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Borehole Magnetometry: Detection of a Steel Liner from a Nearby Observation Borehole

by

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ABSTRACT

Steel casings and liners in boreholes produce magnetic fields which can be observed in adjacent boreholes and on the earth's surface. In this application, we attempted to measure the perturbation to the magnetic declination caused by a steel liner at depth. At one site the presence of the liner was clearly revealed by the horizontal and vertical magnetic fields in boreholes located 20 m and 25 m from the hole containing the liner. However, reproducibility of the declination among subsequent runs was never better than ±2 degrees, and was as much as ±5 degrees. Despite the poor repeatability, constraints can be placed upon the declination by using a monopole model of the liner which duplicates the character of the magnetic field components.

INTRODUCTION

Steel casing in wells produces regional and local perturbations to the earth's magnetic field. Early studies by Van Weeldon (1933) and Barret (1931) examined the magnetic field anomalies both theoretically and in the field; their goal was to determine the effect of a developed oil field on the regional magnetic field. Recent work by Frischknecht and others (1983, 1985) determined the magnetic character of casing using ground and airborne magnetic surveys; their goal was to develop procedures for locating abandoned wells.

In the subsurface, the magnetic effect of casing has been used to estimate the proximity of a relief well being drilled to intersect and extinguish a blowout well (Warren, 1981). The magnetic effect of a drill string upon a directional survey compass housed in a non-magnetic drill section is examined by Scott and MacDonald (1979).

The USGS was requested to obtain magnetic field logs in "satellite" boreholes close to emplacement holes which are partially lined with steel. Work was done at two sites, emplacement hole U20bd, which had two satellite boreholes, and U20bb, with one satellite borehole. Both sites are located on Pahute Mesa at the Nevada Test Site.

The objective was to measure the magnetic field in the satellite hole and determine the perturbation to the declination of the earth's field caused by the liner in the emplacement hole. The first part of this report deals with the data acquisition, analysis, and repeatability: we found we were unable to measure the declination to the desired one degree accuracy. Despite the measurement limitations, the magnetic character was defined well enough that it could be modelled; the model serves to estimate the amount of declination to be expected as a function of distance and azimuth around an emplacement hole.

TOOL DESCRIPTION

The borehole tool used for this work was described in detail by Scott and Olson (1985). It contains: (1) three orthogonal fluxgate sensors with a resolution of 10 nT (10 gammas), measuring the magnetic field component colinear with the axis of the tool and two orthogonal components in the plane normal to the tool axis, (2) two inclinometers aligned orthogonally in the plane normal to the tool axis, (3) a gyroscope that records the horizontal angle between its spin axis and a refence on the tool housing, and (4) a temperature sensor. In addition to data from these seven sensors, depth, time, and power supply deviation were also recorded.

The tool was run with and without bow-spring centralizers. Materials used to construct the centralizers are made of non-magnetic materials, as is the tool housing. However, the cable and cable head used to hoist the tool are magnetic. The tool alone is 8 feet, 10 inches long; with centralizer sections attached above and below, the entire assembly is 20 feet long with approximately 15 feet between centralizers.

PROCEDURE

After warmup of the gyro and before logging, the tool was oriented so that a sight could be obtained on a survey stake at grid west or grid east relative to each borehole. The sight was repeated after each run and a gyro reading obtained before and after the survey. A gyro drift rate was computed from these two readings (see Tables A1 and B1) and used to correct the data by interpolating linearly with time. Most runs were accomplished within 2 to 4 hours. The sighting also serves as a geographic reference for the gyrocompass.

Some logs were obtained continuously, at a speed of about 15 feet per minute while sampling at depth intervals of one or two feet. Other logs were obtained by stopping at stations spaced 5, 10, or 50 feet apart and waiting about 30 seconds until measurements stabilized. On some runs, data were obtained both while logging downwards and upwards. The direction of logging can be discerned by the order of depth listed in Tables A1 and B1.

DATA PROCESSING

The data were processed on a Hewlett-Packard 9845 desktop computer using software developed by J.H. Scott and modified by the author. Two schemes were used, simplified processing and full processing. The simplified processing was used for preliminary evaluation in the field immediately after the logs were acquired. The simplified processing sequence assumes that the hole is perfectly vertical and does not use the inclinometer data; it assumes that all tool rotation is due strictly to rotation of a vertical tool about its own axis. Full processing, on the other hand, makes use of the inclinometer readings to remove the effect of tool rotation from the gyro reading. The two processing schemes provided assurance that declination was computed correctly; results were quite close wherever the borehole was within 0.5 degree of vertical. All figures and data in this report are from full processing.

The full processing sequence is as follows:

1. Apply corrections for temperature to the inclinometers and magnetic sensors. Correct for magnetic contribution of logging cable and cable head.

2. Convert the magnetometer output to microTesla (uT).

3. Convert inclinometer readings from sensor units to the sine of the angle between the tool axis and vertical.

4. Remove drift from gyro readings.

5. Correct the inclinometer readings for rotation about the probe axis. Subtract tool (inclinometer) rotation and the initial sight reading from the gyro.

6. Perform a series of three coordinate transforms to rotate the magnetic components from a tool frame of reference to a geographic frame of reference. In the latter reference frame, x,y, and z are geographic north, geographic east, and vertical, respectively.

7. Compute horizontal field, vertical field, inclination and declination.

DISCUSSION

The magnetic field logs are shown in Appendices A and B. The logs sampled every foot show more character and more noise than the logs sampled every 10 or 50 feet. Surface casing, which extends from surface to 60 or 120 feet depending upon the hole, completely disrupts the readings and appears as a black band on some logs.

Above 350 m, the horizontal and vertical components respond to the remanent magnetization of the tuffs. Normal remanence decreases the vertical field and increases the horizontal field within the borehole, as seen at a depth of 110 m in U20bb1. Reverse remanence produces the opposite result; large increases in the vertical field and decreases in the horizontal field occur from 200 to 260 m in U20bb1. Below 350 m, variations of the field components due to geological causes are less than 1 uT, with the notable exception of a reversely magnetized vitrophyre unit at 450 m in U20bd1 and U20bd2.

Repeatability of the field components depends upon the ability to relocate at a given depth station and upon the tilt of the tool in the borehole. It is clear from inspection of the figures in the Appendices that repeatability of the vertical component is considerably better than that of the horizontal component. Tilt of the probe affects the horizontal measurement more than the vertical measurement, as pointed out by Scott and Olson (1985). In U20bd1 we measured nominal horizontal and vertical fields of 23,500 and 45,500 nT, equivalent to a total field of 51,210 nT at an inclination of 62.68 degrees. If the sensors were misaligned by 0.1 degree or if the tilt error were 0.1 degree, so that the inclination angle were actually 62.78 degrees, then the horizontal and vertical components would be 23,420 and 45,541 nT, producing an error of -80 and 41 nT respectively. This factor of two in uncertainty is about what is observed in the figures, although the tilt uncertainty must be closer to 0.5 degrees if tilt alone is to account for the lack of repeatability.

For any run in which measurements were made on both the "in-run" (tool going down) and "out-run" (tool coming up), the repeatability of the declination is no better than 2 to 4 degrees (figures A-2 and B-1 through B-5). (An exception is the first run in U20bd1 (figure A-3), where the out-run was impaired by a damaged centralizer band. This out-run will be excluded from further consideration.) Comparison of the declination obtained among sequential runs in hole U20bb1 shows that one run (figure B-4) differs greatly from the others (figures B-3 and B-5), by about 10 degrees at the bottom of the hole. No explanation has been found for this discrepancy: the tool operated normally, the in-run matched the out-run, and gyro drift was normal. With this log removed from further consideration, the spread between the third and fifth runs at the bottom of the hole is about 5 degrees. At 368 m (1200 feet) the declination ranges from 12 to 21 degrees among the logs of figures B-1, B-2, B-3 and B-5. Similar problems with repeatability were noted for the U20bd holes (Nelson, 1990) and can be examined in Appendix A, although there are not as many repeat runs as in U20bb1. Clearly the tool requires improvement so that declination can be determined with better repeatability.

It should be pointed out that the declination log tracks the east-west component of the horizontal field (see examples in Nelson, 1990), as expected for small declination angles. Thus the declination uncertainty is linked to uncertainty in the east-west component. Scott and Olson (1985) have already pointed out that the east-west component is measured with the highest uncertainty of the three orthogonal magnetic components. Thus, the declination measurement can be improved by reducing the uncertainty in the east-west component.

Data acquired continuously (tool moving) without centralizers (figs. B1, B4, and A-2) are not as noisy as data obtained continuously with centralizers (figs. A-1 and A-4). The noise is attributed to jitter of the tool which is recorded on the inclinometers. The noise can be reduced by filtering the inclinometer data (fig. A-5) and could probably be further reduced by filtering the magnetometer measurements.

MONOPOLE MODEL

The field from the steel liner can be modeled with magnetic monopoles. View the liner in the plane of the earth's field (upper half of figure 2), where B_{hn} and B_{zn} represent the horizontal and vertical components. Each component induces a magnetic polarization which can be represented by a pair of monopoles in the vertical case, and by a string of horizontal monopoles in the horizontal case. The field surrounding the vertical model possesses vertical and radial components, has no azimuthal component, and is axi-symmetric (lower half of figure 2). The field surrounding the horizontal model has predominantly radial and azimuthal components, although above and below the ends it can be expected to have a vertical component as well. The separation of the poles is taken to be the length of the liner for the vertical case, and therefore the resulting field can be expected to be much greater than for the horizontal case, where the poles are separated by approximately two meters.

