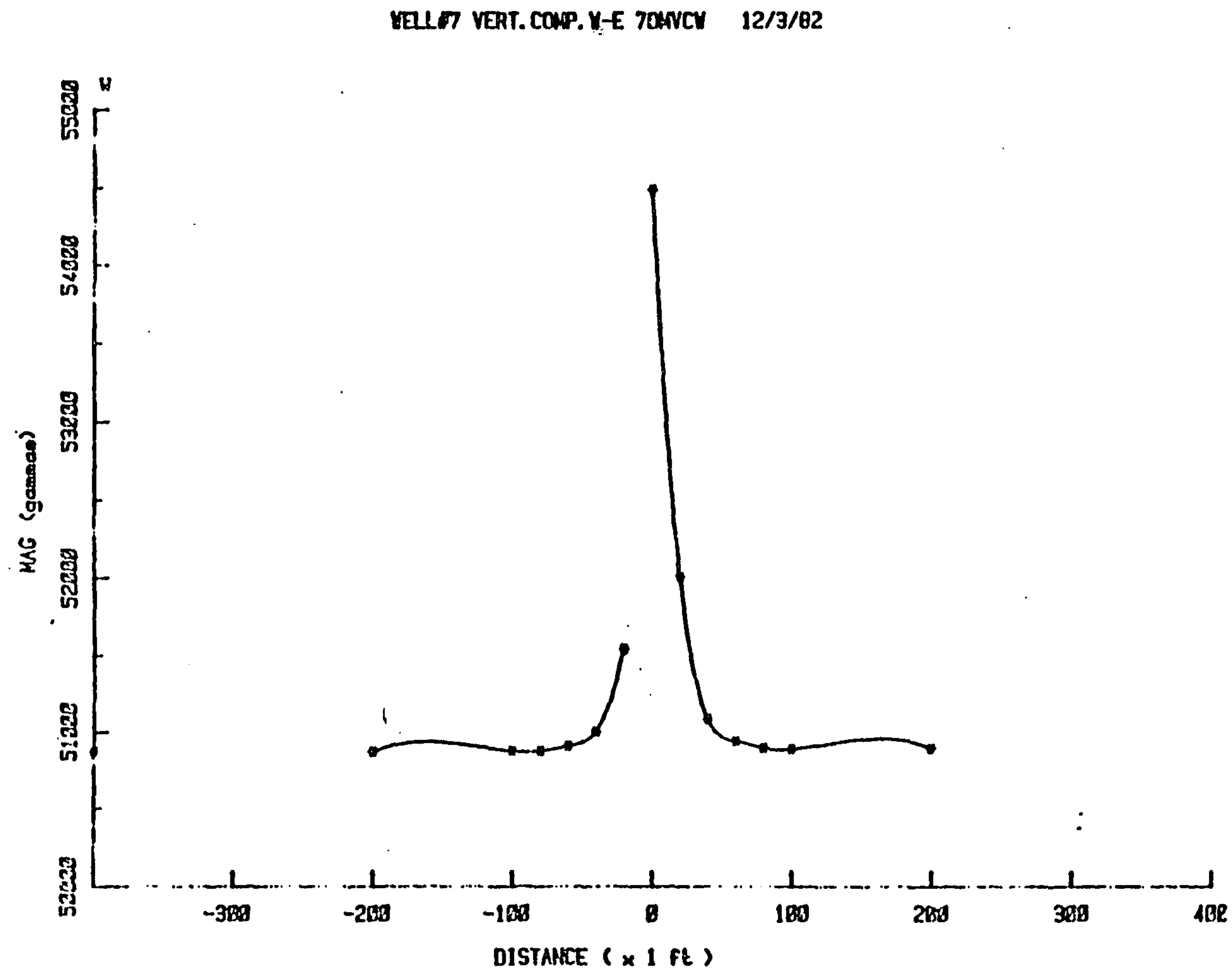


Figure 48. East-west profile of vertical component.

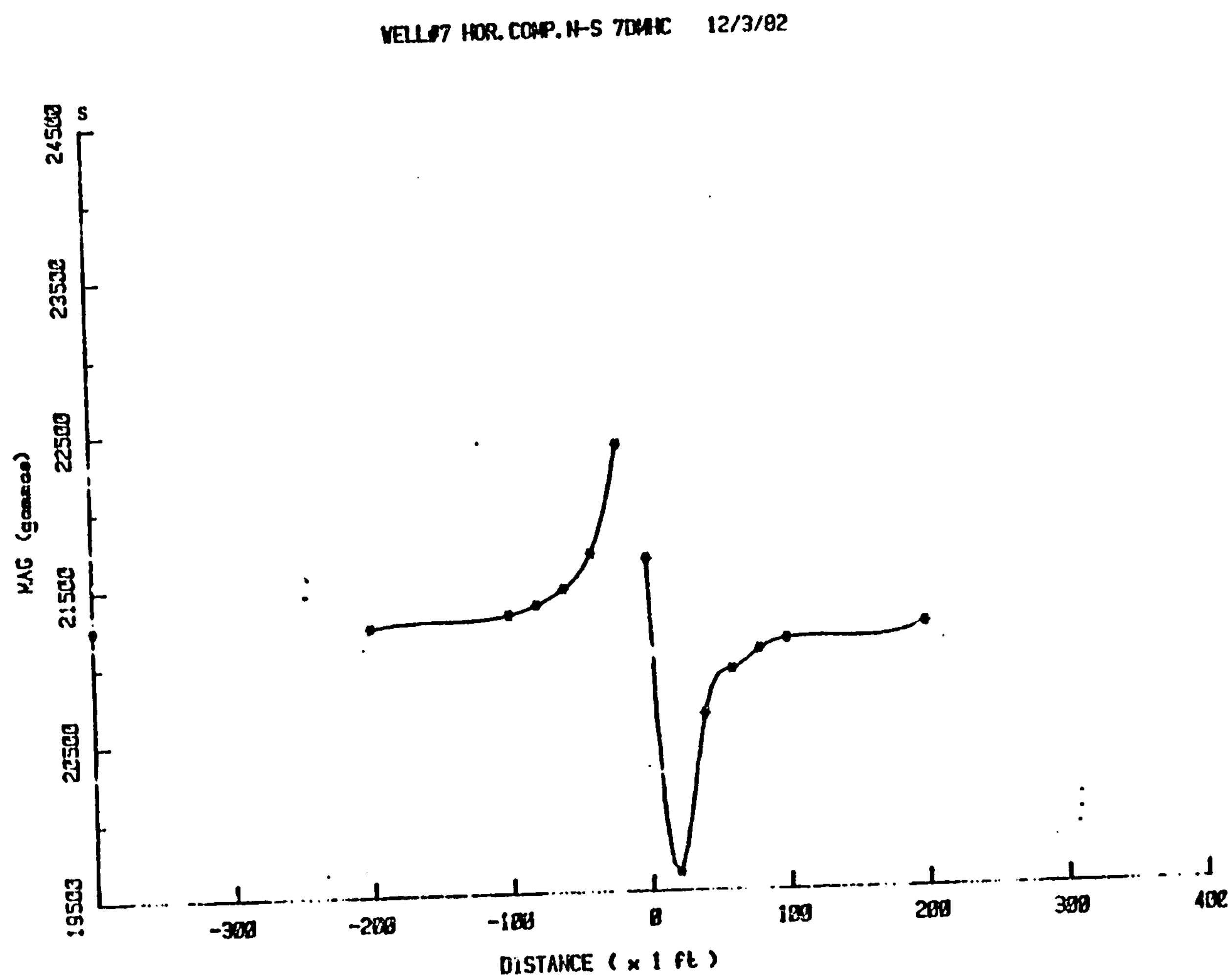


Figure 49. North-south profile of horizontal component.

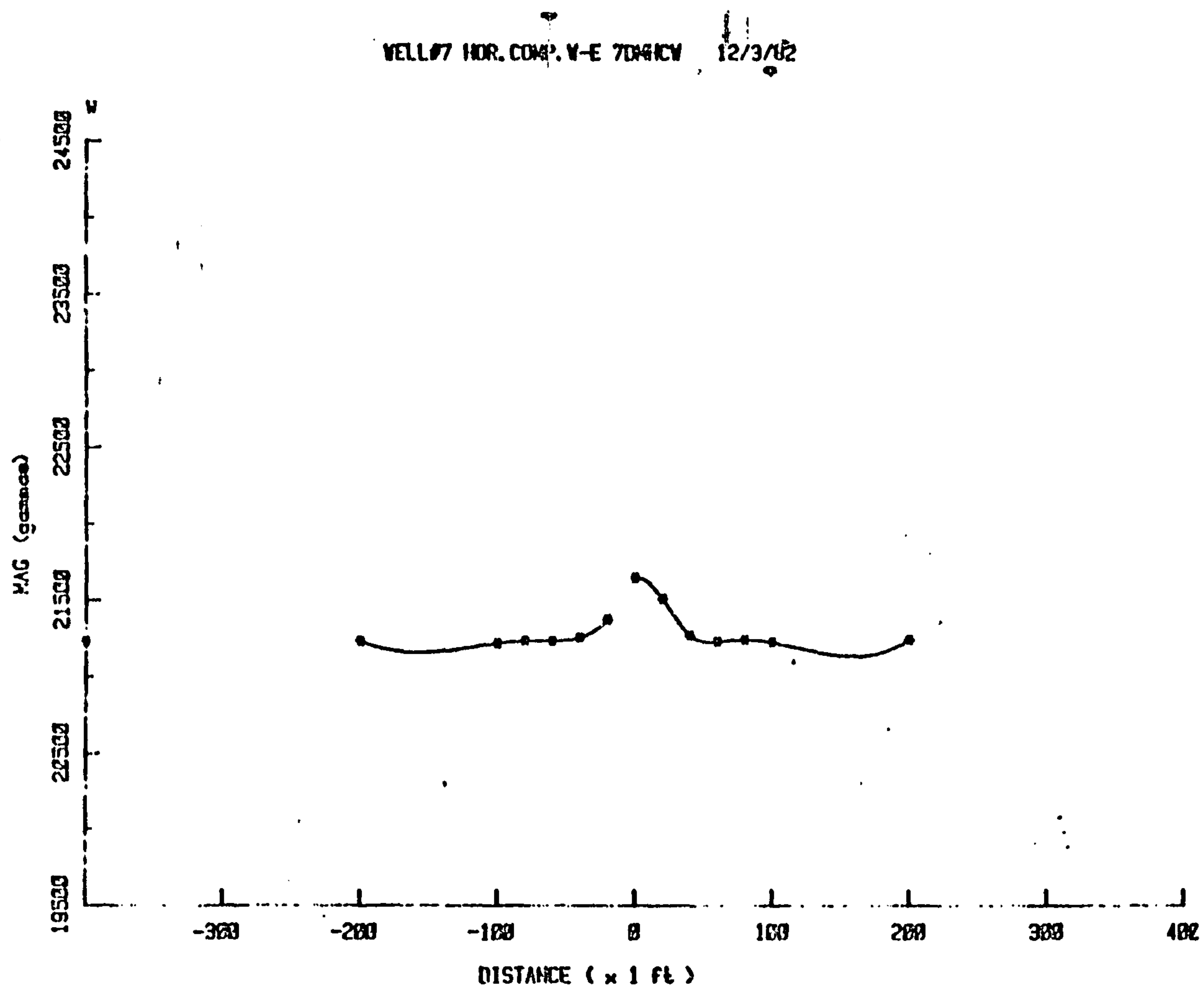


Figure 50. East-west profile of horizontal component.

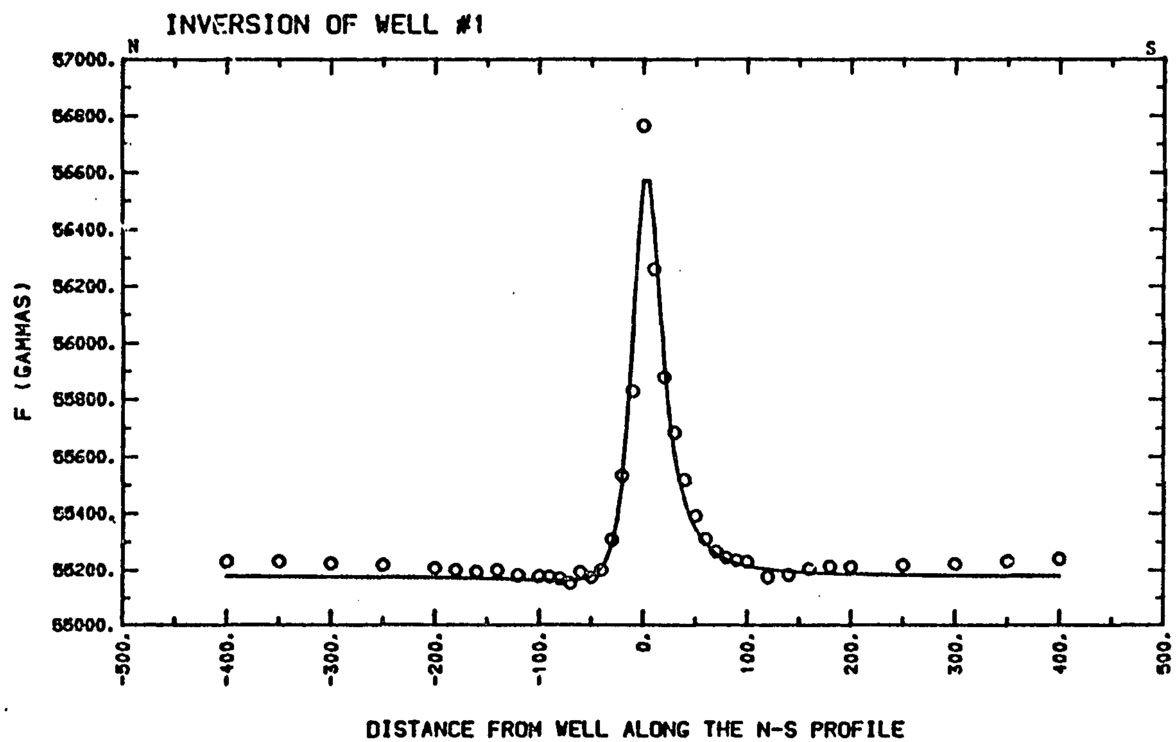


Figure 51. Observed and calculated results for Well Number 1.

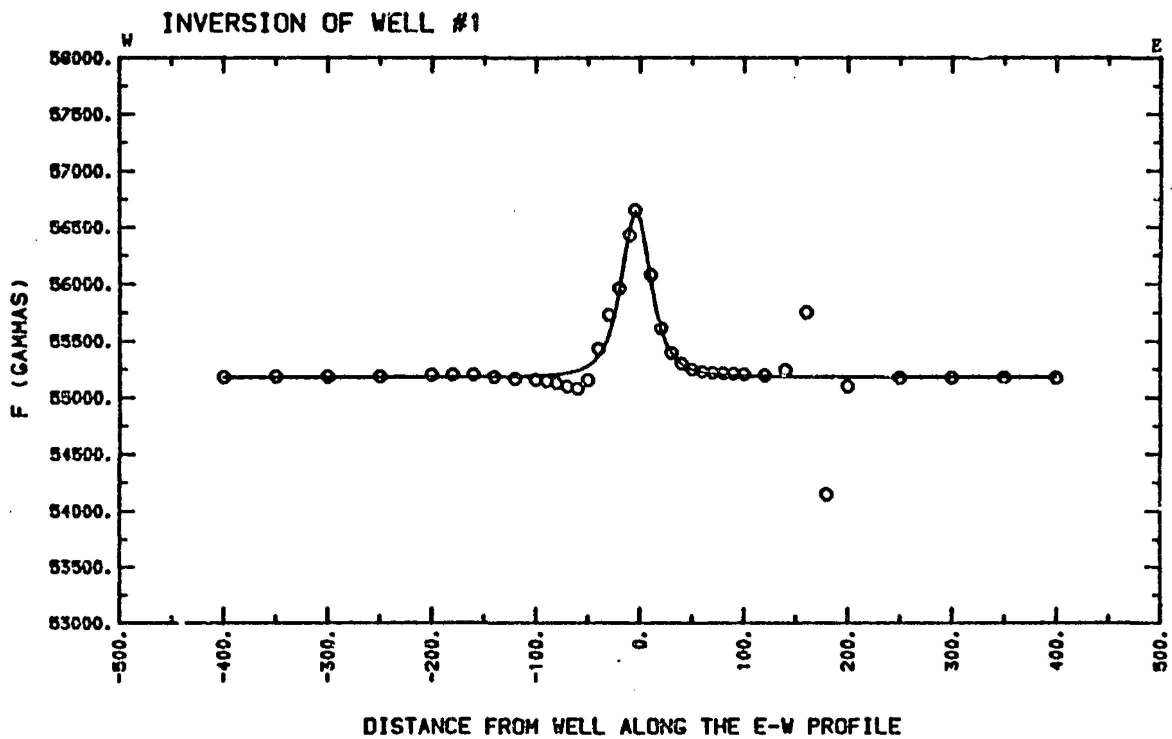


Figure 52. Observed and calculated results for Well Number 1.

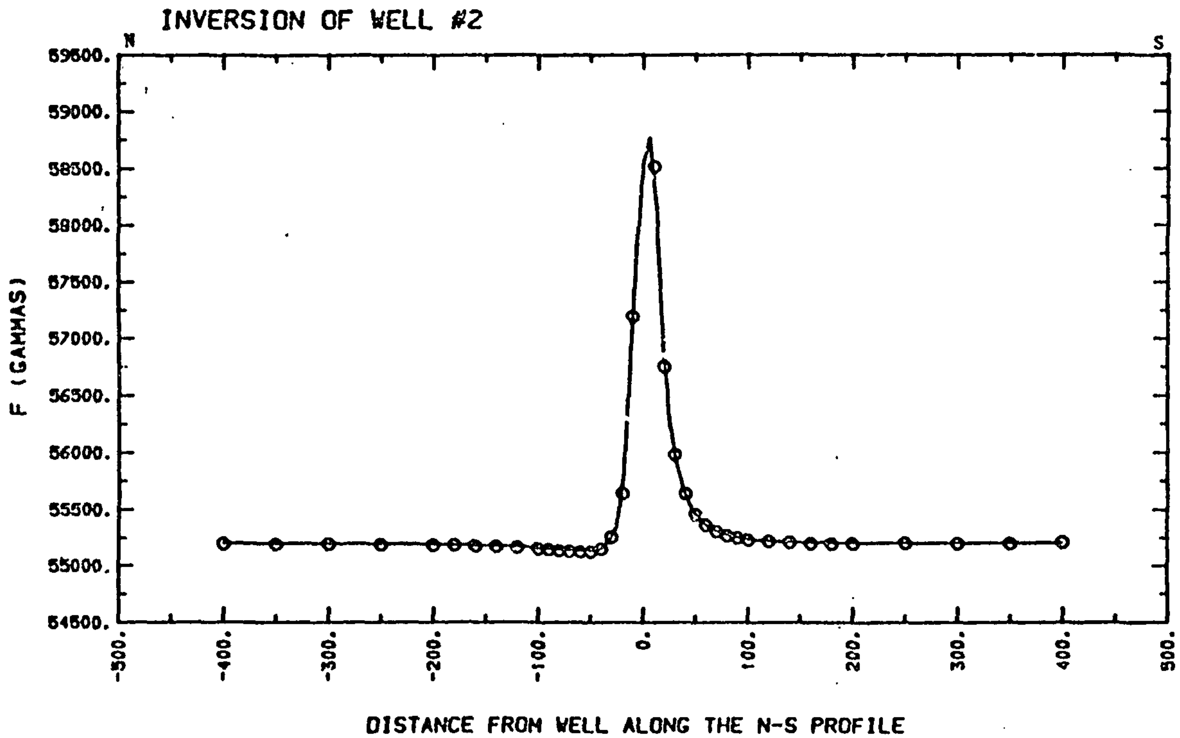


Figure 53. Observed and calculated results for Well Number 2.

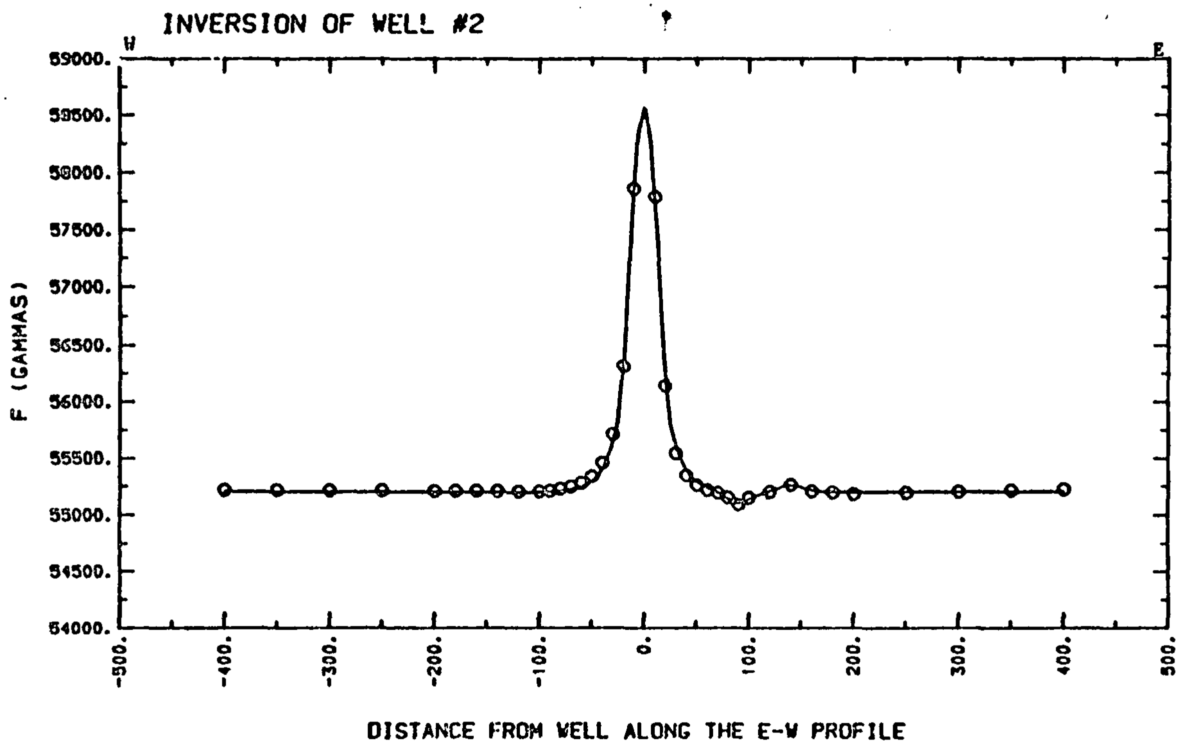


Figure 54. Observed and calculated results for Well Number 2.

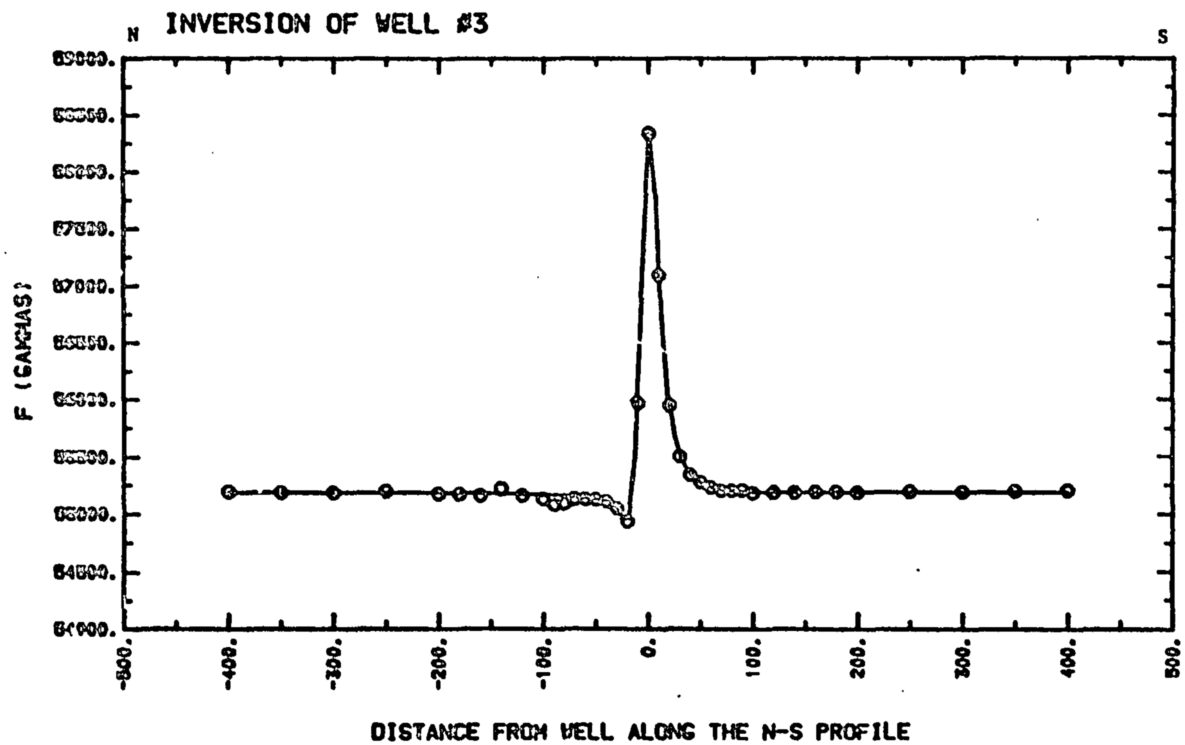


Figure 55. Observed and calculated results for Well Number 3.

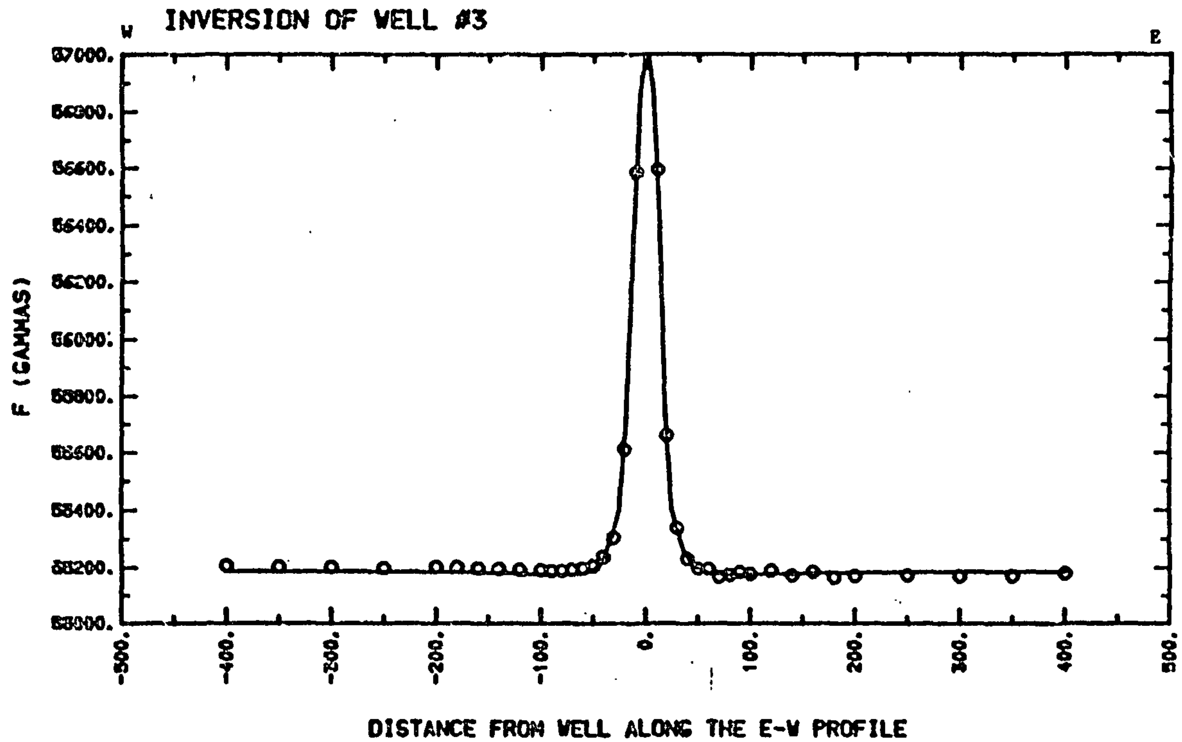


Figure 56. Observed and calculated results for Well Number 3.

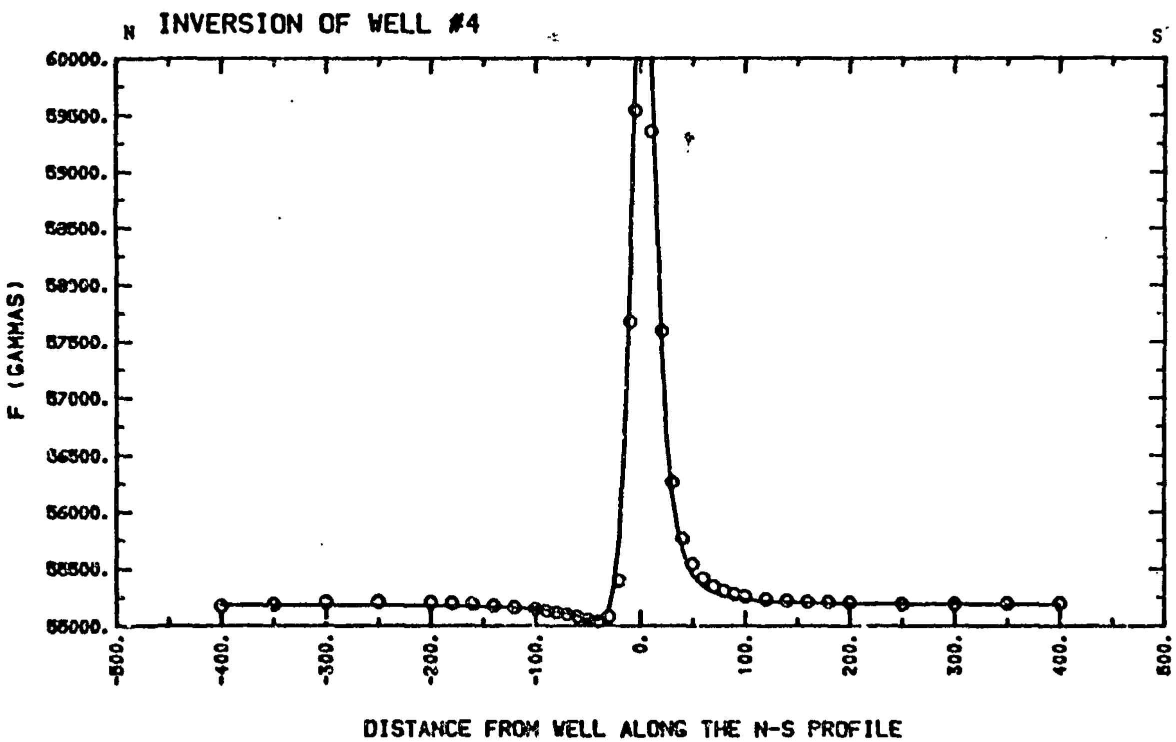


Figure 57. Observed and calculated results for Well Number 4.

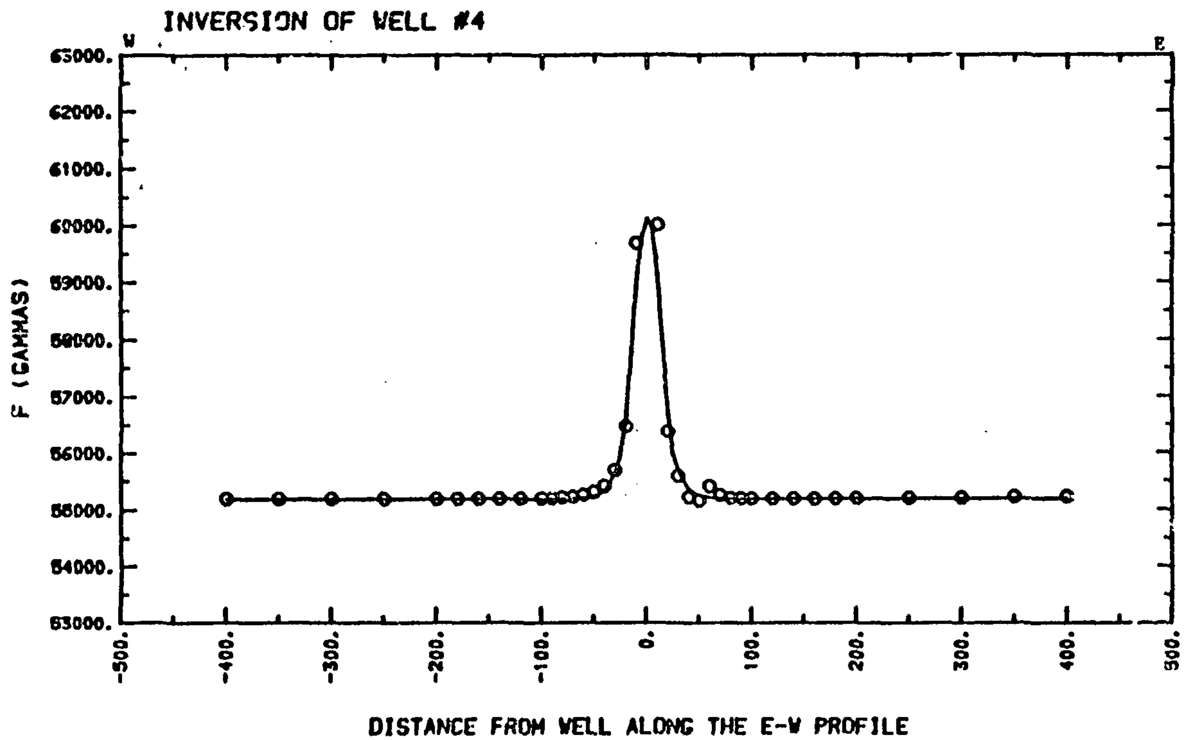


Figure 58. Observed and calculated results for Well Number 4.

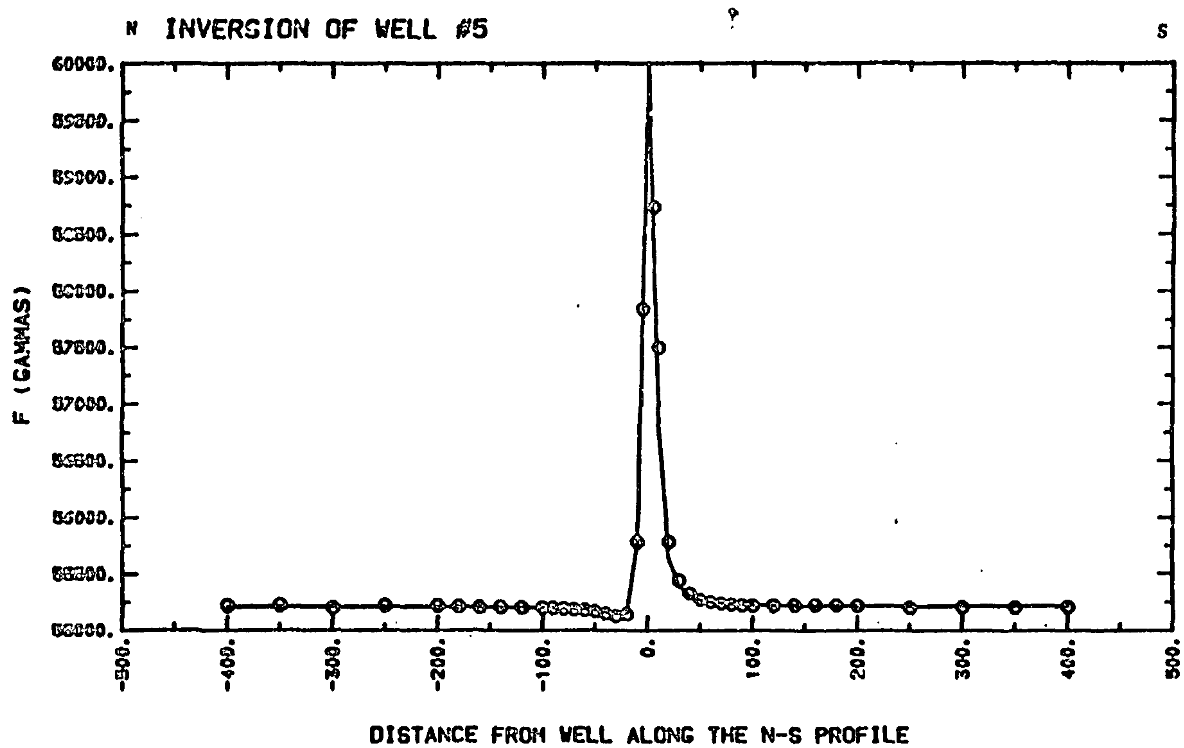


Figure 59. Observed and calculated results for Well Number 5.

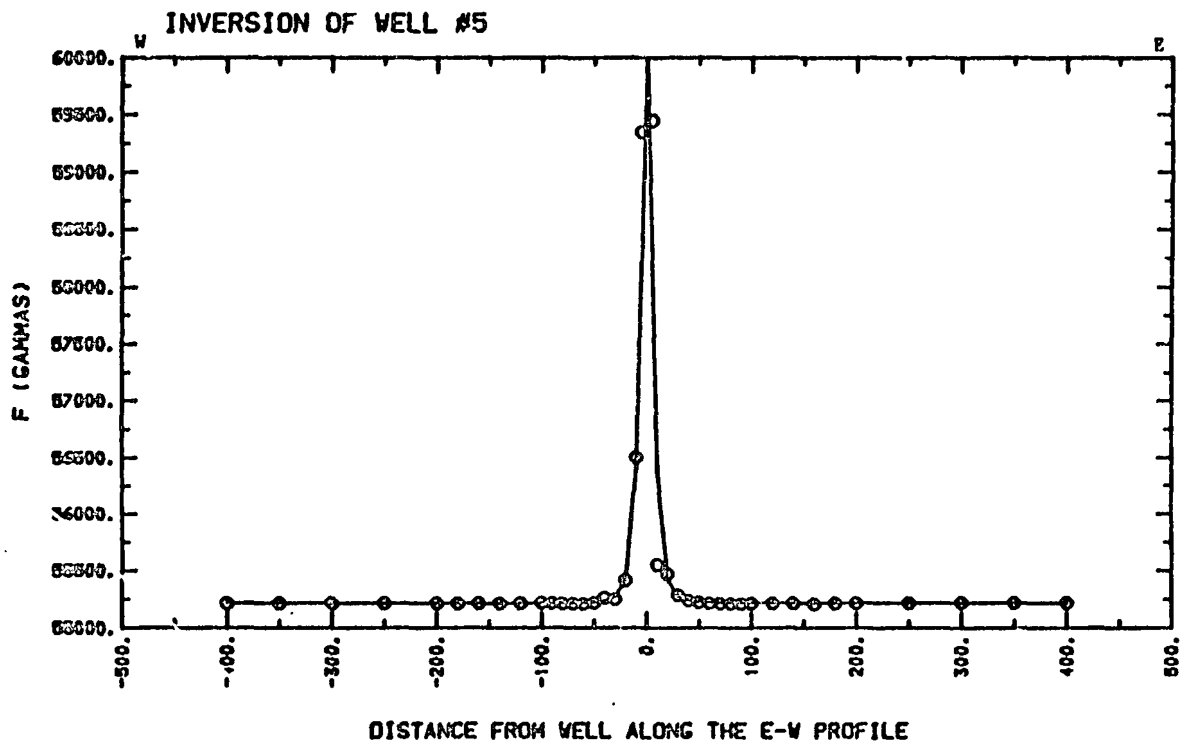


Figure 60. Observed and calculated results for Well Number 5.

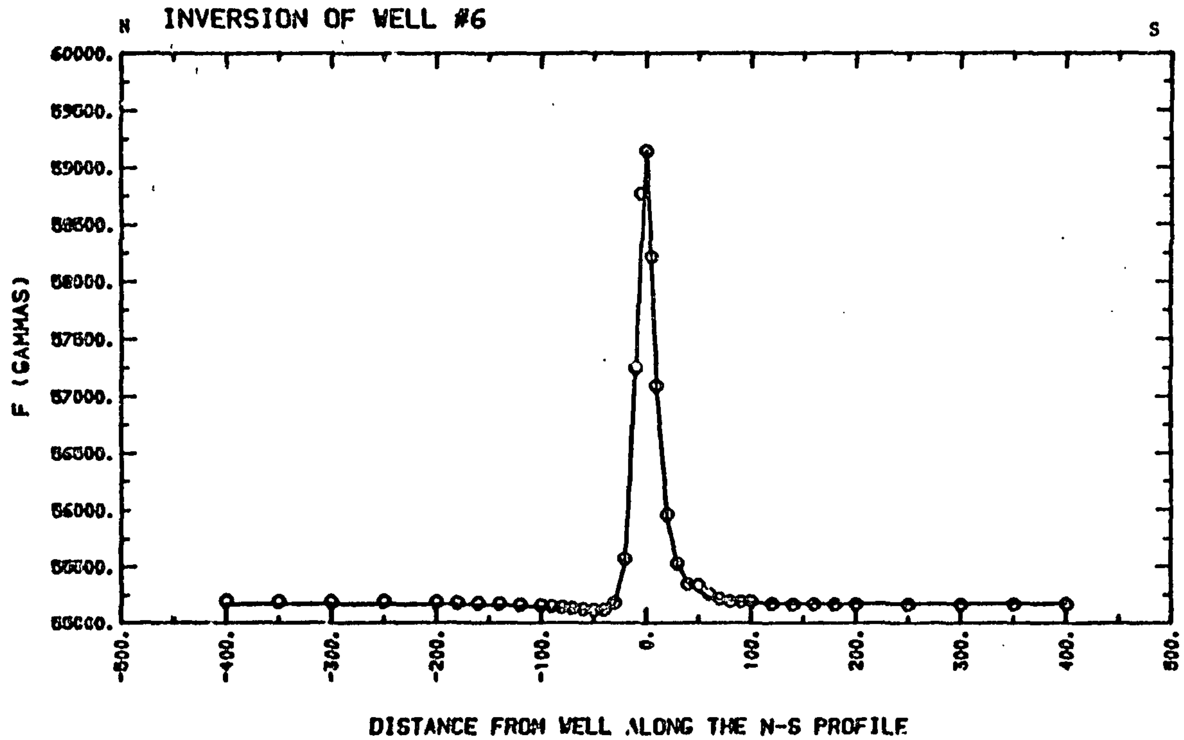


Figure 61. Observed and calculated results for Well Number 6.

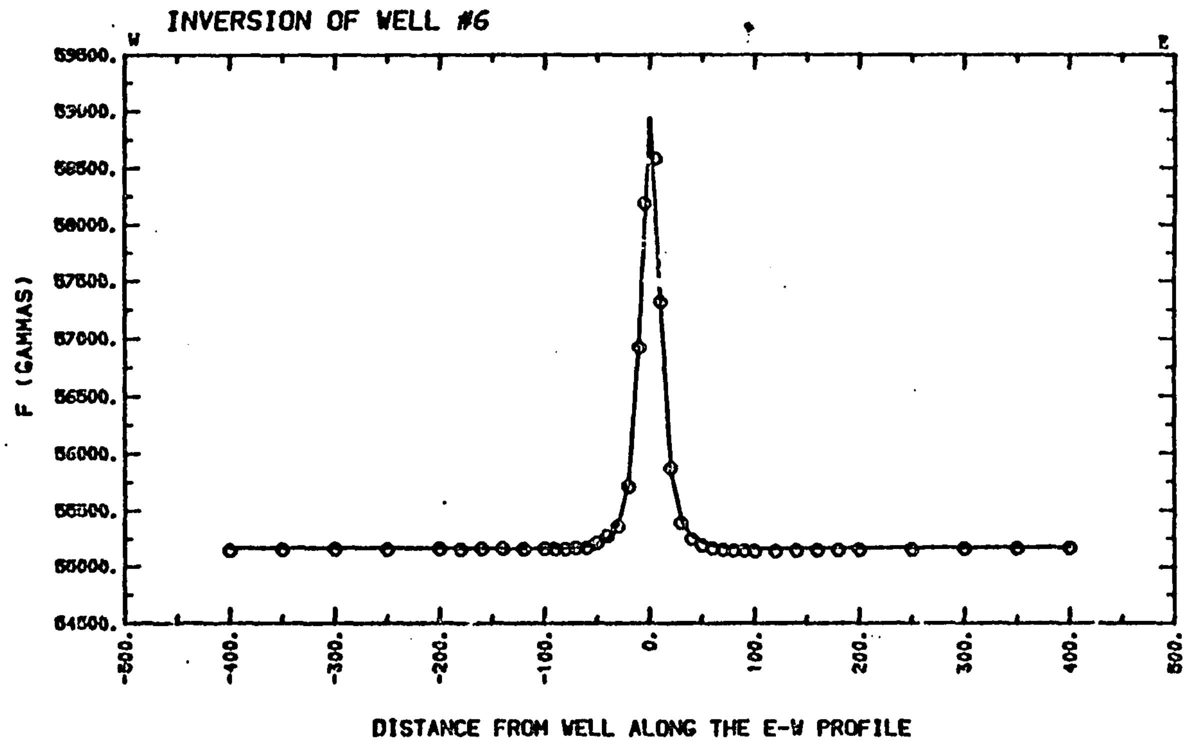


Figure 62. Observed and calculated results for Well Number 6.

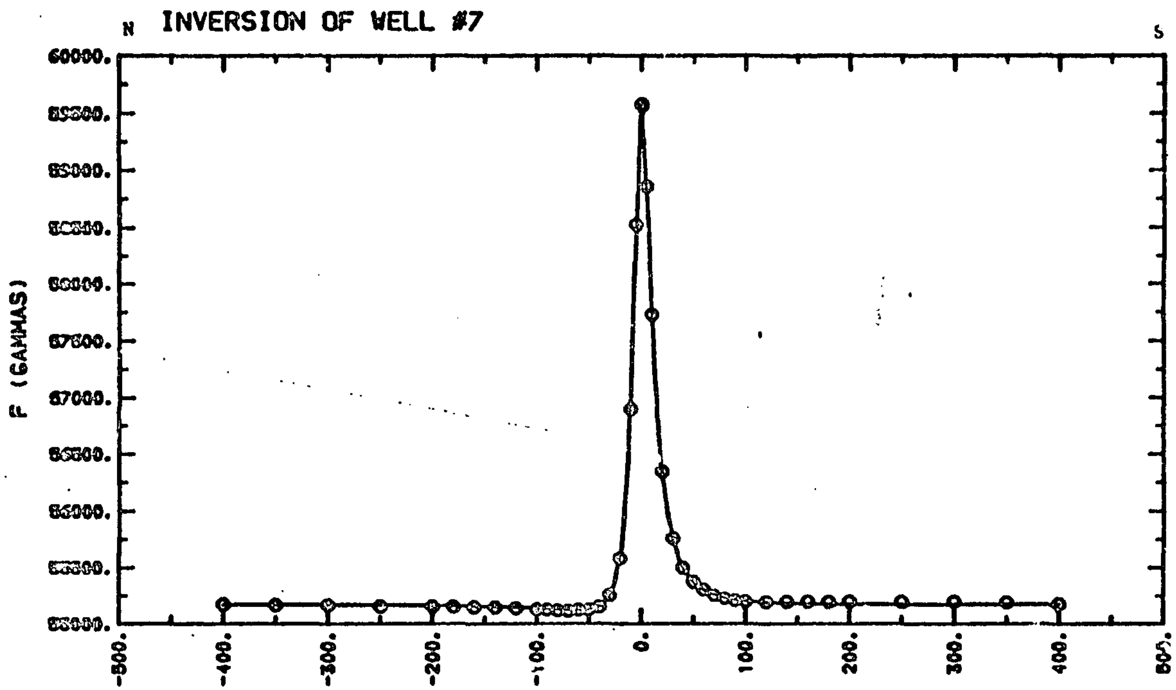


Figure 63. Observed and calculated results for Well Number 7.

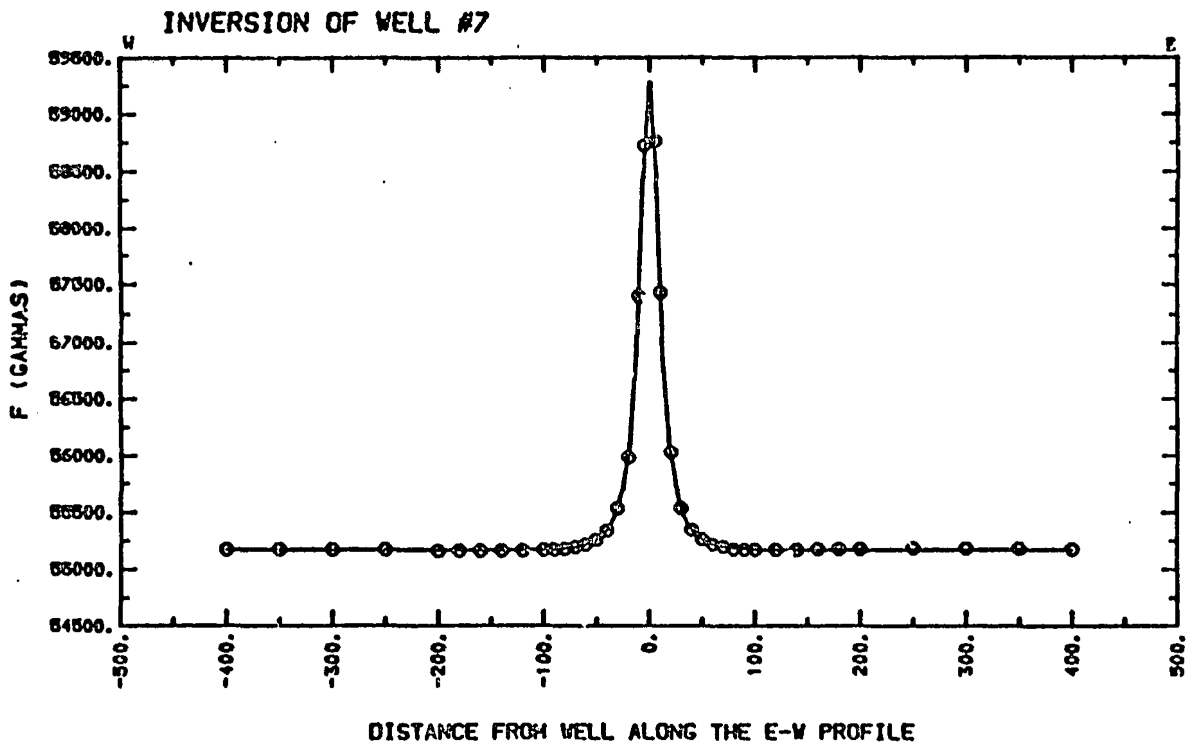


Figure 64. Observed and calculated results for Well Number 7.

