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Interpretation of Geophysical Well-Log Measurements in Drill Hole UE25a-1, Nevada Test Site, Radioactive Waste Program

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by

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This report is preliminary and has not been edited or reviewed
for conformity with U.S. Geological Survey standards.

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Abstract

An exploratory hole (UE25a-1) was drilled at Nevada Test Site (NTS) to determine the suitability of pyroclastic deposits as storage sites for radioactive waste. Studies have been conducted to investigate the stratigraphy, structure, mineralogy, petrology, and physical properties of the tuff units encountered in the drill hole. This report deals with the interpretation of physical properties for the tuff units from geophysical well-log measurements.

The ash-flow and bedded tuff sequences at NTS comprise complex lithologies of variously welded tuffs with superimposed crystallization and altered zones. To characterize these units, resistivity, density, neutron, gamma-ray, induced polarization, and magnetic susceptibility geophysical well-log measurements were made. Although inherently subjective, a consistent interpretation of the well-log measurements was facilitated by a computer program designed to interpret well logs either individually or simultaneously. The broad features of the welded tuff units are readily distinguished by the geophysical well-log measurements. However, many details revealed by the logs indicate that more work is necessary to clarify the causal elements of well-log response in welded tuffs.

Introduction

To study the suitability of pyroclastic deposits as storage sites for radioactive waste, an exploratory hole was drilled in July 1978 (under the auspices of the U.S. Department of Energy) at the Nevada Test Site (NTS). Erupted from the Timber Mountain-Oasis Valley caldera complex in late Tertiary time (16-9 m.y.), up to 3000 m of rhyolitic tuffs at NTS mantle an eastern portion of the basin and range province. In recent years, the tuff units and their associated calderas have been the subject of mapping and detailed study by the U.S. Geological Survey (Byers, et al, 1976; Christiansen, et al, 1977; and Lipman, et al, 1966).

Exploratory drill hole UE25a-1 was drilled and cored to a depth of 762 m off the northeastern flank of Yucca Mountain to investigate the stratigraphy, structure, mineralogy, petrology, and physical properties of the Paintbrush Tuff, the tuffaceous Beds of Calico Hills, and a portion of the lower member of the Crater Flat Tuff. This study discusses the physical properties of the tuff units as measured by U.S. Geological Survey borehole geophysical research equipment that is operated and maintained by the Branch of Petrophysics and Remote Sensing.

Geologic Considerations

The sequences of ash-flow and bedded tuffs at NTS have been classified as stratigraphic units primarily on the basis of genetic relationships and cooling histories. The cooling histories of the tuff units determine the degree to which they become welded (i.e., non- to partially welded, moderately welded, densely welded) and are due largely to the temperature of emplacement and the thickness of cooling units (Smith, 1960).

Zones of crystallization and alteration are superimposed on the variously welded portions of the vitric tuffs, although their presence may be dependent on the degree of welding. Devitrification of the pyroclastic flows has occurred throughout almost all of the densely welded portions of the tuffs. Associated with the thickest densely welded zones are inner cores characterized by lithophysal cavities. These are nearly spherical, mainly unconnected voids that are commonly lined with secondary minerals. Vapor phase minerals that crystallize from the hot volatiles released by the cooling tuff units are found mostly as linings or fillings of lenticular vugs. Alteration of the tuffs by ground water has resulted in zones of zeolitization, silicification, and calcitization. Zeolitization, the most prevalent of these, occurs for the most part in the non- to partially welded portions of the Crater Flat Tuff. Although the ground-water level is presently at 469 m in drill hole UE25a-1, alteration related to ground-water saturation occurs 80 m above this level, indicating a higher water table in the geologic past (Sykes, et al, 1979). The lithologic intervals and the distribution of crystallization and alteration zones as determined by Spengler (1979) are given in Figure 1. Detailed descriptions of the authigenic phases found in UE25a-1 are given in Sykes, et al (1979).

Response Characteristics of Geophysical Well Logs in Volcanics

Each geophysical well-log measurement is affected by the physical properties of the rock, the interstitial fluid of the formation, the conditions in the borehole (fluid and rugosity), the volume of rock investigated by the probe, the vertical resolution of the probe, and the design characteristics of each probe, and so should be considered an apparent rather than a true physical property value. Some characteristics of individual well-logging probes follow:

(1) Resistivity

Resistivity is a measure of the facility with which electric current passes through a material. Borehole resistivity measurements depend upon the porosity, fluid resistivity, and grain resistivity of the rock investigated. Densely welded tuffs have apparent resistivities in the 248-630 ohm meter

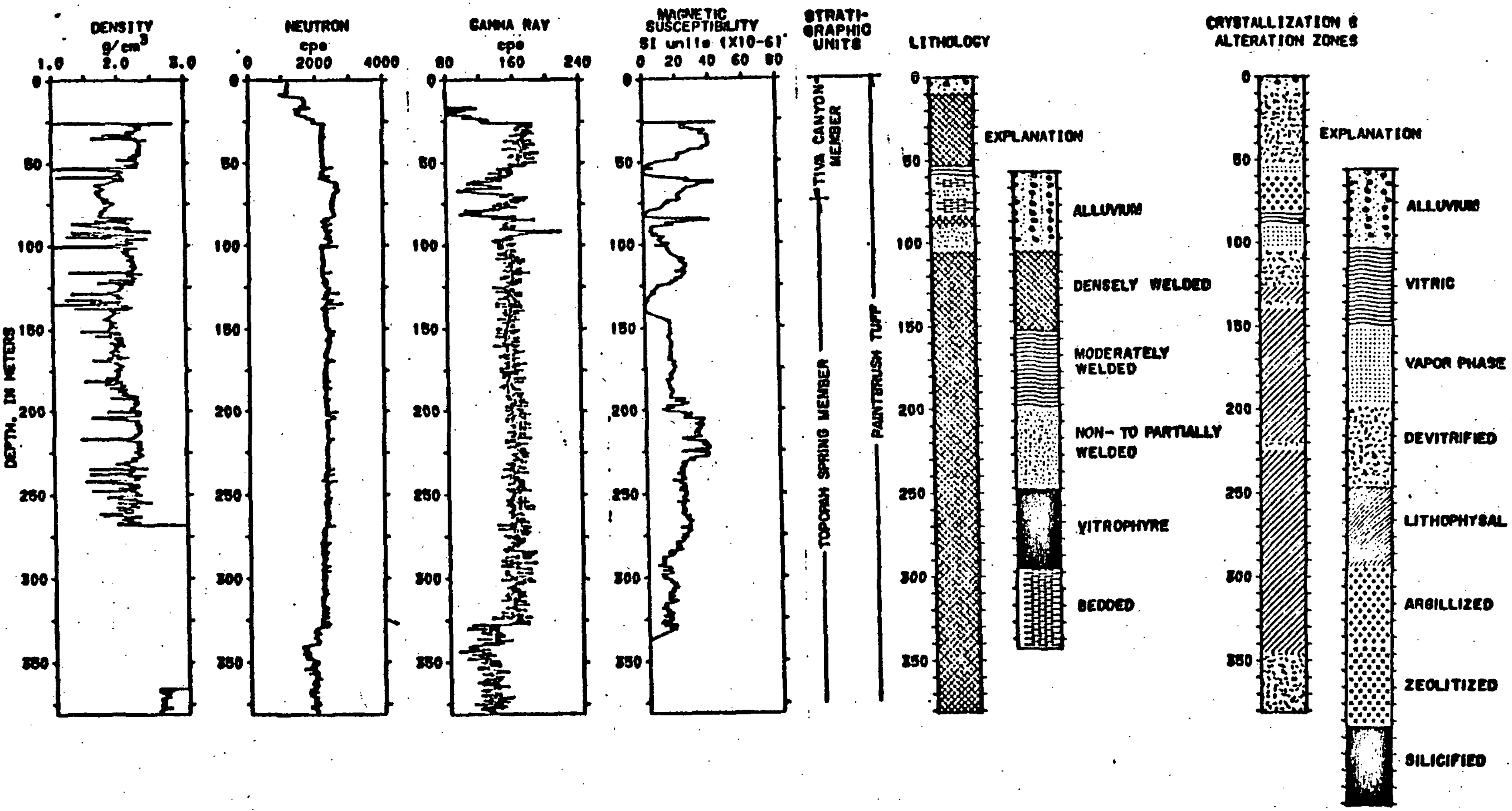

Figure 1(a).--Geophysical well logs (density, neutron, gamma-ray, magnetic susceptibility) from upper half of drill hole UE25a-1 with lithology, crystallized and altered zones, and stratigraphic units assigned to depth intervals as determined by Spengler (1979).

