Computer-Assisted Interpretation of Geophysical Well Logs in a Coal Depositional Environment, Illinois Basin, Kentucky

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By JEFFREY J. DANIELS *and* JAMES H. SCOTT

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Physical properties associated with various lithologies in a coal depositional environment are interpreted from digital geophysical well-log measurements

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By JEFFREY J. DANIELS and JAMES H. SCOTT

ABSTRACT

Physical properties detected by well-logging probes include density, porosity, water content, resistivity, electrical polarizability, and natural gamma-ray radiation. Well-logging probes respond primarily to physical properties of the rock surrounding the drill hole, but are also affected by the properties of the fluid in the hole and by irregularities of the hole surface. A particular lithology may be characterized by physical properties that are measured by one type of geophysical well-logging device and not by another. Therefore, the geologic section near a borehole must be interpreted by using more than one type of well log to selectively determine individual lithologies.

Interpretations of lithologies from borehole geophysical measurements are based on the fact that different rock types exhibit characteristic physical properties that can be measured by the probes. For example, the following response values (relative to the average probe response values in a sedimentary environment) can be used for lithologic identification: (1) coal yields a low density response, (2) limestone conglomerate and sandstone have high neutron and resistivity responses, and (3) kaolinite shale has a high gamma-ray response. Interpretation of lithologies in a shallow sedimentary coal environment can be facilitated by using products and ratios of well logs. Coal is characterized by a low density, a low natural gamma-ray count rate, and a high induced polarization response. The density and gamma-ray responses of black shale are slightly higher than those of coal. Limestone conglomerate and sandstone both have high resistivity and neutron responses and low gamma-ray responses, but the product of the resistivity and neutron response is higher for limestone conglomerate than for sandstone. The approximate amount of shale in shaly sandstone can be determined by the product of the resistivity and neutron well logs. In shale that contains only clay, the induced polarization well log can be used to distinguish the clays with a high cation-exchange capacity from those with a low cation-exchange capacity. After the geologic section has been interpreted using product and ratio well logs, the stratigraphic features in an area can be determined by comparing composite interpretations from drill hole to drill hole.

INTRODUCTION

Density, gamma-ray, and single-point resistance well logs are now commonly used by mining geologists and engineers for identification of coal deposits and for lateral correlation of stratigraphic units associated with coal deposits. Authors of previous papers on well-log analysis in coal deposits have limited their topics to identification of coal seams and to analysis of the economic and engineering parameters of the seams (Weltz, 1976; Kowalski and Fertl, 1976; Reeves, 1976). For example, Bond and others (1969) discussed the following applications of well-log analysis to coal-prospect evaluation: (1) identification of coal seams, (2) measurement of coal seam thickness, (3) evaluation of lithology and moisture index of formations surrounding coal seams, (4) determination of a strength index for formations penetrated by the drill hole, and (5) analysis of coal quality. Bond's paper implies that all these problems can be easily solved to a high degree of accuracy with conventional well logs (gamma-ray, density, sonic, neutron, laterolog, and caliper) that are commercially available and are used routinely in the petroleum industry. Unfortunately, most well-logging tools that are used in the petroleum industry require a minimum drill-hole diameter of 6 inches, but most holes drilled for coal exploration and development are less than 5 inches in diameter. Also, interpretive parameters developed for consolidated sedimentary environments, such as those used in petroleum exploration, are not valid for unconsolidated or poorly consolidated sediments that are characteristic of sub-bituminous and bituminous coal environments.

No single type of well log can be used to completely interpret the lithology of rock surrounding a drill hole. However, detailed lithologic and stratigraphic interpretations of shallow sedimentary coal depositional environments can be made by using combinations of well logs that measure several different physical properties of the rocks. The following well logs, all of which can be obtained with commercially available small-diameter probes (<6 cm (centimeter)), are discussed in this paper: gamma-ray, density, resistivity, neutron, and induced polarization (IP). A computer-aided interpretive technique is described for determining the following geologic features in a coal depositional environment: (1) the lithologic section, (2) the presence of pyrite, (3) the presence of high cation-exchange capacity clays, and (4) the presence of lateral facies changes.

WELL-LOG RESPONSES CHARACTERISTICS

It is important to understand the response characteristics of different types of geophysical well-logging probes in terms of the physical properties of the rocks. A single well-logging probe can yield similar response values in different lithologies. Conversely, different types of well-logging probes can yield different lithologic interpretations in the same drill hole.

Geophysical well-logging probes can be divided into two groups based upon the complexity of their response characteristics: (1) well-logging probes that respond to specific physical properties, and (2) well-logging probes that respond to combinations of physical property changes. The gamma-ray probe detects the amount of natural gamma radiation emanating from potassium-40 and uranium-series isotopes in a rock unit. Resistivity and neutron probes respond to a combination of physical characteristics of a rock unit, primarily its water content which reflects porosity and, to a lesser degree, the intrinsic resistivity of minerals in the rock. The density-probe response is primarily a function of the rock bulk density; however, the electron density of the rocks (the density of the rock that is measured by the gamma-gamma density probe) is also affected by secondary physical properties including porosity, water content, and invasion of drilling mud, and by the chemical composition of the rocks as it affects the ratio of average atomic number to average atomic weight, Z/A (Robbins, 1979). In addition, a geophysical well-log measurement is a function of the volume of rock investigated by the probe and the vertical resolution of the probe ("thin" bed resolution). Therefore, the response recorded by a geophysical well-logging probe that responds to combinations of physical properties should always be thought of as an "apparent", rather than a "true", measure of a physical property value. The functions and response characteristics of individual well-logging probes in a shallow sedimentary coal environment can be summarized as follows:

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 enclosing rock wall and absorbed as a direct function of the electron density of the rock unit. The Compton-scattered gamma radiation that is measured at the gamma-ray detector on the probe is inversely related to the electron density of the rock. When two detectors at different spacings from the source are used to measure the scattered gamma radiation, the local effects of error-producing borehole conditions (rugosity, invasion of drilling mud, and presence of borehole fluid between probe and rock) on the calibrated density measurement can be compensated, and the computed density is approximately equal to the electron density of the rocks (Scott, 1977).

The apparent density of coal is commonly the lowest response value on the density well log, averaging less than 1.6 g/cm^3 (grams per cubic centimeter) for sub-bituminous and bituminous coal. The bulk density of coal is a function of the ash content, where ash is defined as the nonburnable percentage of the coal. The densities of other interbedded sediments are a function of the porosity and grain density of the individual rock units. Clays and shales exhibit low densities (2.2–2.5 g/cm^3), sandstone has an intermediate density (2.5–2.65 g/cm^3), and limestone has a high density (2.7–2.9 g/cm^3).

RESISTIVITY

Resistivity is a measure of the pore water resistivity and the grain resistivity of a rock. Clay has an apparent resistivity of generally less than 10 ohm meters, shale has a resistivity of less than 50 ohm meters, sandstone has a resistivity between 50 and 200 ohm meters, and limestone and bituminous coal have resistivities of more than 200 ohm meters. Shale partings can significantly decrease the apparent resistivity of coal, sandstone, and limestone. The wide range of resistivity values (from less than 10 to more than 500 ohm meters) recorded in shallow sedimentary rocks makes resistivity a good indicator of lithologic changes in logged sections.

GAMMA RAY

The gamma-ray probe measures the natural gamma radiation emitted by the rocks surrounding the borehole. The principal sources of natural gamma radiation in shallow sedimentary rocks are uranium-series isotopes and potassium-40. Pure limestone contains practically no natural gamma-ray emitting elements. Shale and clay containing potassium-40 have an intermediate gamma-ray response. Coal is associated with a reducing environment that enhances the deposition of uranium, but coal itself rarely contains significant concentrations of uranium minerals. Uranium may be concentrated in some detrital sediments by the presence of organic matter. Uranium-bearing black shales commonly have extremely high gamma-ray levels and are therefore important marker horizons for between-hole stratigraphic correlations.

NEUTRON

The neutron well-logging probe consists of a neutron source and a neutron detector that is located on the probe approximately 40 cm from the source. The count rate of the neutron detector is inversely related to the hydrogen content of the rocks surrounding the borehole, and is primarily a measure of the amount of water and hydrocarbons in the rocks. Coal has a low neutron count rate because of its high hydrocarbon content, whereas low-porosity limestone has

TABLE 1.—*Relative response levels of well-logging probes in coal depositional environments*

[The lowest response is assigned the value of 1; the highest reponse is assigned the value of 7. For some probes, certain rock types exhibit a range of values which overlap or are essentially coincident; these values are shown in the table by two or more "level" values]

Probe type	Coal	Gray shale	Black shale	Sand-stone	Lime-stone	Con-glomerate	Clay
Density-------------	1	4	2	5,6	7	5,6	3
Resistivity---------	6,7	3	2	4,5	6,7	4,5	1
Gamma-ray-----------	2,3,4	6	7	2,3,4	1	2,3	5
Neutron-------------	1	2,3,4	2,3,4	5,6	7	5,6	2,3,4
Induced polarization	2,3,4	5,6	7	2,3,4	1	2,3,4	5,6

a high neutron count rate because of its low water content. Sandstone and shale (intermediate porosity and high porosity, respectively) have intermediate and low neutron count rates. The neutron response is also affected by the borehole fluid and the rugosity of the borehole.

INDUCED POLARIZATION (IP)

The IP is measured by recording the decay voltage (emitted from an "on-off" current source) at a two-potential electrode that is positioned on the probe at a spacing of 10–40 cm from an electrical current source. The rate of decay of the potential during the current off time is related to the electrical polarizability of the rock, and is called the induced potential (IP) effect. A high IP response may be caused by the presence of pyrite or cation-rich clays (such as montmorillonite or illite). A high IP response in black shale or coal usually indicates the presence of pyrite.

The relative range of values for these five types of well-logging probes are listed in Table 1 for various shallow sedimentary rock types. The relative response values listed in this table are subjective.

COMPUTER-ASSISTED APPROACH TO INTERPRETATION OF LITHOLOGY

As stated previously, each individual well-logging probe responds to physical properties associated with the drill hole and the rock surrounding the drill hole. Physical properties detected by well-logging probes used in this study include density, porosity, water content, resistivity, electrical polarizability (IP effect), and natural gamma-ray radiation. Interpretation of physical properties from geophysical well logs assumes that the effects of borehole conditions on the well-log response values have been quantitatively considered in the analysis, or that the physical condition of the borehole can be considered to have the same effect on the well-log response throughout the intervals being logged. Not all well-logging probes respond to every change in the geology because: (1) the response values of the well-logging probe to lithologic variations depends upon the range of values of the physical properties, and (2) a particular rock type may be characterized by a physical property that is measured by one type of well-logging probe, and not measured by another probe. In order to interpret a geologic section from physical-properties measurements, the measurements from several different well-logging probes must be used and a composite interpretation must be made that considers all of the physical properties characteristic of a particular lithology.

The interpretation procedure that was followed in this study involves the following steps. After visual inspection of the geophysical logs and the driller's logs, the interpreter assigns (1) a well-log response value range to each geologic parameter of interest and uses the computer to assign a lithology for those depth intervals where the individual well log values are within the assigned value ranges. (2) These individually interpreted well logs are compared to existing geologic information (such as cores and driller's well logs) to find where gaps exist and where interpretations are unreasonable. (3) To fill in the gaps and to correct unreasonable interpretations, products and ratios of different types of well logs are calculated and assigned lithologies based upon specified value ranges. (4) A final interpretation is made that includes all the individual and product-ratio geophysical well-log interpretations as well as all the available geologic information. The final interpretation is subjective and utilizes the well-log response, or combination of well-log responses, that best characterize a particular lithology.

GEOLOGY

The six holes in this study were drilled into the Carbondale Formation of Middle Pennsylvanian age at a site located approximately 1 mile south of Centertown in Ohio County, Kentucky. Detailed descriptions of the geology of the Carbondale Formation are not available in the literature; the descriptions and interpretations of the unit are based upon geological information provided by coal-company geologists.

The areal positions of the six drill holes and old mine workings are shown in figure 1. Lithologic well logs for each of the six drill holes are shown in figure 2. These lithologic well logs were compiled from the driller's and company geologist's descriptions of sample cuttings taken at the time these holes were drilled. The three major coal seams penetrated by the drill hole were the Nos. 9, 10, and 11 coals, all of which are classified as bituminous. Only the No. 9 coal has economic value at the present time. The No. 9 coal is approximately 1.2 m (meters) thick; the Nos. 10 and 11 coals are each approximately 0.3 m thick. The driller's logs note three types of shale and clay: (1) fire clay, (2) gray shale, and (3) black shale. The shale referred to in the remainder of the present text is gray shale, unless otherwise noted.

The lithology above the No. 11 coal is primarily shale and sandy shale with some sandstone stringers. The interval between the No. 10 and No. 11 coals includes shale, shaly sandstone clay, and sandstone, but the facies distribution in this interval varies from hole to hole. Coal interbedded with shale overlies the No. 10 coal in holes 2, 3, and 6. Clay described by the drillers as fire clay underlies the No. 11 coal in holes 2–6, but not in hole 1.

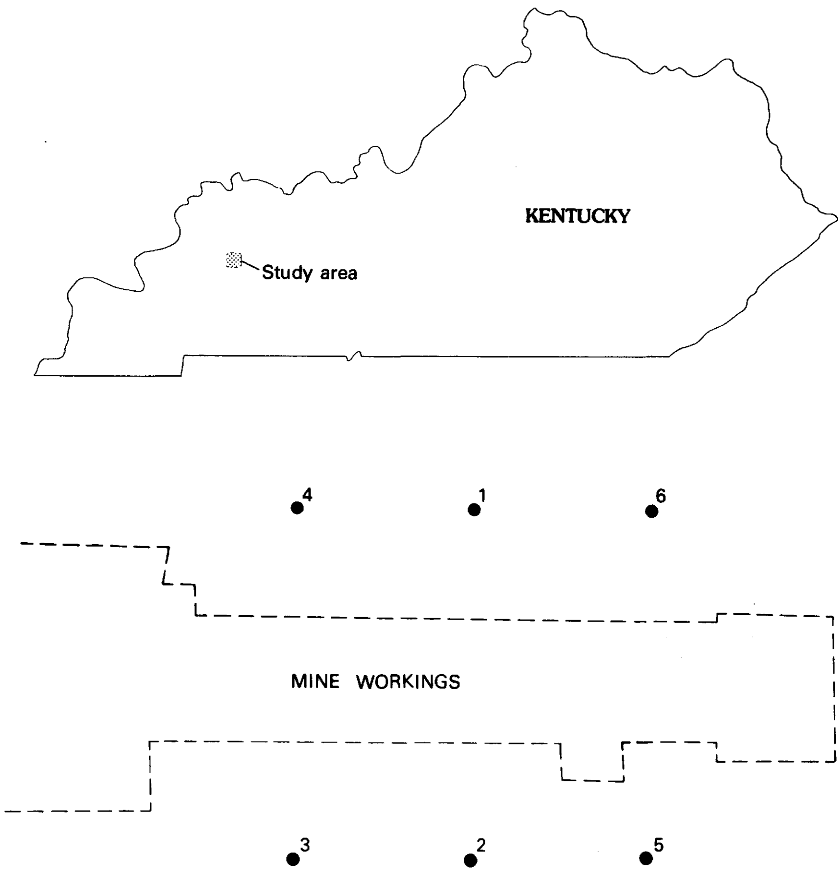

FIGURE 1.—Location of study area and of the six drill holes with respect to the mine workings near Centertown, Ky.

