Open-File Report 81-389

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Interpretation of Geophysical Well-Log Measurements in Drill Holes UE25a-4, -5, -6, and -7, Yucca Mountain, Nevada Test Site

by

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Open-File Report 81-389

1981

Prepared by the U.S. Geological Survey
for
Nevada Operations Office
U.S. Department of Energy
(Memorandum of Understanding DE-AI08-78ET44802)

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Abstract

Exploratory holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 were drilled at the 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. Ash-flow and bedded tuff sequences at NTS comprise complex lithologies of variously welded tuffs with superimposed crystallization and altered zones. Resistivity, density, neutron, gamma-ray, induced-polarization, and magnetic-susceptibility geophysical well-log measurements were made to determine the physical properties of these units. The interpretation of the well-log measurements was facilitated by using a computer program designed to interpret well logs. The broad features of the welded tuff units are readily distinguished by the geophysical well-log measurements. Some mineralogic features in the drill holes can be identified on the gamma ray, induced polarization, and magnetic susceptibility well logs.

Introduction

As much as 3000 m of rhyolitic tuffs that were erupted from the Timber Mountain-Oasis Valley caldera complex (late Tertiary time (16-9 m.y.)) at NTS mantle an eastern portion of the Basin and Range province. 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).

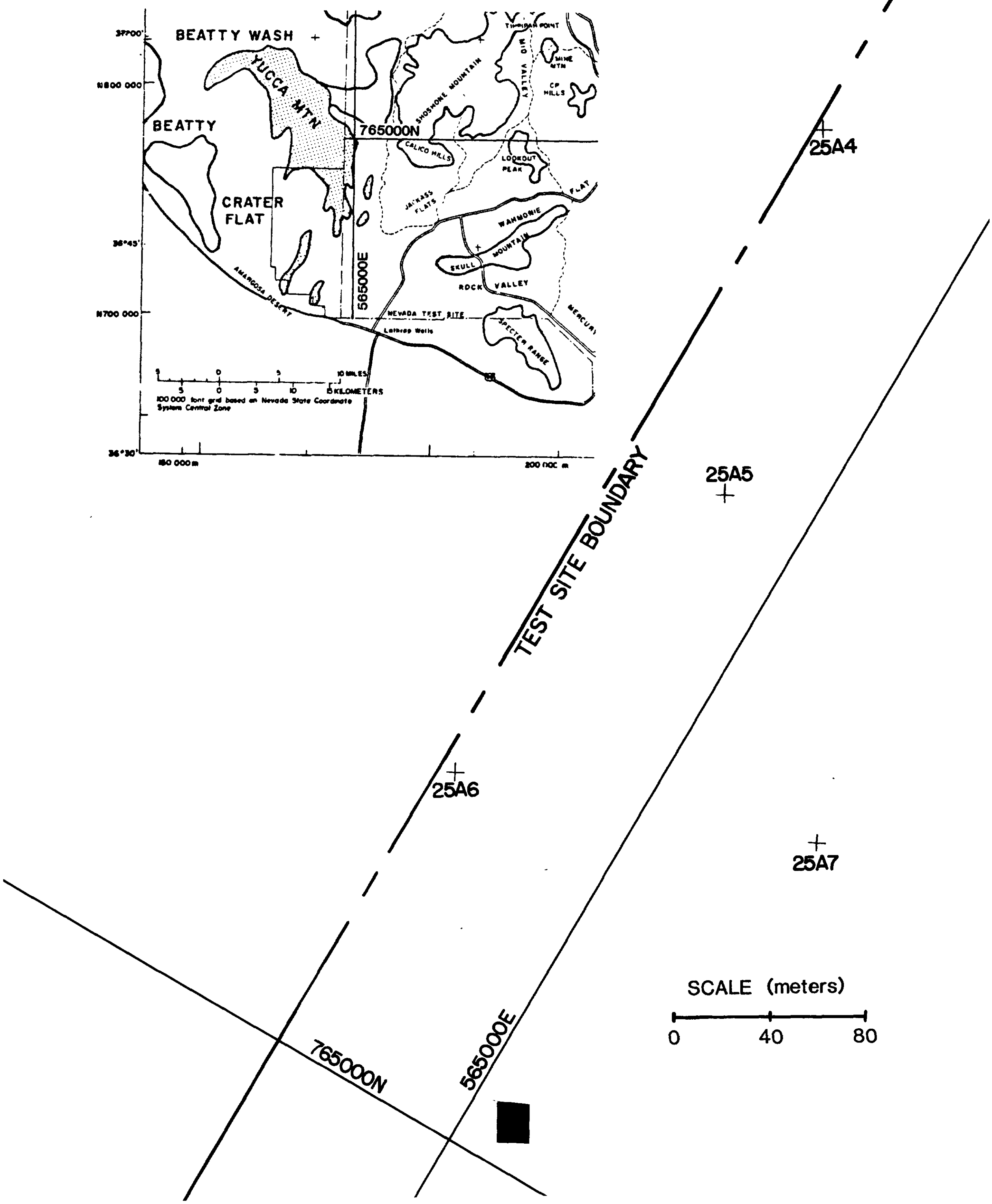
To study the suitability of pyroclastic deposits as storage sites for radioactive waste, four exploratory holes were drilled in the summer of 1979 (under the auspices of the U.S. Department of Energy) at NTS. Exploratory drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 were drilled and cored to depths of 138 m, 133 m, 128 m, and 143 m, respectively, on the northeastern flank of Yucca Mountain to investigate the geologic characteristics of the (listed in order of increasing age): Tiva Canyon, Yucca Mountain, Pah Canyon, and Topapah Spring Members of the Miocene Paintbrush Tuff. Holes UE25a-4, -5, and -6 were vertical core holes, while hole UE25a-7 was drilled at an angle of 26^{o} from vertical. The location of these drill holes is shown in Figure 1. This study discusses the physical properties of the tuff units as measured with U.S. Geological Survey borehole geophysical research equipment.

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

Figure 1.--Location of drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 Yucca Mountain, Nevada Test Site.



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. The ground water level is well below the bottom depth of each of the drill holes considered in this study. The lithologic intervals and the distribution of crystallization and alteration zones as determined by Spengler (1980) are given in Figure 2.

Lithologic interpretation from the Response Characteristics of Geophysical Well Logs in Ash Flow Tuffs

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 (fluidity 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.

The initially unsaturated condition of the rocks surrounding these shallow drill holes makes interpretation of the lithologies particularly difficult. Drilling artificially introduces fluid into the formation, causing the rocks surrounding the drill hole to become partially saturated. Large closed voids in the rocks can remain dry throughout the period of time that geophysical well-log measurements are made. The resistivity and neutron-neutron measurements are sensitive to the degree of saturation of the rocks with fluid. The fluid level could not be maintained to the surface in any of the drill holes in this study. Therefore, the resistivity and neutron well logs are shown for that portion of the drill holes for which a "standing" water level could be maintained.

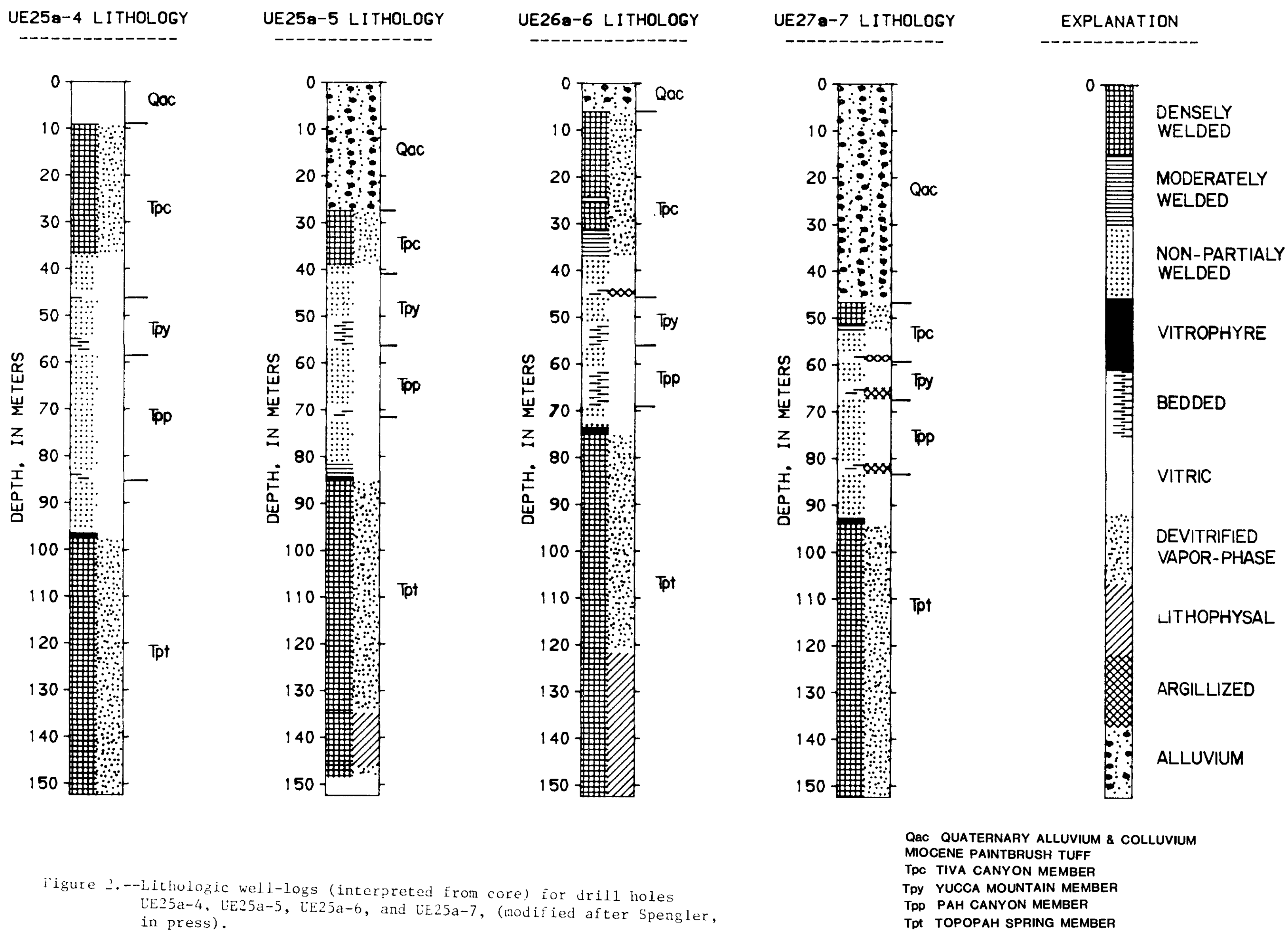


Figure 2.--Lithologic well-logs (interpreted from core) for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7, (modified after Spengler, in press).

