Use of Surface and Borehole Geophysics to Delineate the Glacial-Drift Stratigraphy of Northeastern St. Joseph County, Indiana

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED GEOPHYSICAL AND WATER-QUALITY UNITS

Multiply	By	To obtain
kilometer (km)	0.6214	mile
meter (m)	39.37	inches
meter (m)	3.281	foot
liters per second (L/s)	5.69	gallons per minute

Temperature in degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = (1.8 \times °C) + 32$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Datum Sea Level of 1929.

The following terms and abbreviations also are used in this report:

µS/cm	microSiemens per centimeter at 25° C
Ωm	ohm meter

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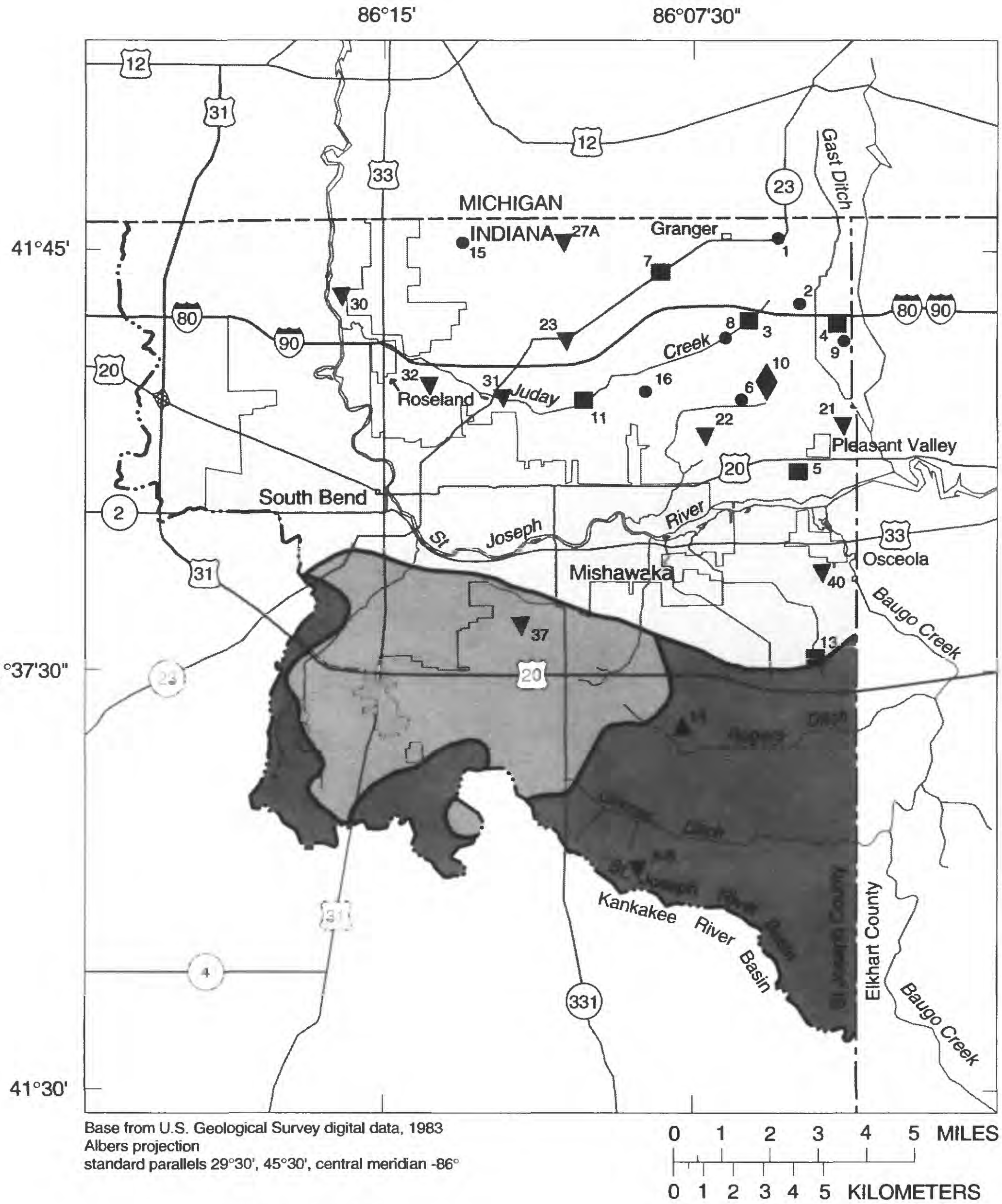
Abstract

Inverse models of direct current electrical-resistivity sounding data and normal-resistivity and natural-gamma logs were used to assist delineation of the glacial-drift stratigraphy in a 580-square-kilometer area of northeastern St. Joseph County, Indiana. Unconsolidated deposits in the study area are composed of glacial-drift, including outwash, till, and lacustrine sediments; thicknesses range from about 15 to more than 70 meters. The glacial outwash deposits are mostly composed of sand and gravel and are the primary source of drinking water to northeastern St. Joseph County. The glacial till and glacio-lacustrine deposits contain a larger fraction of clay than the outwash deposits and may retard ground-water flow between shallow and deeper sand and gravel aquifers.