We adopt a coordinate system in which the x-axis is aligned with magnetic north, the y-axis with magnetic east, and the z-axis is positive downwards. For the vertical polarization case, the components of the anomalous magnetic field due to two monopoles of strength m are:

$$B_x = \frac{m\,\mu_o}{4\pi}(x-x_i)\left\{-\frac{1}{r_i^3}+\frac{1}{r_b^3}\right\} \qquad (1)$$

$$B_y = \frac{m\,\mu_o}{4\pi}(y-y_i)\left\{-\frac{1}{r_i^3}+\frac{1}{r_b^3}\right\} \qquad (2)$$

$$B_z = \frac{m\,\mu_o}{4\pi}\left\{-\frac{z-z_i}{r_i^3}+\frac{z-z_b}{r_b^3}\right\} \qquad (3)$$

where x, y, z; x_i, y_i, z_i; and x_b, y_b, z_b are the coordinates of the measurement point, the upper monopole, and the lower monopole, respectively. The lengths r_i and r_b are the distances from the measurement point to the upper and lower monopole. The permeability of free space is μ_o.

To these anomalous components are added the components of the earth's field, B_{xn}, B_{yn} and B_{zn} with numerical values of 23.7 μT, 0 μT, and 45.5 μT, respectively. These values were selected to match the measurements of the unperturbed field in the lower halves of holes U20bd1 and U20bd2. The total field components are represented by B_{xt}, B_{yt}, and B_{zt}. The total horizontal field is calculated as

$$B_t = (B_{xt}^2 + B_{yt}^2)^{1/2} \qquad (4)$$

and the declination from magnetic north is

$$\theta = \arctan (B_{yt}/B_{xt}) \qquad (5)$$

The monopole model is compared with the magnetic logs in figures 3 and 4. The monopole strength was adjusted to match the horizontal field measurements of U20bd2; the match with the vertical component and with both components of U20bd1 confirm the fit. The salient features of the horizontal and vertical fields in both holes are replicated by the model. The placement of the monopoles at the extreme ends of the liner seems justified by the data in U20bd2. Perhaps the monopoles could be placed 6 or 7 m from the ends to satisfy the data of U20bd1, but the 15.2-m measurement spacing in U20bd1 makes the optimum placement less clear.

The matches between the computed and measured declination are not as good as the matches on the vertical and horizontal components because of the noise on the measured declination. At least the reversal in sign of the declination can be discerned: in U20bd2 the declination is reduced at the top of the liner whereas in U20bd1 it is increased.

Another confirmation of the monopole model results from the pole strength of 58,500 A-m used to match the data. Frischknecht and others (1985) list values ranging from 118 to 5,214 A-m from their surveys over 25 wells. Our value of 58,500 is an order of magnitude greater than the highest values reported by Frischknecht and others (1985). This appears to be reasonable, as the cross-sectional area of the steel liner is about an order of magnitude greater than that of oil-field well casing.

A limitation of the monopole model can be discerned in the vertical field. Midway between the monopoles the anomalous vertical field decreases, resulting in curvature of the log. However, the measured log is flat or increasing at the liner mid-point. Representing the liner as a magnetic continuum instead of discrete poles might correct this discrepancy.

It is clear that perturbations to the horizontal component are confined largely to a height immediately above and below the ends of the liner. In particular, the vertical monopole model predicts no perturbation of declination at elevations corresponding to the central portion of the liner.

Figures 5 and 6 demonstrate the expected behavior of the magnetic field as the observation hole is placed at different azimuths and distances from the liner. If the observation hole is located in the east-west (magnetic) plane, then the perturbation to declination is maximized and the perturbation to the magnitude of the horizontal component is minimized. If the observation hole is in the north-south plane, then these effects are reversed (compare upper and lower parts of figure 5). The anomalous vertical field, having azimuthal symmetry in both sign and magnitude, remains unchanged for a hypothetical observation hole at fixed distance but varying azimuth.

The magnitudes of the anomalous fields are quite sensitive to distance (fig. 6). An observation hole located 12.2 m (40 ft) east of the liner would record over 8 degrees of declination change opposite the top and bottom of the liner, whereas a hole placed 36 m distant would record only 1 degree of change. A comparable decline also occurs in the vertical field. Because the anomalous horizontal component is small compared to the ambient horizontal field and is directed to the magnetic south (fig. 2), there is little or no change in the total (observed) horizontal component.

What of the horizontal moment induced in the liner by the horizontal component of the earth's field? According to the sketch in figure 2, a horizontal moment produces an east-directed horizontal component at the location of U20bd2 and a west-directed component at U20bd1. Consequently, the declination would be increased at U20bd2 and decreased at U20bd1. The changes should be greatest at a depth corresonding to the center of the liner. However, the logs did not respond in this manner. The declination measured in U20bd2 at 600 m is about 13 degrees, less than the nominal declination of 14.8 degrees (fig. A-1). The declination at 600 m in U20bd1 is 17 to 19 degrees (figs. A-3 and A-4), greater than the nominal declination of 14.8 degrees. These measurements are counter to the expected field from a horizontal moment, but lie within the range of uncertainty from the nominal declination. We conclude that the horizontal moment is not sufficient to perturb the field at points 20 m distant from the liner.

SUMMARY

At the U20bd site, the liner in the emplacement hole was detected by vertical and horizontal magnetic field components in boreholes 20 and 25 m distant. Perturbations to the magnetic declination were about 1 or 2 degrees, were barely discernible due to noise, and seemed to occur at depths corresponding to the top and bottom of the liner. The anomalous behavior can be explained by vertical polarization of the liner, represented by a pair of magnetic monopoles.

At the U20bb site, the test was marred by the presence of drill string in the emplacement hole at the time of logging. As a consequence, the top of the liner is barely discernible in the vertical and horizontal field components. Despite this experimental difficulty, it is very unlikely that the declination is perturbed in U20bb1, because neither the vertical nor the horizontal induced moment of the liner would perturb the field at a point lying to magnetic north or south.

ACKNOWLEDGEMENTS

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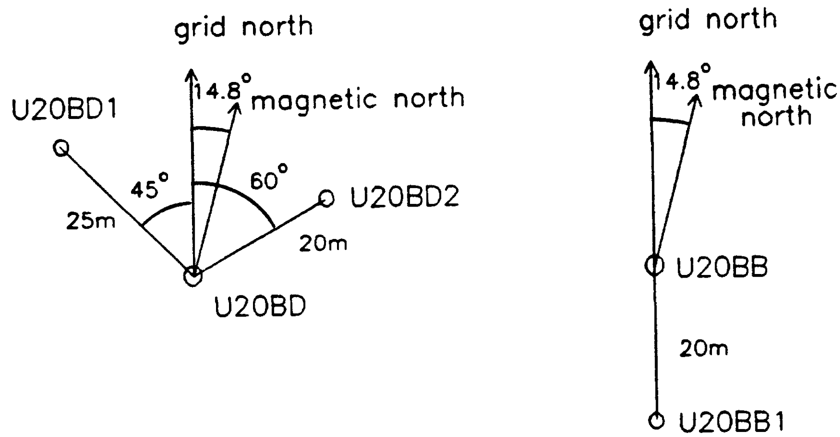


Figure 1. Location of satellite boreholes U20bd1 and U20bd2 relative to emplacement hole U20bd, and location of satellite borehole U20bb1 relative to emplacement hole U20bb.

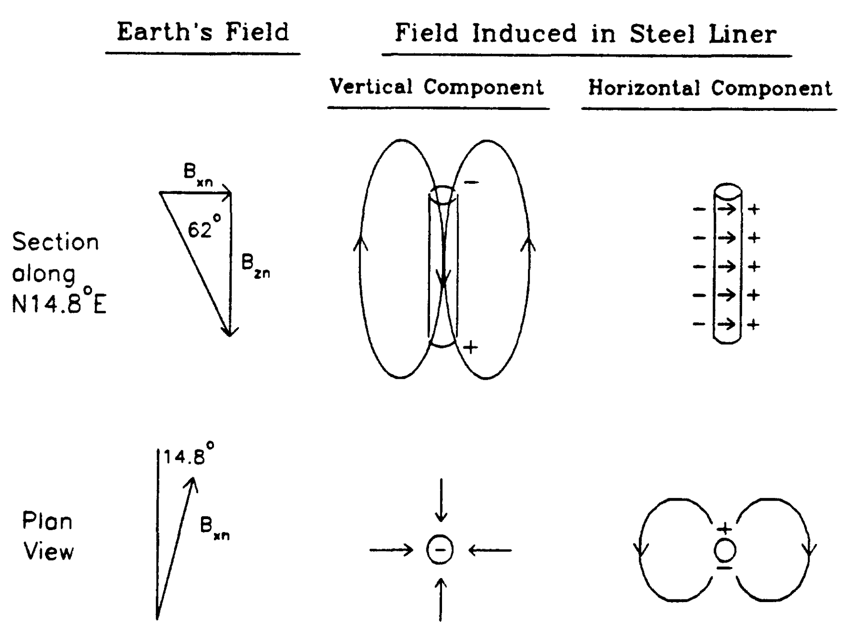


Figure 2. Schematic of the earth's magnetic field and induced components along a vertical section and a horizontal plan.

