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Geophysical Well Logs for Eleven Drill Holes at the Colorado School of Mines Experimental Mine Site, Idaho Springs, Colorado

by

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Abstract

The following geohysical well log measurements were made in eleven drill holes above the Colorado School of Mines Experimental Mine at Idaho Springs, Colorado: (1) acoustic velocity (2) resistivity, (3) caliper, (4) gamma-gamma density, (5) neutron-thermal neutron, (6) gamma ray, (7) induced polarization (IP), (8) self potential (SP), and magnetic susceptibility. The density and acoustic velocity logs indicate exensive fracturing in each of the drill holes. Variations in the relative amount of felsic or mafic mineral components in the rocks can be inferred from the magnetic susceptibity and gamma ray well log responses. Zones containing metallic sulfide mineralization are interpreted from the IP well log response.

Introduction

Eleven exploratory holes were rotary drilled above the Colorado School of Mines Experimental Mine Site for the purpose of determining the ability of a variety of geophysical techniques to detect tunnels. These drill holes were not cored, and drill-cuttings samples were not available to establish the mineralogy of the rocks penetrated by the drill holes. Locations of the eleven drill holes considered in this study are shown in Figure 1.

A suite of nine geophysical well logging measurements were made in each of the eleven drill holes, including: (1) acoustic velocity, (2) resistivity, (3) caliper, (4) density, (5) neutron-thermal neutron, (6) gamma ray, (7)induced polarization (IP), (8) self-potential (SP), and (9) magnetic susceptibility. Interpretation of these measurements is restricted by the lack of core, or other supporting geologic data. However, information concerning fracturing, mineralization, and general rock mineralogy can still be interpreted from the geophysical well logs. In addition, the resistivity, acoustic velocity, magnetic susceptibility, density, and electric polarizability of the rocks near the drill hole can be obtained from the geophysical well logs.

The holes could not be filled with water to the surface, and measurements that required the probe to be surrounded by fluid were obtained from the bottom of the drill hole up to the level where water would stay in the drill hole. The water was poured into the hole at the time that the geophysical well log measurements were obtained, resulting in an unknown fluid saturation of the rocks surrounding the drill hole. In addition, the drill holes designated by the letters C, D, E, F, G, and H had been grouted and re-drilled prior to making the geophysical well log measurements. The holes were grouted in an attempt to seal the rock to maintain a high fluid level in each drill

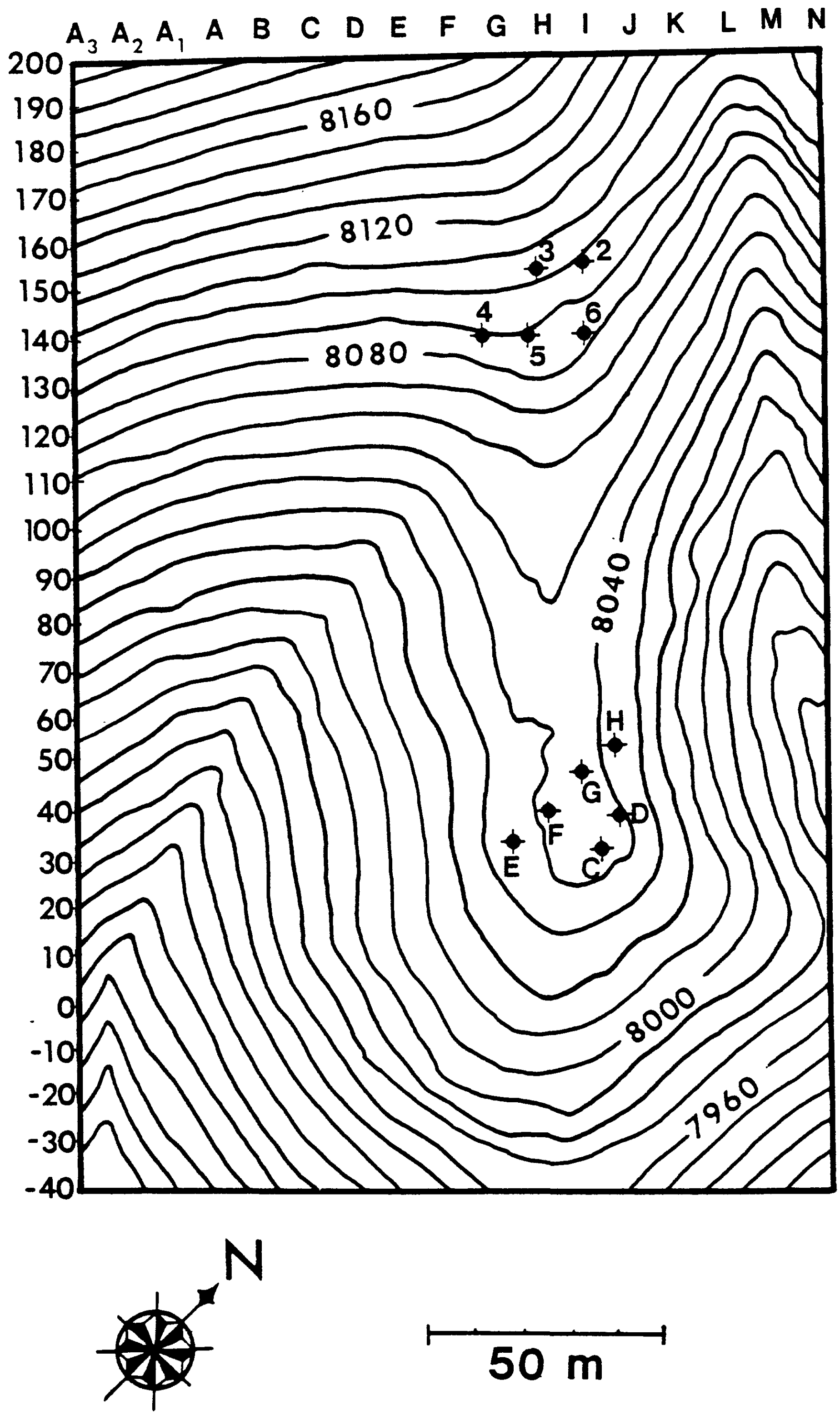

Figure 1. Drill hole location map for the tunnel detection study area, with topographic contours and grid locations. Contours interval is 10 feet (10 ft=3.048 m), and the grid stations (A_1 through N)are 10 m apart.

hole. The physical properties of the grouting material are unknown, resulting in additional uncertainties in the quantitative accuracy of the geophysical well log measurements.

Response Characteristics of Geophysical Well Logs

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, and the design characteristics of each probe. Therefore, each physical property interpreted from the well logs should be considered an apparent value rather than a true value. The response for each of the types of the well logs follow:

Resistivity

Resistivity is a measure of the ease with which electric current passes through a material. Borehole resistivity values primarily depend upon the porosity, fluid resistivity, and grain resistivity of the rock investigated. However, the resistivity measured in the borehole is also dependent upon the borehole fluid resistivity, and the borehole diameter. Low resistivity values occur in fractured, altered, or mineralized rocks, while high resistivity values generally occur in rocks devoid of these characteristics.

The resistivity well logs for the holes in this study are shown in Figure 2. The resistivity values in the grouted drill holes (drill holes C, D, E, F, G, and H) are lower than values for the non-grouted drill holes. Anomalously high resistivity values, indicating unfractured rocks, occur most prominantly in drill hole 6 below a depth

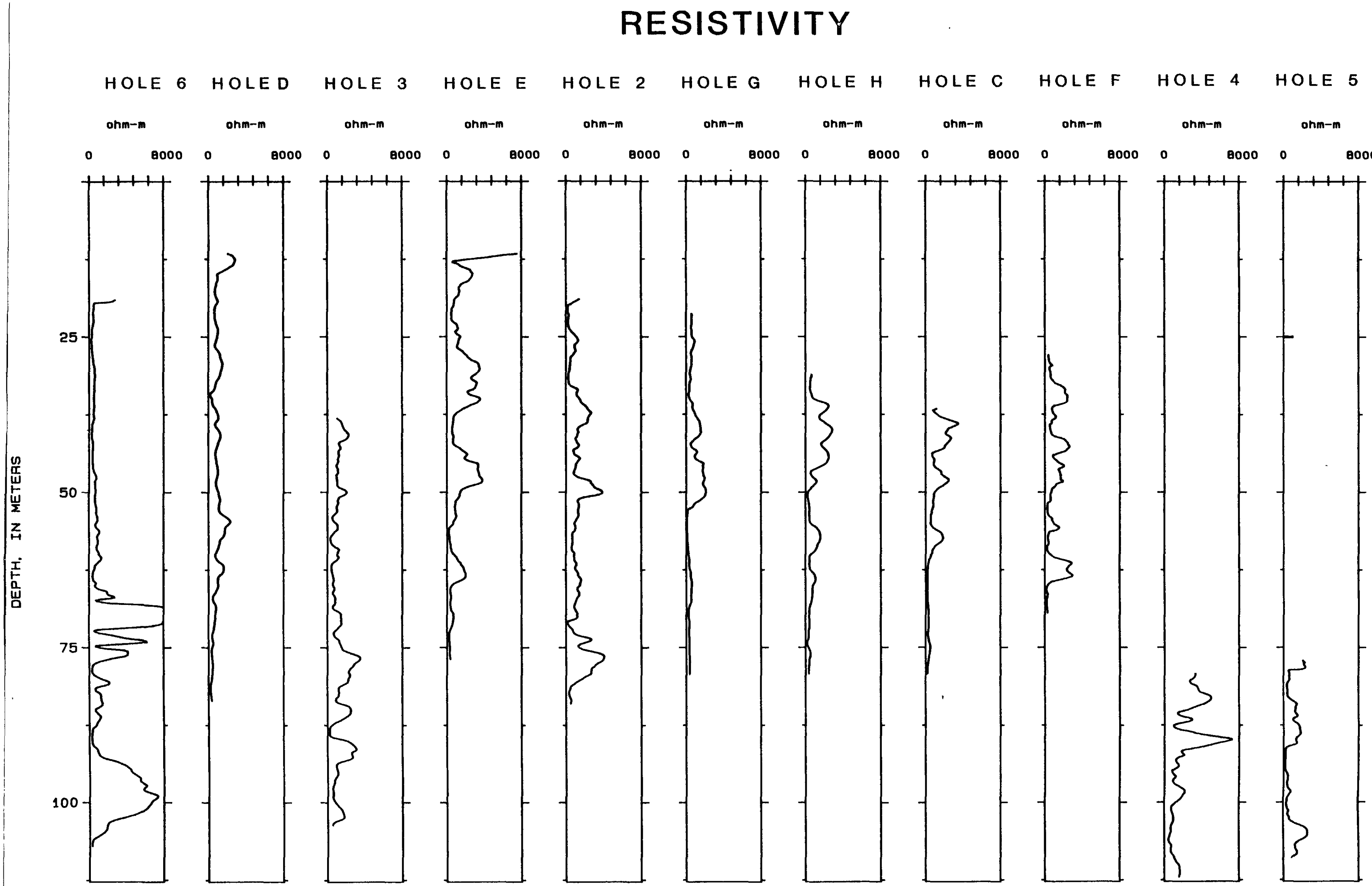

Figure 2. Resistivity well logs for drill holes drill holes in this study.

of 65 m, and in drill hole 4 in the depth interval from 83 to 90 m. All of the other drill holes have resistivity values that are indicative of alteration, fractures, or mineralization.

Density

The density probe consists of a gamma ray source and two gamma ray detectors. Gamma rays emitted by the source are scattered by electrons in the rock, and the number of scattered gamma rays counted by the detectors is an inverse function of the electron density of the rock. Borehole rugosity and small fractures adjacent to the borehole wall can cause abnormally low apparent density values. Density values computed from the far-detector are more representative of the bulk density of the rocks surrounding the drill hole than near-detector density values.

Near and far detector density values for the drill holes in this study are shown in Figure 3 and 4, respectively. The fractured zones indicated by the near-detector density logs are shown on the density logs in Figure 3. The far-detector density logs (Figure 4) show a general increase in density with depth for the non-grouted drill holes (holes 2, 3, 4, 5, and 6), which suggests that alteration decreases with depth.