Results of the geophysical measurements collected during this study indicate that glacial-drift deposits in the area north and east of the St. Joseph River are mostly composed of sand and gravel with interlayered clay-rich deposits that are laterally discontinuous. In the area south of the St. Joseph River, the thickness of sand and gravel deposits diminishes, and clay-rich deposits dominate the stratigraphy. The presence of an electrically conductive bedrock, the Ellsworth Shale, beneath the glacial-drift deposits is identified in inverse models of direct current electrical-resistivity sounding data.

INTRODUCTION

A cooperative agreement between the U.S. Geological Survey (USGS) and the Indiana Department of Natural Resources (IDNR) identified a 580-km^2 area in northeastern St. Joseph County, Ind., where data were insufficient to assess the availability and quality of ground water under present and future withdrawal conditions (fig. 1). The stratigraphy and thickness of glacial drift were identified as two important factors that affect the distribution and quality of ground water in St. Joseph County; however, data describing the subsurface geology of northeastern St. Joseph County generally are limited to records of shallow water wells (less than 15 m depth) or hydrocarbon-exploration drill holes (greater than 70 m depth). The St. Joseph Aquifer System, located in the northern part of the study area, is identified by the U.S. Environmental Protection Agency (USEPA) as Indiana's only sole-source aquifer (Anna Miller, U.S. Environmental Protection Agency, oral commun., 1995).



EXPLANATION

- St.Joseph Aquifer System
- Hilltop Aquifer System
- Nappanee Aquifer System
- St. Joseph River drainage divide
- ●16 Direct current electrical-resistivity sounding, normal-resistivity and natural-gamma logs, and site number
- ▲14 Direct current electrical-resistivity sounding, natural-gamma logs, and site number
- ▼22 Natural-gamma logs and site number
- ■11 Direct current electrical-resistivity sounding and site number
- ◆10 Direct current electrical-resistivity sounding, normal resistivity logs, and site number

Figure 1. Location of study area, distribution of aquifer types, and geophysical data-collection sites.

Purpose and Scope

This report describes the analysis of borehole logs of normal-resistivity and natural-gamma radiation and inverse models of direct current electrical-sounding data. Direct current electrical-resistivity soundings are a means of quickly and economically examining the total thickness of unconsolidated deposits without the expense of drilling. Where conditions preclude the use of direct current electrical-resistivity measurements and where installation of boreholes is necessary, borehole logs of normal-resistivity and natural-gamma radiation provide hydrogeological information that cannot be deduced from well-drillers' records alone. The geophysical information interpreted in this report improves the geological understanding of the glacial-drift stratigraphy of northeastern St. Joseph County and establishes a basis for interpreting information related to other on-going studies of ground-water quality, ground-water flow, and ground-water availability.

Sites selected for direct current electrical-resistivity soundings targeted areas where stratigraphic information to bedrock was not available, access was possible and permitted, and electrical interferences were limited. In August 1990, direct current electrical-resistivity soundings were made by the USGS at 15 sites. Inverse models of the sounding data were computed, and profiles of the geoelectric stratigraphy were created.

Observations wells were installed during the period December 1990 through October 1991. Observation wells initially were installed at sites where direct current electrical-resistivity soundings had been made. Borehole logs and inverse models of the direct current electrical-resistivity sounding data collected at the same site were coevaluated. Comparisons indicated that the surface geophysical measurements provided some useful information; however, interpretive capabilities of the inverse models were lacking in some respects.

Observation wells eventually were installed at 36 sites in the study area. Borehole logs were measured in observation wells at 19 sites during the period September 1991 through December 1991. Normal-resistivity logs were measured in eight wells at or near the sites of direct current electrical-resistivity soundings. Natural-gamma logs were measured at 18 sites, including 8 of the 15 sites where direct current electrical-resistivity soundings were made and 7 of the 8 sites where normal-resistivity logs were measured. Normal-resistivity logs were collected in mud-filled, uncased boreholes prior to observation-well installation, and natural-gamma logs were measured in completed wells.

Acknowledgments

The authors received assistance from many people during this study. The Indiana Department of Natural Resources provided data and vital input for the study. The citizens and officials of South Bend, Mishawaka, and north-eastern St. Joseph County allowed access to their properties for well installation and data collection.