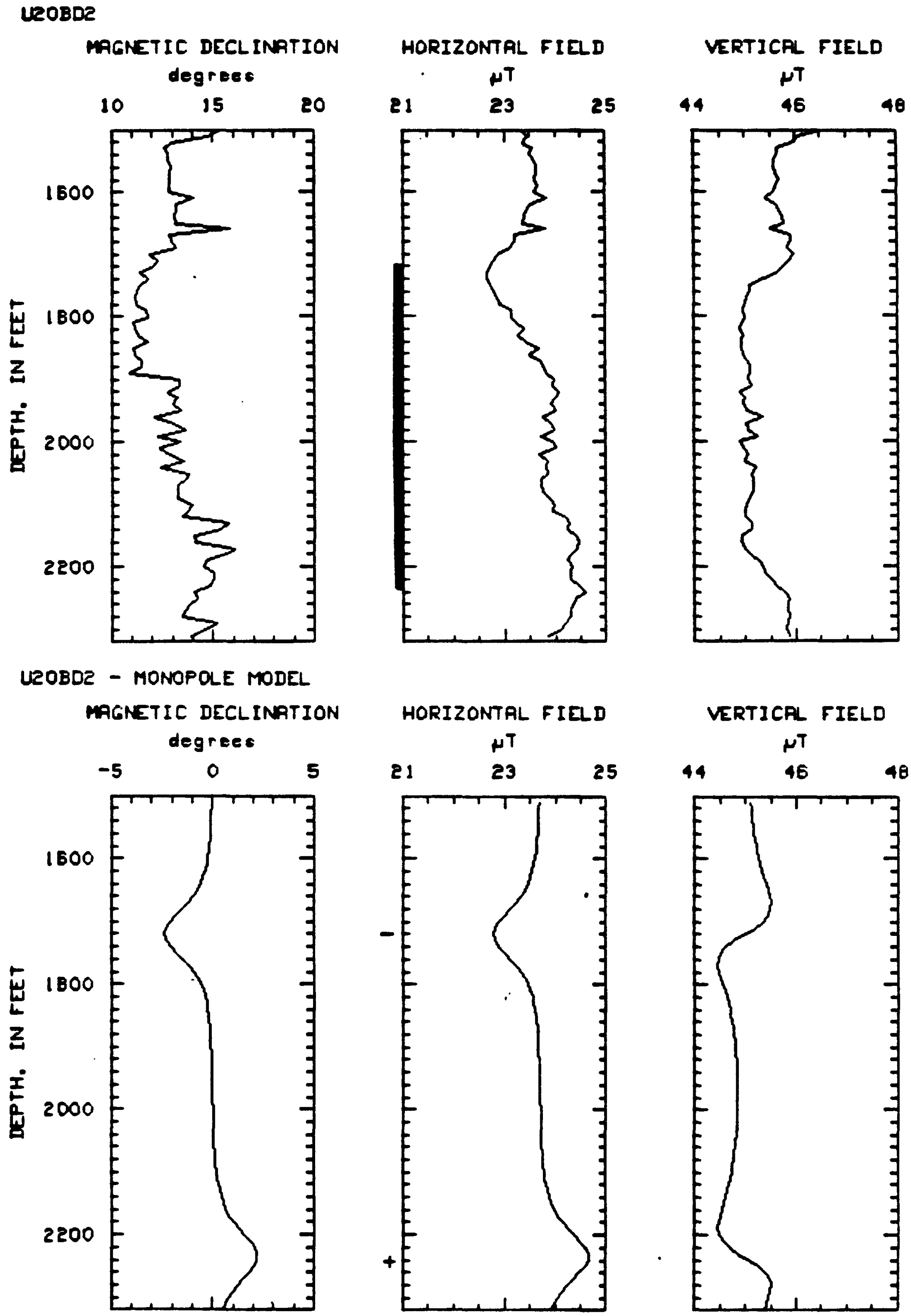


Figure 3. Magnetic declination, horizontal field, and vertical field as measured in U20bd2 (upper) and as computed for a monopole model (lower).

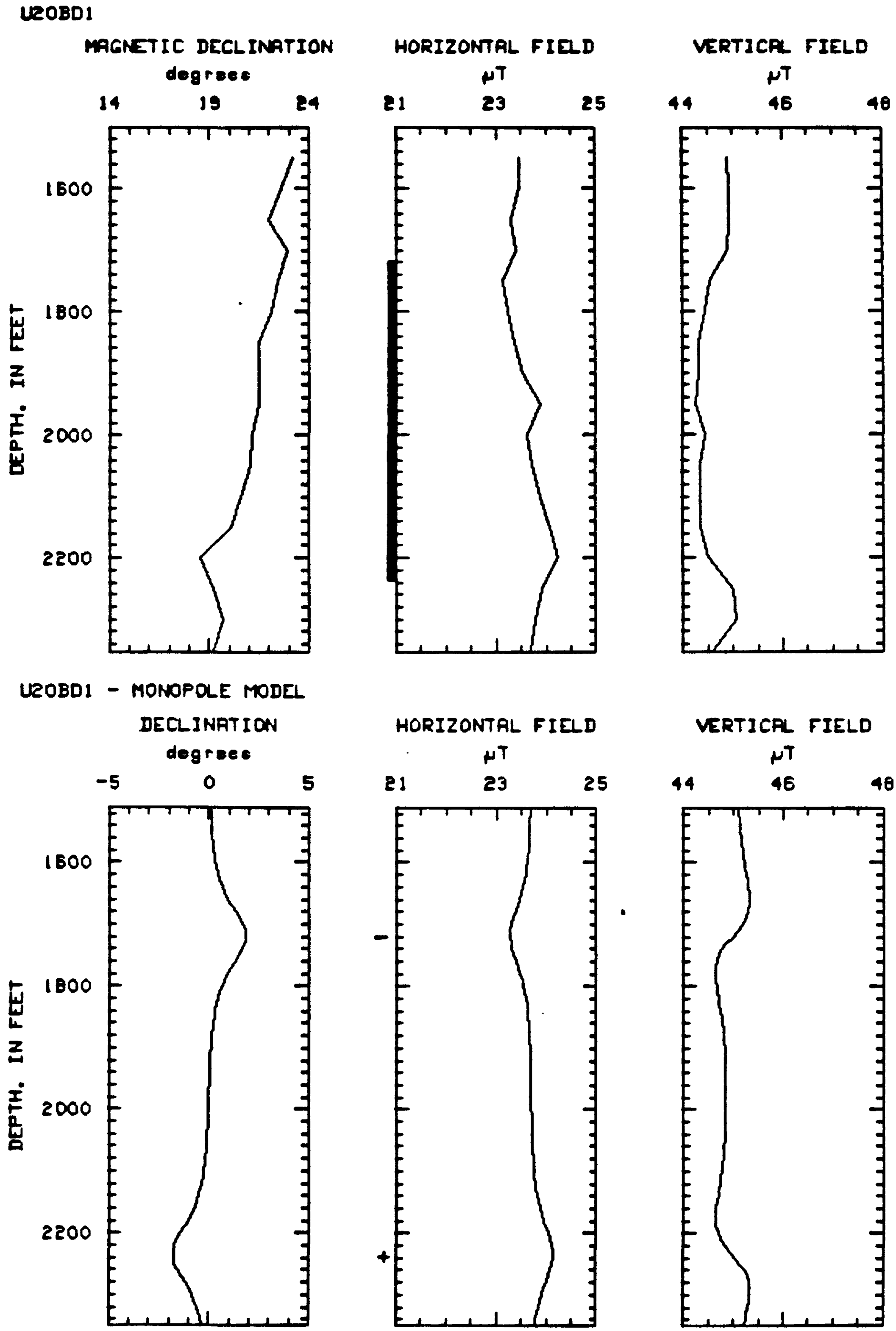


Figure 4. Magnetic declination, horizontal field, and vertical field as measured in U20bd1 (upper) and as computed for a monopole model (lower).