Interpretation of individual geophysical well logs is made by assigning symbols to different value ranges on the geophysical well logs. The value ranges are chosen to best correspond with the lithologies given in Figure 2. However, the lithologies in Figure 2 were not chosen on the basis of physical properties and are often different from the computer-assigned symbols for the geophysical well logs.

Resistivity

Resistivity is a measure of the ease with which electric current passes through a material. Borehole resistivity depends upon the porosity, the fluid resistivity and the grain resistivity of the rock. The resistivity of ash-flow tuffs should be a function of (a) welding, (b) devitrification, and (c) void space in the rocks. Resistivity in saturated welded tuffs should increase with the degree of welding and decrease with the degree of devitrification and the amount of void space (including fractures) in the rocks. When the lithophysal zones are unsaturated, the void space may cause an increase in the measured resistivity.

The resistivity well logs (16" normal) for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 are shown in Figures 3, 4, 5, and 6, respectively. Symbol-logs, obtained by assigning lithologic symbols to resistivity value ranges, are also shown in these figures. There is a general correspondence between the lithologic log and the symbol log interpreted from the resistivity values. The high resistivity values for the Topopah Spring Member can be fairly consistently interpreted as welded tuffs. However, in each of the drill holes there is a zone of high resistivity at the top of the Topopah Spring and a zone of low resistivity at the base of the drilled Topopah Spring

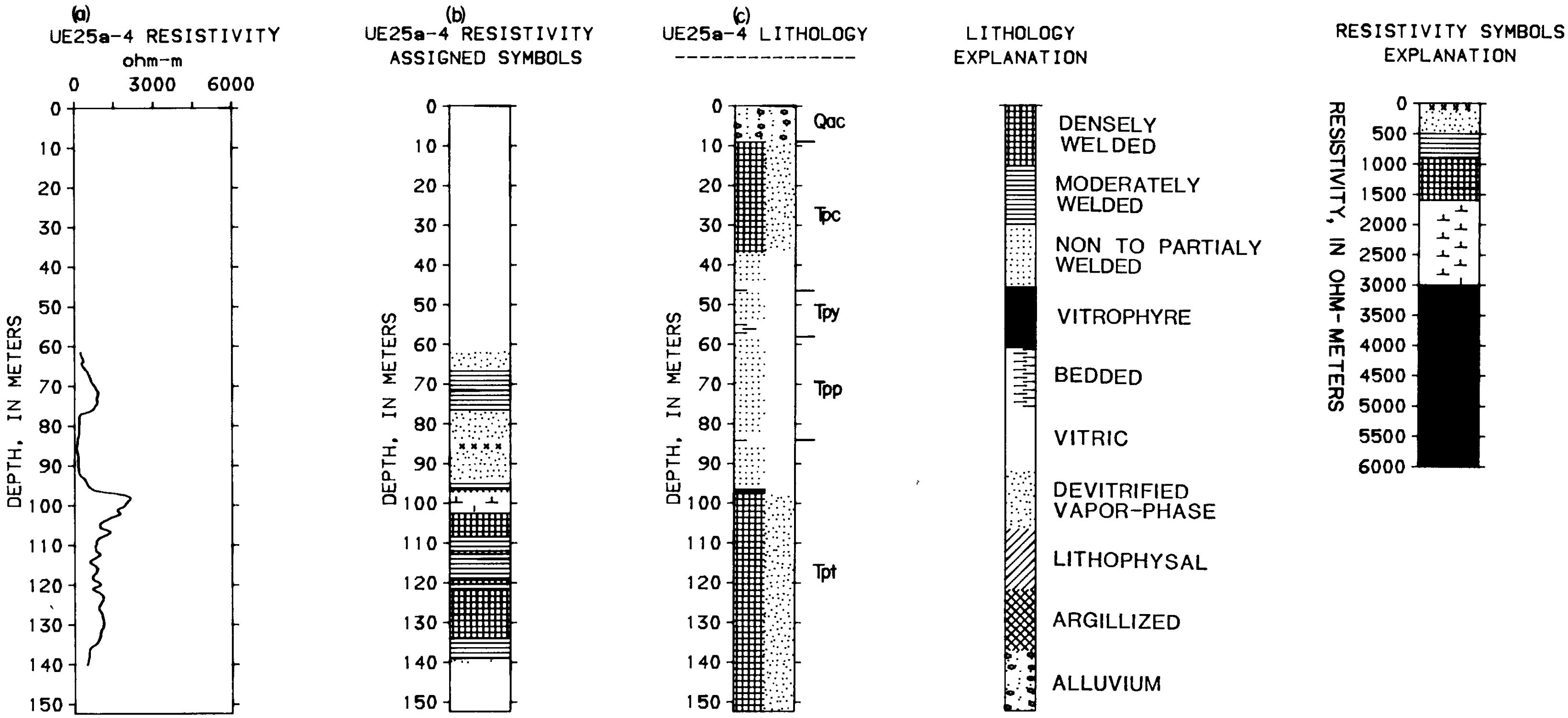


Figure 3.--Resistivity well-logs and interpretation for drill hole UE25a-4:
(a) resistivity well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

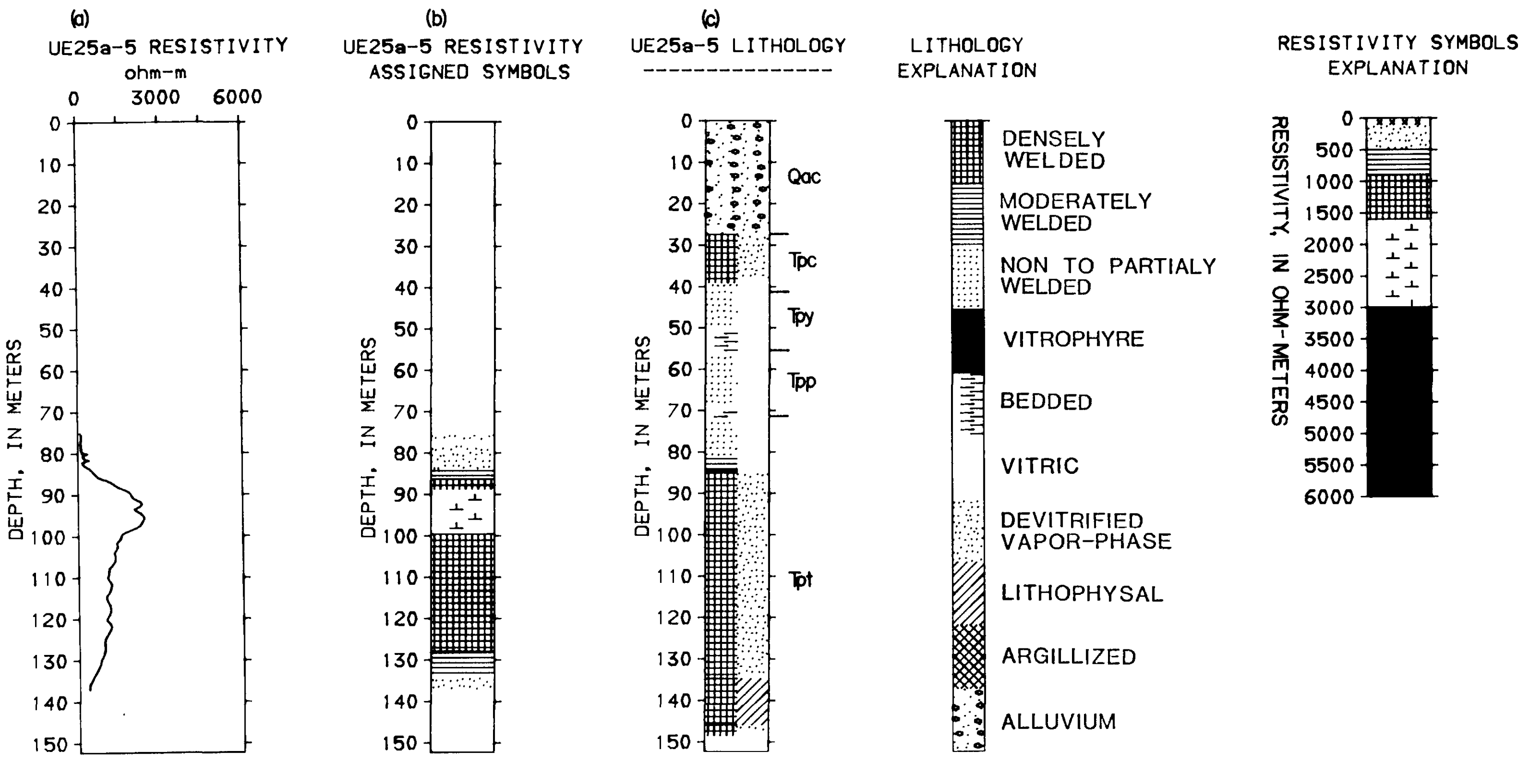


Figure 4.--Resistivity well-logs and interpretation for drill hole UE25a-5:
(a) resistivity well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