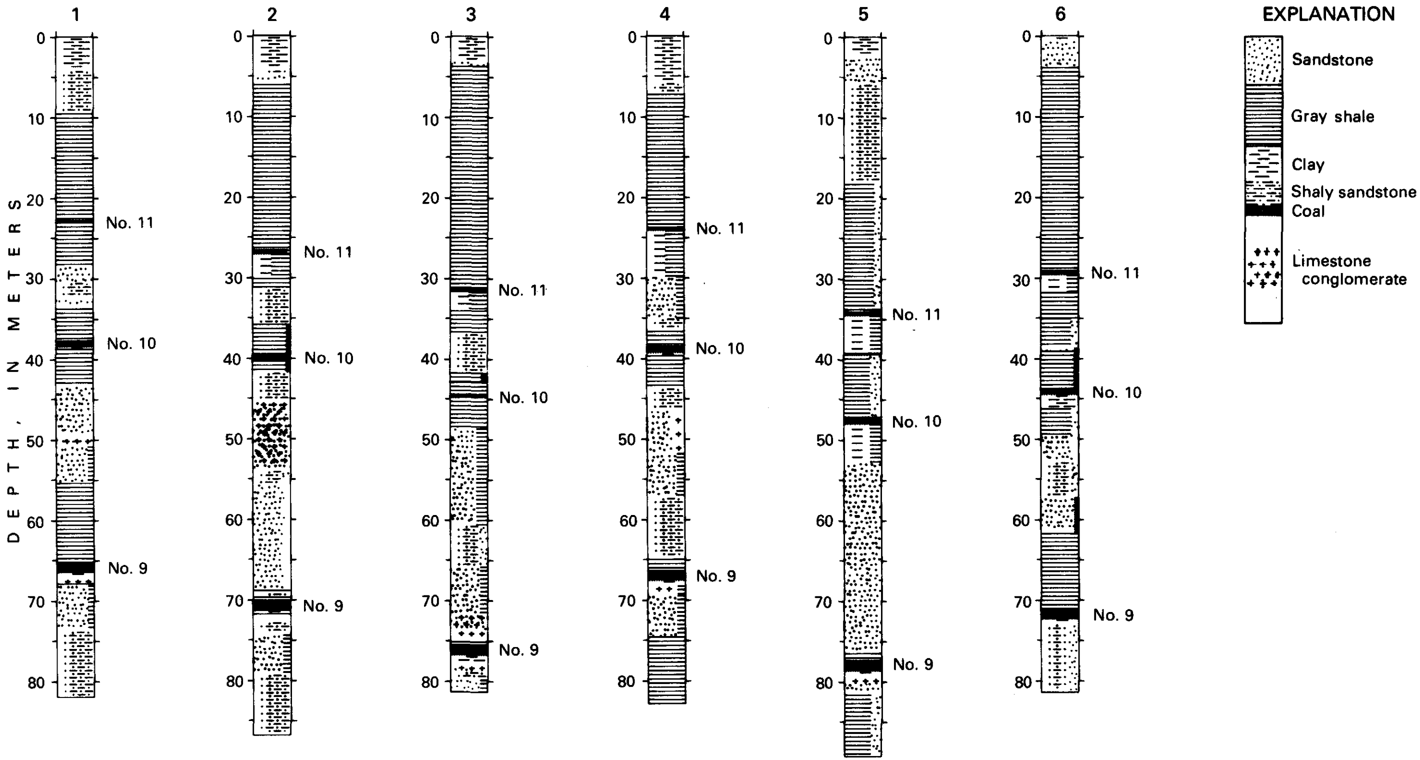

FIGURE 2.—General lithologic logs, interpreted from drill-cutting samples, for each of the six drill holes in this study. Location of the Nos. 9, 10, and 11 coals is indicated on each of the lithologic logs.

The stratigraphic section between the No. 9 and No. 10 coals is about 30 m thick and consists of a clay, a shale, or a sandy shale. A thick shale overlies the No. 9 coal in holes 1 and 6, but is nearly absent in holes 2–5. Limestone is present in holes 1 through 4 not as an independent rock type, but as fragments in a conglomerate whose matrix is composed of calcite-cemented sand (Marc Silverman, oral communication, 1979). This conglomerate is important because it is the basal conglomerate for channel-sandstone sequences. The presence of channel sandstones cannot readily be inferred from the lithologic well logs. Also, these logs do not show any obvious lateral correlation of lithologic units or stratigraphic features between the No. 9 and No. 10 coals. The lithology below the No. 9 coal is primarily shaly sandstone, shale, and sandy shale and there are no correlatable stratigraphic features in any of the drill holes below the No. 9 coal.

INTERPRETATION USING INDIVIDUAL WELL LOGS

The density well logs for holes 1 through 6 are shown in figures 3 and 4. The density well log clearly defines the low-density coals (Nos. 9, 10, and 11) better than does any other geophysical well log. The range of density values for noncoal lithologies is small (2.0 g/cm^3 for some clays and shale to 2.9 g/cm^3 for dense limestone), and these lithologies are difficult to differentiate from the density well logs alone. The value ranges for lithologies shown in figures 3 and 4 emphasize this point; from the density well log alone it is difficult to distinguish between clay and shale, or to determine the relative amounts of sandstone and shale in a mixed-lithology rock strata.

The lowest apparent density values on the well logs are for the Nos. 9, 10, and 11 coals. Low-density values are also associated with black shale, which is present above the No. 10 coal in each of the six drill holes. The low apparent density of the black shale is evidence that it contains a large amount of organic material. The No. 11 coal in drill hole 1 has an apparent density higher than 1.8 g/cm^3 and is consequently interpreted as a black shale.

A comparison of the lithologic well logs that are interpreted from the density well logs indicates the following about the noncoal lithology:

1. There is more shale above the No. 11 coal in drill holes 1 and 6 than in drill holes 2, 3, 4, and 5.
2. There is more shale present between the No. 10 and No. 11 coals in drill holes 1, 5, and 6 than is present in drill holes 2, 3, and 4.
3. There is more shale present between the No. 10 and No. 9 coals in drill holes 1 and 5 than in drill holes 2, 3, 4, and 6.

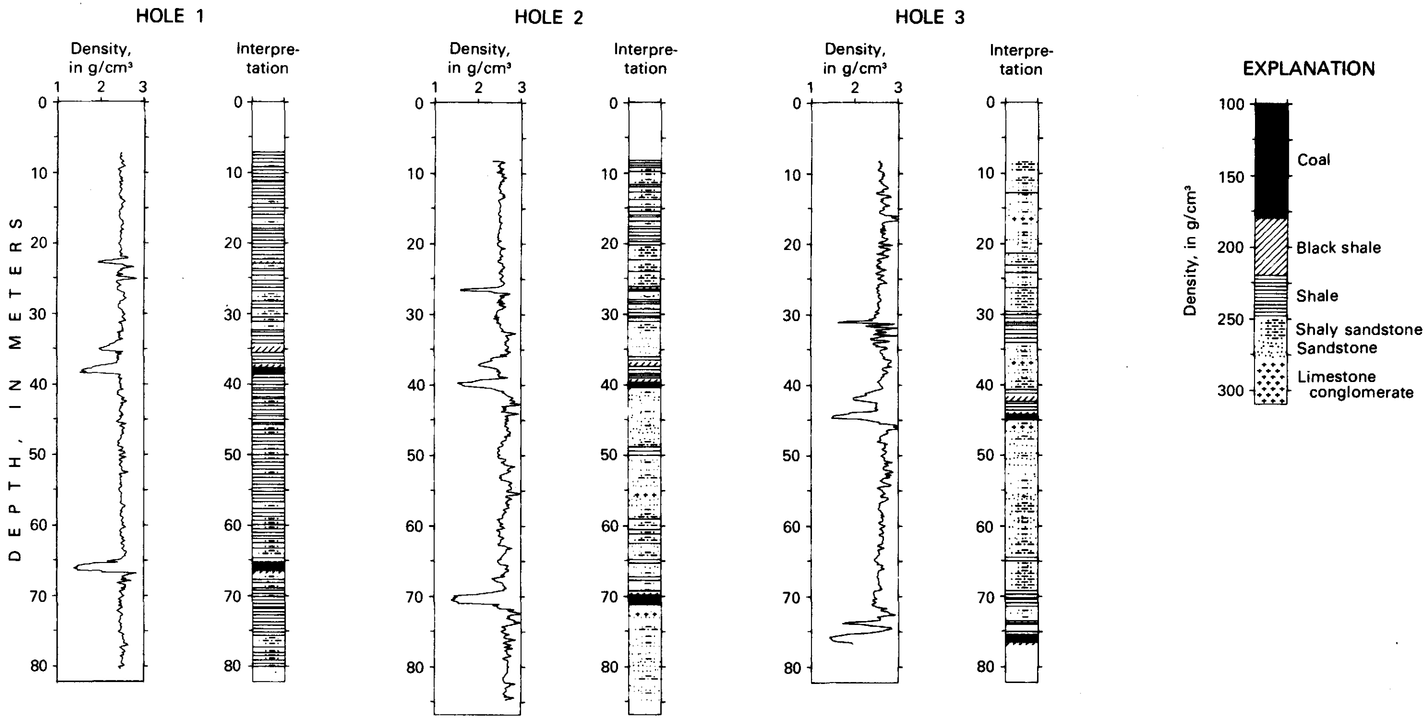

FIGURE 3.—Density well logs and lithologic interpretation of density well logs for holes 1, 2, and 3. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. g/cm³, grams per cubic centimeter.

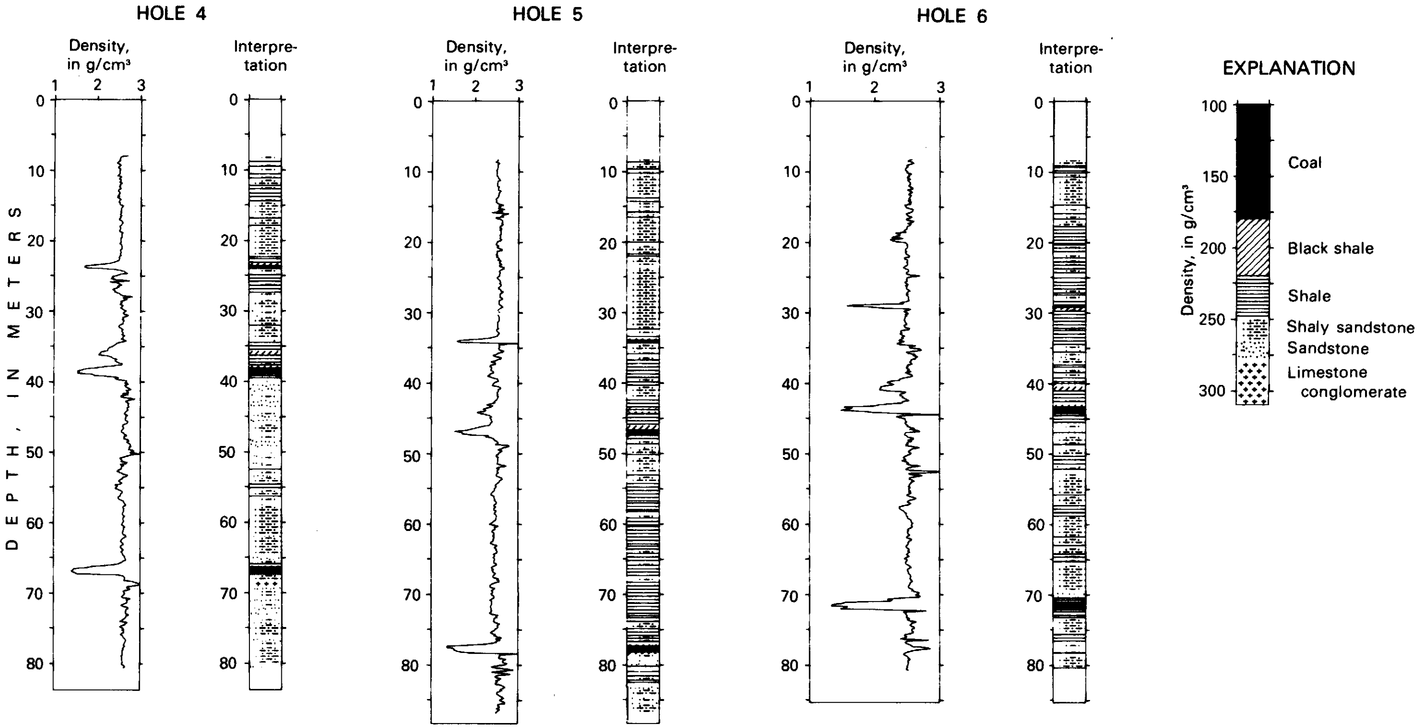

FIGURE 4.—Density well logs and lithologic interpretation of density well logs for holes 4, 5, and 6. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. g/cm³, grams per cubic centimeter.

The sandstone-shale facies can be defined more completely from neutron and resistivity well logs, which will be discussed later.

The neutron well logs for holes 1 through 6 are shown in figures 5 and 6. The neutron well log is primarily an indicator of the amount of hydrogen in hydrocarbons and water in the rock strata. A variation in porosity of the rocks is accompanied by a variation in water content and a corresponding inverse variation in the neutron well-log response. Clays and shales have a higher porosity than sandstones in this lithologic sequence, whereas limestone has a lower porosity than sandstone. Coal has the lowest neutron response seen in the neutron well logs in holes 4 and 5. The broad dynamic range of values of the neutron well-log record makes it particularly useful for determining the relative concentration of individual (noncoal) lithologic components such as sandstone, clay, and shale in a rock unit.

