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CALIBRATION OF A TWO-COIL MAGNETIC SUSCEPTIBILITY LOGGING TOOL

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ABSTRACT

A two-coil magnetic susceptibility logging tool has been calibrated in a three-inch hole in a set of susceptibility calibration pits. System resolution is 0.037 mSI, that is, a change of one count in system response units yields a susceptibility change of 37 x 10^{-6} in SI units. Linearity is quite good over the range 0 to 115 mSI. Logs obtained in an 8-inch (12-inch) hole require a correction of about 7% (31%). A thin, high susceptibility layer comprised of iron chips generates a profile with two minima, each generated as a coil passes the thin layer. Improved characterization of thin bed response and development of a field reference are recommended.

INTRODUCTION

Magnetic susceptibility logs can be acquired by measuring the change in inductance of a single, multi-turn coil or by measuring changes in the direct coupling between coils of a two-coil probe. Characterization of susceptibility tools requires calibration, definition of tool impulse response, and correction for hole size. Susceptibility probes can be calibrated by comparing the response with measurements of core samples or by making measurements in a calibration facility. To characterize the tool response to a thin layer or a half-space, either a full-scale model or a mathematical representation is required. Hole-size effects are best determined empirically in models of varying hole size.

Emilia et al. (1981) experimentallly obtained the layer response and correction factors for varying hole size for a single, multi-turn coil. Single-coil probes produce a positive "rabbit ears" response to beds with thickness comparable to or less than coil length. Separation between the ears is determined by magnetic field geometry and tends to be somewhat less than coil length.

Krammer (1992) derives an expression for the geometric factor of a two-coil susceptibility probe, which is equivalent to an induction probe without any extra coils to cancel the primary field. As with the single-coil probe, the two-coil probe produces a rabbit ears response to a thin layer, with the ear separation equal to the coil separation. Krammer presents correction factors as a function of borehole diameter and probe position for three different coil separations. Probes having coil separations less than the borehole diameter require particularly large corrections.

In this report, a calibration facility is used to calibrate a two-coil logging tool. In addition, the response to a thin layer and to a half-space are presented. The magnetic susceptibility logging tool was manufactured by Geonics Limited (model EM39S, serial number 2199) and modified by Mt. Sopris Instrument Co. for use with a single-wire logging unit designated as model MGX. The tool was calibrated in the calibration blocks at the Denver Federal Center (Snodgrass, 1976) on August 25, 1995.

CALIBRATION PROCEDURE

Measurement units. The voltage-to-frequency converter installed in the logging tool by Mt Sopris Instruments supplies 12,500 counts at zero volts and 17,500 counts at +1.0 volts. Readings were recorded on diskette in millivolts and also in parts per thousand of primary field using software supplied by Mt Sopris Instruments Company. The data logging software used for the calibration work at the calibration pits used the following conversion from counts to parts per thousand (ppt) of primary field:

$$y(\text{ppt}) = 1.40 + \frac{29.1 - 1.40}{11636 - 12304}\,[x(\text{counts}) - 12304] \qquad (1)$$

Prior to calibration of the logging tool in the calibration pits, this conversion was established using a small reference coil called the "Q" coil and a data sheet supplied by Geonics Limited. The calibration is quite sensitive to the position of the Q coil on the logging tool and should be regarded as approximate. The response in ppt increases as the count rate decreases below the base value of 12,304 indicating that the output voltage from the logging tool is negative.

Susceptibility Response. Logs were recorded in each of six holes in the calibration pits (Table 1). The pits are constructed of sand, shale, cement, water, and hematite (Snodgrass, 1976). Nominal dimensions are 8 feet vertical and 4 feet in diameter, with the hole centered in the pit. The cable head was located at the top of the hole and the depth set to 3.31 feet, so that depth was recorded relative to the nominal coil midpoint. Single values from 5.0-foot depths are given in Table 1. No attempt was made to center the tool within the three 3-inch holes. The tool was run against the side of the hole in the 5, 8, and 12-inch holes.

The readings recorded in Table 1 are plotted in Figure 1. The response of the EM39S to change in susceptibility is quite linear, more linear than that recorded by a USGS single-coil tool.

Figure 1 shows that the response in ppt is within 12% of the susceptibility in mSI. In fact, readings in ppt should be identical to milliSI (M. Bosnar, Geonics Limited, personal communication, 1995). The disparity is attributed to the lack of precision in the small-coil reference.