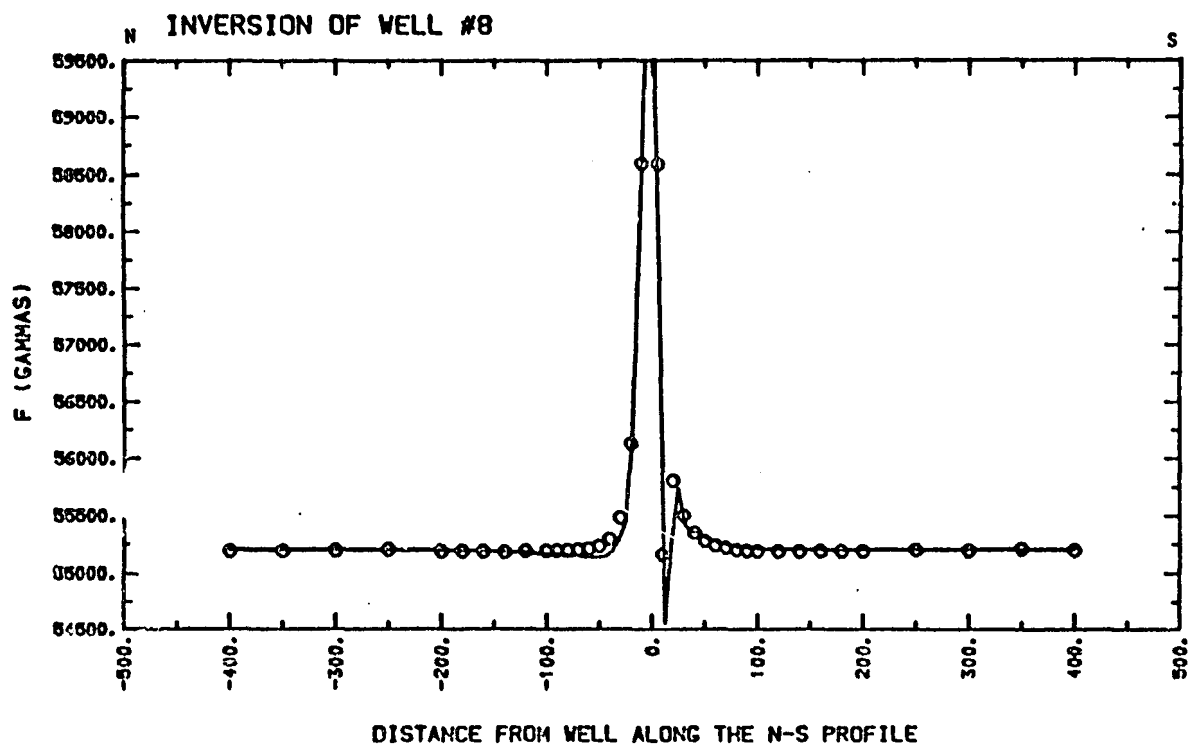


Figure 65. Observed and calculated results for Well Number 8.

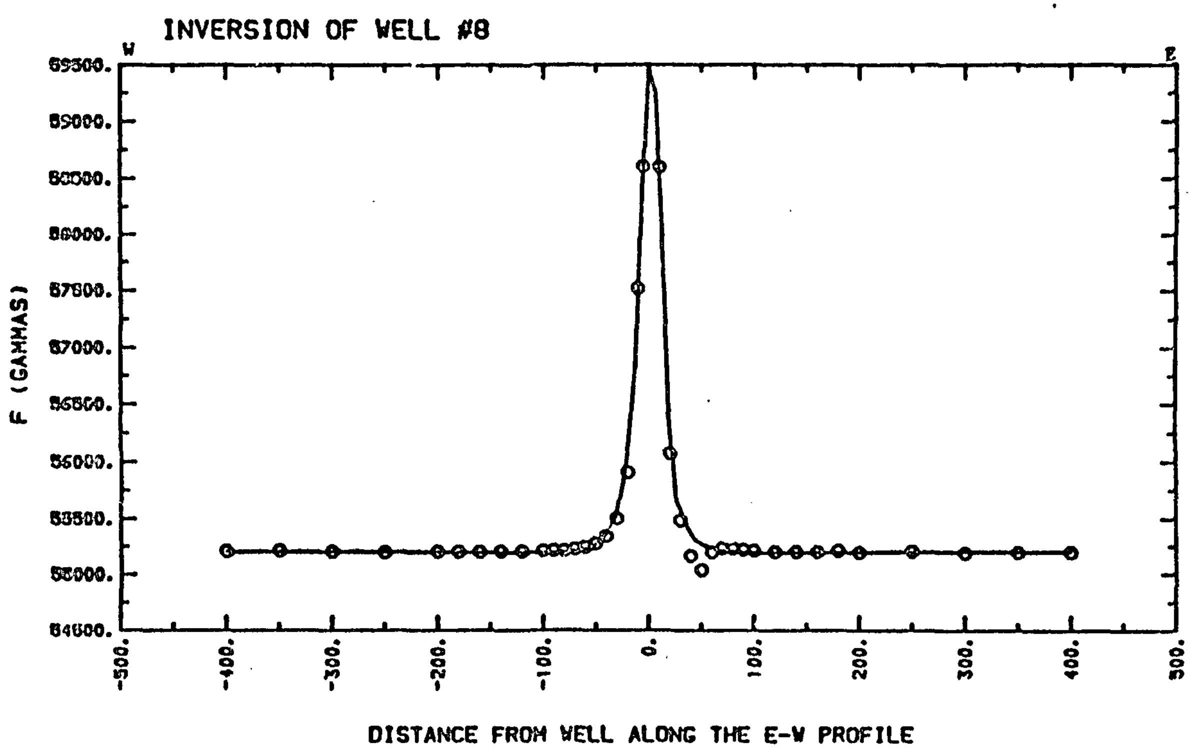


Figure 66. Observed and calculated results for Well Number 8.

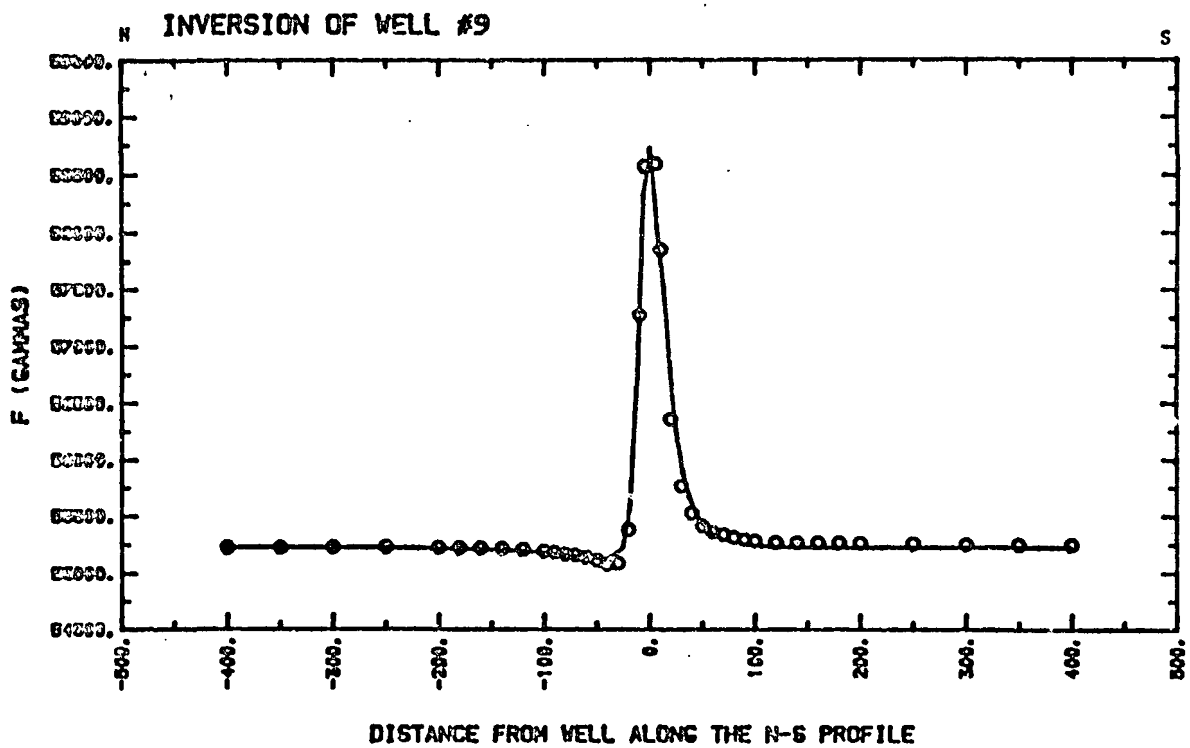


Figure 67. Observed and calculated results for Well Number 9.

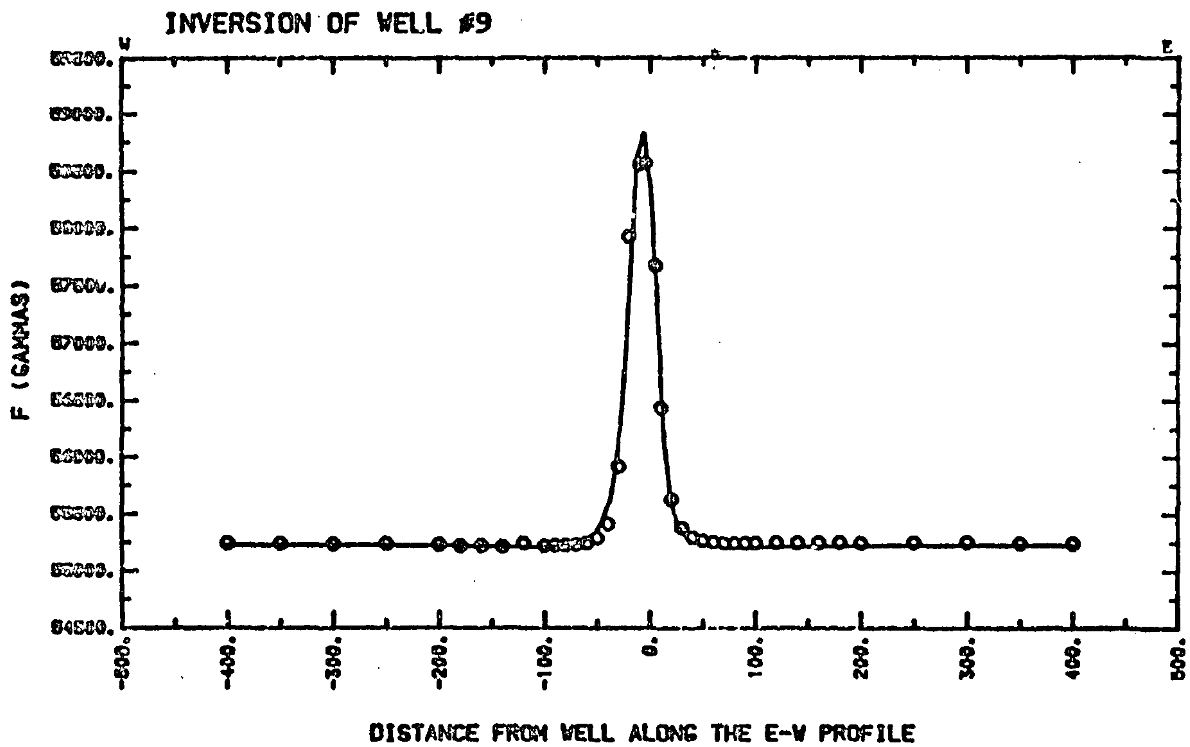


Figure 68. Observed and calculated results for Well Number 9.

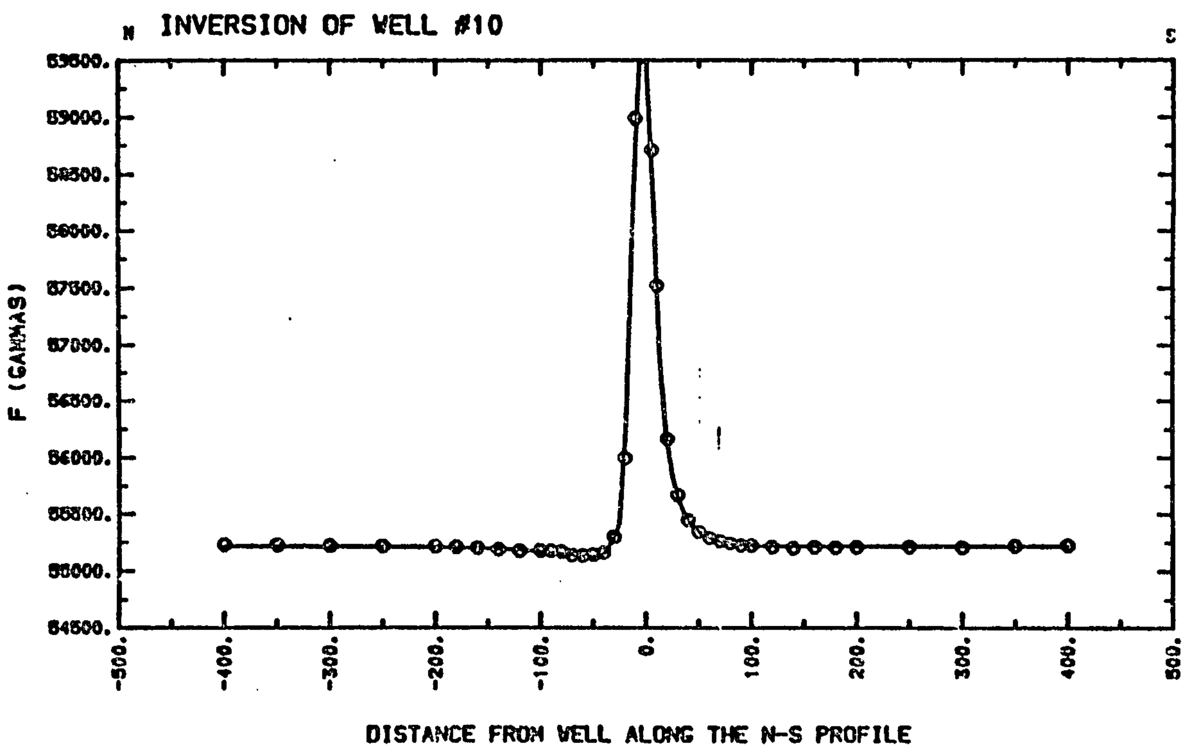


Figure 69. Observed and calculated results for Well Number 10.

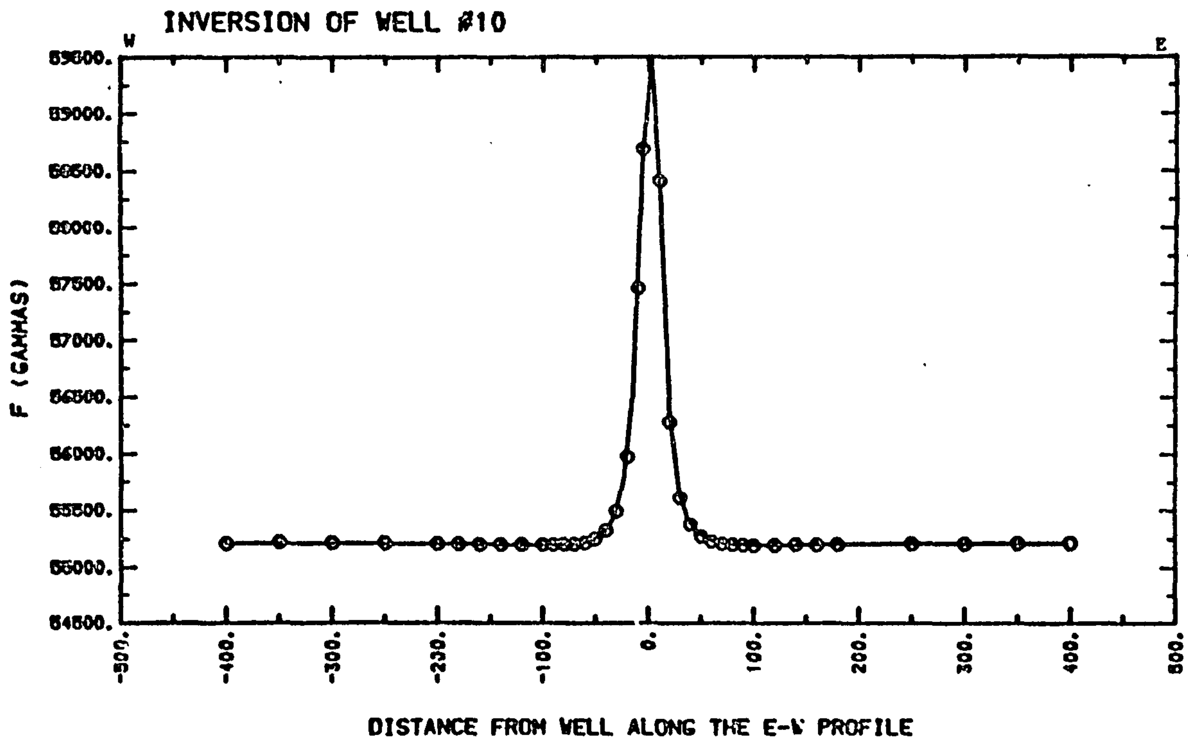


Figure 70. Observed and calculated results for Well Number 10.

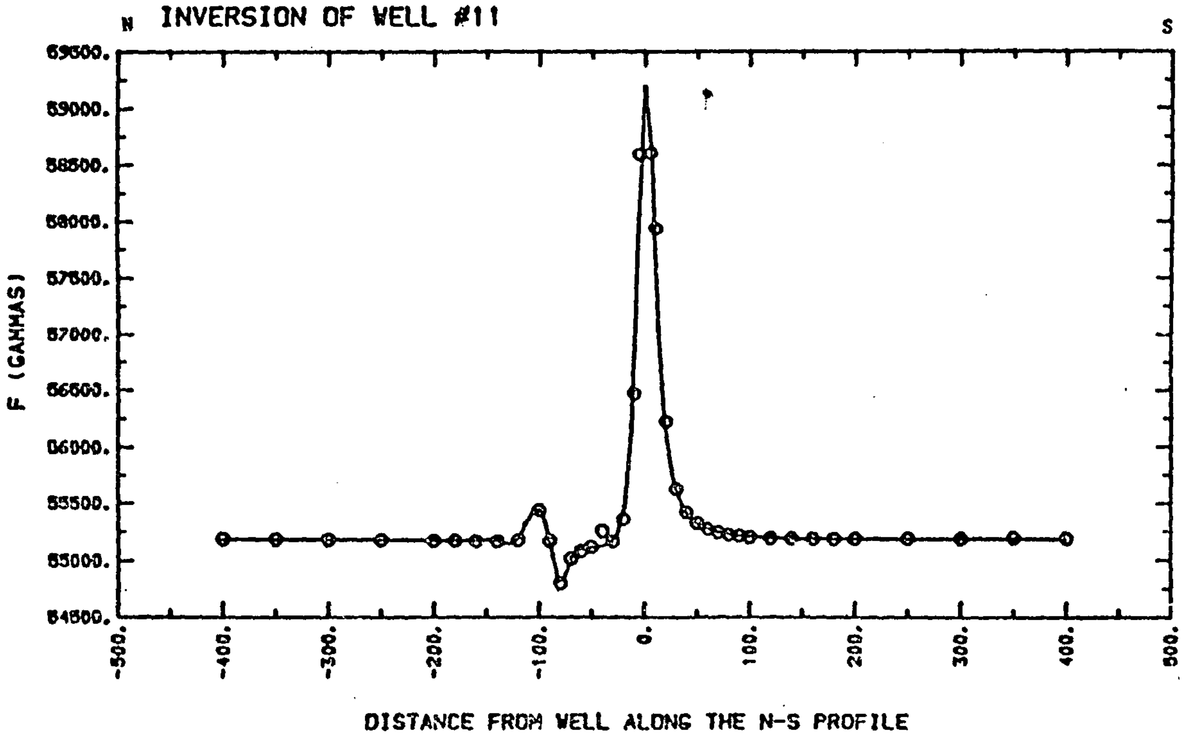


Figure 71. Observed and calculated results for Well Number 11.

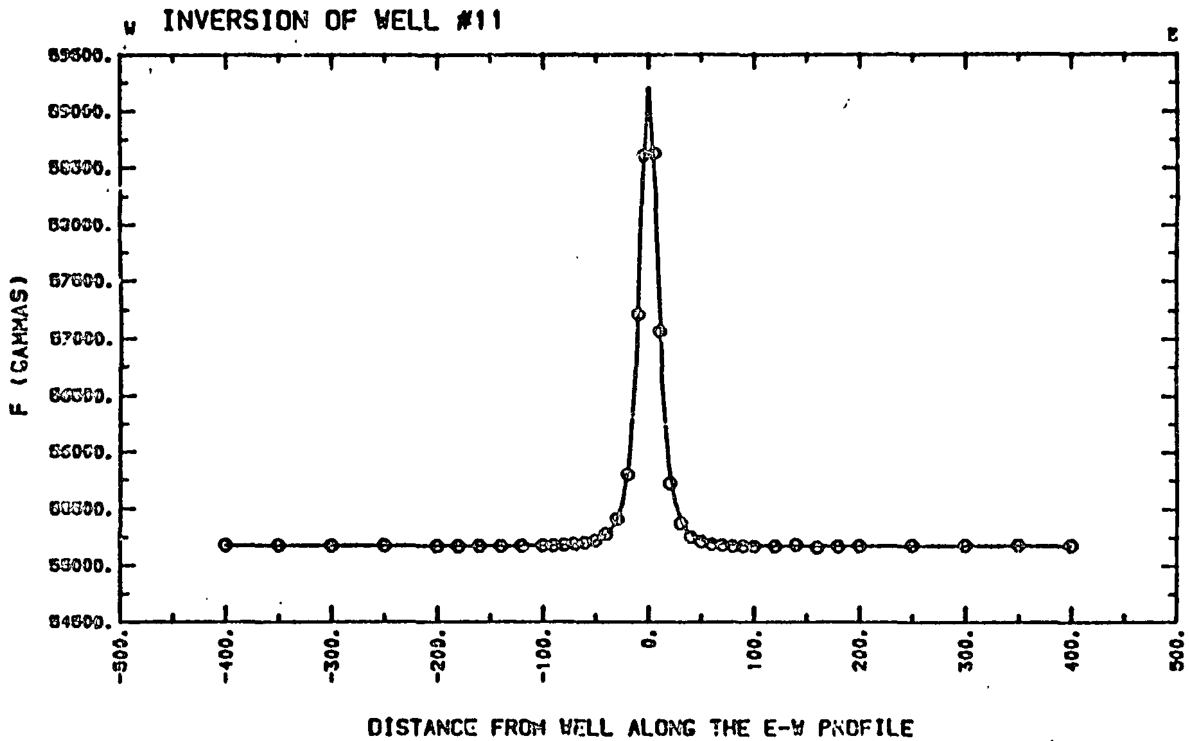


Figure 72. Observed and calculated results for Well Number 11.

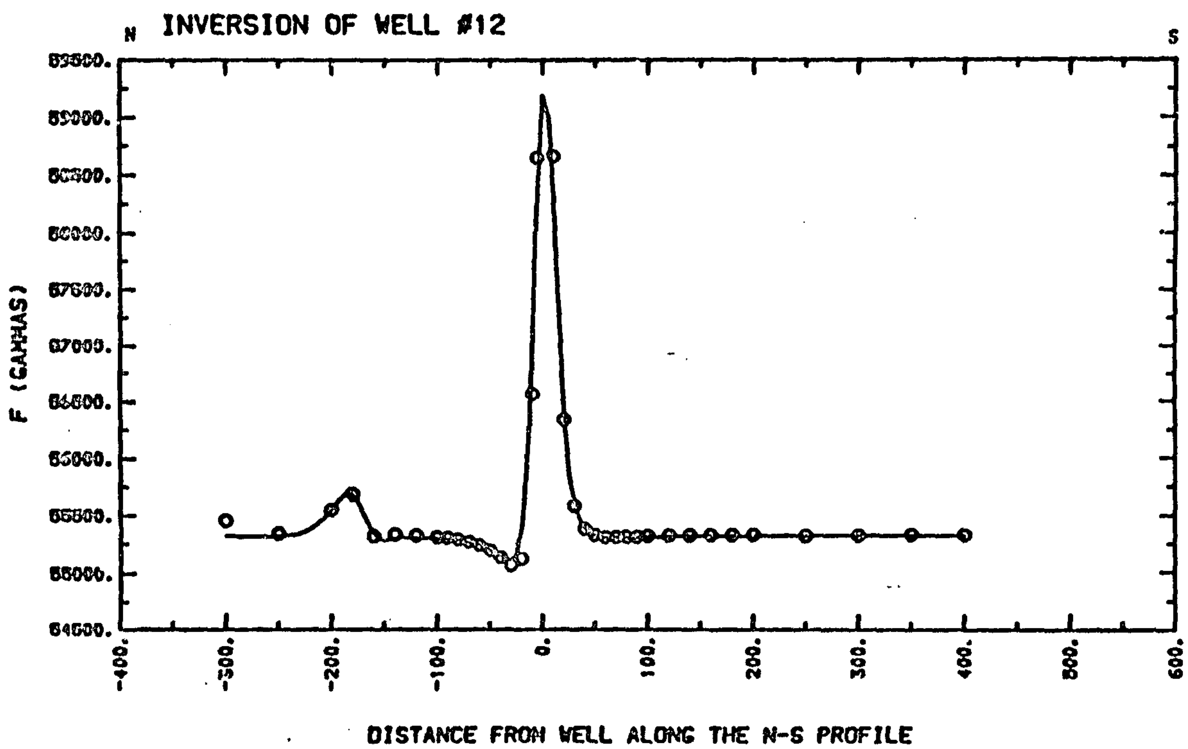


Figure 73. Observed and calculated results for Well Number 12.

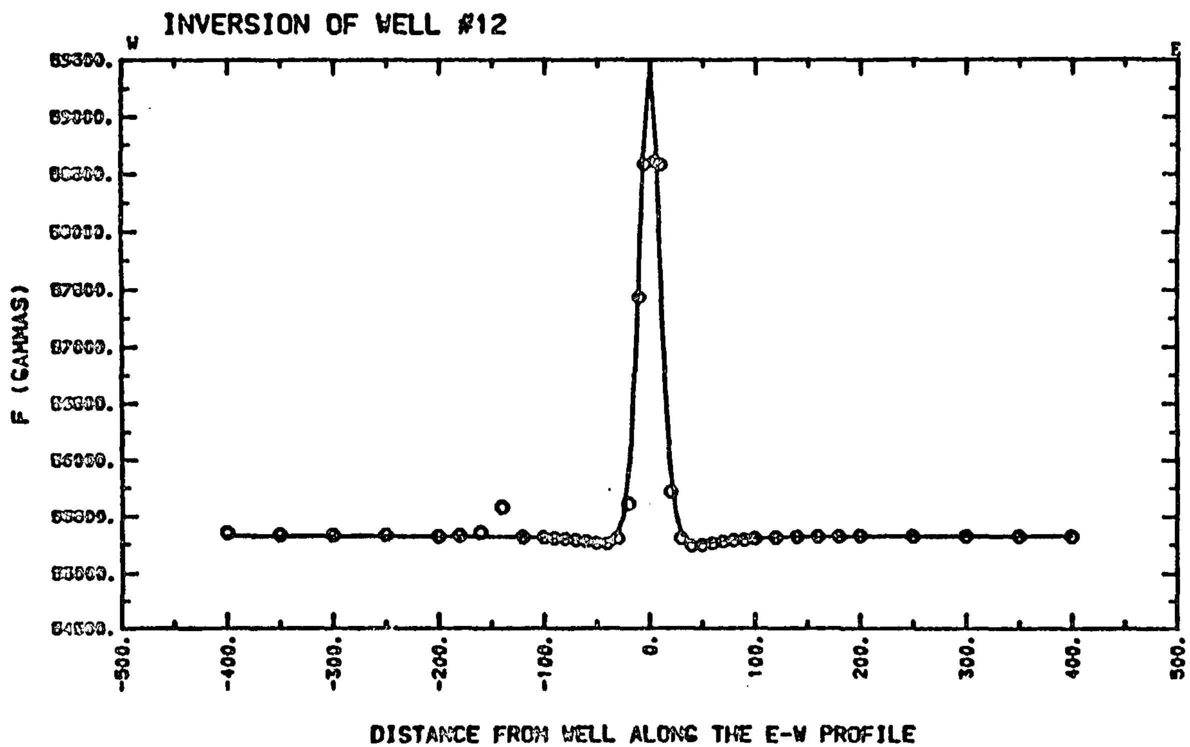


Figure 74. Observed and calculated results for Well Number 12.

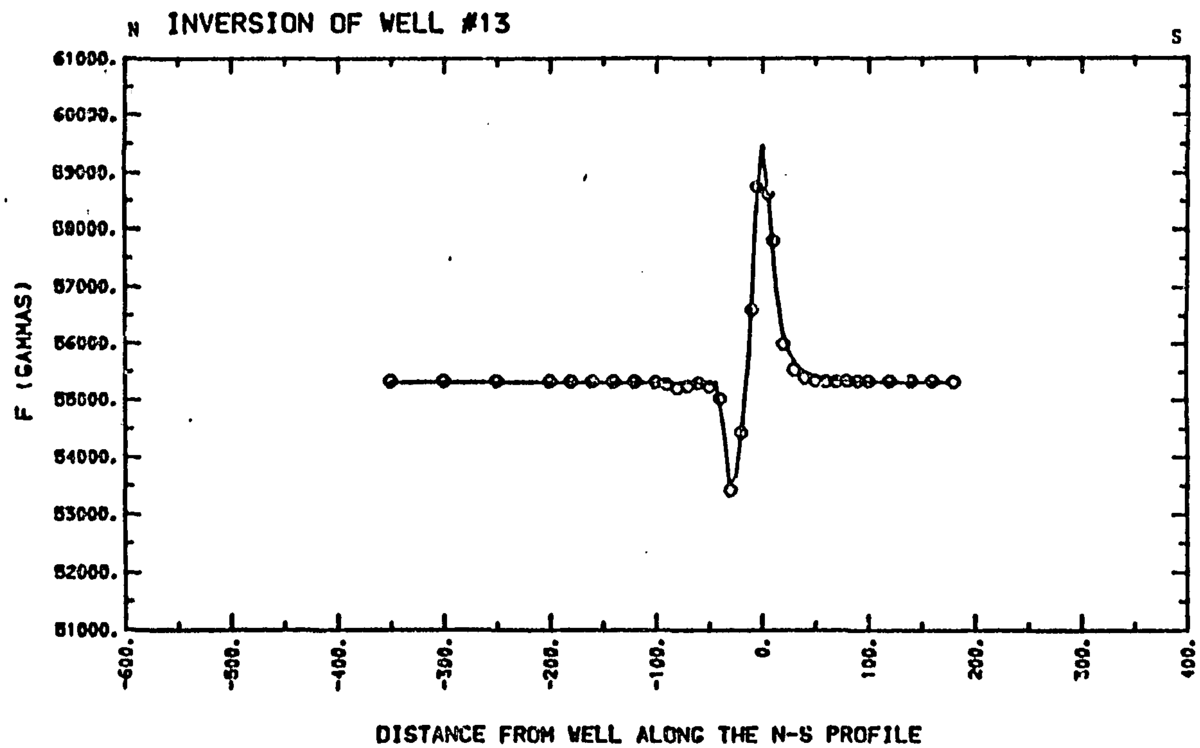


Figure 75. Observed and calculated results for Well Number 13.

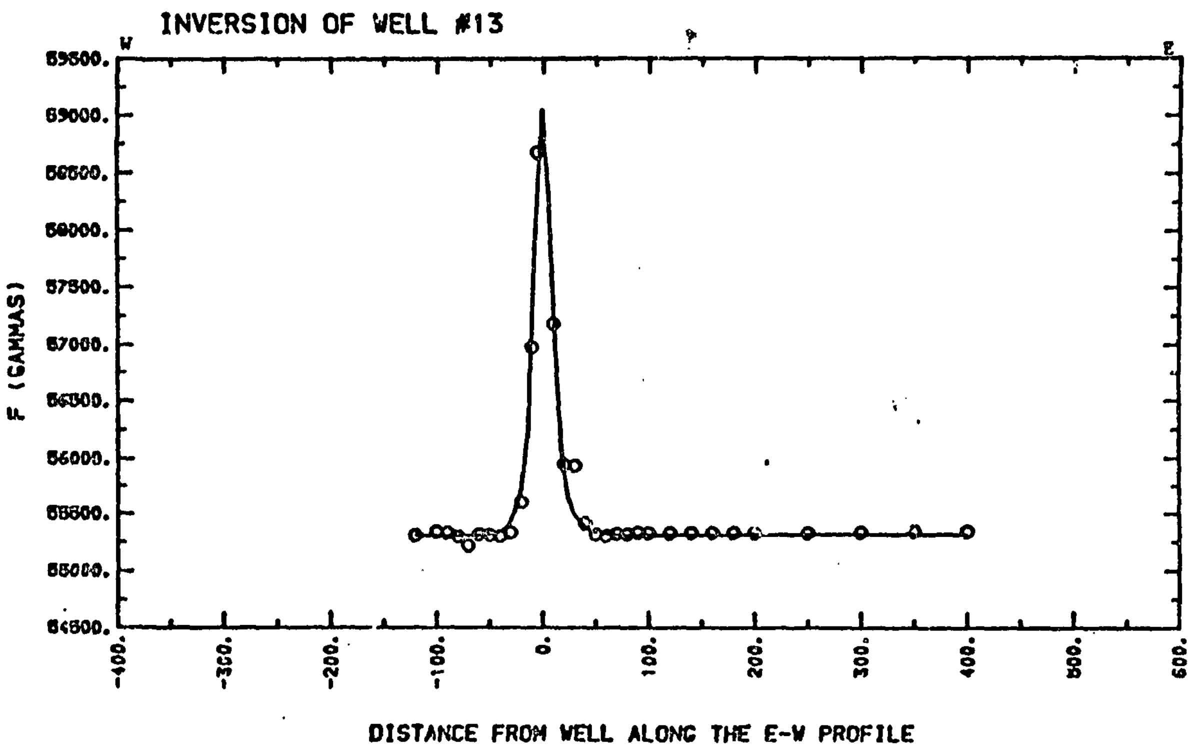


Figure 76. Observed and calculated results for Well Number 13.

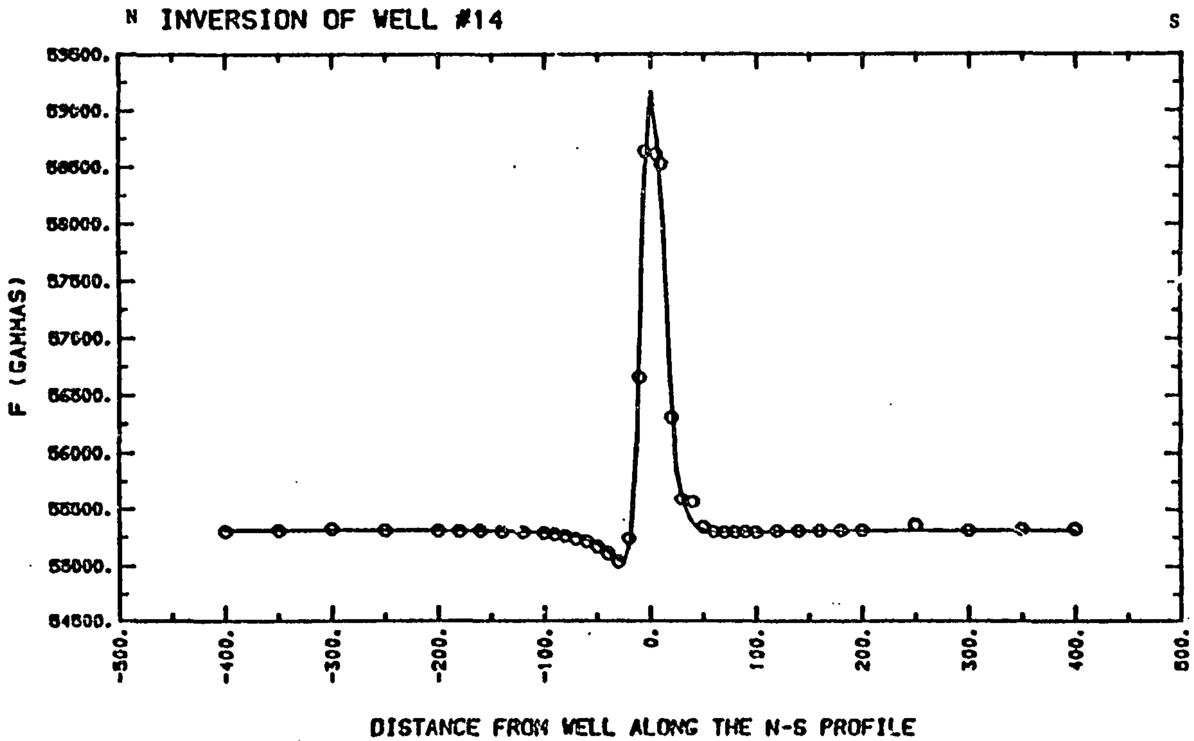


Figure 77. Observed and calculated results for Well Number 14.

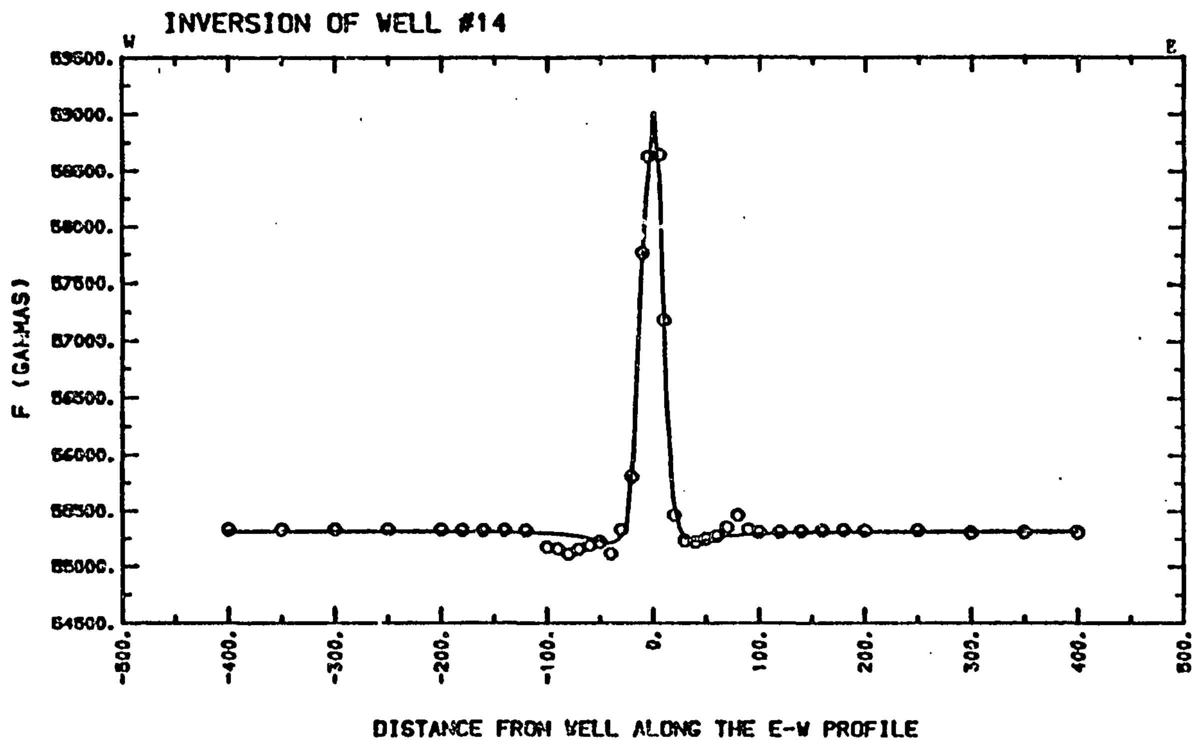


Figure 78. Observed and calculated results for Well Number 14.

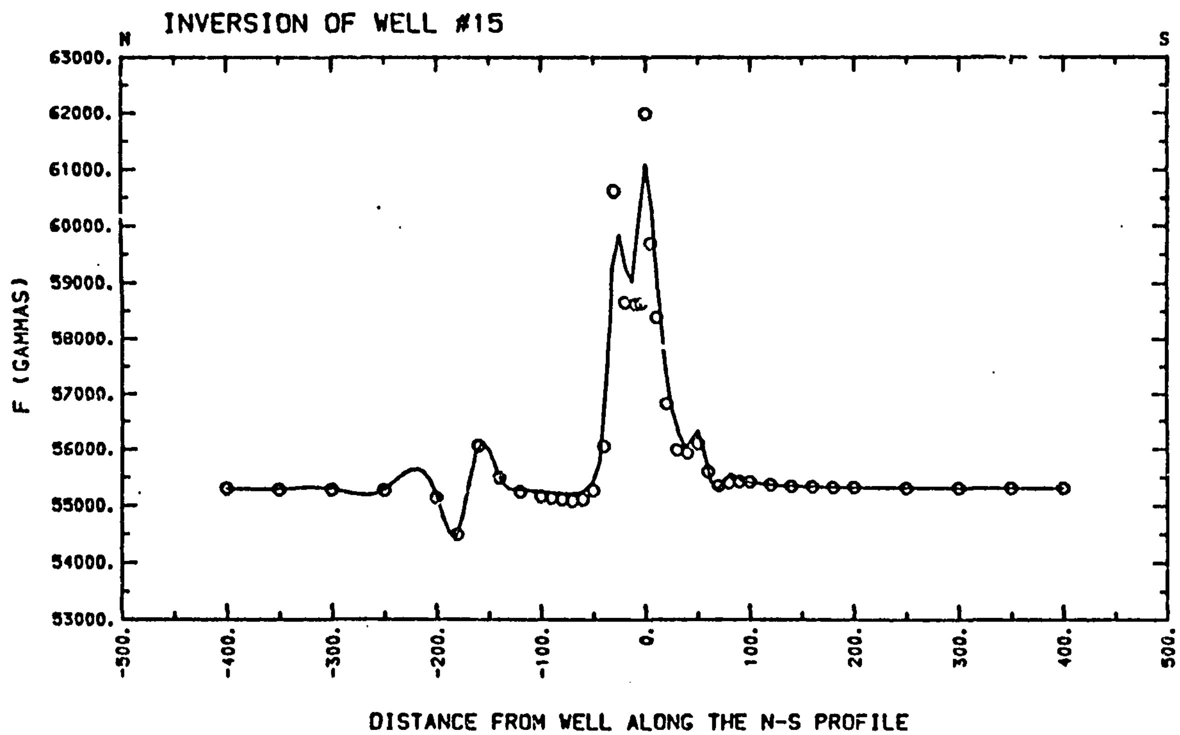


Figure 79a. Observed and calculated results for Well Number 15 S.

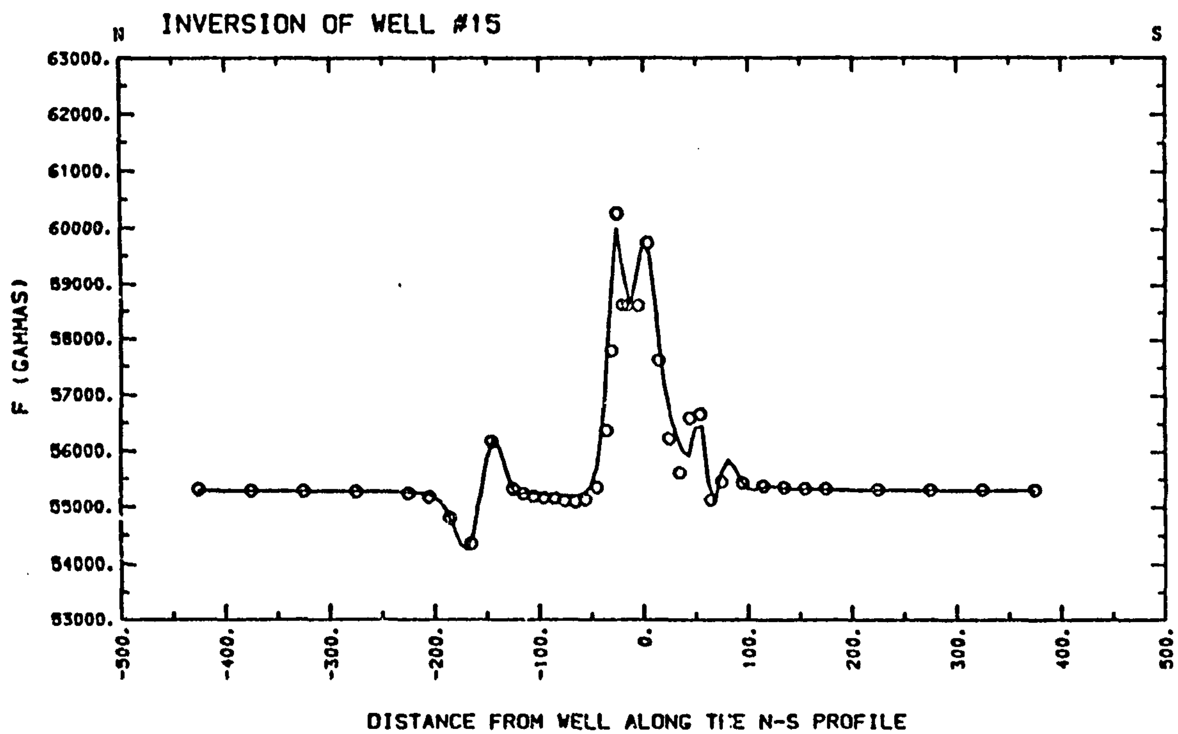


Figure 79b. Observed and calculated results for Well Number 15 N.

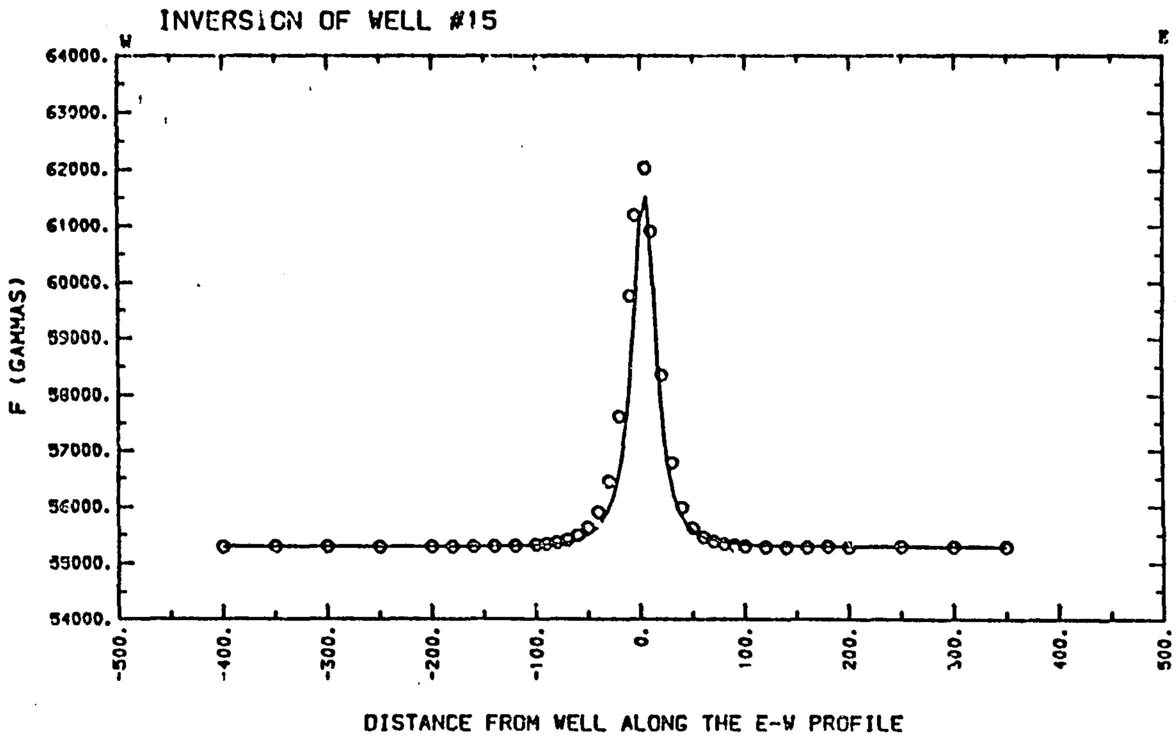


Figure 80a. Observed and calculated results for Well Number 15 S.