Interpretation of the neutron well logs shows more variability in the sand-to-shale ratio than is indicated on the driller's well logs. The well-log response value ranges that were chosen identify the coal layers with the following exceptions: (1) the No. 11 coal in drill hole 1 has the neutron response of a shale, and (2) a clay layer at a depth of 43 m on the driller's well log in drill hole 5 is interpreted as a coal on the neutron well log.

A low-porosity zone that is interpreted as a limestone conglomerate is present in drill holes 2, 3, 4, 5, and 6 at depths of 51, 59, 48, 58, and 50 m, respectively. A low-porosity zone is also present above the No. 9 coal in drill holes 2, 3, and 5 at depths of 66, 73, and 74 m, respectively. The neutron well logs show that the porosity steadily increases above these limestone conglomerates, and indicates that the low-porosity limestone conglomerate may be the base of a fining-upward channel sequence. The lower channel sequence is absent in drill holes 1, 4, and 6. The upper channel sequence is not interpreted in drill hole 1; however, there is an indication of a low-porosity zone at a depth of 46 m in this drill hole.

A sandy shale that is not clearly defined on the driller's well logs is present between the No. 10 and No. 11 coals in drill holes 1, 4, and 6 in the depth intervals from 27 to 33 m, from 28 to 34 m, and from 34 to 39 m, respectively. This sandy shale may also be present in drill holes 2 and 5 (in the depth intervals of from 31 to 34 m, and 38 to 42 m, respectively), but the sandy shale in these drill holes has a higher apparent porosity (more shale) than does the same layer in drill holes 1, 4, and 6.

The 16-inch normal resistivity measurement is one of the best geophysical well logs for defining the relative amounts of the main lithologic constituents (other than coal) in a shallow sedimentary environment. Daniels and others (1977) showed the nearly linear relationship between increasing clay content and decreasing resistivity for samples taken from a shallow sedimentary uranium deposit in south Texas. Limestone, or limestone conglomerate, has a relatively high resistivity. The apparent resistivity of thin coal seams is often less than the apparent resistivity of limestone conglomerate or limestone.

The apparent resistivity of the coals is generally less than the resistivity of the limestone conglomerate; therefore, the high-resistivity coals are difficult to distinguish from the limestone conglomerates by use of the resistivity log alone. Smith (1967) also noted this problem in his investigations. The thin coal beds also yield apparent resistivity values that are much lower than the true resistivity of the coal. The coal layers penetrated by drill holes 1 through 6 are interpreted as sandstone, sandy shale, or limestone conglomerate, depending upon the amount of ash contained in the coal and the thickness of the coal seam.

The resistivity well logs, and corresponding lithologic interpretations, for holes 1 through 6 are shown in figures 7 and 8. A high resistivity zone, that is interpreted as a limestone conglomerate, is present in drill holes 1, 2, 3, 4, and 6 at depths of 46, 52, 59, 49, and 52 m, respectively. The resistivity well logs show that the resistivity values steadily decrease above these limestone conglomerates in drill holes 1, 2, and 4. The lower resistivity is caused by an increasing amount of clay-size material that results in an increase in porosity. The lack of interpretive agreement between the neutron and resistivity well logs for these high-resistivity, low-porosity zones may be caused by differences in the lateral distances into the formation that the two well logging tools investigate. A high-resistivity zone is also present above the No. 9 coal in drill holes 2, 3, and 5 at depths of 66, 73, and 74 m, respectively. This high-resistivity layer is located at the same depth as the base of the fining-upward channel sequence seen on the neutron well logs in figures 5 and 6.

The gamma-ray probe measures the natural gamma radiation, primarily from potassium-40 in shale and from uranium-series istopes in black shale and sandstone. The organic matter in black shale provides a reducing environment that is conducive to the accumulation of uranium were a source of uranium present during deposition or later. In the shallow sedimentary environment of this study, the general order of gamma radiation, from highest to lowest, is as follows: (1) black shales, (2) shales and clays, (3) sandstone, (4) coal, and (5) limestone. However, coal can yield a higher gamma-radiation count if it contains uranium, or a high percentage of clay (low-grade coal).

Figures 9 and 10 show the gamma-ray well-log response and interpretation of the gamma-ray well logs for holes 1 through 6. In all these logs, the coal is characterized by its low gamma-ray count, with

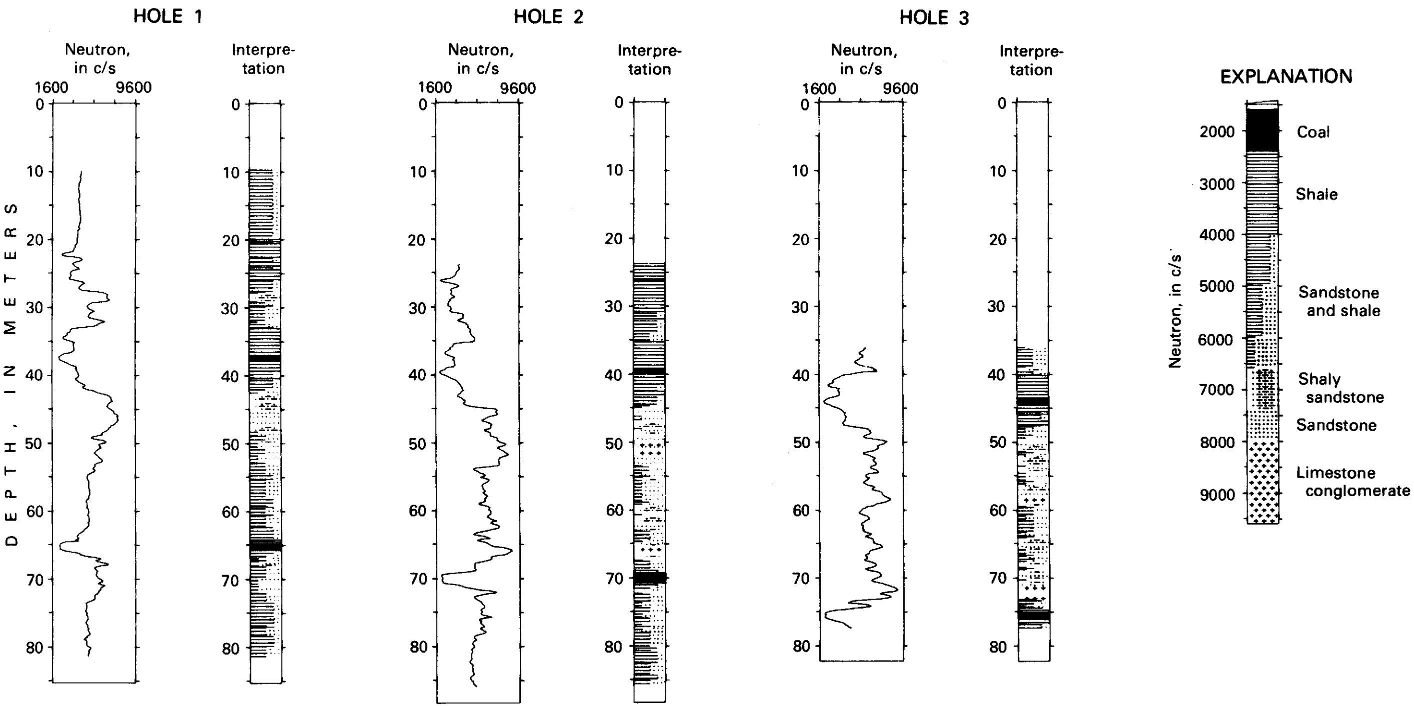

Figure 5.—Neutron-neutron well logs and lithologic interpretation of neutron-neutron well logs for holes 1, 2, and 3. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. c/s, counts per second.

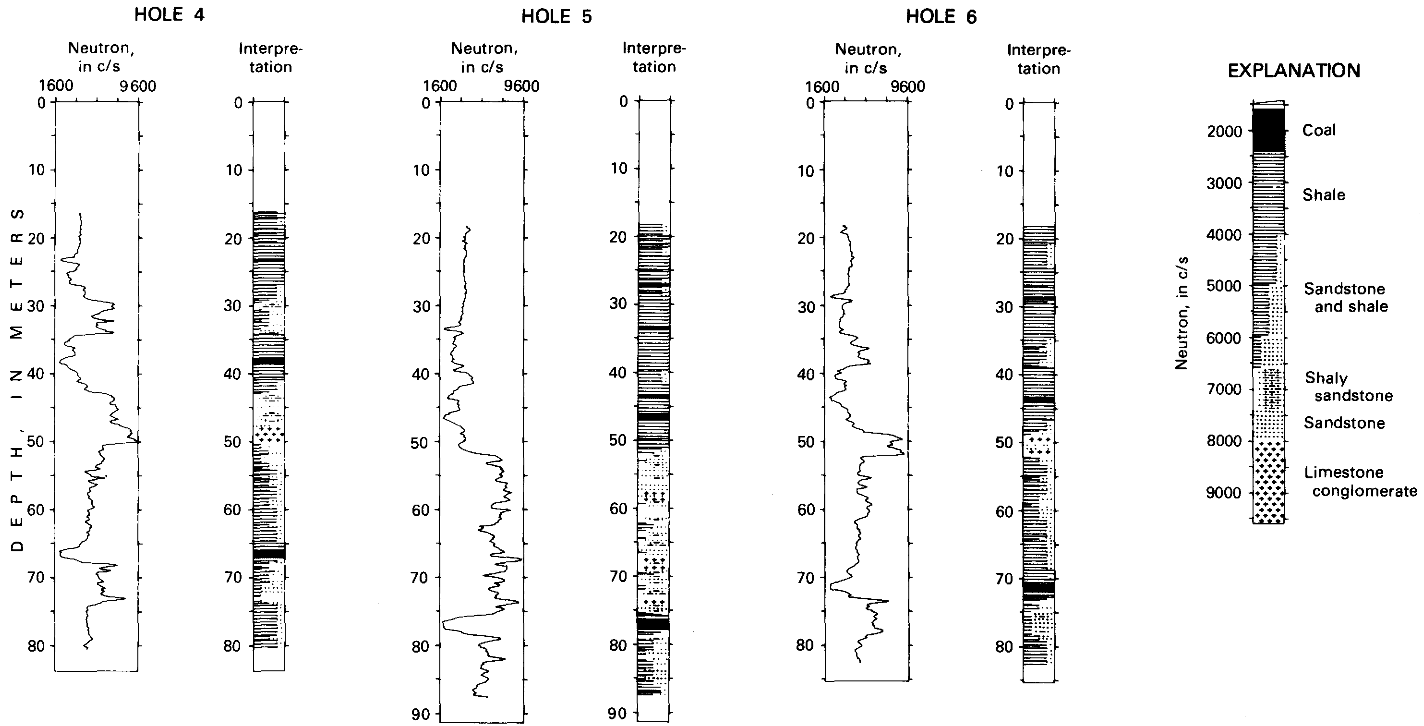

FIGURE 6.—Neutron-neutron well logs and lithologic interpretation of neutron-neutron well logs for holes 4, 5, and 6. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. c/s, counts per second.

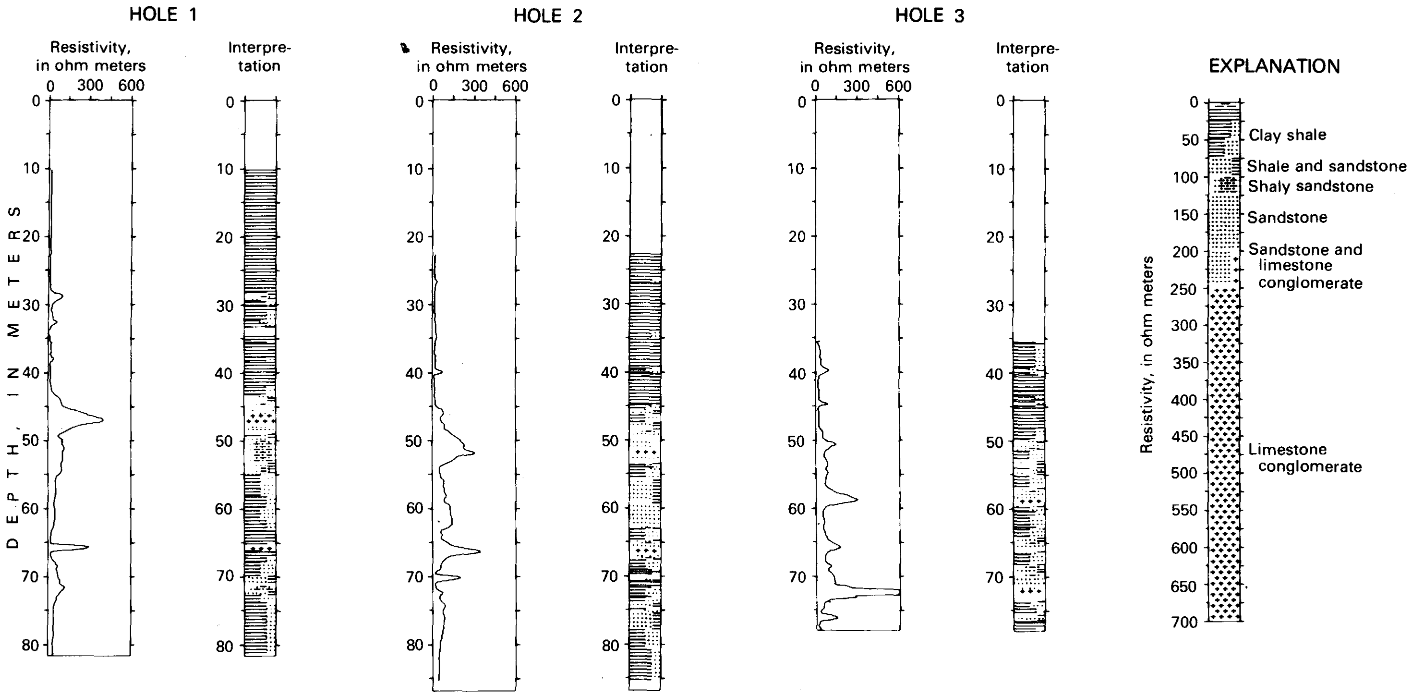

FIGURE 7.—Resistivity well logs and lithologic interpretation for 16-inch normal resistivity well logs for holes 1, 2, and 3. Lithologic symbols and corresponding velocity value ranges that were used for interpretation are shown in explanation.