Table 1. Response of EM39S magnetic susceptibility tool in calibration pits at Denver Federal Center, August 25, 1995. A value obtained in air of 1.42 ppt has been subtracted from the readings. Susceptibility values are from Snodgrass (1976).

Hole Designation and Diameter	Susceptibility (microcgs)	Reading at 5-ft depth (ppt)
A1 / 12 inch	Medium: 1,685	19.3
A2 / 3 inch	Medium: 1,685	25.2
A3 / 5 inch	Medium: 1,685	26.3
A4 / 8 inch	Medium: 1,685	23.5
A5 / 3 inch	Low: 605	8.74
A6 / 3 inch	High: 9,090	129.0

Response Equation. The desired response equation converts from counts to susceptibility expressed in milliSI,

$$y(\mathrm{mSI}) = m[x - x_o] \tag{2}$$

The reading in air should be removed from the field data, both in deriving and using Equation 2. The susceptibility values given in Table 1 in microcgs have been multiplied by $4\pi \times 10^{-3}$ to convert to milliSI, so the value of 1,685 microcgs for hole A2 converts to 21.174 milliSI. Readings in ppt have been converted to counts using eq. 1. The results are given in Table 2.

Table 2. Values used to establish response equation, based upon readings in Table 1. Susceptibility values in brackets are values predicted from regression equation.

Hole Designation	Susceptibility (mSI)	Reading (counts)
Air	0.0 {0.356}	12303.5
A2	21.174 {21.568}	11730.1
A5	7.602 {6.885)	12127.0
A6	114.2 {114.2}	9226.9

Linear regression using the data in Table 2 results in,

$$y(\mathrm{mSI}) = 455.50 - 0.03699\ x(\mathrm{counts})$$

$$= -0.03699\ [x - 12313.12] \tag{3}$$

The r value is -1.000. The susceptibility given by Equation 3, given in brackets in Table 2, can be compared with the values of the calibration blocks, which are unbracketed in Table 2. Measurements and the regression line are graphed in Figure 2. The slope of -0.03699 corresponds to 27 counts per mSI; system resolution of one count corresponds to 0.037 mSI. By way of comparison, average values in sedimentary rocks range from 0.1 to 0.7 mSI (Nelson, 1993).

The values used in the calibration data file are given in Table 3. Comparison with a susceptibility log obtained previously with the USGS probe supports this calibration result (Figure 6).

Table 3. Calibration settings for files Magsuse.pb2 (depth in feet) and Magsusm.pb2 (depth in meters). Parameter Magpit is susceptibility in mSI in accordance with Eqn. 3; Magsus is in ppt according to Eqn. 1.

Parameter	LeftInp	RgtInp	LftOut	RgtOut
MagPit	12313	9610	0	100
MagSus	12304	11636	1.40	29.1

Recommended Field Practice. It is recommended that the LeftInp value for the parameter MagPit be reset in the field by holding the tool inverted overhead and pressing F3. Lacking a field calibrator, there is no way to reset the RgtInp variable, so it should remain at 9610. In other words, do a one-point adjustment to the zero setting for MagPit, thereby adjusting the susceptibility scale. The conversion for the parameter MagSus is given in eq. 1; leave it unchanged. A field calibrator should be built to allow field adjustment for finite susceptibility.

Variability of the Calibration Blocks. The susceptibility and resistivity of the calibration blocks are shown in Figures 3 and 4. It can be seen that the resistivity of the blocks at a depth of five feet ranges from 9 to 16 ohm-m. Variation within any given hole is one or two ohm-m except in the low-susceptibility block, A5.

Hole-Size Dependence. One would expect that tool response decreases as hole size increases. Table 1 shows that an increase was recorded in the 5-inch hole; this increase is attributed to lack of homogeneity in the block. Otherwise, a log run in an 8-inch hole requires a correction of about 7% and a log run in a 12-inch hole requires a correction of about 31%.

RESPONSE TO A THIN LAYER

The response of the susceptibility tool to a thin layer was examined by arranging an assortment of iron chips on a horizontal wooden sheet located above hole A2. The chips were about 1/8 inch thick and 2 to 5 inches on a side. The chips were separated so that their edges did not touch. The depth reference was set to zero with the cable head at the elevation of the sheet. The tool was drawn through the platform, acquiring 20 data samples per foot. Five passes are shown in Figure 3. The first pass (curve 2) had the chips set closest to the "hole". On subsequent passes, the near chips were moved away from the "hole", as indicated in the key to Figure 3. On the pass labeled "V", four chips were set vertically, their edges forming an eight-inch square; all other chips were removed. The lower limb of the response pattern is greater than the upper limb because either one coil (0.9 to 2.5 feet) or both coils (0.0 to 0.9 feet) were within the medium susceptibility block.