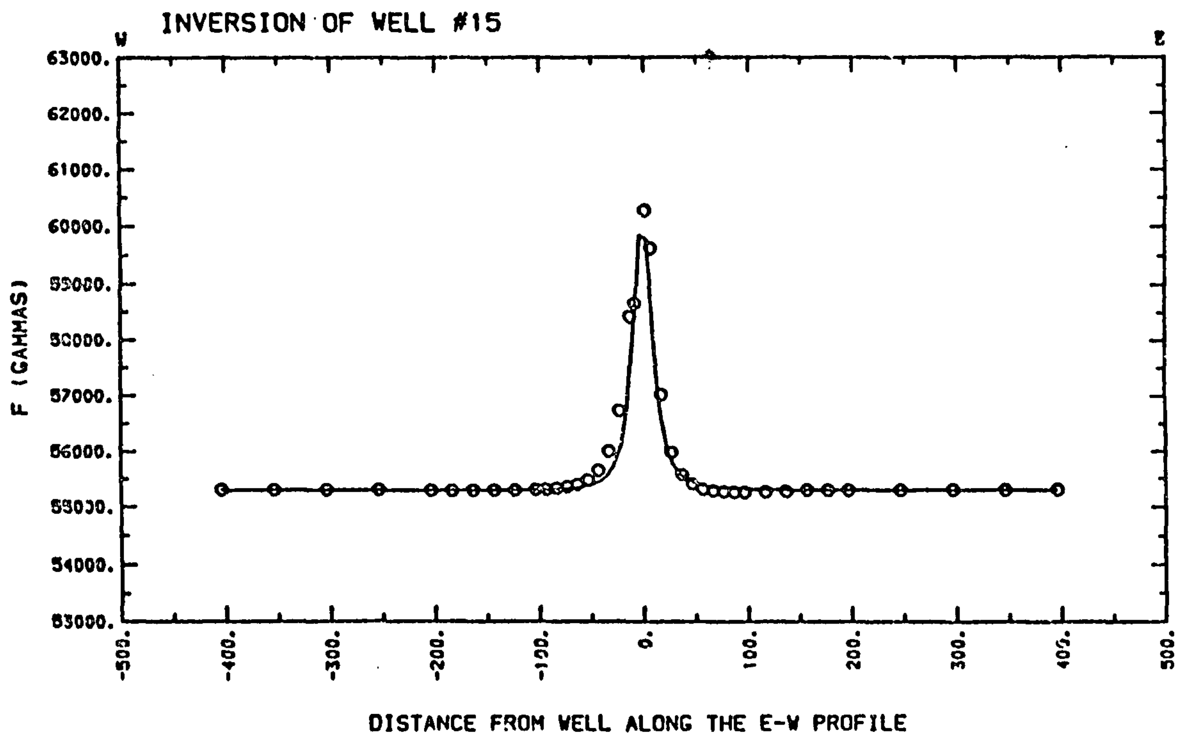


Figure 80b. Observed and calculated results for Well Number 15 N.

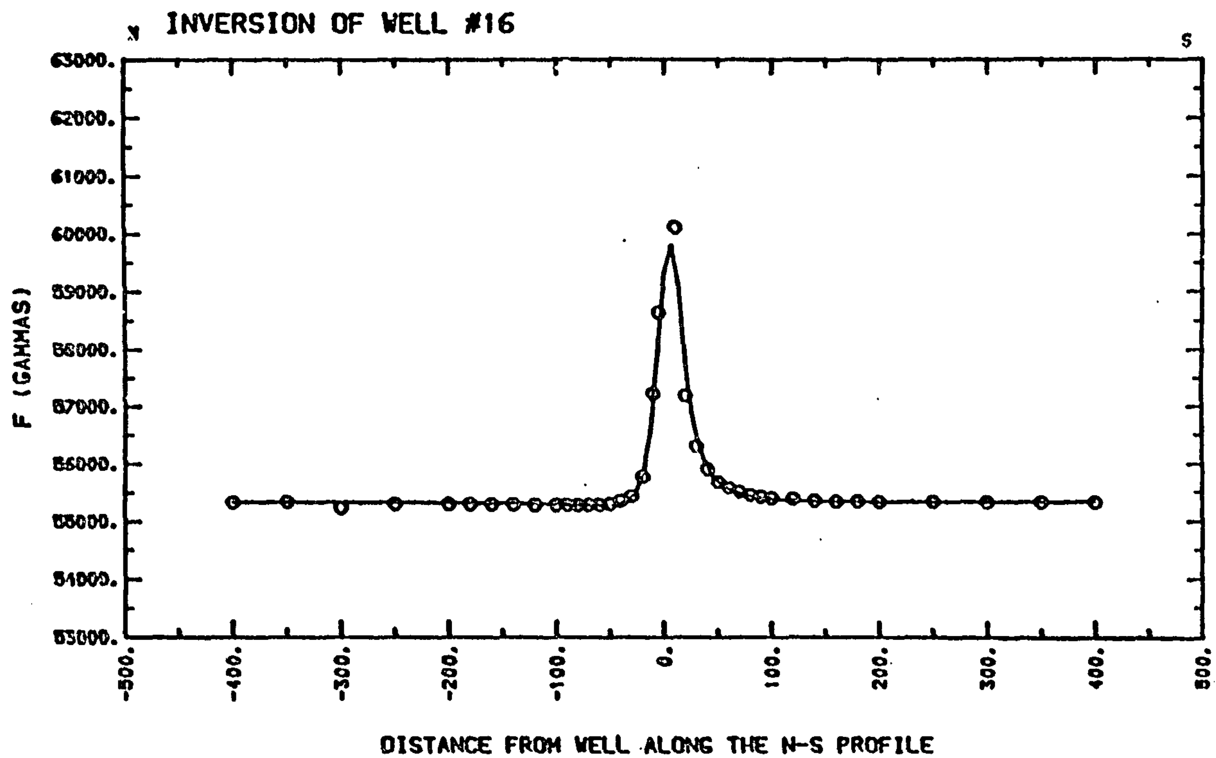


Figure 81. Observed and calculated results for Well Number 16.

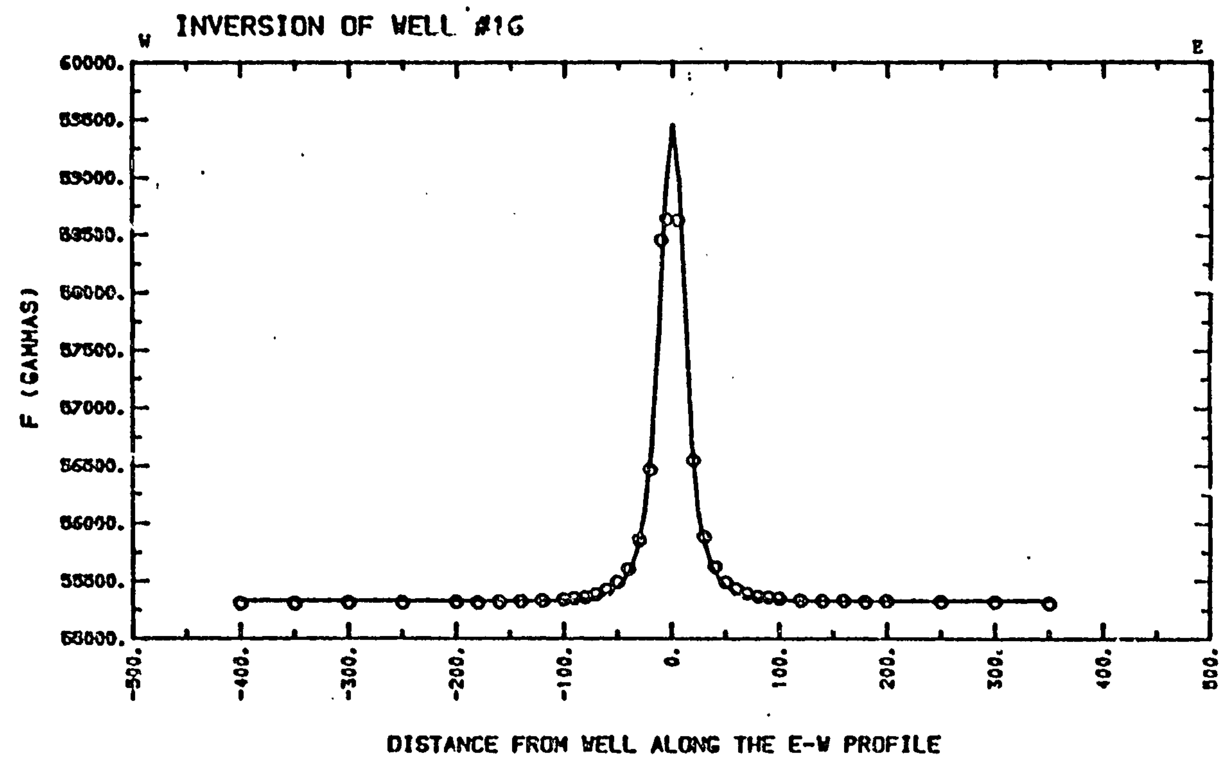


Figure 82. Observed and calculated results for Well Number 16.

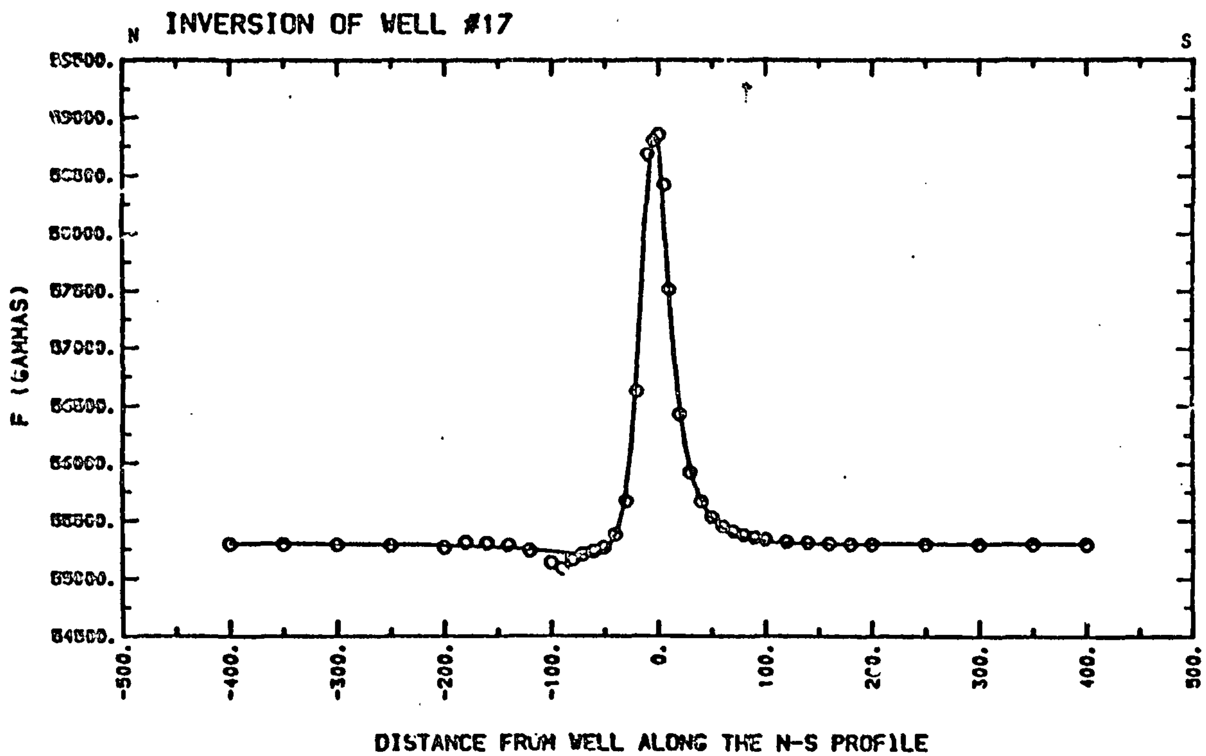


Figure 83. Observed and calculated results for Well Number 17.

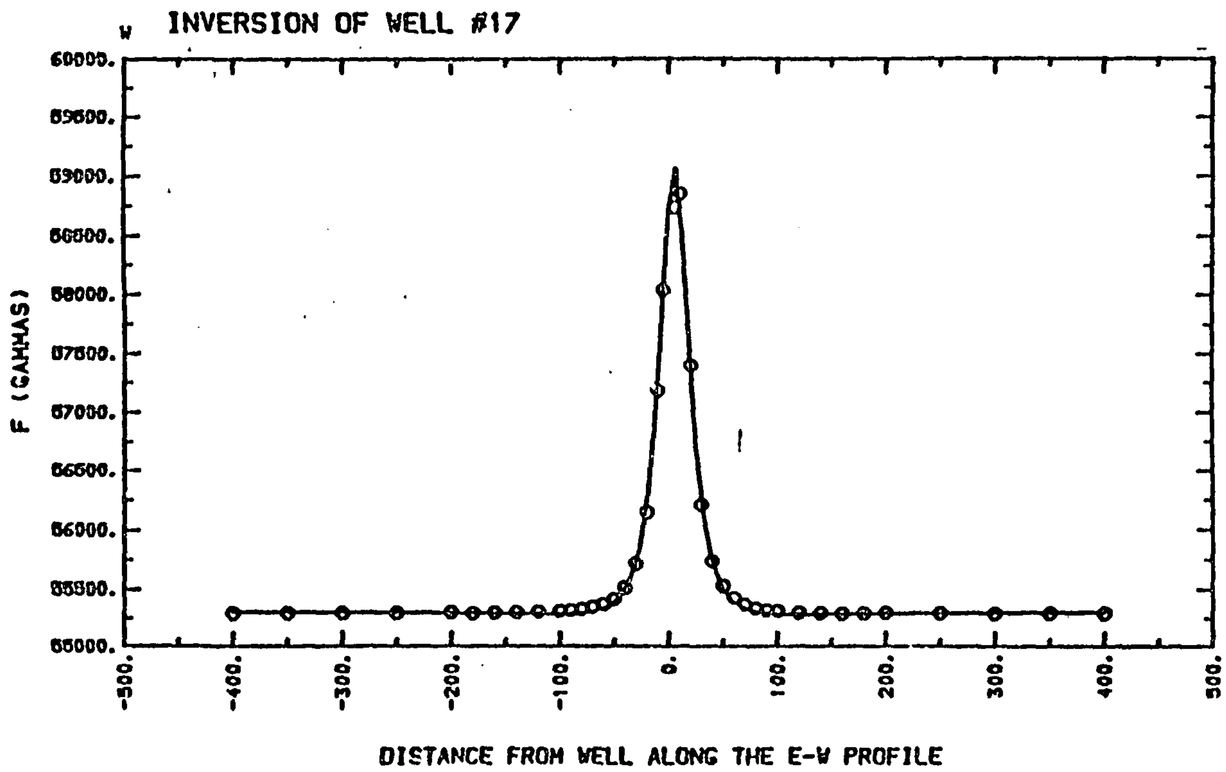


Figure 84. Observed and calculated results for Well Number 17.

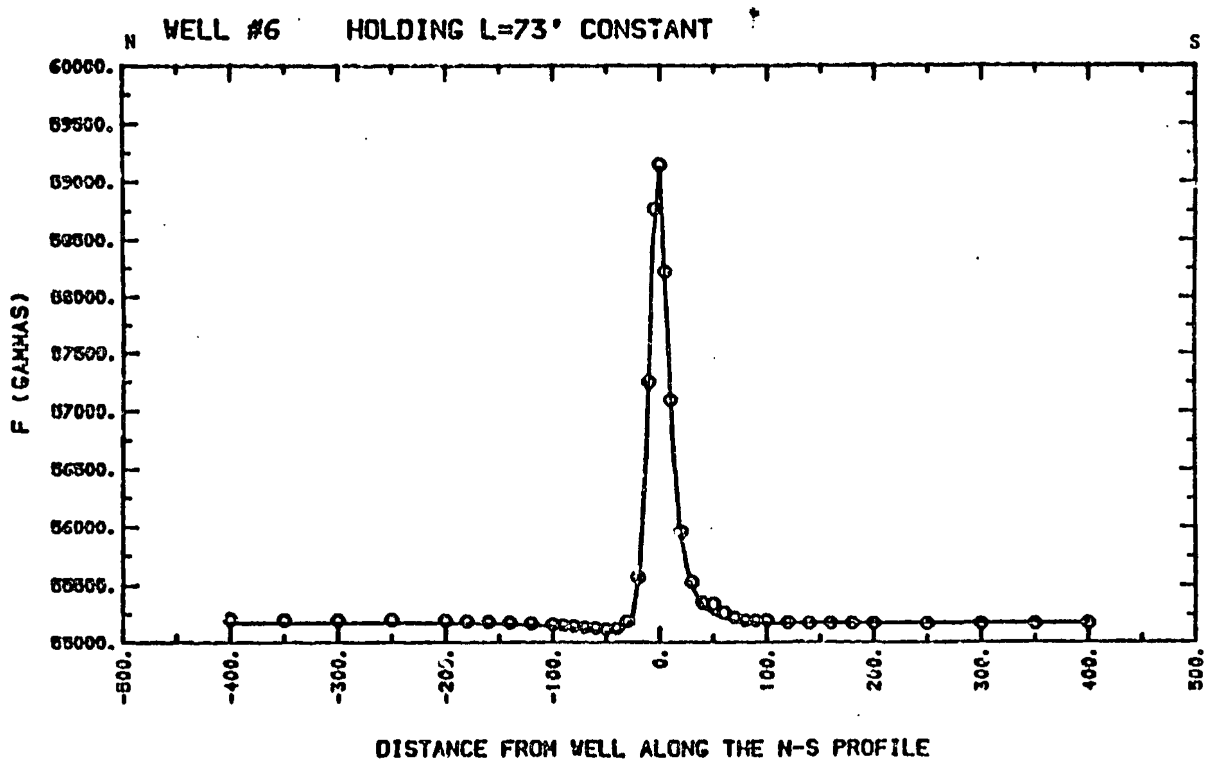


Figure 85. Observed and calculated results for Well Number 6.

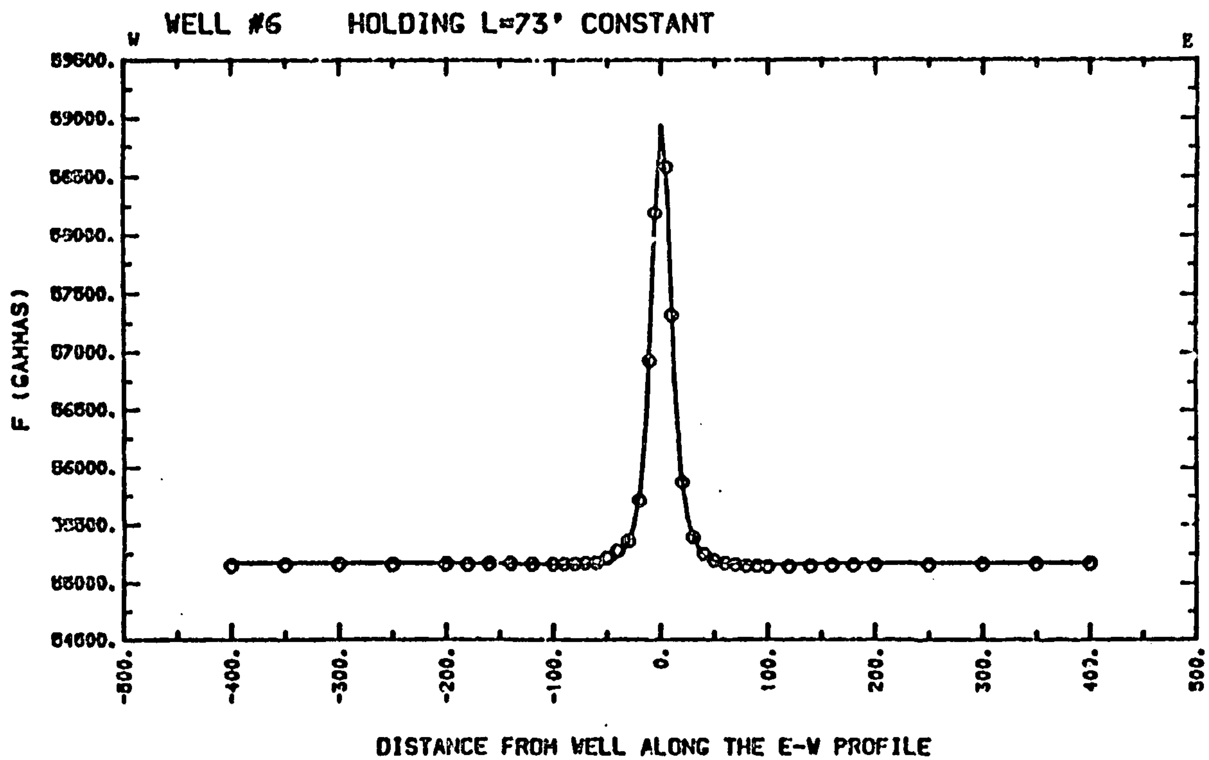


Figure 86. Observed and calculated results for Well Number 6.

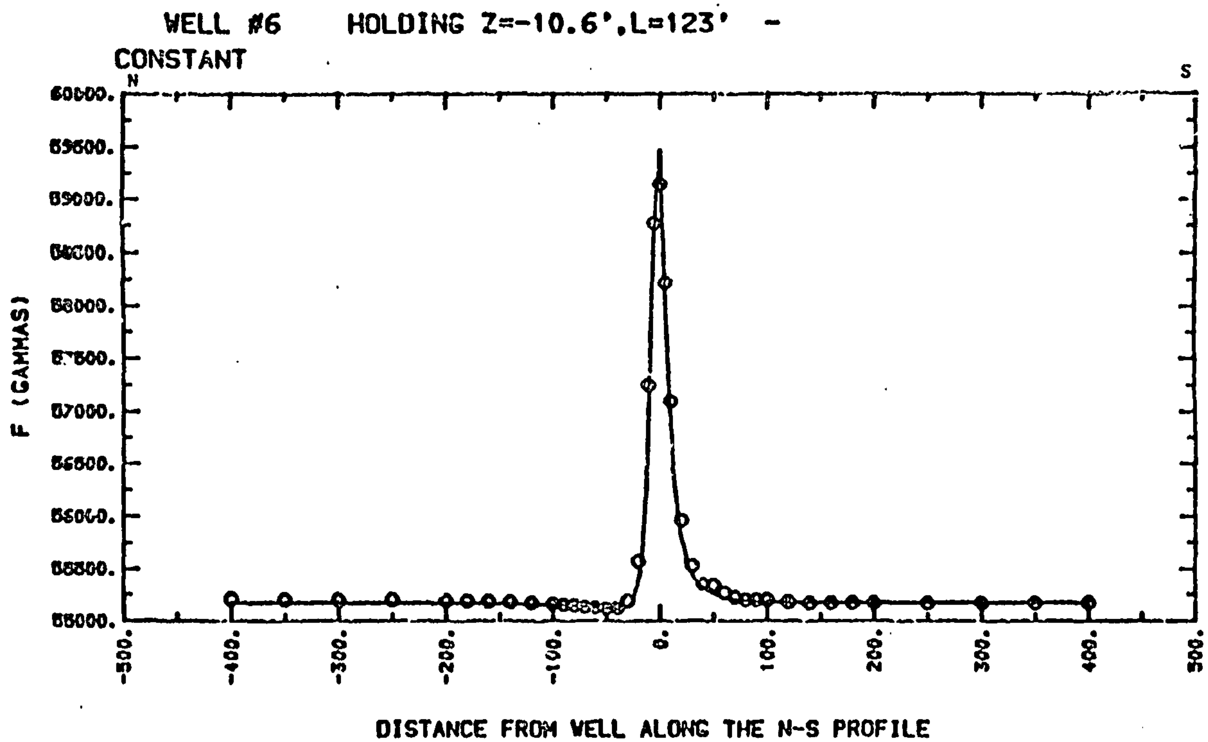


Figure 87. Observed and calculated results for Well Number 6.

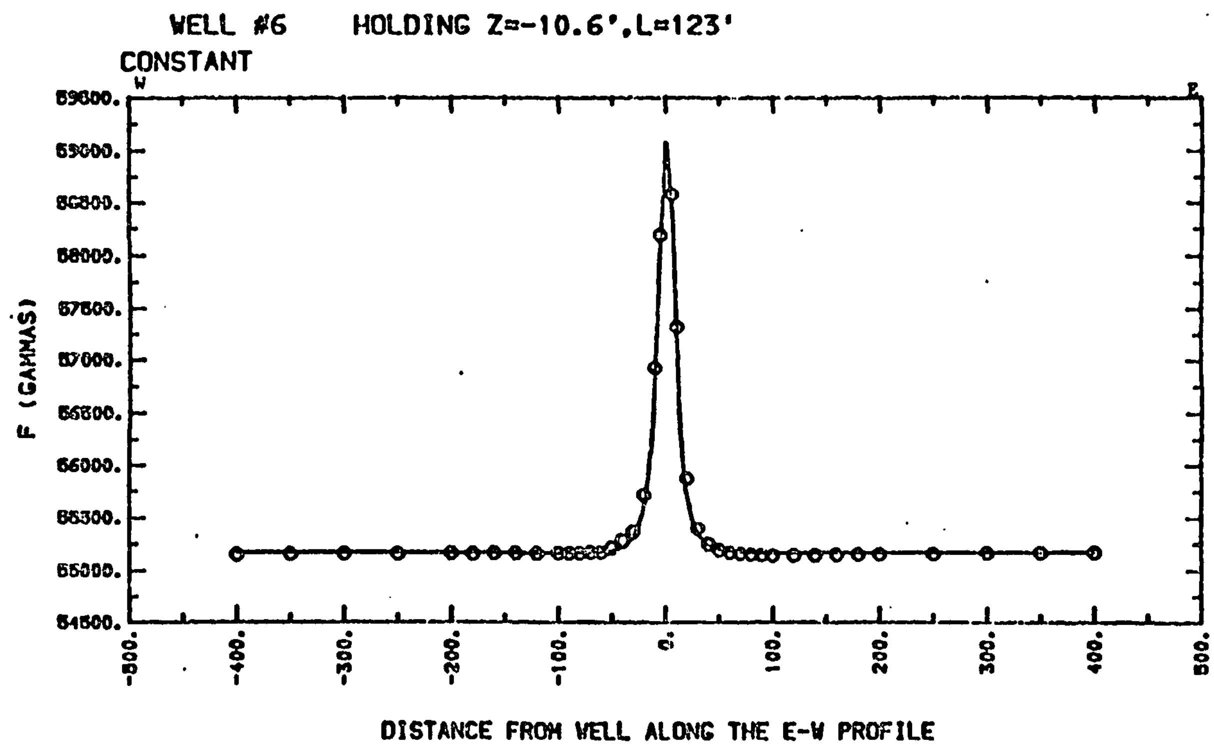
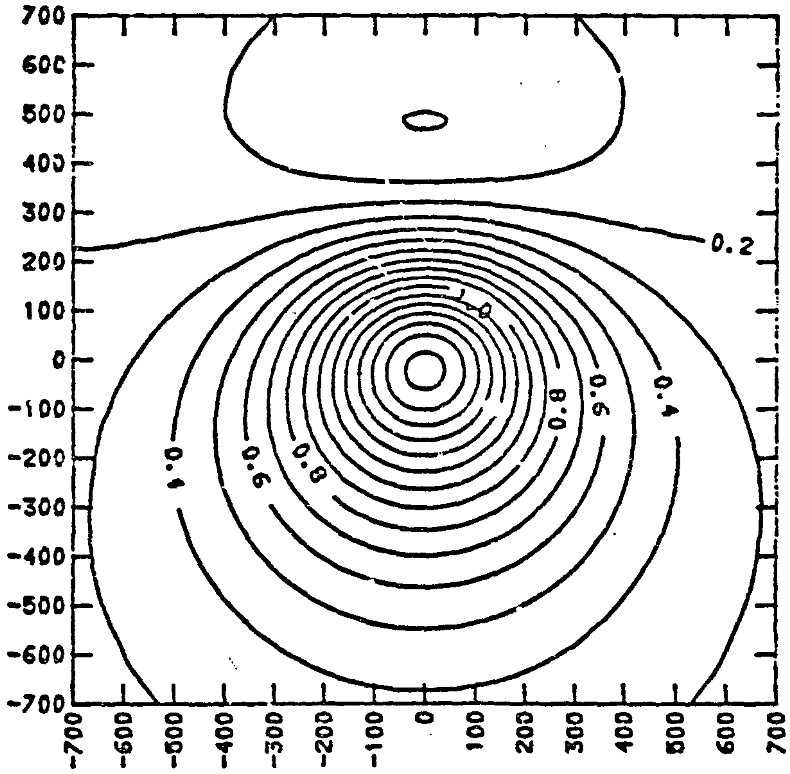
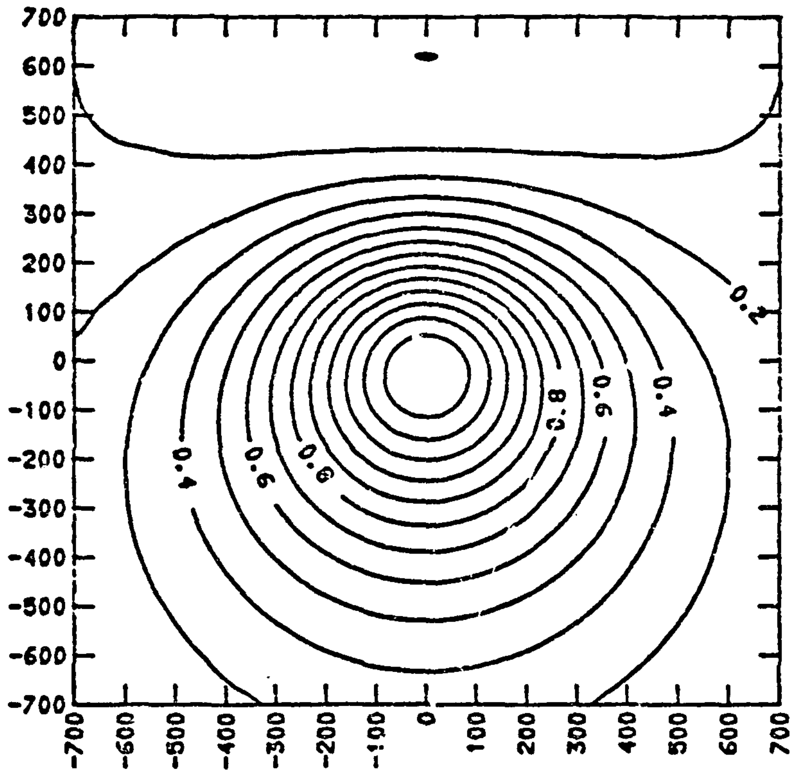


Figure 88. Observed and calculated results for Well Number 6.



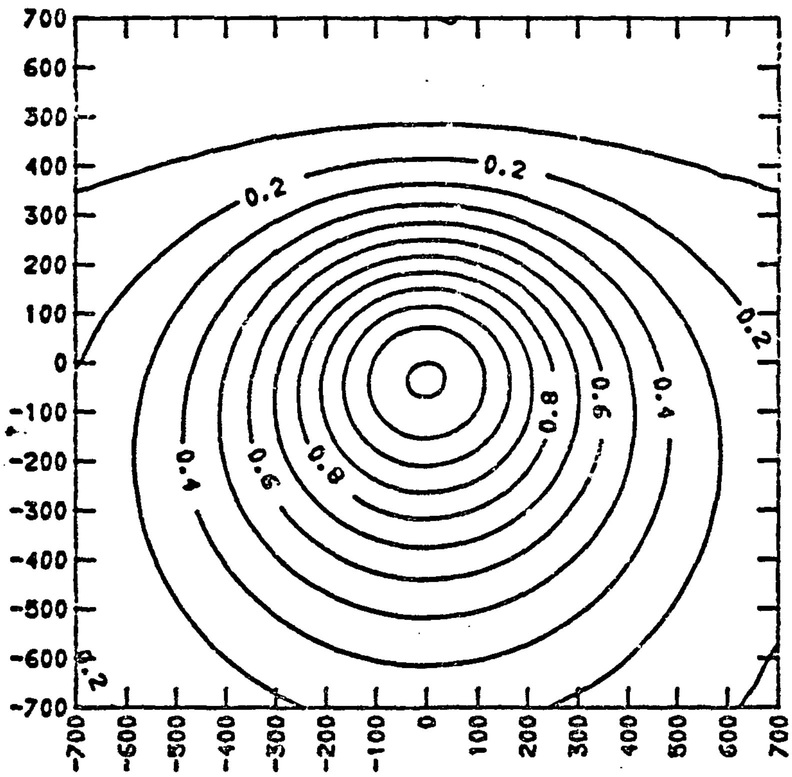
MAP OF WELL #4, 150 FT. ABOVE GROUND

Figure 89. Calculated airborne total field contour map of $\log_{10}(F-F_{min})$.



MAP OF WELL #4, 200 FT. ABOVE GROUND

Figure 90. Calculated airborne total field contour map of $\log_{10}(F-F_{min})$.



MAP OF WELL #4, 250 FT. ABOVE GROUND

Figure 91. Calculated airborne total field contour map of $\log_{10} (F-F_{min})$.

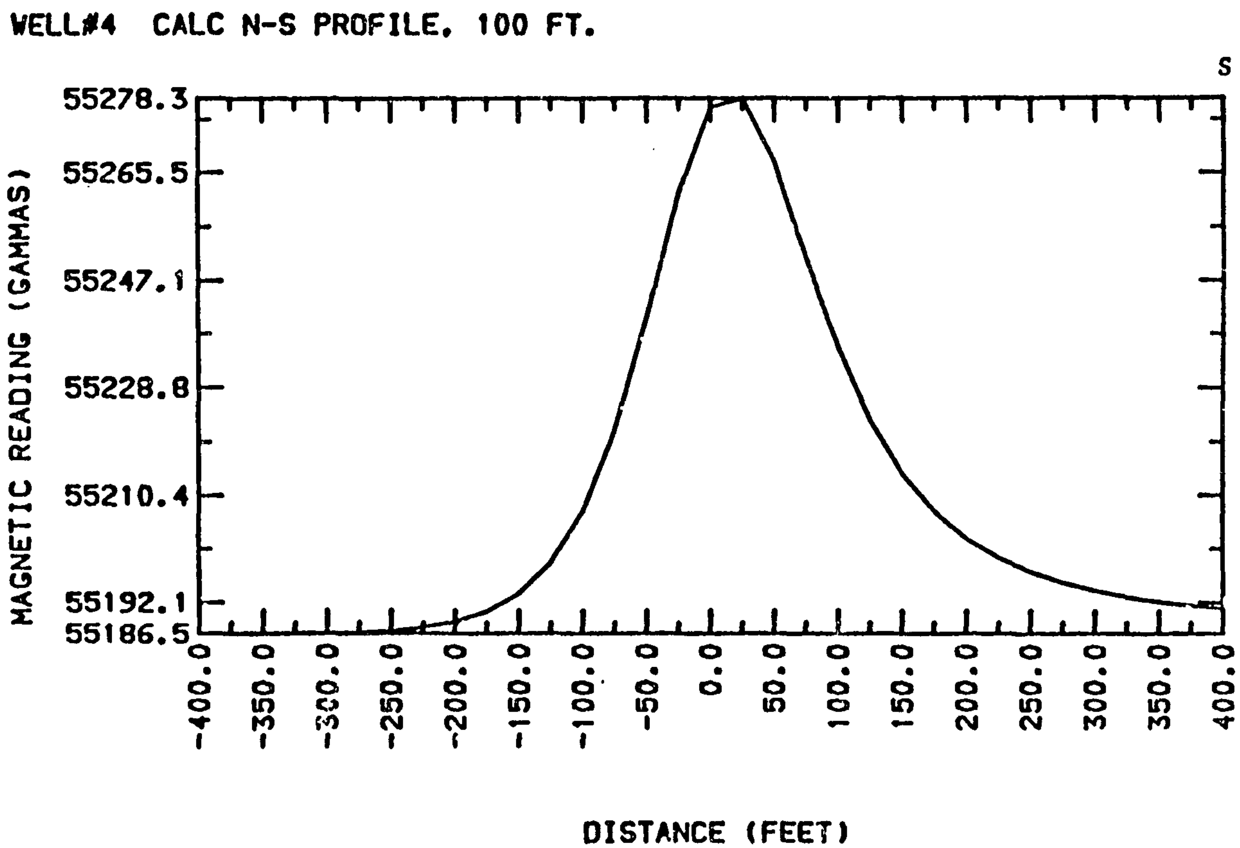


Figure 92. Calculated airborne total field profile at 100 ft for Well Number 4.

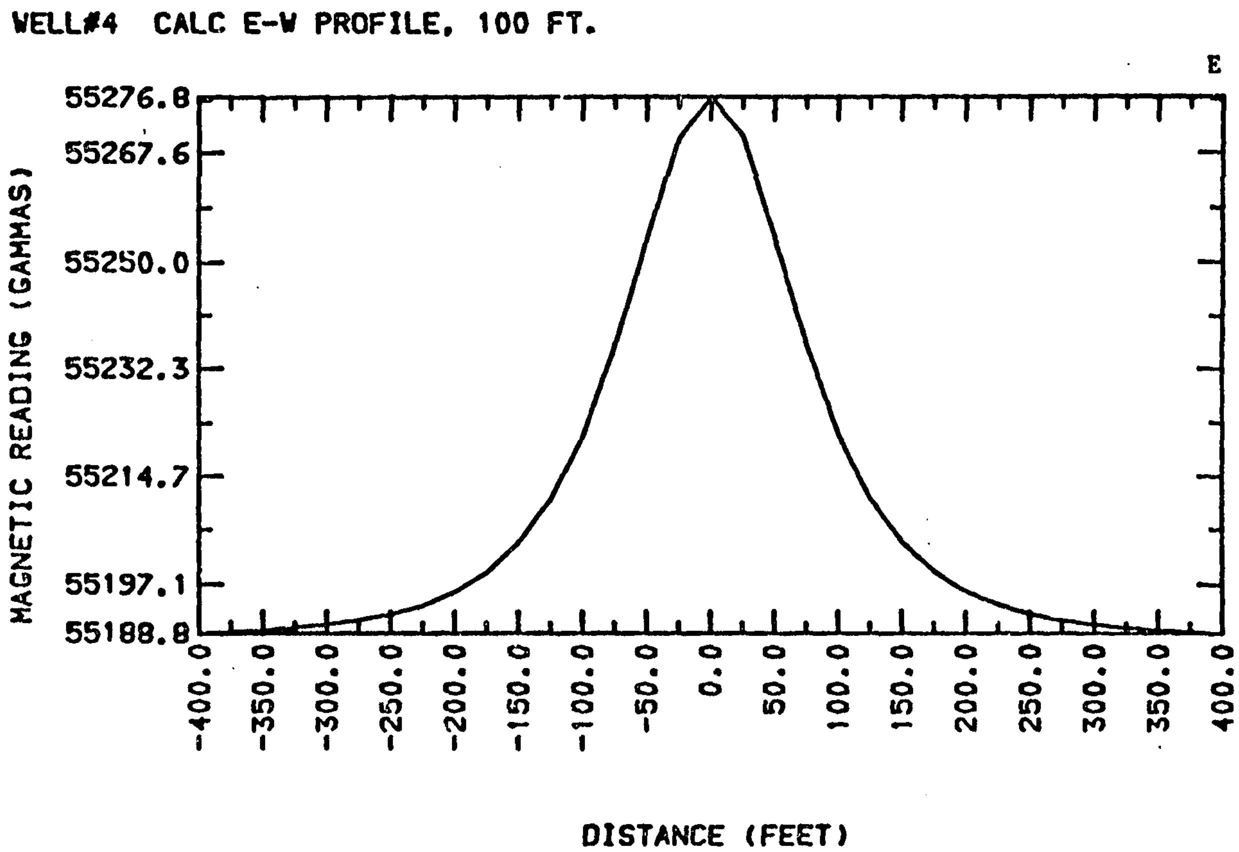


Figure 93. Calculated airborne total field profile at 100 ft for Well Number 4.

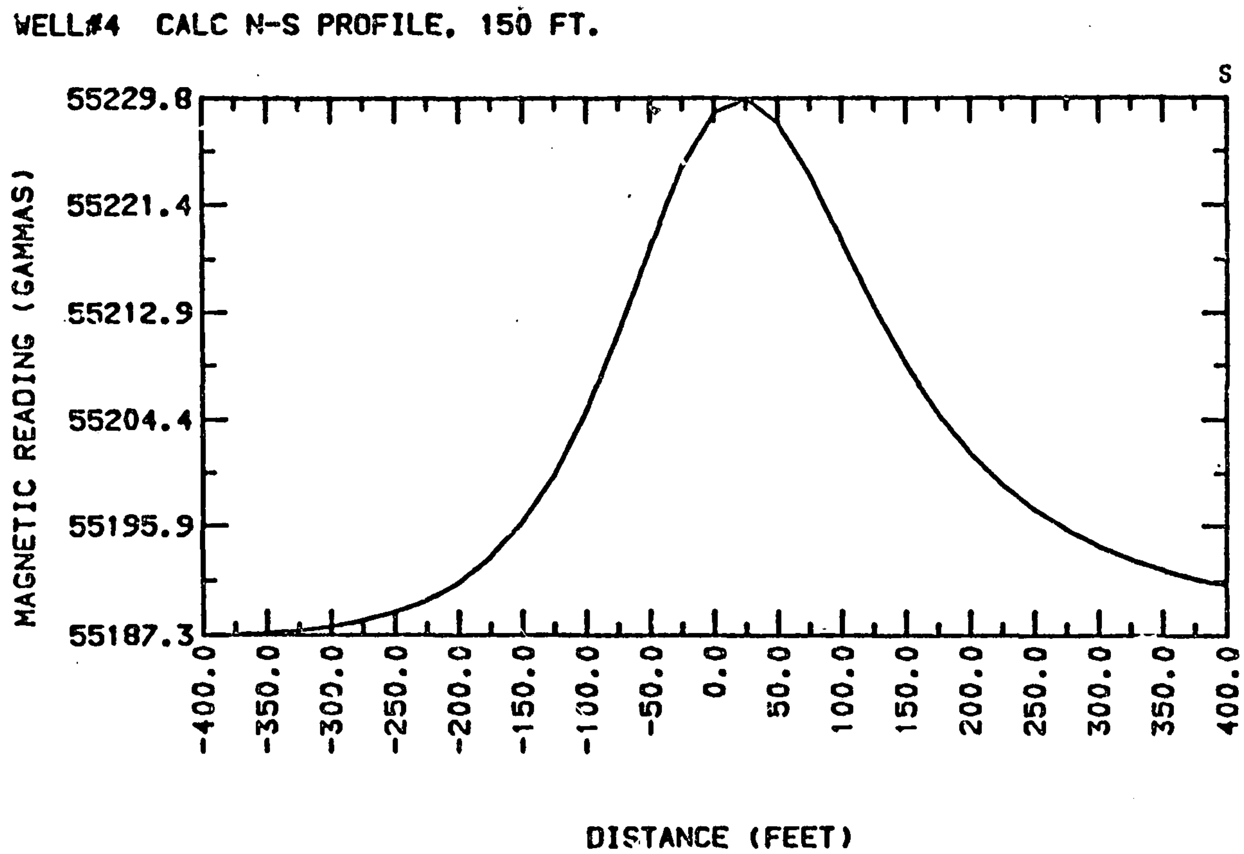


Figure 94. Calculated airborne total field profile at 150 ft for Well Number 4.

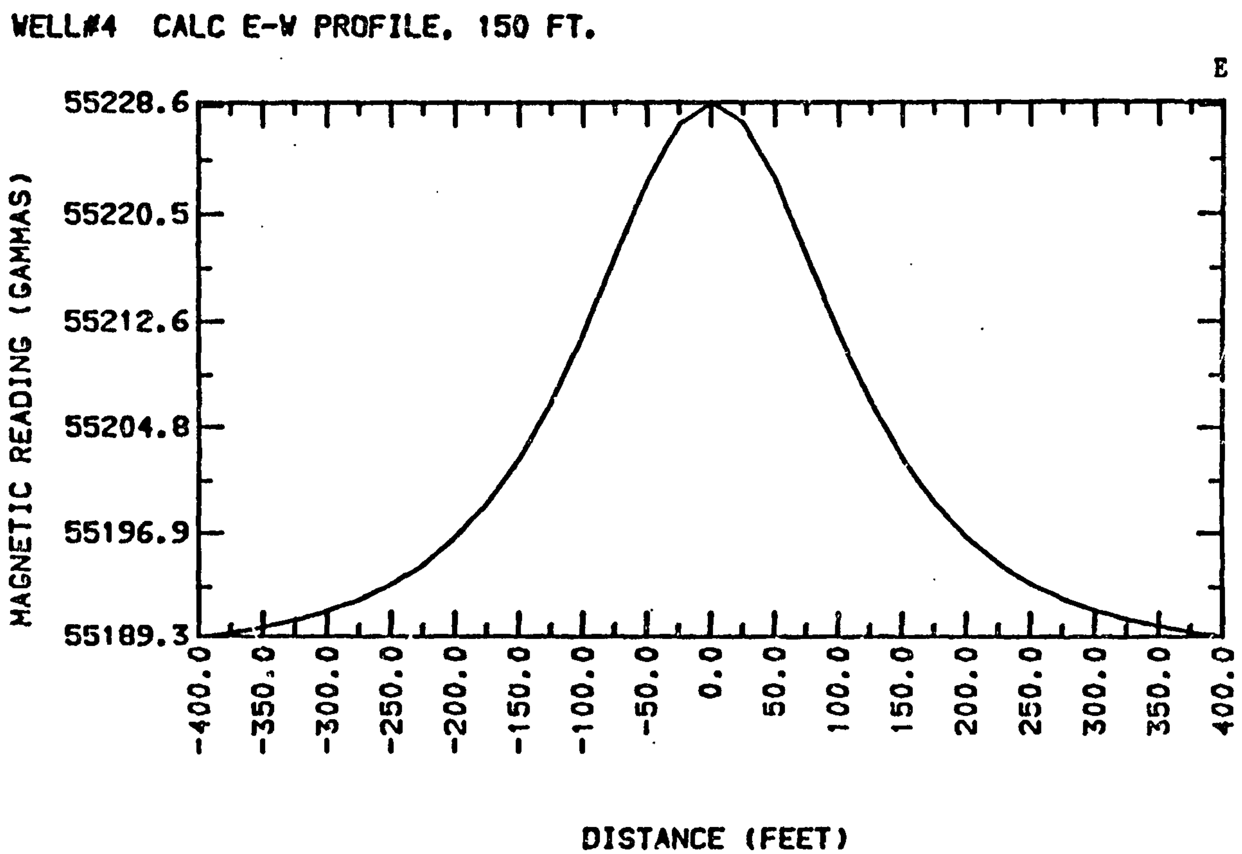


Figure 95. Calculated airborne total field profile at 150 ft for Well Number 4.

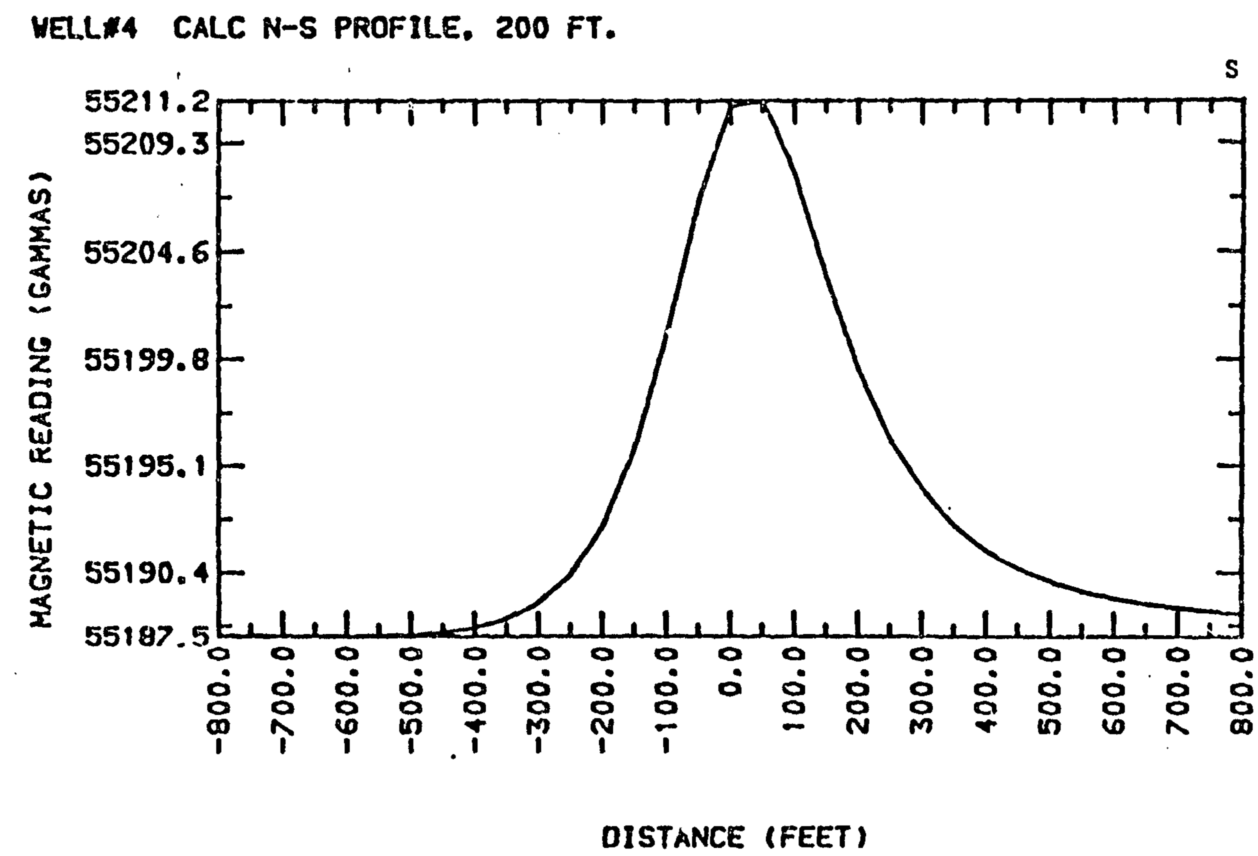


Figure 96. Calculated airborne total field profile at 200 ft for Well Number 4.