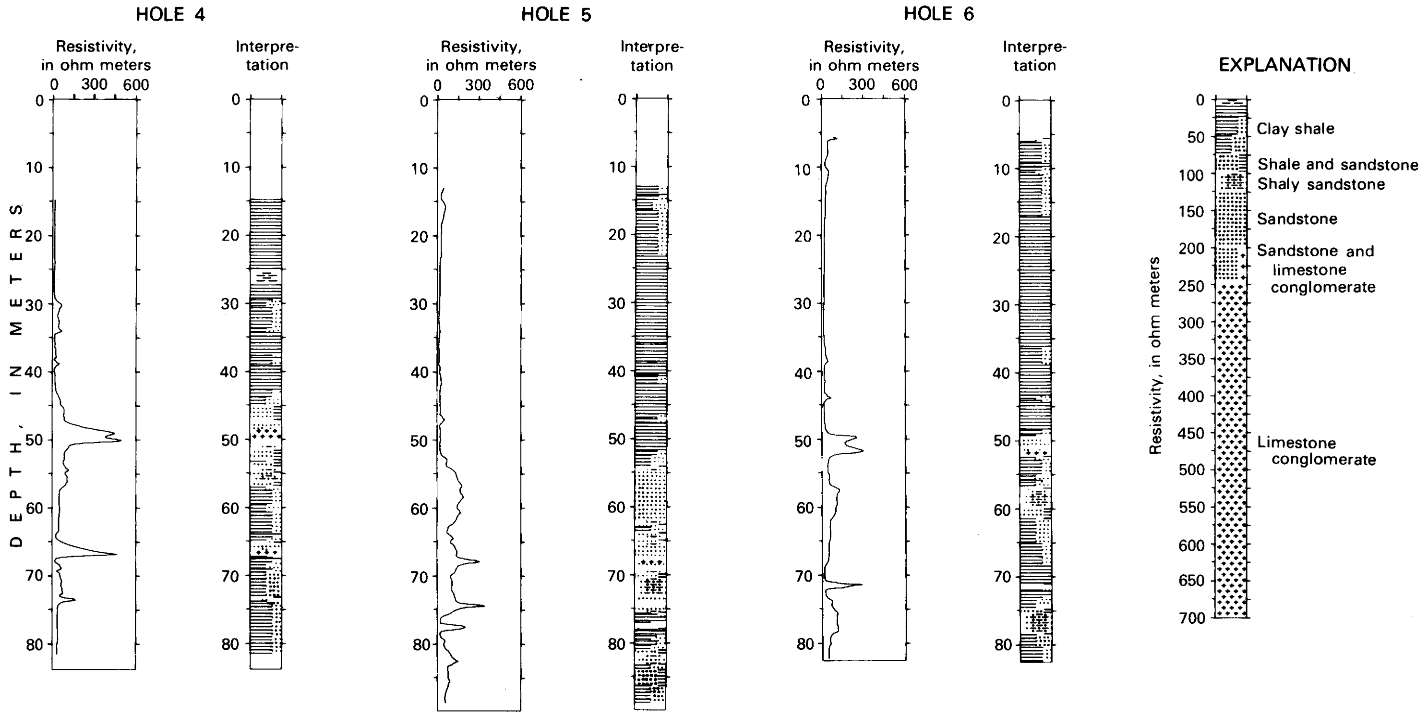

FIGURE 8.—Resistivity well logs and lithologic interpretation for 16-inch normal resistivity well logs for holes 4, 5, and 6. Lithologic symbols and corresponding velocity value ranges that were used for interpretation are shown in explanation.

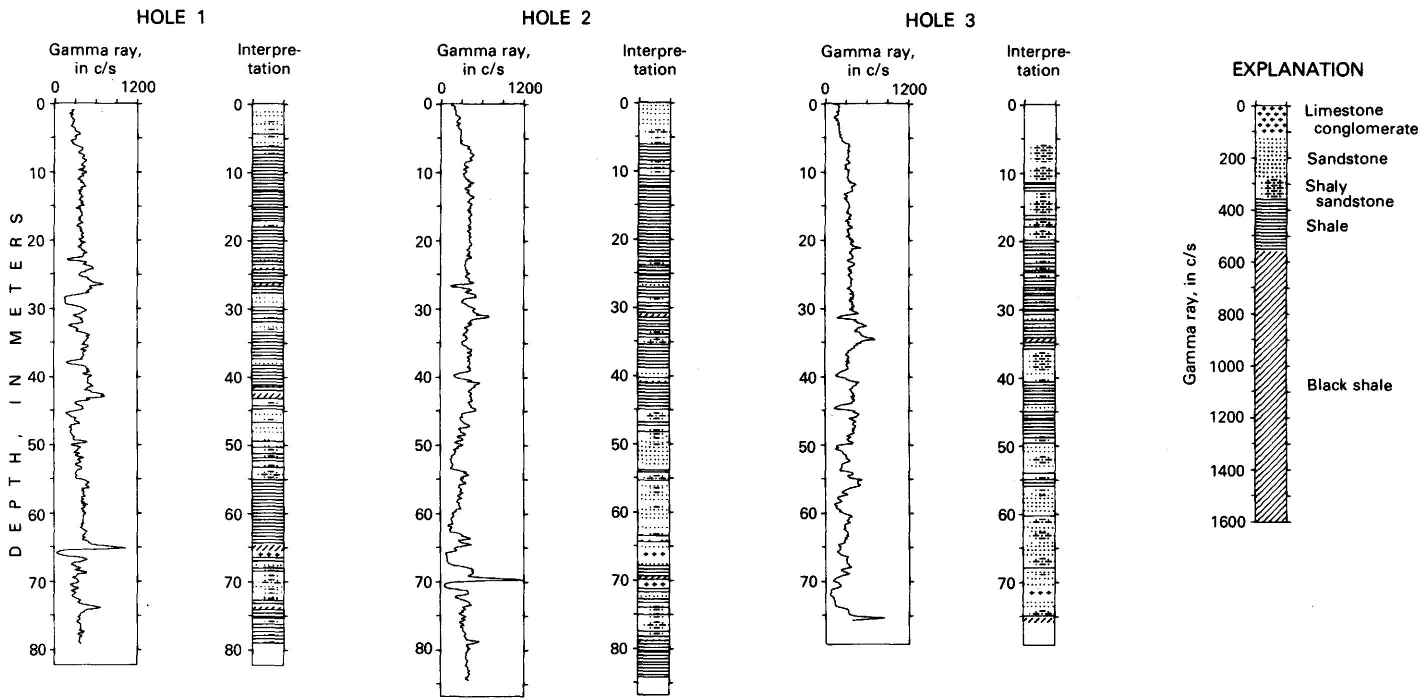

FIGURE 9.—Gamma-ray well logs and lithologic interpretation of gamma-ray well logs for holes 1, 2, and 3. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. c/s, counts per second.

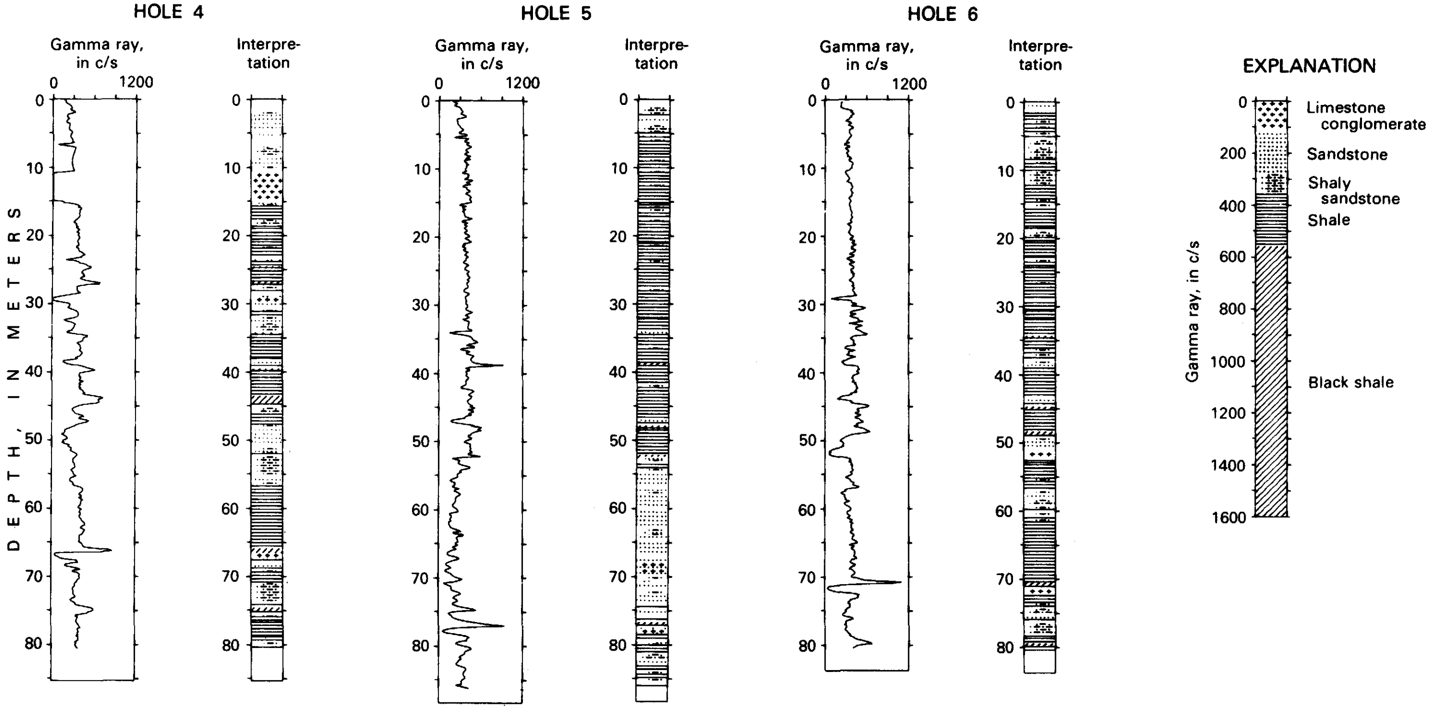

FIGURE 10.—Gamma-ray well logs and lithologic interpretation for gamma-ray well logs for holes 4, 5, and 6. Lithologic symbols and corresponding density value ranges that were used for interpretation are shown in explanation. c/s, counts per second.

a high gamma-ray count rate recorded for the overlying black shale. This is particularly true for the No. 10 coal. A pure limestone should be characterized by a near-zero gamma-ray response; limestones that are defined on the driller's logs have a low, but nonzero, gamma-ray count rate. Because the gamma-ray count rate is higher for the limestones than for the coal layers, the limestones must contain impurities.

The gamma-ray well-log response indicates the following concerning the shale content in the drill holes:

1. There is more shale above the No. 11 coal in drill holes 1, 2, and 5 than in drill holes 3, 4, and 6.
2. There is more shale present between the No. 10 and No. 11 coals in drill holes 2, 5, and 6 than is present in drill holes 1, 3, and 4.
3. There is more shale present between the No. 9 and No. 10 coals in drill holes 1, 4, and 6 than in drill holes 2, 3, and 5.

The gamma-ray response below the No. 11 coal is high in each of the drill holes. This high response is interpreted as being caused by black shale and is located at depths of 27, 31, 34, 28, 38, and 34 m, in drill holes 1, 2, 3, 4, 5, and 6, respectively. Other high gamma-ray response values are in each of the drill holes below the No. 10 coal and above the No. 9 coal. Only in the No. 9 coal is the black shale layer apparently located above the coal.

The induced-polarization well logs and interpretations are shown in figures 11 and 12 for each of the six drill holes. Of all of the well-log responses, the IP well log is the most difficult to interpret individually. The IP response in shallow sedimentary environments is primarily affected by the presence of pyrite and clays with a high cation-exchange capacity (montmorillonite or illite). Therefore, if the IP log is to be interpreted with minimum ambiguity, the relative sand and shale content must first be established. Later in this paper it will be shown that the IP well log can be used to determine certain mineralogic components when the IP log is interpreted simultaneously with other types of well-log responses.

The interpretation procedure that was found to work best for indi vidual geophysical well logs in the shallow sedimentary coal environment of this study includes the following:

1. Determination and depth correction of the coal seams on the driller's well logs with the density well logs.

2. Refinement of the determination of sandstone and shale shown on the driller's well logs with the neutron, gamma-ray, and 16-inch normal resistivity well logs.
3. Determination of the depths and relative amounts of limestone conglomerate from the resistivity well log.
4. Determination of the depth and relative amounts of black shale and fire clay from the gamma-ray and IP well logs.
5. Determination of pyrite-bearing zones within the sandstone and shale from the IP well logs.

The following conclusions can be drawn from the preceding interpretation of individual well logs in a coal depositional environment:

1. The density well log is the only well log that clearly and consistently defines the coal seams. However, organic black shale can yield a low-density response on the density well log and can be misinterpreted as a coal layer.
2. Limestone conglomerate produces a high neutron response and a high resistivity response. But a very thin limestone conglomerate will not be detected by the resistivity well log and a well-cemented sandstone (calcite or silica matrix cement) can also yield a high neutron and a high resistivity well-log response. Coal can also be misinterpreted as limestone conglomerate from the resistivity well log.
3. Shale can generally be identified from the gamma-ray well log. However, variations in the potassium content of the shale can lead to false interpretations of the amount of shale in the geologic section.

Comparison of the interpretations for the six different types of well logs reveals the inadequacy of individual geophysical well logs for interpreting lithology. (The lithologic well logs interpreted from the individual well logs are shown in Appendix A for each hole.) Different types of well logs often yield different geologic interpretations. To overcome this limitation, the interpreter must apply his knowledge of geology and of the physical properties of the rocks to all of the available information, and make a final composite interpretation of the well-log data. Thus, the interpreter must recognize well-log response values and combinations of well-log response values from the various well-log responses that are indicative of certain geologic media.

A refined interpretation for each well can be achieved by comparing the interpreted lithology and mineralogy for each individual type of well log (driller's, neutron, gamma-ray, resistivity, and IP well logs).