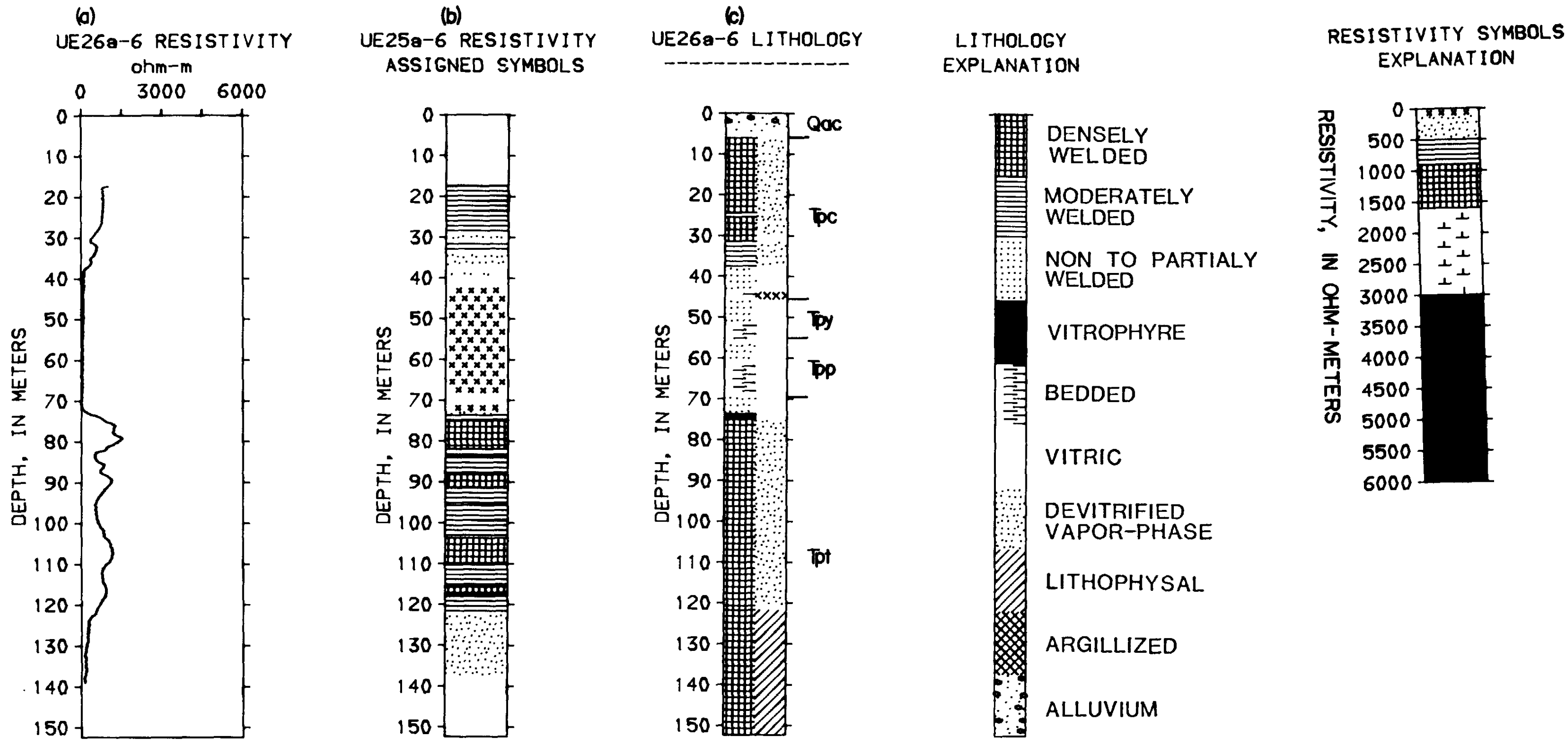


Figure 5.--Resistivity well-logs and interpretation for drill hole UE25a-6: (a) resistivity well-log, (b) computer assigned symbols, and (c) lithologic well-logs (after Spengler, in press).

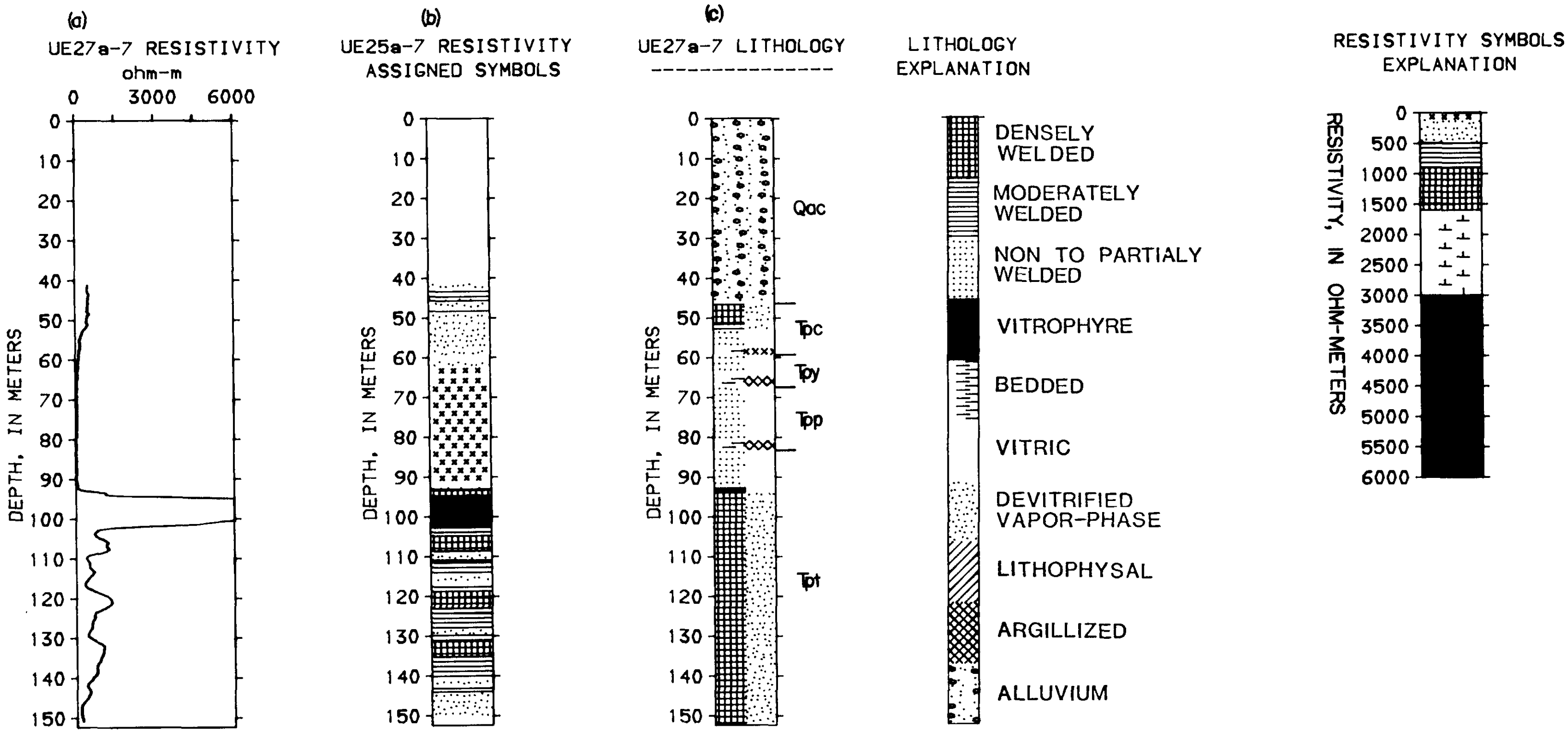


Figure 6.--Resistivity well-logs and interpretation for drill hole UE25a-7:
(a) resistivity well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

interval that cannot be explained solely by variations in the degree of welding. It is possible that a vitrophyre causes the high-resistivity zone at the top of the Topopah Spring and a lithophysal zone causes the low resistivities at the bottom of drill holes UE25a-5 and UE25a-6. However, it is also likely that there are variations in the degree of welding which cannot be seen in the drill core but do affect the resistivity. A comparison of the four resistivity well logs for the Topopah Spring Member indicates the following: (a) a high degree of welding (or low alteration and fracturing) for drill hole UE25a-5, (b) an intermediate degree of welding for drill hole UE25a-4, and (c) a low degree of welding (or high alteration and fracturing) for drill holes UE25a-6, and UE25a-7. The stratigraphic members above the Topopah Spring are less densely welded, resulting in low resistivity values. If the degree of welding in the Topopah Spring is approximately the same for each drill hole, then near-surface fracture zones (with increased seasonal ground water percolation) are most likely to occur near drill holes UE25a-6 and UE25a-7 and least likely to be present near drill hole UE25a-5.

Density

The density measurement probe consists of a gamma ray source (Cs^{137}) 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 decreases as the electron density of the rock increases. By using two detectors, the adverse effects of fluid invasion, mudcake and rugosity can be minimized, resulting in a computed compensated-density that is approximately equal to the bulk density of the rock. The computed bulk density may be too low when there are large (sharp) variations in the diameter of the borehole.

Therefore, the density well log should always be interpreted in conjunction with the caliper well log (Figure 11). Non-welded and highly altered units have low bulk densities, while densely welded units have high bulk densities. Devitrified and lithophysal zones should have relatively low densities.

The density well logs for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 are shown in Figures 7, 8, 9, and 10, respectively. Density symbol-logs, obtained by assigning lithologic symbols to density value ranges are also shown in these figures. The high density values in the Topopah Spring Member can be consistently interpreted as being caused by the presence of welded tuffs. In each of the drill holes there is an increase in the density near the top of the Topopah Spring which is probably caused by the vitrophyre indicated on the lithologic log. The lowest densities for the logged interval in each drill hole occur in the non- to partially welded zones in the Yucca Mountain and Pah Canyon Members, while intermediate density values were measured in the Tiva Canyon. However, the Tiva Canyon is classified as a densely welded unit by the lithologic core description. The average bulk density values, computed from the geophysical well logs, for the logged interval below the upper Topopah Spring vitrophyre are as follows: (a) UE25a-4 has an average bulk density of 2.09, (b) UE25a-5 has an average bulk density of 2.16, (c) UE25a-6 has an average bulk density of 2.13, and (d) UE25a-7 has an average bulk density of 2.11. Therefore, the Topopah Spring in UE25a-5 has the highest bulk density, while UE25a-4 has the lowest bulk density. The high bulk density values in drill hole UE25a-5 are consistent with the high resistivity values (and the least amount of fracturing) noted previously in this paper.