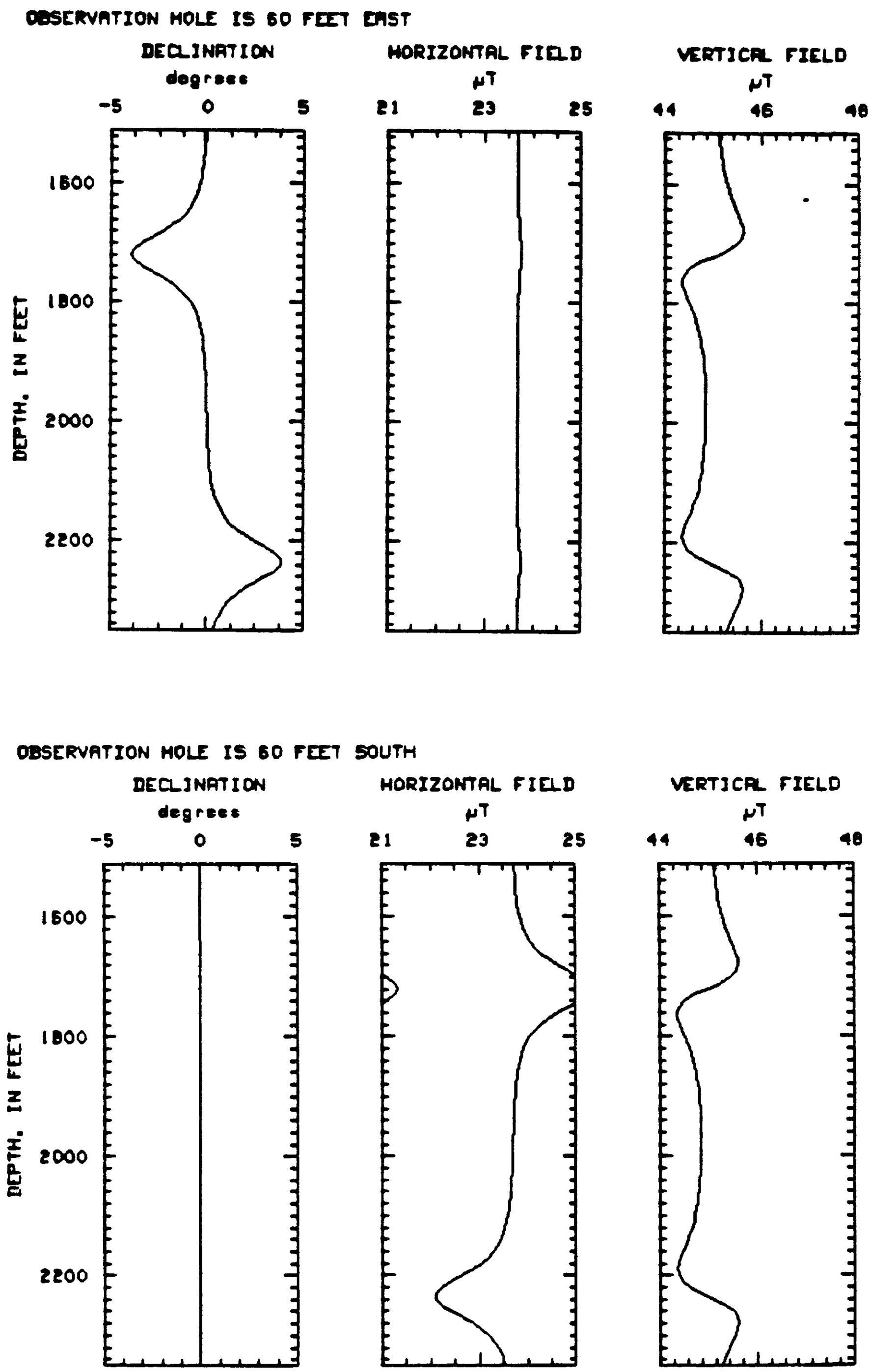


Figure 5. Magnetic declination, horizontal field, and vertical field computed for a monopole model, with the observation hole 18.3 m (60 feet) east and south of the hole containing the liner.

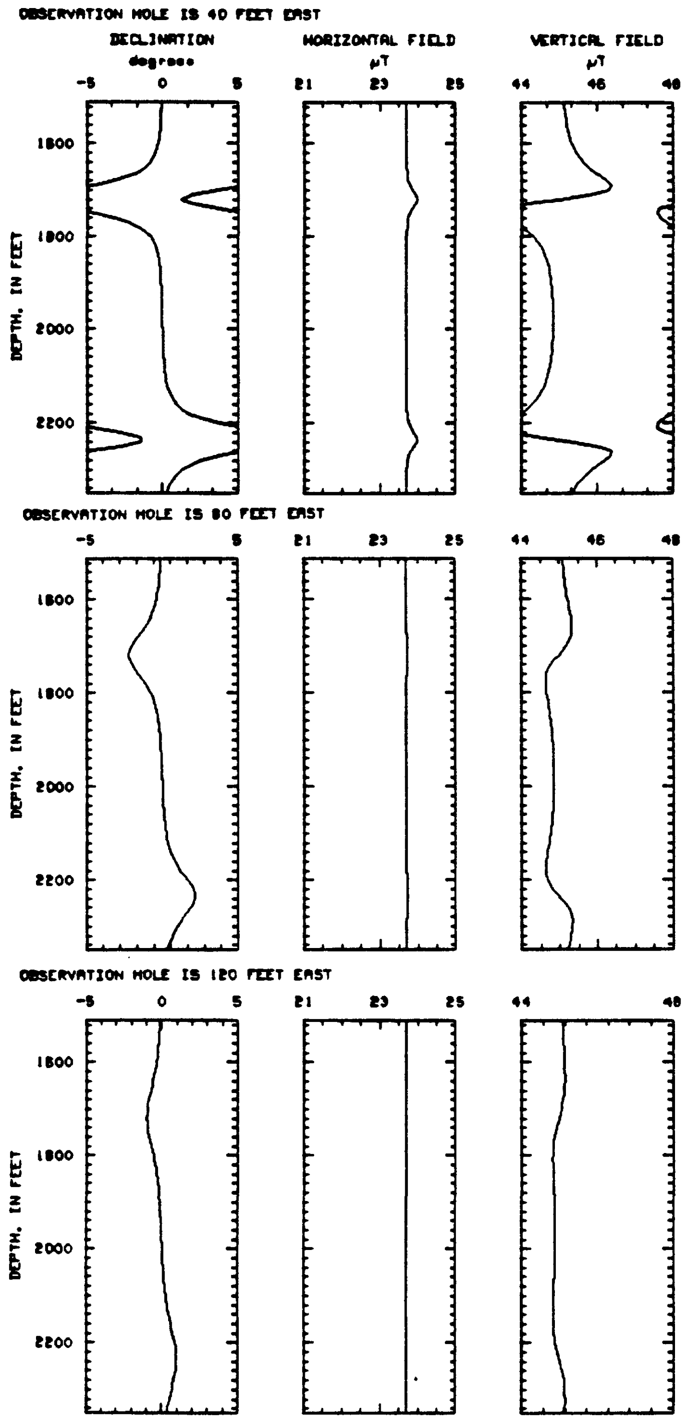


Figure 6. Magnetic declination, horizontal field, and vertical field computed for a monopole model, with the observation hole 12.2, 18.3, and 36.6 m (40, 60 and 120 feet) east of the hole containing the liner.

APPENDIX A. MAGNETIC LOGS FROM U20bd1 AND U20bd2

Magnetic field logs were acquired on five runs in hole U20bd2 and two runs in hole U20bd1 during Jan. 23-26, 1990 (Table A-1). Measurements were made as indicated in the "depth range" column. For example, on the first run in hole U20bd2, measurements were made on the in-run from surface to 680 feet and also on the out-run from 680 feet to surface. On the last run (Tape 9.1), measurements were made only on the out-run from 2030 feet to surface.

The boreholes penetrate a sequence of ash-flow and bedded tuffs. In hole U20bd, the Thirsty Canyon Tuff extends from 14 to 80 m, undifferentiated tuffs from 80 to 123 m, the Timber Mountain Tuff from 123 to 591 m, the Paintbrush Tuff from 591 to 646 m, and the Tuffs and Rhyolites of Area 20 from 646 to 732 m, (McKague and Newmark, Lawrence Livermore National Laboratory, written communication, 1989).

The top of the water column was at 2032 feet in U20bd2; most of the logging was done in an air-filled borehole. Both U20bd1 and U20bd2 were drilled with a 17.5-inch bit; according to caliper logs run by us and by Atlas Wireline Services, the hole size varied from bit size to 22 inches with a few washout zones of greater diameter.

Satellite hole U20bd1 lies 25 m (82 feet) northwest of the emplacement hole and satellite hole U20bd2 lies 20 m (66 feet) from the emplacement hole at a bearing of N60E. A steel liner in emplacement hole U20bd extends from 524 m to 681 m (1720 to 2235 feet); no other steel objects were known to be in the hole at the time of logging. The prime objective was to obtain the magnetic declination within two test intervals, 2000-2150 feet in Satellite #1 and 2100-2220 feet in Satellite #2.

Logs were acquired in segments to minimize the time spent in the hole, so that the gyro drift would be minimized. Magnetic declination, horizontal field, and vertical field, all computed with full processing, are shown in Figures A-1 through A-5. Data from the in-runs are drawn with a solid line; a dashed line designates the out-runs.

Table A-1. Magnetic field logs obtained in holes U20bd1 and U20bd2. The tool was run with (Y) or without (N) centralizers; logging was continuous (C) or at stations (S), and the minimum measurement spacing was 1, 2, 5, or 10 feet.

Hole	Tape	Date	Depth Range (feet)	Cent	Cont	Spc	Drift (deg/hr)
2	3.1	23 Jan	0-680-0	Y	C	2	-7.1
2	4.1	23 Jan	2100-2225-2100	Y	S	5	+0.5
2	5.1	25 Jan	0-300-0	N	C	1	+2.1
2	5.2*	25 Jan	0-1300-0	N	C	1	+3.3
2	7.1	25 Jan	1250-2350	N	S	10	+0.6
1	8.1	26 Jan	1300-2350-1480	Y	S	5	+1.7
1	9.1	26 Jan	2030-0	Y	C	1	+4.5

* Tape 5.2 had an error; data could not be recovered.