Neutron

The neutron log response is principally a measure of the water content of the rock (Pirson, 1963, Nelson and Glenn, 1975). The neutron probe consists of a neutron source and a neutron detector. The neutron detector measures the thermal (and minor epithermal) neutrons scattered by the rocks surrounding the borehole. The number of neutrons counted by the detector is an inverse function of the hydrogen content of the rock surrounding the

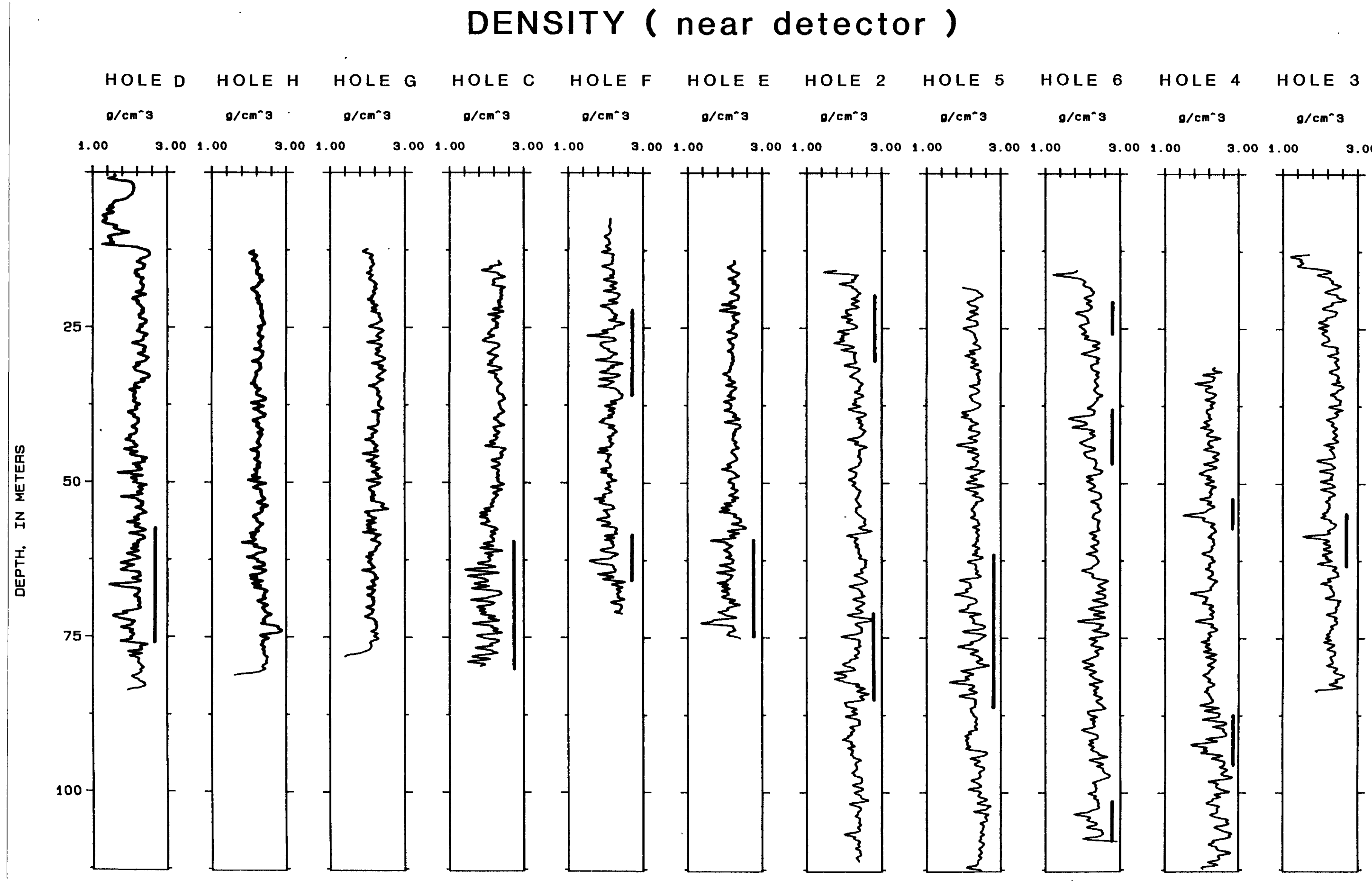

Figure 3. Near detector density well logs for the drill holes in this study. The severly fractured zones, interpreted from the near detector logs, are indicated by the heavy vertical lines on the well logs.

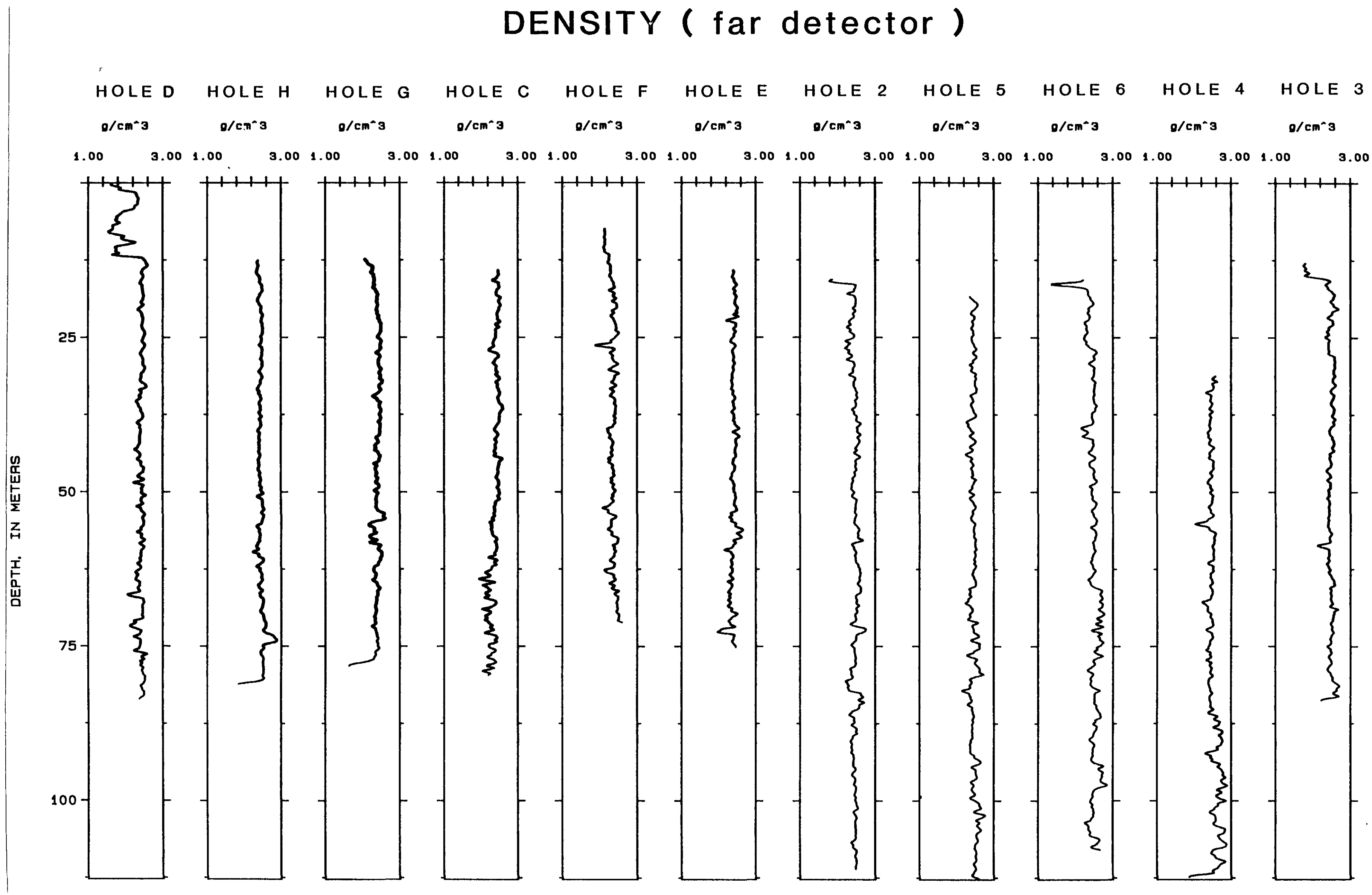

Figure 4. Far detector density well logs for the drill holes in this study.

borehole, and is primarily a measure of the amount of water contained in the rock. The neutron log response is affected by chemically bound water and pore water, and in rocks containing abundant micaceous and clay minerals the neutron log is not a good indicator of porosity (Nelson and Glenn, 1975; Keys, 1979; Daniels and others, 1981). Fractures commonly contain hydrated clay and micaceous minerals that combine with the free water in the open region of the fractures to yield a low neutron response compared to the unfractured regions.

The neutron well logs for the study area are shown in Figure 5. The neutron log responses for each drill hole indicate the presence of many fractured, or altered zones. The zones that are most likely to be non-altered are indicated on the individual well logs. The choice of these intervals is subjective, and the interpretation of the fractured and altered intervals can only be interpreted by comparing the neutron, resistivity, density, and sonic velocity logs.

Gamma Ray

Gamma ray well log measurements were made in the study drill holes using a total count scintillation detector. The probe measures the total gamma radiation emitted by radioisotopes in the rocks surrounding the borehole, and does not discriminate between various gamma ray energy levels (Pirson, 1963). The principle gamma ray emitting isotopes in igneous and metamorphic rocks are from the uranium and thorium decay series, with a lower contribution from potassium-40. Variations in the urano-thoric minerals are commonly related to the grain size and mafic mineral content of the rock (where the term "mafic" refers to an increase in the ferromagnesium silicates; Hatch, 1973). Increases in some felsic mineral components (e.g., orthoclase, and muscovite) increase the potassium-40 content

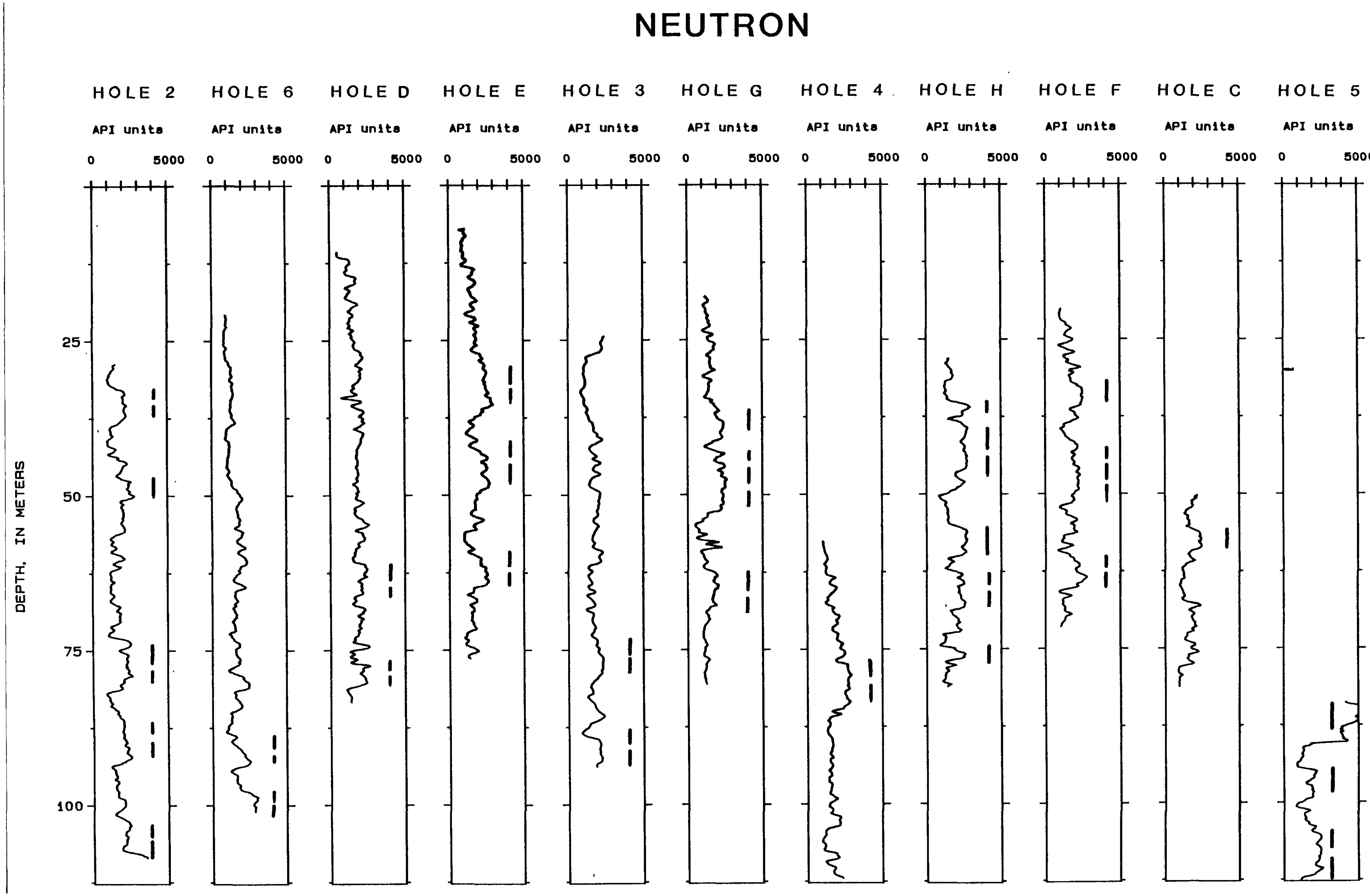

Figure 5. Neutron-thermal neutron well logs for the drill holes in this study. The non-altered zones, interpreted from the neutron-thermal neutron logs, are indicated by the vertical heavy-dashed lines.

of the rock and also result in an increase in the gamma ray response, but high gamma radiation from the uranium and thorium isotope series masks the smaller contribution from potassium-40. Uranium and thorium also have a positive correlation with the presence of muscovite, resulting in an additional increase in the gamma ray response with increasing muscovite.

The gamma ray well logs in Figure 6 show a few high concentrations of radioisotopes, with some other smaller variations. The smaller amplitude variations may be caused by differences in the mafic mineral content, or by concentrations of alteration minerals in fracture zones.

Acoustic Velocity

The acoustic log measures the compressional velocity of the rock adjacent to the borehole wall between two detectors spaced 0.3 m apart. When inhomogenities are present along the borehole wall, the signal received by the detectors is distorted, and the first compressional wave arrivals at the two detectors are often weak. This can result in an arrival other than the compressional arrival being picked as the first arrival, and the resulting recorded acoustic velocity is in error. The recorded anomaly in this case is called a cycle skip. These anomolous amplitude cycle skips are often indicative of large fractures, or sets of fractures, but are not always reliable fracture indicators.

The cycle skips are readily apparent on the acoustic logs for the study area, shown in Figure 7. The compressional velocity of these rocks varies from 4.5 to 6 km/S. Deviations from this range of values are probably caused by fractures.