HYDROGEOLOGIC SETTING

Precipitation falling on the study area each year is about 0.95 m. About 0.64 m of water evaporates or is transpired by plants into the atmosphere (Klaer and Stallman, 1948). Of the remaining 0.31 m of precipitation, 0.12 m is storm runoff and 0.19 m recharges the aquifer system (Klaer and Stallman, 1948). Recharge to the aquifer is withdrawn eventually for domestic, commercial, industrial, and agricultural use, or it is discharged as base flow to the St. Joseph River and tributaries.

Surface drainage in the study area flows primarily to the St. Joseph River. Tributaries to the St. Joseph River in northeastern St. Joseph County include Juday Creek, Willow Creek, and several constructed ditches (fig. 1). Cobus Creek and Baugo Creek are St. Joseph River tributaries located immediately east of the St. Joseph County-Elkhart County political boundary. West of the

St. Joseph River drainage divide, which marks the western boundary of the study area, are several natural lakes, including Mud Lake, Twin Lakes, North and South Chain Lakes, and South Clear Lake.

Ground water generally flows towards the St. Joseph River but may be locally affected by the presence of creeks, ditches, pumping, and geologic heterogeneity. Depth to ground water ranges from less than 1.5 m in low-lying outwash deposits of the St. Joseph Aquifer System to more than 25 m in topographically elevated areas of the St. Joseph Aquifer System and in the clay-rich deposits of the Nappanee and Hilltop Aquifer Systems (fig. 1).

General Geology

The unconsolidated geology in the study area is composed of Wisconsin Age glacial-drift deposits, including outwash-plain and till-plain features, and lacustrine sediments. These deposits form the three aquifer systems in northeastern St. Joseph County—the St. Joseph Aquifer System, the Hilltop Aquifer System, and the Nappanee Aquifer System (fig. 1).

Glacial-drift deposits in the northern half of the study area are designated by IDNR as the St. Joseph Aquifer System (fig. 1). The St. Joseph Aquifer System has a total areal extent of 987 km^2, including parts of six counties in north-central Indiana and eight counties in southeastern Michigan (Beaty, 1987).

The Hilltop Aquifer System is located in the southwestern part of the study area. Total extent of the Hilltop Aquifer System is 91 km^2, most of which lies within the study area.

The Nappanee Aquifer System primarily is located in the southeastern part of the study area. The Nappanee Aquifer System includes 624 km^2 in several north-central Indiana counties. A 25- to 60-m escarpment delineates the boundary between the topographically higher Nappanee and Hilltop Aquifer Systems and the St. Joseph Aquifer System.

Glacial-drift deposits throughout the study area are underlain by the Devonian-Mississippian Ellsworth Shale. The Ellsworth Shale is characterized as "alternating gray-green and black in bottom part; grayish-green and containing some limestone and dolomite lenses in top part" (Beaty, 1987; p.108). Thickness of the Ellsworth Shale is 12 to 60 m (Beaty, 1987).

Aquifer Properties

The St. Joseph Aquifer System is primarily glacial-outwash deposits that are composed mostly of sand and gravel. The outwash deposits are continuous and productive, supplying water for most high-capacity well fields in the study area. Ground-water yields in the St. Joseph Aquifer System range from 1,500 to 23,500 L/s (Beaty, 1987). Throughout much of the St. Joseph Aquifer System, the outwash deposits are separated by clay-rich deposits composed of glacial-till or glacio-lacustrine sediments (Beaty, 1987). The clay-rich deposits are discontinuous, with thicknesses generally ranging from 0 to 30 m. In areas where the clay-rich deposits are particularly thick or clay rich, vertical ground-water flow between the deep and shallow outwash aquifers may be inhibited. Because ground-water from deeper sand and gravel deposits has generally higher concentrations of dissolved constituents than water in the shallow aquifers (J.M. Fenelon, U.S. Geological Survey, oral commun., 1994), the clay-rich deposits may protect shallow ground-water users from water having less desirable qualities.

The Nappanee Aquifer System is characterized by thin sand and gravel units (1–3 m thick) contained within relatively thick sequences of glacial till. Areal extent of aquifers in the system is limited to less than 5.2 km^2 (Beaty, 1987). The range of ground-water yields in the Nappanee Aquifer System (400–9,500 L/s) is generally much less than the St. Joseph Aquifer System. One borehole drilled into the Nappanee Aquifer System as part of this project identified no suitable depth for screening a well in the 40 m of unconsolidated material that was penetrated.

The Hilltop Aquifer System is described as sand and gravel deposits overlain by 1.5 to 15 m of till (Beaty, 1987). Ground-water yields in the Hilltop Aquifer System (290–1,420 L/s) are less than the St. Joseph Aquifer System and the Nappanee Aquifer System (Beaty, 1987). Production wells in the Nappanee and Hilltop Aquifer Systems are not common.