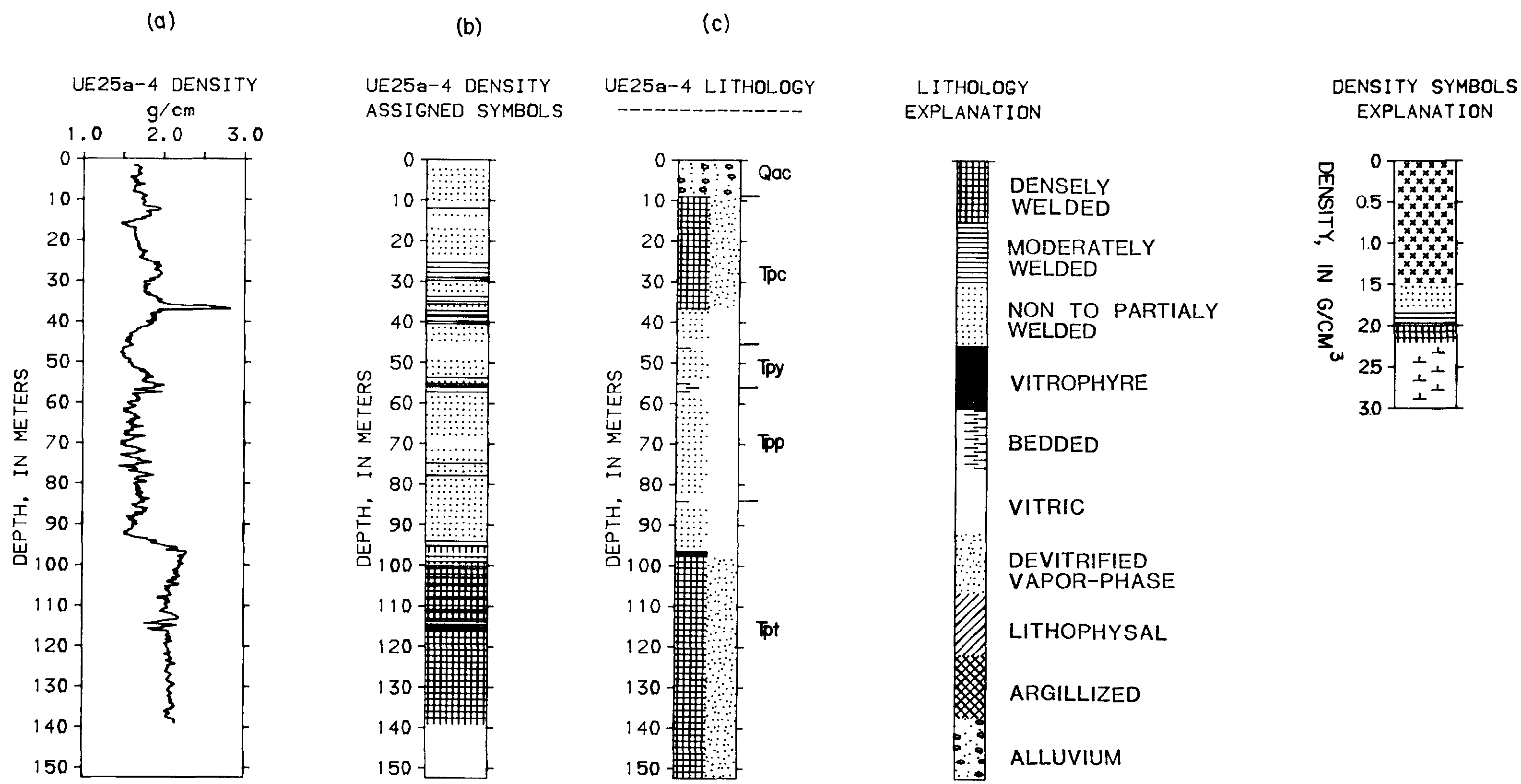


Figure 7.--Density well-logs and interpretation for drill hole UE25a-4: (a) density well-log, (b) computer assigned symbols, and (c) lithologic well-logs (after Spengler, in press).

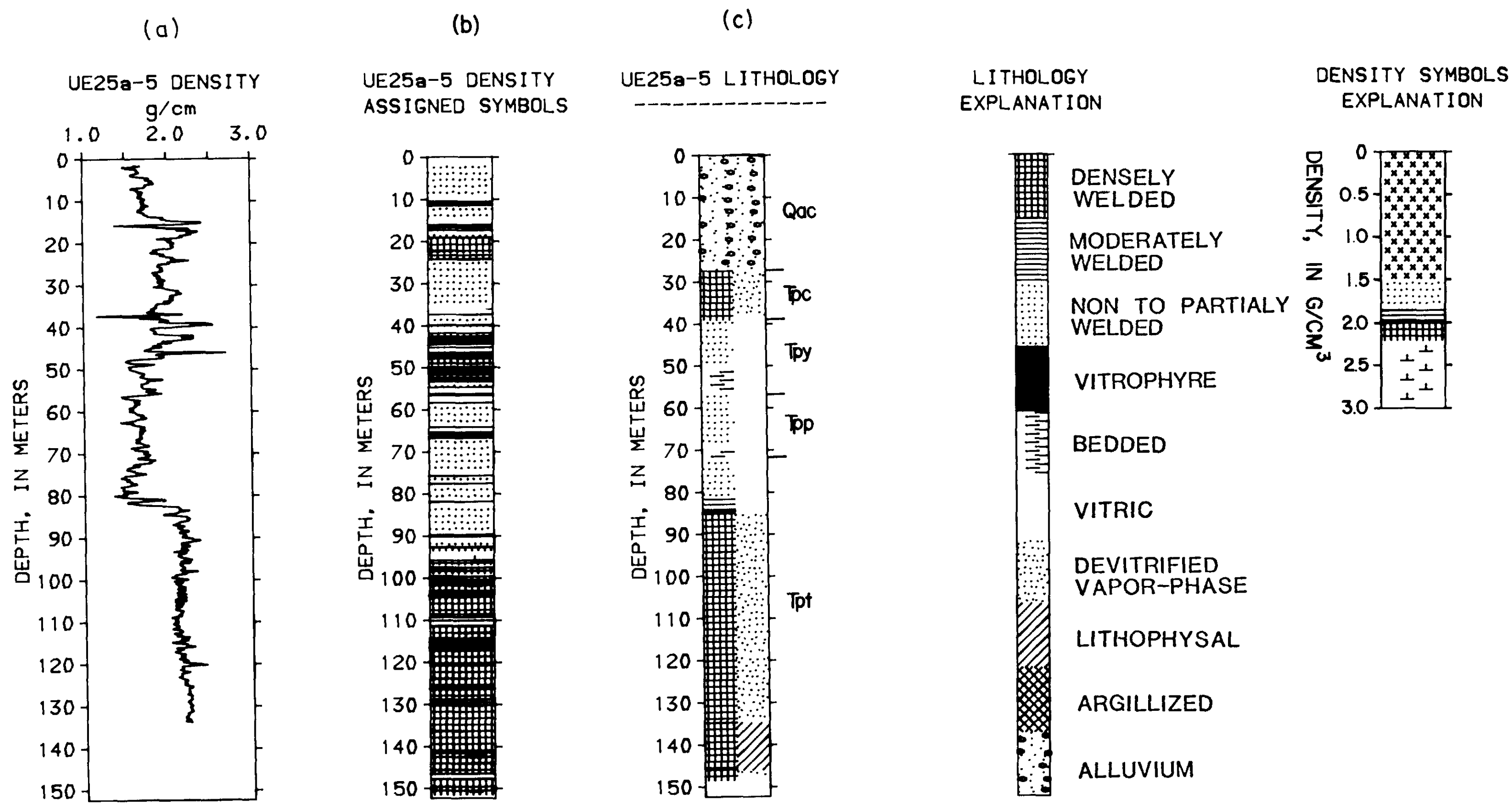


Figure 8.--Density well-logs and interpretation for drill hole UE25a-5:
(a) density well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

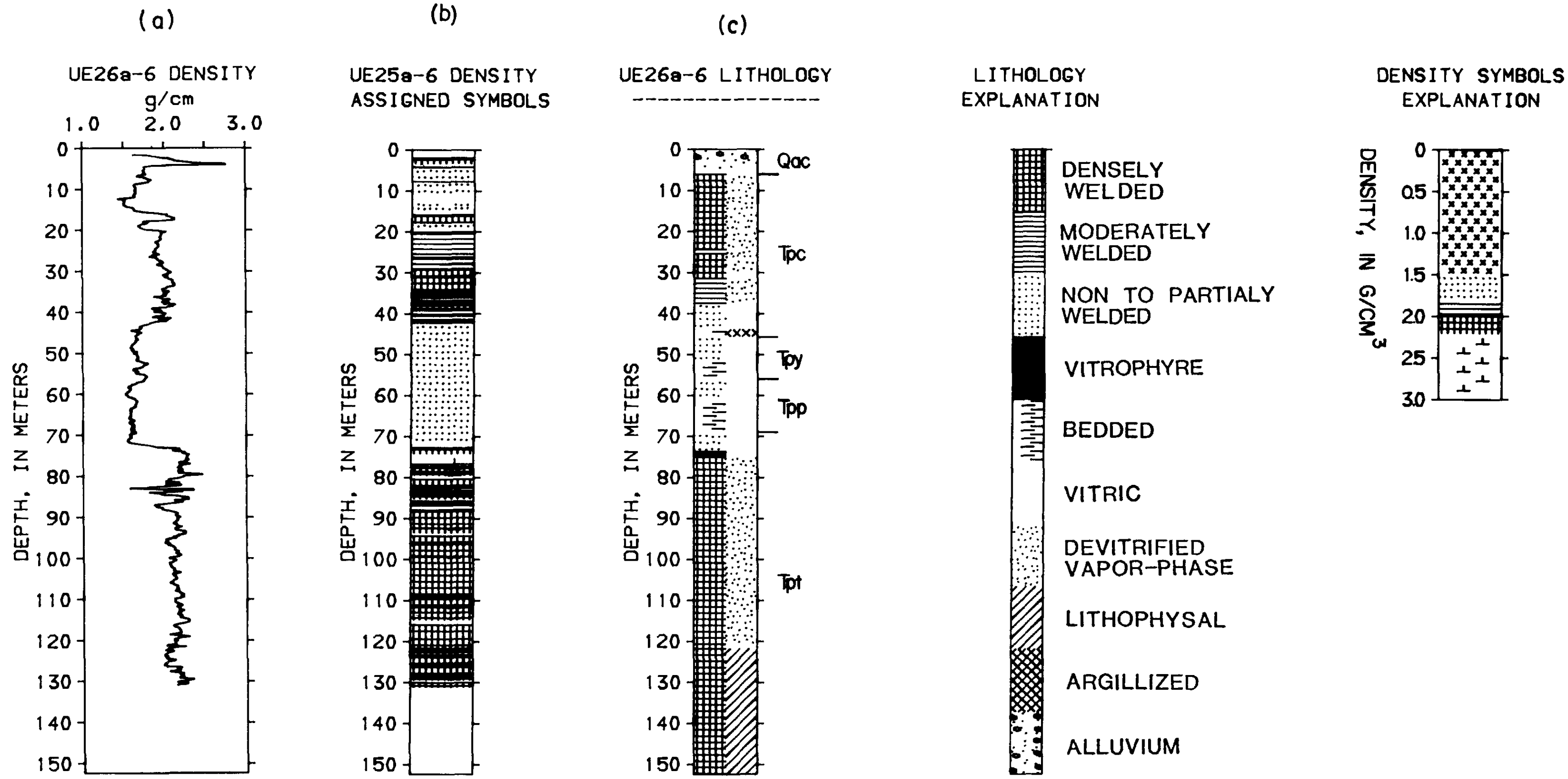


Figure 9.--Density well-logs and interpretation for drill hole UE25a-6:
(a) density well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