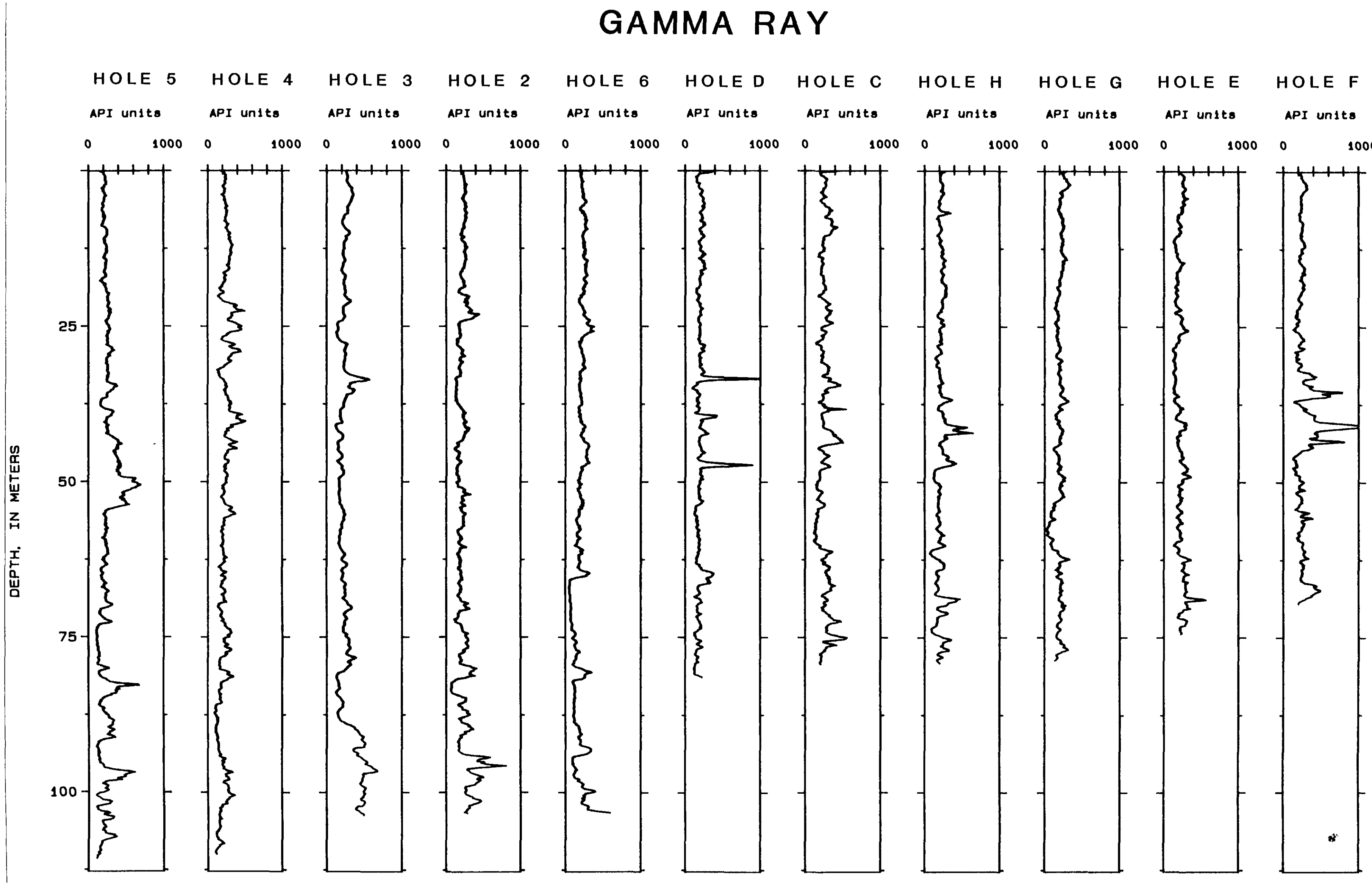

Figure 6. Gamma ray well logs for the drill holes in this study.

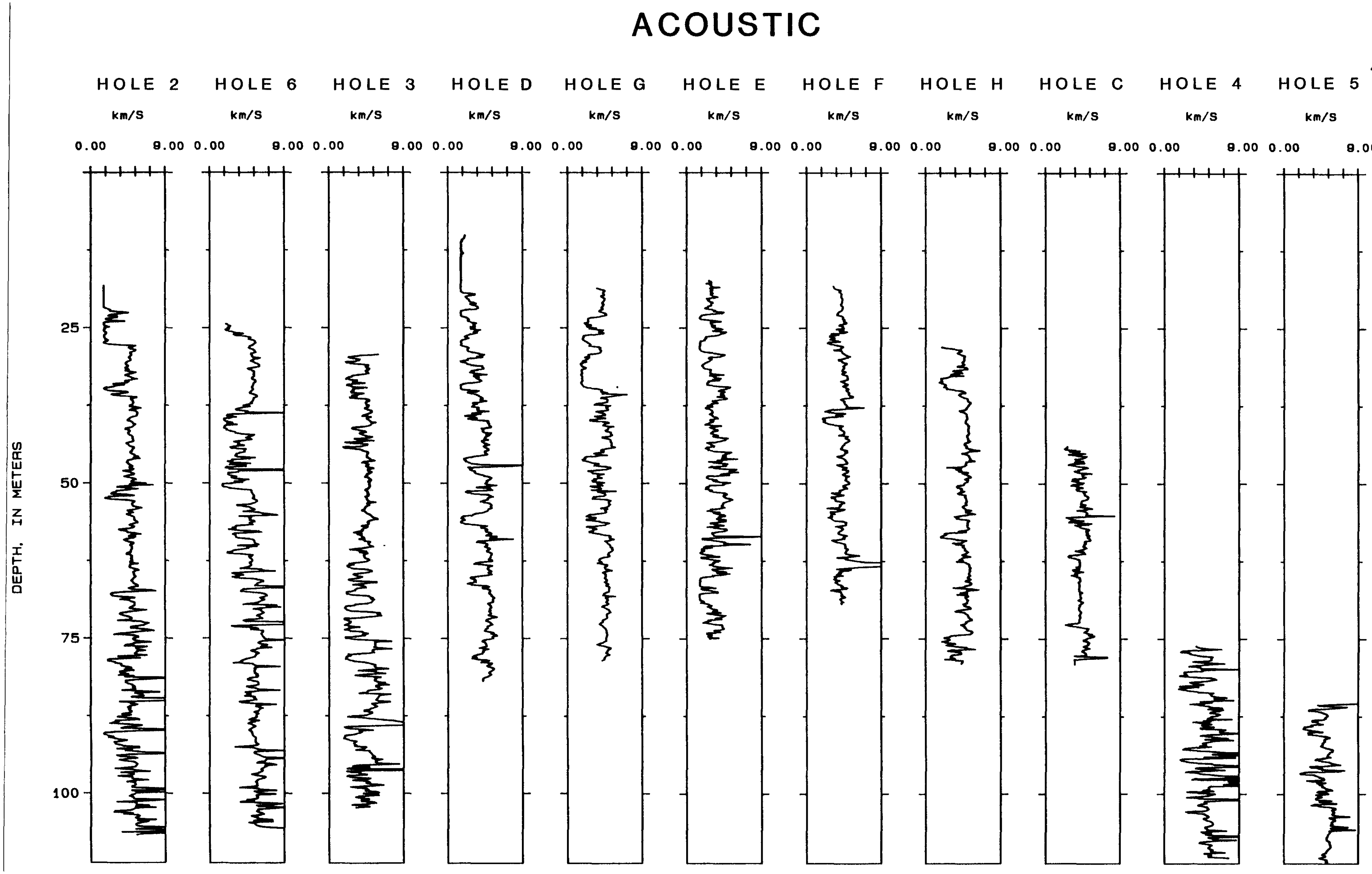

Figure 7. Acoustic well logs for the drill holes in this study.

Magnetic Susceptibility

Magnetic susceptibility is the ratio of the intensity of magnetization of a magnetizable substance to the intensity of an applied magnetic field, and is a measure of the ease with which a substance may be magnetized. The magnetic susceptibility of a rock depends largely on the amount of ferromagnetic minerals that it contains. Magnetite is the most important ferromagnetic mineral due to its widespread occurence and high value of magnetic susceptibility, but other ferromagnetic minerals (including ilmenite, maghemite, and pyrrhotite) may also cause magnetic susceptibility anomalies. Unfortunately, core samples are not available to establish the relationship between the various types of ferromagnetic minerals and the magnetic susceptibility well log response. A general interpretation that attributes an increase in magnetic susceptibility to increasing ferromagnesian minerals is consistent with other interpretations in similar geologic environments (Daniels and others, 1981;Daniels and others, 1982). The magnetic susceptibility well logs for the study area are shown in Figure 8.

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 distance of 40 cm from an electrical current electrode. A square waveform is transmitted through the current electrode, with the current turned-off between half-cycles of the square wave. The rate of decay of the electrical potential measured at the potential electrode during the off time of the current source is an inverse function of the electrical polarizability of the rock. Polarizable minerals include magnetite, some metallic sulfides, some clay minerals, and hydrated minerals (eg.

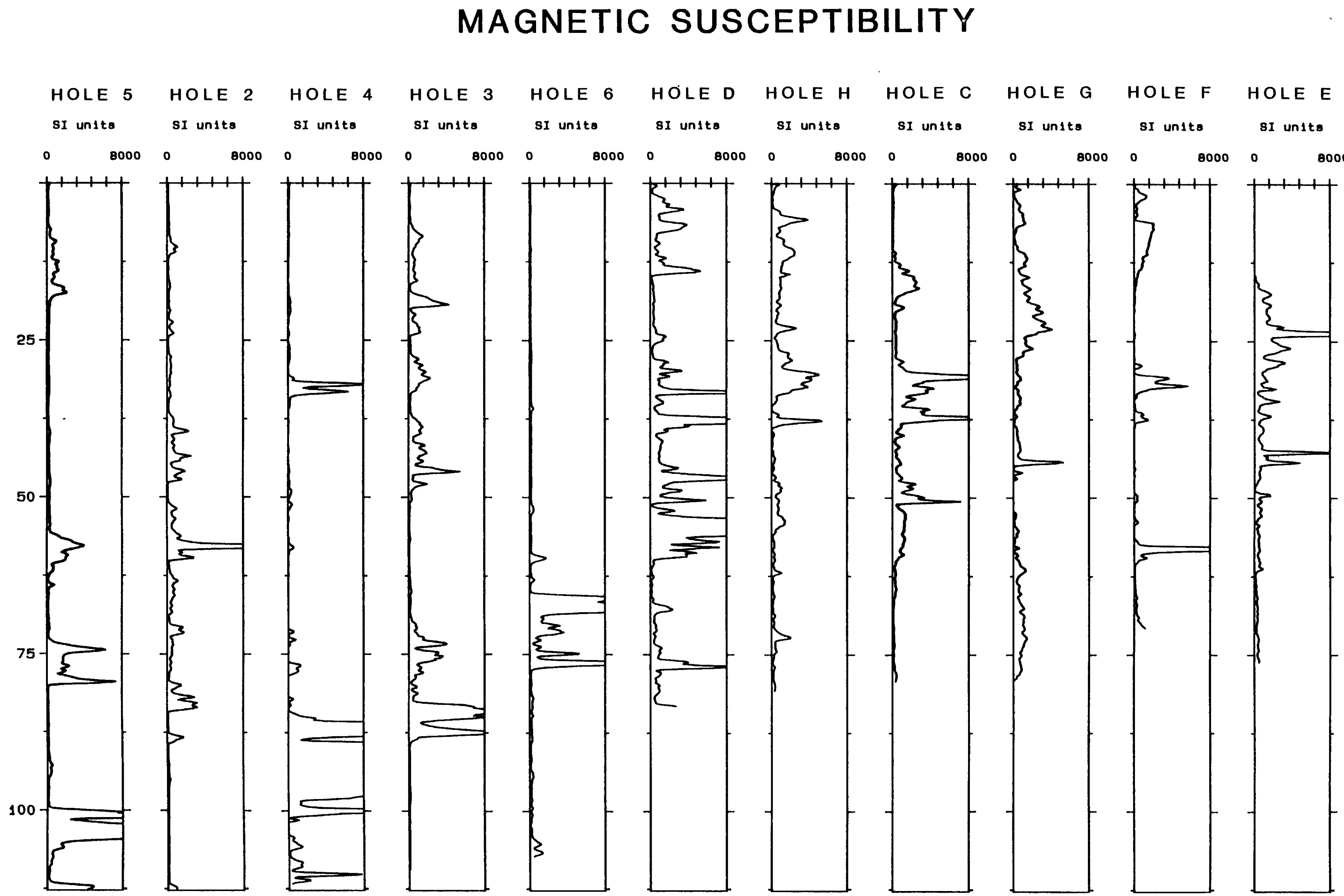

Figure 8. Magnetic susceptibility (Mag. Susc.) well logs for the drill holes in this study. Values are SI units x 10^6.

amphiboles). Polarizable minerals must be open to the flow of electric current in order to respond to the electrical polarization measurement, and therefore higher IP well log values occur in fractured or altered regions of a drill hole. The high IP values in the study drill holes (Figure 9) can generally be assumed to be caused by metallicsulfide mineralization, except in those cases where a high IP response corresponds with a high magnetic susceptibility response. A high IP response and a high magnetic susceptibility response can be caused by the presence of magnetite or pyrrhotite.

Composite Interpretation

Individual well logs can be utilized to isolate individual anomalies in the study area, but a detailed interpretation of the data must be made by simultaneously considering all of the data. A composite interpretation of geophysical well logs can often be accomplished by automated assignment of rock types to depth intervals where the geophysical well log measurements are within specified value ranges (Daniels and Scott, 1981). Unfortunately, the nature of the anomalies on the well logs in the study area does not lend itself to this type of interpretation. Core petrographic analysis that could provide detailed information on specific anomalies is not available, and anomalies must be interpreted using generalized guidelines. The following guidelines and assumptions have been used in this interpretation:

(1) Magnetite is the dominant magnetic mineral present in the rocks.

(2) A high gamma ray response indicates the presence of uranium or thorium, which are commonly associated with felsic micas. The effect of potassium-40 on the gamma ray response may be neglected.