Geophysical Properties of Bedrock and Glacial Drift

Electrical resistivity and natural-gamma radiation are two geophysical properties that commonly are measured in boreholes. Electrical resistivity of the subsurface also can be measured nonintrusively by inducing electrical current into surficial materials and monitoring the returned signal at a specified distance; the result is commonly known as a direct current electrical-resistivity sounding. Ideally, surface- and borehole-resistivity methods should reflect similar stratigraphy and electrical properties of the geologic units. Complex mathematical processing of data and spatial averaging of measured values, however, can be sources of apparent disagreement between borehole logs and inverse models of direct current electrical-resistivity sounding data.

The electrical resistivity of geologic materials is determined by several factors, including the degree of saturation, the conductivity of pore fluids, and the amount of conductive minerals (such as clay minerals and sulfides) that are present in the rock or sediment matrix. An increase in the magnitude of any of these factors results in decreased electrical resistance. In natural settings, where the geologic materials are water-saturated and the specific conductance of pore fluids is constant, electrical resistance is related directly to conductive mineral content—clay being the most conductive mineral in glacial-drift settings. The mean difference between specific conductance or pore fluids in deep and shallow wells at eight clustered-well sites in the study area was only 115 µS/cm.

In geophysical studies of similar glacial-drift deposits in Michigan, electrical-resistivity values of sand and gravel ranged from 120 to 420 Ωm and ranged from 30 to 75 Ωm for clay-rich deposits (Westjohn and Carter, 1989). Glacial-drift deposits in Michigan and Indiana were derived from similar parent rock, deposited through similar geologic processes, and should have electrical properties that are approximately the same. Electrical-resistivity data for bedrock in southeastern Michigan, where the Ellsworth Shale also underlies the glacial drift, show values of 6 to 14 Ωm.

Values of natural-gamma radiation in the glacial deposits of St. Joseph County and adjacent counties were not available. Natural-gamma radiation is a result of the spontaneous decay of radioactive elements that are common constituents of clay minerals. Abundant clay minerals in shale, till, and lacustrine deposits produce a higher number of gamma emissions than do outwash deposits that contain a greater proportion of sand and gravel. The relation between natural-gamma radiation and clay-mineral content is opposite to the relation between electrical resistivity and clay-mineral content, and natural-gamma radiation is not affected by the degree of saturation or specific conductance of pore fluids.

GEOPHYSICAL METHODS

Surface measurements of direct current electrical-resistivity and borehole measurements of normal-resistivity and natural-gamma radiation were used to assist the delineation of glacial-drift stratigraphy and depth to bedrock in northeastern St. Joseph County. These methods have been successfully applied in similar hydrogeologic settings (Westjohn and Carter, 1989).

Normal-Resistivity and Natural-Gamma Logs

Normal-resistivity and natural-gamma logs were measured during the period September 1991 through December 1991. Normal-resistivity logs (16-in. normal electrode configuration) were measured in eight uncased, mud-filled boreholes located near corresponding direct current electrical-resistivity sounding sites. Natural-gamma logs were measured in completed wells at 7 of the 8 borehole-resistivity sites and at 11 additional sites that had no surface- or borehole-resistivity data. Standard methods were used in all measurements made (Keys, 1990).

The borehole logs measured in this study provided useful information for describing the glacial-drift deposits of northeastern St. Joseph County. Borehole logs also were used to assess the reliability of applying inverse models of direct current electrical-resistivity sounding data to sites where no monitoring wells were installed.

Direct Current Electrical-Resistivity Soundings

Prior to data collection, a computer program was used to construct forward models for various geologic settings that might be encountered in northeastern St. Joseph County. Forward models were constructed from electrical-resistivity measurements of similar glacial-drift deposits and bedrock in southern Michigan (Westjohn and Carter, 1989) and borehole measurements of glacial-drift thickness from previous studies of St. Joseph County (Beaty, 1987). Forward models for St. Joseph County indicated that an electrode spacing of 600 m (300 m AB/2) would be necessary to penetrate the entire thickness of unconsolidated deposits.

Direct current electrical-resistivity soundings were made at 15 sites (fig. 1) in August 1990 by use of the Schlumberger[1] array of potential and current electrode placement (Zohdy and others, 1974). Sites for direct current electrical-resistivity soundings were selected in areas where information was not sufficient to accurately describe glacial-drift stratigraphy and depth to bedrock. Site selection also required the absence of electrical interferences such as over-head power lines, buried cables, buried pipelines, and metal fences. The sounding data collected during this part of the study are shown in table 1 (at back of report).