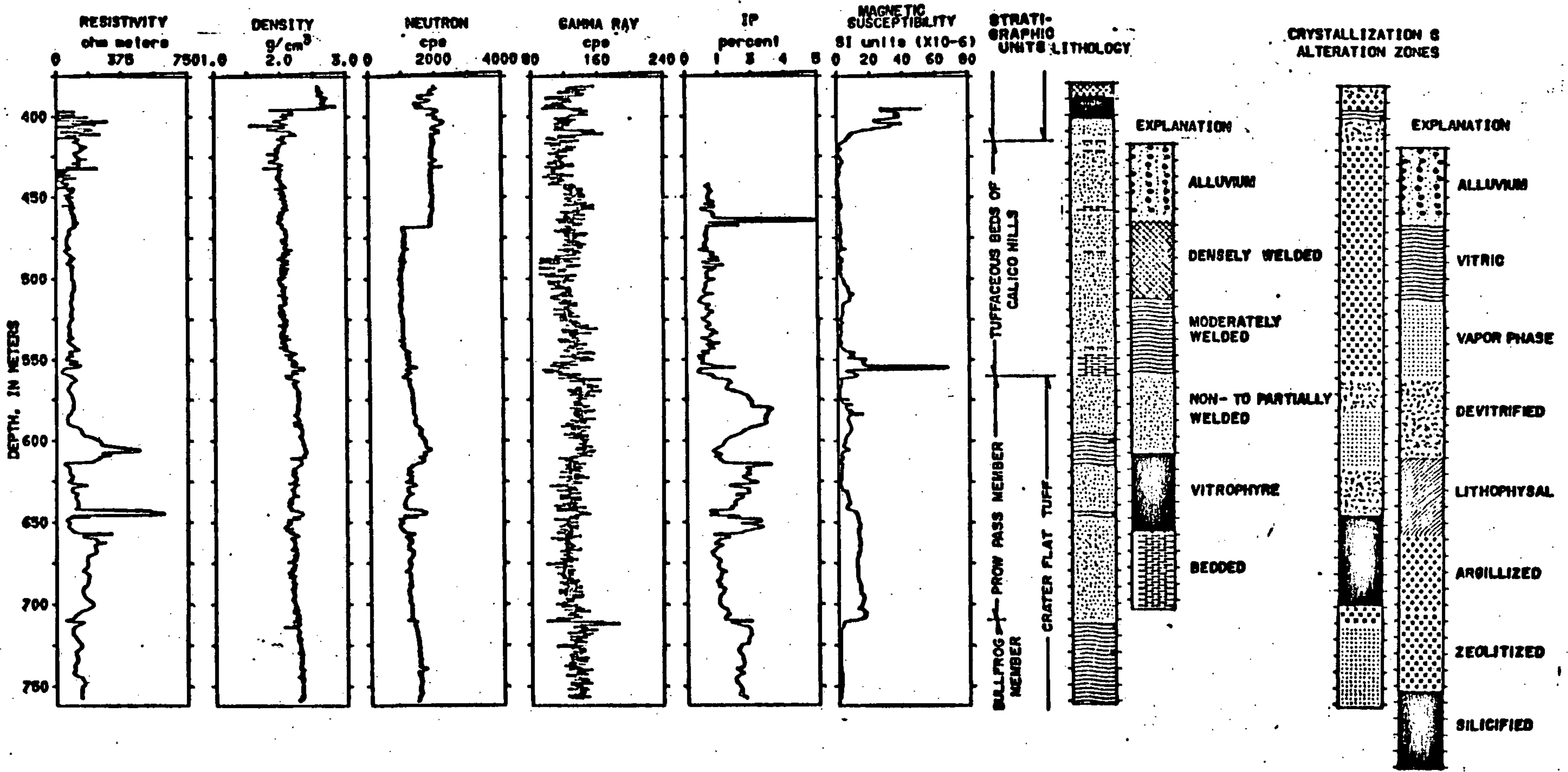

Figure 1(b).--Geophysical well logs (resistivity (16-inch normal), density, neutron, gamma-ray, IP, magnetic susceptibility) from lower half of drill hole UE25a-1 with lithology, crystallized and altered zones, and stratigraphic units assigned in depth intervals as determined by Spengler (1979).

range while non-welded and bedded tuffs have shown much lower values (19-158 ohm meters). Due to borehole diameter considerations, the 16" normal resistivity log is considered the most reliable and is used in this report.

(2) Density

The density probe consists of a gamma-ray source and one or more gamma-ray detectors. Gamma rays emitted by the source are scattered by the rock, and the gamma radiation measured at the detector is inversely proportional to the electron density of the rock. By using two detectors, the effects of fluid density and rugosity on the calibrated density measurement often can be compensated, yielding a computed density that is approximately equal to the bulk density of the rock. Non-welded units have low rock densities, densely welded units have high rock densities, while highly altered units have low rock densities (see Table 1). The unstable borehole wall conditions yield measured bulk density values for the tuffs in the upper portion of UE25a-1 which are probably lower than the true bulk density of the rock.

(3) Neutron

A neutron source and detector, separated by approximately 50 cm, compose the neutron well-logging probe. The number of neutrons counted by the detector is an inverse function of the hydrogen content of the rock surrounding the borehole, and is primarily a measure of the amount of water contained in the rock. The neutron count in volcanic tuffs appears to be approximately proportional to the degree of welding.

(4) Gamma Ray

The gamma-ray probe measures the natural gamma radiation emitted by the rocks surrounding the borehole. The principal natural gamma-ray-emitting minerals are uranium-series isotopes and potassium-40. Because potassiumbearing minerals are common in both primary and secondary crystallization regimes in UE25a-1, the gamma-ray values are considered principally to be a measure of relative potassium abundance.

(5) Induced Polarization (IP)

The IP measurement is made by recording the decay voltage at a potential electrode that is positioned on the probe at a spacing of 10 cm from an abruptly terminated electrical current source. The rate of decay of the potential during the current off time is inversely proportional to the electrical polarizability of the rock. A high IP response in volcanics may be caused by the presence of cation-rich clays, zeolites, or pyrite and other sulfides. However, in some cases magnetite (and, to a lesser extent, hematite) can contribute to the IP response.

(6) Magnetic Susceptibility

Magnetic susceptibility is a measure of the intensity of magnetization of a magnetizable substance in the presence of a known magnetic field. The magnetic susceptibility of a rock depends largely on the amount of ferrimagnetic minerals that it contains. Magnetite is the most important ferrimagnetic mineral due to its widespread occurence and high values of magnetic susceptibility. Magnetic susceptibility measurements in the welded tuffs are primarily a measure of the volume content of magnetite in the rock. Additional studies are needed to determine the exact relationship of the various magnetic minerals in volcanics to the magnetic susceptibility of the rocks.

Problems with fluid loss and borehole wall stability made complete coverage of the entire drill hole with all logs impossible. The resistivity and induced potential measurements were not made in the upper 469 m of the hole, as they need a fluid couple with the formation. The neutron log values were strongly affected by the absence of borehole fluid. Variations in borehole rugosity in the drill hole above fluid level resulted in poor density data and, in places, unreliable neutron data. Also affecting the density log was a segment of casing, used to stabilize the upper portion of the hole during logging below, that was left stuck in the hole from 267-396 m during logging of the upper portion.

Computer-Assisted Interpretation of Lithologies from Geophysical Well Logs

The geophysical well logs from drill hole UE25a-1 are given in Appendix A and are shown in Figures 1(a) and 1(b); the stratigraphic units of the region are assigned to depth intervals within the hole as determined by Spengler (1979). The geologic observations of Spengler (1979) and of Sykes, et al (1979) collectively form the initial data with which the geophysical well-log measurements are compared. Although there are many consistent correlations between the stratigraphic units and the geophysical well logs, there are also notable exceptions and wide variation in values within single stratigraphic units. To synthesize a consistent interpretation of the well-log data, a computer program was written that assigns particular lithologies for those depth intervals that contain one or more geophysical well-log measurements within specified value ranges.

Because the most significant feature of the ash-flow tuff units is the degree of welding, which is well correlated with density (Fig. 2) and neutron (Fig. 3) logs in the lower portion of the hole, value ranges for the degree of welding (Table 1) were subjectively selected for these logs to best match the welded zones described by Spengler (1979). In Figure 1 the logs have been separated into top and bottom halves since the different borehole conditions

Table 1.—Well-log value ranges for computer-assisted assignment of lithologies

[Selected value ranges for the individual well logs correspond primarily to the degree of welding (density and neutron), to the mineralogic content (magnetic susceptibility and IP), or to a combination of both (gamma ray and resistivity).]

Well Log	Well-Log Value Ranges
Density (lower portion of drill hole)	g/cm^3
Low values	1.76 - 2.17
Medium values	2.17 - 2.27
High values	2.27 - 2.42
Neutron (lower portion of drill hole)	cps
Low values	814.3 - 1119.6
Medium values	1119.6 - 1424.9
High values	1424.9 - 1883.0
Gamma Ray	cps
Low values	92.3 - 139.3
High values	139.3 - 215.0
Resistivity	ohm
Low values	0 - 157.5
High values	157.5 - 618.8
Magnetic Susceptibility	SI units ($x10^{-6}$)
Low values	0 - 10.2
Medium values	10.2 - 18.5
High values	18.5 - 68.9
IP	percent
Low values	.38 - 1.79
High values	1.79 - 3.32

between top and bottom resulted in different response values for all but the gamma-ray and magnetic susceptibility logs. The low density values for the densely welded rock in the top portion of the hole are due to borehole wall instability caused in part by the extensive fracturing of these units. The lack of fluid in the upper part of the hole makes the neutron response values consistently high and difficult to compare with similar units below the water level (469 m). Although the gamma-ray (Fig. 4) and resistivity (Fig. 5) logs tend to show high values in densely welded rocks and lower values in rocks less densely welded, there are exceptions to this trend (e.g., the lower portion of the Topopah Spring Member and the Bullfrog Member, respectively). Similarly, the magnetic susceptibility (Fig. 6) and IP (Fig. 7) measurements are for the most part consistent within units or groups of units, but show no consistent relation to the degree of welding as described in the core analysis. The value ranges (Table 1) for these logs, then, were subjectively selected on the basis of the largest groups of units within a log that give similar values.

The densely welded sections of the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff (Fig. 1) give gamma-ray measurements of 128.2-152.7 cps and 103.8-140.5 cps, respectively, while the densely welded sections of the Crater Flat Tuff fall within a 79.4-103.8 cps range. Because all of these densely welded zones have been devitrified, the difference in the gamma-ray response values can be attributed to the fact that the fine-grained devitrification products of the Paintbrush Tuff units are 40 percent richer in K-feldspar than the Crater Flat Tuff units, and that spherulitic textures, which are more K-feldspar rich than the other phases, are more prevalent in the Paintbrush Tuff (Sykes, et al, 1979). The lower units are also sites of vapor