(3) The combination of a low gamma ray response and a high

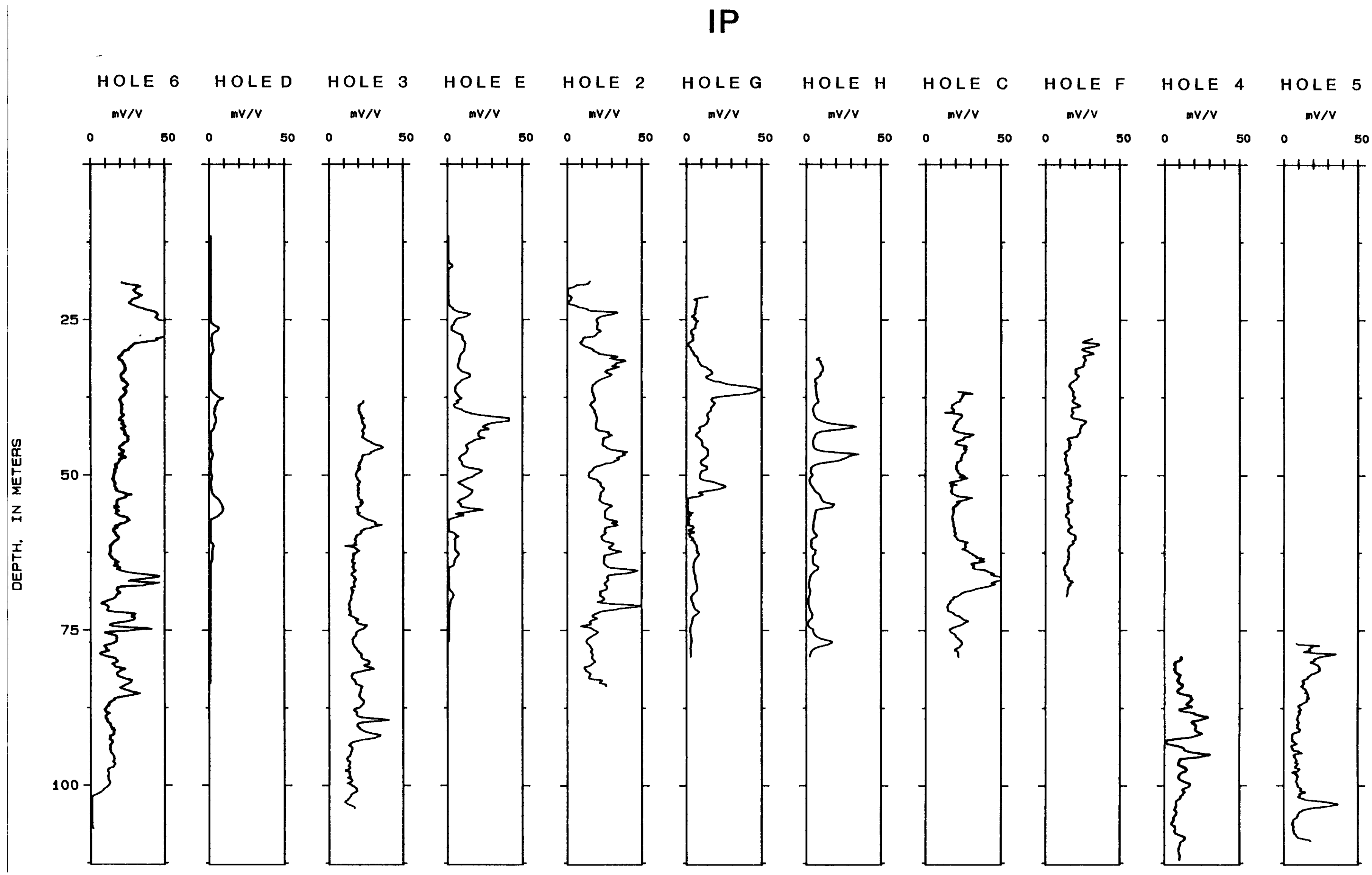

Figure 9. Induced polarization (IP) well logs for the drill holes in the study area.

neutron response in an unfractured zone is indicative of a quartz pegmatite.

(4) The combination of a low gamma ray response and a high magnetic susceptibility response indicates the presence of mafic rocks.

(5) Fracture zones are indicated by cycle skipping on the acoustic velocity log, anomalously low near detector density values, and anomalously low neutron values.

The suite of well logs for each of the eleven drill holes in the study area are shown in Figures 10-21, with the exception of the caliper and SP well logs which are shown in Appendix A. The off-scale logs in Figures 10-21 are plotted full scale in Appendix B. Each of the suites of well logs in Figures 10-21 contains selected anomalies that have been assigned the letters appearing to the right of each suite of well logs. These letters represent individual zones that are described in the table following each of the suites of well logs.

HOLE 2

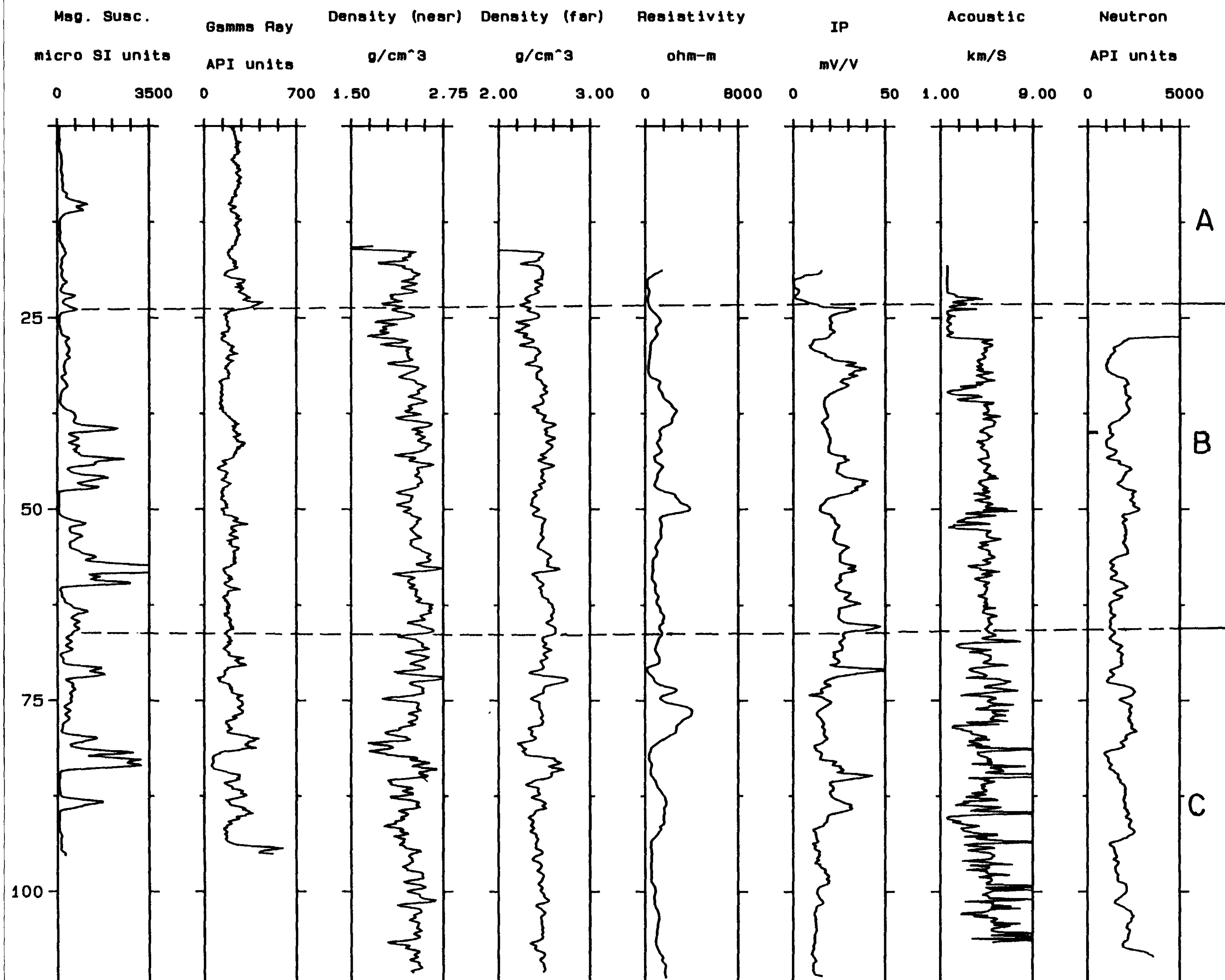

Figure 10. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole 2.

Table 1. Explanation of zones for drill hole 2.

Zone	Description
A	Moderate mafic content. Unknown degree of fracturing.
B	Small amount of fracturing, with the exception of the regions (a) at the top of the zone, (b) at a depth of approximately 30m, and (c) at a depth of approximately 50 m. High metallic sulfide mineralization is indicated by the IP well log response. Low to moderate mafic mineral content is indicated by the gamma ray well log response.
C	Moderate to severe fracturing is indicated by the acoustic velocity, and near detector density well logs. Increasing felsic mineral components with depth. Moderate to low metallic sulfide mineralization is indicated by the IP well log response.

HOLE 3

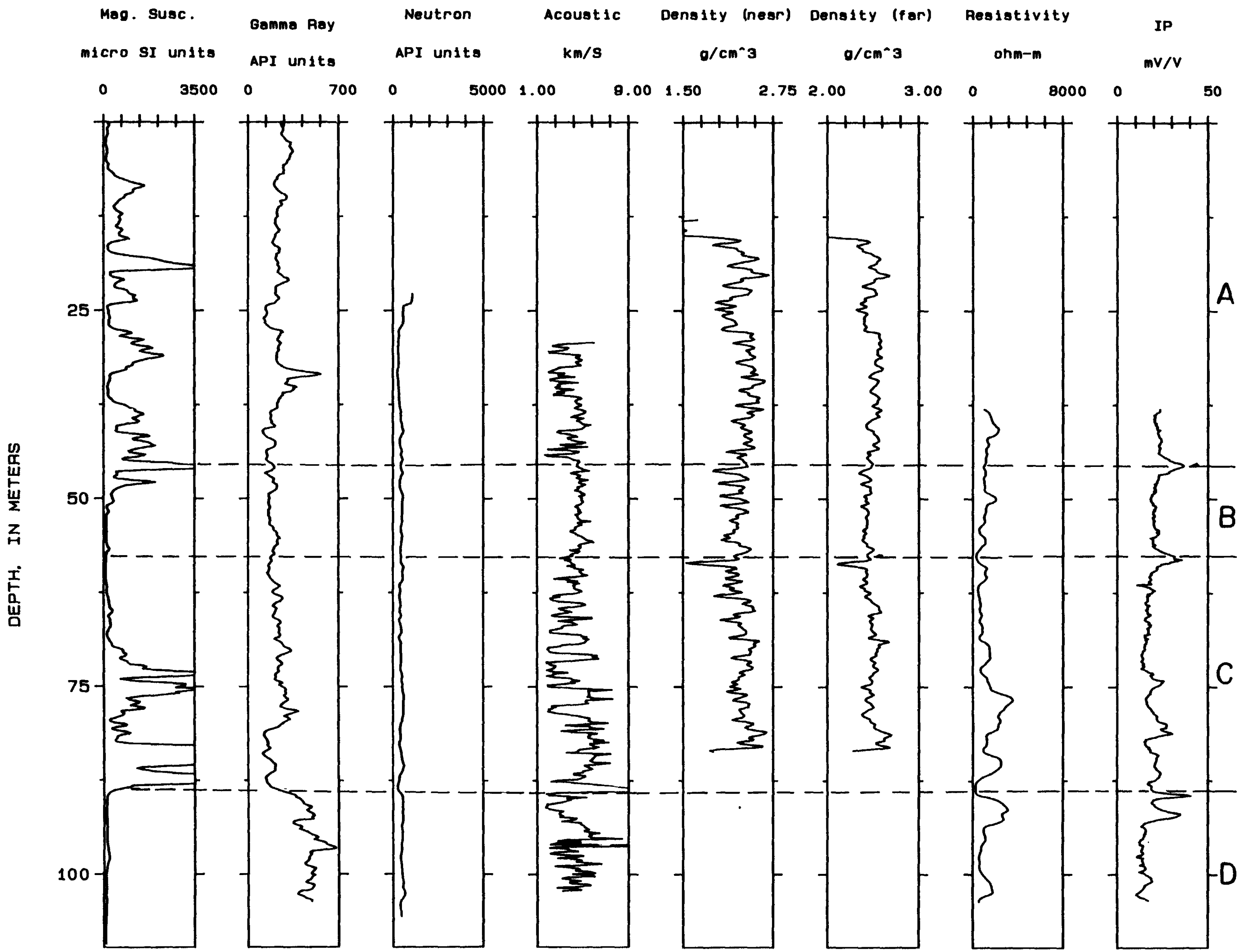

Figure 11. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole 3.

Table 2. Explanation of zones for drill hole 3.

Zone	Description
A	Moderate fracturing is indicated by the near detector density and the acoustic velocity logs. Low to moderate mafic mineral content as shown by the magnetic susceptibility and gamma ray well logs.
B	Small amount of fracturing. Moderate to high metallic sulfide mineralization.
C	Severe fracturing, decreasing at the bottom of the zone. Moderate mineralization, increasing at the bottom of the zone. Increased mafic mineral content at the bottom of the zone.
D	Low mafic mineral content, with moderate to severe fracturing.