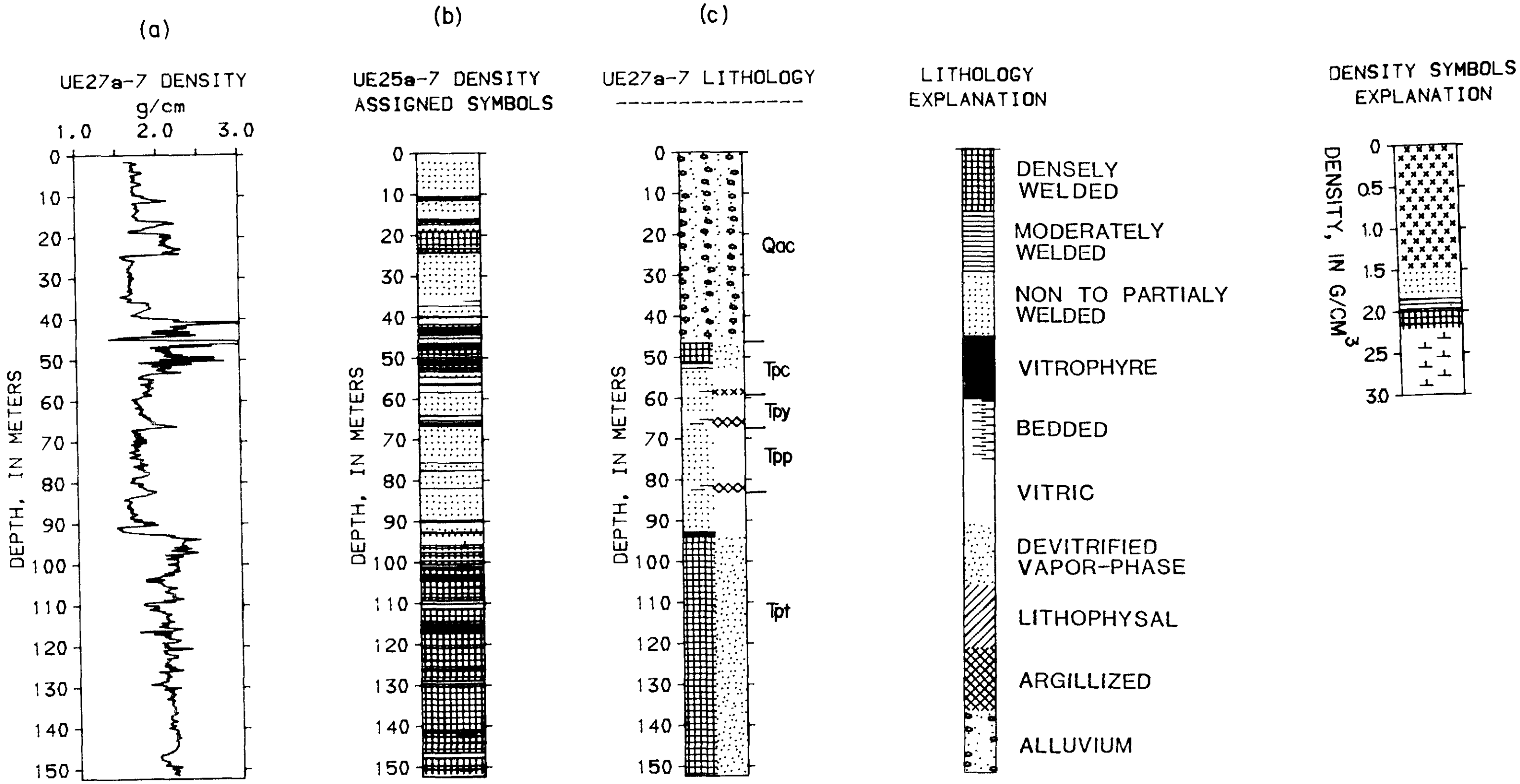


Figure 10.--Density well-logs and interpretation for drill hole UE25a-7: (a) density well-log, (b) computer assigned symbols, and (c) lithologic well logs (after Spengler, in press).

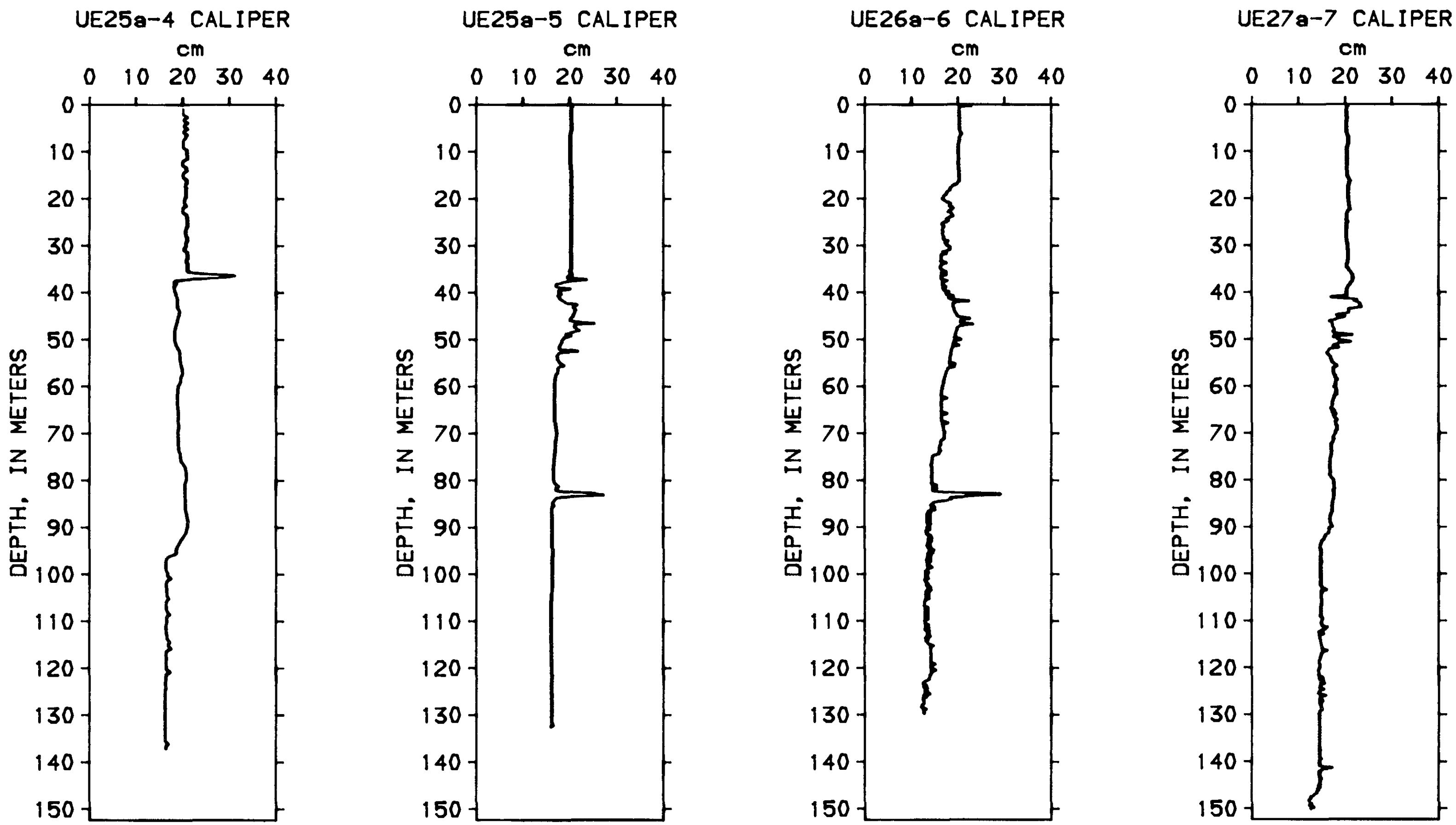


Figure 11.--Caliper logs for UE25a-4, UE25a-5, UE25a-6, and UE25a-7.

Neutron

The neutron well-logging probe consists of a neutron source and detector separated by approximately 50 cm. The number of neutrons counted by the detector is an inverse function of the hydrogen content of the rock surrounding the borehole. In saturated material the neutron count rate is approximately proportional to the degree of welding. However, this is not necessarily true in unsaturated rocks. In fact, the neutron well logs for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 (Figures 12, 13, 14, and 15, respectively) show an inverse relationship between the degree of welding and the neutron count rate! The assigned symbols for the neutron well logs correspond closely to the core-interpreted lithology, when the neutron well logs interpretation is based on this paradox. A constant value for fluid saturation in each of the formations must be assumed in order for this interpretation to be valid. The lithophysal zone located near the bottom of drill hole UE25a-6 (Figure 14) shows a very low neutron count, rate which indicates that the cavities in this zone probably are interconnected.