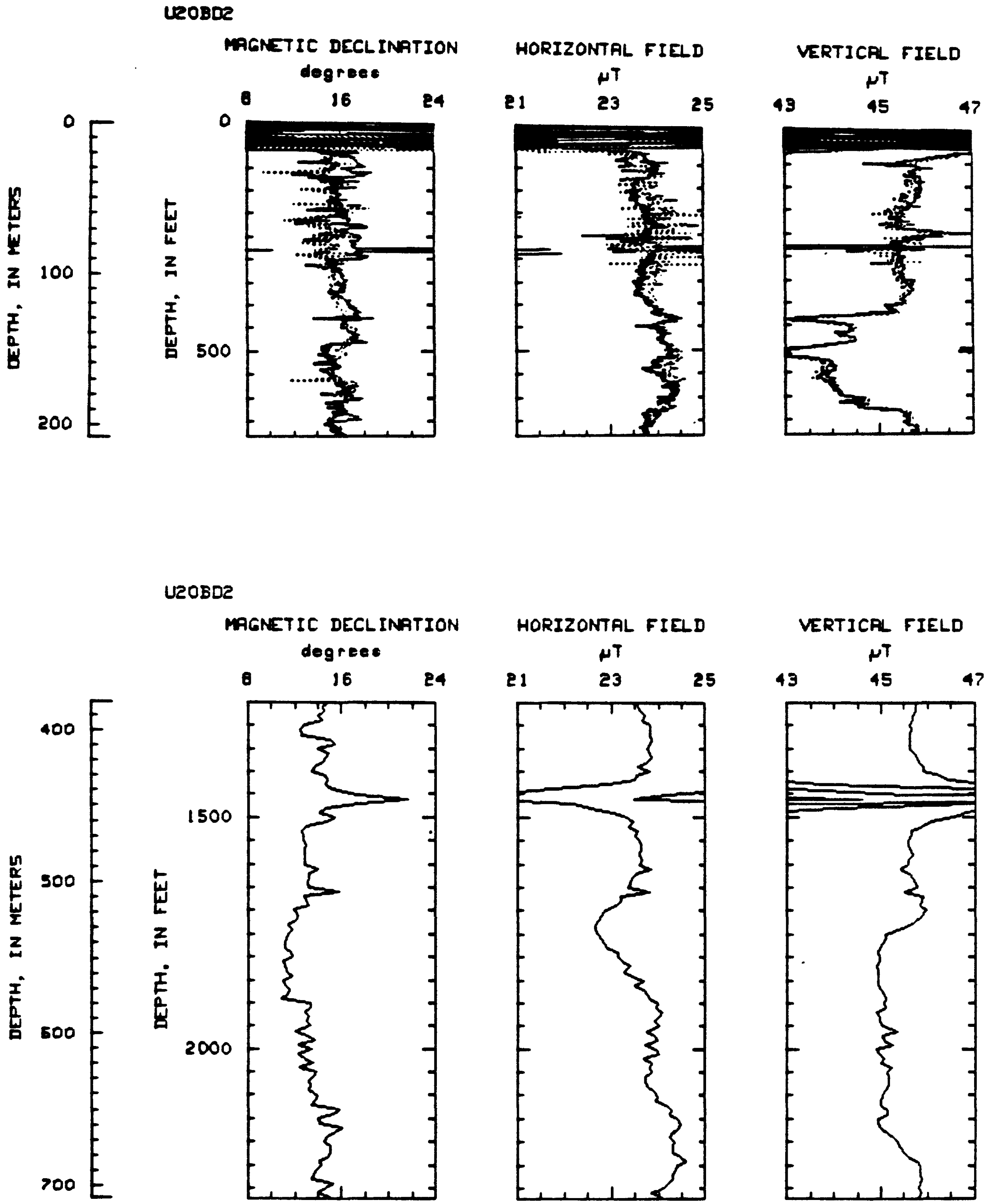
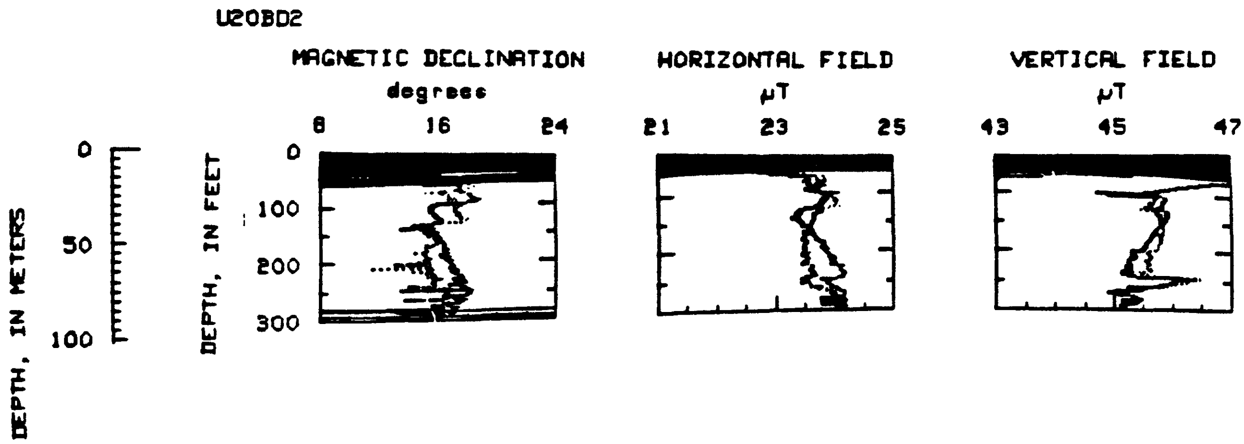


Figure A-1. Magnetic components from the first (upper) and fifth (lower) runs in hole U20bd2.



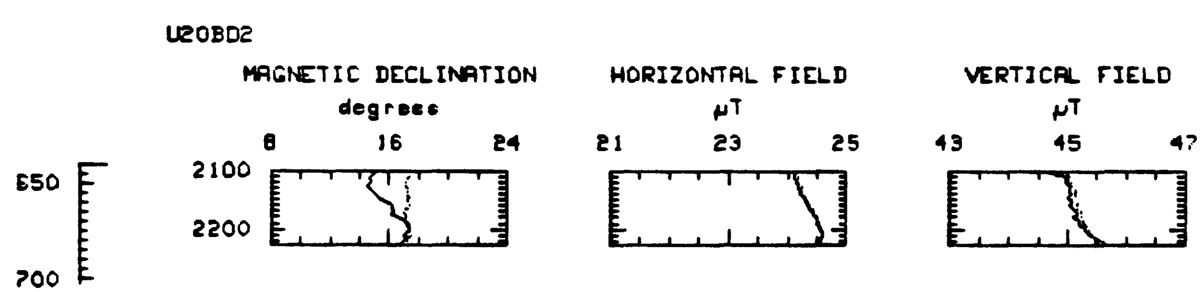


Figure A-2. Magnetic components from the third (upper) and second (lower) runs in hole U20bd2.

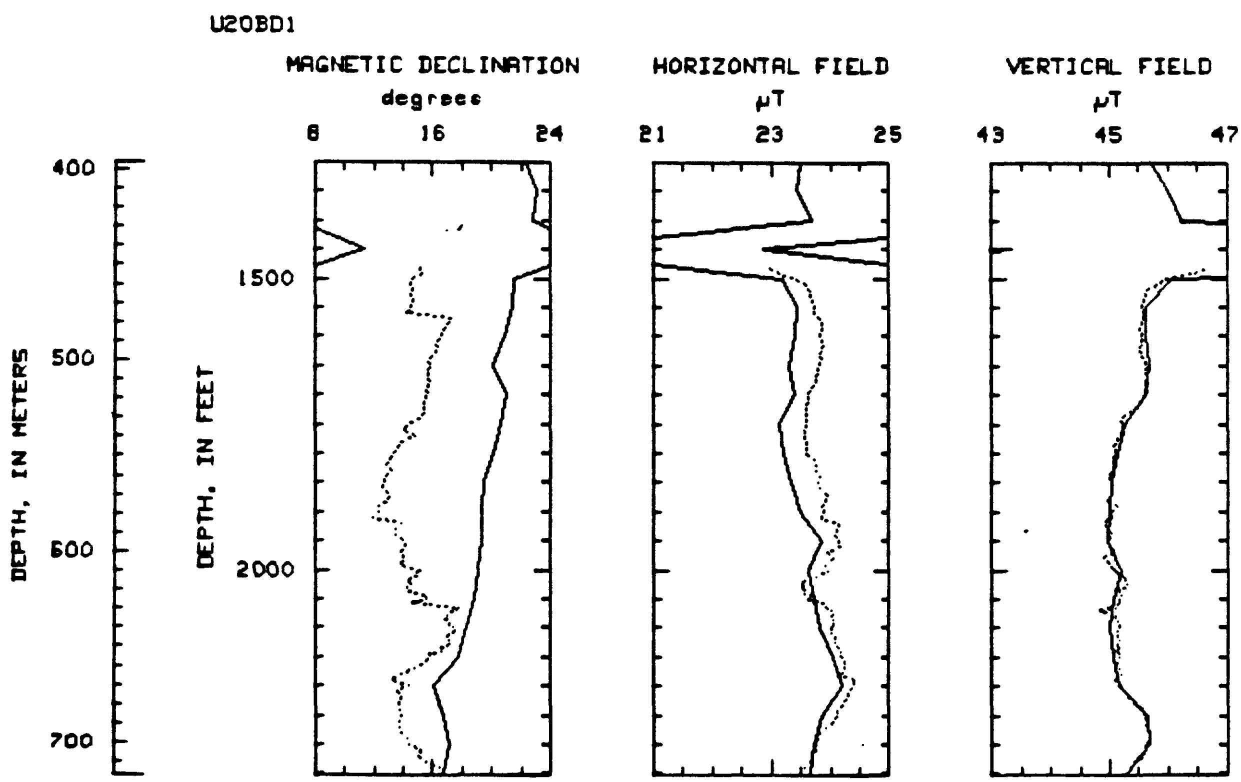


Figure A-3. Magnetic components from the first run in hole U20bdl. The out-run (dashed) is impaired by a damaged centralizer band.