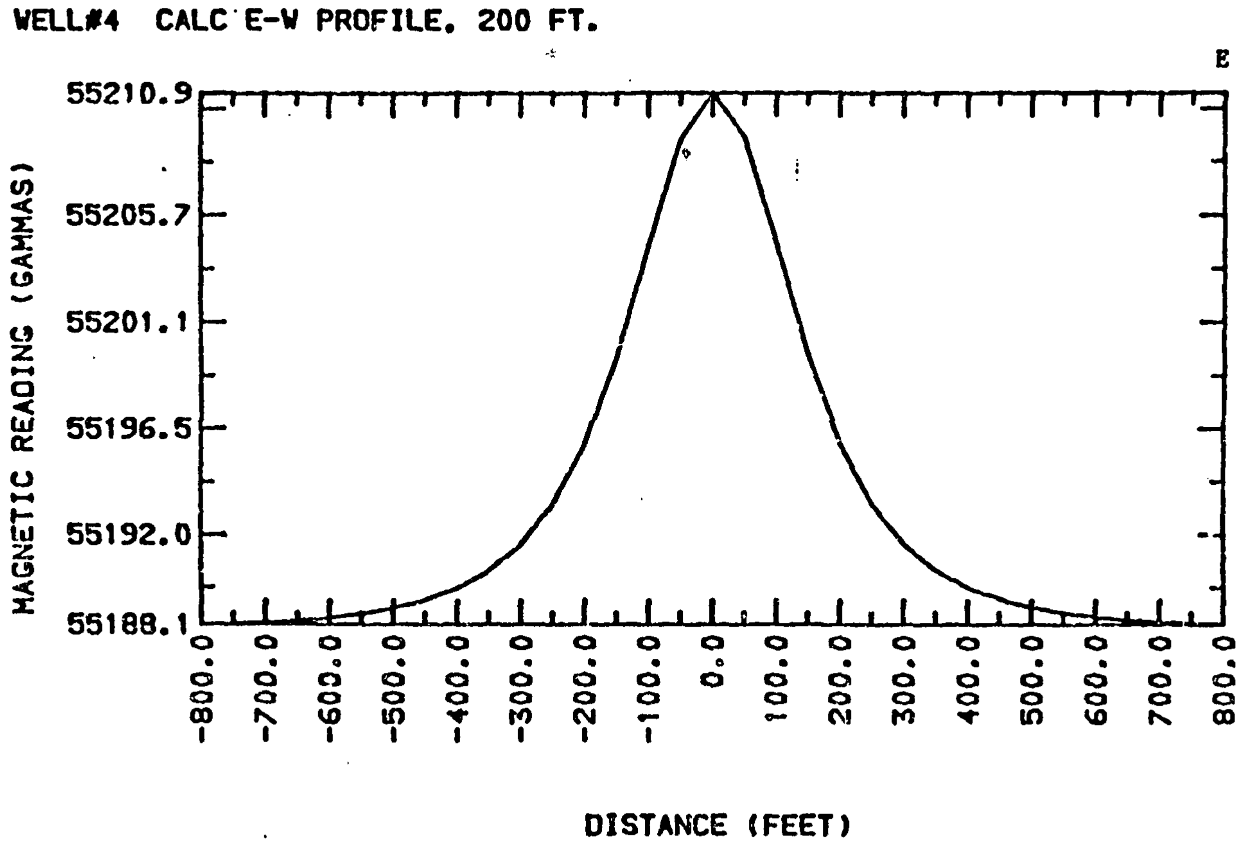


Figure 97. Calculated airborne total field profile at 200 ft for Well Number 4.

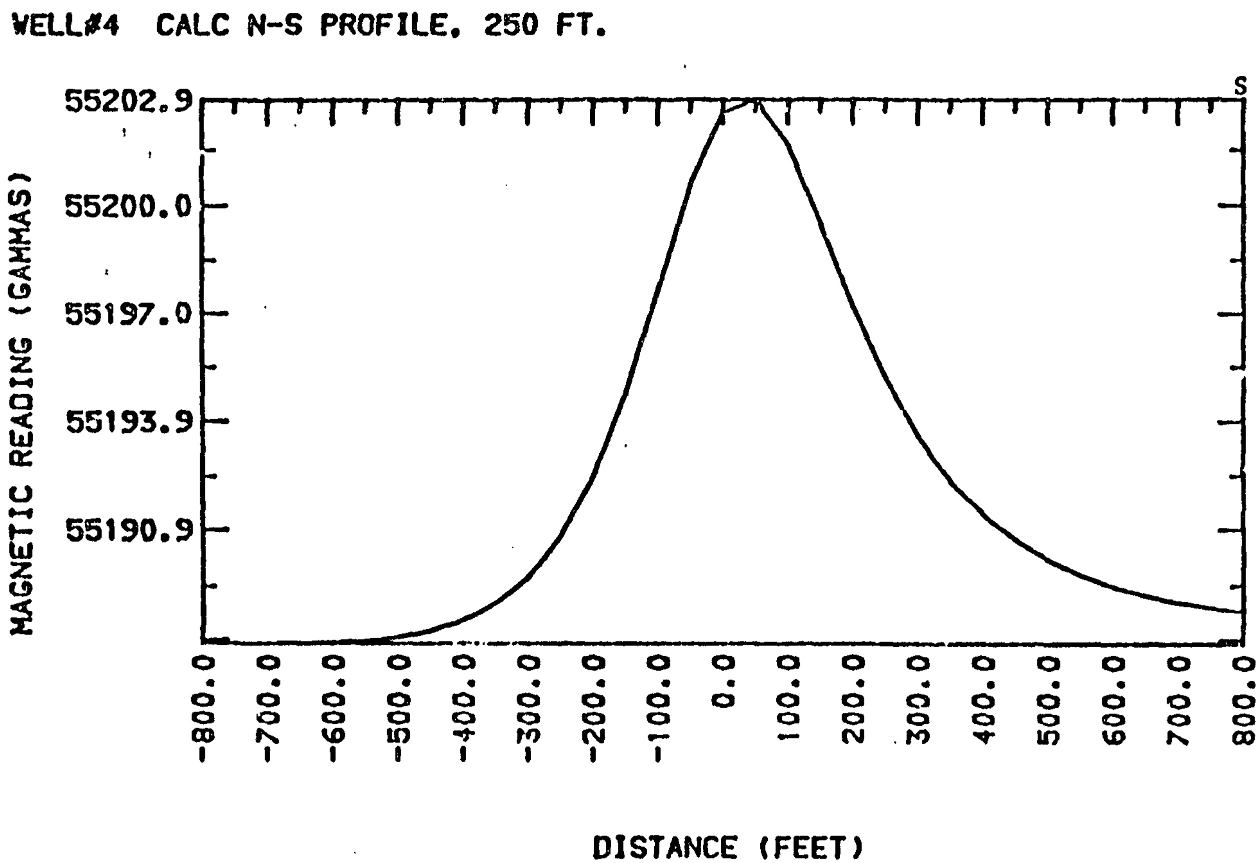


Figure 98. Calculated airborne total field profile at 250 ft for Well Number 4.

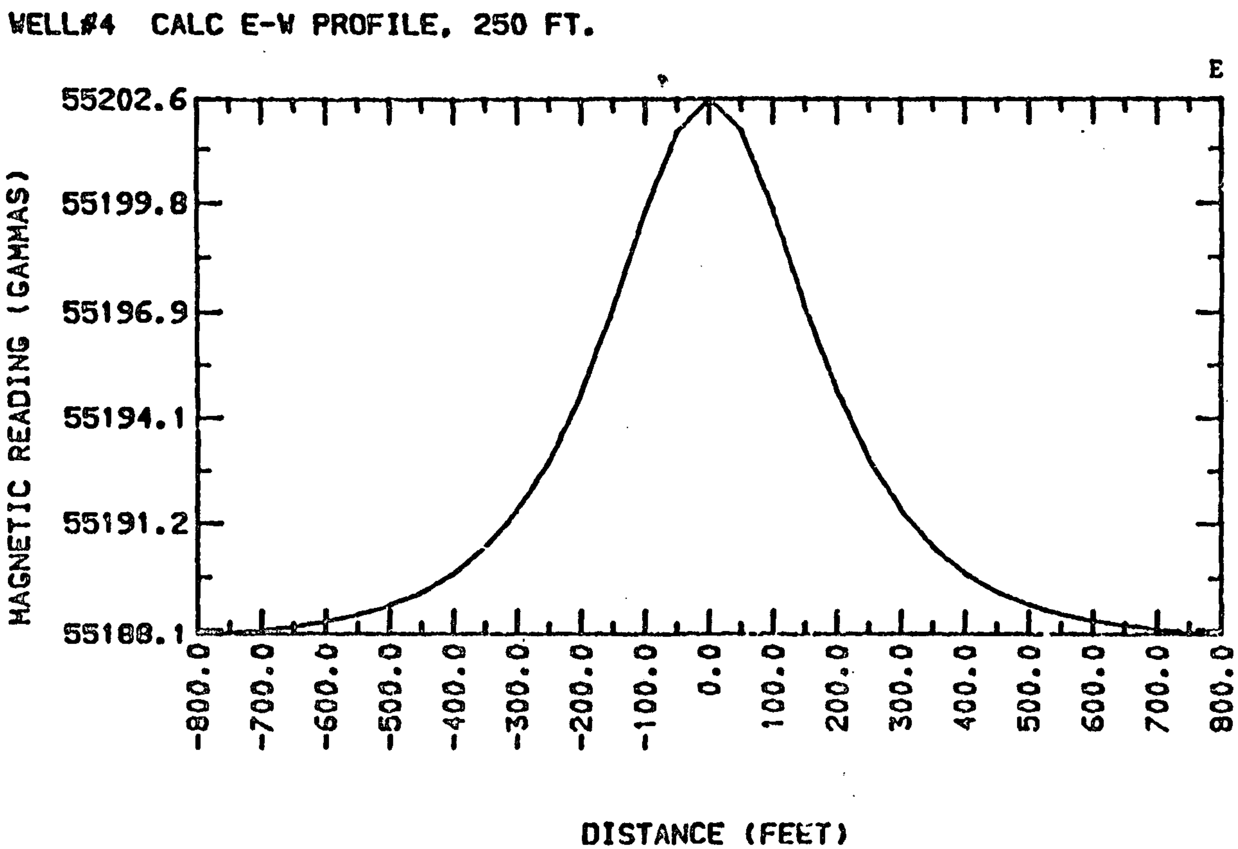


Figure 99. Calculated airborne total field profile at 250 ft for Well Number 4.

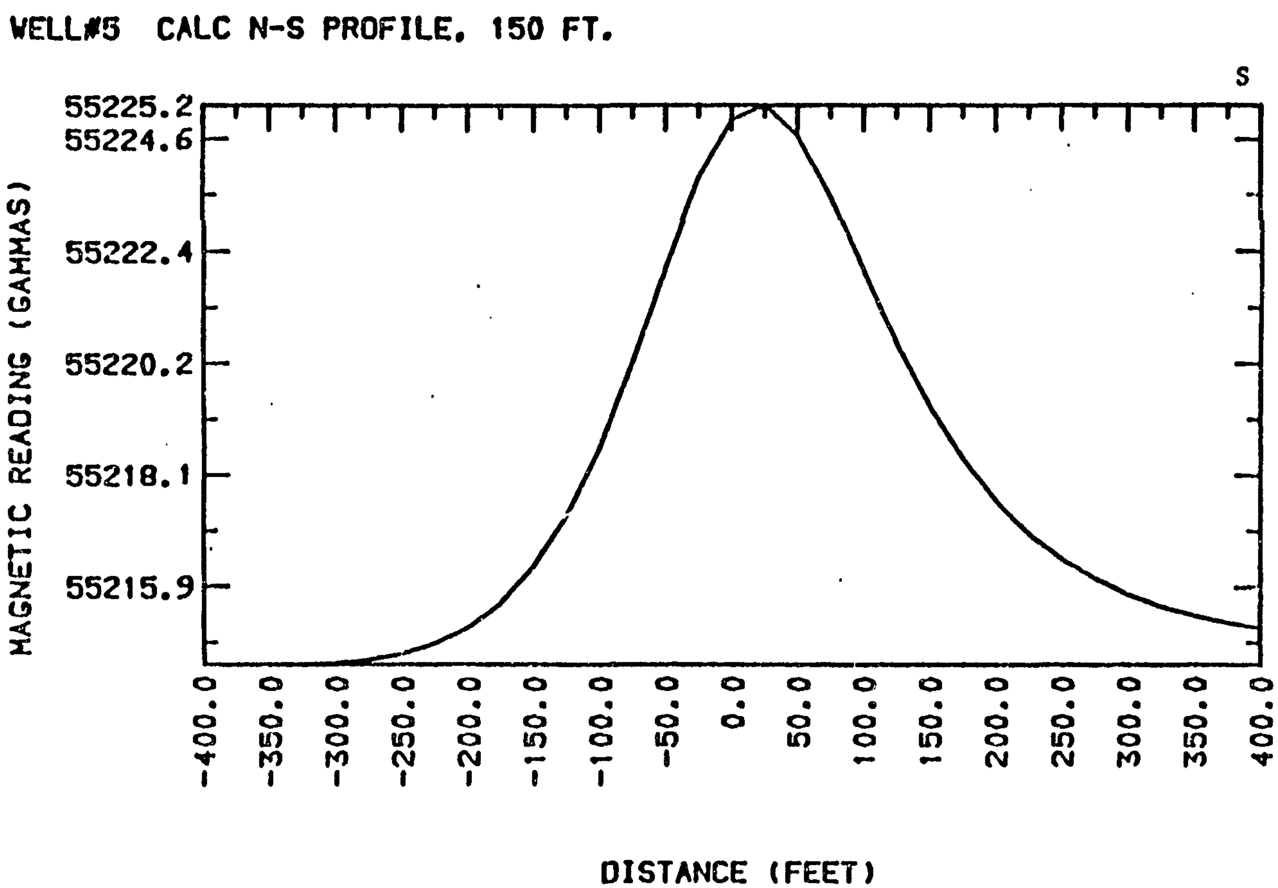


Figure 100. Calculated airborne total field profile at 100 ft for Well Number 5.

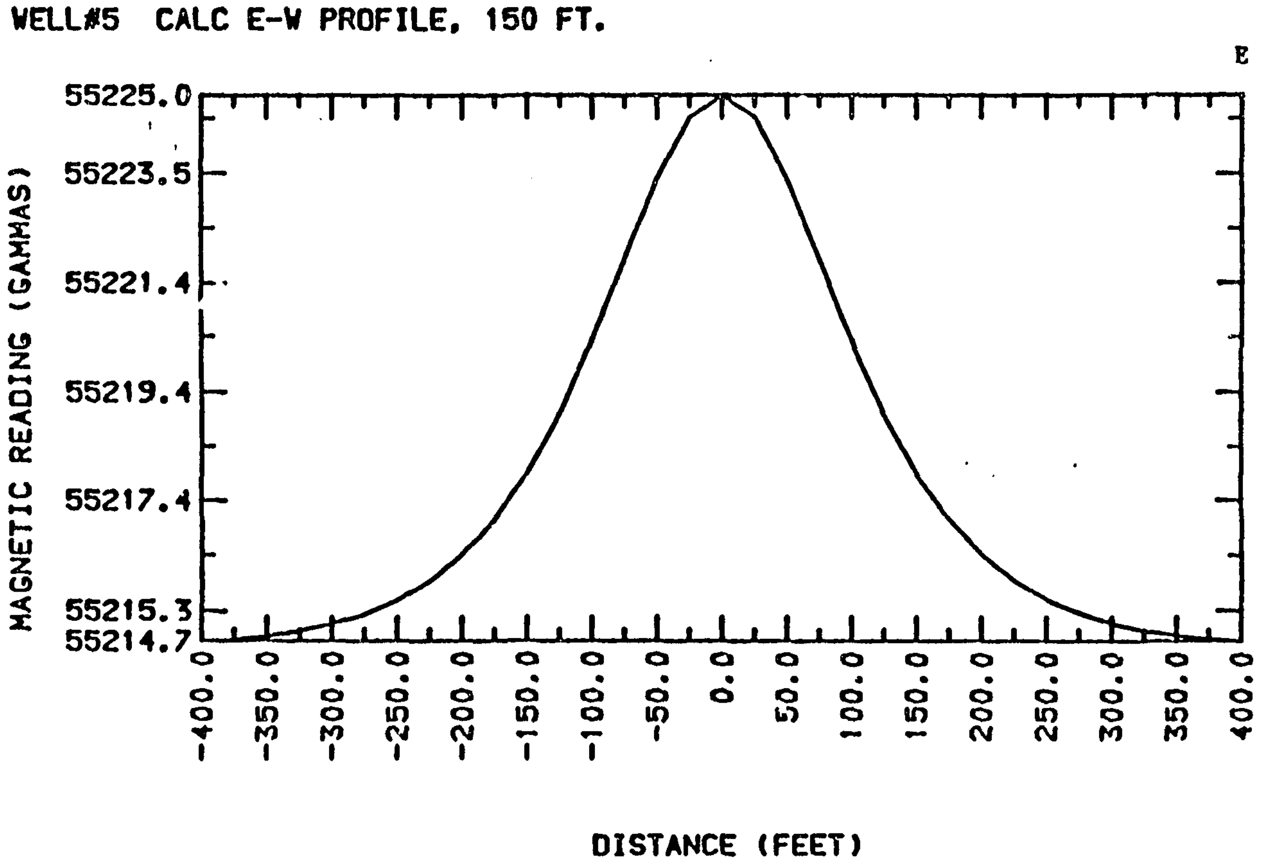


Figure 101. Calculated airborne total field profile at 150 ft for Well Number 5.

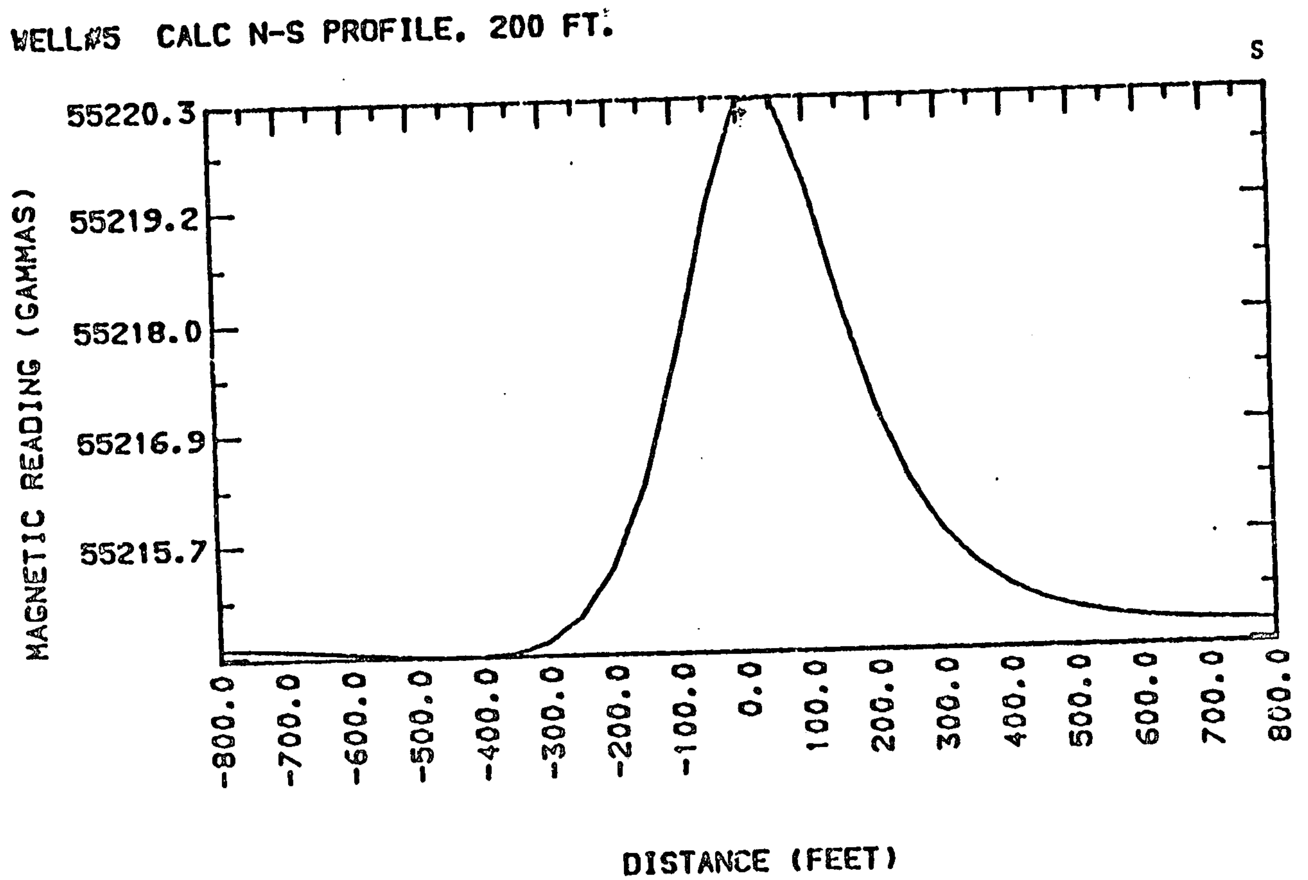


Figure 102. Calculated airborne total field profile at 200 ft for Well Number 5.

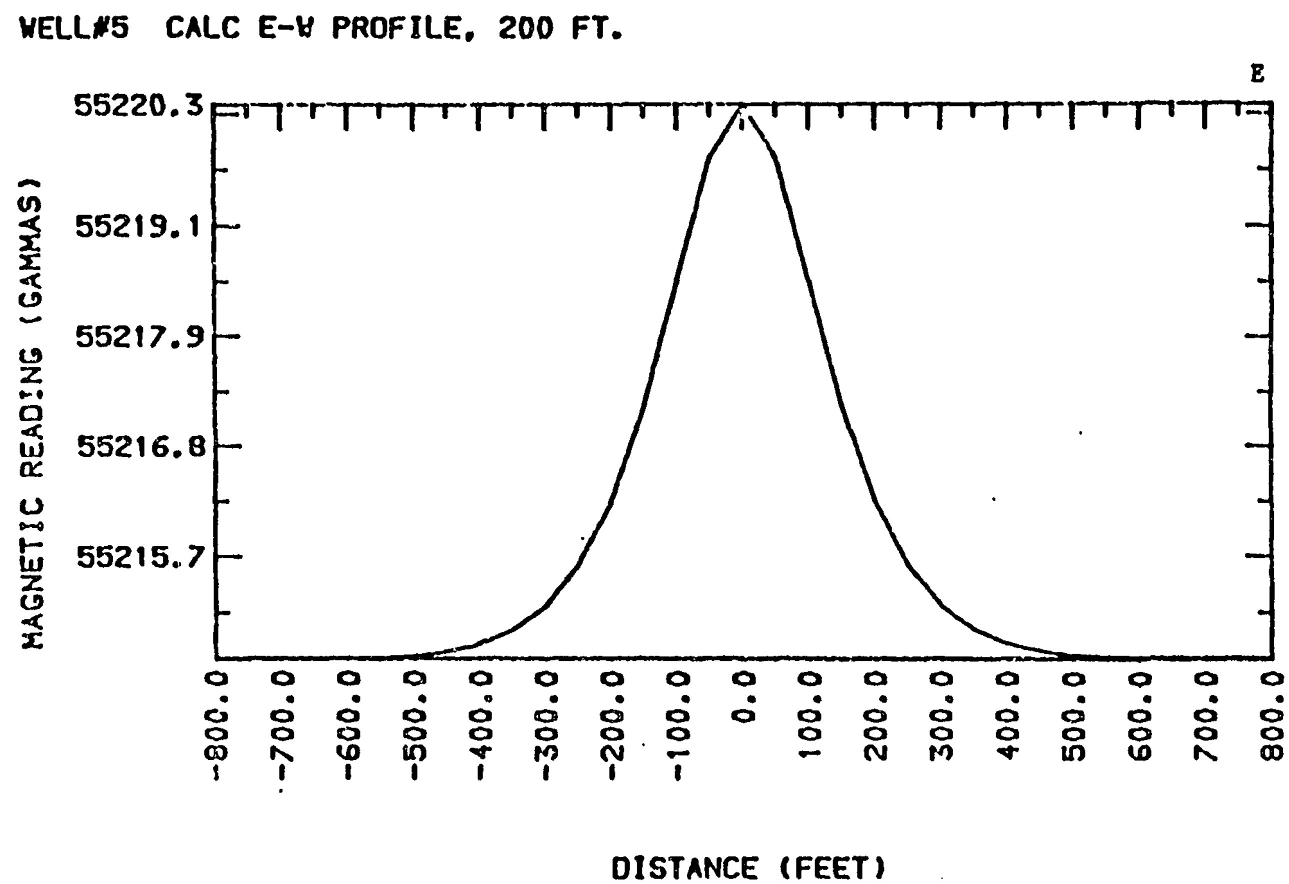


Figure 103. Calculated airborne total field profile at 200 ft for Well Number 5.

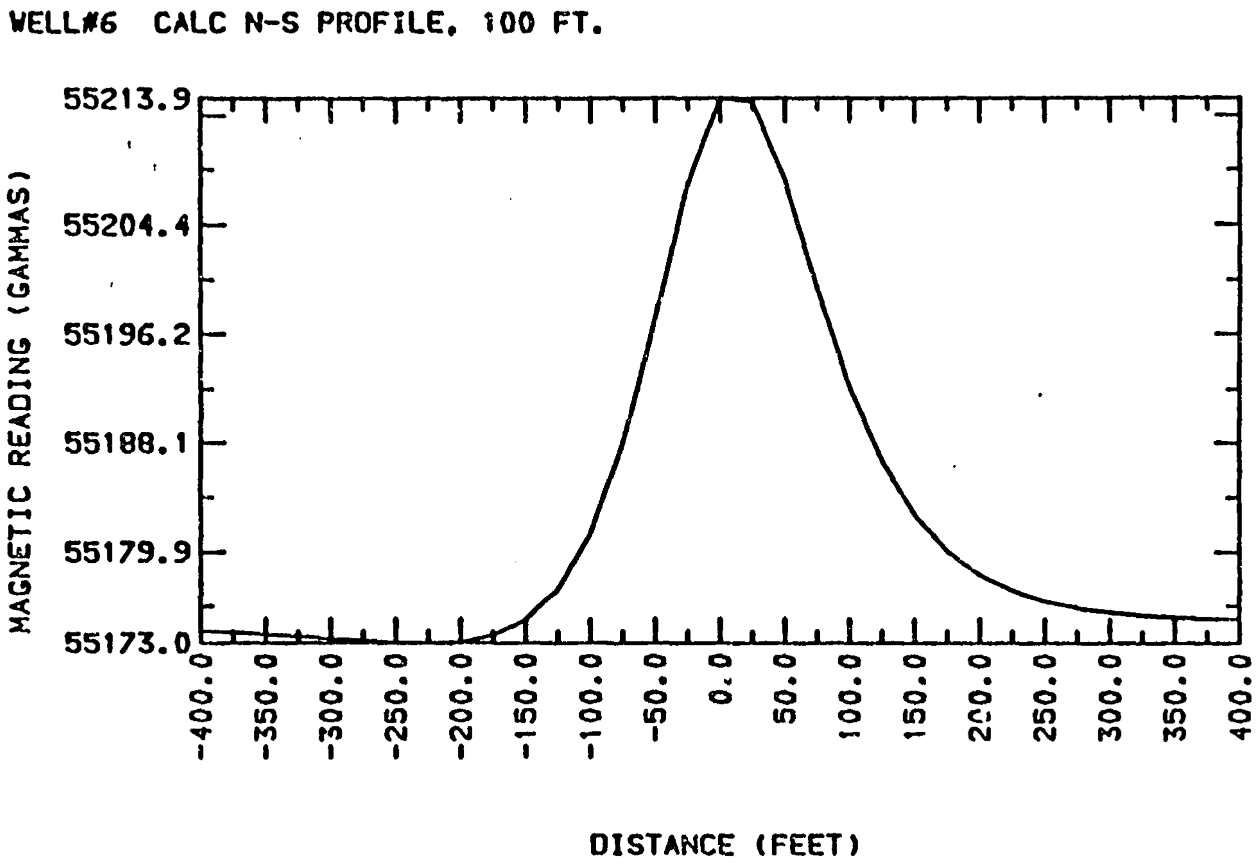


Figure 104. Calculated airborne total field profile at 100 ft for Well Number 6.

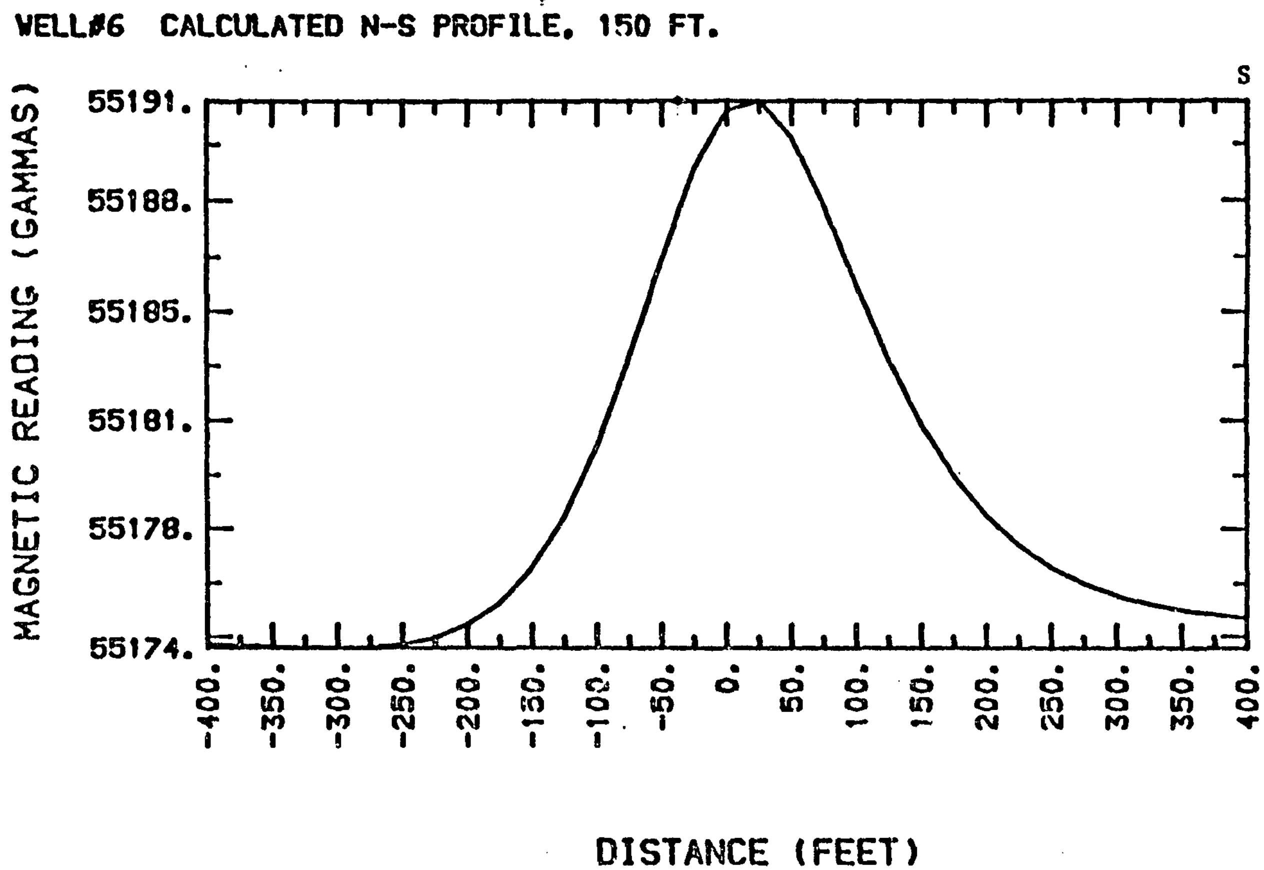


Figure 105. Calculated airborne total field profile at 150 ft for Well Number 6.

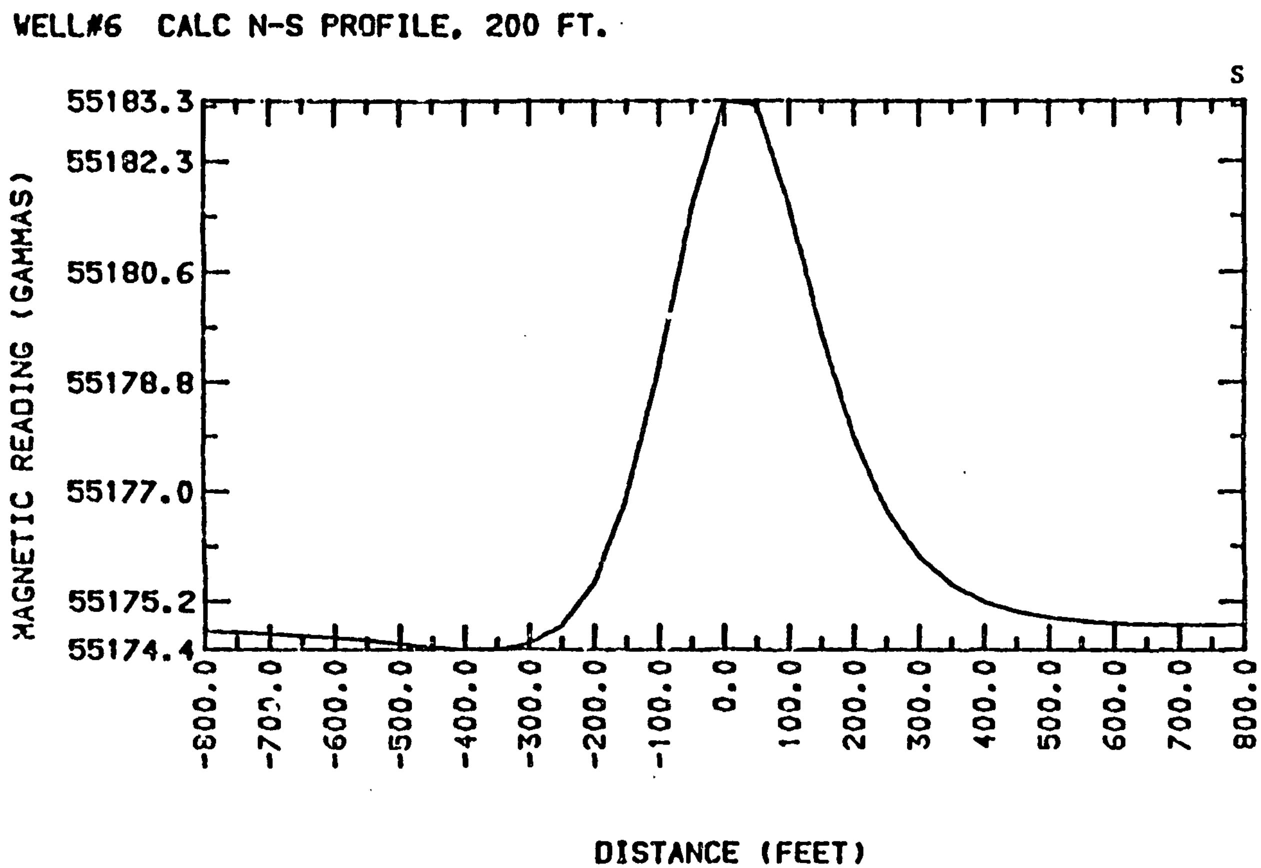


Figure 106. Calculated airborne total field profile at 200 ft for Well Number 6.

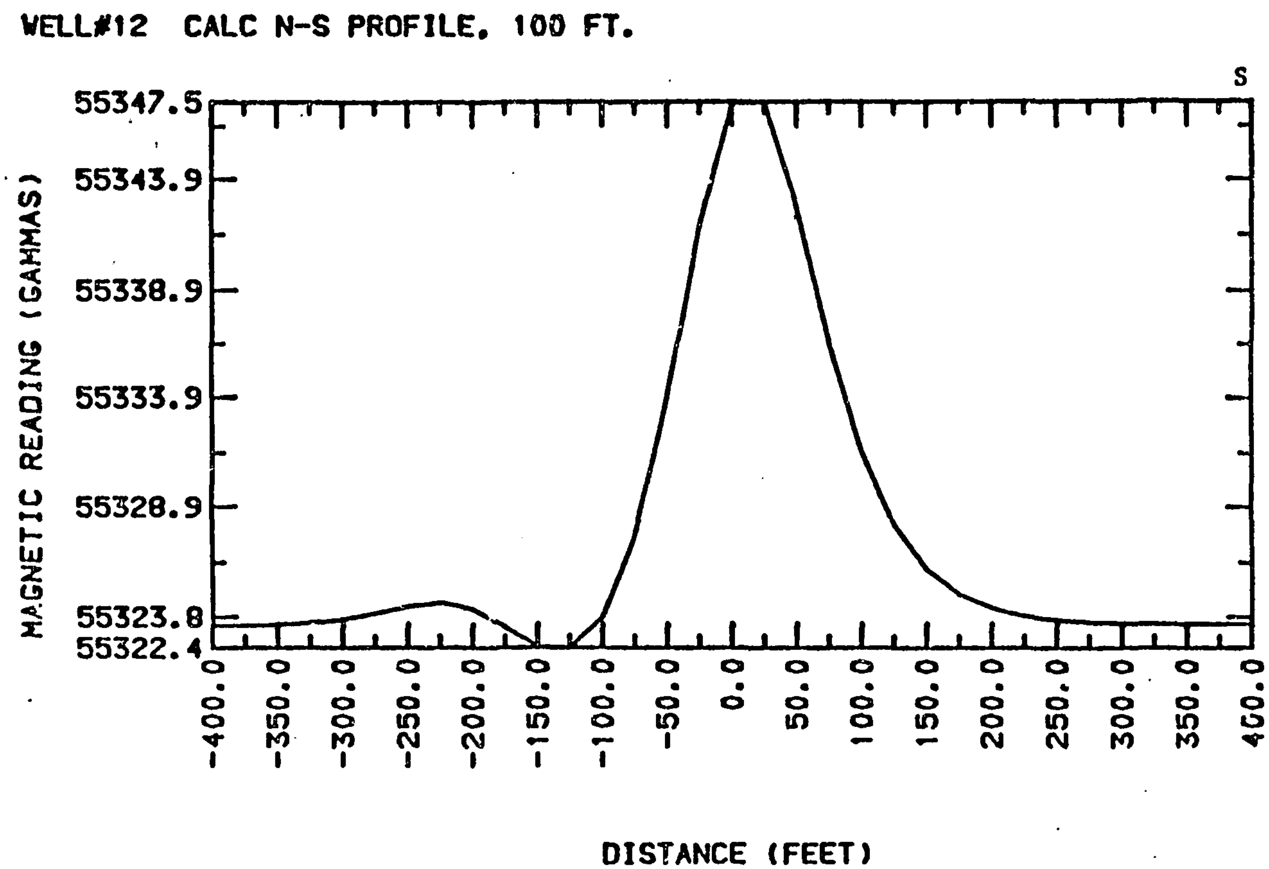


Figure 107. Calculated airborne total field profile at 100 ft for Well Number 12.

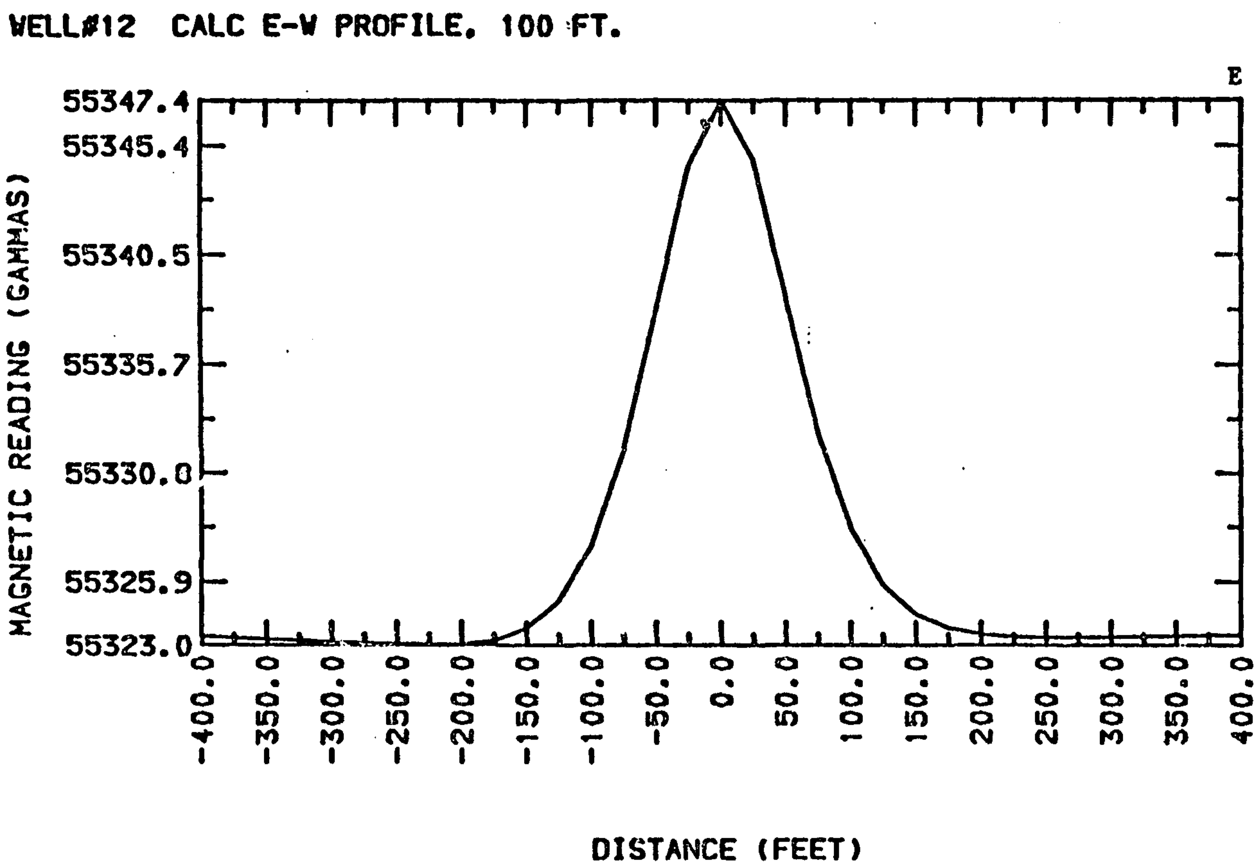


Figure 108. Calculated airborne total field profile at 100 ft for Well Number 12.

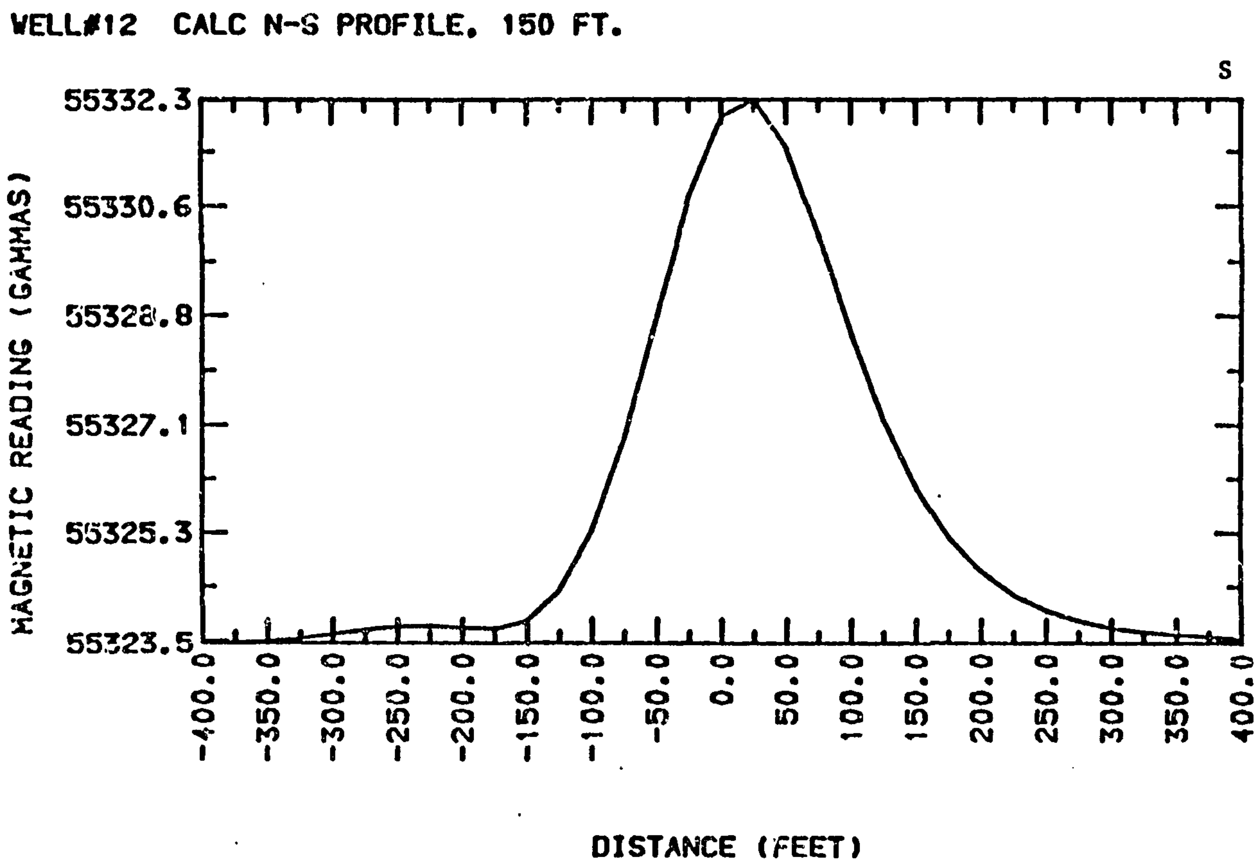


Figure 109. Calculated airborne total field profile at 150 ft for Well Number 12.

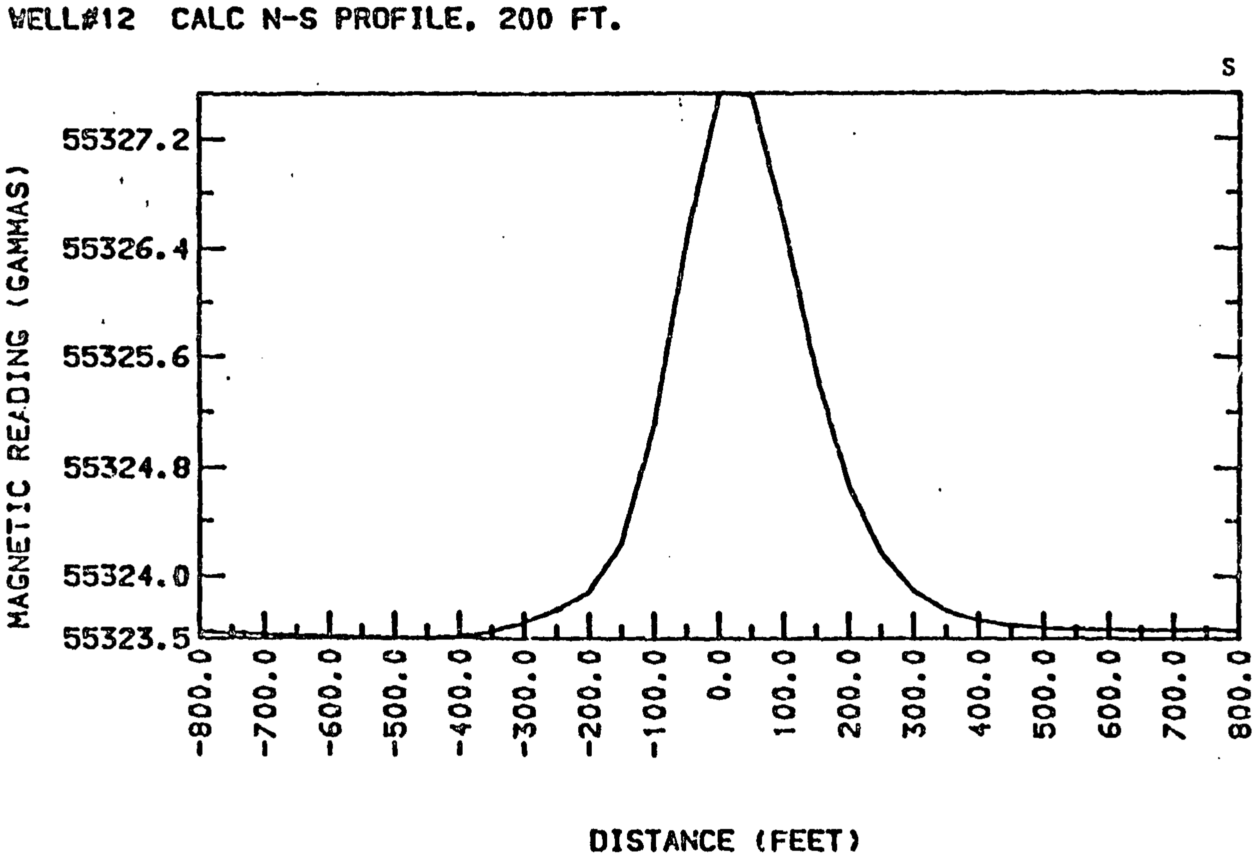


Figure 110. Calculated airborne total field profile at 200 ft for Well Number 12.