[1]Use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Interpretation of Direct Current Electrical-Resistivity Sounding Data

Field data from direct current electrical-resistivity soundings were analyzed with a computer program by Zohdy and Bisdorf (1989). This computer program uses field-measured data sets of apparent resistivity and electrode spacing (table 1) to generate a vertical assemblage of iso-resistive units that is known as an inverse model. The inverse model can be displayed and interpreted in a way that is consistent with borehole logs and stratigraphic columns (fig. 2, at back of report). The resistivity, depth, and thickness of each iso-resistive stratigraphic unit in an inverse model is based on the electrode spacings, the apparent resistivity measurements, and the shape of the "field curve"—a regression line fitted to a log-log plot of field-measured resistivity by electrode spacing (or depth). Stratigraphic layers, not shown in figure 2, are defined as the areas that are separated by sequential inflection points in the interpreted model. If delineated, these would produce standard 3- and 4-layer geologic profiles.

In theory, several inverse models can be produced from the same data set. However, elimination of unlikely models and improved accuracy of a probable model can be attained by (1) making careful field measurements, (2) eliminating abhorrent data prior to computing the models, and (3) constraining the models with known information about the geoelectric properties of the glacial drift and bedrock. In this study, the accuracy of inverse models was improved by (1) using standard methods of data collection, as in Zohdy and others (1974), (2) removing abhorrent data points from the field curves before computing the inverse models, and (3) carefully considering the plausibility of each inverse model by comparing it with existing information about the geoelectric properties of glacial drift and bedrock. For purposes of this study, abhorrent data were identified as values of apparent resistivity that noticeably deviated from an otherwise smooth field curve. Abhorrent data generally are attributed to electrical interferences in ground conductivity, equipment malfunctions, current leaks, and abrupt lateral changes in stratigraphy (Zohdy and others, 1974).

USE OF SURFACE AND BOREHOLE GEOPHYSICS TO DELINEATE THE GLACIAL-DRIFT STRATIGRAPHY

At locations where geologic, cultural, and hydrologic conditions favor the collection of surface geophysical data, application of direct current electrical-resistivity sounding techniques can be a fast and cost-effective alternative to exploration drilling. Even under ideal conditions, however, interpretive models of direct current electrical-resistivity sounding data are not unique solutions, and formulations used to calculate inverse models of direct current electrical-resistivity sounding data require several simplifying assumptions, such as (1) a horizontal ground surface, (2) horizontal, planar stratigraphic boundaries, (3) isoresistive stratigraphic units, and (4) geohydrologic isotropy. Quite obviously, the assumptions used to develop inverse models cannot be realized completely in a field application.

Borehole measurements, alternatively, make direct measurements of hydrogeologic properties and do not require interpretive data processing. In this study, borehole measurements were used to (1) describe the glacial drift stratigraphy of northeastern St. Joseph County, and (2) establish a standard that could be used to evaluate the reliability of applying inverse models of direct current electrical-resistivity sounding data to sites where no borehole data were available.

Observations from Natural-Gamma Logs

Natural-gamma logs were used initially to describe the stratigraphy of northeastern St. Joseph County. An important aspect of the description was a characterization of the location and thickness of clay-rich deposits that potentially can affect ground-water quality and availability. A practical criterion for distinguishing glacial outwash from till and lacustrine deposits was based on a comparison of water-level records and natural-gamma logs. In general, water levels in deep and shallow well clusters were noticeably different at sites where an intervening clay-rich deposit had a measured natural-gamma radiation in excess of 1,400 counts per second. In settings unaffected by heavy withdrawals, different water levels in paired shallow and deep wells probably indicate the presence of a stratigraphic unit with a clay content that is high enough to inhibit ground-water flow between shallow and deep aquifers. Values of normal resistivity for these clay-rich deposits ranged from 45 to 85 Ωm and similarly could have been used to distinguish sand and gravel from clay-rich deposits; however, natural-gamma logs were available for more sites.

Based on the criterion that natural-gamma measurements of 1,400 counts per second indicated relatively impermeable sediments, clay-rich deposits were identified at 17 sites. Clay-rich deposits were identified at nine of the sites (21, 22, 23, 30, 31, 32, 37, 40, and A6) where only natural-gamma logs were measured. Clay-rich deposits were identified in natural-gamma logs at six sites (2, 6, 8, 9, 15, and 16) where normal resistivity logs and direct current electrical-resistivity soundings also were measured. Clay-rich deposits were identified in a natural-gamma log at site 14 where a direct current electrical-resistivity sounding also was measured but no borehole-resistivity log was available. Clay-rich deposits were not present in natural-gamma logs at sites 1, 9, and 27A, and natural-gamma logs were not measured at sites 3, 4, 5, 7, 10, 11, and 13.