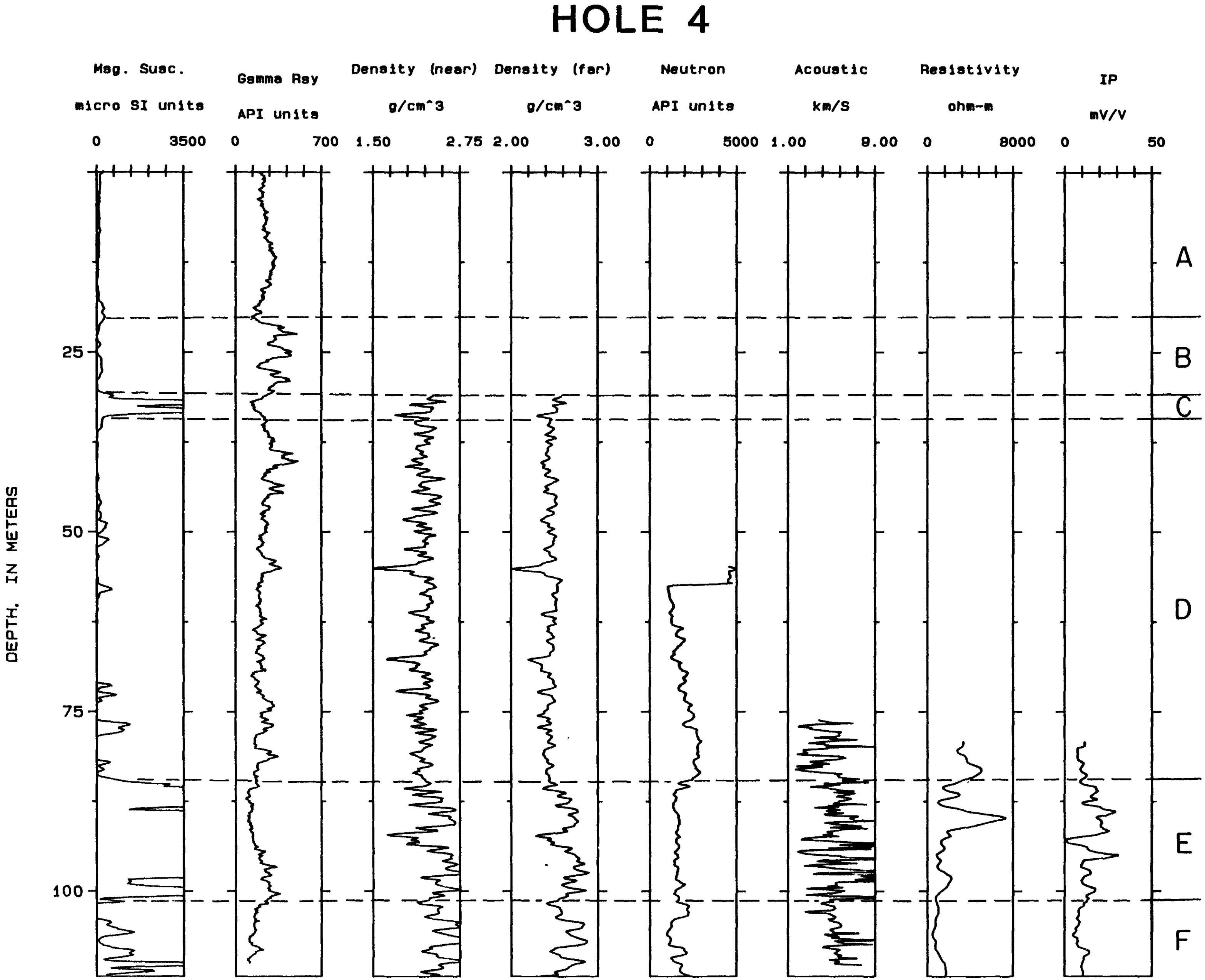

Figure 12. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole 4.

Table 3. Explanation of zones for drill hole 4.

Zone	Description
A	Weathered zone, with moderate felsic mineral content.
B	Weathered zone, with variable felsic mineral content.
C	High mafic mineral concentration.
D	Low to moderate fracturing, with fractures increasing at the bottom of the zone. Moderate to low felsic mineral components, decreasing with depth.
E	Moderate to severe fracturing. High mafic mineral components, with some metallic sulfide mineralization.
F	Low to moderate fracturing. Low to moderate felsic mineral components.

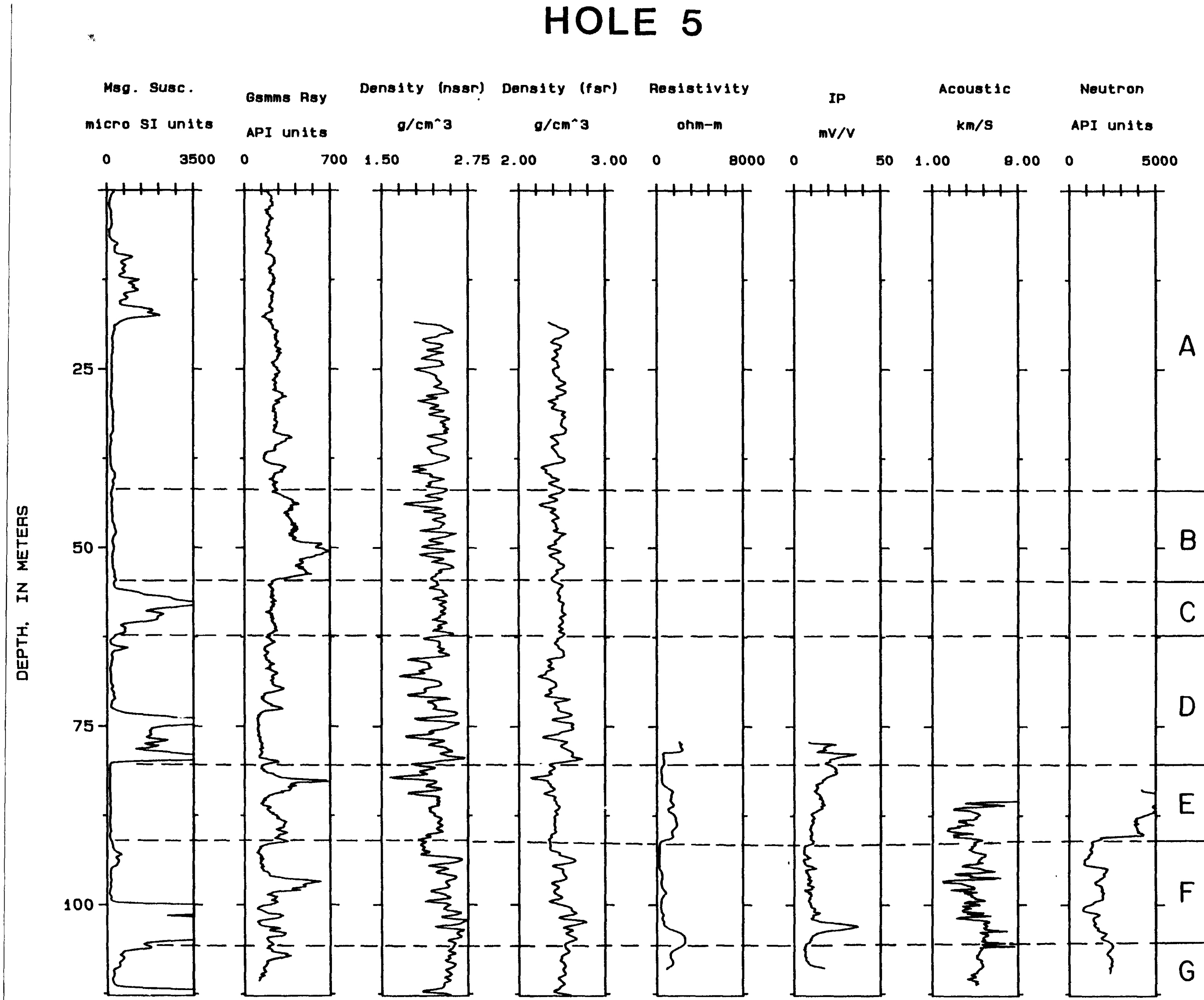

Figure 13. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole 5.

Table 4. Explanation of zones for hole 5.

Zone	Description
A	Low to moderate felsic mineral content. Near detector density log shows a small amount of fracturing in the logged interval.
B	Moderate to high felsic mineral content. Near detector density log shows a small amount of fracturing.
C	Low to moderate felsic mineral content. No fracturing.
D	Low to moderate felsic mineral content. Anomalous magnetite at the base of the zone. Near detector density indicates moderate fracturing.
E	Moderate to high felsic mineral content. Severe fracturing throughout the zone. Metallic sulfide mineralization at the top of the zone.
F	Moderate fracturing is indicated by the acoustic and density logs. Metallic sulfide mineralization at the bottom of the zone. High magnetite content at the bottom of the zone.
G	Low to moderate felsic mineral content. Low fracturing is indicated by the acoustic and density logs.

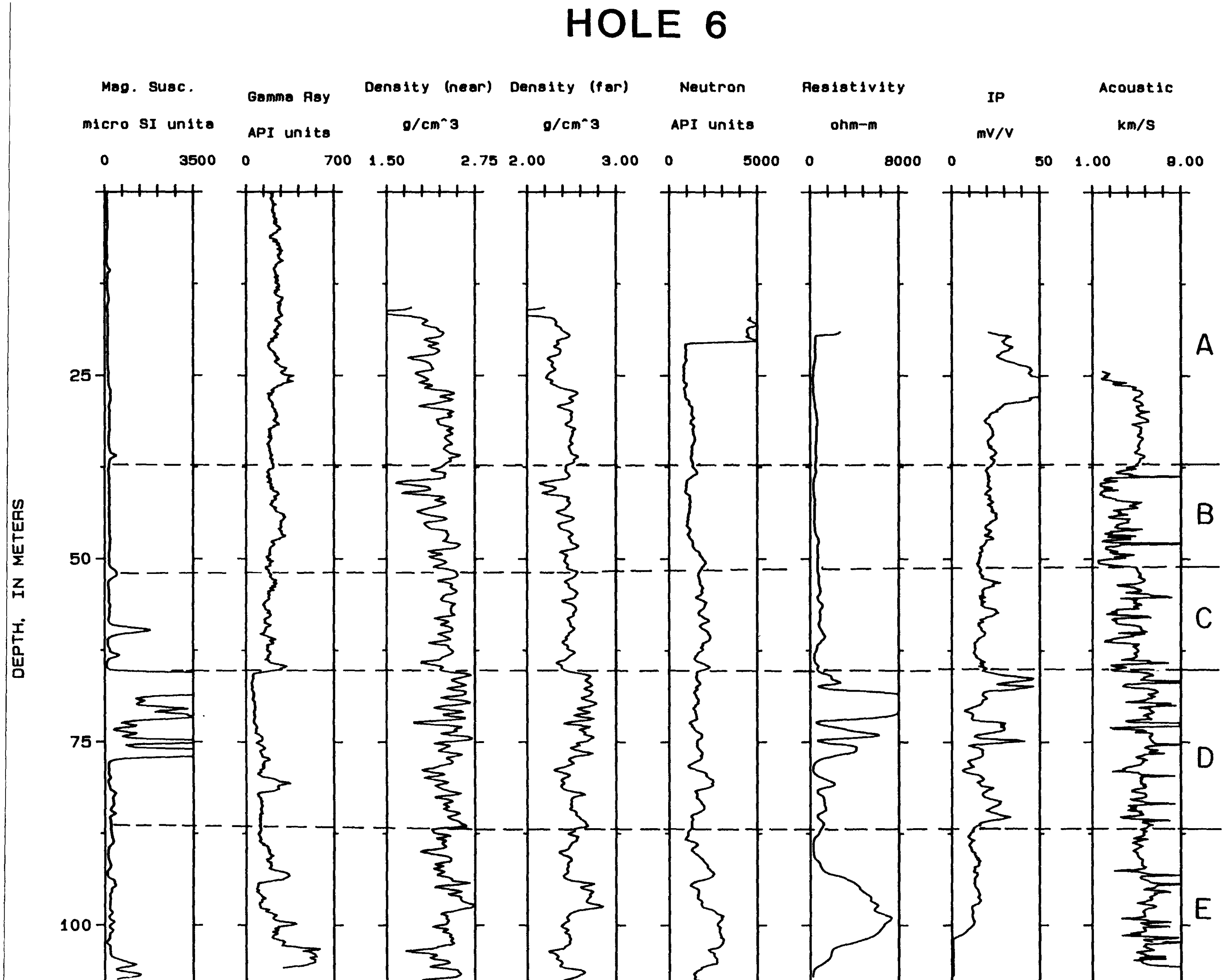

Figure 14. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole 6.

Table 5. Explanation of zones for hole 6.

Zone	Description
A	Low to moderate felsic mineral content. Low fracturing at the bottom of the zone. High metallic sulfide mineralization in the depth interval from 24 to 29 m.
B	Low to moderate felsic mineral content. Severe fracturing throughout the zone.
C	Moderate fracturing throughout the zone.
D	High mafic mineral content at the top of the zone. Sulfide mineralization at the top and bottom of the zone. Low to moderate fracturing throughout the zone.
E	Low felsic mineral content at the top of the zone, and high felsic mineral content at the base. Low to moderate fracturing throughout the zone.