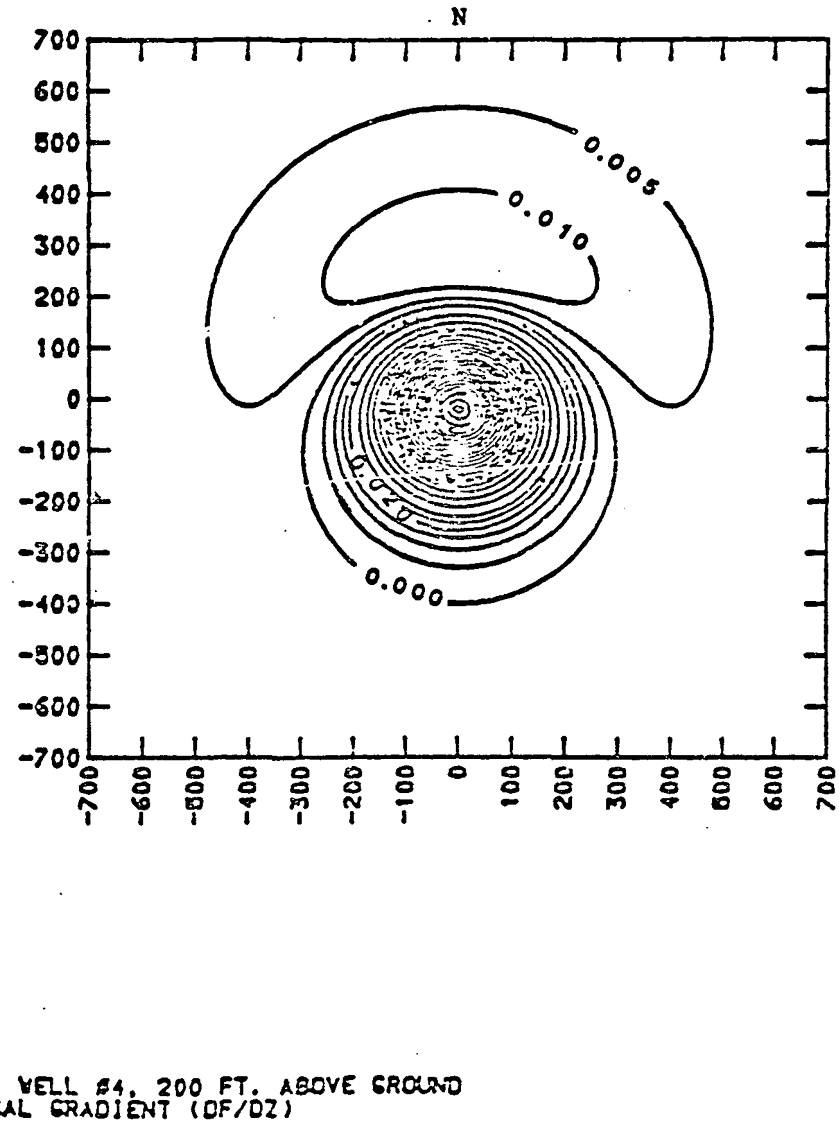
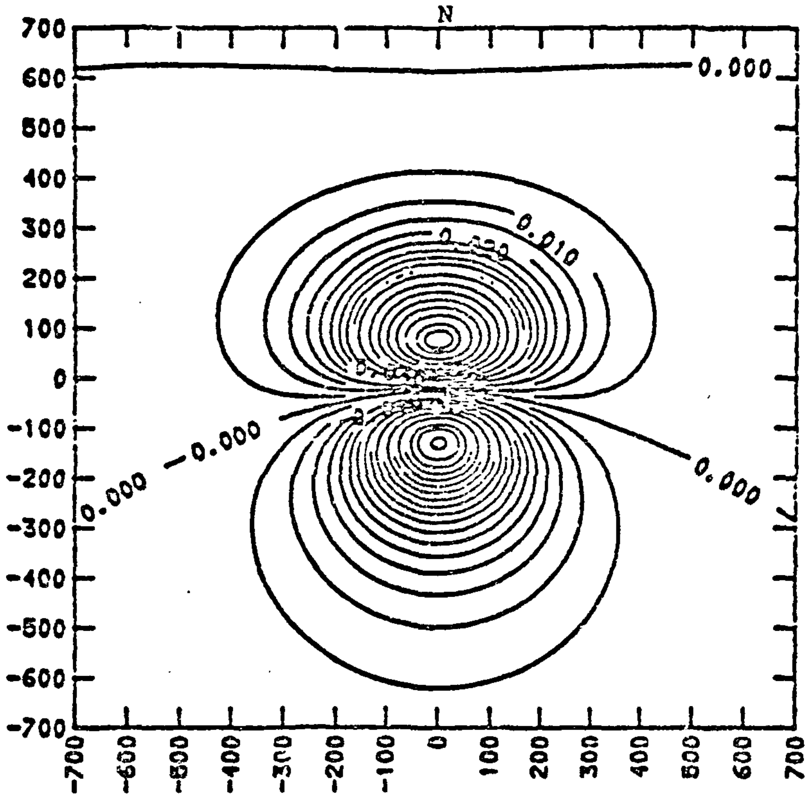
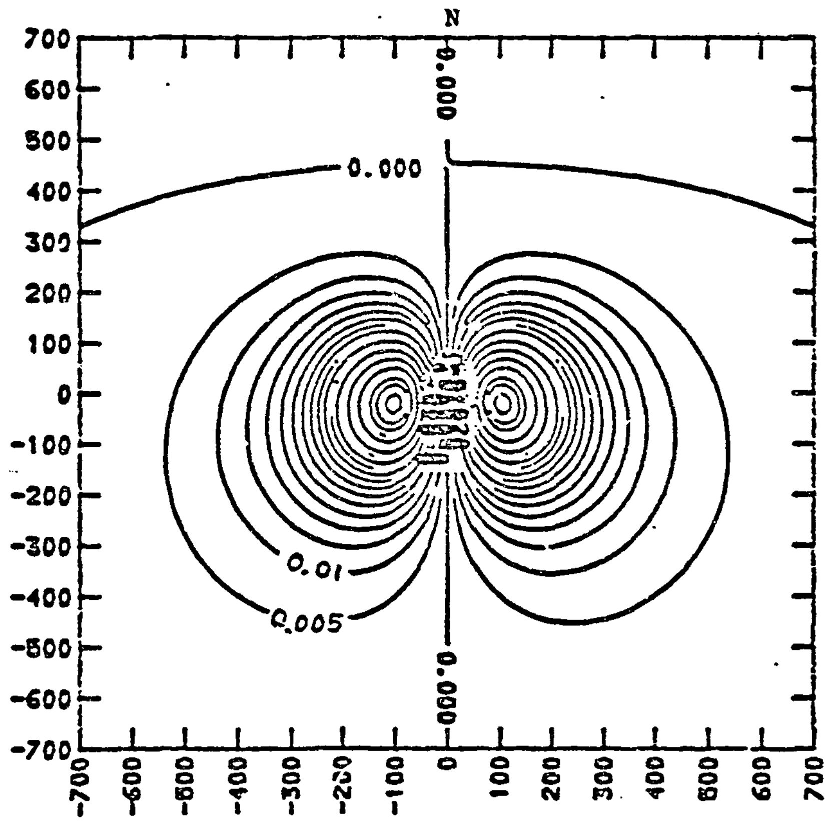


Figure 111. Calculated airborne vertical gradient for Well Number 4.



MAP OF WELL #4, 200 FT. ABOVE GROUND
HORIZONTAL GRADIENT (DF/DX)

Figure 112. Calculated airborne north-south horizontal gradient for Well Number 4.



MAP OF WELL #4, 200 FT. ABOVE GROUND
HORIZONTAL GRADIENT (DF/DY)

Figure 113. Calculated airborne east-west horizontal gradient at 200 ft for Well Number 4.

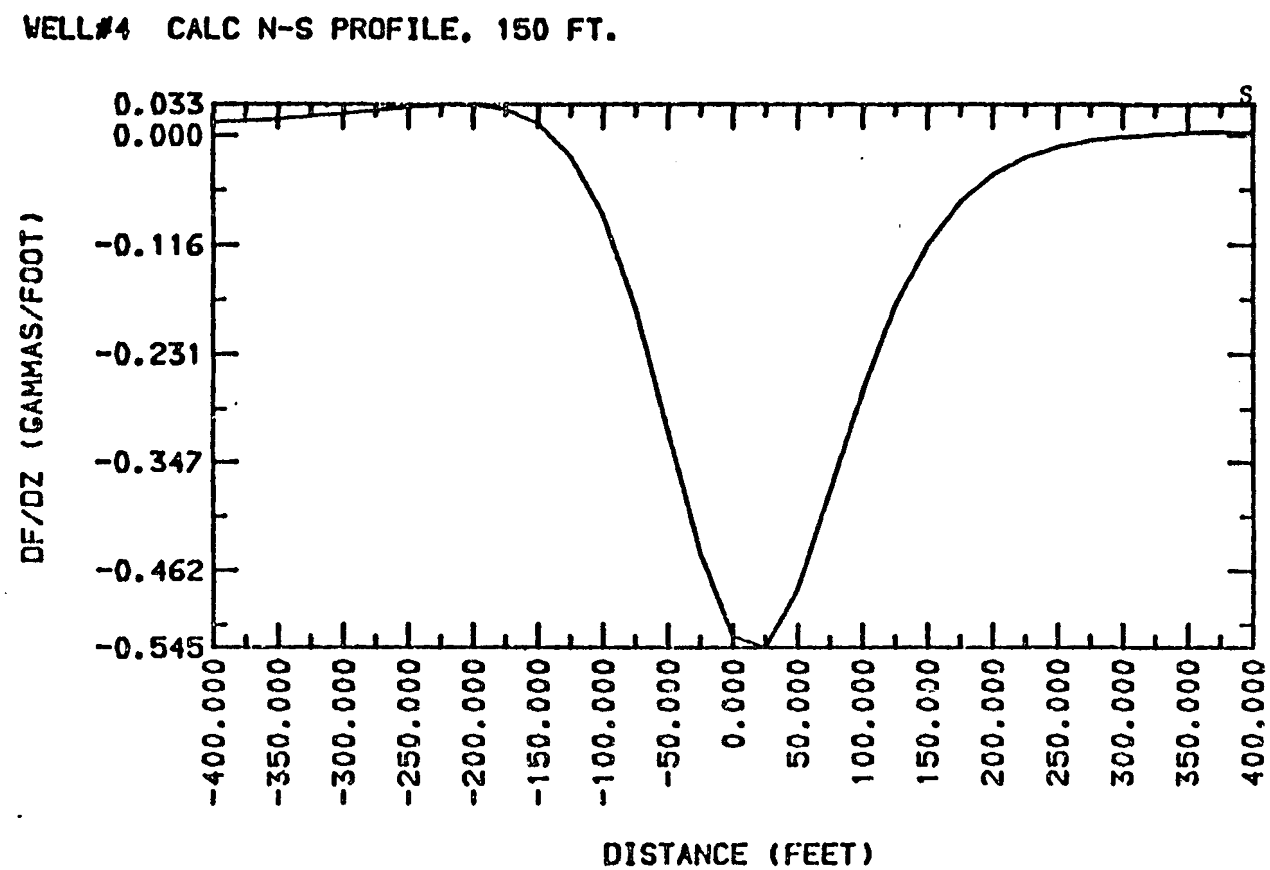


Figure 114. Calculated airborne vertical gradient at 150 ft for Well Number 4.

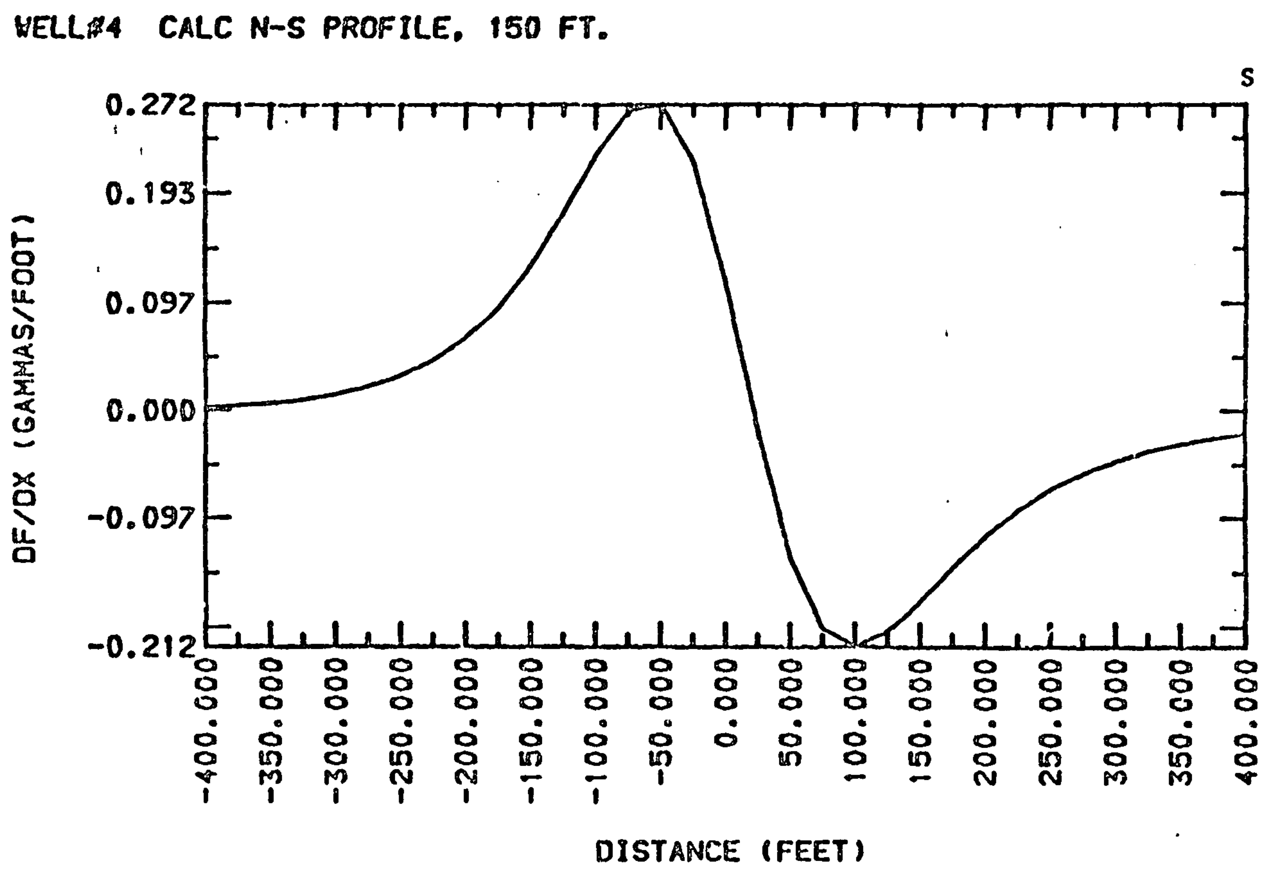


Figure 115. Calculated airborne north-south horizontal gradient at 150 ft for Well Number 4.

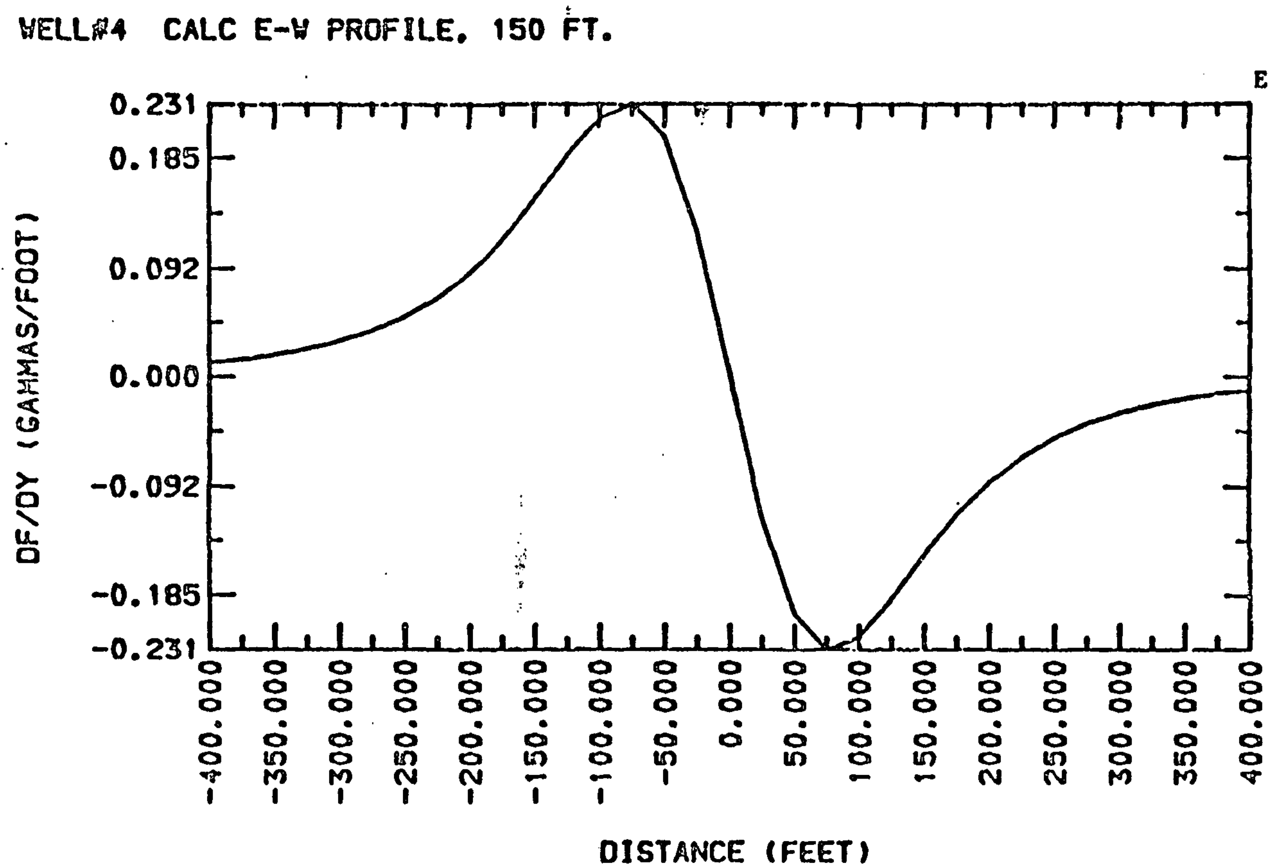


Figure 116. Calculated airborne east-west horizontal gradient at 150 ft for Well Number 4.

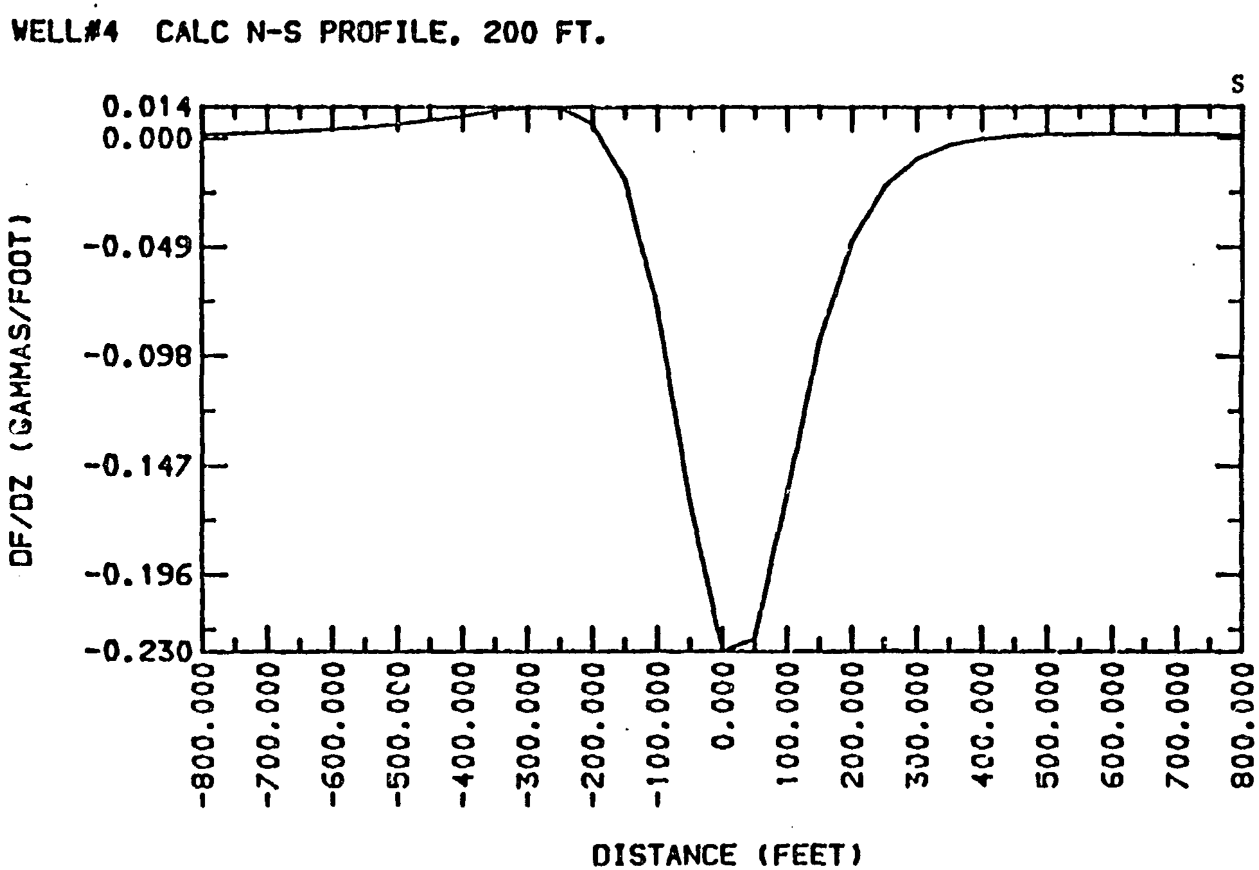


Figure 117. Calculated airborne vertical gradient at 200 ft for Well Number 4.

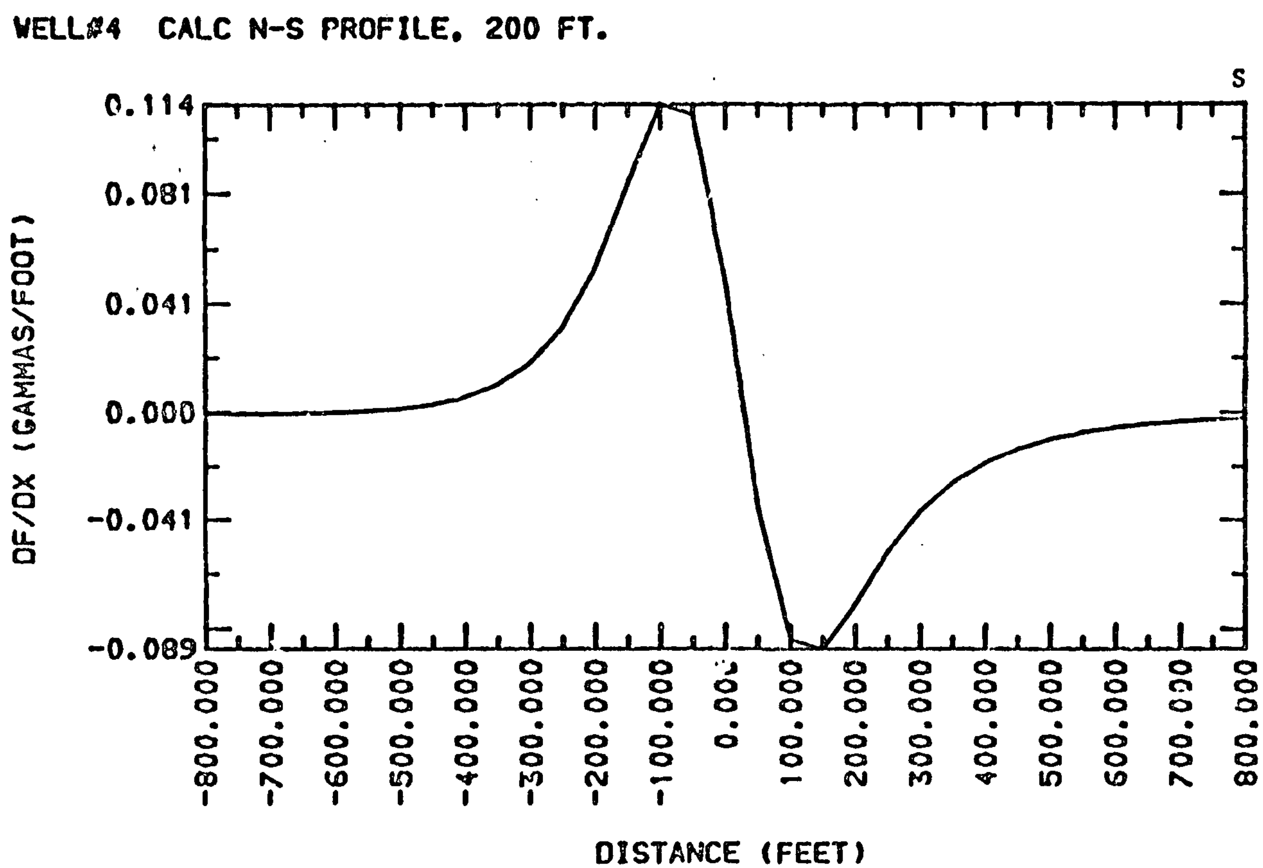


Figure 118. Calculated airborne north-south horizontal gradient at 200 ft for Well Number 4.

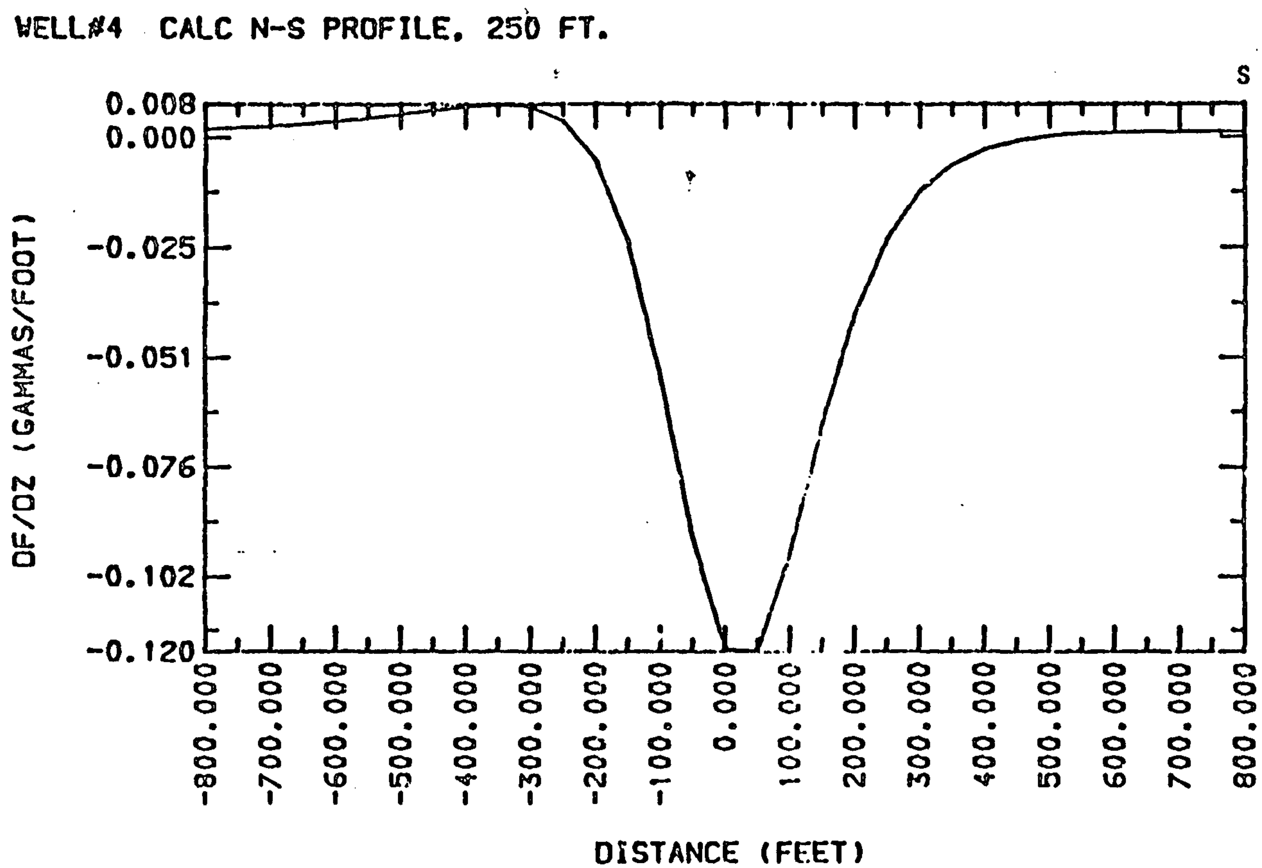


Figure 119. Calculated airborne vertical gradient at 250 ft for Well Number 4.

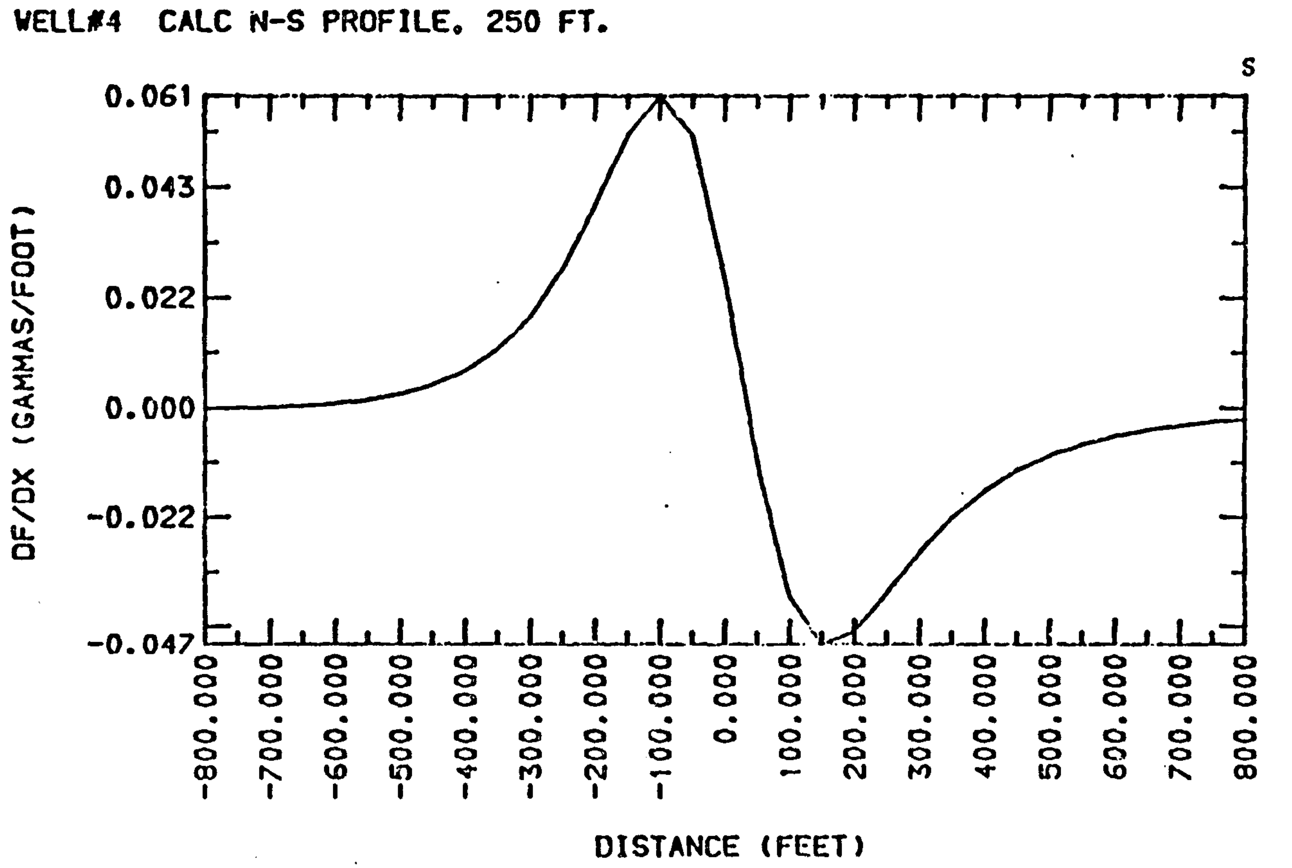


Figure 120. Calculated airborne north-south horizontal gradient at 250 ft for Well Number 4.

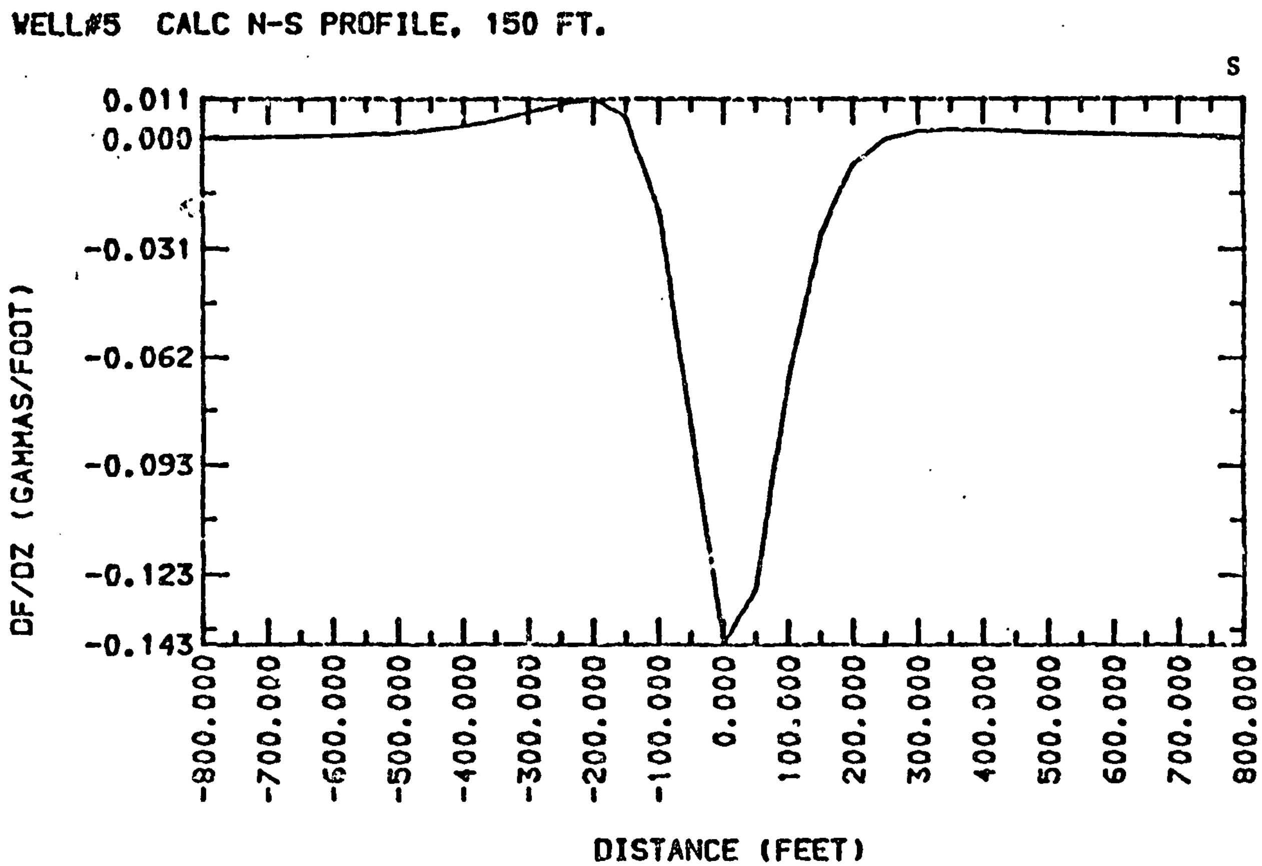


Figure 121. Calculated airborne vertical gradient at 150 ft for Well Number 5.

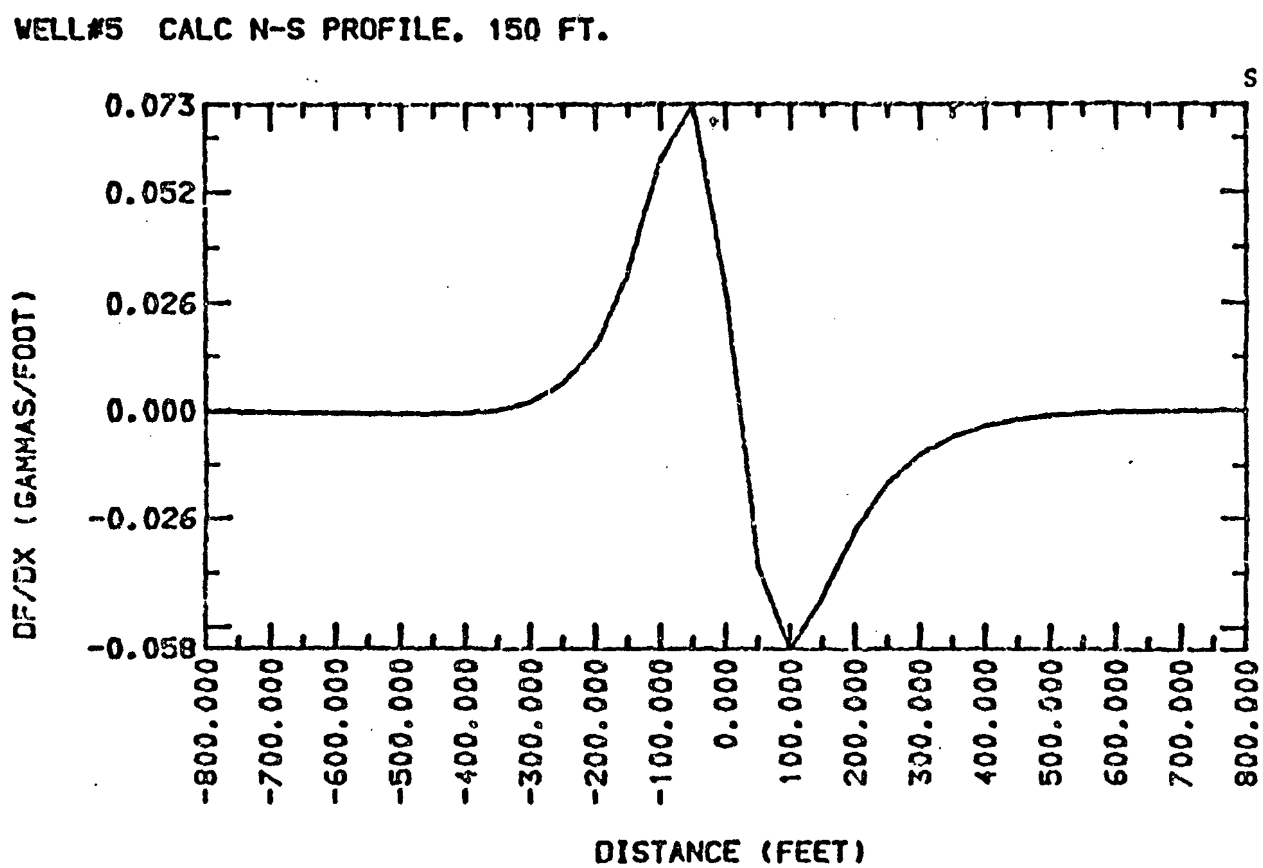


Figure 122. Calculated airborne north-south horizontal gradient at 150 ft for Well Number 5.

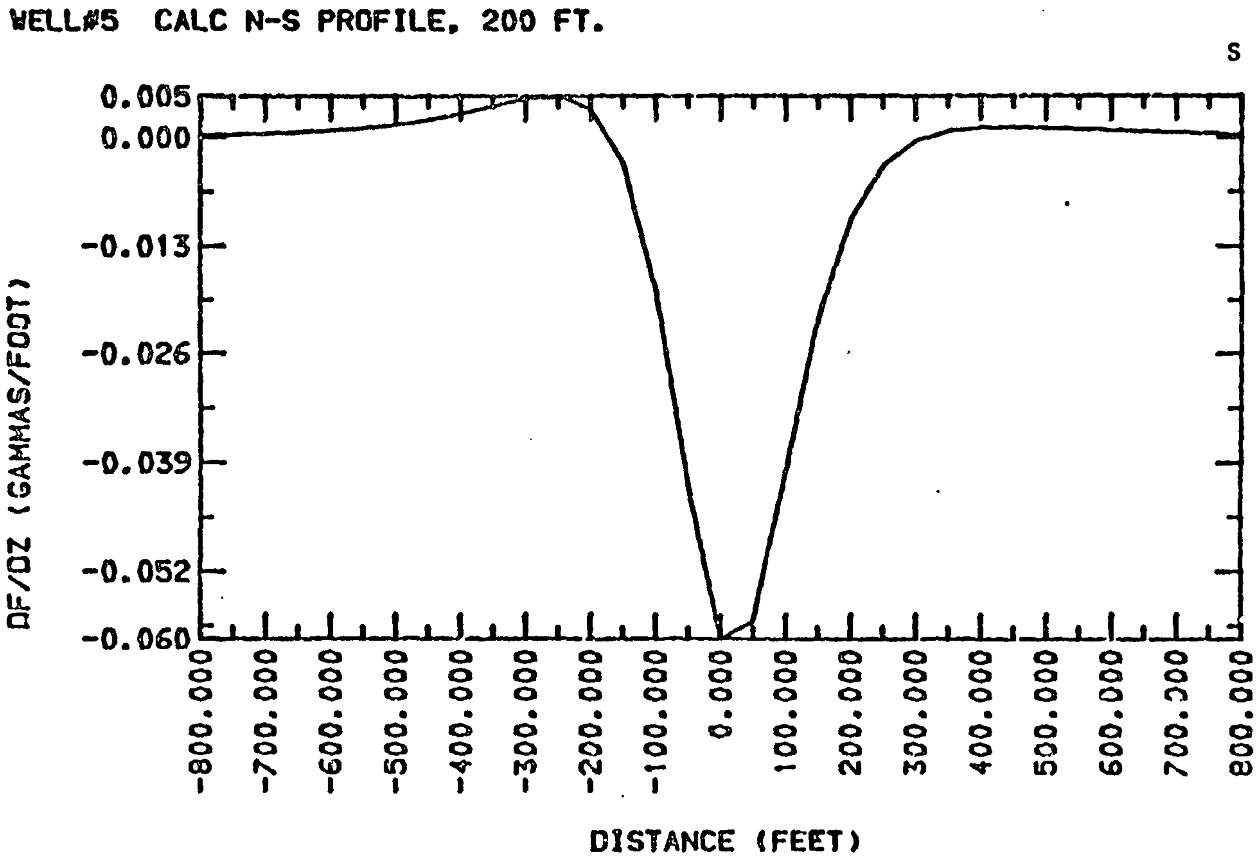


Figure 123. Calculated airborne vertical gradient at 200 ft for Well Number 5.

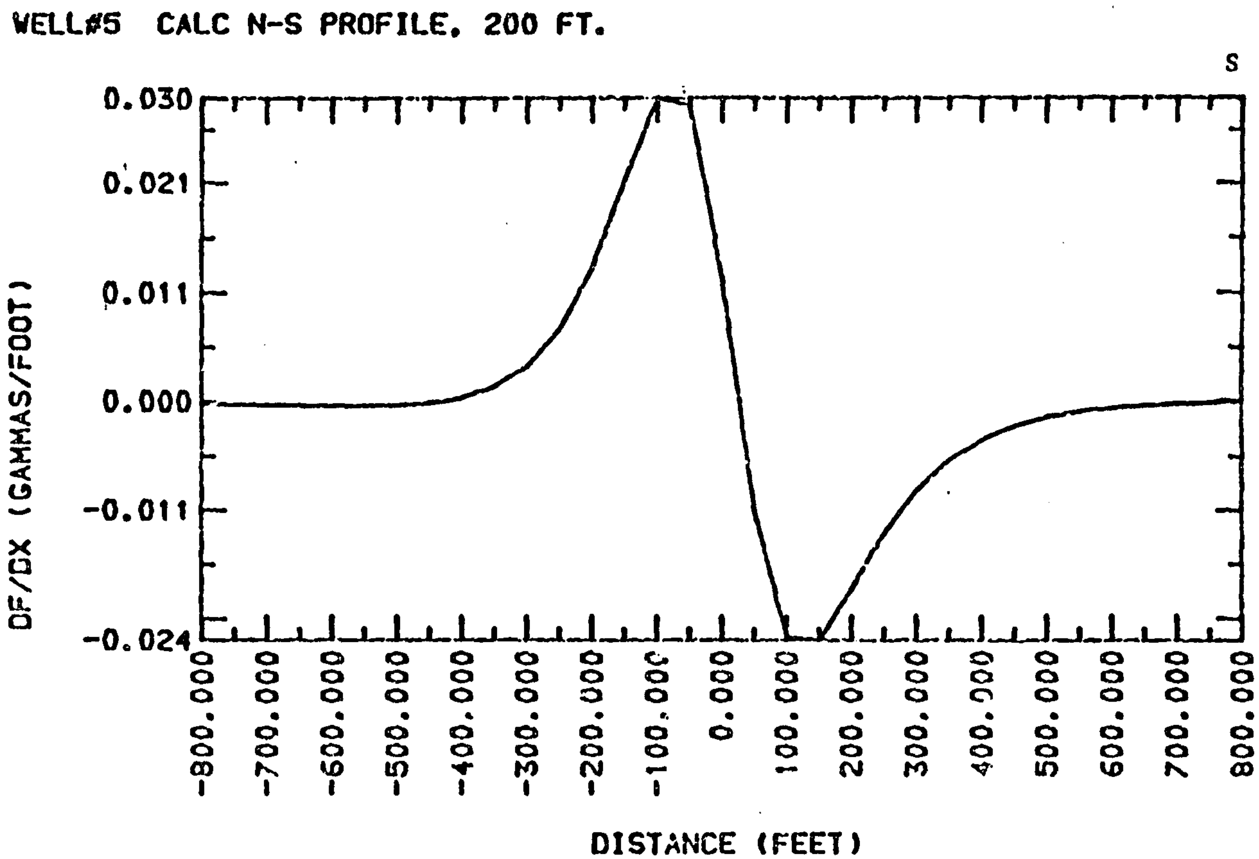


Figure 124. Calculated airborne north-south horizontal gradient at 200 ft for Well Number 5.

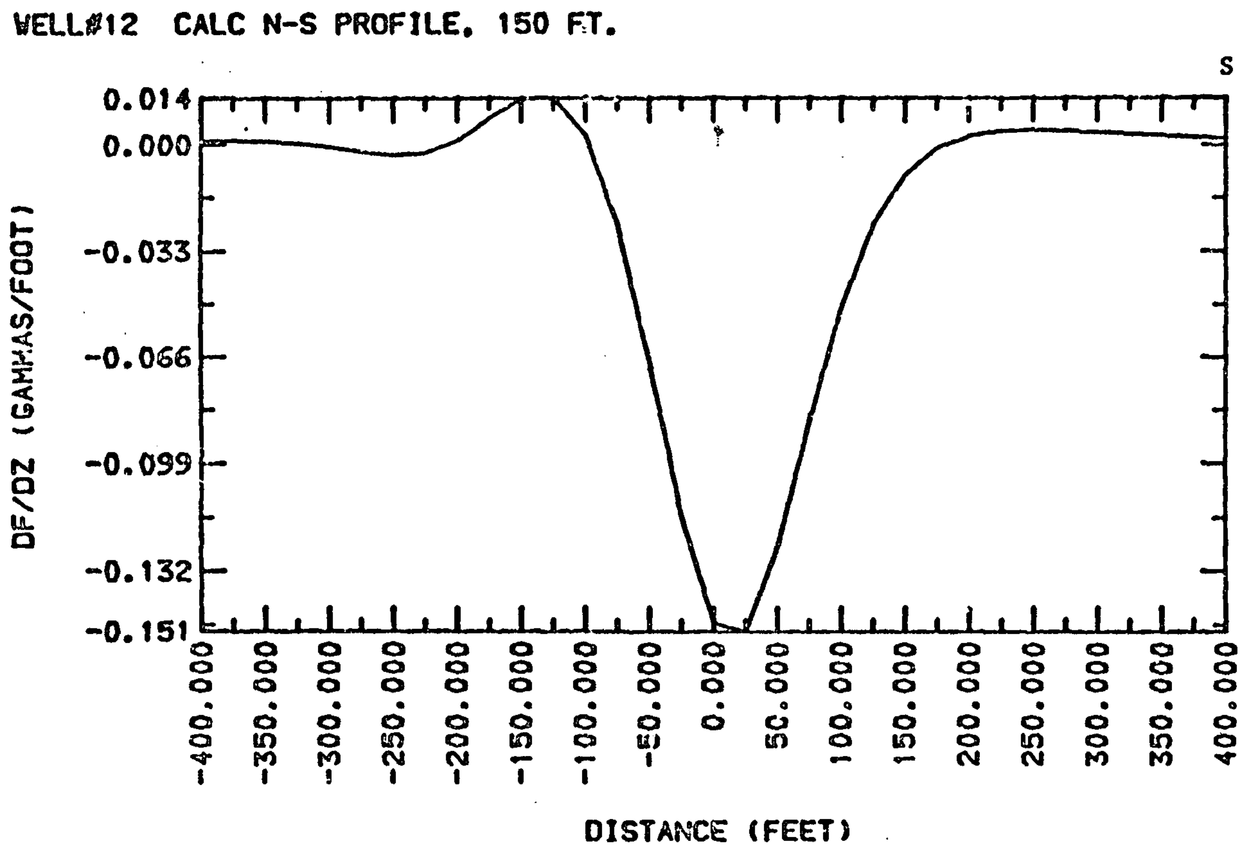


Figure 125. Calculated airborne north-south profile of vertical gradient at 150 ft for Well Number 12.