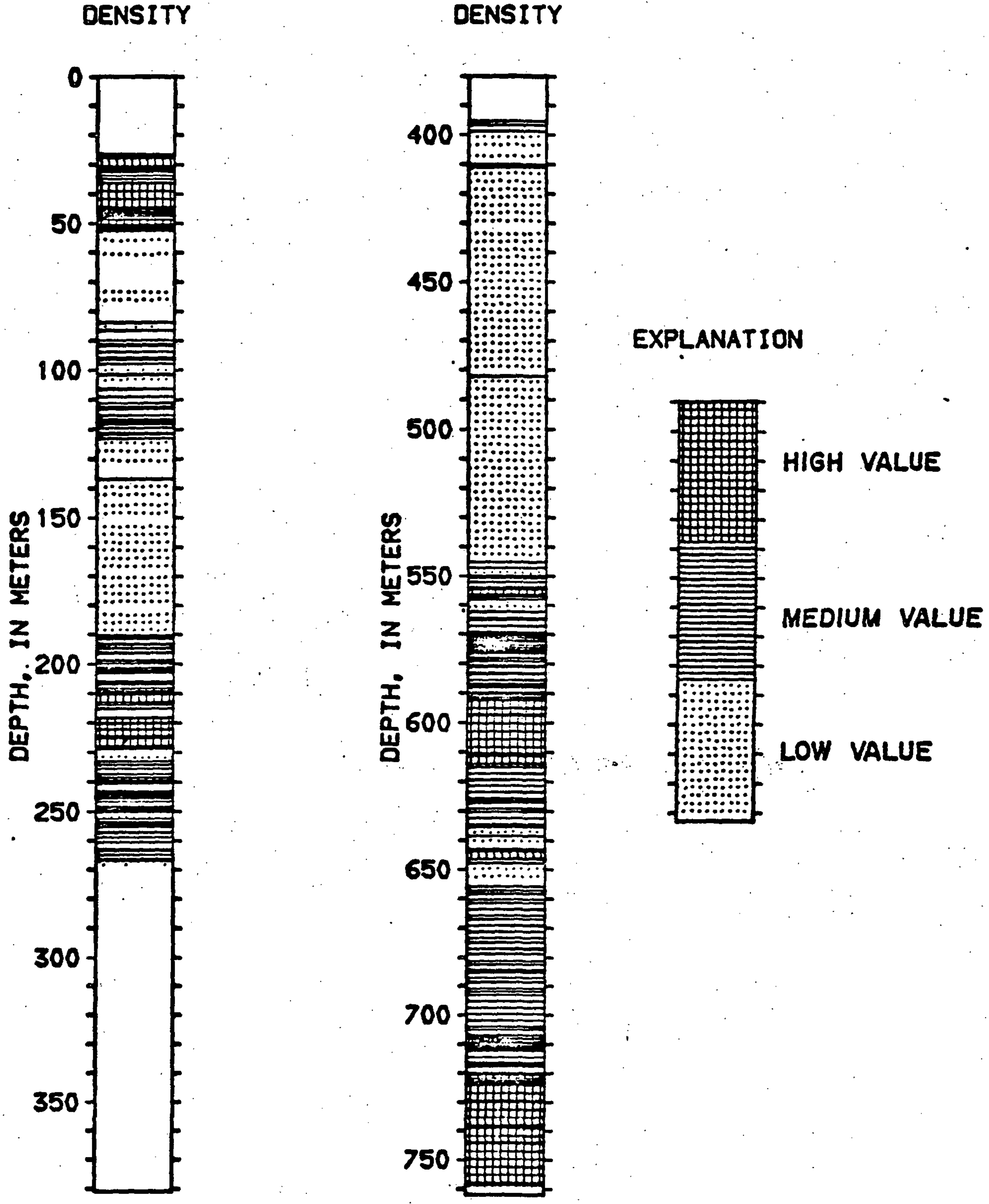

Figure 2.—Computer-assisted interpretation of the density well log from drill hole UE25a-1 based on the value ranges given in Table 1. High, medium, and low value ranges correspond to densely, partially, and non-welded lithologies, respectively.

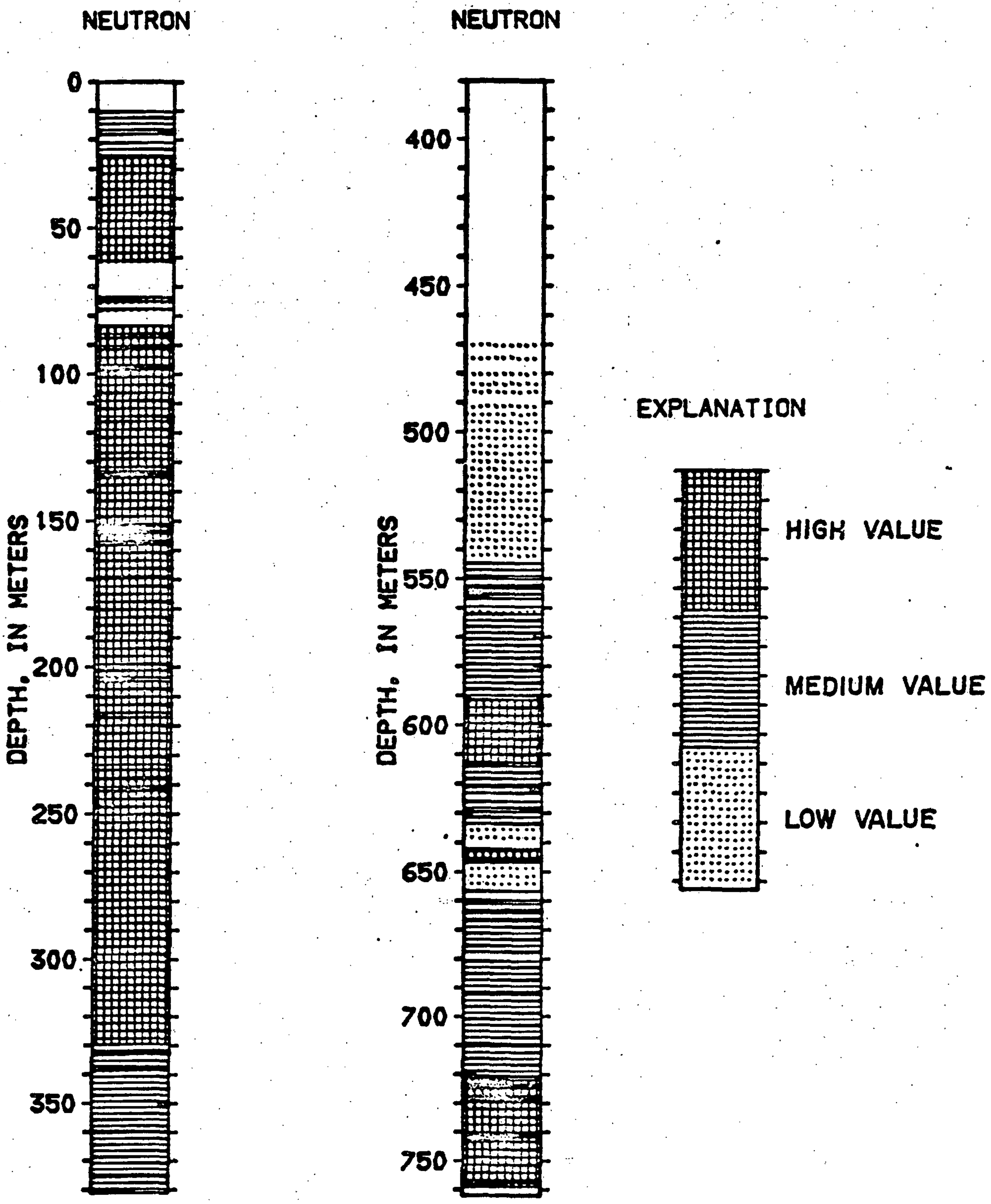

Figure 3.—Computer-assisted interpretation of the neutron well log from drill hole UE25a-1 based on the value ranges given in Table 1. High, medium, and low value ranges correspond to densely, partially, and non-welded lithologies, respectively.

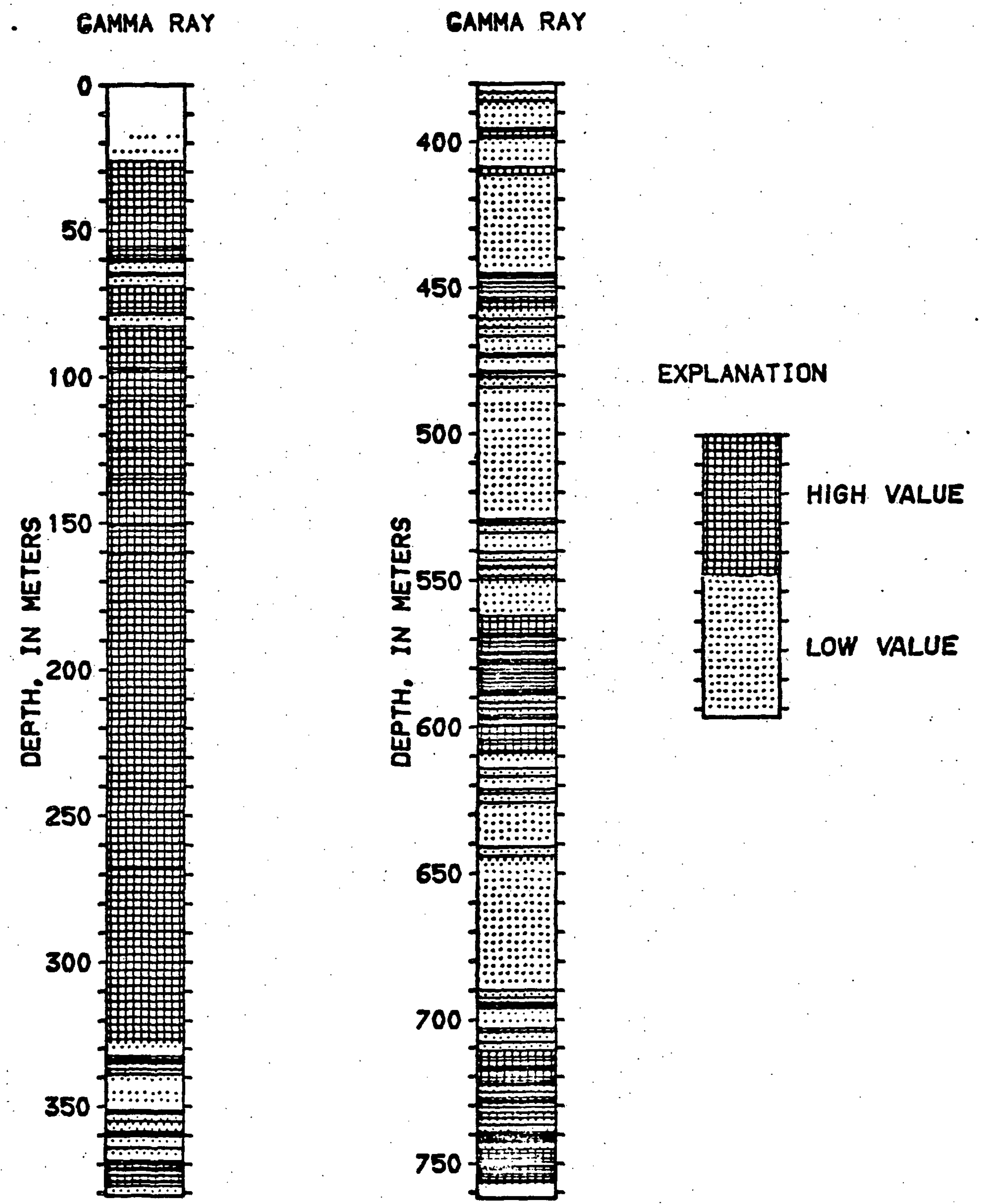

Figure 4.—Computer-assisted interpretation of the gamma-ray well log from drill hole UE25a-1 based on the value ranges given in Table 1. High and low value ranges approximately correspond to densely and non- to partially welded lithologies, respectively, although anomalous concentrations or depletions of K-rich minerals would adversely influence this interpretation.