Interpretation of well logs that are indicative of mineralogy

The measured responses of magnetic susceptibility, induced polarization, and gamma ray well logs are primarily a function of changes in the mineralogy and chemistry of the rocks rather than changes in physical properties. Interpretation of these logs is as follows:

Gamma Ray

The gamma ray probe measures the natural gamma radiation emitted by the rocks surrounding the borehole. The principle natural gamma ray-emitting

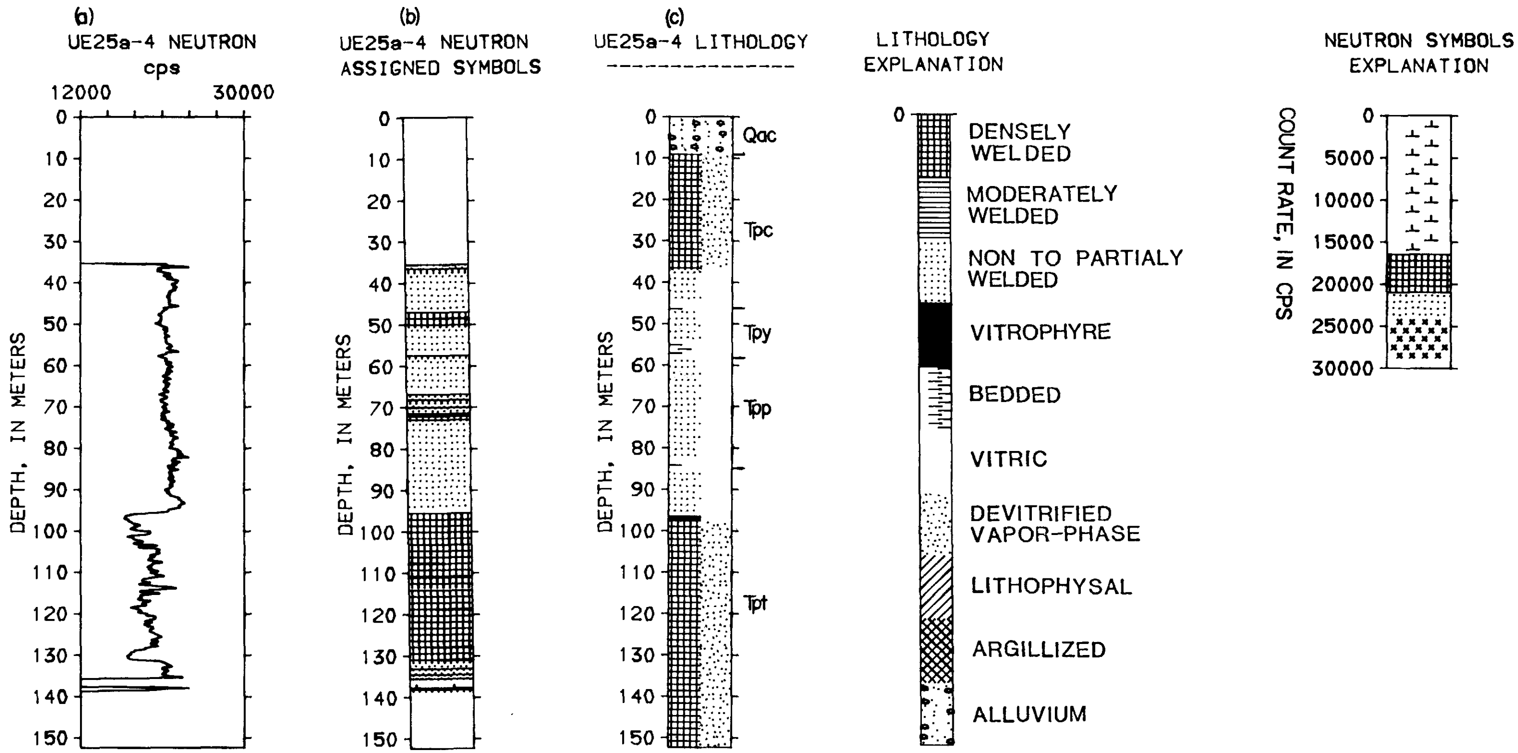


Figure 12.--Neutron well-logs and interpretation for drill hole UE25a-4:
(a) neutron well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

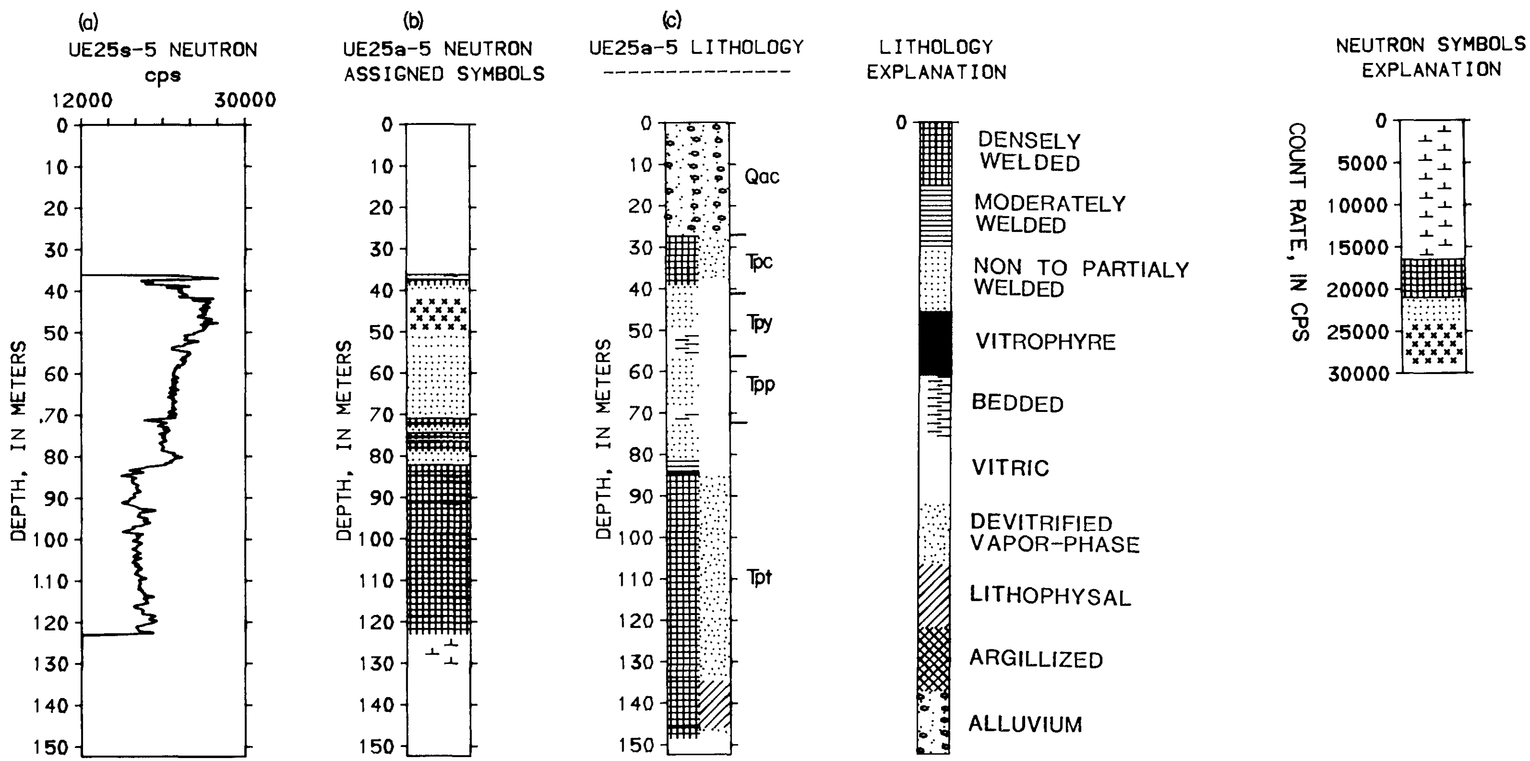


Figure 13.--Neutron well-logs and interpretation for drill hole UE25a-5:
(a) neutron well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