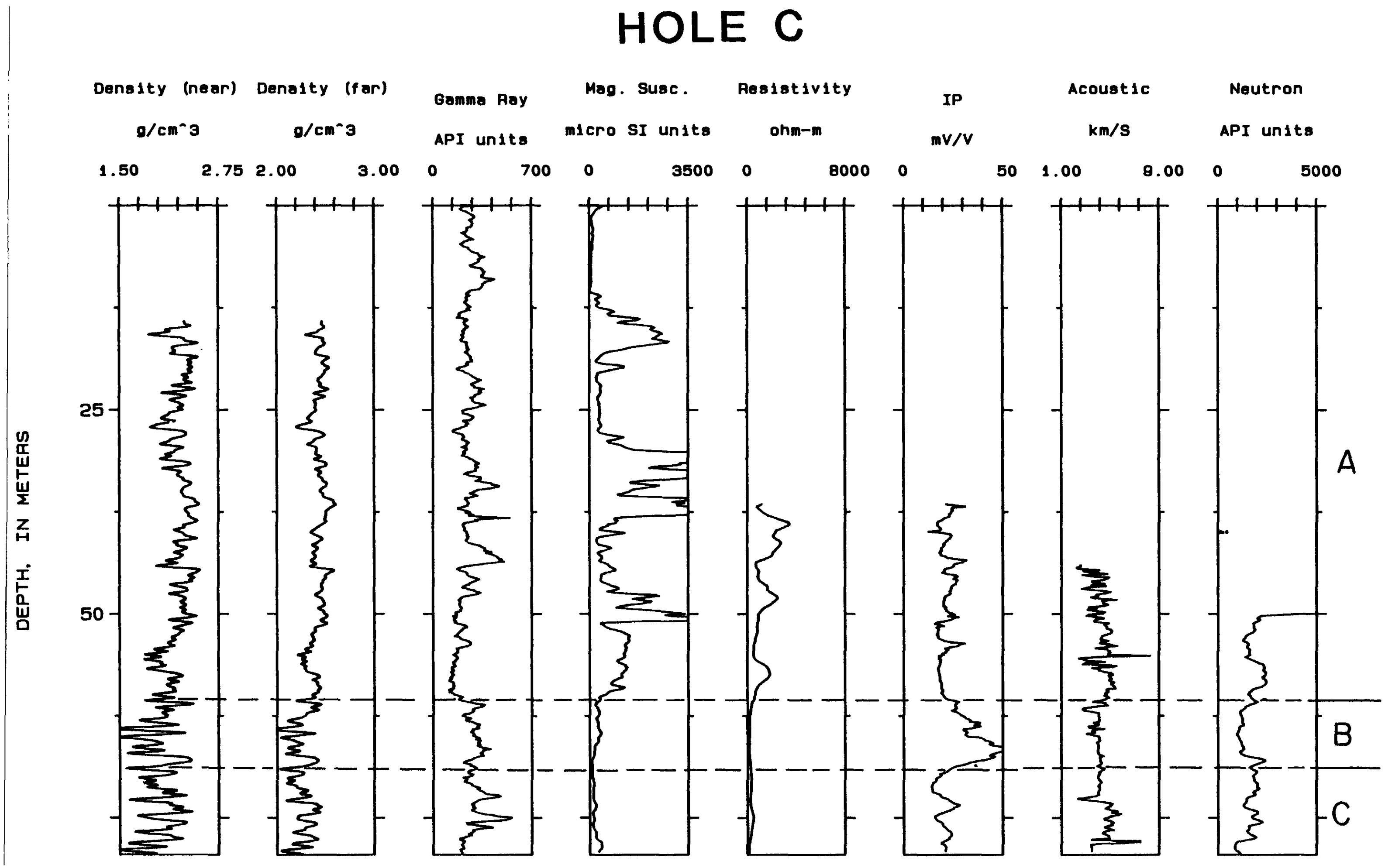

Figure 15. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole C.

Table 6. Explanation of zones for drill hole C.

Zone	Description
A	Moderate felsic mineral content, with anomalously high concentrations of magnetite. Low to moderate fracturing at the base of the zone is indicated by the acoustic velocity log. Moderate fracturing indicated by the near detector density log in the depth interval from 25 to 28 m.
B	Large density variations indicate fracturing. Effects of fractures on the acoustic log are apparently eliminated by the grout sealing the drill hole. The grout in the fractures has the effect of providing a continuous acoustic path, but the recorded compressional velocity is lower than that where grouted-fractures are absent. The IP log indicates the presence of anomalous metallic sulfide mineralization. Felsic mineral content is moderate to high in this zone.
C	Similar to zone B, but the metallic sulfide mineralization is lower in this zone than in zone B. Higher acoustic velocity values are probably caused by a change in rock type.

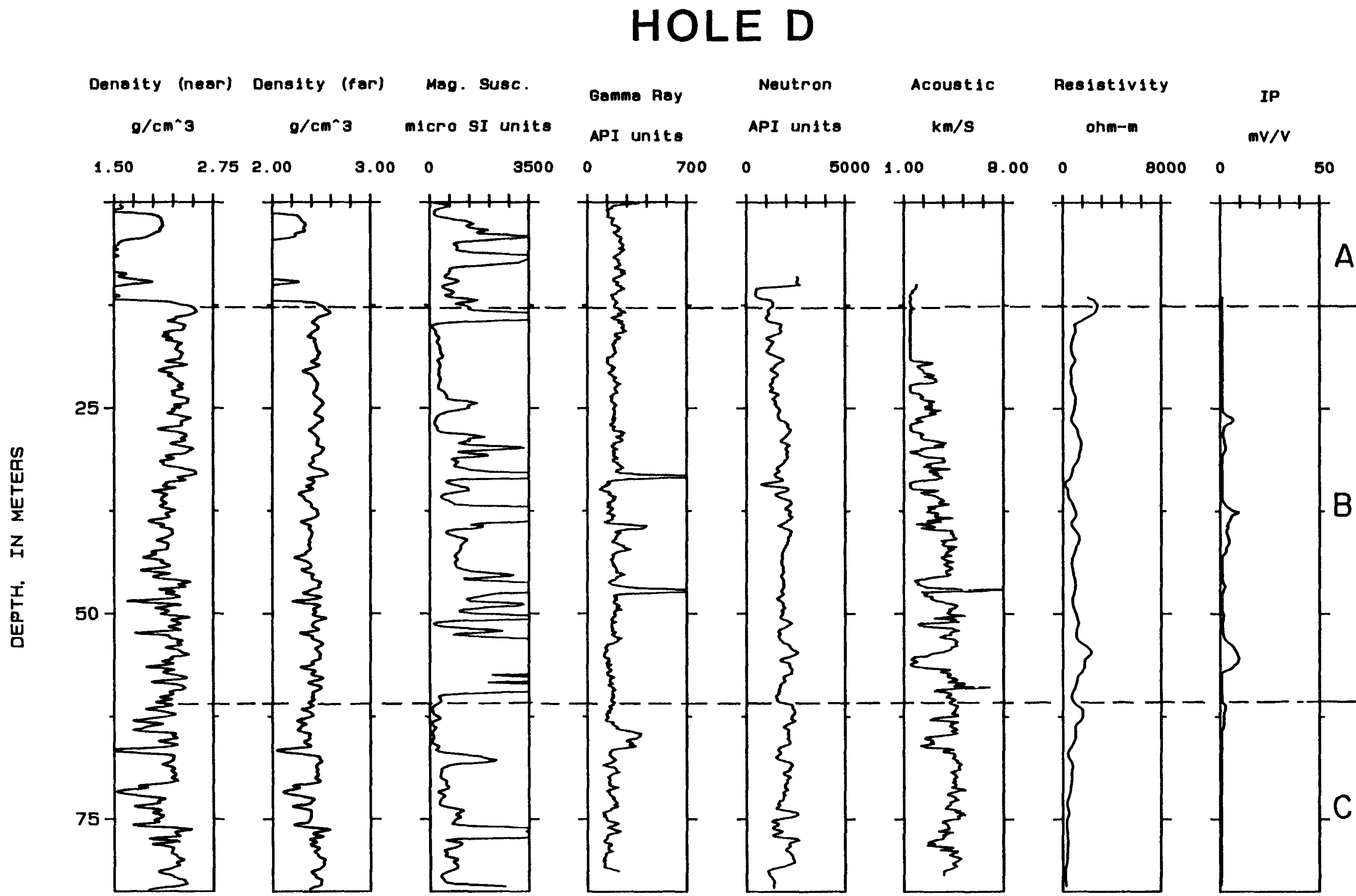

Figure 16. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole D.

Table 7. Explanation of well logs for drill hole D.

Zone	Description
A	Weathered zone, with intense fracturing. Moderate to low felsic mineral content.
B	Moderate to high fracturing in the zone, with apparently low metallic sulfide mineralization. The low metallic sulfide mineralization indicated by the IP log may be caused by low electric current accessibility due to the presence of grout in the drill hole. Low felsic, and high mafic, mineral content is indicated by the gamma ray and magnetic susceptibility well logs.
C	Low to moderate fracturing is indicated by the acoustic velocity well log. There is some discrepency between fractures indicated by the acoustic log and fractures interpreted from the near detector density log. This difference may be caused by grout in the drill hole. The felsic mineral content is generally low in this zone, while the interpretation for the IP well log response is similar to that for zone B.

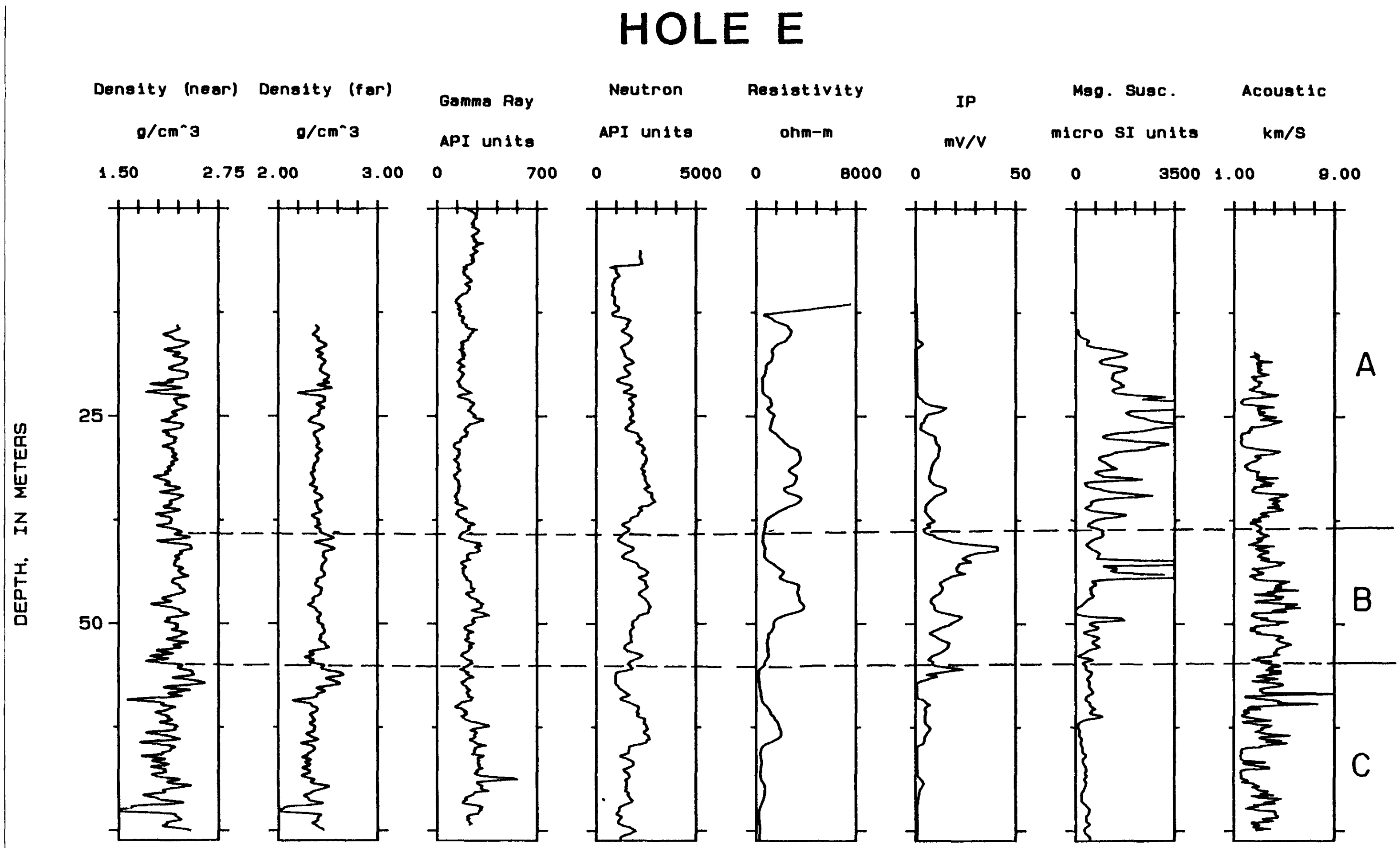

Figure 17. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole E.

Table 8. Explanation of zones for drill hole E.

Zone	Description
A	Moderate to high fracturing is indicated by the acoustic velocity log. Near detector density log indicates low fracturing. This conflict may be caused by partially saturated grouting material in the fractures. The density curve is relatively smooth, but the average values are anomalously low when compared to other non-fractured zones. Low felsic mineral content is indicated by the gamma ray log. Low to moderate metallic sulfide mineralization is indicated by the IP well log.
B	Similar to zone A, with an increase in metallic sulfide mineralization.
C	Similar to zone A, with a decrease in metallic sulfide mineralization and magnetite content. Felsic mineral content increases below a depth of 62 m.

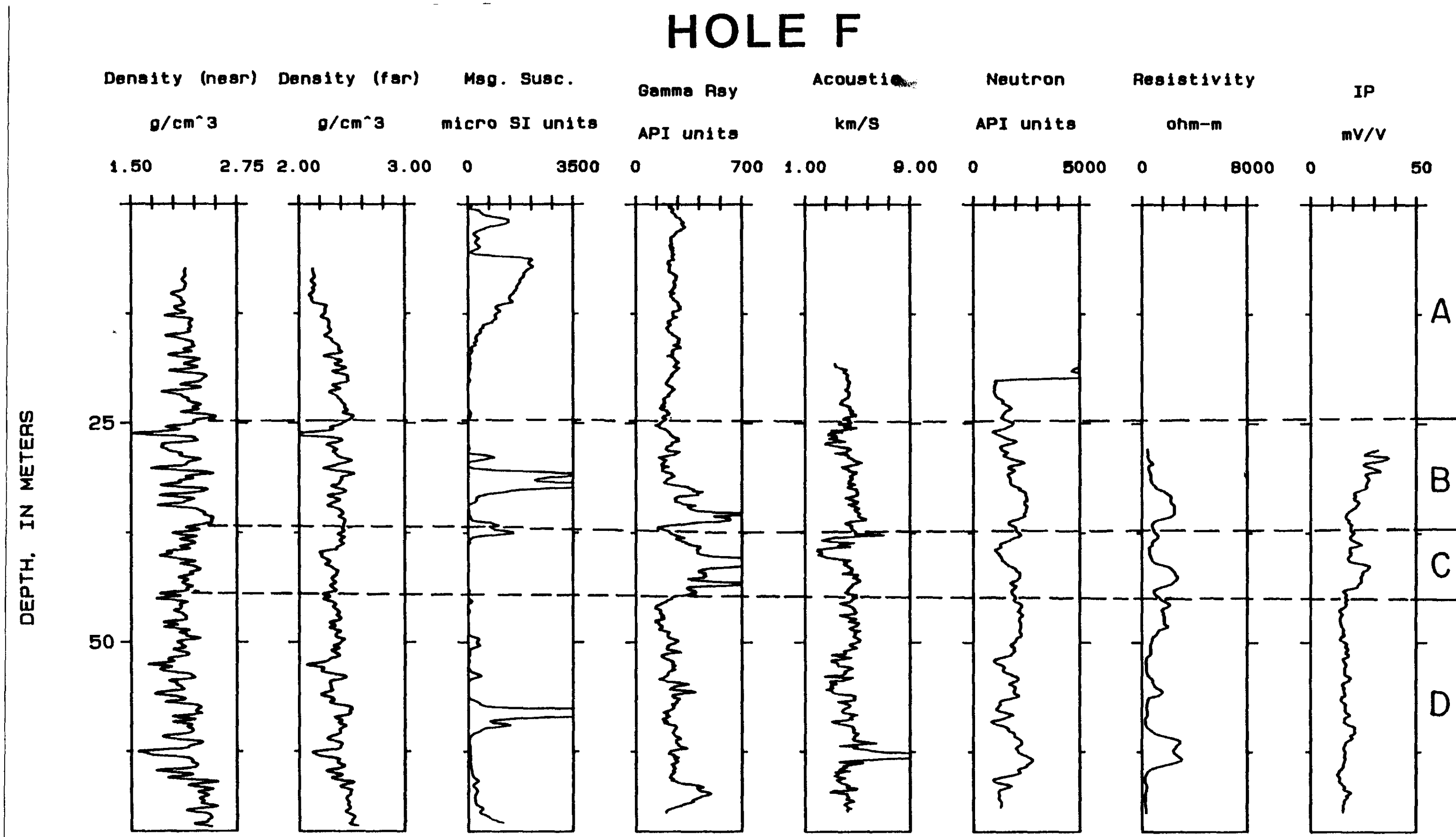

Figure 18. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole F.