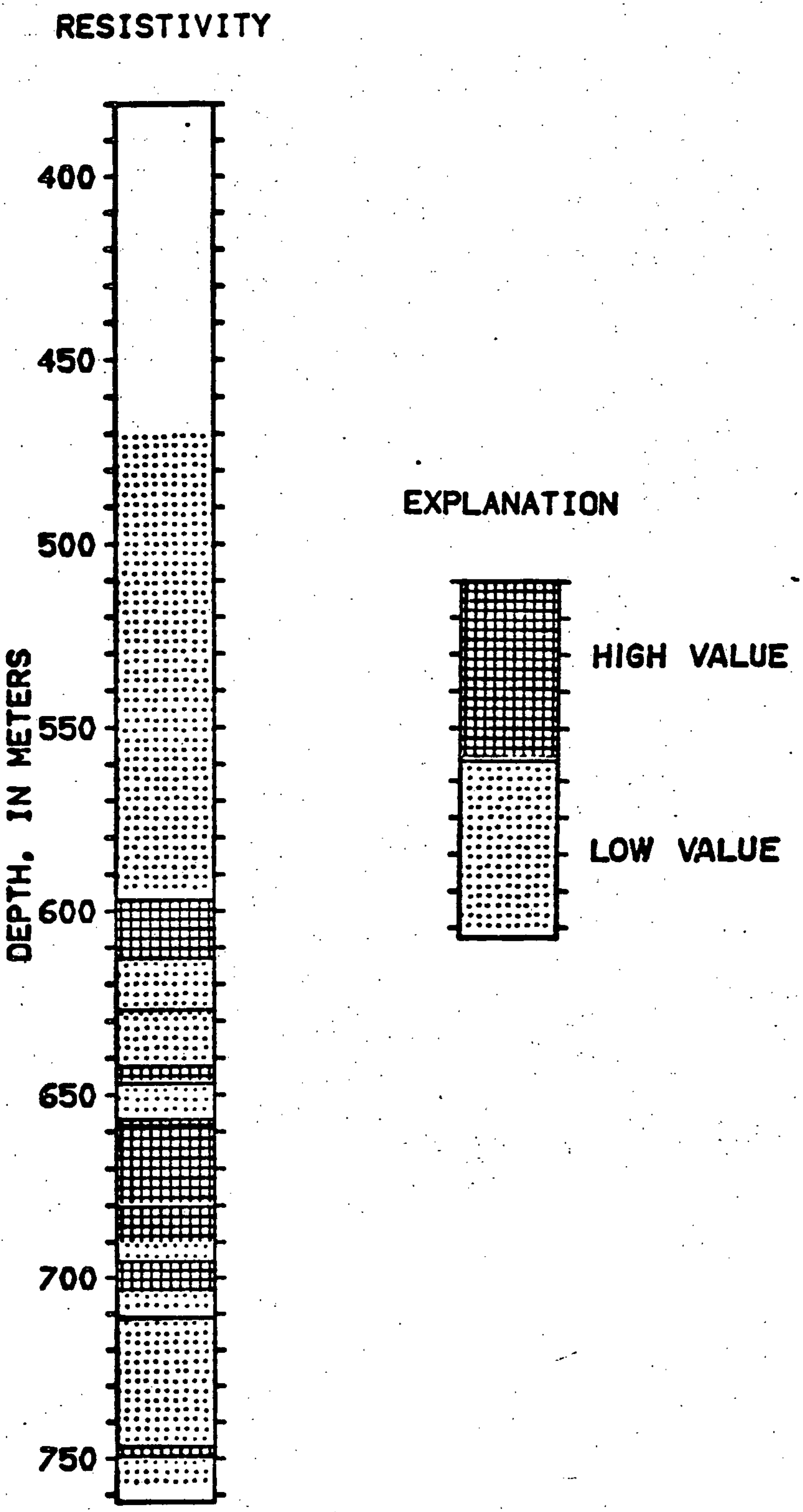

Figure 5.—Computer-assisted interpretation of the 16-inch normal resistivity well log from drill hole UE25a-1 based on the value ranges given in Table 1. High and low value ranges approximately correspond to densely and non- to partially welded lithologies, respectively, although secondary features (i.e., fracturing, highly conductive minerals) could mask the true lithology.

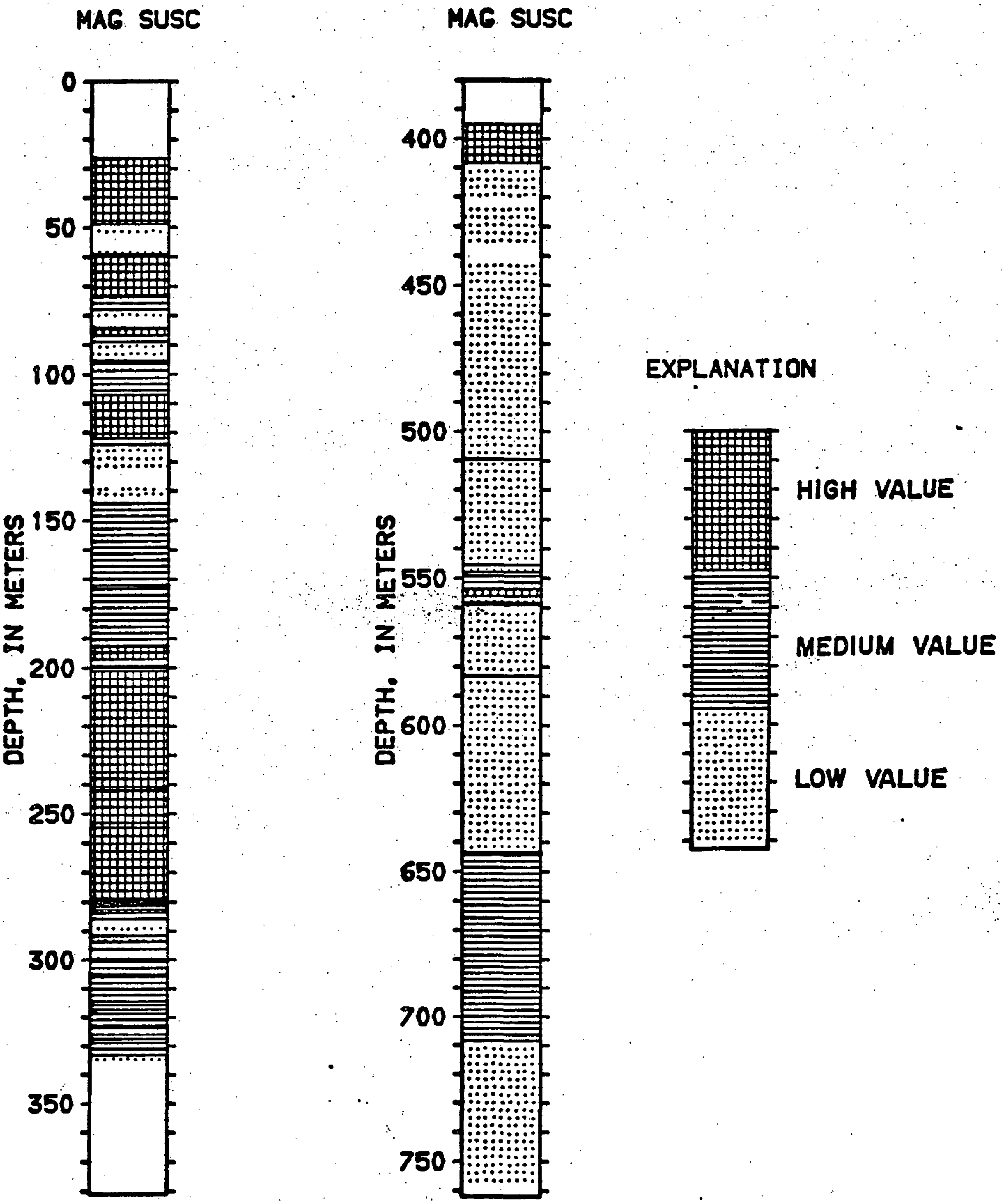

Figure 6.—Computer-assisted interpretation of the magnetic susceptibility well logs from drill hole UE25a-1 based on the value ranges given in Table 1. High, medium, and low value ranges correspond to the relative amount of magnetic minerals (primarily magnetite) present in the lithologic unit.

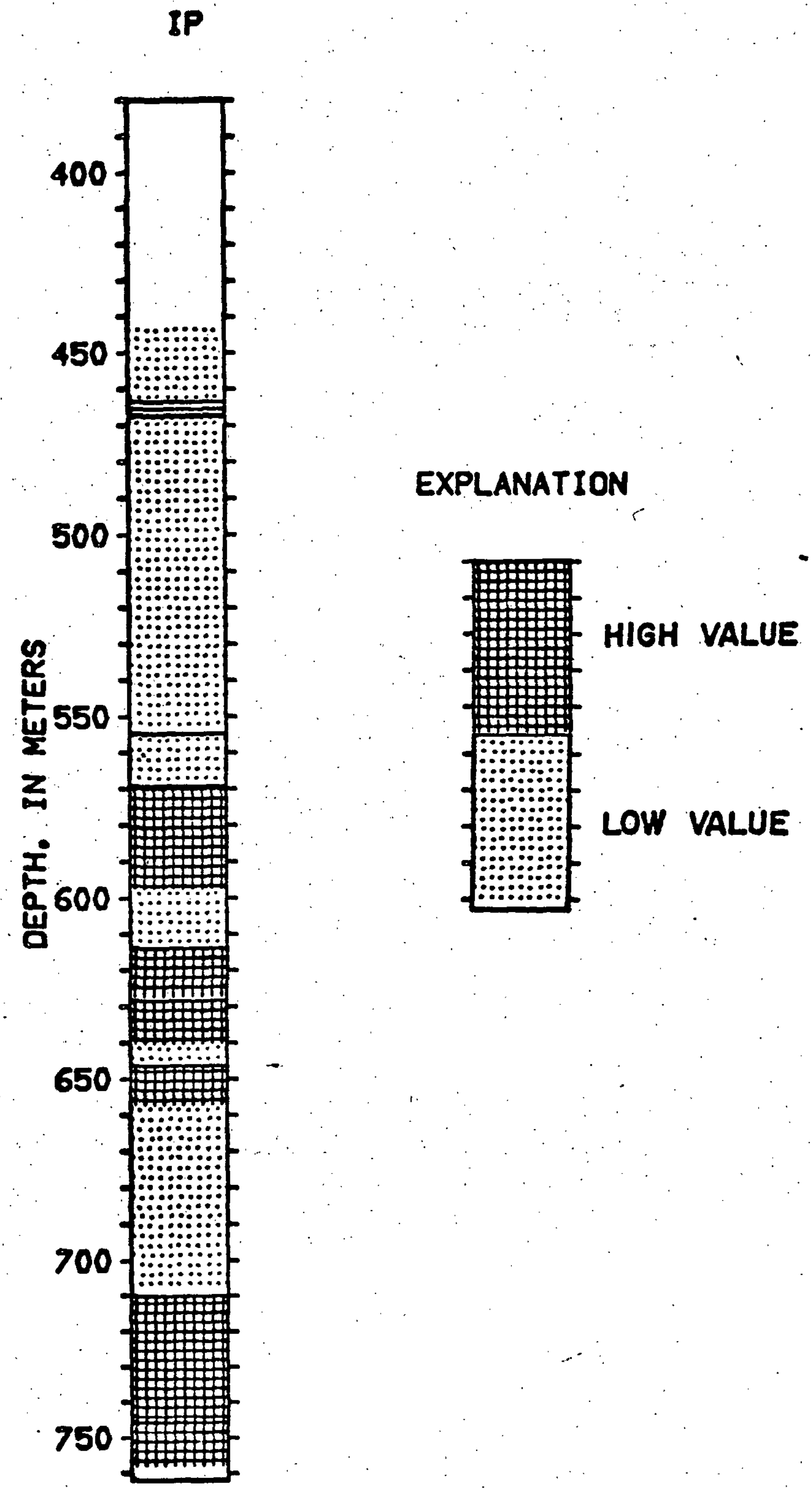

Figure 7.—Computer-assisted interpretation of the induced polarization (IP) well log from drill hole UE25a-1 based on the value ranges given in Table 1. High and low value ranges correspond to the relative amount of polarizable minerals present in the lithologic unit which may include cation-rich clays, zeolites, or pyrite, and to a lesser extent magnetite and possibly hematite.