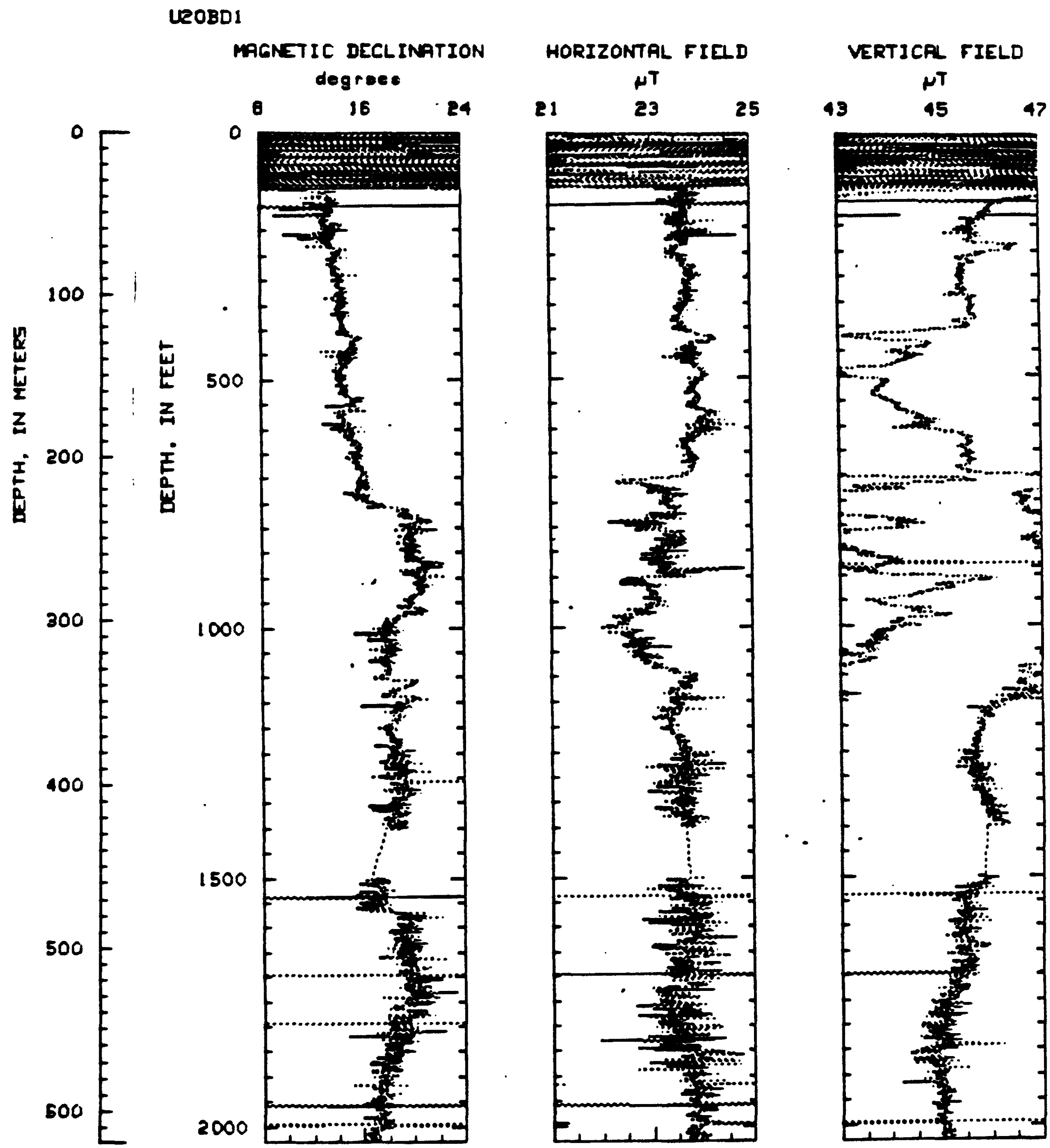


Figure A-4. Magnetic components from the second run in hole U20bdl.

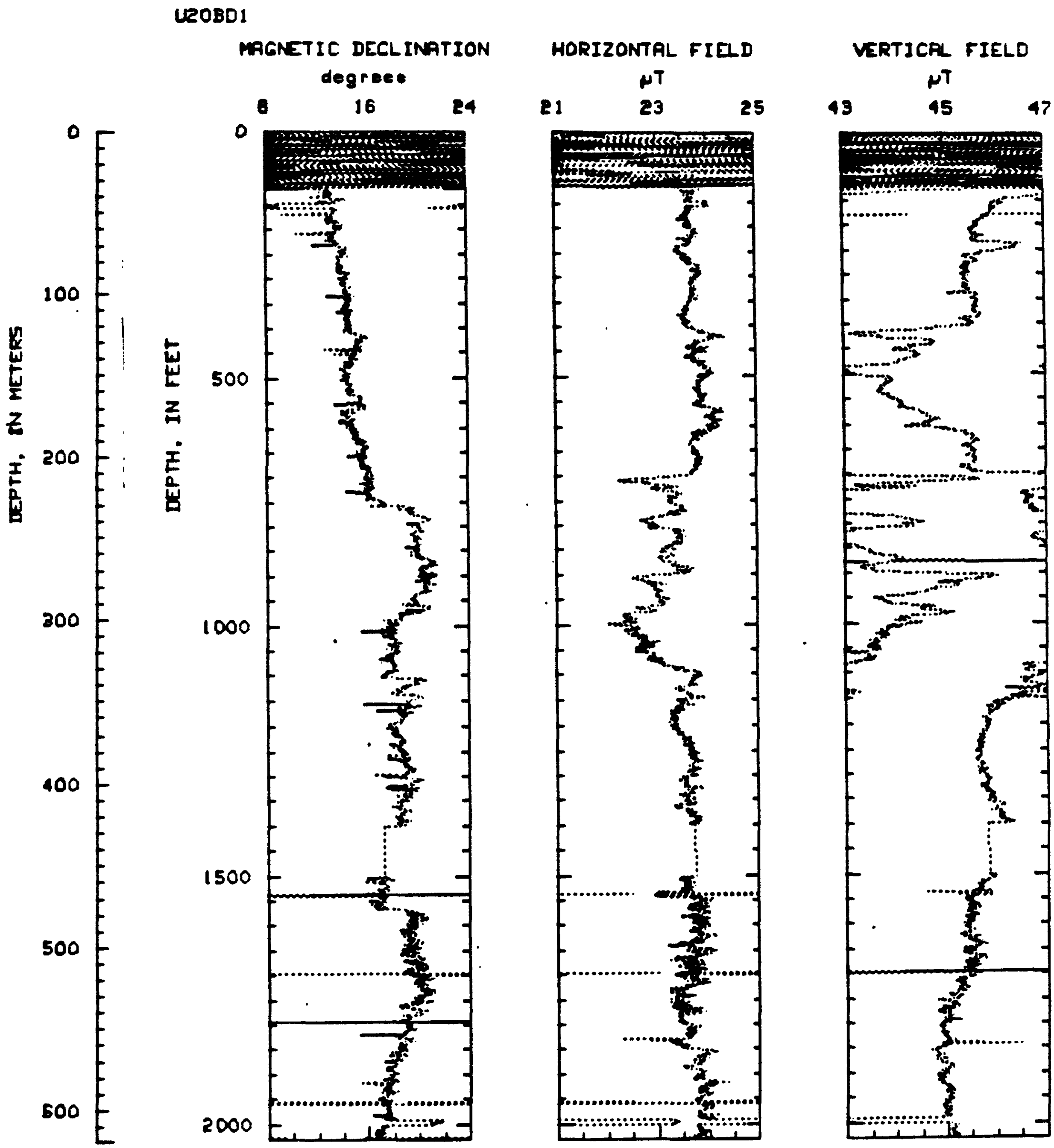


Figure A-5. Magnetic components from the second run in hole U20bdl, after filtering of the inclinometer data.

APPENDIX B. MAGNETIC LOGS FROM U20bb1

Magnetic field logs were acquired on five runs (Table B-1) during May 22-24, 1990. In this hole, measurements were made on both the in-run and the out-run in order to check for offsets in the gyro reading. The tool was centralized on three of the five runs and was run "slick" (without centralizers) on two runs. On the four runs where station measurements were made, the spacing on the in-run was 50 feet; a finer spacing of 10 feet was used on the out-run. On two runs, the tool was in motion while data were acquired at a spacing of 1 foot.

Top of the water column was encountered at 2019 feet, so all logging was done in an air-filled borehole. The hole was drilled with a 17.5-inch bit. According to caliper logs run by the USGS and by Atlas Wireline Services, hole diameter varies from bit size to about 22 inches. The stratigraphy encountered in U20bb1 is similar to that of U20bd (Appendix A). The Thirsty Canyon Tuff extends from surface to 73 m, the Volcanics of Fortymile Canyon from 73 to 85 m, the Timber Mountain Tuffs from 85 to 614 m, and the Paintbrush Tuff from 614 to 677 m (Newmark and Wagoner, Lawrence Livermore National Laboratory, written communication, 1989).

The satellite hole is located 20 m (65.6 feet) south of the emplacement hole U20bb. The emplacement hole has a steel liner 2.49 m (98 inches) in diameter extending from 458 m to 624 m (1502 to 2047 feet). Inadvertently, at the time of logging, drill rod was hanging in the hole from surface to 624 m (2047 feet). Of particular interest is the magnetic field in the test zone extending from 533 to 594 m (1750 to 1950 feet) subsurface.

Magnetic declination, horizontal field, and vertical field, all computed with full processing, are shown in Figures B-1 through B-5. Data from the in-runs are drawn with a solid line; a dashed line designates the out-runs.

Table B-1. List of magnetic field logs by tape number and depth range. The tool was run with (Y) or without (N) centralizers; logging was continuous (C) or at stations (S); minimum spacing between measurements did not extend over entire depth range; change in reading of gyro before and after run is called drift; elapsed time of run.