From the five responses in Figure 3, we observe that:

1. The separation between the cable head and the midpoint of the symmetric response is about 3.35 feet, close to the offset of 3.31 feet specified by the manufacturer.

2. The minima obtained with chips close to the hole (curve 2) are 1.65 feet apart or 50 cm, which is the coil separation specified by the manufacturer.

3. As the chips are moved away from the hole, simulating a larger diameter hole, both the minima and maxima reduce in value.

4. The polarity of the signature reverses when the chips are oriented vertically (curve V).

From these profiles, it appears that the tool produces a double minima when passing through a thin zone of high susceptibility. Each minima occurs as a coil is at the elevation of the thin zone. However, these profiles are contrary to the vertical responses computed by Krammer (1992), which produce maxima, not minima, as the coils pass a thin layer. Because the magnetic field is a vector field, the response is a function of the orientation and location of the chips relative to the "hole" in our simple test. The results of Figure 5 are suspect because of the geometry of the chips. Consequently, these profiles should not be used to derive a vertical response function for deconvolution. It is recommended that the tests be redone using thin layers fabricated with dispersed mixtures such as sand and a magnetic mineral.

<u>Response to a Half Space.</u> As the tool moves from a low susceptibility to a high susceptibility zone, an overshoot appears (Figures 3 and 5). The overshoot seems to occur as the second coil moves across the boundary.

REFERENCES

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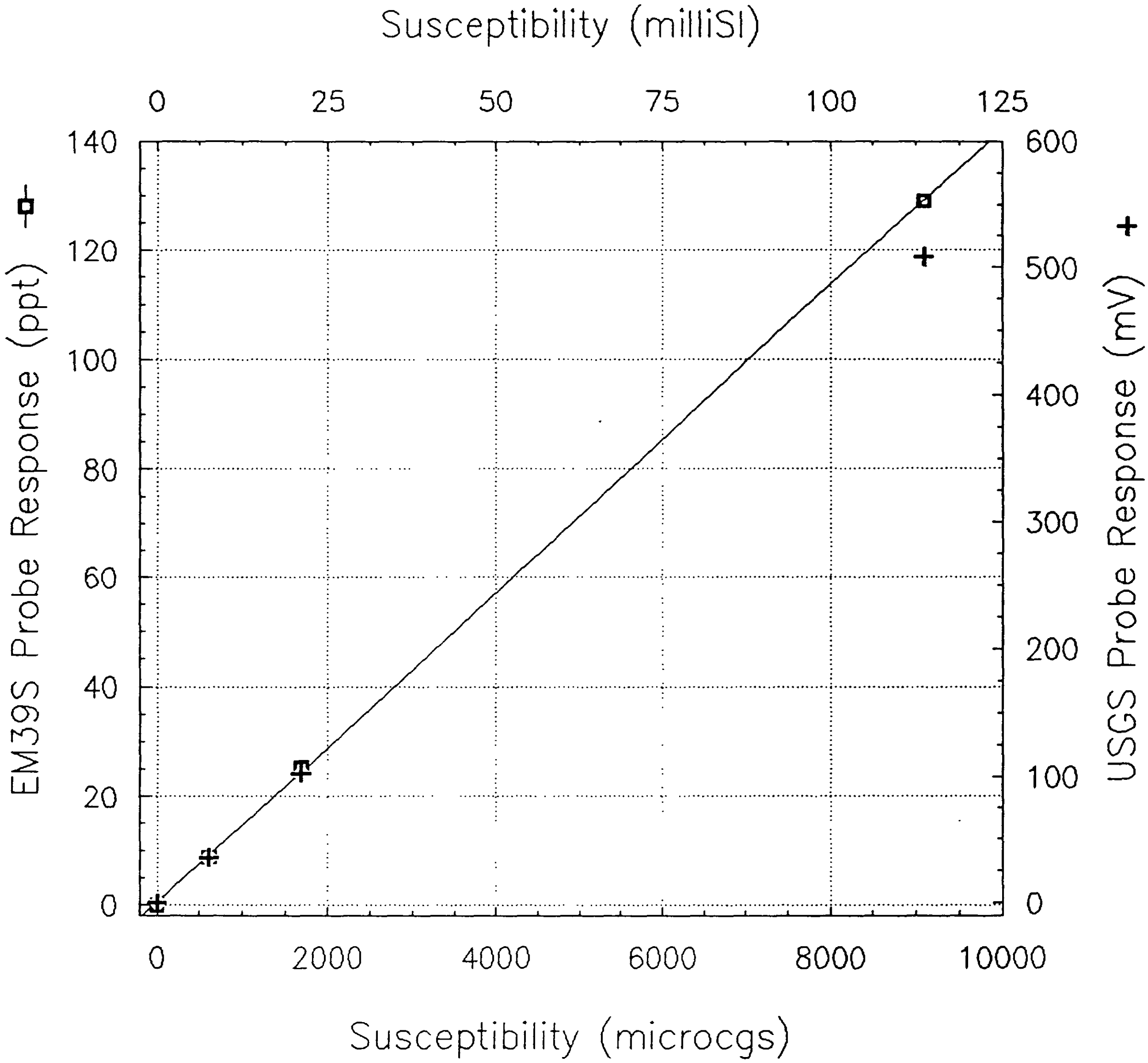