phase crystallization which is SiO_2 rich with only minor amounts of K-feldspar. The moderate-to-high magnetic susceptibility values for the densely welded Paintbrush Tuff sections, compared to the low magnetic susceptibility values for those of the Crater Flat Tuff, may be related to the variation of magnetite in the initial composition of the magma, but the lower values may also be an indication of the degree of oxidation of magnetite to hematite. Particularly high magnetic susceptibility values are associated with a vitrophyre interval at the base of the Paintbrush Tuff. There is also a zone toward the base of the densely welded Paintbrush Tuff (330-380 m) where the gamma-ray values, along with those for the neutron log, drop off sharply to values that suggest a less densely welded or intensely fractured interval.

Values (density and neutron) for the lower non-welded portion of the Tiva Canyon Member (63-73 m) are not reliable due to borehole wall collapse that has enlarged the drill hole from about 24-80 cm in this region. This crystal-rich (14 percent) non-welded zone, however, exhibits high magnetic susceptibility values (55.7-175.1($\times 10^{-6}$) SI units) and regions of high gamma-ray values (91.6-140.5 cps) that are on par with those for the upper crystal-poor (<5 percent) welded portion; this suggests equally high concentrations of K-bearing minerals and magnetite within the two units.

Composite Interpretation of Geophysical Well Logs

Because a geophysical well-log measurement may represent a sum of several properties or a single property consistent throughout a varied lithology, it becomes necessary to simultaneously interpret several well logs to best characterize the encountered rock. Our computer program uses several digitized well logs and the corresponding value ranges subjectively assigned to a particular lithology. The result is a lithologic column where a lithologic symbol has been assigned only to those depth intervals where the given set of value ranges for the well logs are found to overlap. Due to the problems encountered in logging the upper portion of UE25a-1, only the lower logs are considered in the multiple log analysis.

Figure 8 shows the results of multiple log interpretation combining the density and neutron logs. In the first case, 8(a), each log was divided into two value ranges: non-welded and densely welded. The analysis for this oversimplified model left gaps (570-580 m, 705-715 m), indicating disagreement between the value ranges for the lithologies assigned. The density and neutron logs were subsequently divided into three value ranges (non-, partially, and densely welded) as given in Table 1, and the result is shown in Figure 8(b). Accepting this interpretation as having essentially established the welding intervals, the value ranges of these intervals were set against those for each well log (Table 1) to form matrices of possible welding interval vs. well-log value associations (Fig. 9, explanations). The results of the computer analysis, which assigned depth ranges to the value ranges (Table 1) of those existing possibilities in an individual well log, are shown in Figure 9. Figure 9 is a preliminary interpretation that should be augmented by geologist's logs, driller's records, and the detail of the original geophysical well-log measurements.

There are notable differences of the resistivity and IP response values between the densely welded zones of the Prow Pass Member and the Bullfrog Member of the Crater Flat Tuff (Figs. 2 through 7, and Fig. 9). The densely welded intervals of the Prow Pass Member have high resistivity values and low IP values, and the Bullfrog Member has low resistivity values and high IP

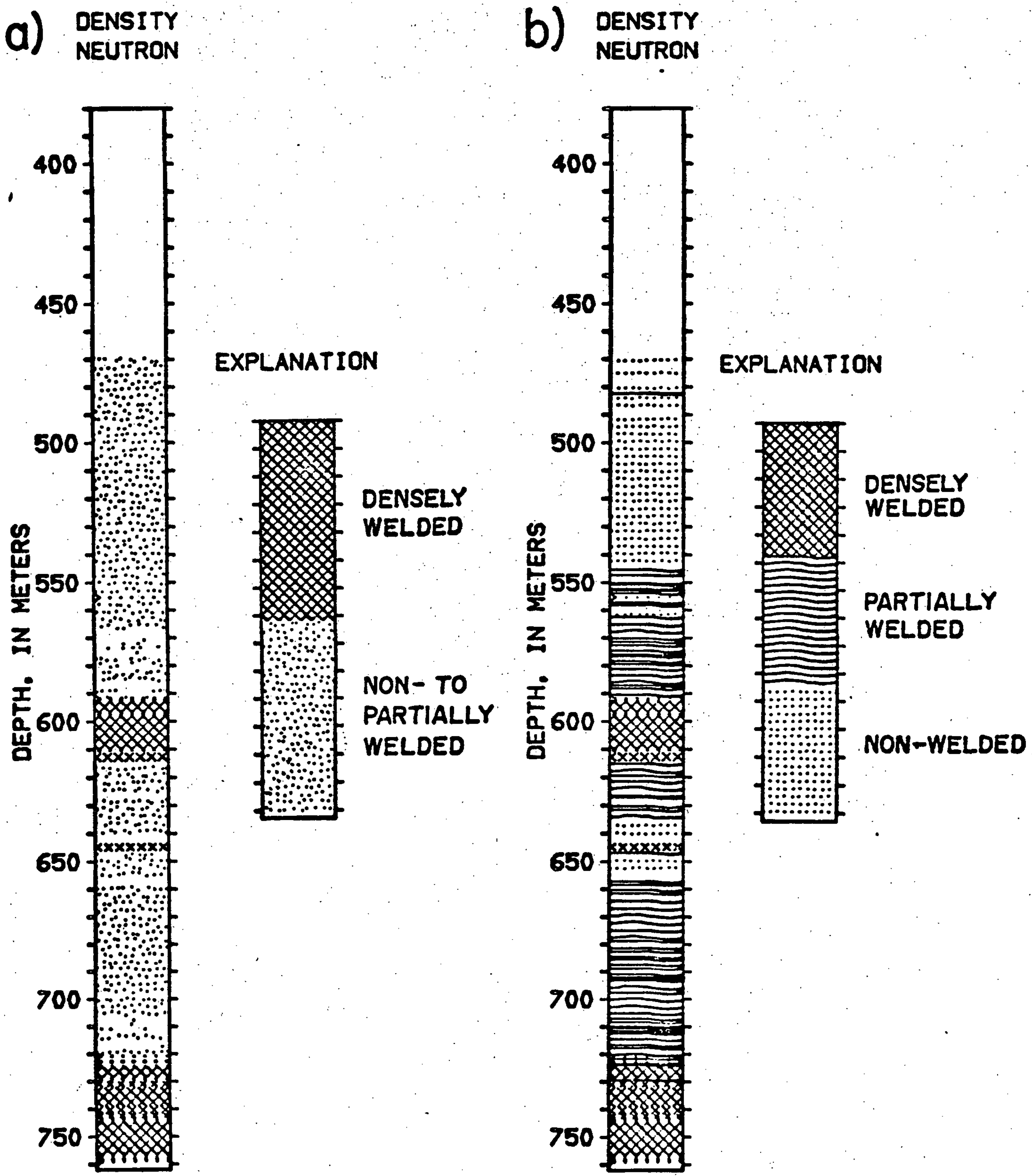

Figure 8.—Computer-assisted simultaneous interpretation of the density and neutron well logs from drill hole UE25a-1 using two values ranges in part (a) non-welded density = 1.76-2.27 g/cm^3; neutron = 814.3-1329.9 cps; and densely welded density = 2.27-2.42 g/cm^3; neutron = 1329.9-1883.0 cps; and three value ranges in part (b) (those given in Table 1).