Natural-gamma logs indicate that the clay-rich deposits in northeastern St. Joseph County are relatively thick (3–17 m) at sites 2, 14, 15, 16, 22, 23, 30, 31, 32, 40, and A6, and relatively thin (less than 3 m) at sites 6, 8, 9, 21, and 37. At most sites, the clay-rich deposits are positioned between shallow and deep aquifers, as would be expected for the St. Joseph Aquifer System. At sites 9 and 15, also located in the St. Joseph Aquifer System, the clay-rich deposits may be positioned directly upon the Ellsworth Shale. At site 14, a thick, clay-rich deposit occurs at the surface; at site A6, the entire 52 m of logged well is composed of clay-rich deposits. Geophysical measurements were not made at any site in the Hilltop Aquifer System. Sites 14 and A6 are located in the Nappanee Aquifer System.

Natural-gamma and normal-resistivity logs of the Ellsworth Shale were not possible in this study. Three boreholes (sites 2, 9, and 15) may have impinged on the upper surface of the Ellsworth Shale, but less than 0.6 m of the Ellsworth Shale was penetrated at any site. The natural-gamma and normal-resistivity probes require at least 1.2 m of open borehole to make a measurement. For the purposes of this report, drilling contact with the Ellsworth Shale at sites 2, 9, and 15 is suggested by drill cuttings and extremely slow penetration rates; however, deeper borings would be required to verify this information. Budgetary restrictions prohibited drilling to greater depths at these sites.

Observations from Normal-Resistivity Logs

At sites where natural-gamma and normal-resistivity logs were measured, the interpreted stratigraphy was essentially the same. The logs were not, however, a mirror reflection of each other (fig. 2) because natural-gamma and normal-resistivity probes sample different volumes of geologic material and average the measurements over different depth intervals. In addition, normal-resistivity measurements are affected by additional factors such as pore-water conductivity, drilling-fluid conductivity, and the degree of saturation of the sediments. The position of the clay-rich deposits identified in natural-gamma logs by use of the 1,400 counts per second criterion was unchanged in normal-resistivity logs.

At site 10, the clay-rich deposits were identified based solely on normal-resistivity measurements because a natural-gamma log was not available. Resistivity measurements at site 10 ranged from 60 to 75 Ωm at depths of 27 to 37 m below land surface (fig. 2); however, the clay-rich deposits were not completely penetrated and, therefore, the unit's stratigraphic position is not known.

Observations from Inverse Models of Direct Current Electrical-Resistivity Sounding Data

Direct current electrical-resistivity soundings were made at 15 sites in northeastern St. Joseph County. Soundings were made at six sites (3, 4, 5, 7, 11, and 13) where no borehole logs were measured. Water levels and drillers' records were available to assist interpretations at sites 5 and 11. Before applying the inverse models of direct current electrical-resistivity sounding data to the six sites with no borehole logs, comparisons were made between borehole logs and inverse models at sites where both types of data were available. Identification of the clay-rich deposits and estimation of the total drift thickness were the primary criteria for the comparisons.

In general, the clay-rich deposits observed in borehole logs were not identifiable in inverse models of direct current electrical-resistivity sounding data. Possible explanations for the inability of inverse models to clearly show the clay-rich deposits include (1) insufficient thickness of the clay-rich deposits, (2) insufficient resistivity contrast between the aquifer deposits and the confining unit, and/or (3) proximity of the clay-rich deposits to the Ellsworth Shale. Distances between sites where direct current electrical-resistivity soundings and normal-resistivity logs were coevaluated varied between 0.10 and 1.05 km, with a mean separation of 0.45 km (table 2).

A mean separation of 0.45 km is not large, considering that the maximum electrode separation of 0.60 km frequently caused the area sampled by the surface-resistivity measurements to overlap with the future borehole site.

Table 2. Distances separating compared surface- and borehole-resistivity measurements

Well site	Surface resistivity site	Separation distance (km)
1	1	0.60
2	2	.05
6	6	1.05
8	8	.45
9	9	.75
10	10	.65
14	14	.30
15	15	.20
16	16	.10

The stratigraphic position of the clay-rich deposits was successfully identified in inverse models at one location where comparative surface and borehole information was available—site 14. Site 14 is located in the Nappanee Aquifer System. Clay-rich deposits at site 14 occur at the surface and are about 20 m thick. The presence of conductive materials at the surface, as opposed to a comparable thickness of variably saturated sand and gravel may account for the different results in the two aquifer systems. All other comparison sites were located in the St. Joseph Aquifer System.

Evaluation of the reliability of inverse models for predicting the depth to conductive bedrock was limited because the bedrock was only partially penetrated at three sites (2, 9, and 15). The difference between measured and modeled depth to bedrock at sites 2, 9, and 15 was 2 m, 1 m, and 2 m, respectively. Historic drillers' records indicate that the depth to bedrock could be 20 to 30 m deeper than the borings and models generated in this study suggest. Clearly, inverse models at more borehole sites having greater penetration of the bedrock might provide more definitive information about this aspect of the method's usefulness.