Figure 1. Response of two-coil EM39S probe and single-coil USGS probe in three pits of varying susceptibility, at 5-foot depth. Line is least-squares fit to the data for the EM39S.

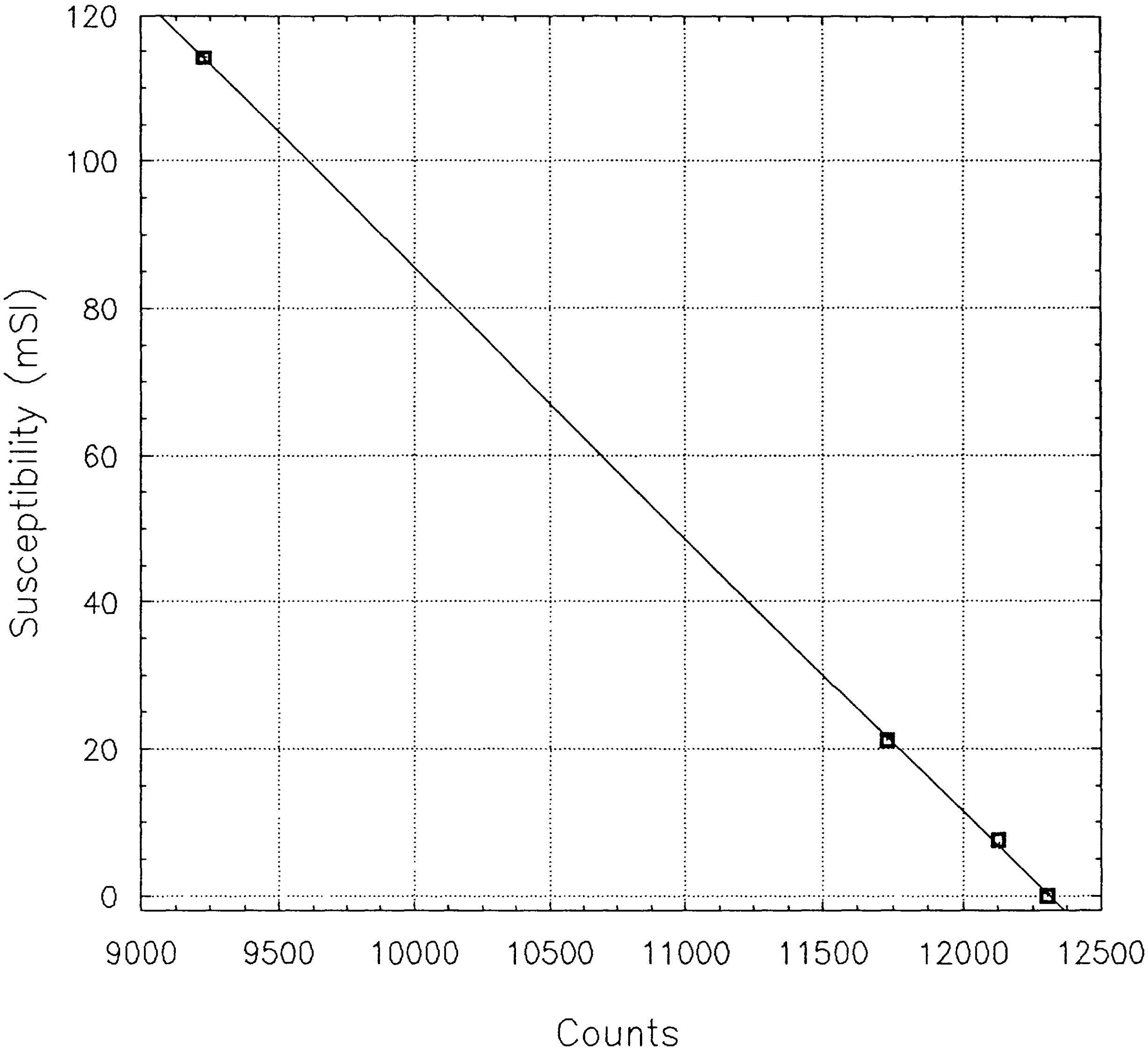

Figure 2. Conversion of two-coil EM39S probe from counts to susceptibility (solid line), as implemented in software as parameter MagPit. Open