Table 9. Explanation of zones for drill hole F.

Zone	Description
A	Fracturing indicated by anomalously low near detector density values. Moderate felsic mineral content. Increasing density with depth.
B	Conflicting interpretation of fractures from near detector density and acoustic velocity. The relative responses of these two logs is similar to the situation for drill hole C, zone B. However, the average acoustic velocity is not anomalously low for hole F, and the density anomalies may be caused by variations in rock type. The felsic mineral content is moderate at the top of the zone, and high at the bottom of the zone. Sulfide mineralization is moderate to high in the logged interval.
C	Fracturing at the top of the zone is indicated by the acoustic log. Possible micaceous pegmatite is shown by the maximum gamma ray response. High overall felsic mineral content, and moderate metallic sulfide mineralization throughout the zone.
D	Fracturing in the intervals from 51 to 55 m, and from 62 to 63 m. Moderate felsic mineral content, with moderate metallic sulfide mineralization.

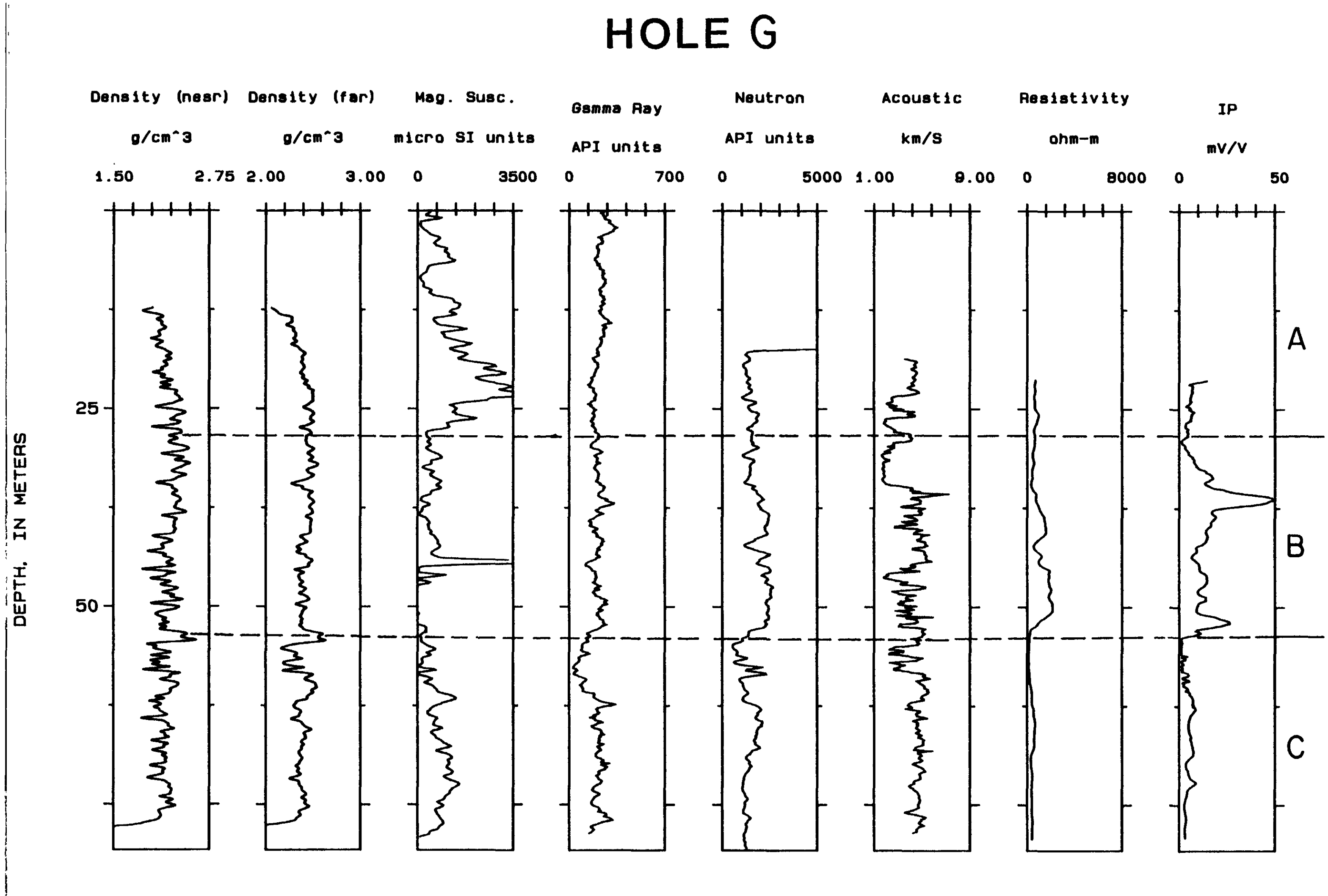

Figure 19. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole G.

Table 10. Explanation of zones for drill hole G.

Zone	Description
A	Increasing mafic mineral content with depth is shown by the gamma ray and magnetic susceptibility logs. Fracturing at the bottom of the zone is shown by the acoustic velocity log.
B	Fracturing at the top and bottom of the zone is indicated by the acoustic velocity log. Moderate to high metallic sulfide mineralization is indicated by the IP log. Low to moderate felsic mineral content.
C	High degree of fracturing at the top of the zone. Low to moderate felsic mineral content. Low metallic sulfide mineralization throughout the zone.

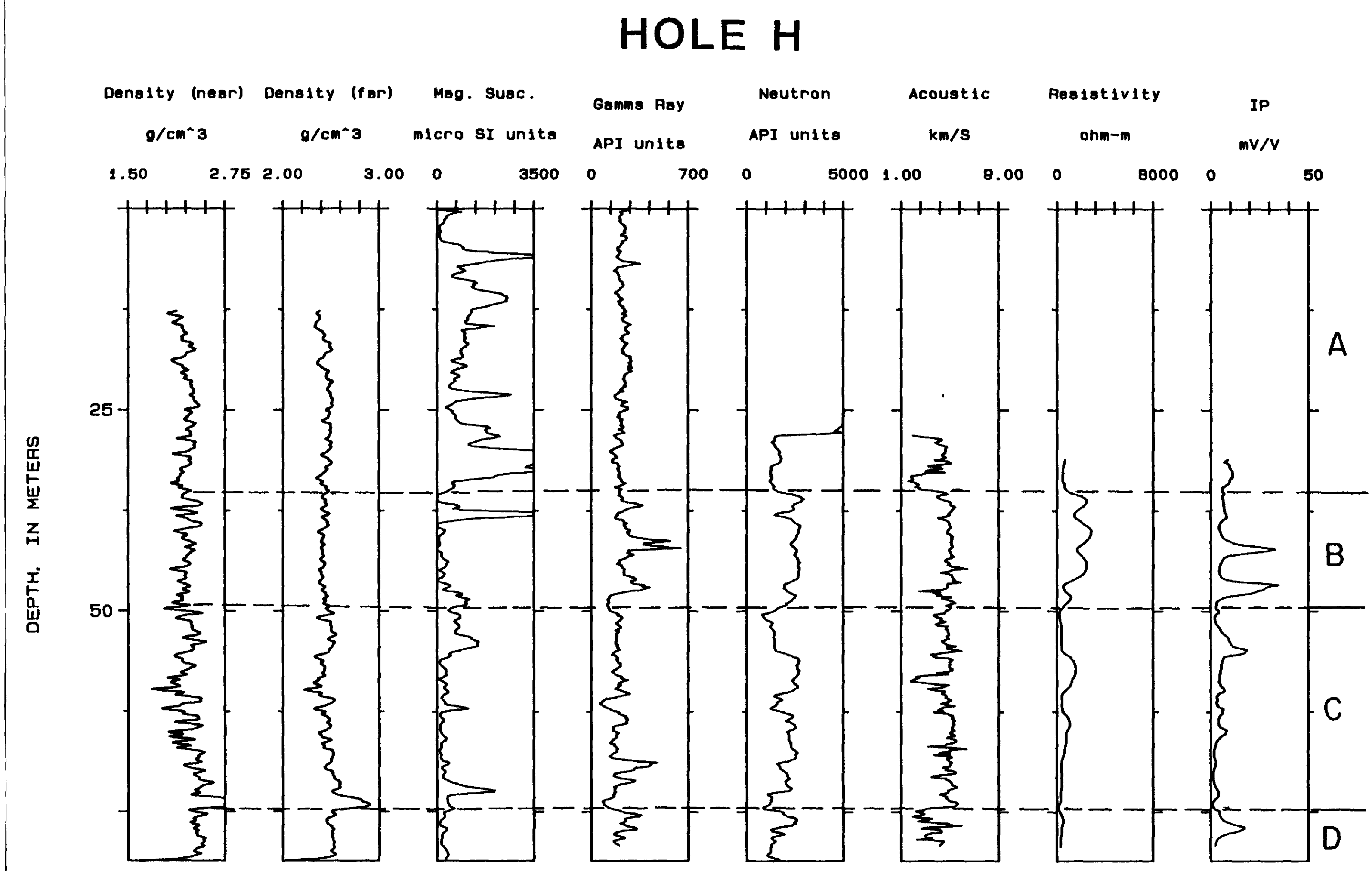

Figure 20. Magnetic susceptibility (Mag. Susc.), gamma ray, near detector density (near), far detector density (far), resistivity, induced polarization (IP), acoustic and neutron well logs for drill hole H.

Table 11. Explanation of zones for drill hole H.

Zone	Description
A	Moderate felsic mineral content. Fracturing at the bottom of the zone. High overall magnetite content.
B	Low fracturing, except at the bottom of the zone. The zone contains two felsic regions associated with metallic sulfide mineralization.
C	Low to moderate fracturing is indicated by the acoustic velocity log. Low felsic mineral content, with low metallic sulfide mineralization.
D	Moderate to high fracturing is indicated by the acoustic velocity log. Fracturing not indicated by the density logs. The IP log indicates some metallic sulfide mineralization.

Conclusions

The geophysical well logs for the drill holes in the study area show wide variations in various physical properties that reflect variations in the geologic properties of the rocks. The acoustic velocity and density logs illustrate that most of the drill holes contain highly fractured sections of rock. The magnetic susceptibility and gamma ray logs define regions containing different felsic and mafic mineral components, while zones of widely different metallic sulfide mineralization are defined by the IP well log. The rock properties interpreted for drill holes C, E, F, G, H, and I are highly questionable because of the presence of grout injected into these drill holes following the initial drilling of the holes.