SUMMARY

The St. Joseph Aquifer System is Indiana's only sole-source aquifer. The aquifer system is composed mainly of glacial outwash deposits, with lesser amounts of glacial till and lacustrine deposits. The Hilltop and Nappanee Aquifer Systems, located in the southern part of the study area, contain larger proportions of clay-rich deposits than the St. Joseph Aquifer System and rarely are utilized for public supply. The glacial-drift of northeastern St. Joseph County is underlain by the Devonian-Mississippian Ellsworth Shale, a relatively impermeable basal unit.

Water quality in the St. Joseph Aquifer System is generally good, but ground water in deeper parts of the aquifer system generally has higher concentrations of dissolved constituents. Water-level measurements indicate that the clay-rich till and lacustrine deposits, where present, can inhibit vertical flow between the deeper and shallower parts of the aquifer system. The thickness and distribution of the clay-rich deposits are therefore important factors affecting ground-water quality and flow. Thickness and distribution of sand and gravel aquifers are similarly important factors affecting the availability of ground water as a source for public suppliers.

This study utilized surface and borehole geophysics to characterize the stratigraphy of glacial-drift aquifers in northeastern St. Joseph County, Ind. Natural-gamma and normal-resistivity logs were measured in 19 boreholes, and direct current electrical-resistivity soundings were made at 15 sites. Direct current electrical-resistivity sounding data were inversely modeled by use of a computer algorithm. At eight sites, where surface and borehole information were available, inverse models of direct current electrical-resistivity sounding data were compared to borehole logs of natural-gamma radiation and electrical resistivity. Borehole logs, which make direct measurements of hydrogeological properties,

were used as the standard for assessing the accuracy of inverse models because the latter are subject to several unrealistic assumptions, utilize indirect measurements as computational input, and must be mathematically processed.

Coevaluation of inverse models of direct current electrical-resistivity sounding data and borehole measurements of natural-gamma and normal resistivity showed that inverse models could not be used in the St. Joseph Aquifer System to characterize the clay-rich deposits. At one site located in the Nappanee Aquifer System, a relatively thick, surficial, clay-rich deposit was identified in the inverse model. Inverse models of direct current electrical-resistivity sounding data indicated that the method may be useful for determining the depth to bedrock and therefore the total thickness of glacial drift, but more data are needed to affirm this result.

The information acquired in this study indicates that clay-rich deposits are present throughout most of northeastern St. Joseph County, Ind. The clay-rich deposits have variable thickness, and their position in the stratigraphic column varies from directly overlaying the Ellsworth Shale to occurring as a surficial deposit. In the St. Joseph Aquifer System, the clay-rich unit generally is positioned between shallow and deep aquifers but may occur at any depth. In the Nappanee Aquifer System, the clay-rich deposits are more abundant and can occur at the surface and possibly throughout the stratigraphic column. Geophysical information was not collected from the Hilltop Aquifer System.

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SUPPLEMENTAL DATA

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana

[AB, current-electrode spacing; MN, voltage-electrode spacing; V, voltage; I, current; m, meter; mV, millivolts; mA, milliamps; Ωm, ohm meter]

Survey identification: Site 1

Survey location: 46.22642 N, 5.75514 W (Universal Transverse Mercator)

41°45′15″ N, 086°05′29″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	25.0	687
4	.5	16.4	815
5	.5	11.6	904
5	1	21.9	826
6	.5	8.56	961
6	1	16.1	886
8	1	9.23	914
10	1	6.16	958
10	2	10.9	824
14	1	2.89	885
14	2	6.16	928
20	2	2.40	746
30	2	.400	281
30	4	.783	272
40	2	.200	251
40	4	.399	248
60	4	.114	160
80	4	.055	138
100	4	.035	137
100	20	.119	127
140	4	.018	138
140	20	.088	133
200	20	.028	87.1
300	20	.010	70.4

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 2

Survey location: 46.20485 N, 5.76289 W (Universal Transverse Mercator)

41°44′05″ N, 086°04′57″ W (latitude, longitude)

Survey azimuth: northwest-southeast

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	2.63	72.3
4	.5	1.48	73.7
5	.5	1.01	78.5
5	1	1.97	74.3
6	.5	.756	84.9
6	1	1.45	80.0
8	1	.915	90.6
10	1	.656	102
10	2	1.33	100
14	1	.388	118
14	2	.786	118
20	2	.405	126
30	2	.200	140
30	4	.840	291
40	2	.090	112
40	4	.200	124
60	4	.070	98.5
80	4	.040	100
100	4	.021	82.3
100	20	.098	73.9
140	4	.007	53.8
140	20	.037	55.8
200	20	.009	24.9