squares are the values of the three susceptibility blocks.

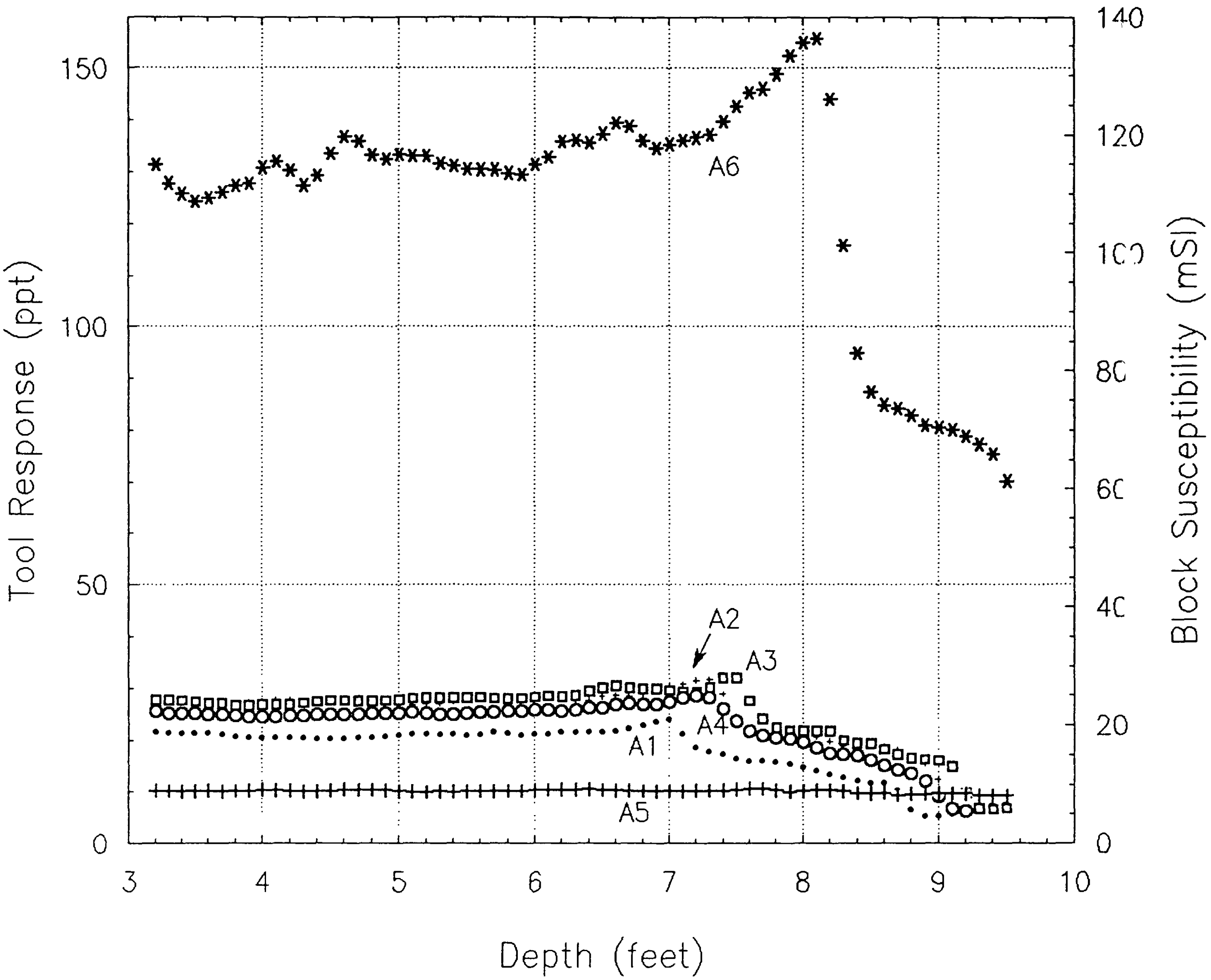

Figure 3. Magnetic susceptibility logs run in calibration pits at Denver Federal Center with EM39S probe. Holes A1 through A4 are in medium susceptibility pit. Hole A5 and A6 are in the low and high susceptibility pits, respectively. Reading in air was 1.42 ppt.