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Appendix A

Caliper and Self Potential Well Logs

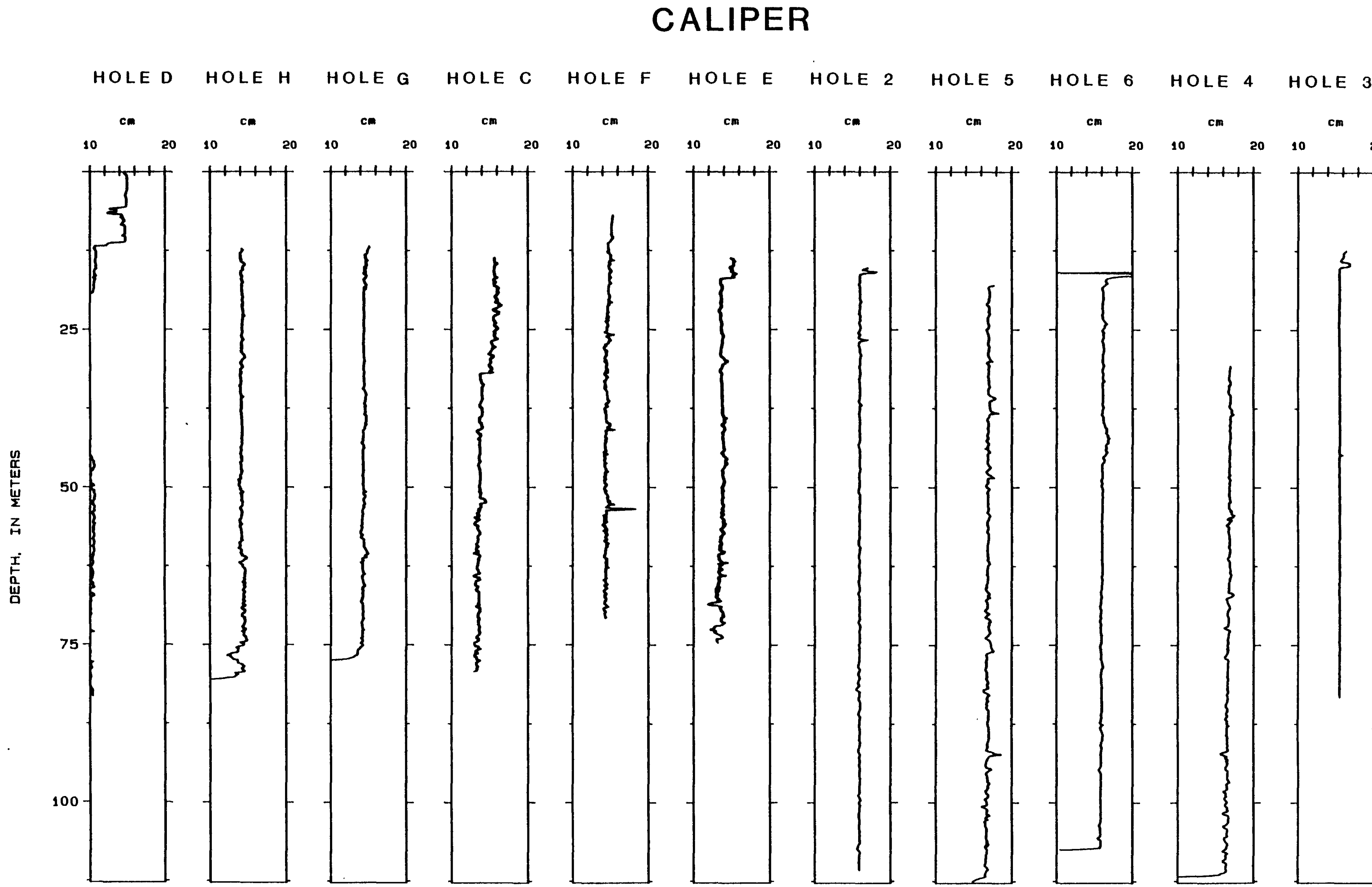

Figure A1. Caliper well logs for each of the drill holes in the study area.

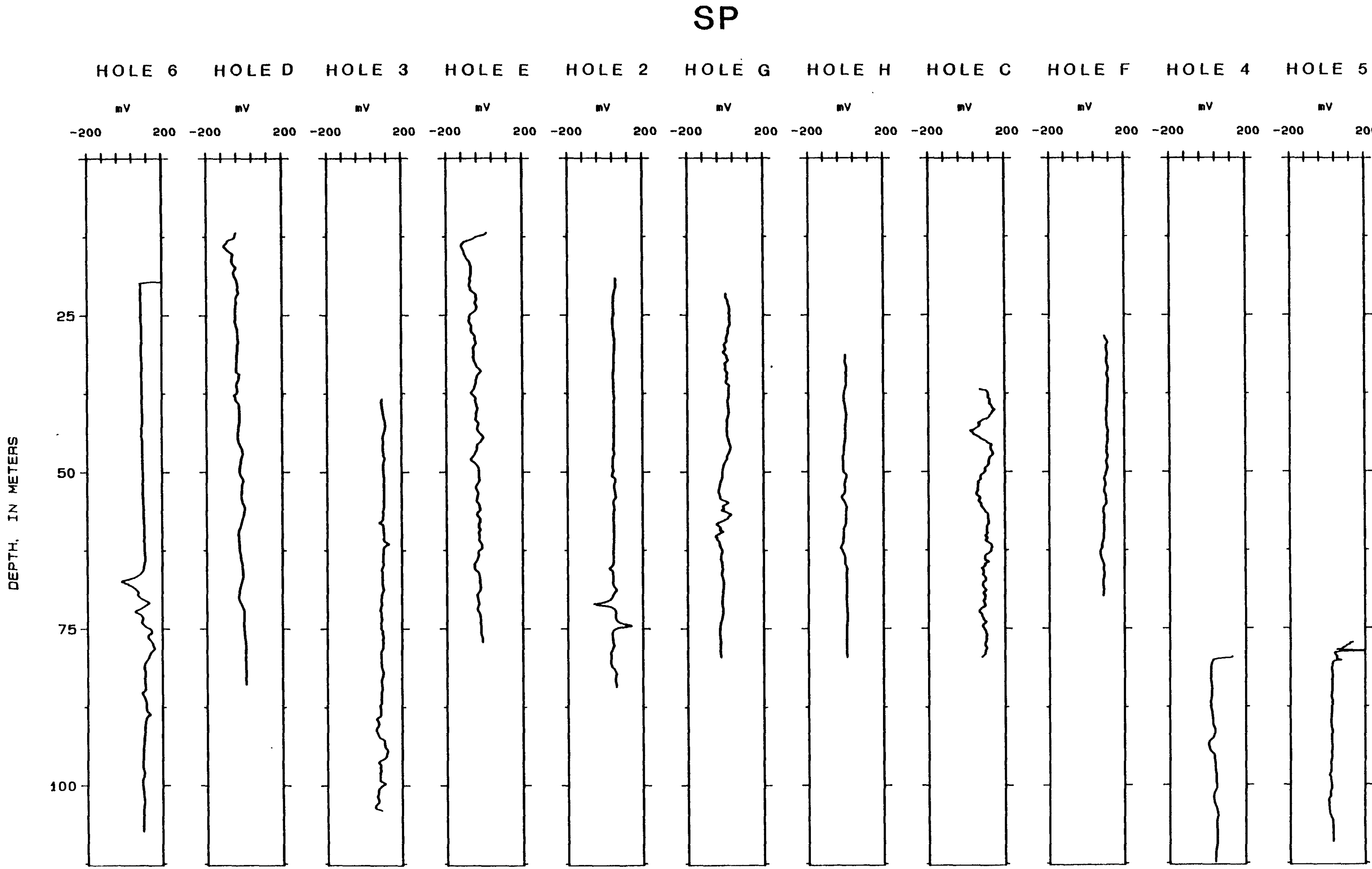

Figure A2. Self Potential well logs for each of the drill holes in the study area.

Appendix B

Off-Scale Well Logs

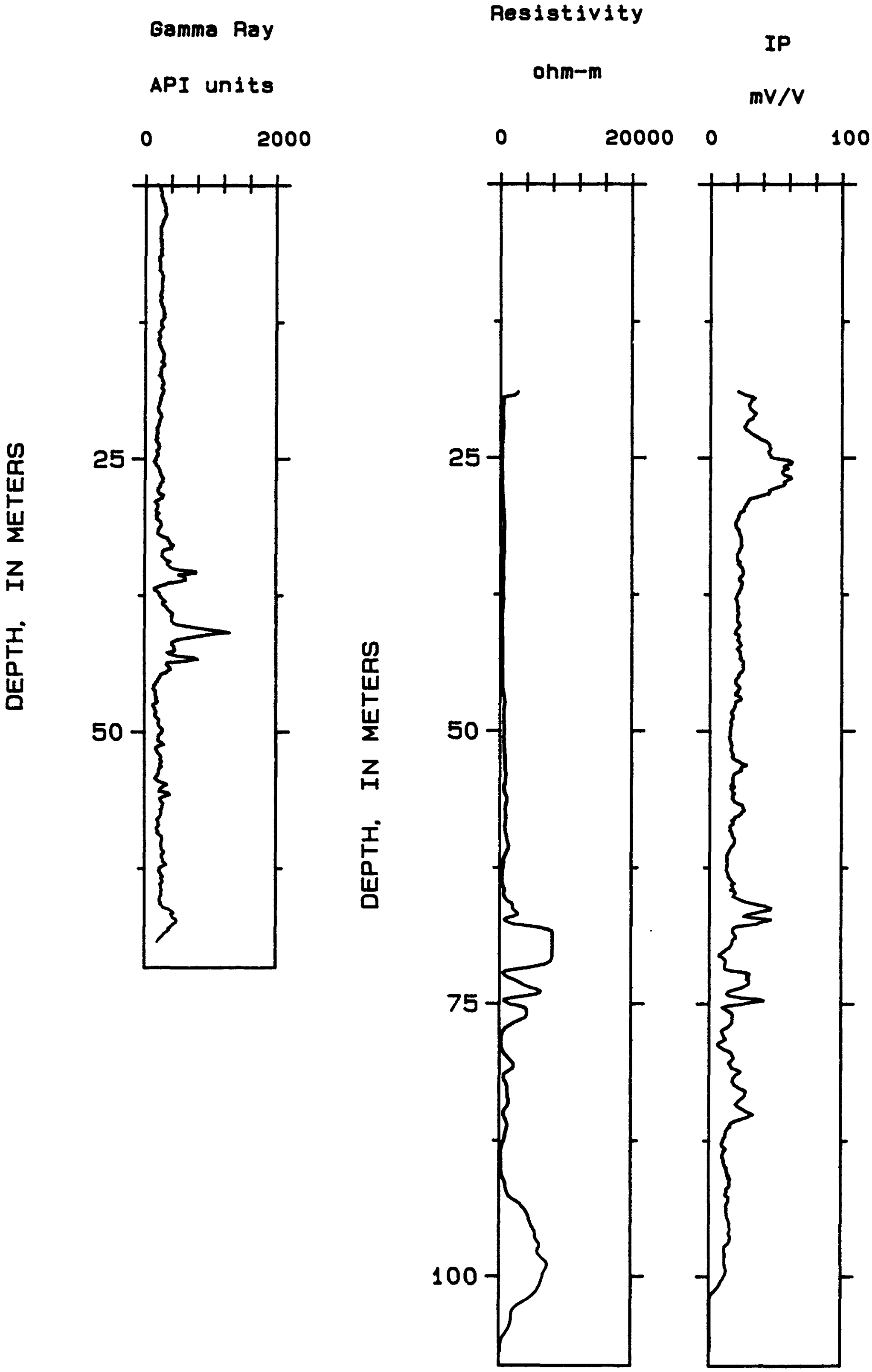

Figure B1. Off-scale replot of the resistivity well log for drill hole 6, of the gamma ray well log for drill hole F, and of the induced polarization (IP) well log for drill hole 6.

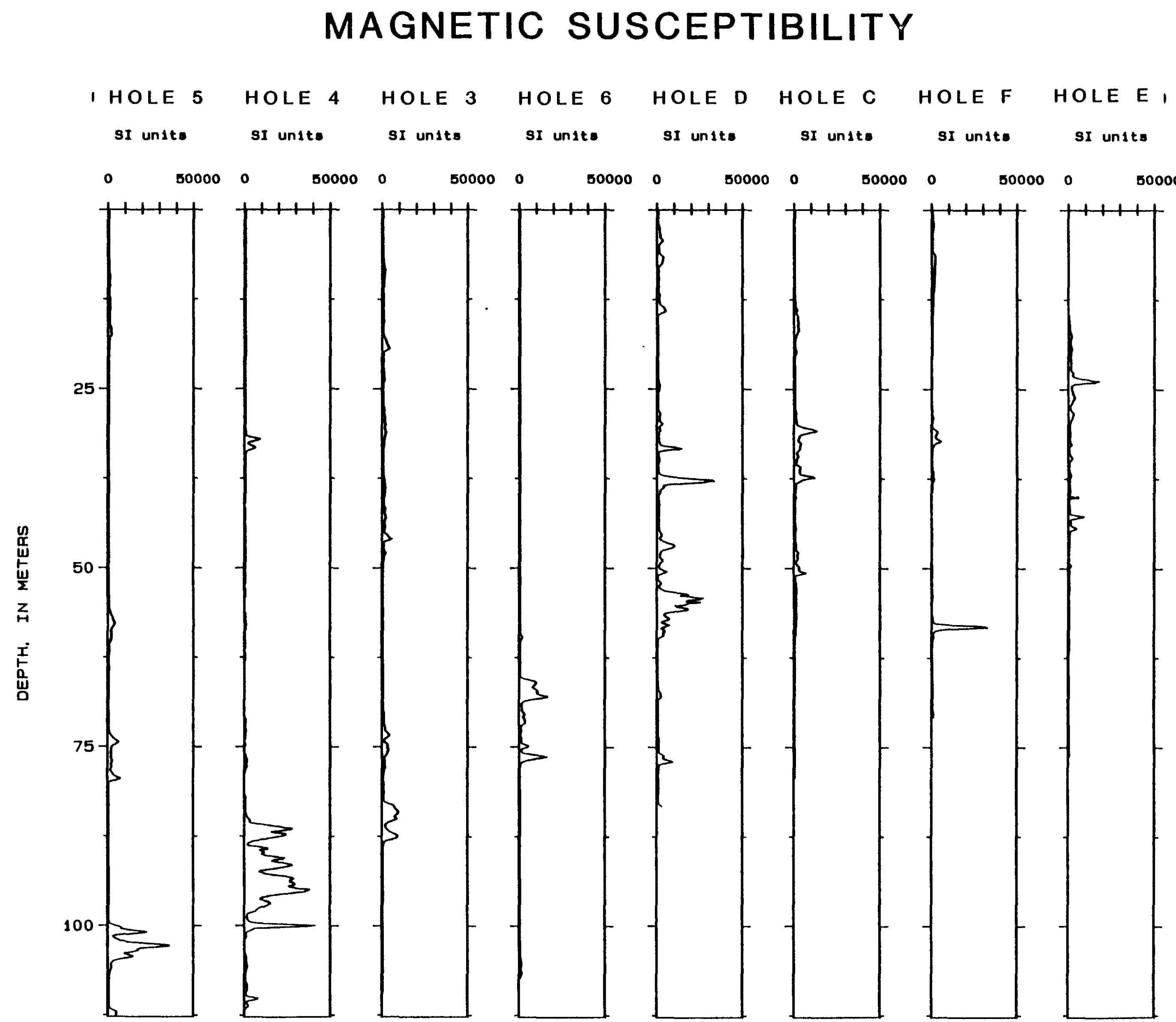

Figure B2. Off-scale replots of the magnetic susceptibility well logs for drill holes 3, 4, 5, 6, C, E, F, and D. Values on the well logs are in SI units x 10^6.