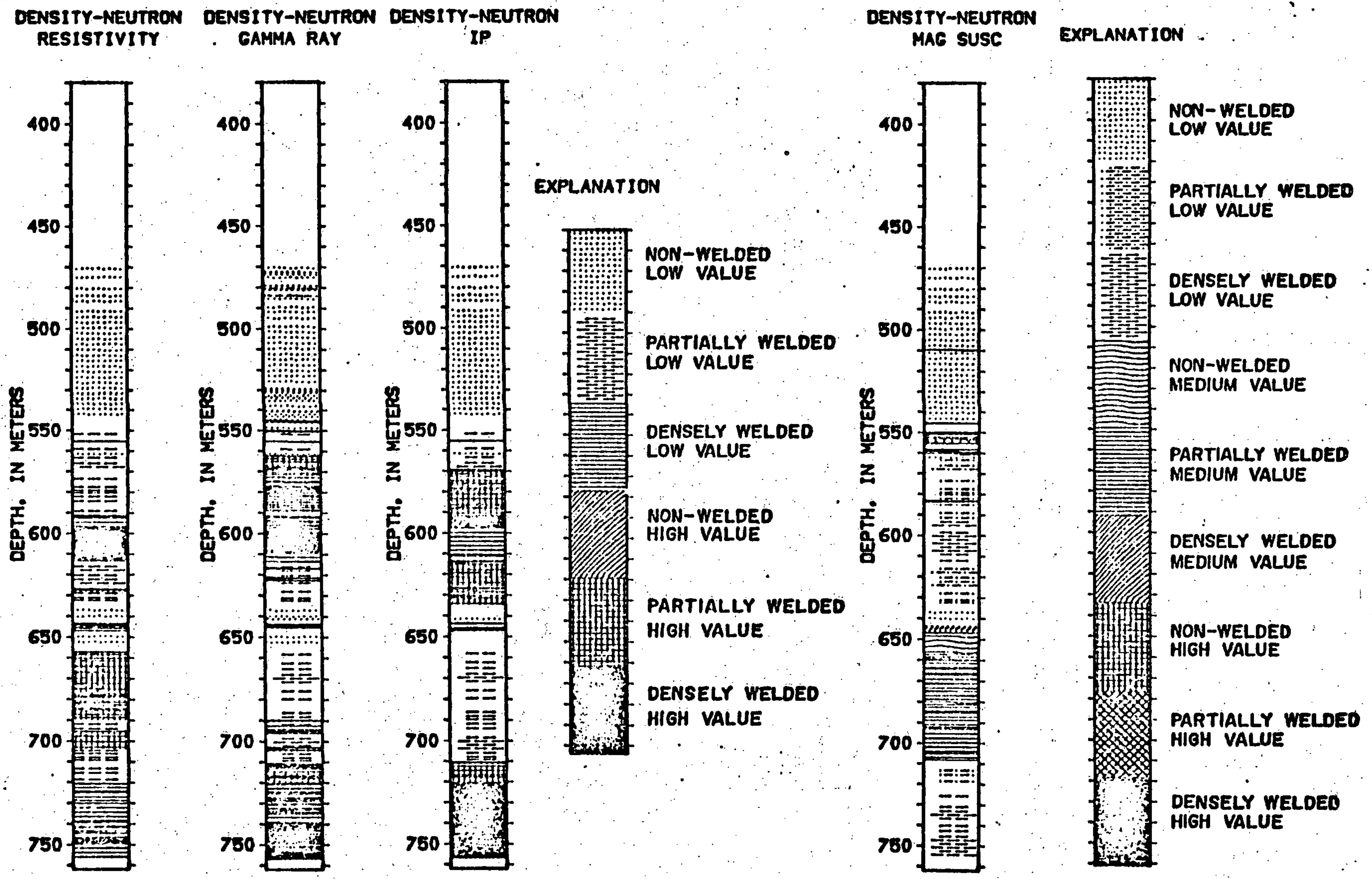

Figure 9.--Computer-assisted simultaneous interpretation of possible welded interval (Fig. 8(b)) vs. well-log value (Table 1) associations for well logs from the lower half of drill hole UE25a-1.

values (Table 1). The density, neutron, gamma-ray and magnetic susceptibility log measurements all show consistent values between these units. The Prow Pass Member has resistivity and IP values indicative of low porosity and low zeolite (?) alteration. The Bullfrog Member probably contains a higher concentration of a low-resistivity polarizable mineral than the Prow Pass Member. Hematite (observed in the Bullfrog Member samples taken from UE25a-1 as an alteration product of mafic xenocrysts (Sykes, et al, 1979)) could cause some of the IP responses seen in the Bullfrog Member.

The non-welded units in the lower half of the borehole show lower density, neutron, and magnetic susceptibility values than the welded units. The tuffaceous Beds of Calico Hills appear to be the least indurated interval and show the lowest density and neutron values (Fig. 8). Resistivity, gamma-ray, and magnetic susceptibility values are also among the lowest encountered in the drill hole indicating a relatively high porosity and low concentrations of K-rich minerals and magnetite (Fig. 9). There is one particular interval within the tuffaceous Beds of Calico Hills (443-493 m) that gives an anomalously high gamma-ray response for this unit (79.4-103.8 cps) with a large IP value (>5 percent) at the 469-m depth (Fig. 1). The high IP response may be the result of conditions at 469 m (possibly associated with the water-table level), similar to those found in a sample recovered from 482.9 m which contained an opaque crack filling that shone bright yellow in reflected light (Sykes, et al, 1979). If this mineral is pyrite, and is present in greater abundance than at the 469-m depth, it could account for the high IP value. The higher gamma-ray value may also reflect fracture filling in the region with K-rich minerals.

The partially welded units of the Prow Pass Member are segregated into similar upper units and a lower unit on the basis of the resistivity, IP, and magnetic susceptibility values (Fig. 9). The upper partially welded units exhibit low resistivity, high IP, and mostly low magnetic susceptibility values. The density and neutron measurements (Figs. 2 and 3) for these upper units suggest a slightly more indurated version of the tuffaceous Beds of Calico Hills, which is supported by the corresponding resistivity and magnetic susceptibility values (Fig. 9). For the lower partially welded section, the density and neutron measurements parallel those of the upper units, but here the resistivity and magnetic susceptibility values differ. High magnetic susceptibility values reflect the relative abundance or magnetite in this lower unit, but the high resistivity values are probably caused by the higher degree of silicification found within this unit (Spengler, 1979). The gamma-ray values are about the same for all zones, but are higher for the uppermost partially welded zone. The crystal-rich (10-14 percent) portion of the Prow Pass Member (upper 60 m) should be relatively abundant in K-rich minerals and magnetite (Sykes, et al, 1979). The magnetic susceptibility values indicate places in this unit that contain moderately high amounts of magnetite. Because zeolites are present throughout the member, the high IP values shown only by the upper partially welded units of the Prow Pass may be caused by the presence of some other cation-rich mineral (clay alteration), or the IP response may be suppressed by conditions in the lower portion of the Prow Pass as well as in the tuffaceous Beds of Calico Hills.

Conclusions

The broad features of the welded tuff sequence encountered in drill hole UE25a-1 are readily characterized by their physical properties measured by the geophysical well logs. Welded tuffs, however, are extremely complex lithologic units involving the superimposition of several factors and processes, and a detailed interpretation requires equally detailed lithologic information. Interpretation of geophysical well logs from UE25a-1 was hampered by incomplete log coverage and the complex response of some well logs. In particular, the IP measurements did not consistently correspond to any single mineral expected to give a high response. More mineralogic and petrologic work is needed to clarify the causal elements of well-log response in welded tuffs, to understand the interrelationships between logs responding to textural and/or mineralogic conditions, and to shed more light on the unexpected response values of the well-log measurements. Future studies must also include laboratory physical properties measurements to link the mineralogic and petrologic work to the geophysical well-log measurements.

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APPENDIX A

Geophysical Well Logs from Drill Hole UE25a-1, Yucca Mountain, Nevada Test Site

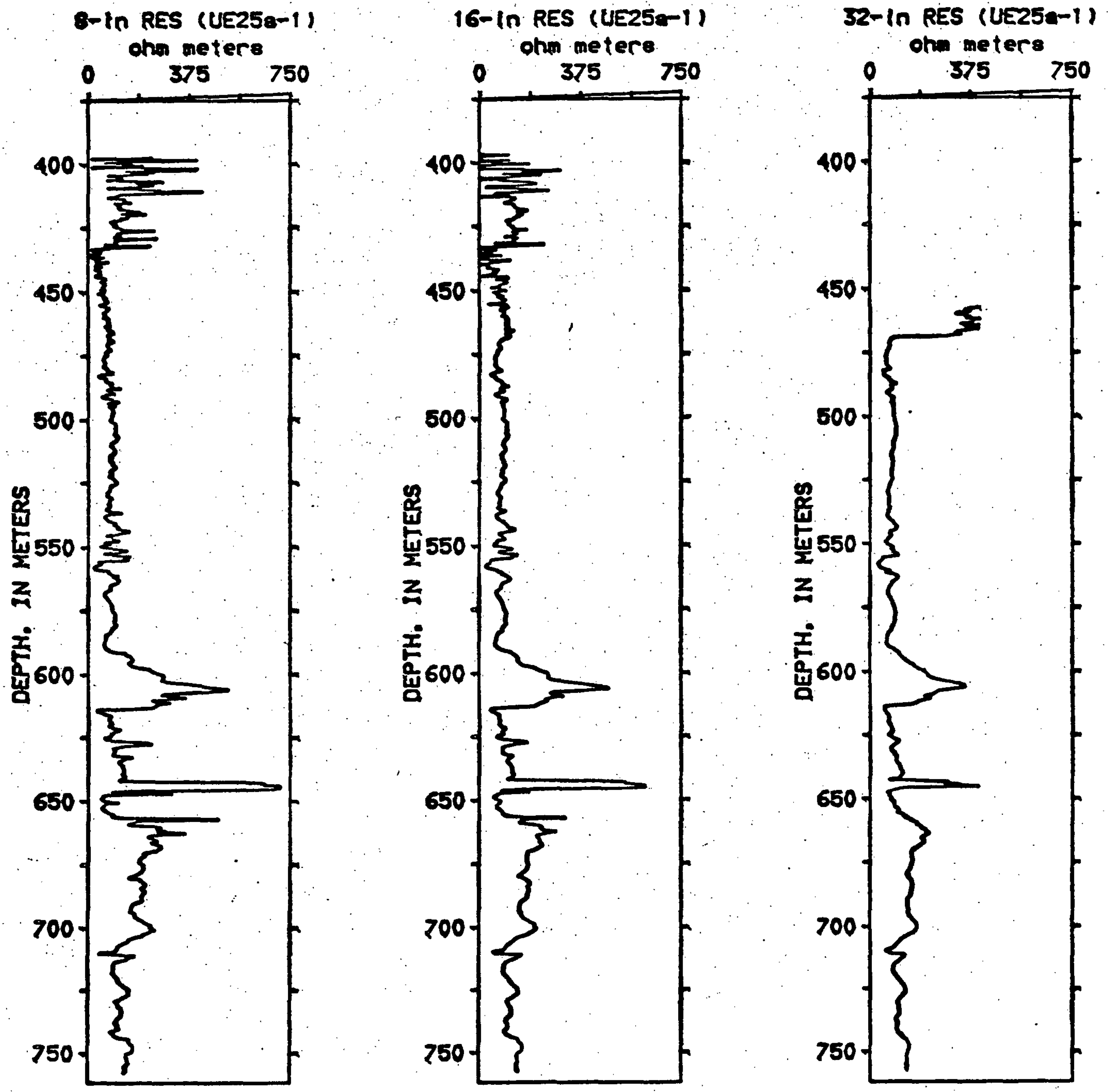

Figure A1.—Normal resistivity well logs (8-in., 16-in., 32-in.) for drill hole UE25a-1. Units are in ohm meters.