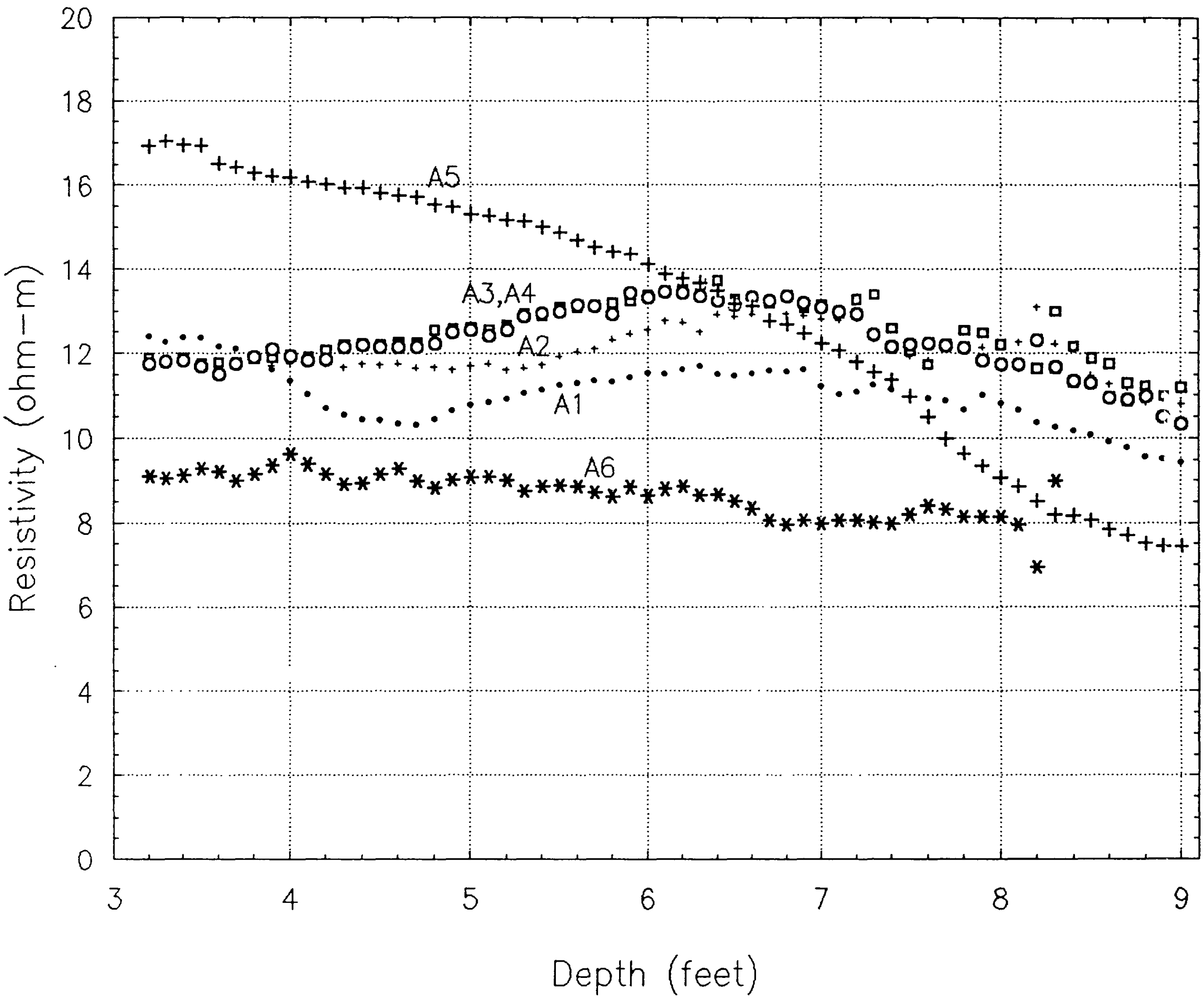

Figure 4. Resistivity logs obtained in the test blocks at Denver Federal Center on August 25, 1995, using the Geonics EM39 induction probe. Nominal depth of blocks is eight feet. Depth scale gives position of coil midpoint.