Tape	Depth Range (feet)	Cent	Cont	Space (feet)	Drift (deg)	Time (hr)
2.1	0-1203-0	N	C	1	-13.9	2.55
3.1	0-1250-0	Y	S	10	+2.8	2.11
4.1	0-2000-0	Y	S	10	-2.8	2.71
5.1	0-2000-0	N	S,C,S	1	-1.0	2.49
6.1	0-2000-0	Y	S	10	-12.5	2.87

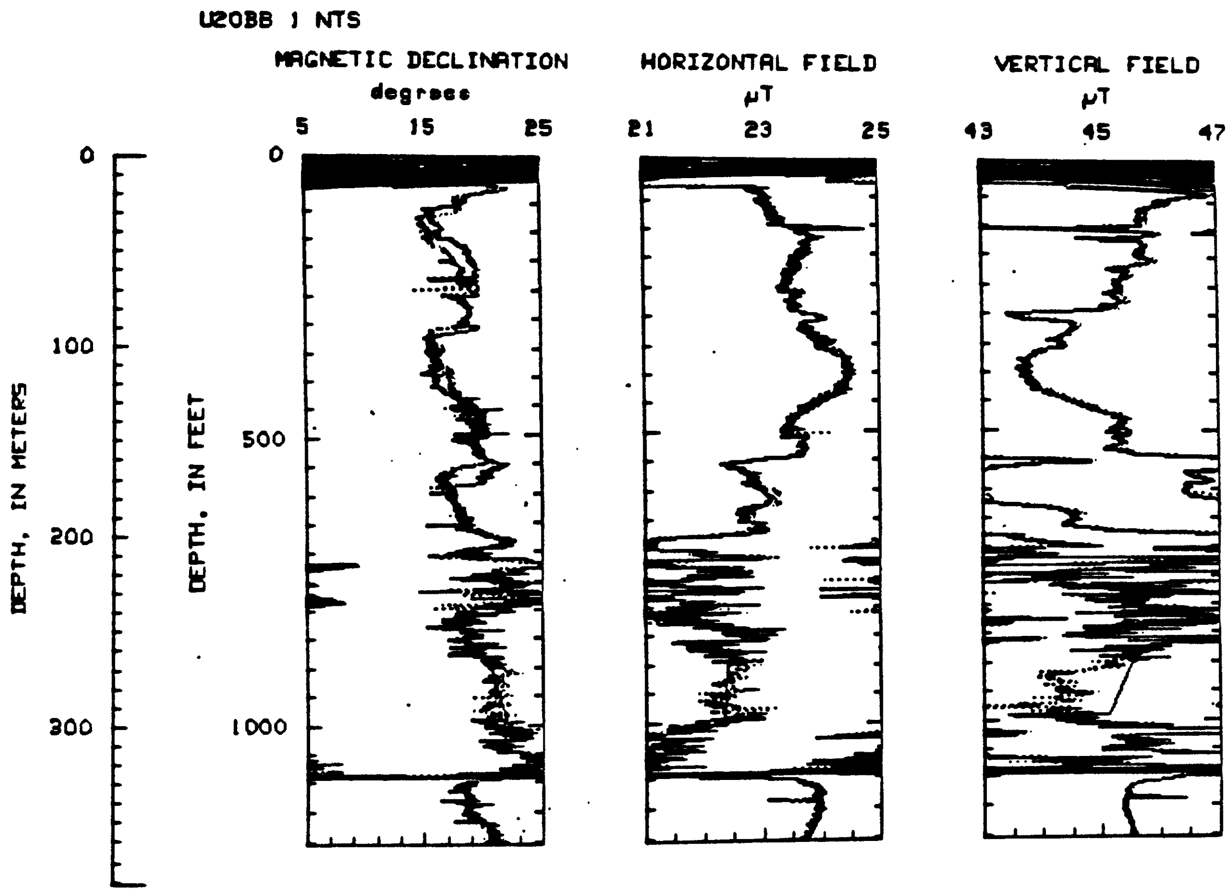


Figure B-1. Magnetic components from the first run in hole U20bb1.

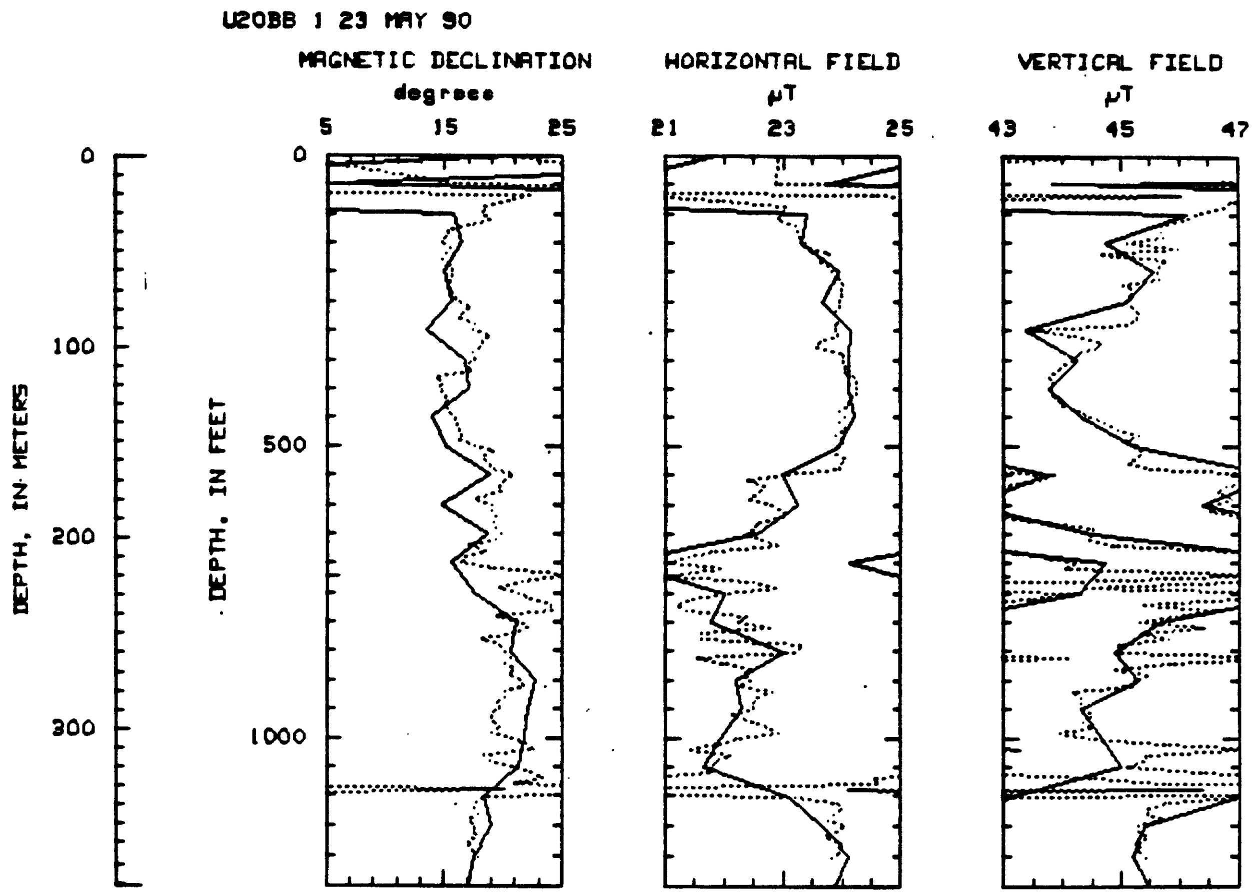


Figure B-2. Magnetic components from the second run in hole U20bb1.