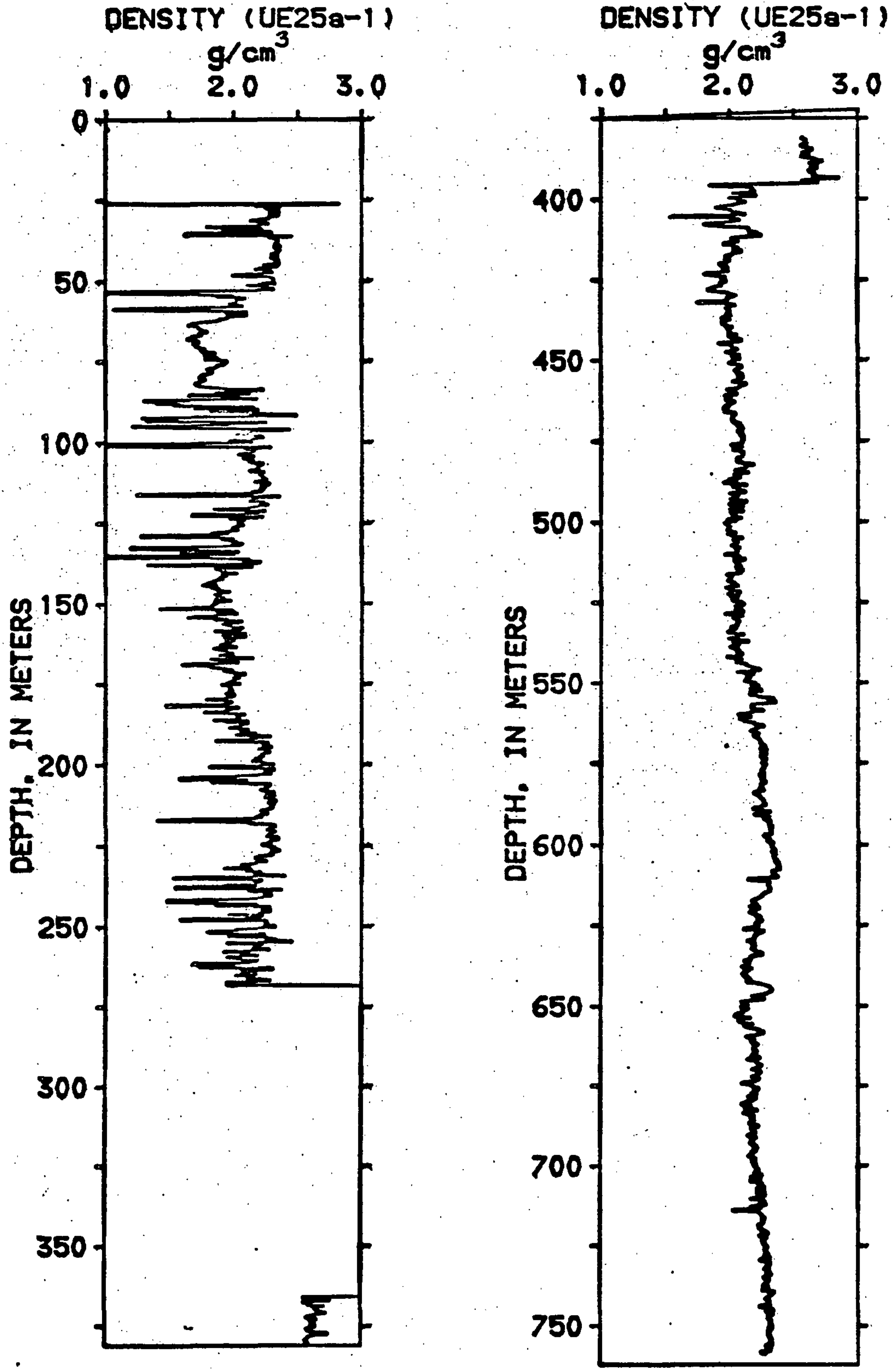

Figure A2.—Compensated density well log for drill hole UE25a-1. Units are in grams/centimeters^3 (g/cm^3).

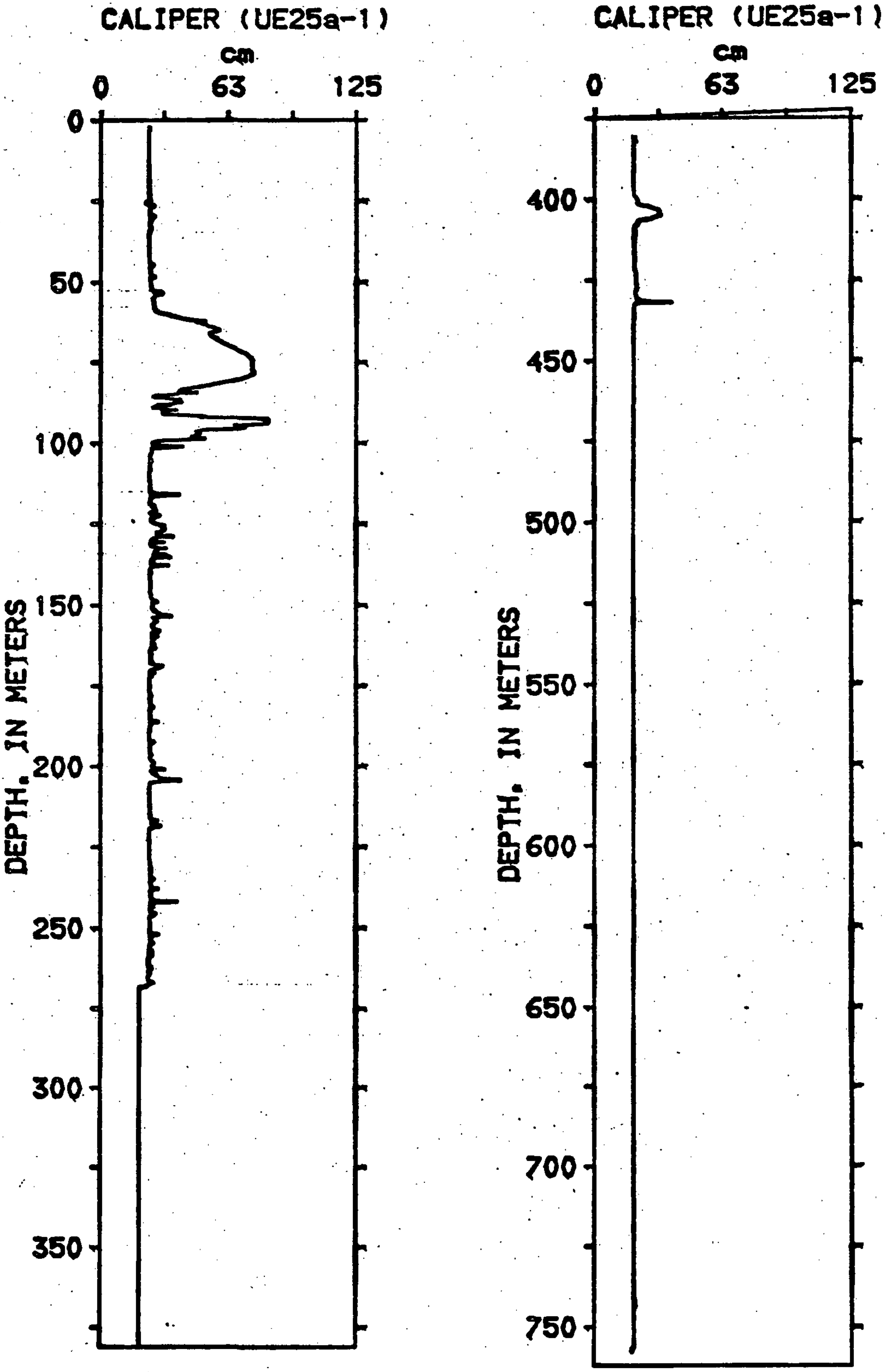

Figure A3.—Caliper well log for drill hole UE25a-1. Units are in centimeters (cm).

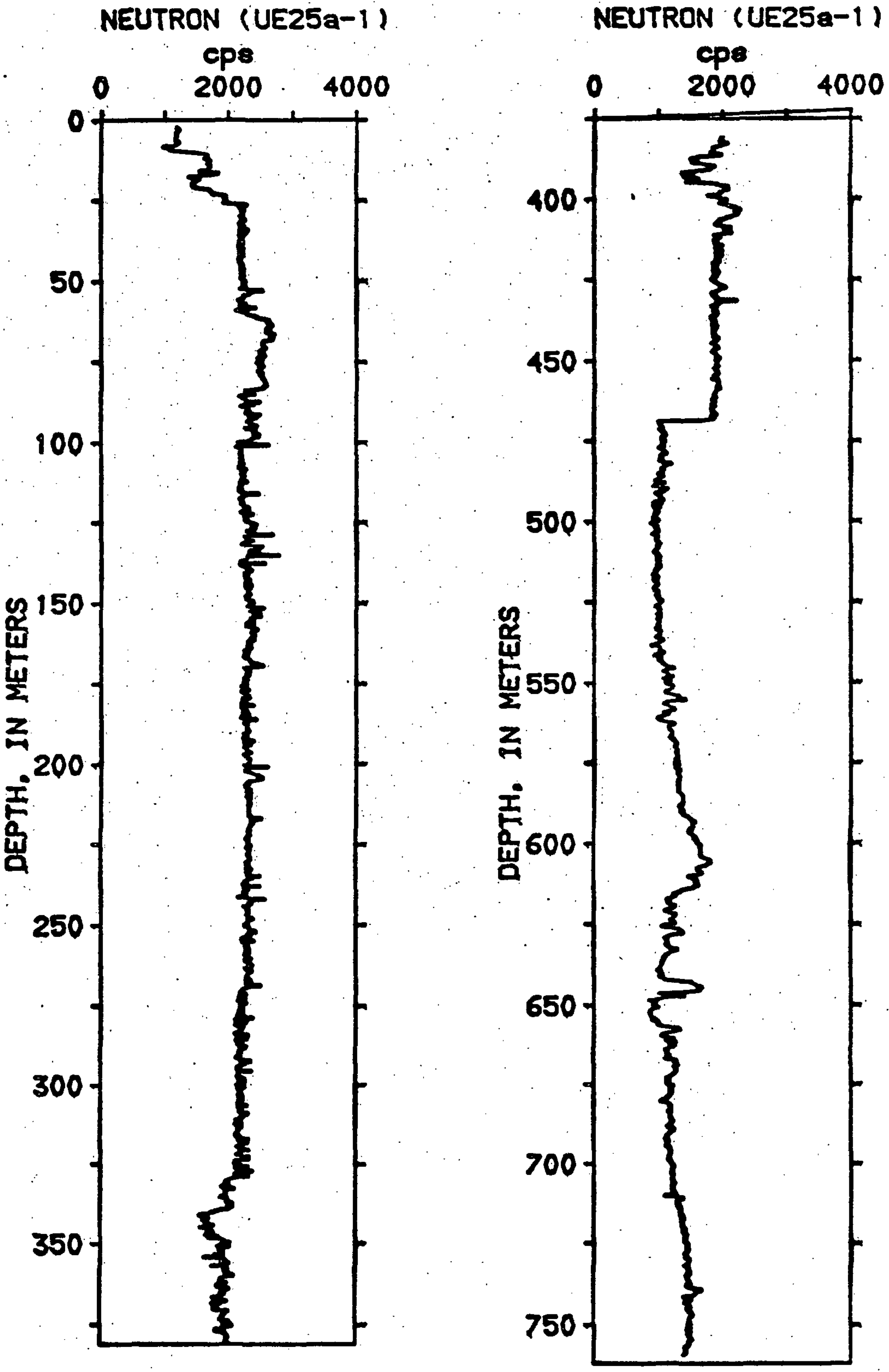

Figure A4.—Neutron well log for drill hole UE25a-1. Units are in counts/second (cps).