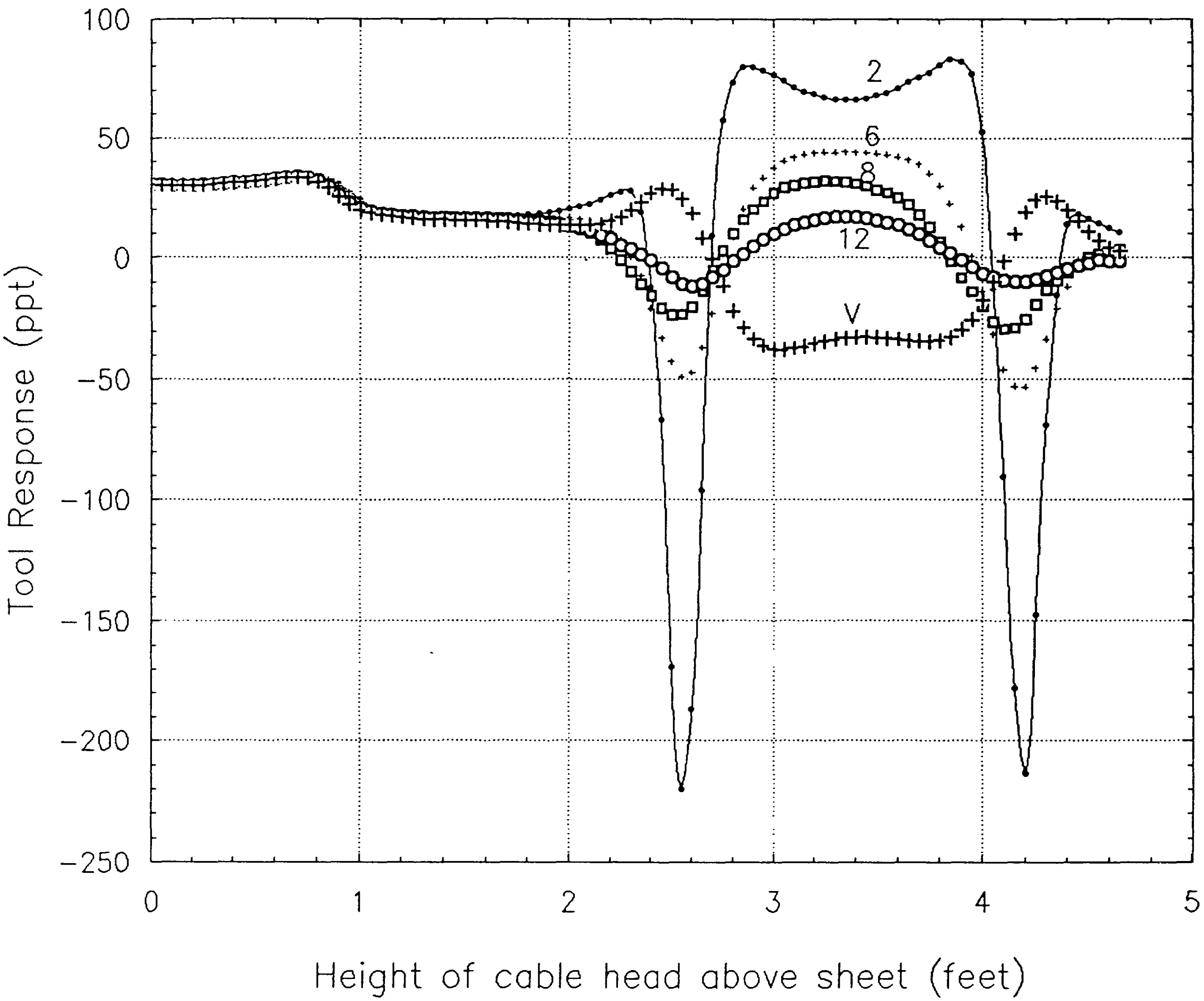

Figure 5. Response of EM39S magnetic susceptibility tool to flat-lying iron chips. Cable head is even with chips at 0.0 feet; tool is pulled to a height of 4.65 feet above the chips. Chips lie on a wooden sheet which is 19 inches (1.58 feet) above hole A2 in the medium susceptibility block. Chips form an annulus around the "hole" with an outer diameter of about 19 inches; the inner diameter is 2, 6, 8, and 12 inches as indicated by the curve number. Curve "V" was acquired with 4 vertically oriented chips forming an 8-inch square.