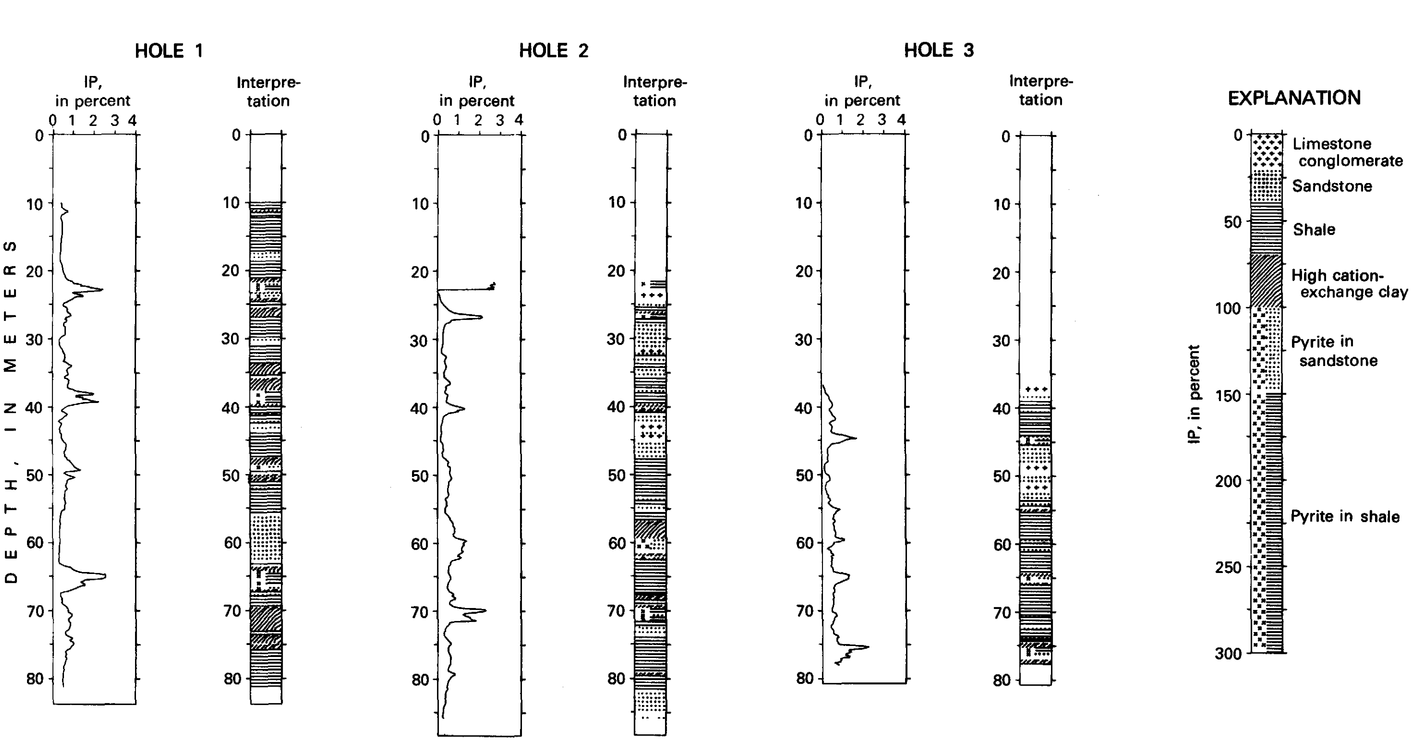

FIGURE 11.—Induced polarization (IP) well logs and lithologic interpretation for IP well logs for holes 1, 2, and 3. Lithologic symbols and corresponding IP value ranges that were used for interpretation are shown in explanation.

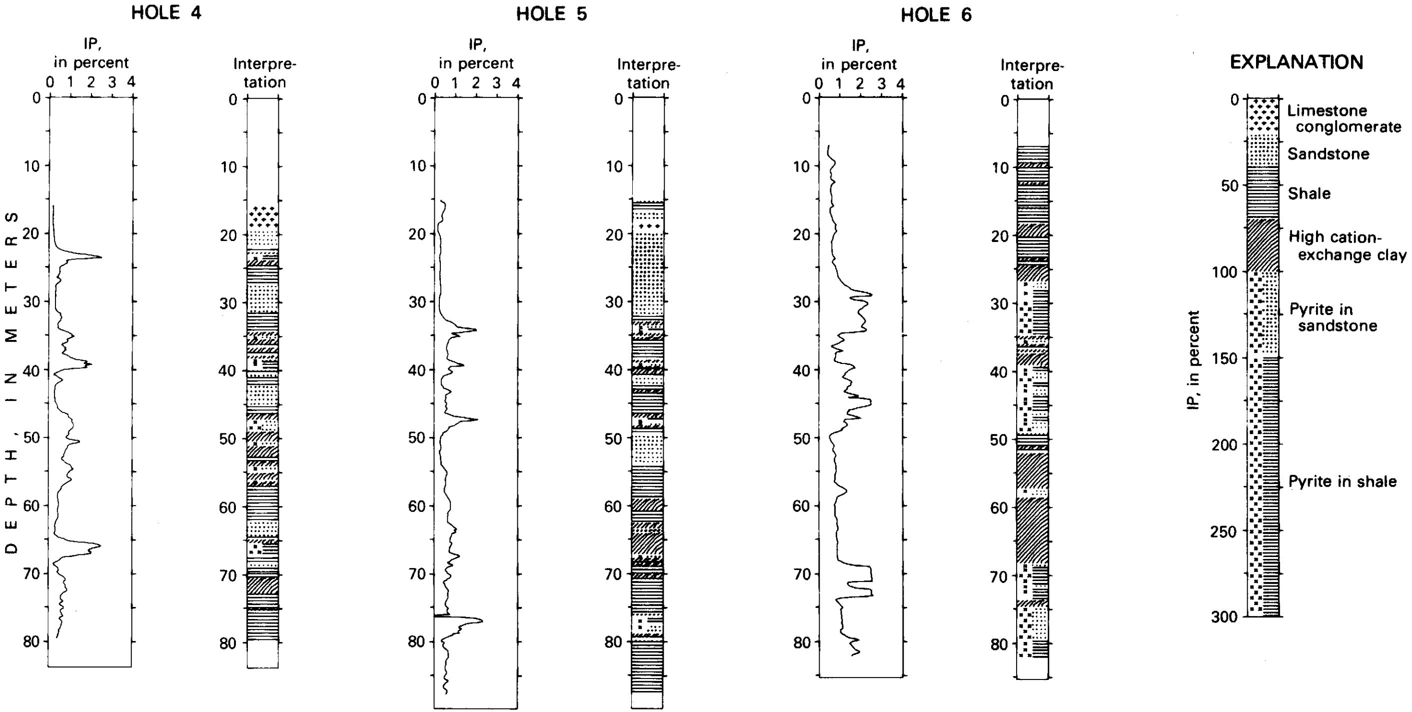

FIGURE 12.—Induced polarization (IP) well logs and lithologic interpretation for IP well logs for holes 4, 5, and 6. Lithologic symbols and corresponding IP value ranges that were used for interpretation are shown in explanation.

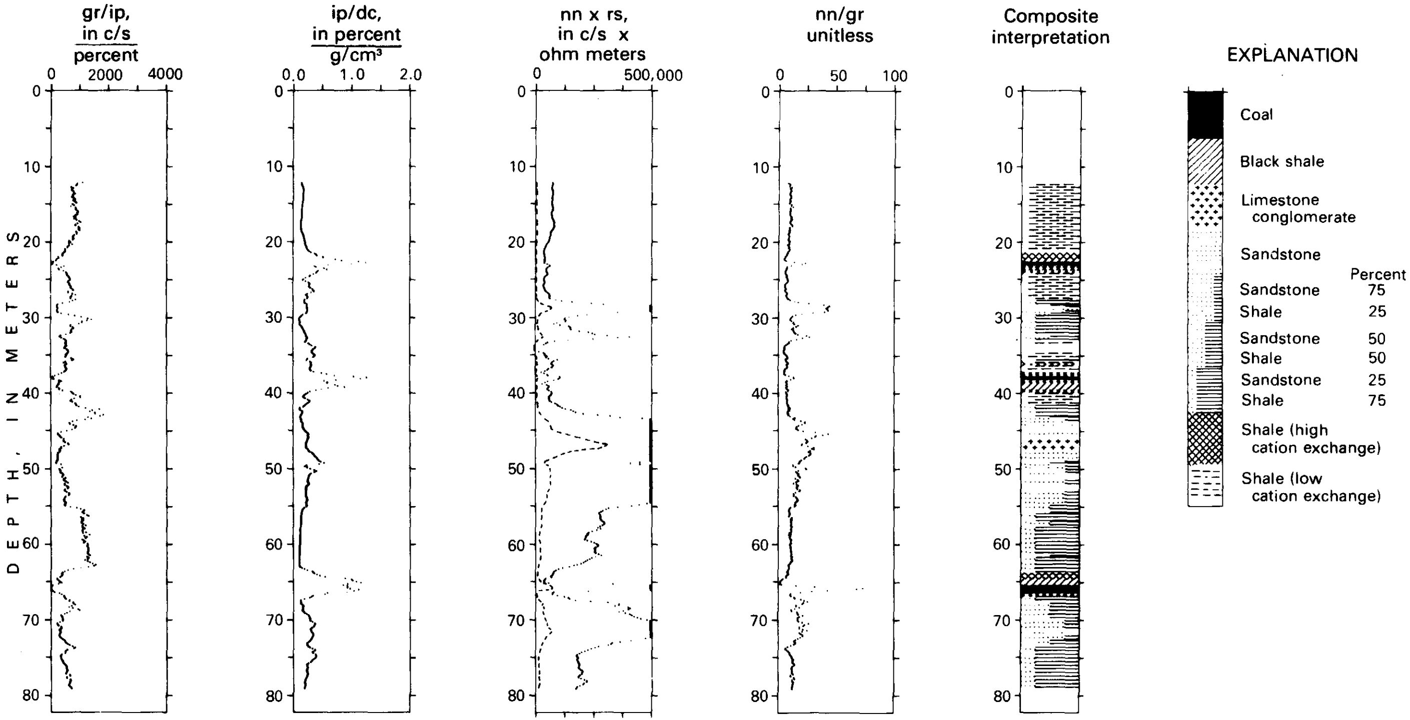

FIGURE 13.—Product and ratio well logs, and composite lithologic interpretation for drill hole 1. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s, counts per second; g/cm³, grams per cubic centimeter.

COMPOSITE WELL-LOG INTERPRETATION

To overcome the ambiguity associated with individual well-log interpretation, simultaneous interpretation of several combinations of individual well logs is advantageous. Composite interpretation utilizes combinations of physical properties that characterize a particular lithology or mineralogy, and can be implemented by choosing response values from two or more well logs and cross-plotting these response values. Good examples of cross-plotting have been given by Keys (1979). The primary disadvantage of this technique is the difficulty of relating cross-plotted values to depth intervals on the original well logs.

An alternative to the cross-plotting technique is to interpret product and ratio values of two or more well logs. Product values can be used for interpretation when the values of two or more well logs increase or decrease in response to a particular lithology. Ratio values can be used when the values of one well log increase and the values of another well log decrease in response to the physical properties associated with a particular lithology. The interpretation of product and ratio well logs can be facilitated by the use of a digital computer.

Figure 13 illustrates the use of product and ratio well logs for interpreting the lithology for drill hole 1. Product and ratio well logs for holes 2 through 6 are shown in "Appendix B." The value ranges and order of interpretation that were used to obtain the final lithologic interpretation are listed in table 2.

The order of interpretation is important because once a lithology has been assigned to a depth interval, the computer program does not consider that depth interval in future lithologic assignments. Lithologies that are the easiest to identify must be interpreted first.

The low gamma-ray, low-density, and high IP response of coal enables the effective use of the gamma-ray/induced polarization and induced polarization/density logs for identifying coal and black shale. The high IP response is caused by the presence of pyrite in the strong reducing environment associated with coal and black shale. Limestone conglomerate and sandstone both have high neutron responses and low gamma-ray responses. However, limestone conglomerate has a higher neutron-resistivity product-log response than does sandstone. These responses are due to the fact that although both limestone conglomerate and sandstone contain relatively low concentrations of gamma-ray emitting minerals (such as kaolinite), they both have low porosities, with the high degree of cementation in limestone conglomerate giving it a slightly higher neutron-to-resistivity product log response than sandstone.

Other than coal, black shale, and limestone conglomerate, the sorting of detrital sedimentary rocks varies greatly, ranging from shale

TABLE 2.—*Composite well-log interpretation for individual and combined lithologies using product and ratio well logs*

[The neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. gr/ip = counts per second/percent; ip/dc = percent/grams per cubic centimeter; nn × res = counts per second × ohm meters; nn/gr is unitless. sh, shale; ls cong, limestone conglomerate; ss, sandstone; pct, percent]

Order of interpretation	Lithology	Product or ratio well log	Value range of product or ratio well log
1	Coal	gr/ip ip/dc	0-130 0.58-1.5
2	Black sh	gr/ip ip/dc	130-500 0.58-1.5
3	ls cong	nn x res nn/gr	2,000,000-5,000,000 20-5,000
4	ss	nn x res nn/gr	675,000-2,000,000 20-5,000
5	ss (75 pct), sh (25 pct)	nn x res	478,000-675,000
6	ss (50 pct), sh (50 pct)	nn x res	285,000-478,000
7	ss (25 pct), sh (75 pct)	nn x res	88,000-285,000
8	sh (high-cation)	nn x res gr/ip	0-88,000 0-500
9	sh (low-cation)	nn x res gr/ip	0-88,000 500-5,000

to shaly or silty sandstone. The relative amount of shale in a sandstone can be roughly estimated by the neutron-resistivity product log. The lithology is interpreted as shale when the values on the neutron-resistivity product log are low. Varying amounts of different types of clay (high- and low-potassium clay) make it impossible to use the gamma-ray log for interpreting the amount of shale in a sandy shale. When the rock consists only of shale, the ratio of the gamma-ray well log to the induced-polarization well log can be used to determine the type of clay in the shale. High cation-exchange capacity clay minerals (illite and montmorillonite) have low gamma-ray responses (low potassium-40 content), and low cation-exchange capacity clay minerals (such as kaolinite) have high gamma-ray response values.