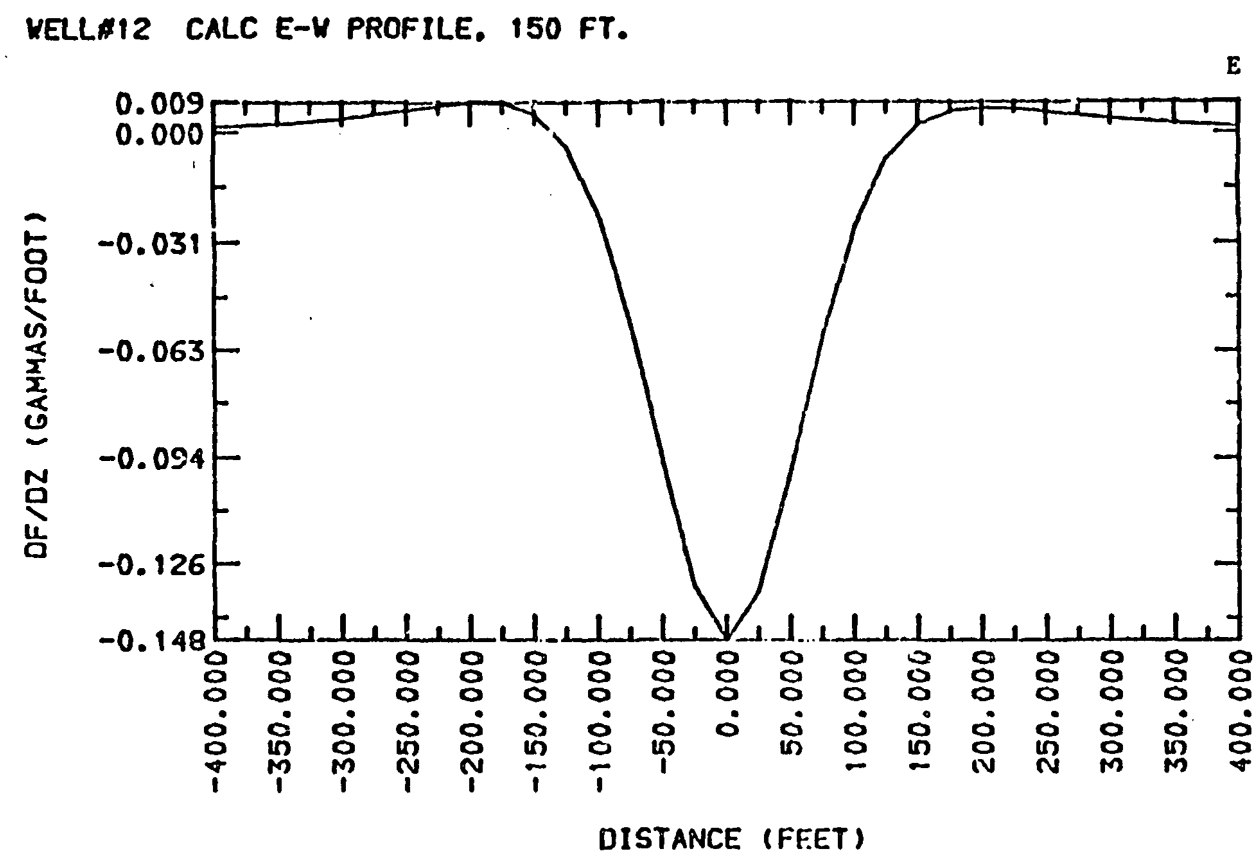


Figure 126. Calculated airborne east-west profile of vertical gradient at 150 ft for Well Number 12.

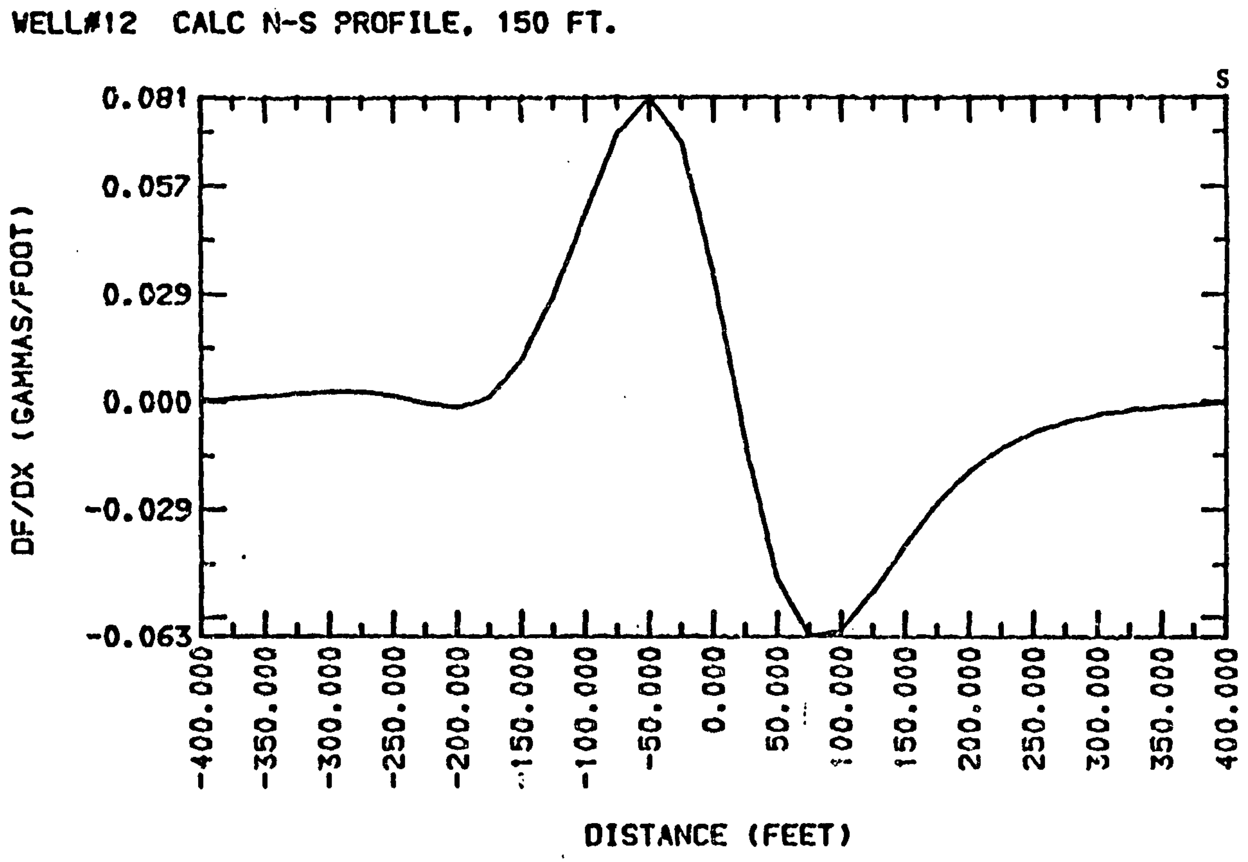


Figure 127. Calculated airborne north-south profile of horizontal gradient at 150 ft for Well Number 12.

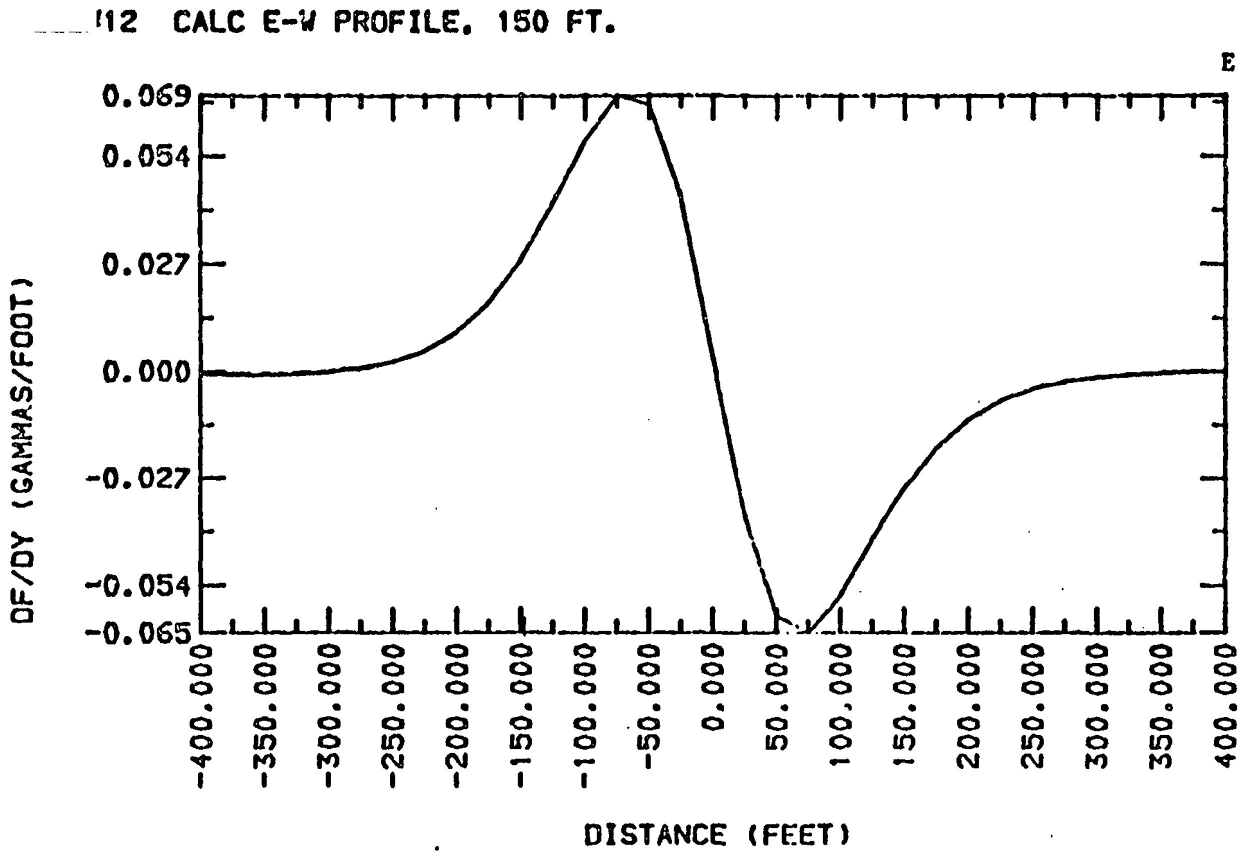


Figure 128. Calculated airborne east-west profile of horizontal gradient at 150 ft for Well Number 12.

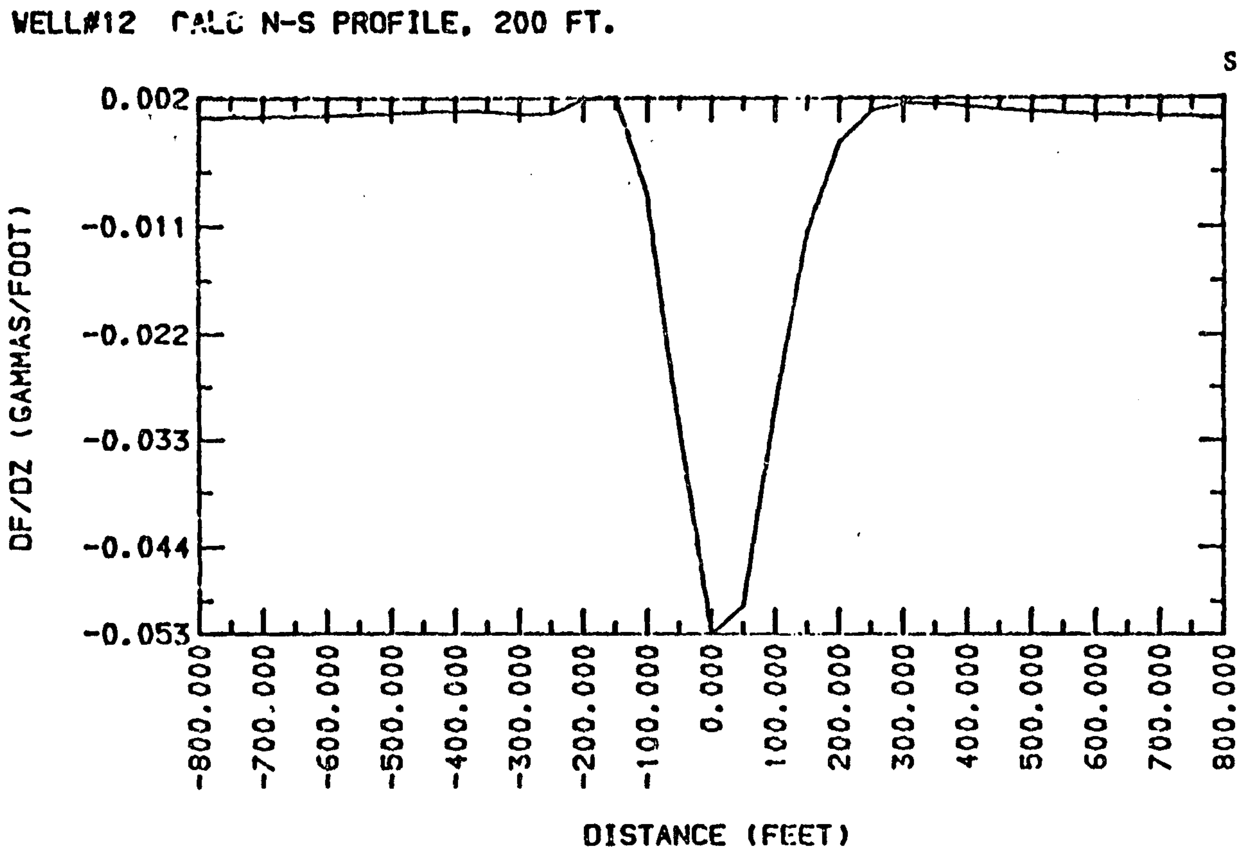


Figure 129. Calculated airborne north-south profile of vertical gradient at 200 ft for Well Number 12.

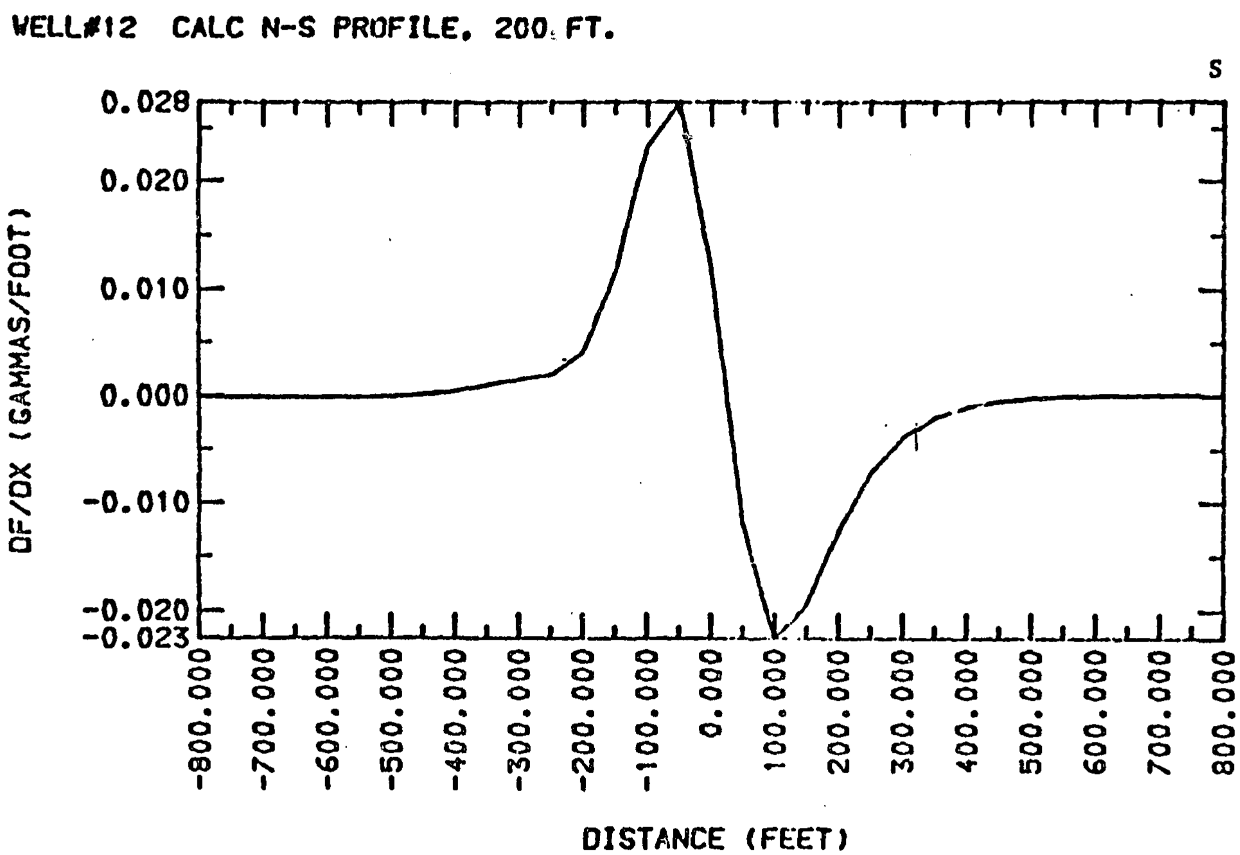


Figure 130. Calculated airborne north-south profile of horizontal gradient at 200 ft for Well Number 12.

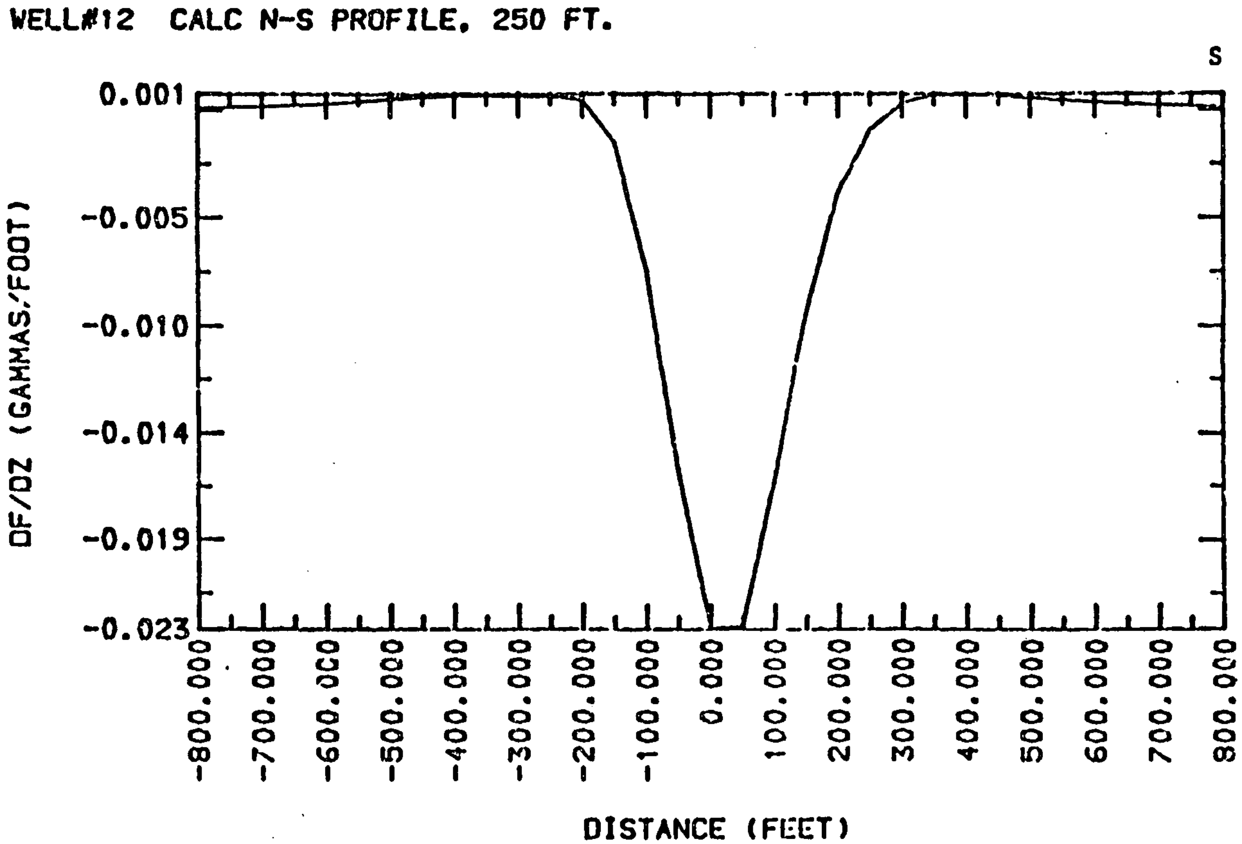


Figure 131. Calculated airborne north-south profile of vertical gradient at 250 ft for Well Number 12.

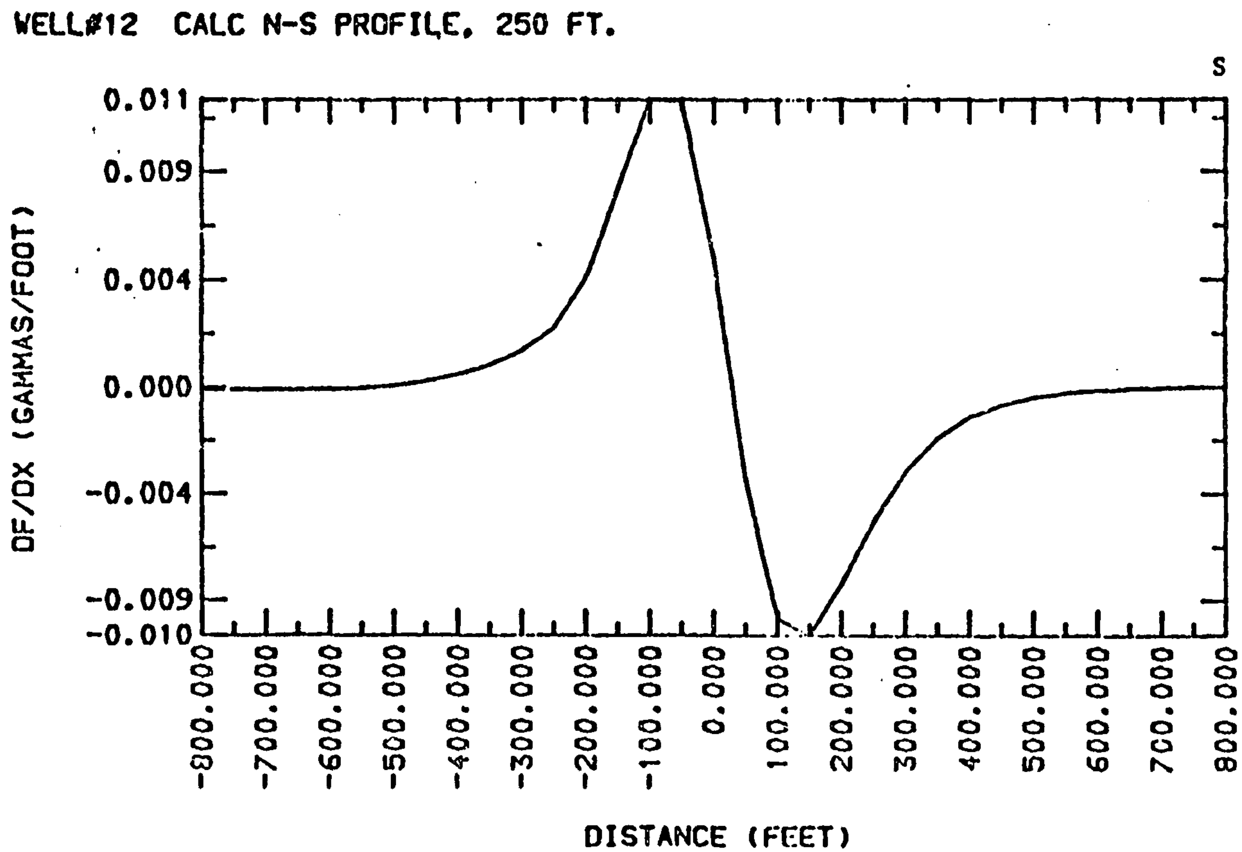


Figure 132. Calculated airborne north-south profile of horizontal gradient at 250 ft for Well Number 12.

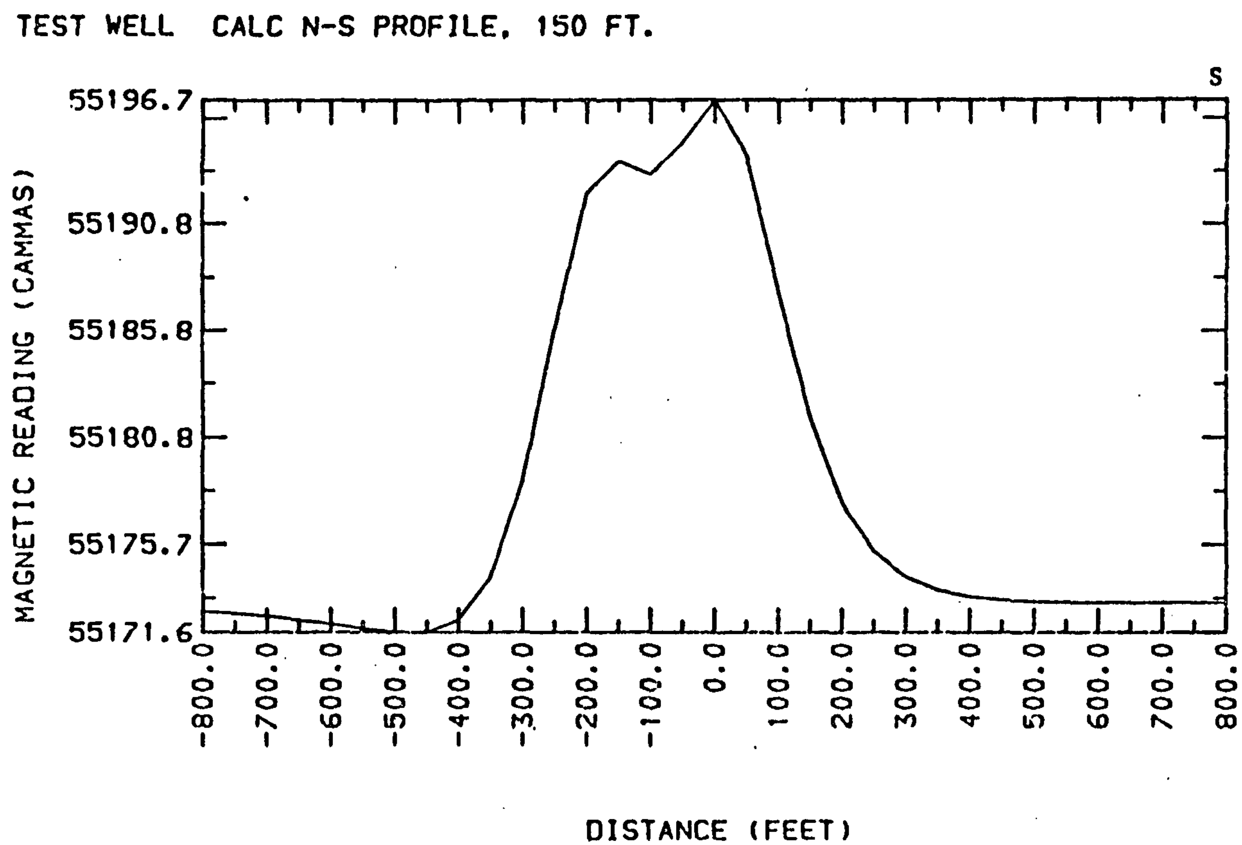


Figure 133. Calculated airborne total field at 150 ft for two identical casings separated 200 ft.

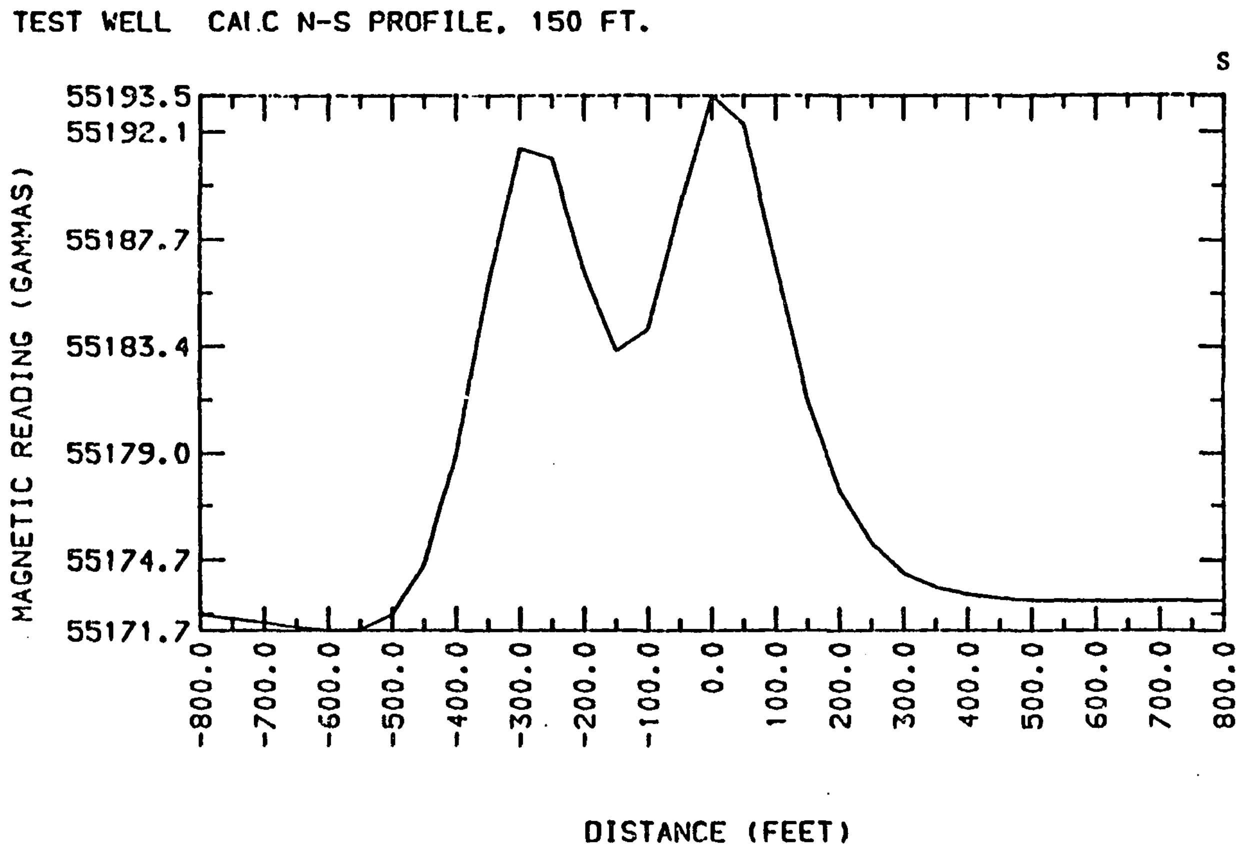


Figure 134. Calculated airborne total field at 150 ft for two identical casings separated 300 ft.

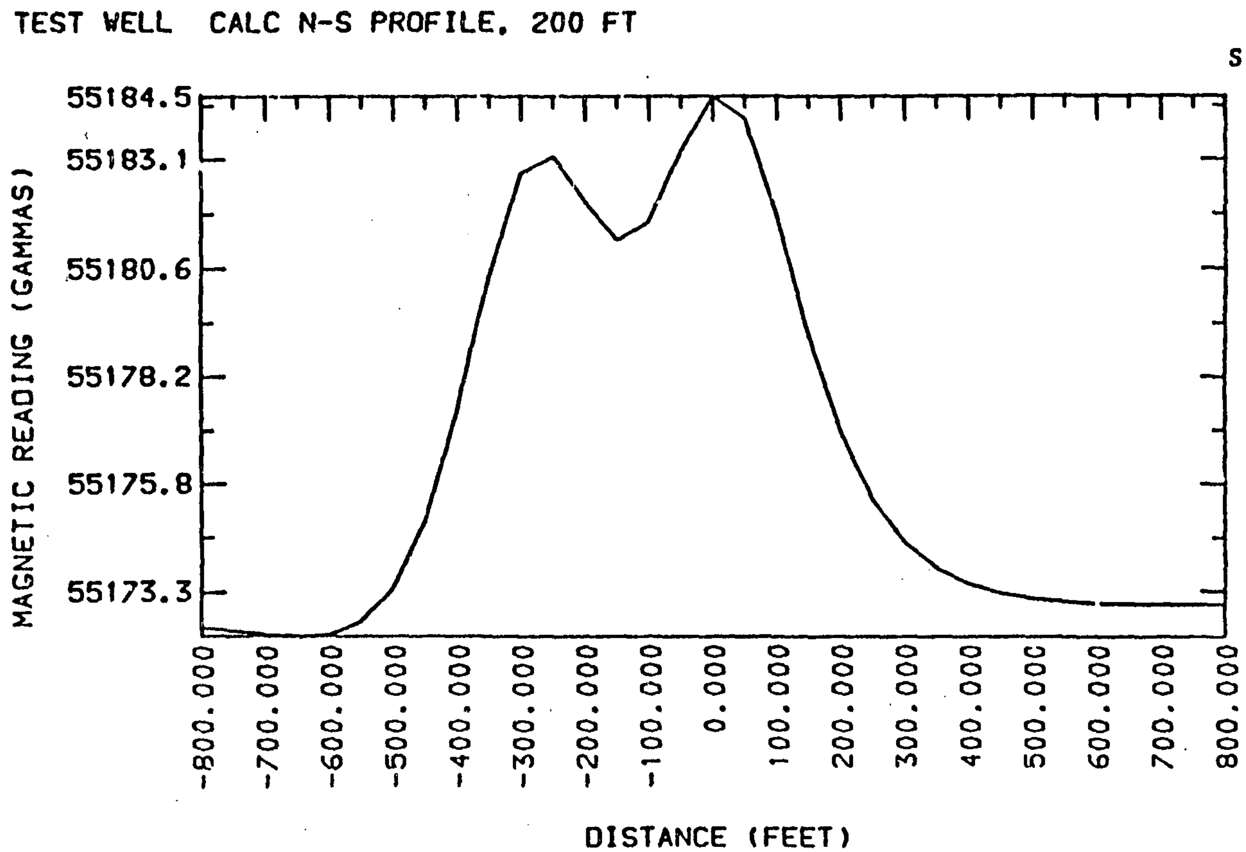


Figure 135. Calculated airborne total field at 200 ft for two identical casings separated 300 ft.

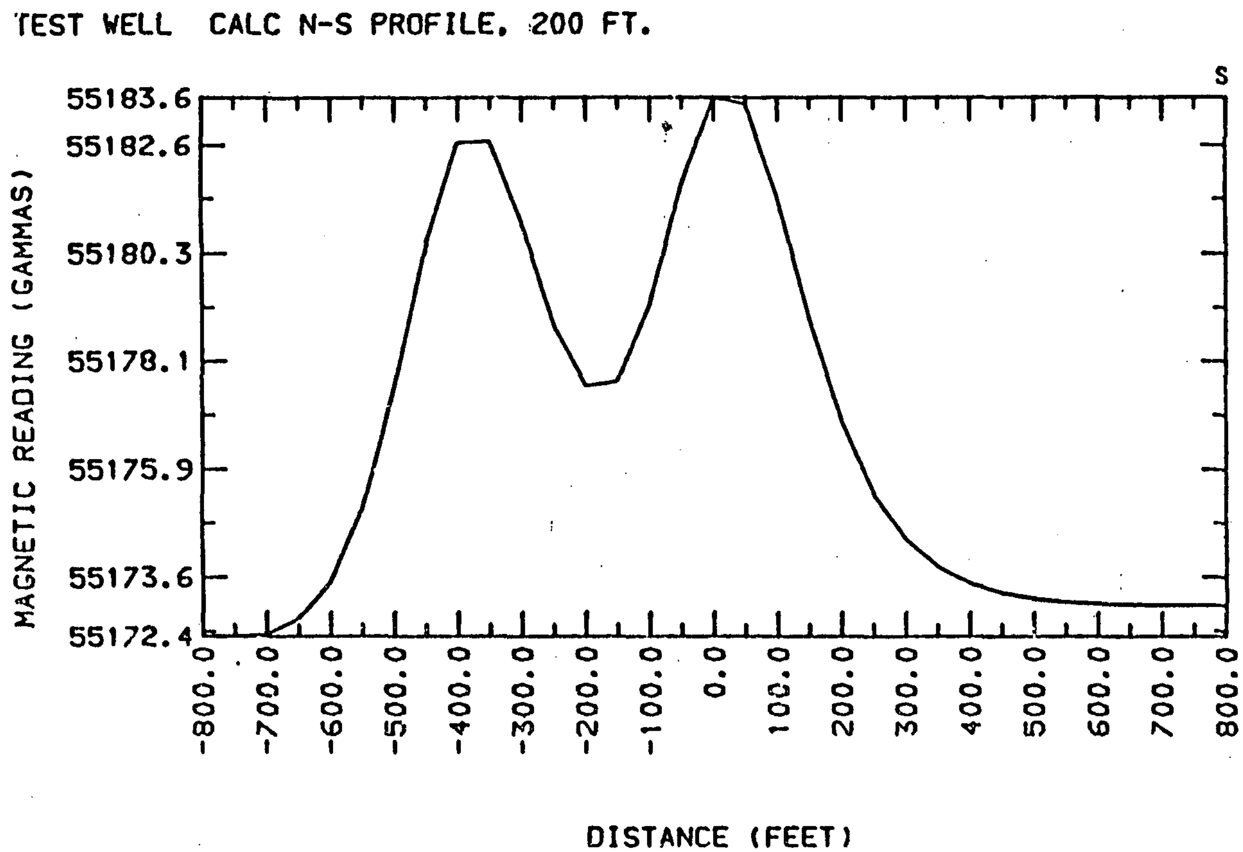


Figure 136. Calculated airborne total field at 200 ft for two identical casings separated 400 ft.

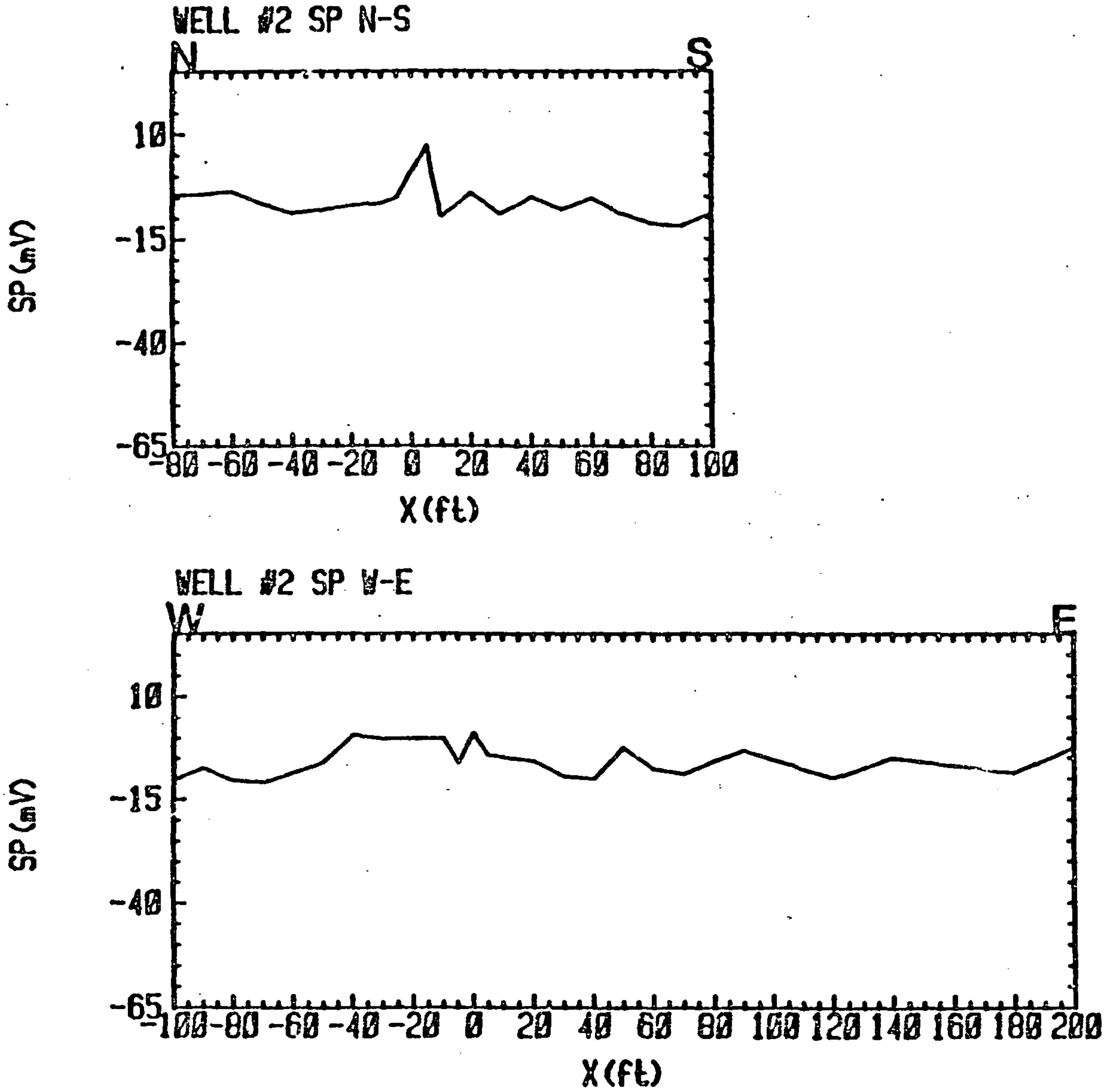


Figure 137. Self-potential profiles over Well Number 2.

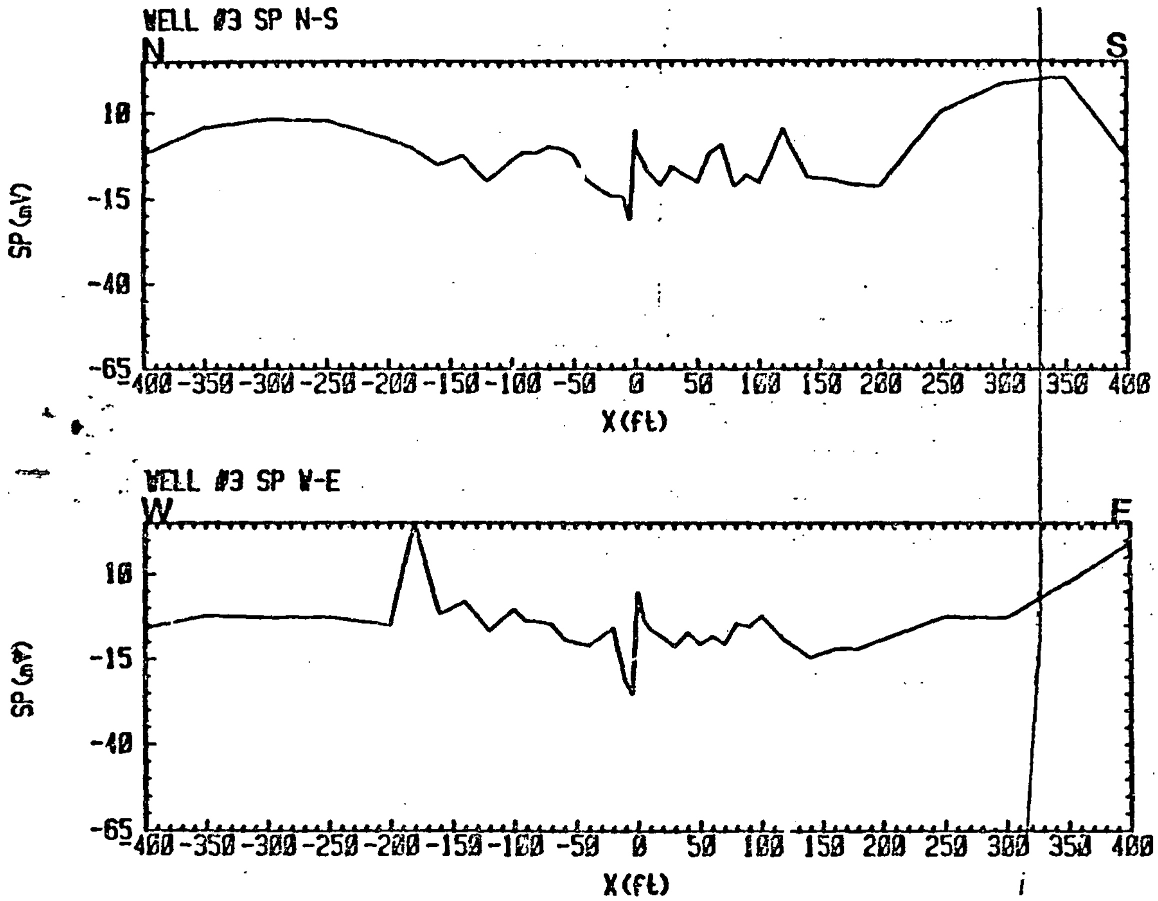


Figure 138. Self-potential profiles over Well Number 3.

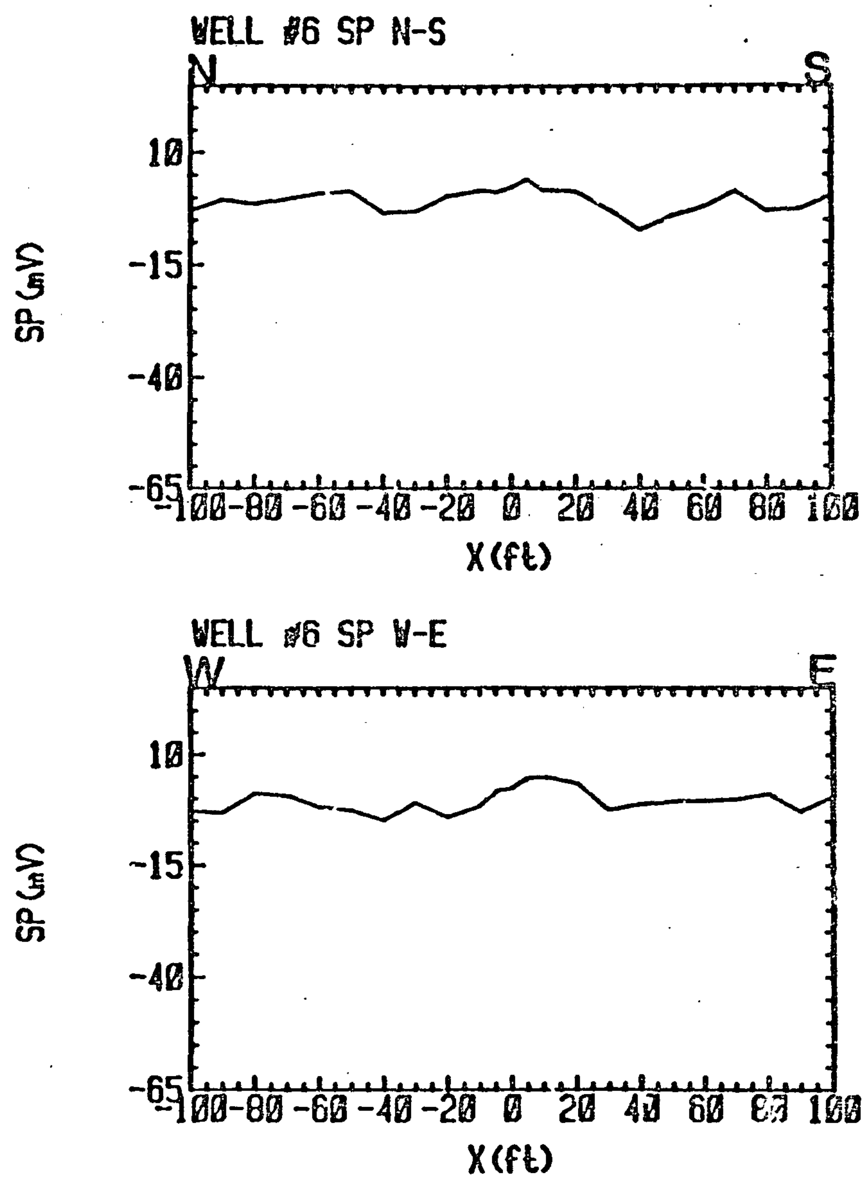


Figure 139. Self-potential profiles over Well Number 6.

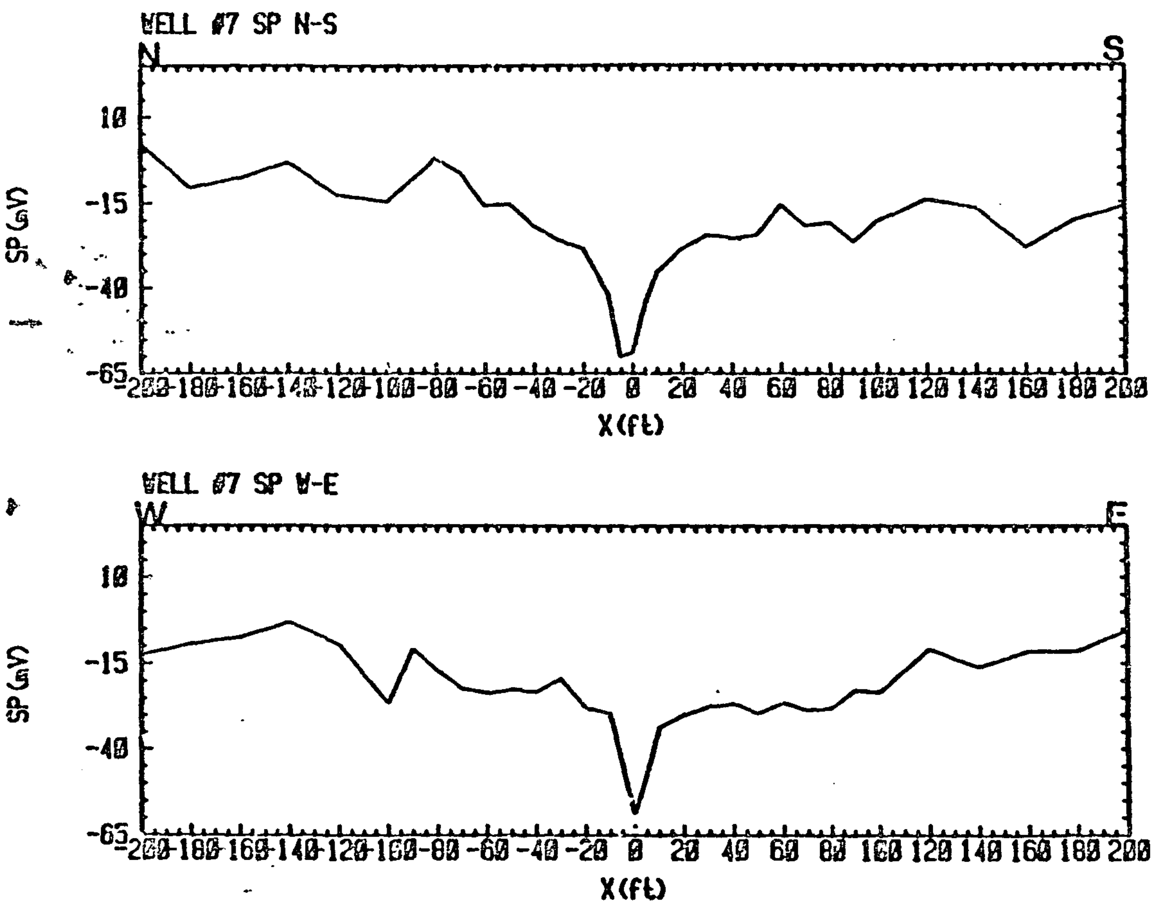


Figure 140. Self-potential profiles over Well Number 7.