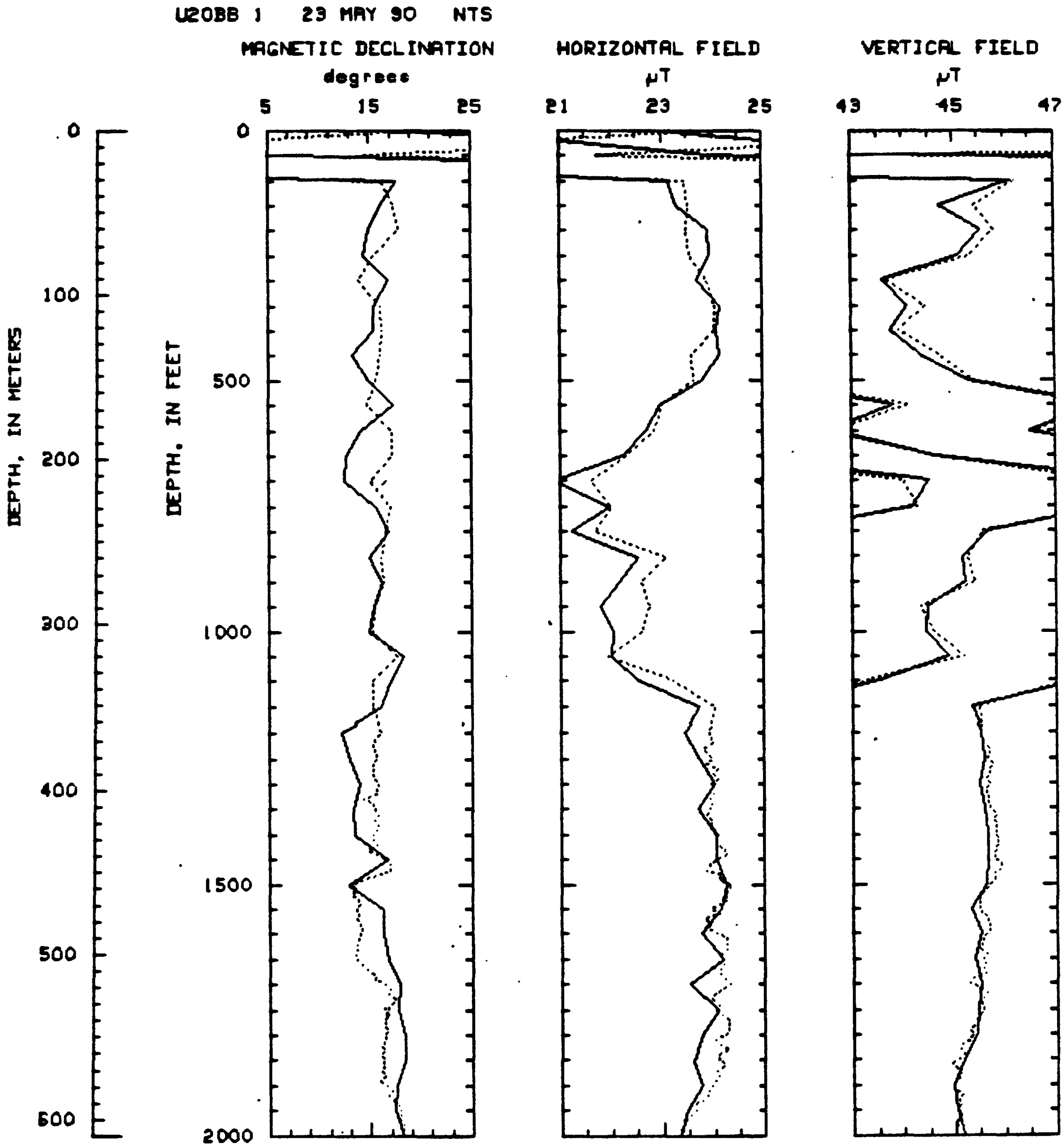


Figure B-3. Magnetic components from the third run in hole U20bb1.

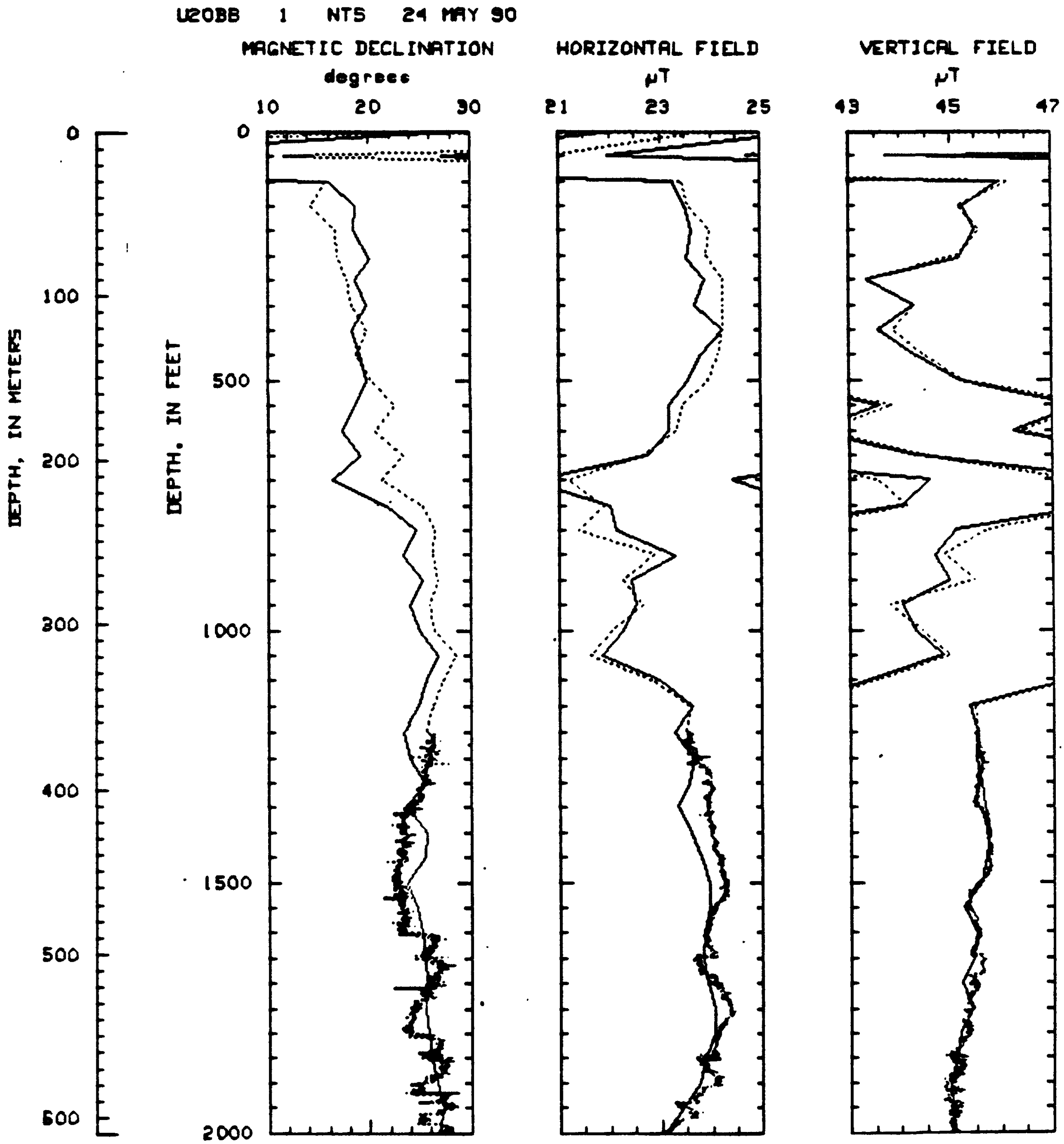


Figure B-4. Magnetic components from the fourth run in hole U20bbl. The declination scale reads 10 to 30 degrees in order to accomodate the data; other figures use a scale of 5 to 25 degrees.

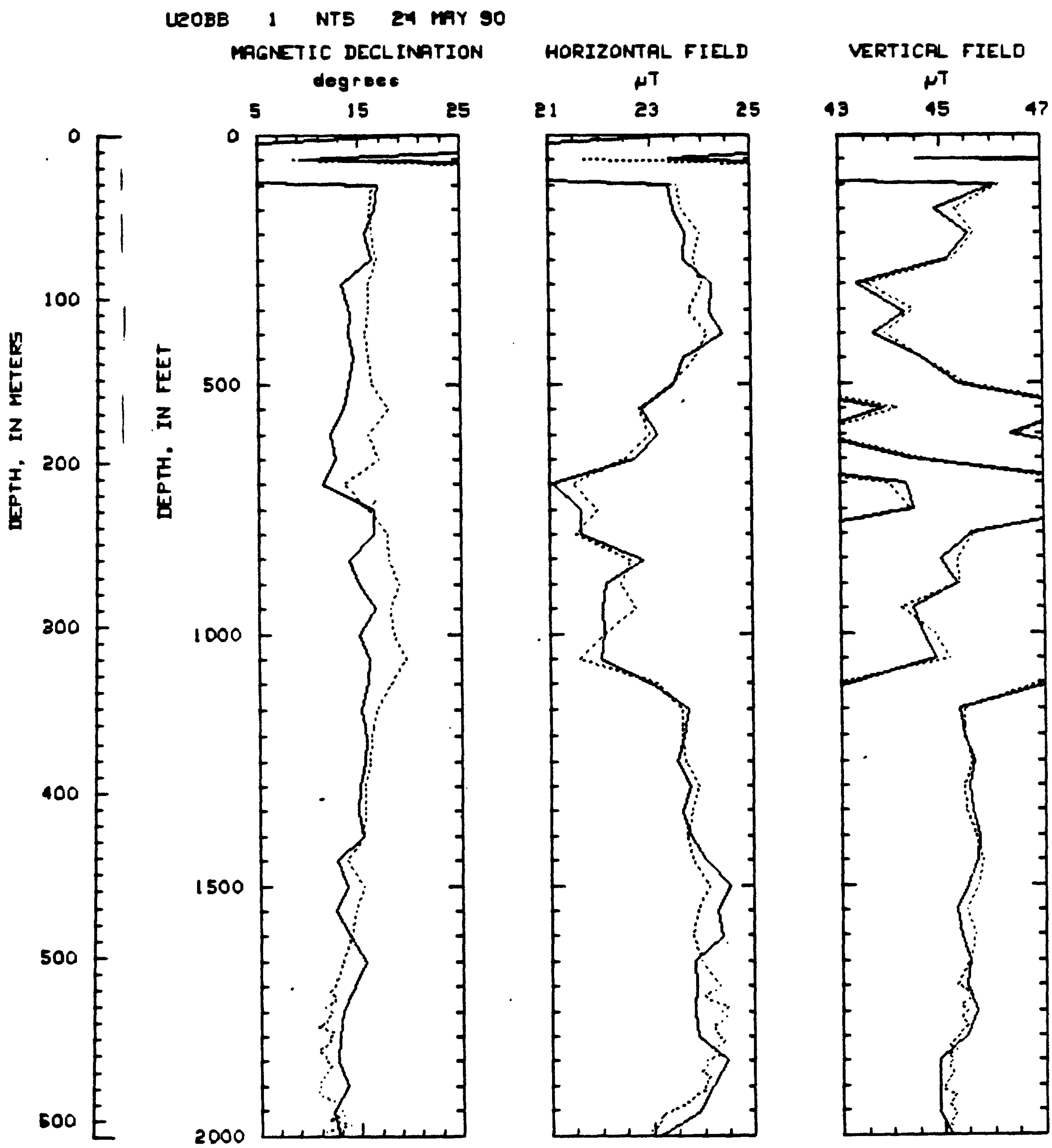


Figure B-5. Magnetic components from the fifth run in hole U20bbl.