The composite lithologic well logs for holes 1 through 6 are shown in figure 14. Some lithologic details indicated by these logs include the following:

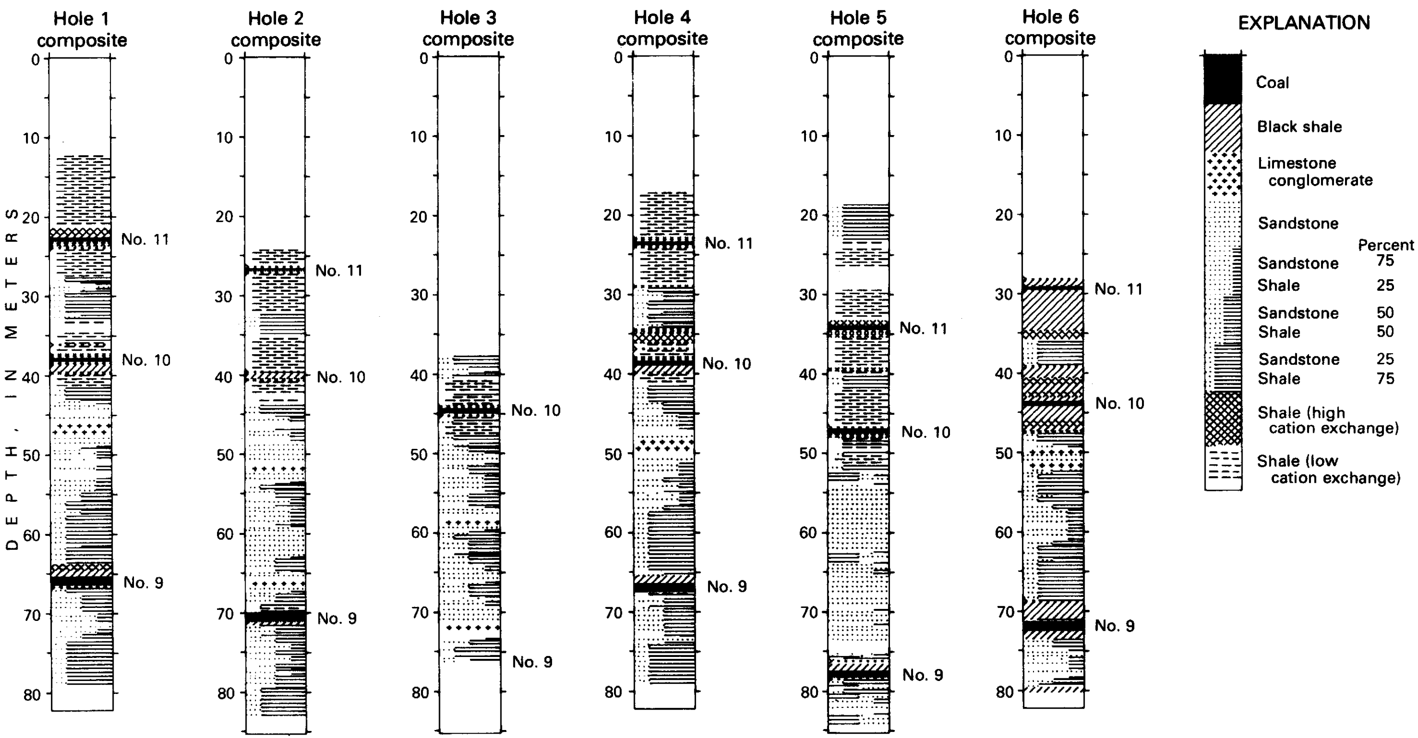

FIGURE 14.—Composite lithologic interpretation for drill holes 1 through 6.

1. There is a dominance of high-potassium clay above the No. 11 coal.
2. With the exception of hole 6, there is a dominance of high-potassium clay between the No. 11 and No. 10 coals.
3. There are two limestone conglomerates in drill holes 2 and 3 between the No. 9 and No. 10 coals, but there is only one limestone conglomerate in drill holes 1, 4, and 6 between the No. 9 and No. 10 coals.
4. Sandstone is the dominant lithology between the No. 9 and No. 10 coals in drill hole 5.

The composite well logs indicate considerable lateral facies changes over a small area in the interval between the No. 9 and No. 10 coals. With the exception of hole 5, there is an inverse correlation between the presence of limestone conglomerates near a drill hole and the amount of shale in the geologic section. There are two cycles of fining-upward sedimentation recorded in drill holes 2 and 3. Upward fining generally characterizes the stratigraphic interval between the No. 9 and No. 10 coals in drill holes 1, 4, and 6, whereas the same interval in drill hole 5 is a relatively uniform sandstone.

The lateral facies changes occur in intervals of nearly uniform thickness between drill holes. This fact implies that the area was slowly subsiding during the time interval of deposition of the sediments between the No. 9 and No. 10 coals. A stream channel was cut into the sediments near drill holes 2 and 3 shortly after the No. 9 coal was deposited. Strata penetrated by drill holes 1, 4, and 6 indicate similar steady deposition above the No. 9 coal. Another channel was cut later (as indicated by the limestone conglomerate) near all of the drill holes except drill hole 5.

CONCLUSIONS

The interpretation of lithologies from geophysical well logs is necessarily subjective. This is particularly true when individual types of geophysical well logs are interpreted without regard for the response of other types of well logs. Adequate interpretations must rely on combinations of well-log data that best characterize each individual lithology. The final interpretation must also agree with the available geologic data (that is, core descriptions, driller's logs). In fact, a good geophysical well-log interpretation is one that adds detailed information to the geologic information obtained from rock samples taken from the well. The study presented in this paper illustrates that only a limited lithologic interpretation can be made when only one type of well log is used for the interpretation. A more consistent and accurate interpretation of the geologic section can be made by interpreting the product and ratio values of more than one type of well log.

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APPENDIX A

Lithology interpreted from the geophysical well logs for each hole

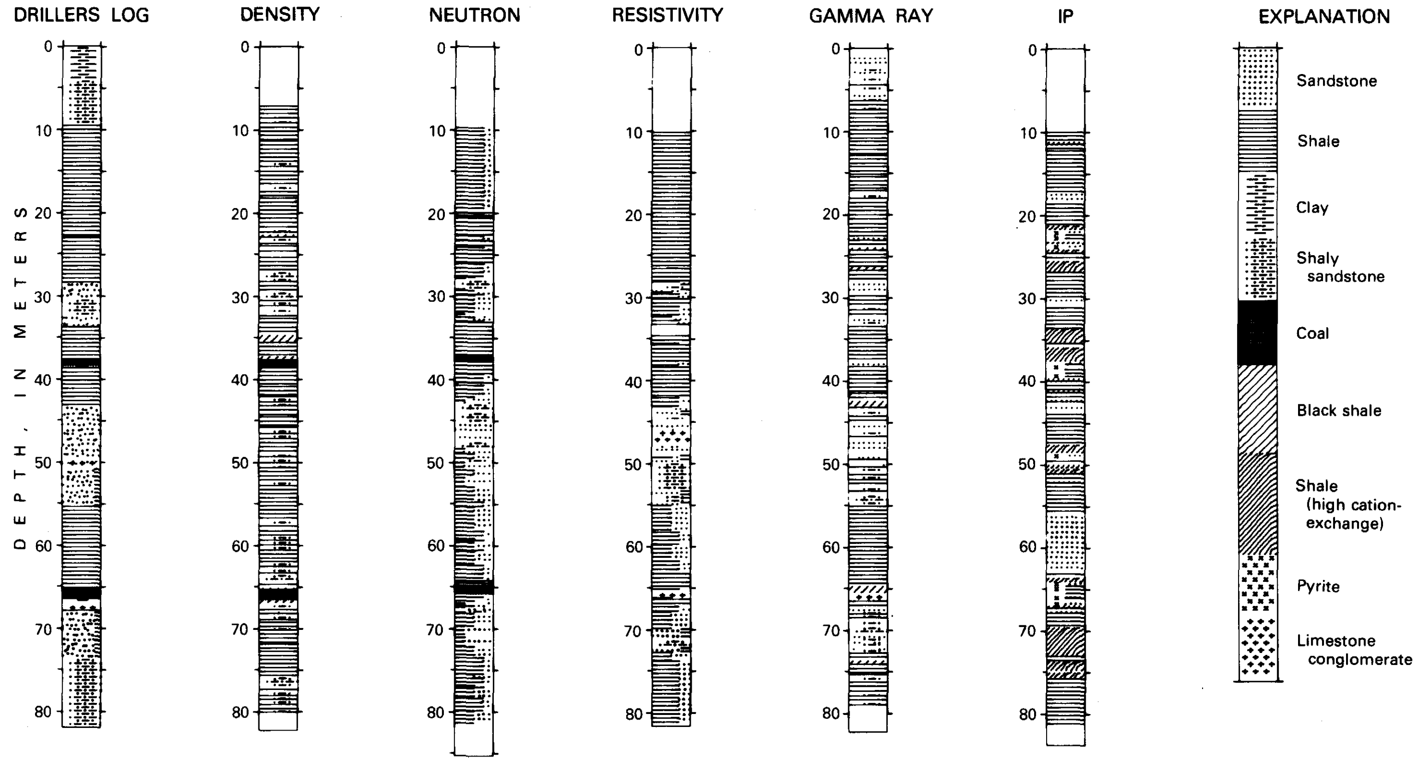

FIGURE A1.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 1.

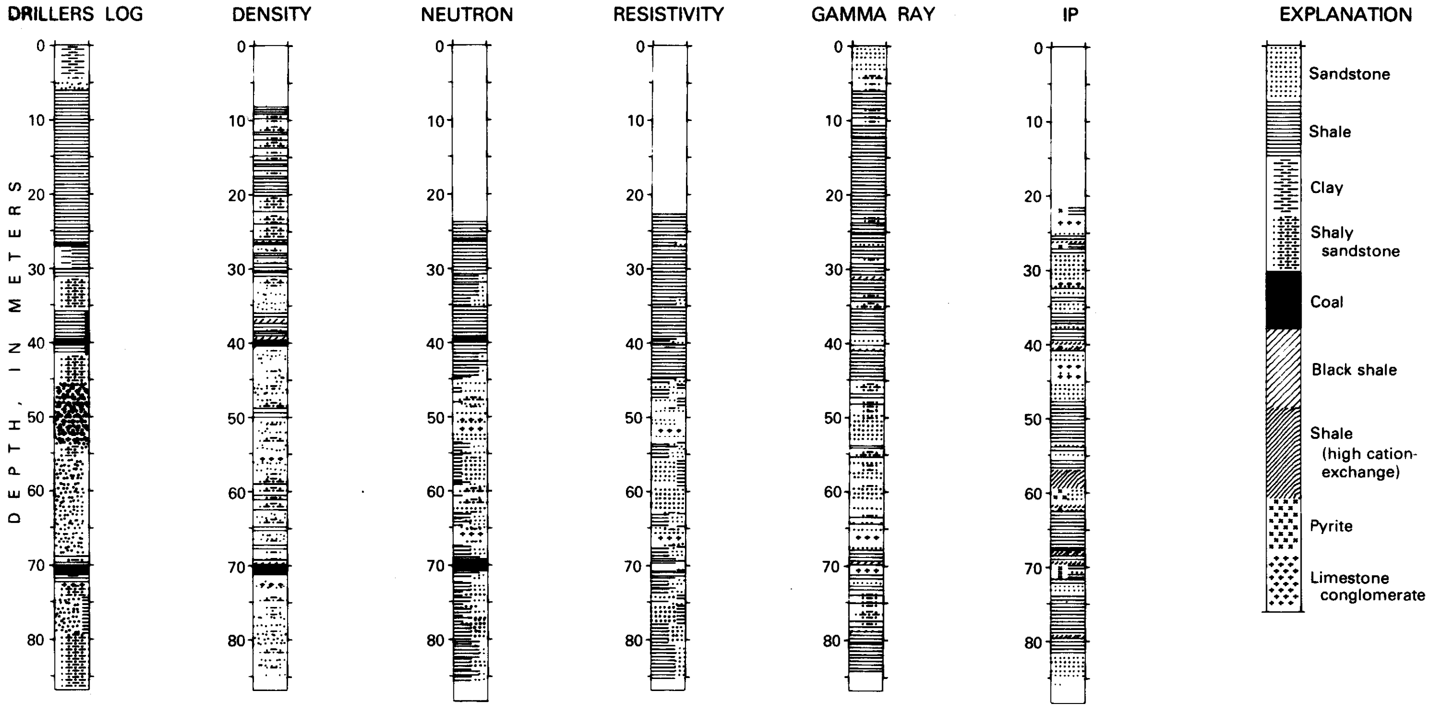

FIGURE A2.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 2.

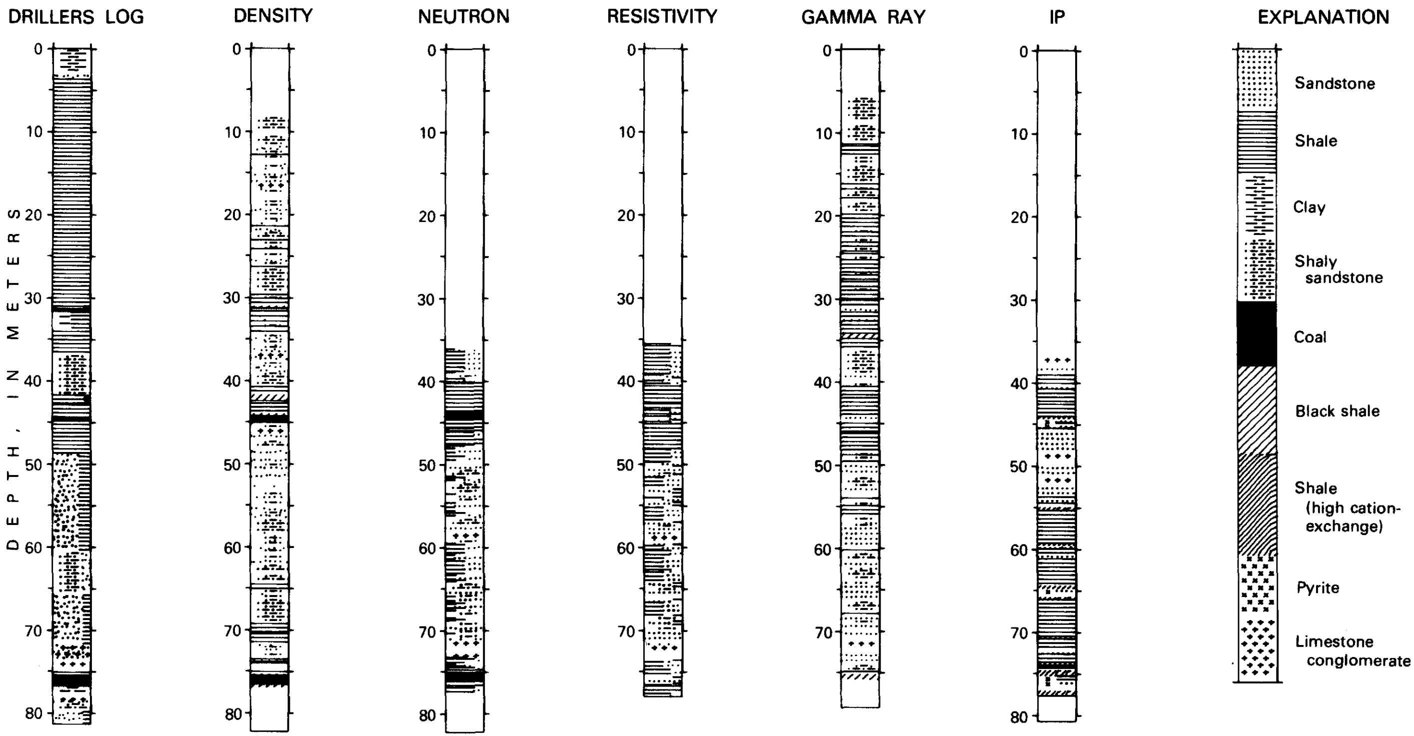

FIGURE A3.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 3.