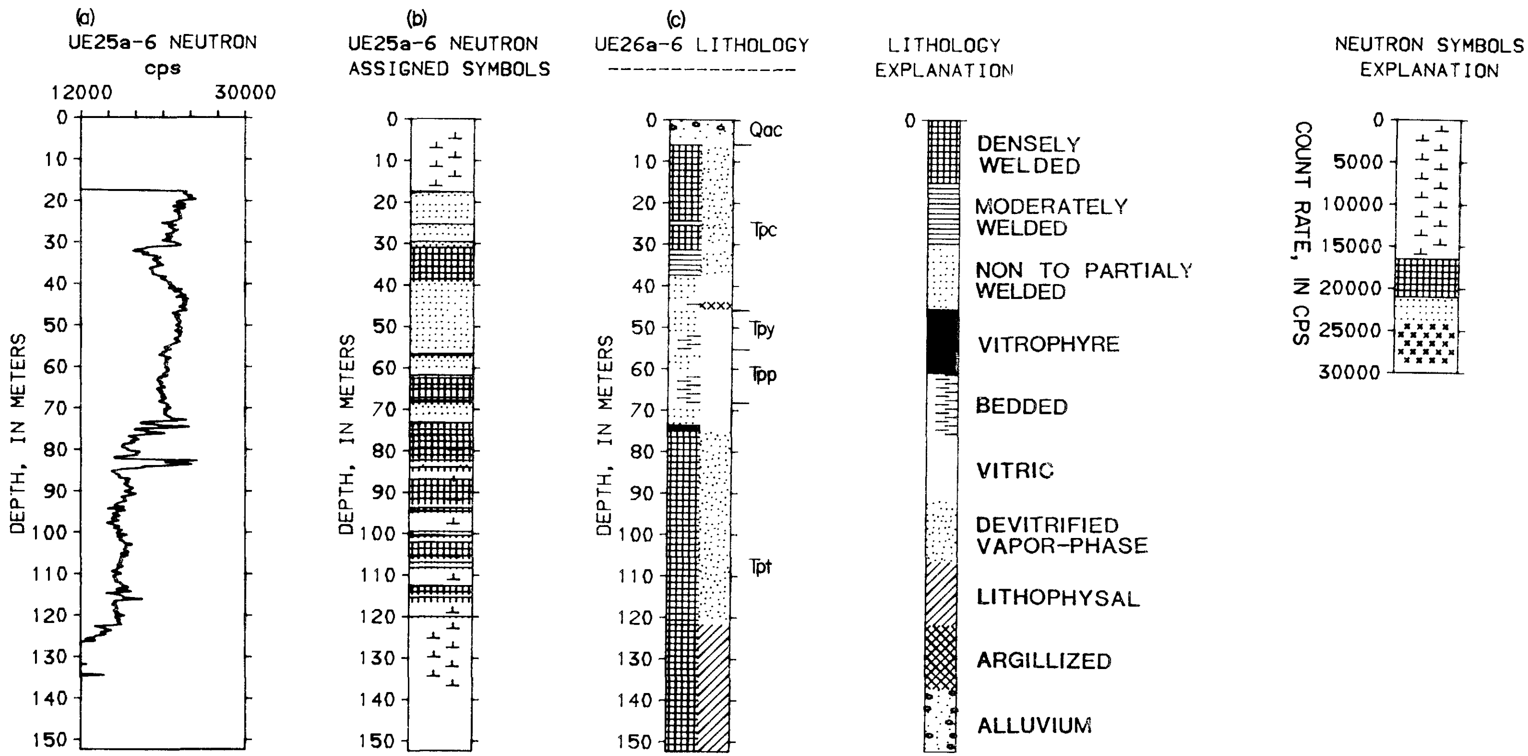


Figure 14.--Neutron well-logs and interpretation for drill hole UE25a-6:
(a) neutron well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

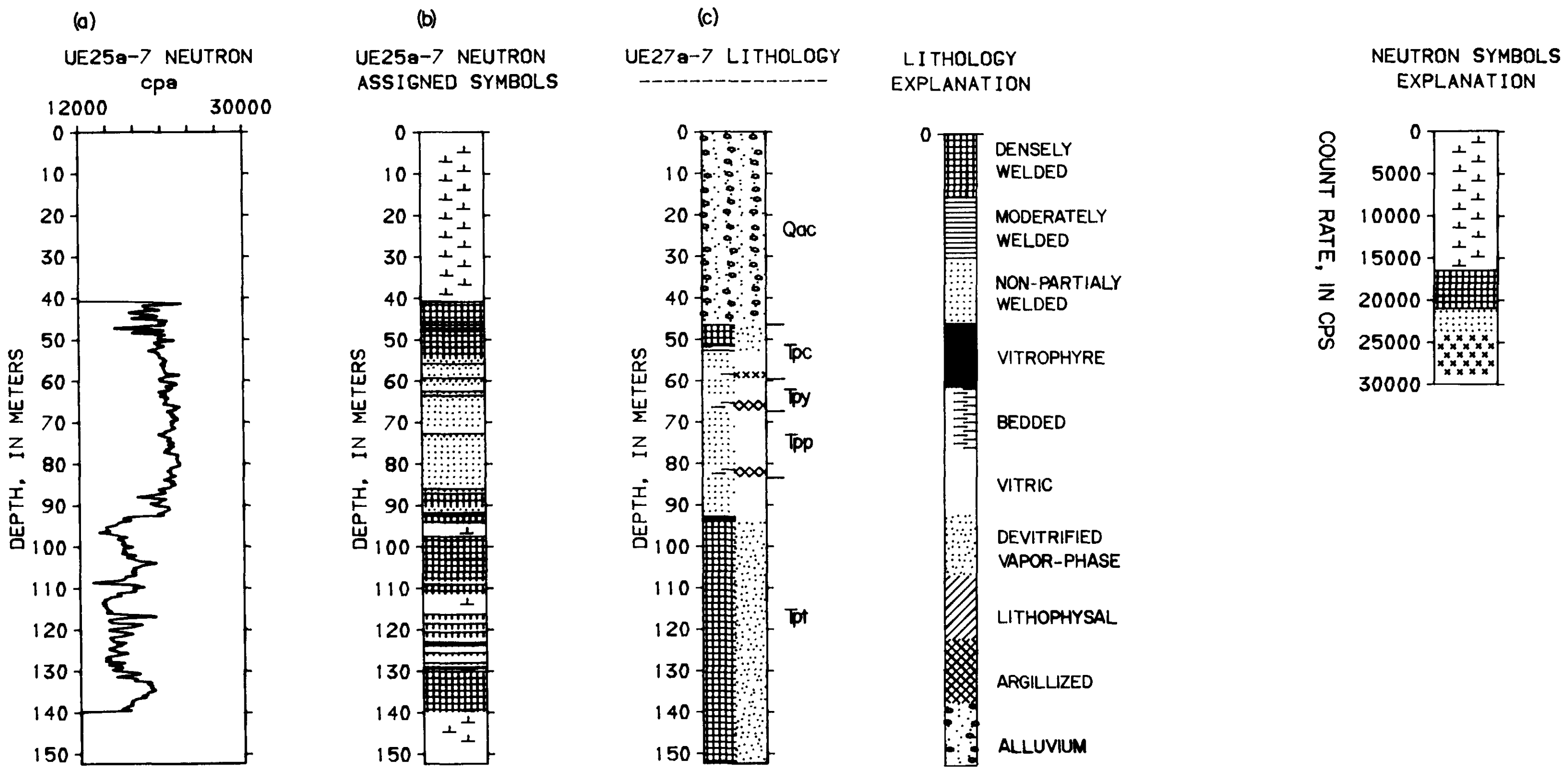


Figure 15.--Neutron well-logs and interpretation for drill hole UE25a-7:
(a) neutron well-log, (b) computer assigned symbols, and
(c) lithologic well-logs (after Spengler, in press).

minerals are uranium-series isotopes and potassium-40. Since potassium bearing minerals are common in both primary and secondary crystallization regimes in welded tuffs, the gamma ray well log measurements are principally a measure of relative abundance of potassium.

The gamma ray well logs for drill hole UE25a-4, UE25a-5, and UE25a-7 are shown in Figure 16. The Topopah Spring Member has a fairly consistent gamma signature that is correlatable between each of the four drill holes. However, the units above the Topopah Spring show that there is a great deal of variation in the potassium content of the four drill holes. The intensity and character of the gamma ray response above the Topopah Spring is approximately the same in drill holes UE25a-6 and UE25a-7 (Figures 16), but is lower than the response in UE25a-4. The intensity of the gamma ray measurements in drill hole UE25a-5 (Figure 17) is the lowest of any of the gamma ray well logs. If the amount of potassium is related to post-emplacement chemical alteration, then these logs indicate that there could be a fairly large differences in alteration between the three drill holes.

Induced Polarization (IP)

The IP measurement is made by recording the decay voltage at a potential electrode from a time-domain current source. The potential electrode is located on the probe at a spacing of 10 cm from the current source. The rate of decay of the potential during the current-off time period 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 iron oxide minerals can contribute to the IP response.

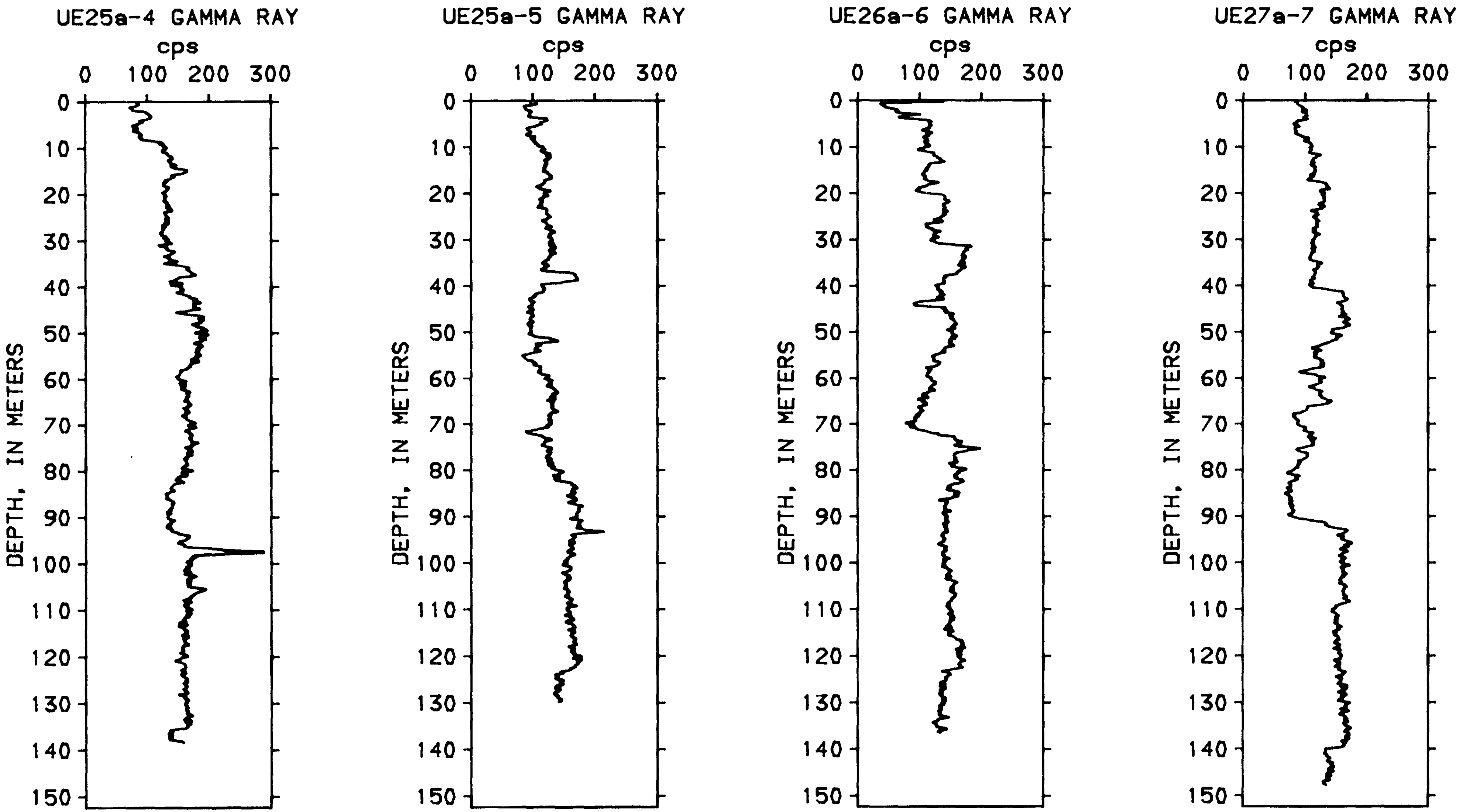


Figure 16.--Gamma ray well-logs for UE25a-4, UE25a-5, UE25a-6, and UE25a-7.