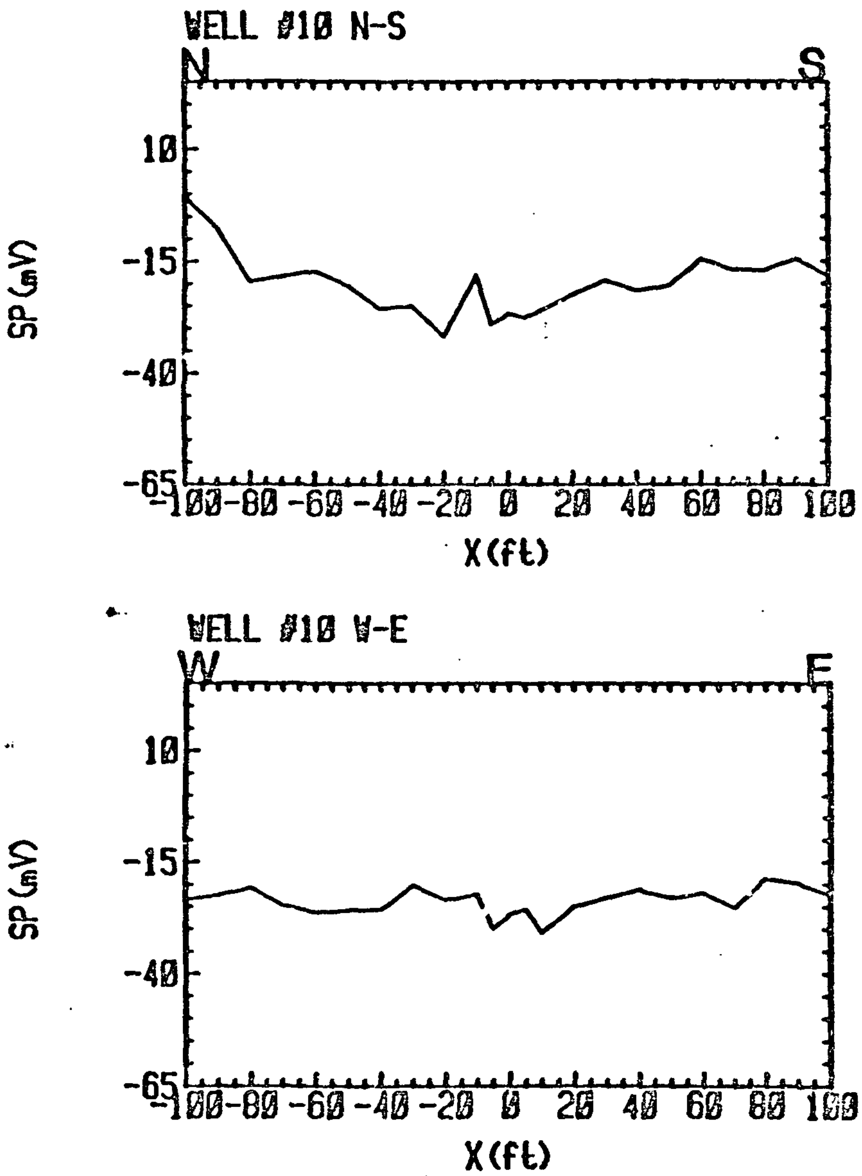


Figure 141. Self-potential profiles over Well Number 10.

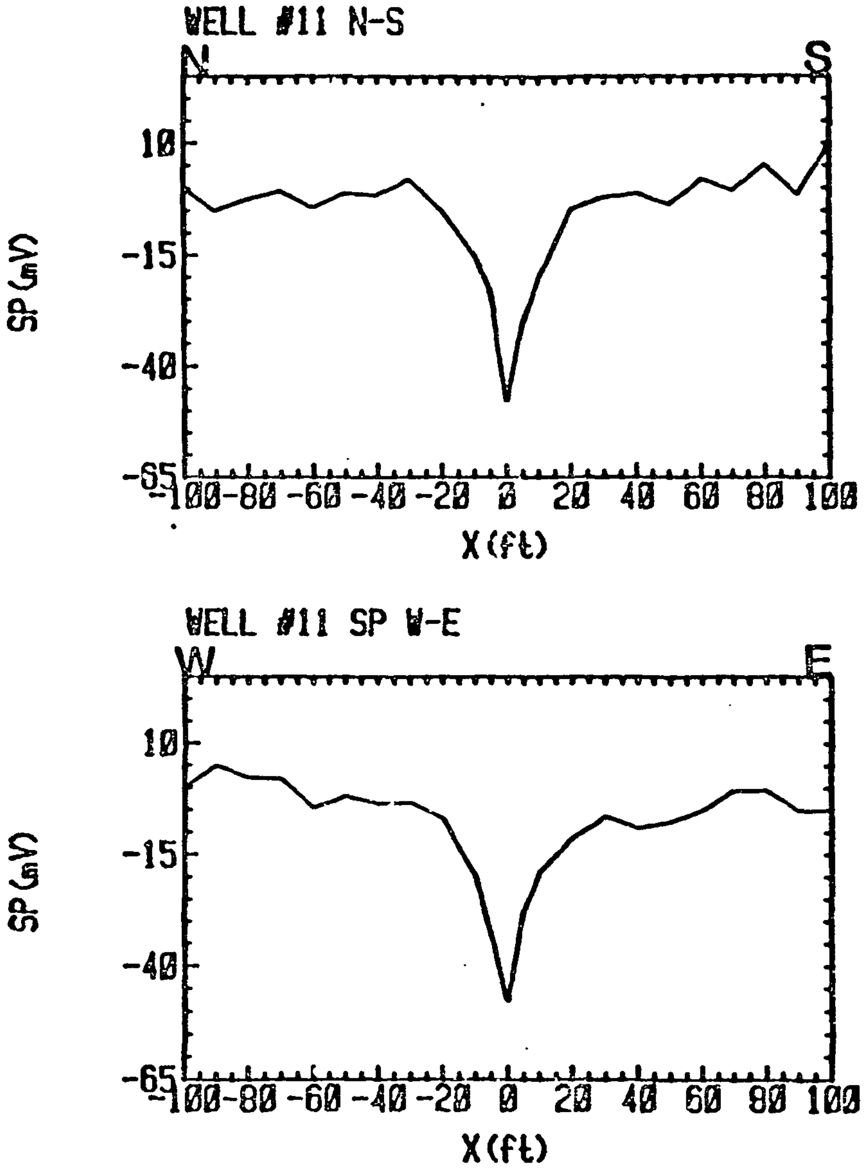


Figure 142. Self-potential profiles over Well Number 11.

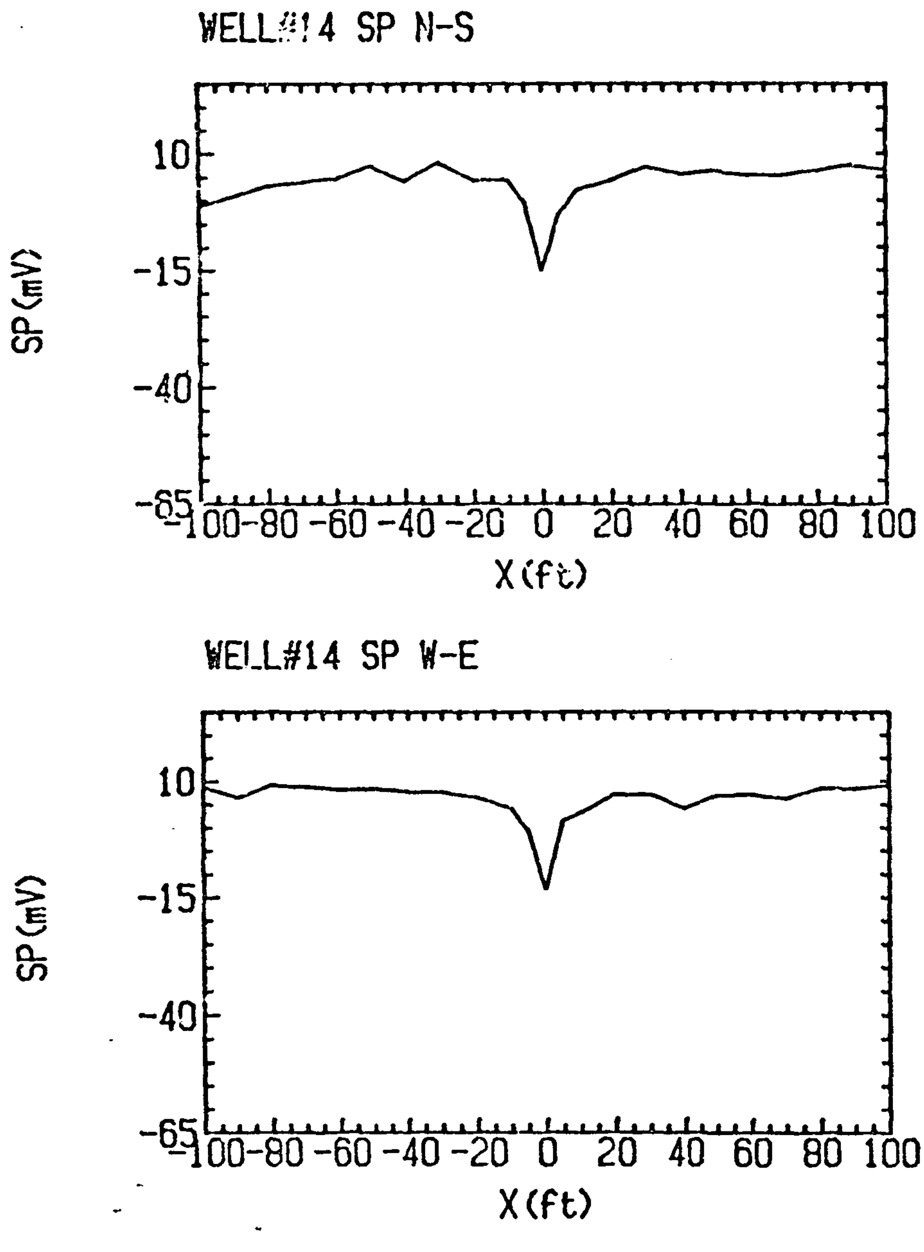


Figure 143. Self-potential profiles over Well Number 14.

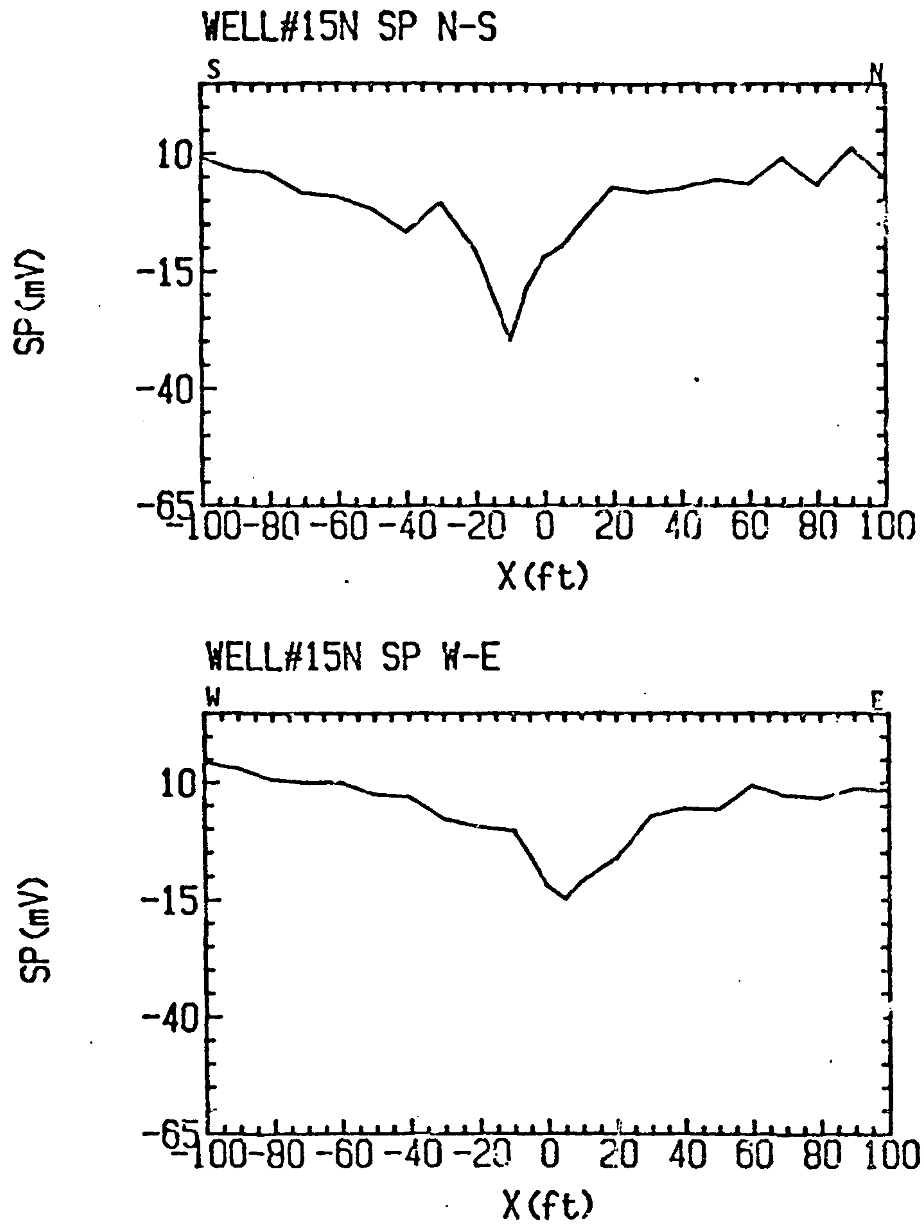


Figure 144. Self-potential profiles over Well Number 15 N (not centered on well).

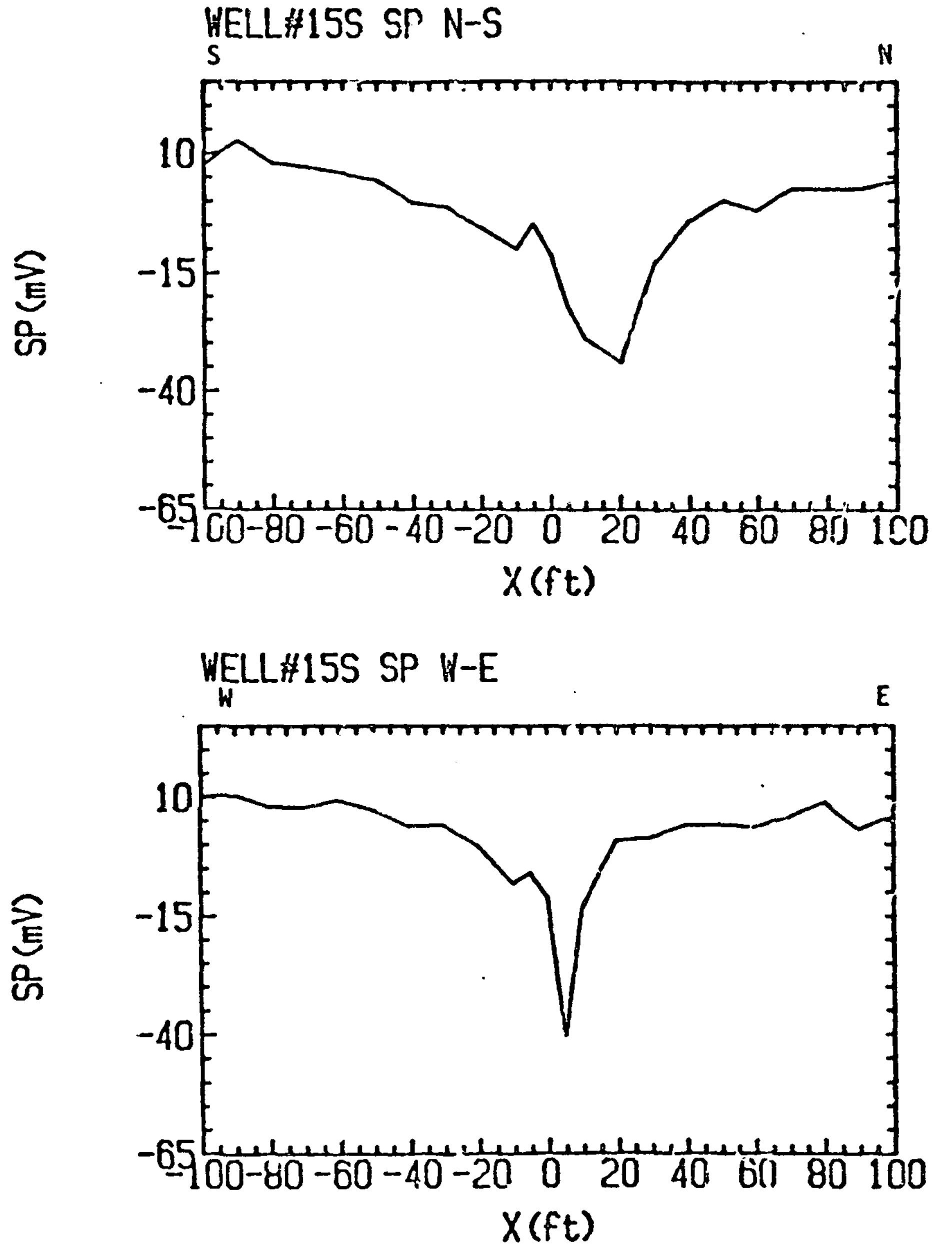


Figure 145. Self-potential profiles over Well Number 15 S (not centered on well).

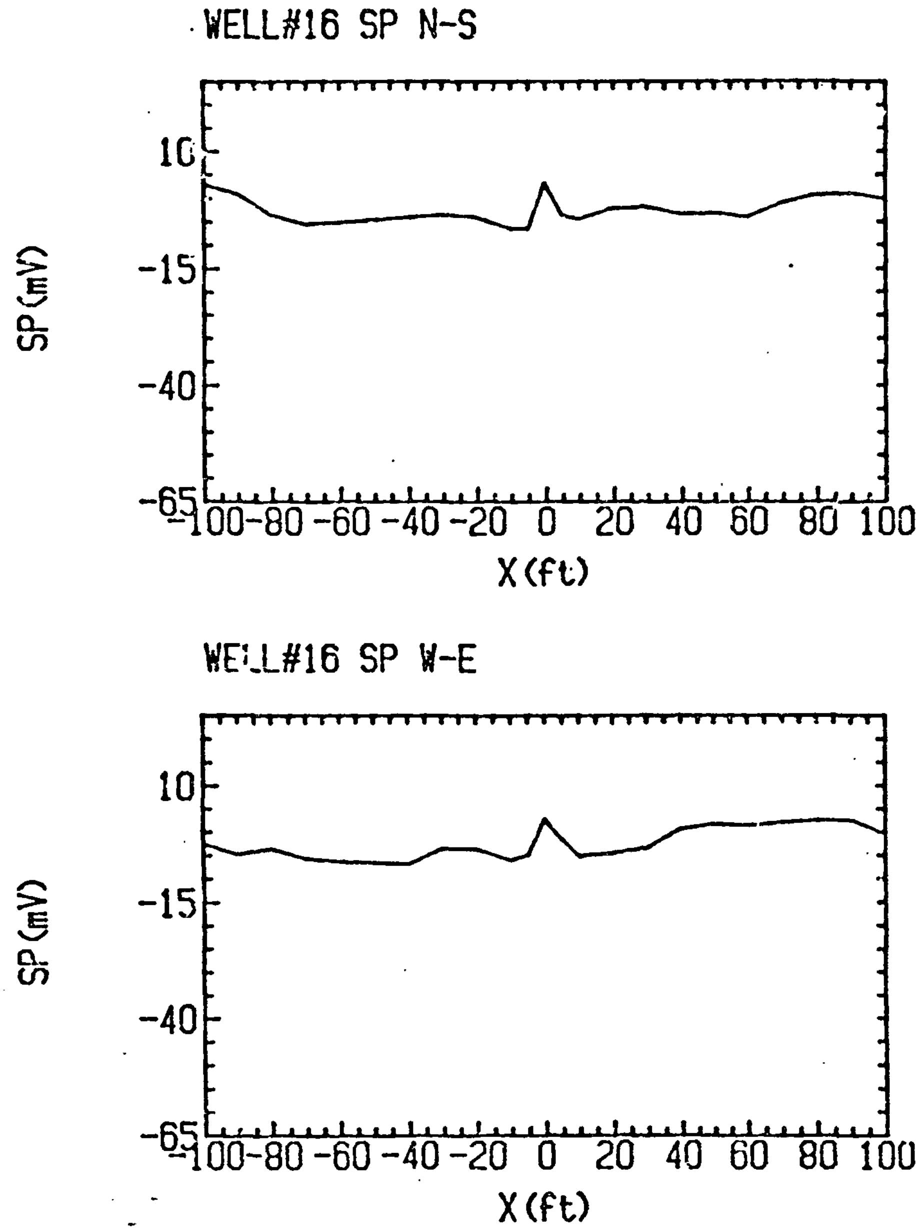


Figure 146. Self-potential profiles over Well Number 16.

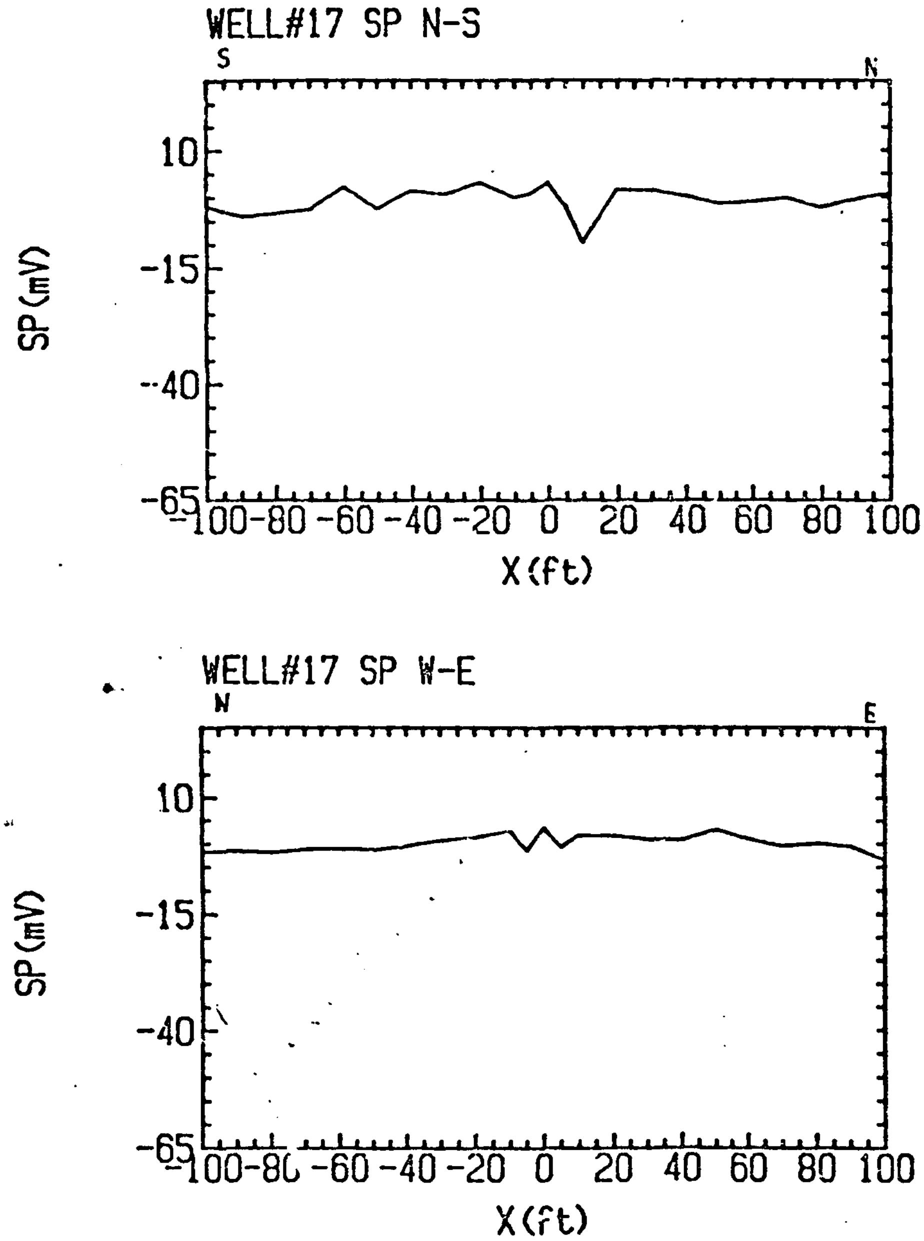


Figure 147. Self-potential profiles over Well Number 17.

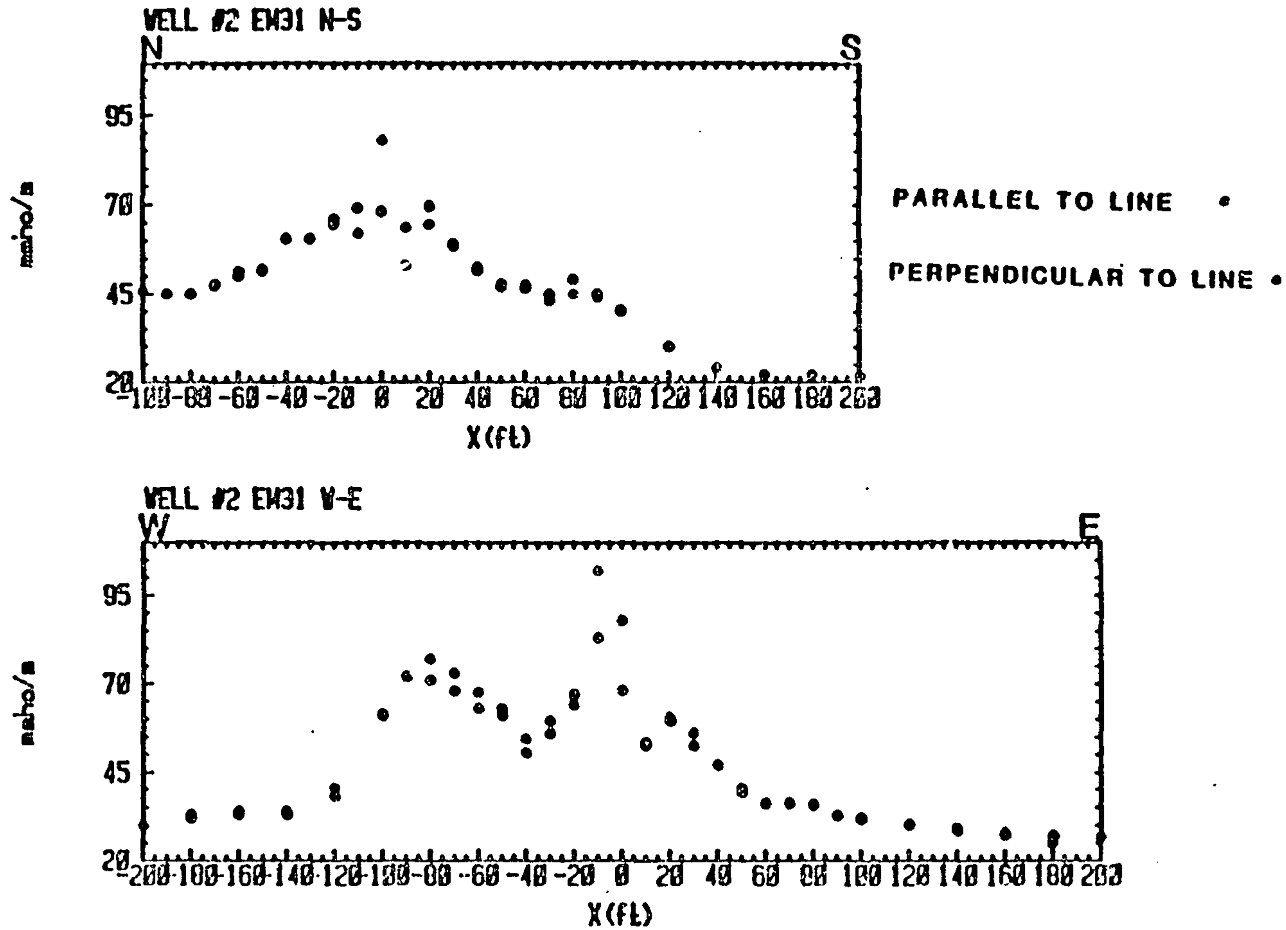


Figure 148. Electromagnetic profiles over Well Number 2, using the EM-31 system.

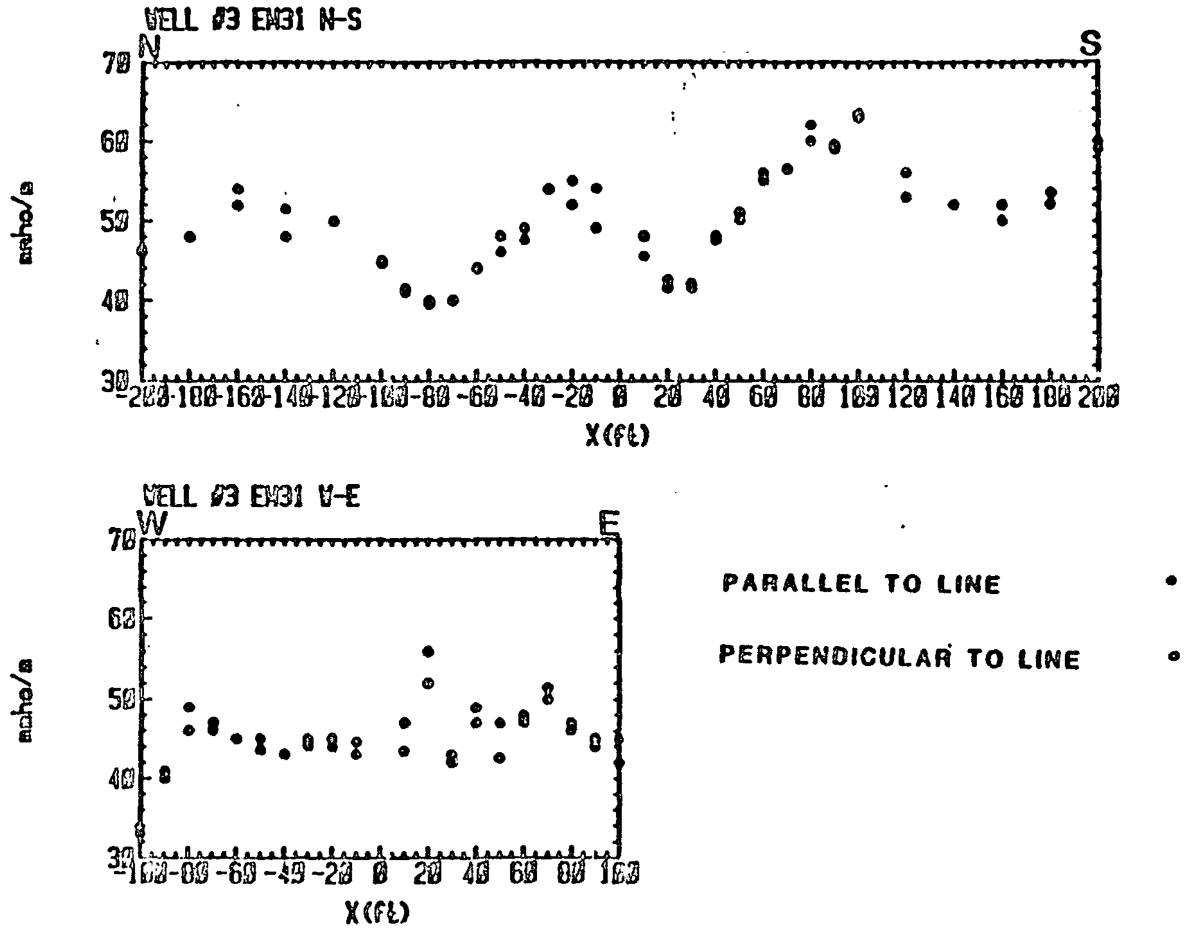


Figure 149. Electromagnetic profiles over Well Number 3, using the EM-31 system.

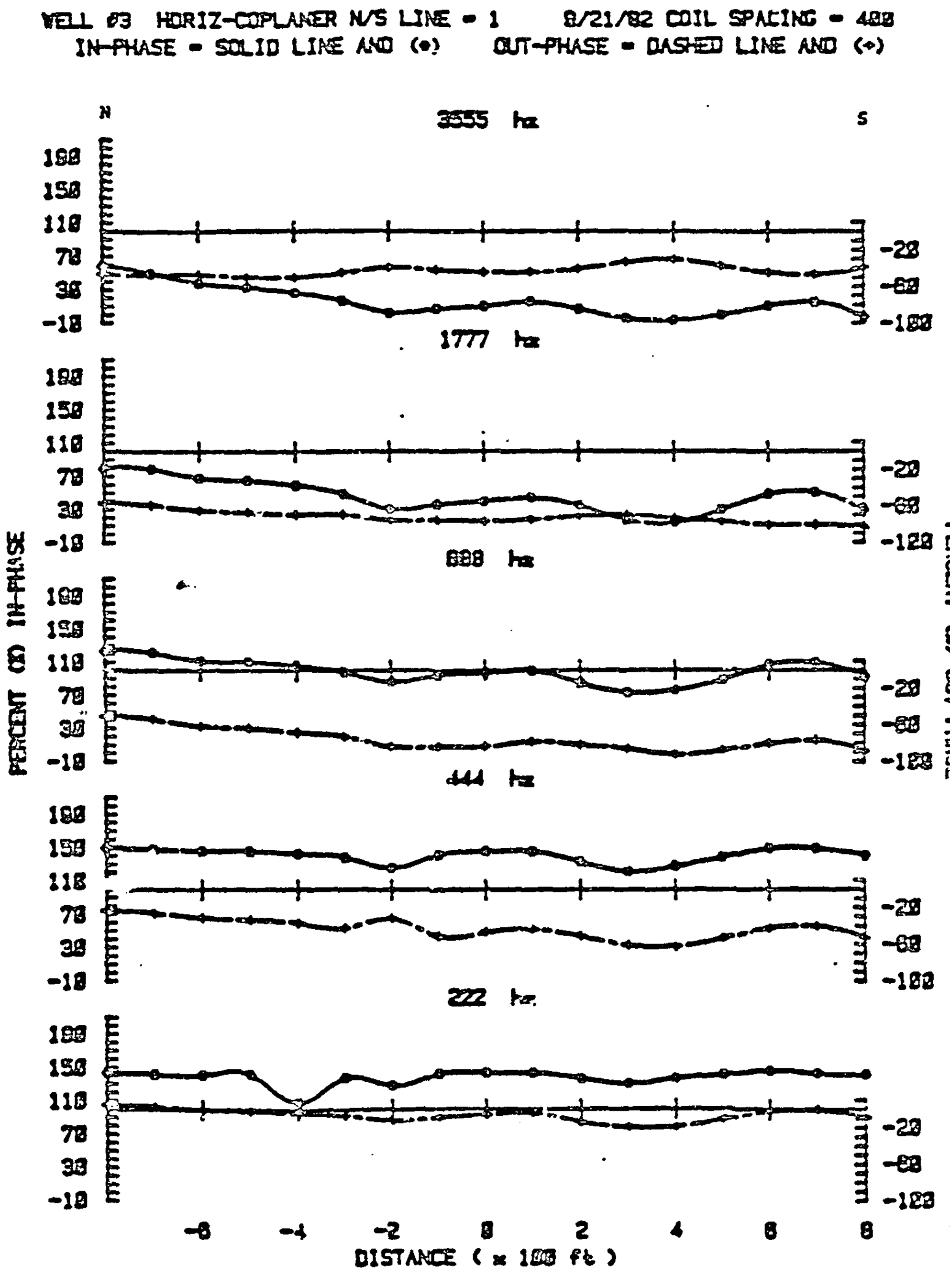


Figure 150. Electromagnetic N-S profile over Well Number 3, using Slingram.

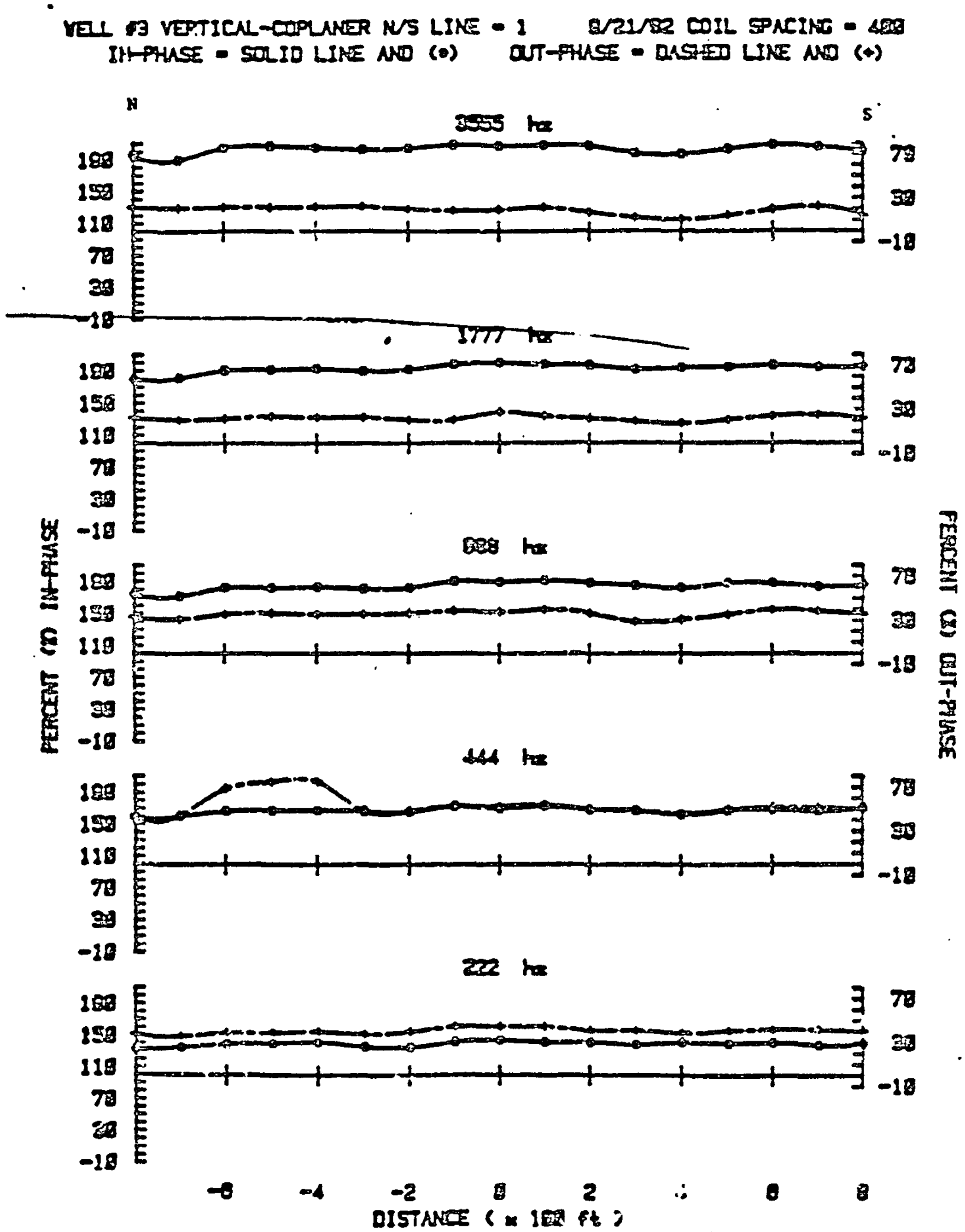


Figure 151. Electromagnetic N-S profile over Well Number 3, using Slingram.

APPENDIX I.

BRIEF SYNOPSIS OF THE PROGRAM "CASING"

The program "CASING", written in Fortran 77, has two modes of operation: 1) the forward mode, and 2) the inverse mode. In the forward mode the program calculates the magnetic field components Bx, By, Bz, H and F, using equations (1) and (3) and the spatial derivitives of these components (except H), using equations, (2) and (4), due to a linear distribution of magnetic monopole pairs.

In the inverse mode, the program initializes the distribution of monopoles within a specified region of interest, and, together with the subroutine "NLSOL" (an adaptive nonlinear least squares solver by Anderson, 1982), determines the final distribution of monopole pairs from a magnetic field data set that specifies the observations, their coordinates, and the component type.

The program was designed to be highly interactive so that on initial use one is assured of correct data entry (on subsequent runs, data can be read from a file that was saved on the initial run). Most other options available in the program, such as saving of data files, generation of randomly perturbed data sets or randomly perturbed parameters, are interactively specified by the user.

Both the forward and the inverse versions of the program rely exclusively on a large set of interdependent statement functions that specify the magnetic field components (or derivatives) of interest. These appear in the subroutine "CASINGFI" before the first executable statement, as required by Fortran. The functions have been coded in elementary subunits (e.g., specifying the distance between two arbitrary points) which are combined to yield the fields due to pole pairs. Further summation over all pole pairs yields the final field values at a point in space.

PLOTTING CAPABILITIES

The forward problem subroutine "CASINGFI" will enter an interactive plotting section after the requested fields or derivatives have been generated. The type of function, the direction of plotting, and the exact location of the line of plotting in 3 dimensions are specified by the user. The data to be plotted are printed, and, if requested, a one-dimensional profile of a magnetic field component is generated. The actual plotting is done by the plot package resident on the VAX -11/780 system at the USGS, Golden, Colorado. Both terminal output graphics for rapid viewing and hard copy graphics produced on a Hewlett-Packard plotter can be obtained. Any number of graphs can be generated sequentially and the program will exit the plotting loop only at the direction of the user.

PORTABILITY OF THE PROGRAM

Except for the plotting section, this program can be implemented on any system supporting Fortran IV plus for Fortran 77. With some minor modification the program could also be adapted to run on smaller systems. There are no machine dependent constants in the code.

FURTHER SCIENTIFIC POTENTIAL

The program "CASING" can be used to generate or analyze geomagnetic data of the type currently of interest to investigations that rely on magnetic field data. It is especially well suited to simulation studies where data inversion techniques are needed. By a sequence of simulations where 1) field data are acquired, 2) these data are randomly perturbed, and 3) the inverse mode is used to attempt to recover the original parameters, one can determine the limits and accuracy of inverting certain types of data sets.

Because of the strong reliance on statement functions, functions currently not in the program can be easily embedded. Thus, dipole (quadrupole, etc.) or even continuous distributions could be incorporated without difficulty. Consequently, demagnetization effects could be studied.