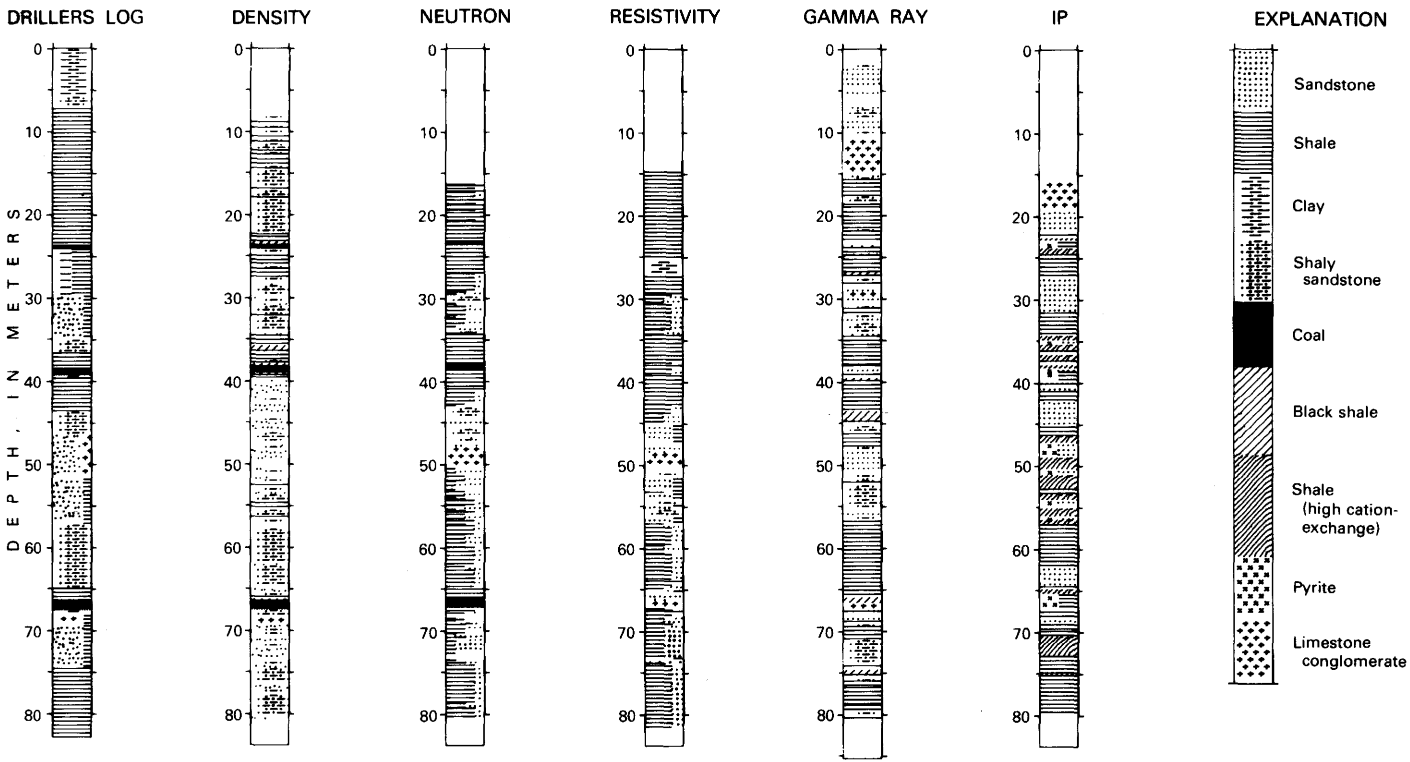

FIGURE A4.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 4.

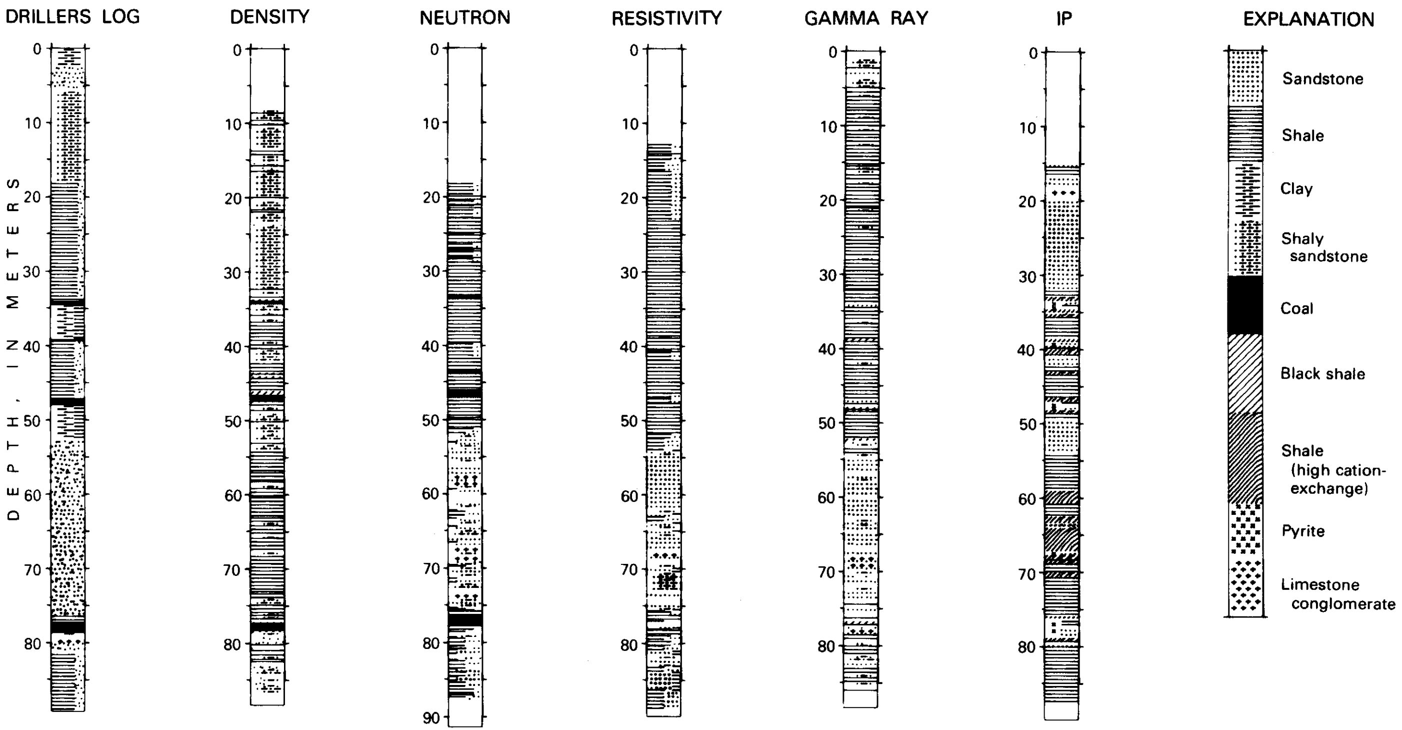

FIGURE A5.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 5.

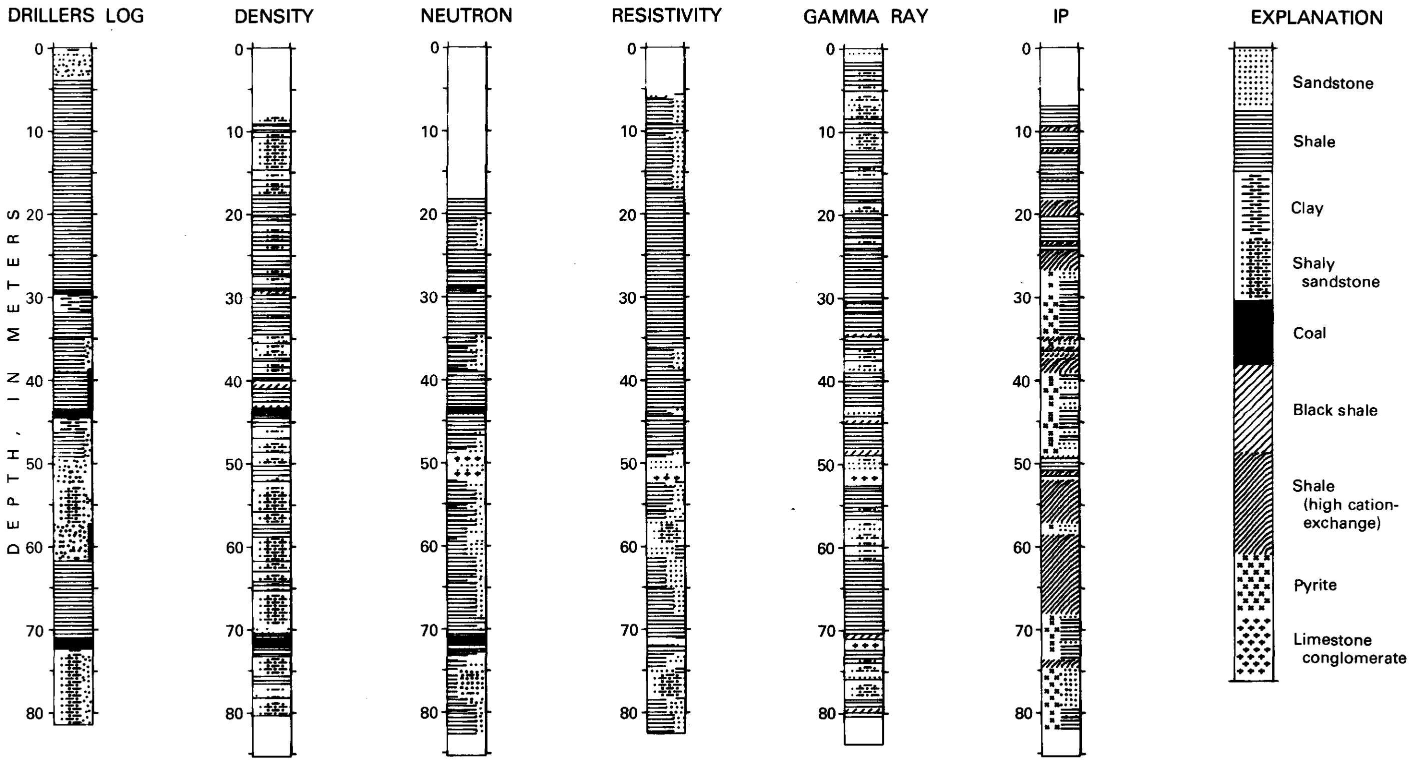

FIGURE A6.—Lithology interpreted from density, neutron, resistivity, gamma-ray, and induced polarization (IP) well logs for drill hole 6.

APPENDIX B

Product and ratio well logs, and composite lithologic interpretation for drill holes 2 through 6

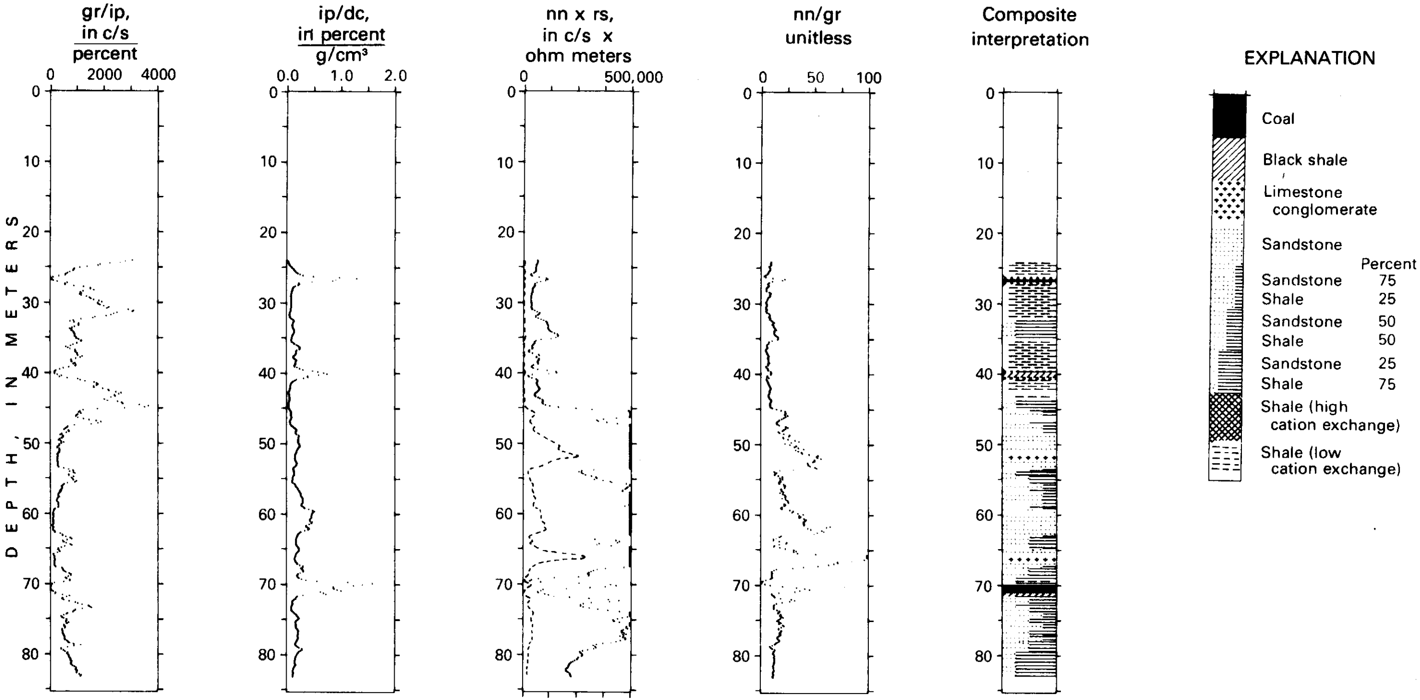

FIGURE B1.—Product and ratio well logs, and composite lithologic interpretation for drill hole 2. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s, counts per second; g/cm³, grams per cubic centimeter.