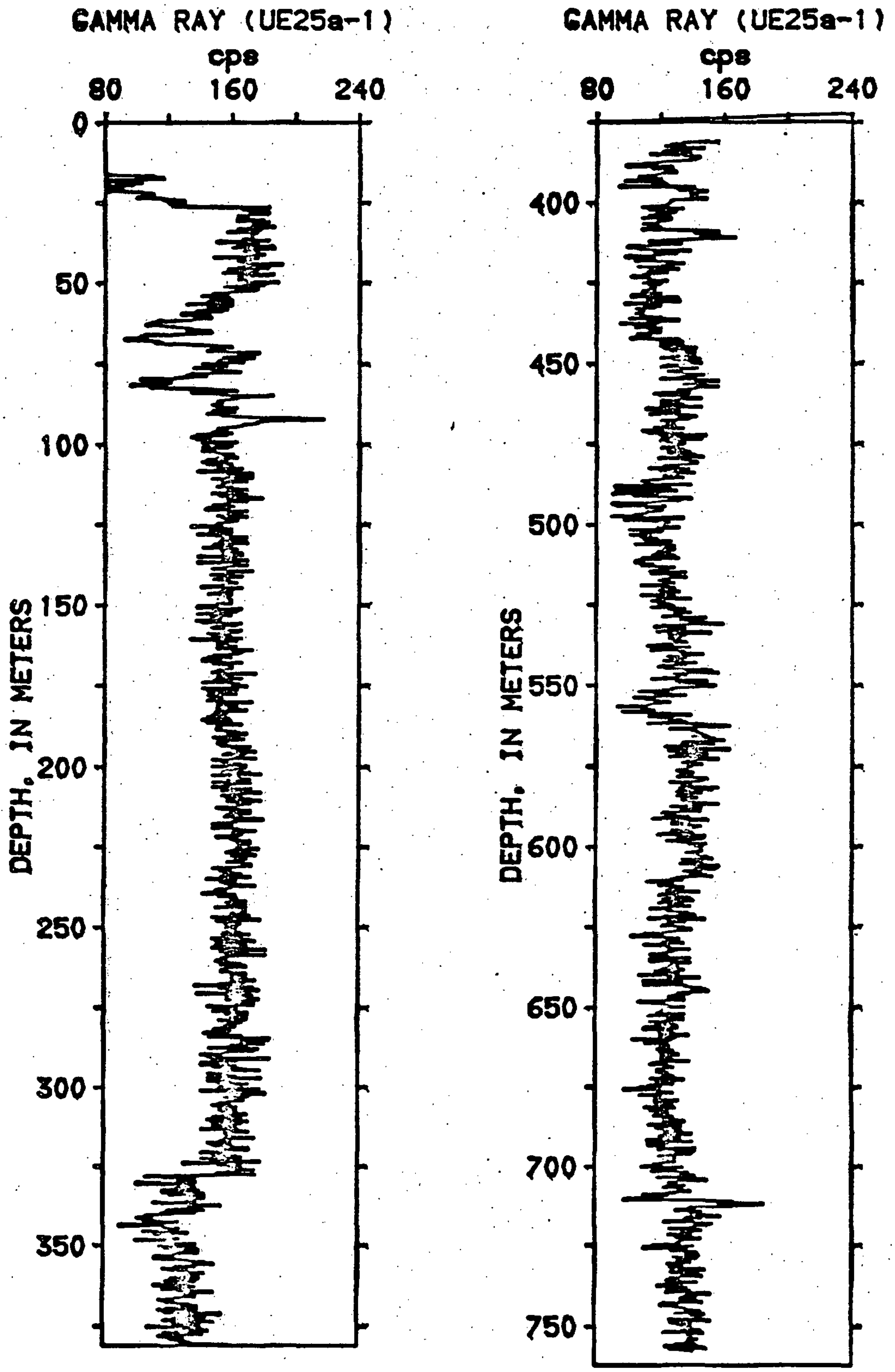

Figure A5.—Gamma-ray well log for drill hole UE25a-1. Units are in counts/second (cps).

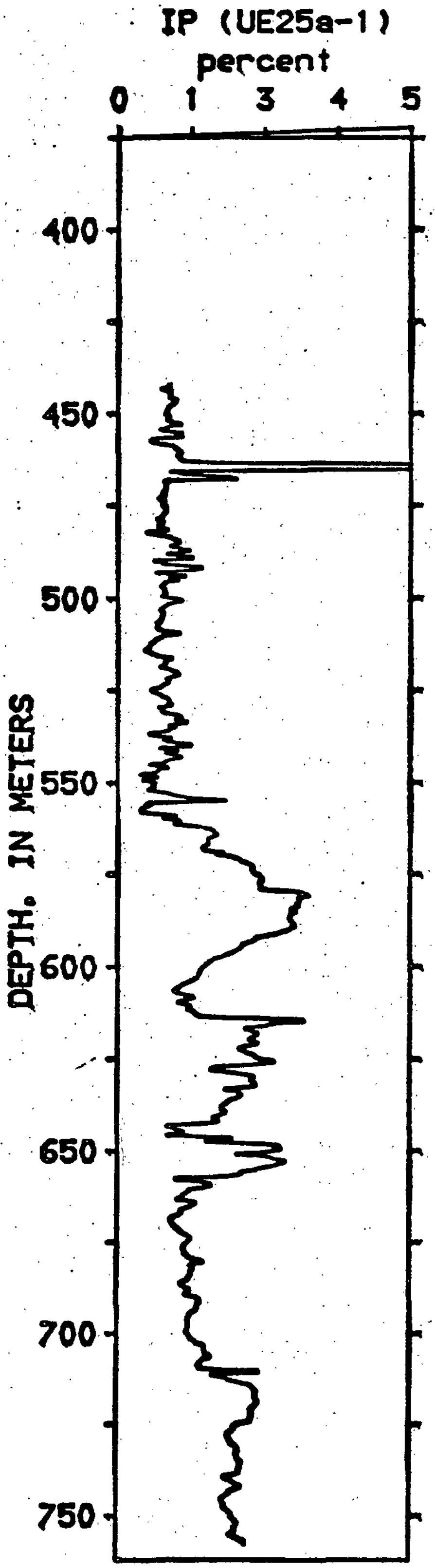

Figure A6.—Induced polarization (IP) well log for drill hole UE25a-1. Units are in percent.

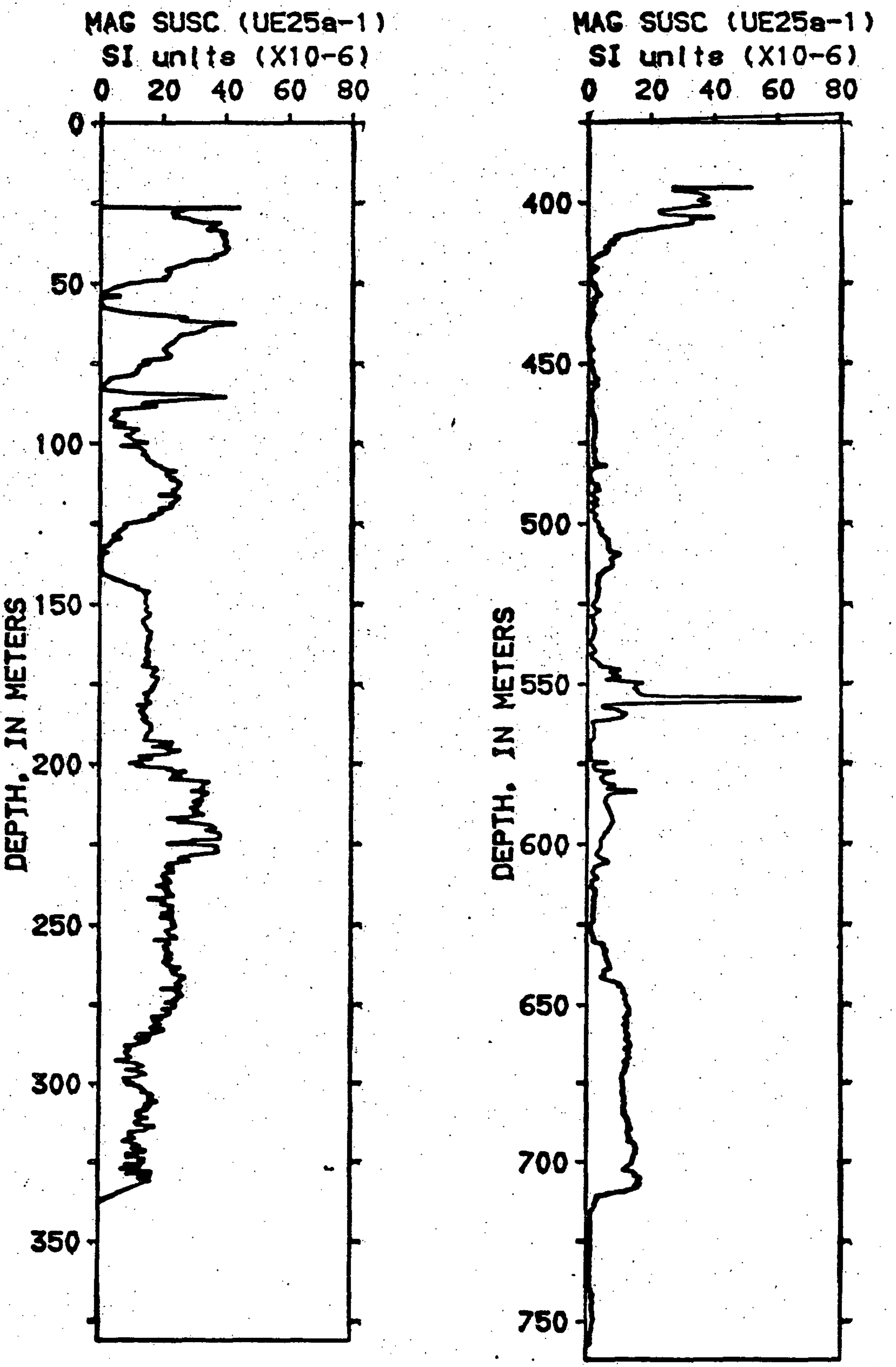

Figure A7.—Magnetic susceptibility well log for drill hole UE25a-1. Units are in SI units x 10^{-6}.