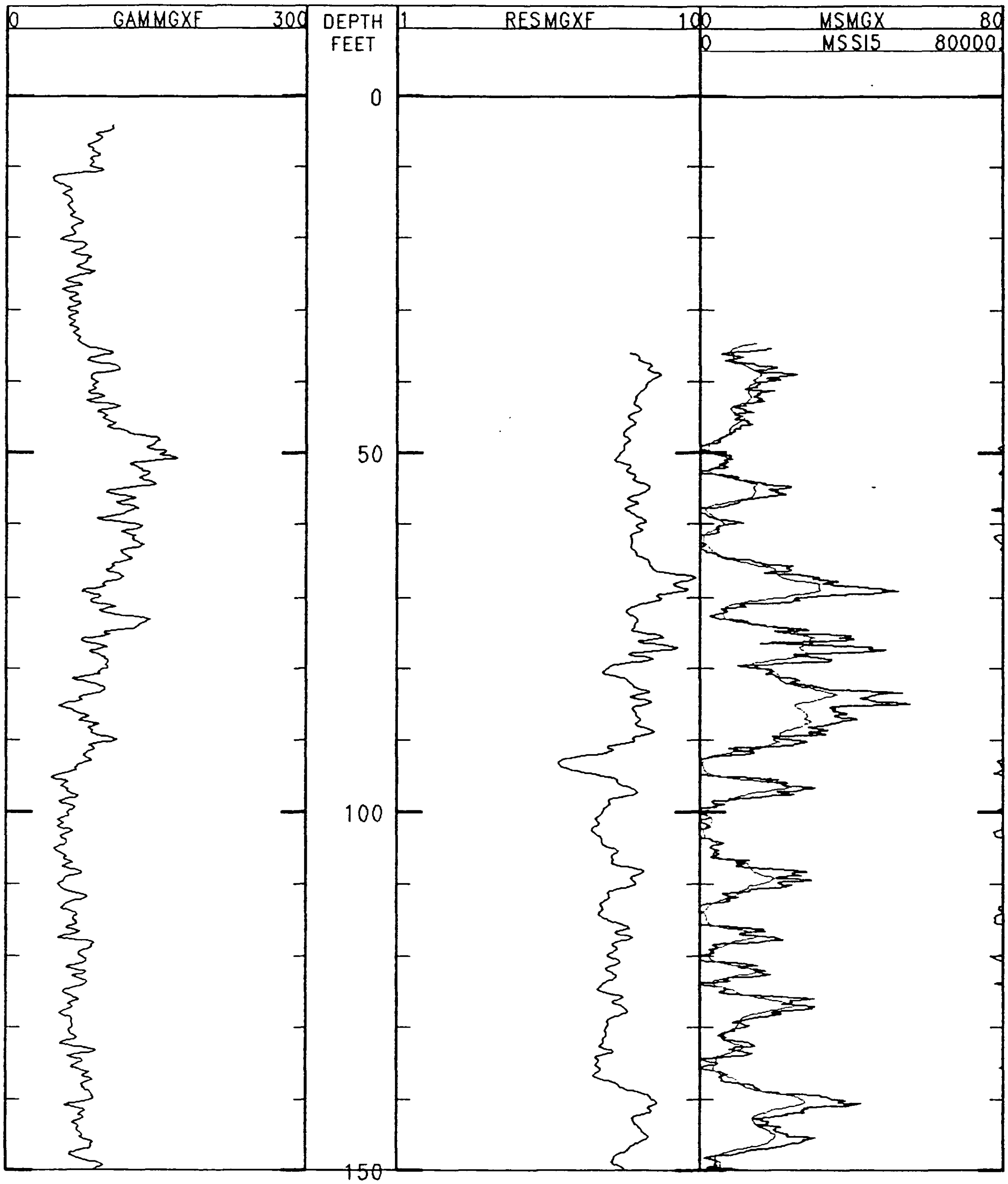

Figure 6. Gamma-ray (counts per second), resistivity (ohm-m), and magnetic susceptibility (mSI) obtained with the Mt. Sopris MGX system in a test hole at the Denver Federal Center during August, 1995. Resistivity and susceptibility logs were obtained with the Geonics EM39 and EM39S probes. Also shown is a magnetic susceptibility log (μSI) obtained with the USGS single-coil susceptibility probe (smooth curve in third column).