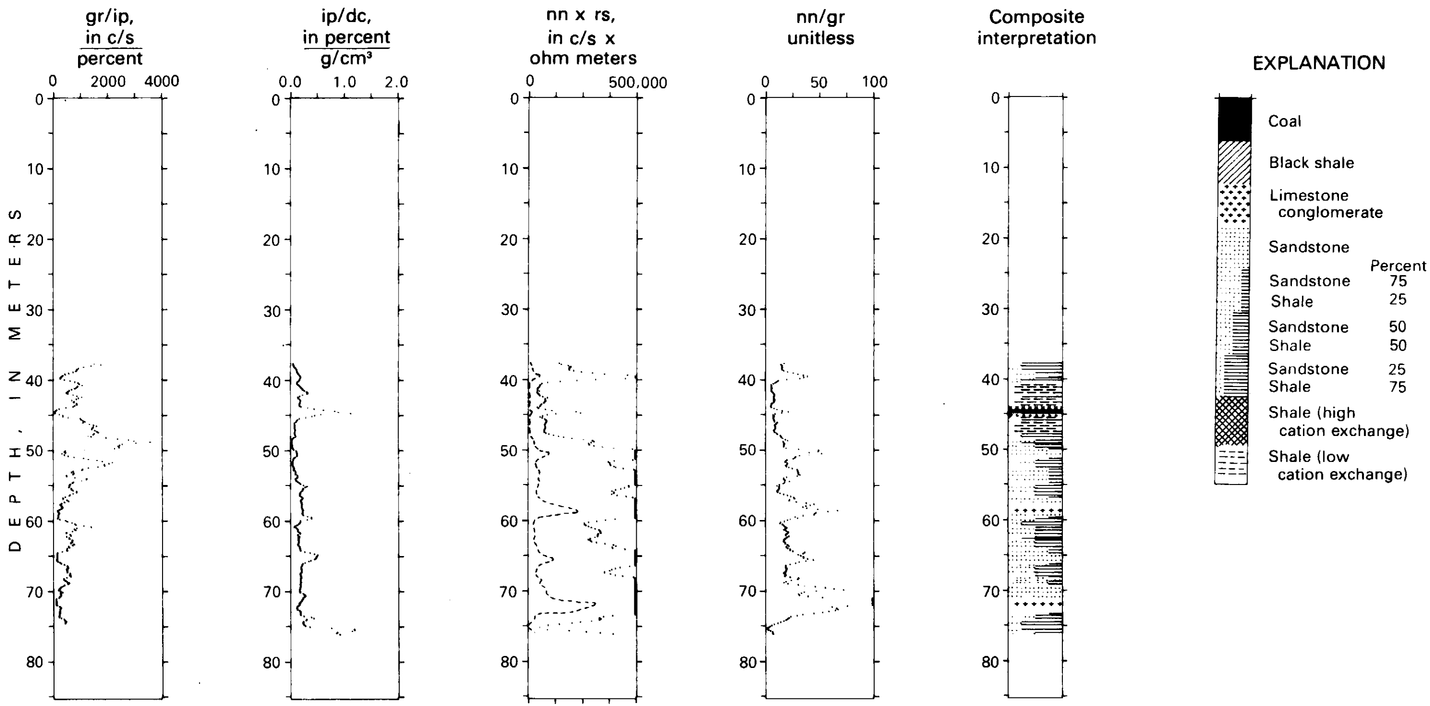

FIGURE B2.—Product and ratio well logs, and composite lithologic interpretation for drill hole 3. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s, counts per second, g/cm³, grams per cubic centimeter.

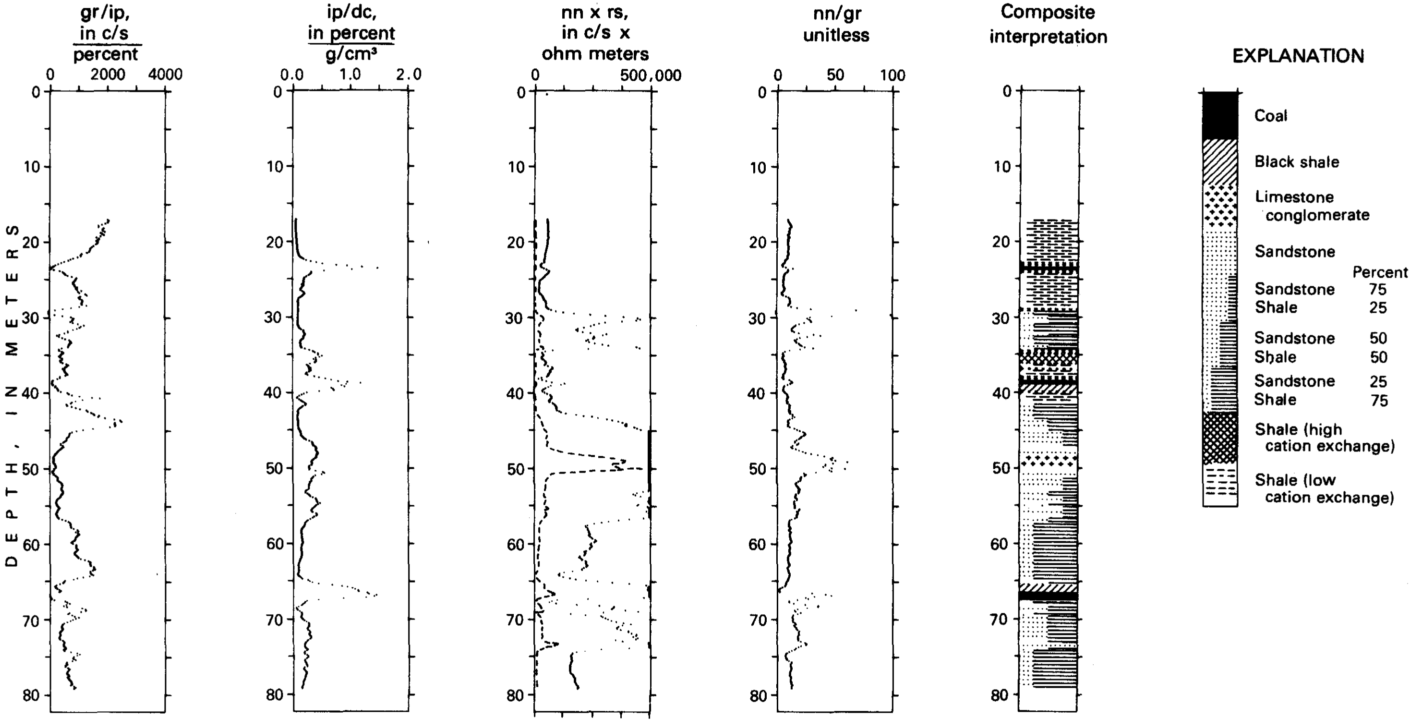

FIGURE B3.—Product and ratio well logs, and composite lithologic interpretation for drill hole 4. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s, counts per second, g/cm³, grams per cubic centimeter.

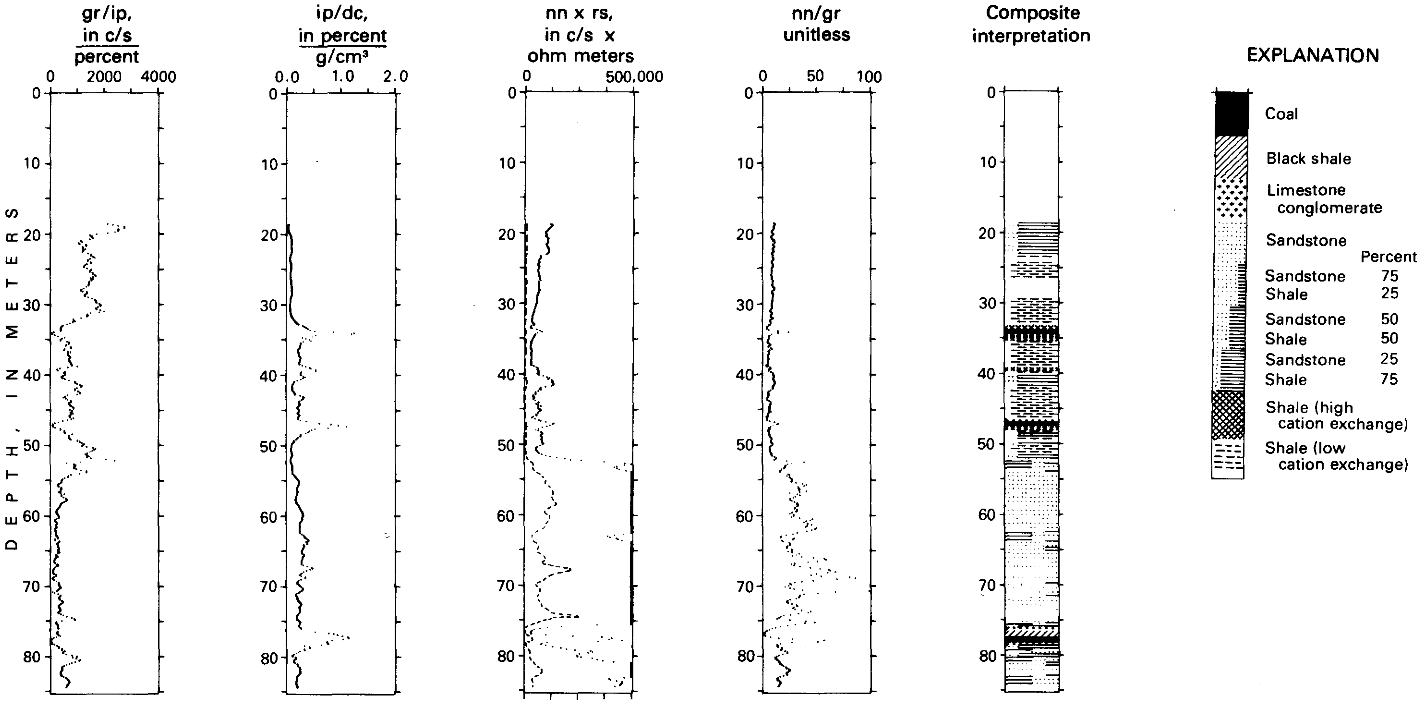

FIGURE B4.—Product and ratio well logs, and composite lithologic interpretation for drill hole 5. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s counts per second, g/cm³, grams per cubic centimeter.

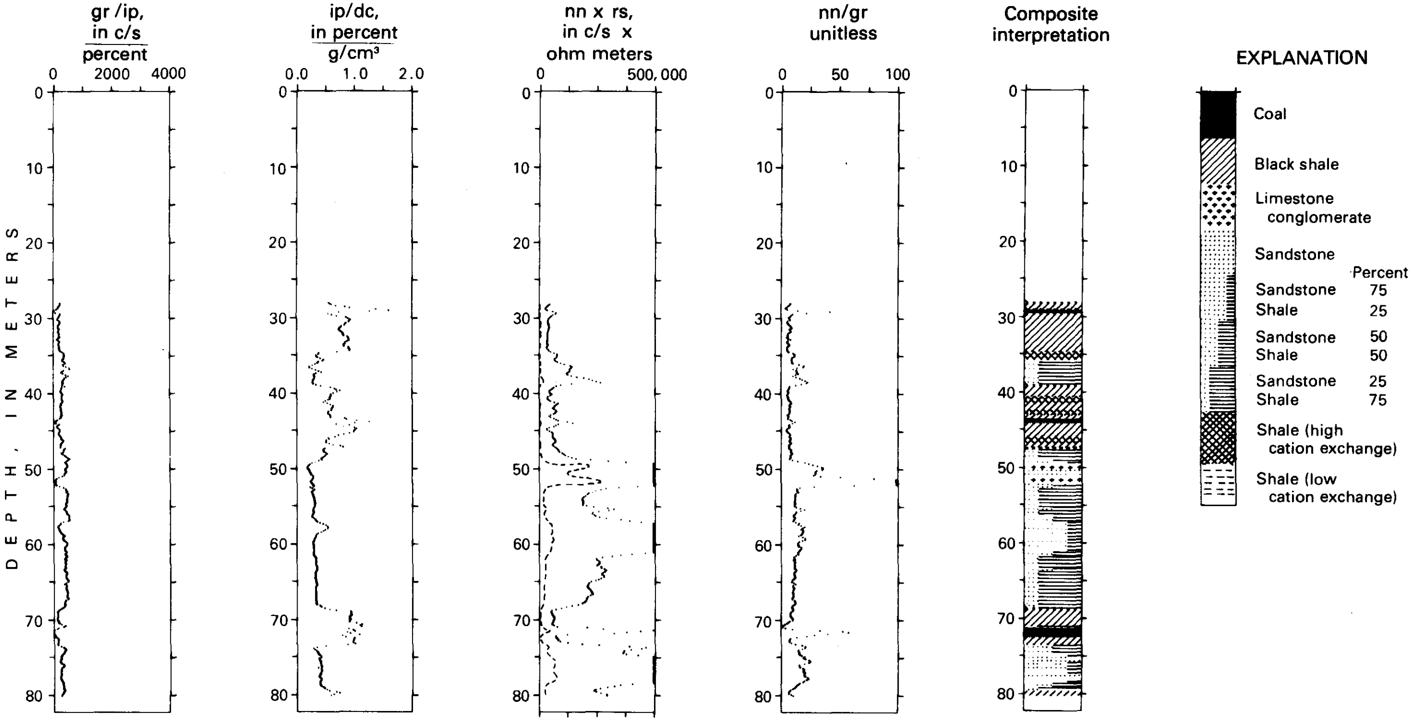

FIGURE B5.—Product and ratio well logs, and composite lithologic interpretation for drill hole 6. Neutron, induced polarization, resistivity, density, and gamma-ray well logs are represented by the symbols nn, ip, res, dc, and gr, respectively. c/s counts per second, g/cm³, grams per cubic centimeter.

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