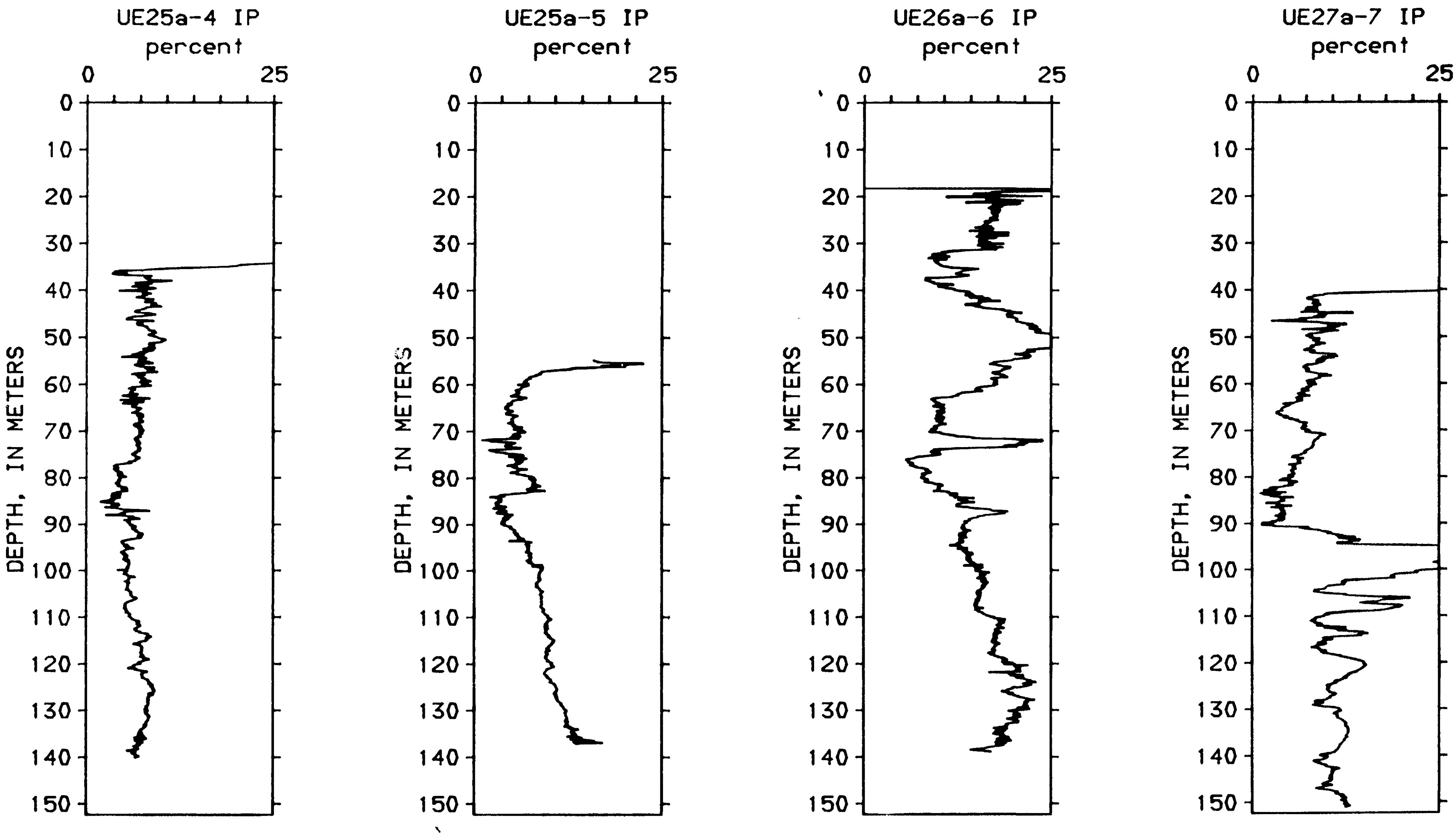


Figure 17.--Induced polarization well-logs for UE25a-4, UE25a-5, UE25a-6, and UE25a-7.

The IP well logs for the drill holes considered in this study are shown in Figure 17. Unfortunately, these values are unreasonably high and the value of these particular well logs is questionable. Hagstrum and others (1980a) has shown that IP well-log measurements in the fluid-saturated zone of ash flow tuffs have values that are normally in the 0-to-4 percent range. The IP log is apparently strongly affected by the fluid invasion in the undersaturated volcanic rocks.

Magnetic Susceptibility

Magnetic susceptibility is the 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 affecting the magnetic susceptibility measurements. Magnetic susceptibility measurements in welded tuffs have been assumed to be primarily a function of the amount of magnetite contained in a rock. However, Hagstrum and others (1980b) have found that the size of the magnetite grains is also an important factor affecting the magnetic susceptibility of welded tuffs. The magnetic susceptibility well logs for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 are shown in Figure 18. These well logs will be discussed in detail in another paper (Hagstrum and others (1980b).

Conclusions

The broad features of the welded tuff sequence encountered in drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 are readily characterized by their physical properties measured by the geophysical well logs. Welded tuffs,

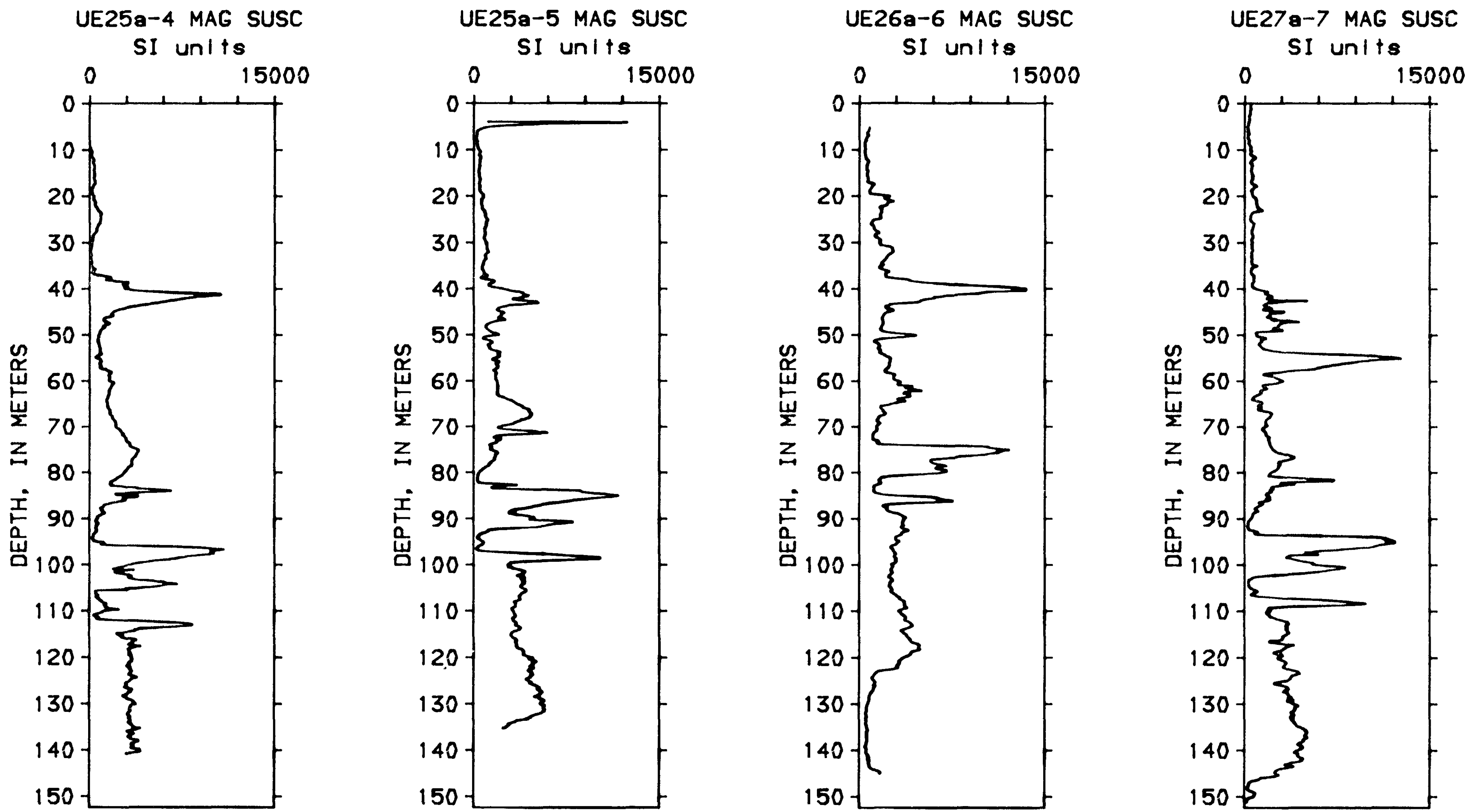


Figure 18.--Magnetic susceptibility well-logs for UE25a-4, UE25a-5, UE25a-6, and UE25a-7.

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 for drill holes UE25a-4, UE25a-5, UE25a-6, and UE25a-7 was complicated by the lack of fluid saturation. Partial fluid saturation caused direct correlation between neutron response and porosity, rather than the usual inverse relationship. The partially fluid-saturated rocks also caused abnormally high IP values. The density, and resistivity logs indicate that near-surface fracture zones are least likely to be present near drill hole UE25a-5.

More mineralogic and petrologic work is needed to clarify the causal elements of well-log response in welded tuffs 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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GPO 830-378