LISTING OF PROGRAM "CASING"

A listing of program "CASING" is given on the following pages.

```
      PROGRAM CASINGS
C
C
C PROGRAM WRITTEN BY LORANT A. MUTH, JULY,1982
C
C
C THE PROGRAM HAS TWO MODES OF USAGE: (1) 'FORWARD' PROBLEM
C                                    AND      (2) 'INVERSE' PROBLEM
C IN THE 'FORWARD' MODE
C THE SUBROUTINE CASINGFI CALCULATES THE MAGNETIC FIELD OF A
C COLLECTION OF CASINGS, EACH OF WHICH IS MADE UP OF A COLLECTION
C OF MAGNETIC MONOPOLE PAIRS.
C
C IN THE 'INVERSE' MODE
C THE SUBROUTINE CASINGFI OBTAINS THE PARAMETERS OF A DISTRIBUTION
C OF POLES AND CASINGS FROM MAGNETIC DATA.
C
C
      PARAMETER(NCASINGS=10,NPOLES=20)
      PARAMETER(NOBS=500,NPARAMS=2*NCASINGS+3*(NPOLES-1)+9)
      COMMON/BINIT/IO,BU(100),IALT
      COMMON/L2READ/LREAD
      COMMON/RUN0/NCASING1,IENTRY,IRUN,IRUN1,IRECORD,IRANDOM,ISEED
     1 ,PERCENT(2)
      COMMON/RUN1/THISRUN
      COMMON/DUMU/DYOBS(NOBS),DXINDEP(NOBS,3),DW(2),DEPARAMS(2)
      COMMON/UNIT/IUNIT
      CHARACTER*80 THISRUN
      CHARACTER*80 FILENAME
      INTEGER SLEN
      INTEGER*4 ISEED
      EXTERNAL CASINGFI,PCODE,SUB2,SUBEND
      DATA IENTRY,IUNIT,ISEED/0,9,24421/
C
C
C READ IN THE TYPE OF RUN THIS IS: SPECIFY EITHER  FORWARD OR
C INVERSE ON THE FIRST DATA CARD STARTING IN THE FIRST COLUMN.
C
      WRITE(6,*)' ENTER FILENAME
     1 OF THE CASING PARAMETER INPUT FILE. (PRESS <RETURN>
     2 IF INPUTING FROM THE TERMINAL.)'
      IUNIT=IUNIT+1
      IRUN=IUNIT
      READ(5,1)FILENAME
      IF(SLEN(FILENAME).EQ.1)IRUN=5
      IF(IRUN.NE.5)THEN
      CALL ASSIGN(IUNIT,FILENAME,SLEN(FILENAME))
      ENDIF
      WRITE(6,*) ' ENTER THE FILENAME
     1 WHERE THE INPUT PARAMETERS ARE TO BE RECORDED.'
     2 ,'IF YOU DO NOT WISH TO RECORD THE PARAMETERS PRESS <RETURN>'
      READ(5,1)FILENAME
      IF(SLEN(FILENAME).GT.1)THEN
      IUNIT=IUNIT+1
      IRUN1=IUNIT
      CALL ASSIGN(IUNIT,FILENAME,SLEN(FILENAME))
      ENDIF
      WRITE(6,*)'IS THIS AN INVERSE/FORWARD PROBLEM?'
      READ(IRUN,1)THISRUN
      IF(IRUN1.NE.0)WRITE(IRUN1,2)THISRUN
    1 FORMAT(A)
```

```
      INTEGER SLEN
      CHARACTER*20 FILENAME
      CHARACTER*13 NAMES
      DATA NAMES/'FIELDS ?','PARAMETERS ?'/
      WRITE(6,*)' DO YOU WANT  RANDOMLY PERTURBED VALUES FOR THE ',
     1NAMES(IASK)
      IF(IASK.EQ.1)THEN
      WRITE(6,*) ' IF NO, PRESS <RETURN>; OTHERWISE, ENTER FILENAME. '
       READ(5,1)FILENAME
      IF(SLEN(FILENAME).EQ.1)RETURN
      ELSEIF(IASK.EQ.2)THEN
      WRITE(6,*) ' 0 = NO ; 1 = YES '
      READ(5,*)IRANDOM
      IF(IRANDOM.EQ.0)RETURN
      ENDIF
      FORMAT(A)
      WRITE(6,*)' ENTER ANY 5 DIGIT INTEGER FOR THE SEED
     1 OF THE RANDOM NUMBER GENERATOR; CURRENT SEED IS ',ISEED
      READ(5,*)ISEED
      WRITE(6,*)' BY WHAT MAXIMUM DECIMAL FRACTION DO YOU WANT
     1 THE DATA TO BE PERTURBED? (E.G., .1=10% , ETC.)'
      READ(5,*)PERCENT(1)
      IF(IASK.EQ.1)THEN
      IUNIT=IUNIT+1
      IRANDOM=IUNIT
      CALL ASSIGN(IUNIT,FILENAME,SLEN(FILENAME))
      ELSEIF(IASK.EQ.2)THEN
      WRITE(6,*)' BY WHAT MAXIMUM DECIMAL FRACTION DO YOU WANT
     1 THE EARTH''S FIELD TO BE PERTURBED?'
      READ(5,*)PERCENT(2)
      ENDIF
      RETURN
      END
C
C
      SUBROUTINE CASINGFI(YOBS,XIN,BPARAMS,N,FCALC,IN,IDER)
C
C
C DEFINE THE PARAMETERS OF THE PROBLEM
C
C
      PARAMETER(NCASINGS=10,NPOLES=20)
      PARAMETER(NCNP=NCASINGS*NPOLES)
      PARAMETER(CONV=1.E+8)
      PARAMETER(NX=41,NY=41,NZ=41)
      PARAMETER(NXPYPZ=NX+NY+NZ)
      PARAMETER(NOBS=500,NPARAMS=2*NCASINGS+3*(NPOLES-1)+8)
      PARAMETER(NXNYNZ=NX*NY*NZ)
      PARAMETER(NCOMP=5,NDERIV=12,NCOMPS=NCOMP+NDERIV,NCOMPP1=NCOMP+1)
      PARAMETER(NXNCOMP=NCOMP*NXNYNZ,NXNDERIV=NDERIV*NXNYNZ)
      PARAMETER(NXNCND=NXNCOMP+NXNDERIV)
C
      COMMON/RUNO/NCASING1,IENTRY,IRUN,IRUN1,IRECORD,IRANDOM,ISEED
     1 ,PERCENT(2)
      COMMON/RUN1/THISRUN
      COMMON/CONST0/CMU(NPOLES,NCASINGS),DEGTORAD
      COMMON/GRID/XYZ(NXPYPZ,3)
      DIMENSION X(NX),Y(NY),Z(NZ)
      EQUIVALENCE(XYZ(1,1),X)
      EQUIVALENCE(XYZ(1,2),Y)
      EQUIVALENCE(XYZ(1,3),Z)
```

```
      INTEGER SLEN
      CHARACTER*20 FILENAME
      CHARACTER*13 NAMES
      DATA NAMES/'FIELDS ?','PARAMETERS ?'/
      WRITE(6,*)' DO YOU WANT  RANDOMLY PERTURBED VALUES FOR THE ',
     1NAMES(IASK)
      IF(IASK.EQ.1)THEN
      WRITE(6,*) ' IF NO, PRESS <RETURN>; OTHERWISE, ENTER FILENAME. '
       READ(5,1)FILENAME
      IF(SLEN(FILENAME).EQ.1)RETURN
      ELSEIF(IASK.EQ.2)THEN
      WRITE(6,*) ' 0 = NO ; 1 = YES '
      READ(5,*)IRANDOM
      IF(IRANDOM.EQ.0)RETURN
      ENDIF
      FORMAT(A)
      WRITE(6,*)' ENTER ANY 5 DIGIT INTEGER FOR THE SEED
     1 OF THE RANDOM NUMBER GENERATOR; CURRENT SEED IS ',ISEED
      READ(5,*)ISEED
      WRITE(6,*)' BY WHAT MAXIMUM DECIMAL FRACTION DO YOU WANT.
     1 THE DATA TO BE PERTURBED? (E.G., .1=10% , ETC.)'
      READ(5,*)PERCENT(1)
      IF(IASK.EQ.1)THEN
      IUNIT=IUNIT+1
      IRANDOM=IUNIT
      CALL ASSIGN(IUNIT,FILENAME,SLEN(FILENAME))
      ELSEIF(IASK.EQ.2)THEN
      WRITE(6,*)' BY WHAT MAXIMUM DECIMAL FRACTION DO YOU WANT
     1 THE EARTH''S FIELD TO BE PERTURBED?'
      READ(5,*)PERCENT(2)
      ENDIF
      RETURN
      END
C
C
      SUBROUTINE CASINGFI(YOBS,XIN,BPARAMS,M,FCALC,IN,IDER)
C
C
C DEFINE THE PARAMETERS OF THE PROBLEM
C
C
      PARAMETER(NCASINGS=10,NPOLES=20)
      PARAMETER(NCNP=NCASINGS*NPOLES)
      PARAMETER(CONV=1.E+8)
      PARAMETER(NX=41,NY=41,NZ=41)
      PARAMETER(NXPYPZ=NX+NY+NZ)
      PARAMETER(NOBS=500,NPARAMS=2*NCASINGS+3*(NPOLES-1)+8)
      PARAMETER(NXNYNZ=NX*NY*NZ)
      PARAMETER(NCOMP=5,NDERIV=12,NCOMPS=NCOMP+NDERIV,NCOMPP1=NCOMP+1)
      PARAMETER(NXNCOMP=NCOMP*NXNYNZ,NXNDERIV=NDERIV*NXNYNZ)
      PARAMETER(NXNCND=NXNCOMP+NXNDERIV)
C
      COMMON/RUNO/NCASING1,IENTRY,IRUN,IRUN1,IRECORD,IRANDOM,ISEED
     1 ,PERCENT(2)
      COMMON/RUN1/THISRUN
      COMMON/CONSTO/CMU(NPOLES,NCASINGS),DEGTORAD
      COMMON/GRID/XYZ(NXPYPZ,3)
      DIMENSION X(NX),Y(NY),Z(NZ)
      EQUIVALENCE(XYZ(1,1),X)
      EQUIVALENCE(XYZ(1,2),Y)
      EQUIVALENCE(XYZ(1,3),Z)
```

```
      COMMON/REGION/X0,XF,Y0,YF,Z0,ZF
      COMMON/CASINGS/X1(NPOLES,NCASINGS),Y1(NPOLES,NCASINGS),
     1 Z1(NPOLES,NCASINGS),X2(NPOLES,NCASINGS),Y2(NPOLES,NCASINGS),
     2 Z2(NPOLES,NCASINGS),LENGTH(NPOLES,NCASINGS),BETA(NCASINGS),
     3 PHI(NCASINGS),POLES(NPOLES,NCASINGS),NPOLE1(NCASINGS)
      COMMON/BEARTH/XEARTH,YEARTH,ZEARTH,HEARTH,FEARTH
C
C
C
      COMMON/NAMES/IFX,IFY,IFZ,IFH,IFF,IFDXDX,IFDXDY,IFDXDZ,IFDYDX,
     1 IFDYDY,IFDYDZ,IFDZDX,IFDZDY,IFDZDZ,IFDFDX,IFDFDY,IFDFDZ
      DIMENSION NAMES0(NCOMPS)
      EQUIVALENCE(NAMES0,IFX)
C
      COMMON/FIELDS0/FIELDS(NX,NY,NZ,NCOMPS)
      COMMON/COMPS0/COMP(NCOMPS),COMP0(NCOMPS)
      COMMON/PLOT0/PLOTTHIS(NXPYPZ)
      CHARACTER*5 DIRXYZ,KOMP,COMP,COMP0
      REAL LENGTH,LX,LY,LZ,L
      CHARACTER*80 THISRUN
      CHARACTER*20 FMT
      INTEGER*4 ISEED
      CHARACTER*40 PTITLE,XTITLE,YTITLE
      DIMENSION IPTITLE(10),IXTITLE(10),IYTITLE(10)
      COMMON/BINIT/I0,E0(100),IALT
      DIMENSION BPARAMS(1),XIN(NOBS,1),YOBS(1),W(1)
      COMMON/TYPE0/ITYPE(NOBS)
      CHARACTER*80 FILENAME
      CHARACTER*5 TYPE
      DIMENSION P(NPARAMS,NPOLES,NCASINGS)
      DIMENSION XP(4),YP(4),DXP(2),DYP(2),IE(10),ISL(5)
C
      DATA COMP0/'X','Y','Z','H','F',
     1  'DXDX','DXDY','DXDZ','DYDX','DYDY','DYDZ',
     2  'DZDX','DZDY','DZDZ','DFDX','DFDY','DFDZ'/
C
      DATA IPLOT/1/
      DATA U04PI/1.E-7/
      DATA XNANCMP*0./
      DATA IZSTEP/1/
      DATA ZERO/0./
      DATA FIELDS/NXNCMD*0./
C
C*************THE BEGINNING OF ARITHMETIC STATEMENT FUNCTIONS**********
C************** USED IN THIS PROBLEM *********************************
C
      LX(L,BETA,PHI)=L*COS(BETA)*COS(PHI)
      LY(L,BETA,PHI)=L*COS(BETA)*SIN(PHI)
      LZ(L,BETA)    =-L*SIN(BETA)
      R1(X,Y,Z,X1,Y1,Z1)=SQRT((X-X1)**2+(Y-Y1)**2+(Z-Z1)**2)
      RX1(X,X1)=X-X1
      RY1(Y,Y1)=Y-Y1
      RZ1(Z,Z1)=Z-Z1
      RXY1(X,Y,X1,Y1)=R1(X,Y,ZERO,X1,Y1,ZERO)
      BX1(X,Y,Z,X1,Y1,Z1)=RX1(X,X1)/(R1(X,Y,Z,X1,Y1,Z1)**3)
      BY1(X,Y,Z,X1,Y1,Z1)=RY1(Y,Y1)/(R1(X,Y,Z,X1,Y1,Z1)**3)
      BZ1(X,Y,Z,X1,Y1,Z1)=RZ1(Z,Z1)/(R1(X,Y,Z,X1,Y1,Z1)**3)
      BX(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (BX1(X,Y,Z,X1,Y1,Z1)-BX1(X,Y,Z,X2,Y2,Z2))
      BY(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (BY1(X,Y,Z,X1,Y1,Z1)-BY1(X,Y,Z,X2,Y2,Z2))
```

```
      BZ(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (BZ1(X,Y,Z,X1,Y1,Z1)-BZ1(X,Y,Z,X2,Y2,Z2))
      DXDX1(X,Y,Z,X1,Y1,Z1)=-3.*RX1(X,X1)**2/R1(X,Y,Z,X1,Y1,Z1)**5+
     1    1./R1(X,Y,Z,X1,Y1,Z1)**3
      DXDY1(X,Y,Z,X1,Y1,Z1)=-3.*RX1(X,X1)*RY1(Y,Y1)/
     1    R1(X,Y,Z,X1,Y1,Z1)**5
      DXDZ1(X,Y,Z,X1,Y1,Z1)=-3.*RX1(X,X1)*RZ1(Z,Z1)/
     1    R1(X,Y,Z,X1,Y1,Z1)**5
      DYDX1(X,Y,Z,X1,Y1,Z1)=-3.*RY1(Y,Y1)*RX1(X,X1)/
     1    R1(X,Y,Z,X1,Y1,Z1)**5
      DYDY1(X,Y,Z,X1,Y1,Z1)=-3.*RY1(Y,Y1)**2/R1(X,Y,Z,X1,Y1,Z1)**5+
     1    1./R1(X,Y,Z,X1,Y1,Z1)**3
      DYDZ1(X,Y,Z,X1,Y1,Z1)=-3.*RY1(Y,Y1)*RZ1(Z,Z1)/
     1    R1(X,Y,Z,X1,Y1,Z1)**5
      DZDX1(X,Y,Z,X1,Y1,Z1)=-3.*RZ1(Z,Z1)*RX1(X,X1)/
     1    R1(X,Y,Z,X1,Y1,Z1)**5
      DZDY1(X,Y,Z,X1,Y1,Z1)=-3.* RZ1(Z,Z1)*RY1(Y,Y1)/
     1   R1(X,Y,Z,X1,Y1,Z1)**5
      DZDZ1(X,Y,Z,X1,Y1,Z1)=-3.*RZ1(Z,Z1)**2/R1(X,Y,Z,X1,Y1,Z1)**5+
     1   1./R1(X,Y,Z,X1,Y1,Z1)**3
      DXDX(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DXDX1(X,Y,Z,X1,Y1,Z1)-DXDX1(X,Y,Z,X2,Y2,Z2))
      DXDY(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DXDY1(X,Y,Z,X1,Y1,Z1)-DXDY1(X,Y,Z,X2,Y2,Z2))
      DXDZ(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DXDZ1(X,Y,Z,X1,Y1,Z1)-DXDZ1(X,Y,Z,X2,Y2,Z2))
      DYDX(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DYDX1(X,Y,Z,X1,Y1,Z1)-DYDX1(X,Y,Z,X2,Y2,Z2))
      DYDY(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DYDY1(X,Y,Z,X1,Y1,Z1)-DYDY1(X,Y,Z,X2,Y2,Z2))
      DYDZ(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DYDZ1(X,Y,Z,X1,Y1,Z1)-DYDZ1(X,Y,Z,X2,Y2,Z2))
      DZDX(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DZDX1(X,Y,Z,X1,Y1,Z1)-DZDX1(X,Y,Z,X2,Y2,Z2))
      DZDY(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DZDY1(X,Y,Z,X1,Y1,Z1)-DZDY1(X,Y,Z,X2,Y2,Z2))
      DZDZ(X,Y,Z,X1,Y1,Z1,X2,Y2,Z2,I,J)=CMU(I,J)*
     1 (DZDZ1(X,Y,Z,X1,Y1,Z1)-DZDZ1(X,Y,Z,X2,Y2,Z2))
C
C
C************** END OF ARITHMATIC STATEMENT FUNCTIONS***************
      IF(IENTRY.EQ.0)THEN
C
C
C DEFINE A FEW RELEVANT CONSTANTS
C
      PI=4.*ATAN(1.)
      DEGTORAD=PI/180.
C
C
C*******************THE BEGINNING OF DATA INPUT************************
C
C
C READ IN THE NUMBER OF CASINGS IN THE PROBLEM,FOLLOWED BY
C THE NUMBER OF PAIRS OF POLES IN EACH CASING.
C
      WRITE(6,*)" WHAT IS THE TOTAL NUMBER OF CASINGS IN THIS PROBLEM?"
      READ(IRUN,*) NCASING1
      IF(IRUN1.NE.0)WRITE(IRUN1,*)NCASING1
      WRITE(6,*)"ENTER THE NUMBER OF POLE PAIRS IN EACH CASING:"
      READ(IRUN,*) (NPOLE1(ICASING),ICASING=1,NCASING1)
```

```
      IF(IRUN1.NE.0)
     1 WRITE(IRUN1,*) (NPOLE1(ICASING),ICASING=1,NCASING1)
C
C CHECK TO SEE IF THE ALLOTED NUMBER OF CASINGS AND THE NUMBER OF
C POLES IN EACH CASING HAVE NOT BEEN EXCEEDED.
C
      IF(NCASING1.GT.NCASINGS)STOP 'NCASINGS'
      DO 70 ICASING=1,NCASING1
   70 IF(NPOLE1(ICASING).GT.NPOLES)STOP 'NPOLES'
C
C
C READ IN THE ORIENTATION OF EACH CASING (IN DEGREES):
C     BETA(ICASING)= THE ANGLE BETWEEN THE HORIZONTAL AND THE
C                    LINE OF THE CASING.
C     PHI(ICASING)= THE ANGLE BETWEEN THE HORIZONTAL PROJECTION
C                   OF THE CASING AND THE USUAL X-AXIS IN 3-D. IT
C                   IS ALSO THE USUAL AZIMUTHAL ANGLE IN SPHERICAL
C                   COORDINATES.
C
      WRITE(6,*)'ENTER THE ORIENTATION (BETA,PHI) OF EACH CASING:'
      DO 6 ICASING=1,NCASING1
      WRITE(6,*)' FOR CASING ',ICASING
      READ(IRUN,*) BETA(ICASING),PHI(ICASING)
      IF(IRUN1.NE.0)WRITE(IRUN1,*) BETA(ICASING),PHI(ICASING)
    6 CONTINUE
C
C CONVERT ORIENTATION PARAMETERS TO RADIANS.
C
      DO 7 ICASING=1,NCASING1
      BETA(ICASING)=BETA(ICASING)*DEGTORAD
    7 PHI(ICASING)=PHI(ICASING)*DEGTORAD
C
C READ IN THE POLE STRENGTH N OF EACH POLE AND THE LENGTH OF EACH
C POLE. (THE DATA FOR A NEW CASING SHOULD START ON A NEW DATA CARD.)
C
      DO 1 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      WRITE(6,*)' THERE ARE ',NP, '  POLE PAIRS IN CASING ',ICASING
      WRITE(6,*)'ENTER THE POLE STRENGTH/POLE SEPARATION (IN METERS)
     1 OF EACH'
      READ(IRUN,*) (POLES(IPOLE,ICASING),LENGTH(IPOLE,ICASING),
     1 IPOLE=1,NP)
      IF(IRUN1.NE.0)
     1 WRITE(IRUN1,*) (POLES(IPOLE,ICASING),LENGTH(IPOLE,ICASING),
     2 IPOLE=1,NP)
    1 CONTINUE
C
C MULTIPLY POLE STRENGTHS BY SOME RELEVANT CONSTANTS.
C
      DO 11 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      DO 11 IPOLE=1,NP
      CMU(IPOLE,ICASING)=CONV*POLES(IPOLE,ICASING)*FMU04PI
   11 CONTINUE
C
C READ IN THE LIMITS OF THE REGION OF INTEREST; ALSO GIVE THE
C NUMBER OF INTERVALS IN EACH DIMENSION OF THE REGION.
C
      WRITE(6,*)'DEFINE THE REGION OF INTEREST IN 3-D:'
      WRITE(6,*)'ENTER THE INITIAL AND FINAL X-COORDINATES, AND THE
     1NUMBER OF INTERVALS IN X; REPEAT FOR THE Y AND Z-COORDINATES:'
```

```
      READ(IRUN,*)X0,XF,INTX,Y0,YF,INTY,Z0,ZF,INTZ
      IF(IRUN1.NE.0)WRITE(IRUN1,*)X0,XF,INTX,Y0,YF,INTY,Z0,ZF,INTZ
C
C CHECK TO SEE IF THE ALLOTED DIMENSIONS HAVE NOT BEEN EXCEEDED
C
      INTX1=INTX+1
      INTY1=INTY+1
      INTZ1=INTZ+1
C
      IF(INTX1.GT.NX.OR.INTY1.GT.NY.OR.INTZ1.GT.NZ)STOP 'NXNYNZ'
C
C
C READ IN THE POSITION X1(1),Y1(1),Z1(1) OF A POLE IN EACH CASING.
C THEN READ IN THE DISTANCE ALONG THE CASING OF THE OTHER POLES;
C STORE THIS INFORMATION IN X1(IPOLE,ICASING). NOTE THAT ONLY ONE
C MEMBER OF EACH POLE PAIR IS READ IN HERE.  ALSO NOTE THAT THE
C DATA FOR A NEW CASING SHOULD START ON A NEW DATA CARD.
C
      DO 12 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      WRITE(6,*)' ENTER THE POSITION (X,Y,Z) OF A POLE IN CASING',
     1 ICASING
      READ(IRUN,*) X1(1,ICASING),Y1(1,ICASING),Z1(1,ICASING)
      IF(IRUN1.NE.0)
     1 WRITE(IRUN1,*) X1(1,ICASING),Y1(1,ICASING),Z1(1,ICASING)
      DO 12 IPOLE=2,NP
      WRITE(6,*)' ENTER THE DISTANCE (IN METERS) ALONG THE CASING OF THE
     1 FIRST POLE OF POLE PAIR',IPOLE,' AS MEASURED FROM THE FIRST
     2 POLE OF POLE PAIR 1.'
      READ(IRUN,*)X1(IPOLE,ICASING)
      IF(IRUN1.NE.0)WRITE(IRUN1,*)X1(IPOLE,ICASING)
   12 CONTINUE
C
      IF(THISRUN.EQ.'INVERSE')GOTO 16
C
C CONVERT THE LENGTH INFORMATION STORED IN X1 TO CARTESIAN COORDINATES
C USING THE ORIENTATIONS OF THE CASINGS.
C
      DO 13 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      DO 13 IPOLE=2,NP
      Z1(IPOLE,ICASING)=Z1(1,ICASING)+
     1  LZ(X1(IPOLE,ICASING),BETA(ICASING))
      Y1(IPOLE,ICASING)=Y1(1,ICASING)+
     1  LY(X1(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      X1(IPOLE,ICASING)=X1(1,ICASING)+
     1  LX(X1(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
   13 CONTINUE
C
C CALCULATE THE POSITION OF THE SECOND POLE OF EACH POLE PAIR IN
C EACH CASING.
C
      DO 14 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      DO 14 IPOLE=1,NP
      X2(IPOLE,ICASING)=X1(IPOLE,ICASING)+
     1 LX(LENGTH(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      Y2(IPOLE,ICASING)=Y1(IPOLE,ICASING)+
     1 LY(LENGTH(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      Z2(IPOLE,ICASING)=Z1(IPOLE,ICASING)+
     1 LZ(LENGTH(IPOLE,ICASING),BETA(ICASING))
```

```
   14 CONTINUE
C
C
C READ IN THE COMPONENTS OF THE EARTH'S MAGNETIC FIELD:
C
C
16    WRITE(6,*)'ENTER THE COMPONENTS X,Y,Z OF THE GEOMAGNETIC FIELD'
      READ(IRUN,*)XEARTH,YEARTH,ZEARTH
      IF(IRUN1.NE.0)WRITE(IRUN1,*)XEARTH,YEARTH,ZEARTH
C
      HEARTH=SQRT(XEARTH**2+YEARTH**2)
      FEARTH=SQRT(HEARTH**2+ZEARTH**2)
C
      WRITE(6,*)'HOW MANY FIELD COMPONENTS ARE YOU INTERESTED IN?'
      READ(IRUN,*)NCOMP1
      IF(IRUN1.NE.0)WRITE(IRUN1,*)NCOMP1
      IF(NCOMP1.NE.0)THEN
      WRITE(6,*)'WHAT FIELD COMPONENTS ARE YOU INTERESTED IN?
     1 (X,Y,Z,H,F). ENTER EACH COMPONENT NAME AND PRESS <RETURN>
     2 AFTER EACH.'
      DO 437 ICOMP=1,NCOMP1
437      READ(IRUN,433)COMP(ICOMP)
433   FORMAT(A)
      IF(IRUN1.NE.0)THEN
      DO 435 ICOMP=1,NCOMP1
435      WRITE(IRUN1,434)COMP(ICOMP)
434   FORMAT(A)
      ENDIF
      ENDIF
      WRITE(6,*)'HOW MANY FIELD DERIVATIVES ARE YOU INTERESTED IN?'
      READ(IRUN,*)NDERIV1
      IF(IRUN1.NE.0)WRITE(IRUN1,*)NDERIV1
      IF(NDERIV1.NE.0)THEN
      WRITE(6,*)'WHICH FIELD DERIVATIVES ARE YOU INTERESTED IN?
     1 (DFDX,DFDY,DFDZ,DXDX,DXDY,DXDZ,DYDX,DYDY,DYDZ,DZDX,DZDY,DZDZ)'
      IDERIV1=NCOMP1+1
      IDERIV2=NCOMP1+NDERIV1
      DO 438 IDERIV=IDERIV1,IDERIV2
438      READ(IRUN,433)COMP(IDERIV)
      IF(IRUN1.NE.0)THEN
      DO 436 IDERIV=IDERIV1,IDERIV2
436   WRITE(IRUN1,434)COMP(IDERIV)
      ENDIF
      ENDIF
      WRITE(6,*)'WHAT IS THE F(0) VALUE TO BE SUBTRACTED FROM F'
      READ(IRUN,*)FCORR
      IF(IRUN1.NE.0)WRITE(IRUN1,*)FCORR

C
      NCOMPS1=NCOMP1+NDERIV1
      IF(NCOMPS1.EQ.0)STOP'"NCOMPS1'
C
      IF(THISRUN.EQ.'INVERSE')THEN
C
C INITIALIZE  THE PARAMETER ARRAY BPARAMS(IPARAM) HERE
C USING THE DATA JUST READ IN.
C
      DO 20 ICASING=1,NCASING1
      DO 20 IPOLE=1,NPOLE1(ICASING)
      IF(IPOLE.EQ.1)THEN
      I=I+1
```

```
      BPARAMS(I)=BETA(ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=PHI(ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=CHU(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=X1(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=Y1(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=Z1(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=LENGTH(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      ELSE
      I=I+1
      BPARAMS(I)=CHU(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=X1(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=LENGTH(IPOLE,ICASING)
      BO(I)=BPARAMS(I)
      ENDIF
   20 CONTINUE
      ILAST=I
      I=I+1
      BPARAMS(I)=XEARTH
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=YEARTH
      BO(I)=BPARAMS(I)
      I=I+1
      BPARAMS(I)=ZEARTH
      BO(I)=BPARAMS(I)
      IO=I
C
      IF(IRANDOM.NE.0)THEN
       DO 303 IBO=1,IO-3
        RANDOM=2.*(.5-RAN(ISEED))
303     BO(IBO)=BO(IBO)*(1.+PERCENT(1)*RANDOM)
       DO 304 IBO=IO-2,IO
        RANDOM=2.*(.5-RAN(ISEED))
304     BO(IBO)=BO(IBO)*(1.+PERCENT(2)*RANDOM)
      ENDIF
C
      ENDIF
C
C
C
C *********************************END OF DATA INPUT**************************
C
C
C PRINT OUT THE INPUT DATA:
```

```
C
      WRITE(6,80)NCASING1
   80 FORMAT('1NUMBER OF CASINGS:'I3,/)
      DO 60 ICASING=1,NCASING1
      WRITE(6,51)ICASING,BETA(ICASING),PHI(ICASING)
   51 FORMAT(' CASING='I3,5X'ORIENTATION: BETA(RAD)='F5.2,',',3X,
     1 ' PHI(RAD)='F5.2/)
      WRITE(6,53)
   53 FORMAT(' POLE'5X'STRENGTH'7X'POSITION(X,Y,Z)'9X'LENGTH'/)
      WRITE(6,52)(IPOLE,POLES(IPOLE,ICASING),
     1 X1(IPOLE,ICASING),Y1(IPOLE,ICASING),Z1(IPOLE,ICASING),
     2 LENGTH(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING)
     3 ,Z2(IPOLE,ICASING),IPOLE=1,NPOLE1(ICASING))
   52 FORMAT((1H I2,5X,4F12.3,2X,F10.3,/,1H 16X,3F10.3))
   60 CONTINUE
      WRITE(6,61)X0,XF,INTX,Y0,YF,INTY,Z0,ZF,INTZ
   61 FORMAT(' THE REGION OF INTEREST IS:'/
     1   5X ' X-LIMITS:'1X,2(F8.3,1X),I3' INTERVALS'/
     2   5X ' Y-LIMITS:'1X,2(F8.3,1X),I3' INTERVALS'/
     3   5X ' Z-LIMITS:'1X,2(F8.3,1X),I3' INTERVALS'//)
C
C PRINT OUT THE GEOMAGNETIC FIELD COMPONENTS
C
      WRITE(6,82)XEARTH,YEARTH,ZEARTH,HEARTH,FEARTH
82    FORMAT(' THE COMPONENTS (X,Y,Z,H,F) OF THE GEOMAGNETIC FIELD ARE:'
     1,1X,/, 5(E12.4,1X)//)
C
C PRINT OUT THE COMPONENTS REQUESTED
C
      WRITE(6,*)' THE FOLLOWING COMPONENTS HAVE BEEN REQUESTED:'
      WRITE(6,*)(COMP(I),I=1,NCOMPS1)
C
C END OF PRINTING OF INPUT DATA
C
      IF(THISRUN.EQ.'INVERSE')RETURN
C
      DO 63 INAME=1,NCOMPS
   63 NAMESO(INAME)=INAME
C
C SET UP THE FINITE DIFFERENCE GRID.
C
C
      IF(INTX.NE.0)THEN
      DX=(XF-X0)/INTX
      ELSE
      DX=0.
      ENDIF
      IF(INTY.NE.0)THEN
      DY=(YF-Y0)/INTY
      ELSE
      DY=0.
      ENDIF
      IF(INTZ.NE.0)THEN
      DZ=(ZF-Z0)/INTZ
      ELSE
      DZ=0.
      ENDIF
C
      DO 21 IX=1,INTX1
   21 X(IX)=X0+(IX-1)*DX
      DO 22 IY=1,INTY1
```

```
   22 Y(IY)=Y0+(IY-1)*DY
      DO 23 IZ=1,INTZ1
   23 Z(IZ)=Z0+(IZ-1)*DZ
C
C PROCEED TO CALCULATE THE MAGNETIC FIELD COMPONENTS AND THEIR DE-
C RIVATIVES FOR THE SPECIFIED DISTRIBUTION OF POLES AND CASINGS.
C
C SET UP THE INDECES FOR THE REQUESTED COMPONENTS
C
      DO 73 IC=1,NCOMPS1
      DO 73 INAME=1,NCOMPS
   73 IF(COMPO(INAME).EQ.COMP(IC))NAMESO(INAME)=IC
C
C
      DO 33 IF=1,NCOMPS1
      DO 33 ICASING=1,NCASING1
      NP=NPOLE1(ICASING)
      DO 33 IPOLE=1,NP
      DO 31 IX=1,INTX1
      DO 31 IY=1,INTY1
      DO 31 IZ=1,INTZ1
      IF(COMP(IF).EQ.'X')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1 BX(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'Y')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1 BY(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'Z')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1 BZ(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DXDX')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DXDX(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DXDY')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DXDY(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DXDZ')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DXDZ(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DYDX')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DYDX(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DYDY')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DYDY(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2    Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3    Z2(IPOLE,ICASING),IPOLE,ICASING)
```

```
      ELSEIF(COMP(IF).EQ.'DYDZ')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DYDZ(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2     Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3     Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DZDX')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DZDX(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2     Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3     Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DZDY')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DZDY(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2     Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3     Z2(IPOLE,ICASING),IPOLE,ICASING)
      ELSEIF(COMP(IF).EQ.'DZDZ')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+
     1  DZDZ(X(IX),Y(IY),Z(IZ),X1(IPOLE,ICASING),Y1(IPOLE,ICASING),
     2     Z1(IPOLE,ICASING),X2(IPOLE,ICASING),Y2(IPOLE,ICASING),
     3     Z2(IPOLE,ICASING),IPOLE,ICASING)
      ENDIF
   31 CONTINUE
   33 CONTINUE
C
C
C ADD IN THE EARTH'S MAGNETIC FIELD
C
C
      DO 42 IF=1,NCOMPS1
      DO 42 IX=1,INTX1
      DO 42 IY=1,INTY1
      DO 42 IZ=1,INTZ1
      IF(COMP(IF).EQ.'X')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+XEARTH
      ELSEIF(COMP(IF).EQ.'Y')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+YEARTH
      ELSEIF(COMP(IF).EQ.'Z')THEN
      FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)+ZEARTH
      ENDIF
   42 CONTINUE
C
C
C
      DO 41 IF=1,NCOMPS1
      DO 41 IX=1,INTX1
      DO 41 IY=1,INTY1
      DO 41 IZ=1,INTZ1
      IF(COMP(IF).EQ.'H')THEN
      FIELDS(IX,IY,IZ,IF)=
     1       SQRT(FIELDS(IX,IY,IZ,IFX)**2+
     2            FIELDS(IX,IY,IZ,IFY)**2)
      ELSEIF(COMP(IF).EQ.'F')THEN
      FIELDS(IX,IY,IZ,IF)=
     1       SQRT(FIELDS(IX,IY,IZ,IFX)**2 +
     2            FIELDS(IX,IY,IZ,IFY)**2 +
     3            FIELDS(IX,IY,IZ,IFZ)**2  )
      ELSEIF(COMP(IF).EQ.'DFDX')THEN
      FIELDS(IX,IY,IZ,IF)=
     1 (FIELDS(IX,IY,IZ,IFX)*FIELDS(IX,IY,IZ,IFDXDX)+
     2  FIELDS(IX,IY,IZ,IFY)*FIELDS(IX,IY,IZ,IFDYDX)+
     3  FIELDS(IX,IY,IZ,IFZ)*FIELDS(IX,IY,IZ,IFDZDX))/
```

```
     4     FIELDS(IX,IY,IZ,IFF)
      ELSEIF(COMP(IF).EQ.'DFDY')THEN
      FIELDS(IX,IY,IZ,IF)=
     1 (FIELDS(IX,IY,IZ,IFX)*FIELDS(IX,IY,IZ,IFDXDY)+
     2  FIELDS(IX,IY,IZ,IFY)*FIELDS(IX,IY,IZ,IFDYDY)+
     3  FIELDS(IX,IY,IZ,IFZ)*FIELDS(IX,IY,IZ,IFDZDY))/
     4     FIELDS(IX,IY,IZ,IFF)
      ELSEIF(COMP(IF).EQ.'DFDZ')THEN
      FIELDS(IX,IY,IZ,IF)=
     1 (FIELDS(IX,IY,IZ,IFX)*FIELDS(IX,IY,IZ,IFDXDZ)+
     2  FIELDS(IX,IY,IZ,IFY)*FIELDS(IX,IY,IZ,IFDYDZ)+
     3  FIELDS(IX,IY,IZ,IFZ)*FIELDS(IX,IY,IZ,IFDZDZ))/
     4     FIELDS(IX,IY,IZ,IFF)
      ENDIF
   41 CONTINUE
C
      IF(IRECORD.NE.0)THEN
      DO 801 IF=1,NCOMPS1
801   WRITE(IRECORD,800)((( FIELDS(IX,IY,IZ,IF),
     1  X(IX),Y(IY),Z(IZ),COMP(IF),
     2     IX=1,INTX1),IY=1,INTY1),IZ=1,INTZ1)
      ENDIF
      IF(IRANDOM.NE.0)THEN
      DO 310 IF=1,NCOMPS1
      DO 310 IX=1,INTX1
      DO 310 IY=1,INTY1
      DO 310 IZ=1,INTZ1
      RANDOM=2.*(.5-RAN(ISEED))
310   FIELDS(IX,IY,IZ,IF)=FIELDS(IX,IY,IZ,IF)*(1.+PERCENT(1)*RANDOM)
      DO 901 IF=1,NCOMPS1
901   WRITE(IRANDOM,800)((( FIELDS(IX,IY,IZ,IF),
     1  X(IX),Y(IY),Z(IZ),COMP(IF),
     2     IX=1,INTX1),IY=1,INTY1),IZ=1,INTZ1)
      ENDIF
800   FORMAT(4E16.8,1X,A5)
C
C
C
C************** START OF PLOTTING SECTION *****************************
C
C PLOT THE REQUESTED DATA:
C
      WRITE(6,*) ' DO YOU WISH TO PLOT A FUNCTION? 1=YES;
     1 ANY OTHER NUMERIC KEY = NO'
      IRUN=5
50    READ(IRUN,*)GOON
      IF(GOON.EQ.1)THEN
C
C SET UP THE PLOTTING DATA
C
      WRITE(6,*)' STARTING PLOT NUMBER:',IPLOT
      WRITE(6,*)'WHICH COMPONENT DO YOU WANT TO PLOT?'
      READ(IRUN,433)KOMP
      WRITE(6,*)'WHICH DIRECTION DO YOU WANT TO PLOT?'
      READ(IRUN,433)DIRXYZ
      WRITE(6,*)' ENTER THE INDECES OF THE OTHER TWO DIRECTIONS THAT
     1 WILL DEFINE THE LINE OF PLOTTING:'
      READ(IRUN,*)INDEX1,INDEX2
      CALL PLOT1(KOMP,DXP,DYP,FIELDS,XYZ,NX,NY,NZ,NXPYPZ,COMP,
     1 IPLOT,INTX1,INTY1,INTZ1,NCOMPS1,DIRXYZ,INDEX1,INDEX2,
     2 IDIR,PLOTTHIS,NP)
```

```
C
      WRITE(5,*) ' DO YOU WANT TO PLOT THESE VALUES?
     1 1=YES,  ANY OTHER NUMERIC KEY=NO'
      READ(IRUN,*)GOOD
      IF(GOOD.NE.1)THEN
      IPLOT=IPLOT-1
      GOTO 71
      ENDIF
C
C SETUP THE PLOTTING SIMULATION
C
      ISL(1)=1
      WRITE(6,*)'ENTER THE PLOTTING DEVICE NUMBER:'
      READ(IRUN,*)IPLOTR
      WRITE(6,*)'ENTER TITLE OF PLOT:'
      READ (IRUN,*)PTITLE
      WRITE(6,*)'ENTER TITLE OF X-AXIS'
      READ (IRUN,*)XTITLE
      WRITE(6,*)'ENTER TITLE OF Y-AXIS'
      READ (IRUN,*)YTITLE
      CALL PLTSET(IPLOTR,XBOARD,YBOARD,ISL)
      NOPTS=4
      XP(4)=XBOARD
      YP(4)=YBOARD
      XP(3)=2.
      YP(3)=2.
      XP(2)=0.
      YP(2)=0.
      XP(1)=XP(4)-XP(3)-1.
      YP(1)=YP(4)-YP(3)-.5
      ICON=0
      IPN=0

      IF(IPLOTR.EQ.1) CALL TEKSETUP

      CALL SCALE(DXP,DYP,XP,YP,NOPTS,IER)
      CALL LINE(XYZ(1,IDIR),PLOTTHIS,NP,ICON,IPN)
       ENCODE(40,991,IXTITLE) XTITLE
991   FORMAT(A40)
      CALL VCHAR(4.2,.9,IXTITLE,40,3,.1,0.,0.,0.)
      ENCODE(40,992,IYTITLE) YTITLE
992   FORMAT(A40)
      CALL VCHAR(1.,2.1,IYTITLE,40,3,.1,1.5706,0.,0.)
      ENCODE(40,993,IPTITLE) PTITLE
993   FORMAT(A40)
      YPOS=YP(4)-.1
      CALL VCHAR(1.,YPOS,IPTITLE,40,3,.1,0.,0.,0.)
      DELY=(DYP(2)-DYP(1))/10
      DELX=(DXP(2)-DXP(1))/32
      SIZE=.1
      IP=2
      FMT='(F7.1)'
      NFMT=7
      CALL XAXIS(DXP,DYP,XP,DELX,IP,SIZE,%REF(FMT),NFMT)
      CALL YAXIS(DYP,DXP,YP,DELY,IP,SIZE,%REF(FMT),NFMT)
      CALL NEATL
      CALL ENDPT(IE)
      CALL VT100
71    WRITE(6,*)'DO YOU WANT ANOTHER PLOT? 1=YES, ANY OTHER KEY=NO
      GOTO 50
      ENDIF
```

```
62    CONTINUE
C
C
C END OF CASINGSF
      IF(THISRUN.EQ.'FORWARD')RETURN
      ENDIF
C
C ********************BEGINNING OF INVERSE PROGRAM*********************
C
      I=0
      DO 500 ICASING=1,NCASING1
      DO 500 IPOLE=1,NPOLE1(ICASING)
      IF(IPOLE.EQ.1)THEN
      IPARAM1=7
      ELSE
      IPARAM1=3
      ENDIF
      DO 500 IPARAM=1,IPARAM1
      I=I+1
      P(IPARAM,IPOLE,ICASING)=BPARAMS(I)
  500 CONTINUE
      DO 600 ICASING=1,NCASING1
      BETA(ICASING)=P(1,1,ICASING)
      PHI(ICASING)=P(2,1,ICASING)
      CMU(1,ICASING)=P(3,1,ICASING)
      X1(1,ICASING)=P(4,1,ICASING)
      Y1(1,ICASING)=P(5,1,ICASING)
      Z1(1,ICASING)=P(6,1,ICASING)
      LENGTH(1,ICASING)=P(7,1,ICASING)
      X2(1,ICASING)=X1(1,ICASING)+LX(LENGTH(1,ICASING),
     1 BETA(ICASING),PHI(ICASING))
      Y2(1,ICASING)=Y1(1,ICASING)+LY(LENGTH(1,ICASING),
     1 BETA(ICASING),PHI(ICASING))
      Z2(1,ICASING)=Z1(1,ICASING)+LZ(LENGTH(1,ICASING),
     1 BETA(ICASING))
      DO 700 IPOLE=2,NPOLE1(ICASING)
      CMU(IPOLE,ICASING)=P(1,IPOLE,ICASING)
      X1(IPOLE,ICASING)=P(2,IPOLE,ICASING)
      Z1(IPOLE,ICASING)=Z1(1,ICASING)+
     1   LZ(X1(IPOLE,ICASING),BETA(ICASING))
      Y1(IPOLE,ICASING)=Y1(1,ICASING)+
     1   LY(X1(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      X1(IPOLE,ICASING)=X1(1,ICASING)+
     1   LX(X1(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      LENGTH(IPOLE,ICASING)=P(3,IPOLE,ICASING)
      X2(IPOLE,ICASING)=X1(IPOLE,ICASING)+
     1  LX(LENGTH(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      Y2(IPOLE,ICASING)=Y1(IPOLE,ICASING)+
     1  LY(LENGTH(IPOLE,ICASING),BETA(ICASING),PHI(ICASING))
      Z2(IPOLE,ICASING)=Z1(IPOLE,ICASING)+
     1  LZ(LENGTH(IPOLE,ICASING),BETA(ICASING))
  700 CONTINUE
  600 CONTINUE
      XEARTH=BPARAMS(ILAST+1)
      YEARTH=BPARAMS(ILAST+2)
      ZEARTH=BPARAMS(ILAST+3)
      HEARTH=SQRT(XEARTH**2+YEARTH**2)
      FEARTH=SQRT(HEARTH**2+ZEARTH**2)
C
C EVALUATE THE FIELD COMPONENTS FOR THE GIVEN DATA POINT
C
```

```
C
      ININ=IN
      XCASINGO=XEARTH
      YCASINGO=YEARTH
      ZCASINGO=ZEARTH
      IF(TYPE(IN).EQ.'          ')TYPE(IN)=TYPE(IN-1)
      DO 18 IC=1,NCASING1
      DO 18 IP=1,NPOLE1(IC)
      IF(TYPE(IN).EQ.'X         '.OR.TYPE(IN).EQ.'F         ')THEN
      XCASINGO = XCASINGO +
     1 BX(XIN(IN,1),XIN(IN,2),XIN(IN,3),
     2 X1(IP,IC),Y1(IP,IC),Z1(IP,IC),
     3   X2(IP,IC),Y2(IP,IC),Z2(IP,IC),IP,IC)
      ENDIF
      IF(TYPE(IN).EQ.'Y         '.OR.TYPE(IN).EQ.'F         ')THEN
      YCASINGO = YCASINGO +
     1 BY(XIN(IN,1),XIN(IN,2),XIN(IN,3),
     2  X1(IP,IC),Y1(IP,IC),Z1(IP,IC),
     3   X2(IP,IC),Y2(IP,IC),Z2(IP,IC),IP,IC)
      ENDIF
      IF(TYPE(IN).EQ.'Z         '.OR.TYPE(IN).EQ.'F         ')THEN
      ZCASINGO = ZCASINGO +
     1 BZ(XIN(IN,1),XIN(IN,2),XIN(IN,3),
     2  X1(IP,IC),Y1(IP,IC),Z1(IP,IC),
     3   X2(IP,IC),Y2(IP,IC),Z2(IP,IC),IP,IC)
      ENDIF
   18 CONTINUE
      IF(TYPE(IN).EQ.'F         ')THEN
      FCASINGO =(SQRT(XCASINGO**2+YCASINGO**2+ZCASINGO**2))-FCORR
      ENDIF
C
      IF(TYPE(IN).EQ.'X         ')THEN
      FCALC=XCASINGO
      ELSEIF(TYPE(IN).EQ.'Y         ')THEN
      FCALC=YCASINGO
      ELSEIF(TYPE(IN).EQ.'Z         ')THEN
        FCALC=ZCASINGO
      ELSEIF(TYPE(IN).EQ.'F         ')THEN
        FCALC=FCASINGO
        ENDIF
C
C
C END OF INVERSE ROUTINE
C
C
      RETURN
      END
C
C
C
      SUBROUTINE PLOT1
     1    (KOMP,DXP,DYP,FIELDS,XYZ,NX,NY,NZ,NXPYPZ,COMP,
     2 IPLOT,INTX1,INTY1,INTZ1,NCOMPS1,DIRXYZ,INDEX1,INDEX2,
     3 IDIR,PLOTTHIS,NP)
C
C THIS ROUTINE PREPARES TO PLOT THE REQUESTED DATA
C
      DIMENSION DXP(1),DYP(1),FIELDS(NX,NY,NZ,1)
      DIMENSION PLOTTHIS(1),DIR(1),XYZ(NXPYPZ,1)
      CHARACTER*5 DIRXYZ,KOMP,COMP(1)
```

```
C
C FIND THE COMPONENT TO BE PLOTTED
C
      DO 5 IC=1,NCOMPS1
      WRITE(6,*)KOMP,COMP(IC),IC,NCOMPS1
    5 IF(COMP(IC).EQ.KOMP)IKOMP=IC
      WRITE(6,*)'IKOMP',IKOMP
C
C SELECT THE DIRECTION OF PLOTTING
C
      IP=0
      IF(DIRXYZ.EQ.'X')THEN
      IEND=INTX1
      IDIR=1
      DO 1 IX=1,INTX1
      IP=IP+1
    1 PLOTTHIS(IP)=FIELDS(IX,INDEX1,INDEX2,IKOMP)
      NP=INTX1
      ELSEIF(DIRXYZ.EQ.'Y')THEN
      IEND=INTY1
      IDIR=2
      DO 2 IY=1,INTY1
      IP=IP+1
    2 PLOTTHIS(IP)=FIELDS(INDEX1,IY,INDEX2,IKOMP)
      NP=INTY1
      ELSEIF(DIRXYZ.EQ.'Z')THEN
      IEND=INTZ1
      IDIR=3
      DO 3 IZ=1,INTZ1
      IP=IP+1
    3 PLOTTHIS(IP)=FIELDS(INDEX1,INDEX2,IZ,IKOMP)
      NP=INTZ1
      ENDIF
      DXP(1)=XYZ(1,IDIR)
      DXP(2)=XYZ(IEND,IDIR)
      DYP(1)=PLOTTHIS(1)
      DYP(2)=PLOTTHIS(1)
      DO 4 IP=1,NP
      DYP(1)=MIN(DYP(1),PLOTTHIS(IP))
    4 DYP(2)=MAX(DYP(2),PLOTTHIS(IP))
      WRITE(6,*)' THE MINIMA/MAXIMA OF THE ARRAY TO BE PLOTTED ARE:'
      WRITE (6,*)DYP(1),DYP(2)
      WRITE(6,*)' THE VALUES BEING PLOTTED ARE:'
      WRITE(6,*)(PLOTTHIS(IP),IP=1,NP)
      RETURN
      END
C
C
C
      SUBROUTINE  SUBEND(YOBS,XINDEP,BPARAMS,KMAX,NOBS,TITLE,IOUT)
      DIMENSION YOBS(1),XINDEP(NOBS,4),BPARAMS(1),A(5),IB(1)
      CHARACTER*80 TITLE
        WRITE(16,313)
313     FORMAT(3X,'FINAL PARMS')
        WRITE(16,314)(I,BPARAMS(I),I=1,KMAX)
314     FORMAT(I3,5X,E15.8)
      RETURN
      ENTRY PCODE(P,X,BPARAMS,A,F,IN,IP,IB)
      RETURN
      ENTRY SUBZ(YOBS,XINDEP,BPARAMS,W,NDUM,NOBS,TITLE,IOUT)
      RETURN
```

```
      END
        subroutine teksetup
        write(*,'(1x,a,$)') char(27)//'2'//char(27)//'[2J'//
     +    char(27)//'1'//char(12)//char(27)//'"'//
     +    char(27)//'*'//char(27)//char(12)
        end
        SUBROUTINE VT100
        write(*,'(1x,a,$)') char(27)//'1'//char(12)//
     +    char(27)//'*'//char(27)//char(12)//char(27)//'0'//
     +    char(27)//'"'//char(27)//',2'//
     +    char(27)//'2'//char(27)//'[2J'//char(27)//'[H'
        end
        INTEGER FUNCTION SLEN(STRING)
        CHARACTER*(*) STRING
        DO 10 I=LEN(STRING),1,-1
                IF(STRING(I:I).NE.' ')THEN
                        SLEN=I
                        RETURN
                        ENDIF
10      CONTINUE
C
        SLEN=1
        RETURN
        END
```

APPENDIX II

TIME AND COST ESTIMATES FOR MAGNETIC SURVEYS

The time and costs of magnetic surveys designed to locate wells are difficult to estimate. Contractors have not had experience in making surveys with the required specification, and actual costs would be highly dependent on the location, size, and peculiarities of the specific area. The following estimates can be used as a guide to relative costs and rates of production, but the actual numbers would be used with great caution in planning potential work.

For small areas, where access is good, it would be more cost effective to use ground surveys than airborne surveys. Using a memory magnetometer, in which readings can be stored for later retrieval, and assuming a station spacing of 25 feet (7.6 m) one person can measure about four stations/minute or cover about 6,000 feet (1,820 m) per hour in sparsely vegetated, flat terrain. Additional time would be required to take more than one reading at a station or to make measurements at additional stations when anomalies are found. By use of a digitally recording base station and a desk top computer and plotter, data could be processed and plotted at the local field office or at the crews' living accommodations. Thus, problems could be identified and anomalies evaluated while the crew was in the field area.

If surveying could be done adequately by use of a magnetic compass for direction and a "hip chain" (which leaves a cotton thread behind) for distance, with occasional use of more accurate instruments to establish reference points, two persons could survey and make magnetic measurements in about the same amount of time as required for one person to make only measurements. If this method were not sufficiently accurate or could not be used in the area of interest for other reasons, surveying and marking station locations would likely require considerably more time than the actual magnetic measurements.

The cost for a two-person crew including salaries, living expenses, vehicle, equipment rental, supplies, and overhead, but not including mobilization to the field site, would be on the order of at least $10,000/4 weeks (1983 costs). By working a reasonable amount of overtime this crew might survey, process, and plot a maximum of 160-line miles in 4 weeks. If a line spacing of 50 feet (15.2 m) were used, this would cover an area of 1.52 square miles (3.94 km^2). This represents a cost of $6,600/square mile (2.59 km^2) covered and $62.50/line-mile (38.84/line-km). This is less than one-half the line-mile costs given by Senti (1982) for mineral exploration, but much mineral exploration is done in heavily vegetated terrain. Rates of production would be less and costs greater if the crew had to spend time in obtaining landowner's authorization for access to the land or if the crew interpreted the results and did additional detailed work to "pin-point" the location of suspected casings or investigate questionable anomalies.

For areas larger than a few square miles, airborne surveys are likely to be considerably less expensive than ground surveys. Although the costs per line mile may be roughly comparable for ground surveys and specialized airborne surveys, the line spacing can be much greater for airborne surveys. Airborne surveys are not practical for very small areas due to the high costs of mobilization.

Costs for routine aeromagnetic surveys using small fixed-wing aircraft are on the order of $8-14/line-mile ($5-9/line-km), including data processing provided: 1) several thousand line miles are flown in one block, 2) the lines are at least 10-20 miles (16-32 km) long, and 3) Doppler radar and photographic methods are used for flight path recovery. The costs for similar work done with rotary-wing aircraft are about $25-30/line-mile ($16-19/line-km). Costs per line mile are much greater if the lines are short and the areas small and if a microwave navigation system is required.

Following are the rough costs, based largely on informal discussion with a particular contractor, for surveying using a rotary-wing aircraft and a microwave navigation system:

Installation and removal of equipment from aircraft	$ 10,500
Helicopter standby time during installation and mobilization to area including up to 14 hours of flight time	$ 7,000
Surveying, placement, and maintainence of transponders	$ 3,000
Four days in field, equipment and crew at $2,000/day	$ 8,000
Ten hours flight time at $500/hour for helicopter and pilot	$ 5,000
Rent of microwave navigation system, one month minimum at $5,000/month	$ 5,000
Supplies and computer	$ 1,500
Total	$ 40,000

Line miles flown	$ 400
Cost per line mile	$ 100
Area flown (400 ft spacing)	30.3 sq. mi.
Cost per sq. mi	$ 1,320

Using the same mobilization costs and assuming that four weeks were spent in the field to do a large project, the costs for the same system would be roughly:

Total cost including 56 hours of production flying....................$125,000

Line miles flown	2,000
Cost per line mile	$ 62.50
Area flown	151.52 sq. mi.
Cost per sq. mi	$ 825

Similar costs were mentioned by other contractors; some items were less and some more. In general, aeromagnetic contractors do not have dedicated helicopters or microwave navigation systems; these are rented as required for special projects.

The costs for gradiometer measurements using a fixed-wing aircraft would likely be somewhat less than for total field measurements using a rotary-wing aircraft. On the other hand, gradient measurements from a rotary-wing aircraft would cost considerably more than total field measurements. Although gradient measurements have been made from rotary-wing aircraft, it appears that no contractor is currently using this configuration.

The above estimates include the cost of initial data processing and plotting data in profile form. There would be additional costs to contour, filter, or interpret the data. Also, of course, in most cases ground checking of some anomalies would be required to complete evaluation of an area.