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 3

Survey location: 46.19772 N, 5.74138 W (Universal Transverse Mercator):

41°43′ 42″ N, 086°06′ 30″ W (latitude, longitude):

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	4.11	113
4	.5	2.21	109
5	.5	1.44	112
5	1	2.74	103
6	.5	.982	110
6	1	1.84	101
8	1	1.01	100
10	1	.726	112
10	2	1.39	105
14	1	.386	118
14	2	.735	110
20	2	.382	118
30	2	.175	123
30	4	.359	124
40	2	.094	118
40	4	.196	121
60	4	.077	108
80	4	.035	89.2
100	4	.018	70.9
100	20	.096	72.4
140	4	.008	63.1
140	20	.037	56.9
200	20	.076	23.6

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 4

Survey location: 46.19678 N, 5.77617 W (Universal Transverse Mercator)

41°43′38″ N, 086°04′00″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	18.0	1135
4	.5	9.18	454
5	.5	5.41	420
5	1	10.3	390
6	.5	3.27	367
6	1	6.16	338
8	1	2.90	287
10	1	1.57	244
10	2	3.31	249
14	1	.626	191
14	2	1.31	198
20	2	.543	168
30	2	.221	155
30	4	.453	157
40	2	.116	146
40	4	.236	146
60	4	.095	134
80	4	.045	114
100	4	.024	95.3
100	20	.128	97.0
140	4	.008	62.3
140	20	.042	63.4
200	20	.014	44.2
300	20	.003	26.7

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 5

Survey location: 46.14958 N, 5.76277 W (Universal Transverse Mercator)

41°41′05″ N, 086°05′00″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	22.6	621
4	.5	14.1	699
5	.5	9.71	754
5	1	18.9	715
6	.5	7.42	833
6	1	14.4	794
8	1	8.99	890
10	1	6.28	976
10	2	12.7	959
14	1	3.24	992
14	2	6.53	984
20	2	2.77	861
30	2	.813	572
30	4	1.73	601
40	2	.304	381
40	4	.646	401
60	4	.152	214
80	4	.059	148
100	4	.030	118
100	20	.162	122
140	40	.010	79.9
140	20	.053	81.1
200	20	.014	44.2

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 6

Survey location: 46.17717 N, 5.72349 W (Universal Transverse Mercator)

41°42′ 35″ N, 086°07′ 50″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	6.94	190
4	.5	3.55	175
5	.5	2.02	157
5	1	4.46	168
6	.5	1.29	145
6	1	2.82	155
8	1	1.39	138
10	1	.830	129
10	2	1.62	122
14	1	.411	125
14	2	.794	119
20	2	.316	98.2
30	2	.169	119
30	4	.346	120
40	2	.093	116
40	4	.188	117
60	4	.081	114
80	4	.042	107
100	4	.025	99.2
100	20	.127	96.1
140	4	.010	79.9
140	20	.052	78.4
200	20	.017	52.9

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 7

Survey location: 46.21494 N, 5.71587 W (Universal Transverse Mercator)

41°44′ 38″ N, 086°08′ 21″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	8.52	234
4	.5	5.91	292
5	.5	4.38	340
5	1	8.30	312
6	.5	3.39	380
6	1	6.43	353
8	1	4.17	412
10	1	2.91	452
10	2	5.86	441
14	1	1.60	490
14	2	3.20	482
20	2	1.43	445
30	2	.433	304
30	4	.923	320
40	2	.180	226
40	4	.382	237
60	4	.102	144
80	4	.046	115
100	4	.027	106
100	20	.151	114
140	4	.012	99.2
140	20	.069	105
200	20	.031	96.4
300	20	.014	101
300	40	.029	102

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 8

Survey location: 46.19326 N, 5.73788 W (Universal Transverse Mercator)

41°43′28″ N, 086°06′45″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	3.60	99.0
4	.5	2.03	101
5	.5	1.27	99.1
5	1	2.49	93.9
6	.5	.911	102
6	1	1.77	97.5
8	1	1.02	101
10	1	.665	101
10	2	1.36	103
14	1	.336	102
14	2	.694	104
20	2	.330	102
30	2	.143	100
30	4	.288	99.9
40	2	.080	100
40	4	.159	99.5
60	4	.066	93.5
80	4	.035	87.9
100	4	.021	83.1
100	20	.108	81.4
140	4	.008	68.4
140	20	.044	66.4
200	20	.015	46.9
300	20	.005	38.0

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 9

Survey location: 46.19356 N, 5.77192 W (Universal Transverse Mercator)

41°43′27″ N, 086°04′19″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	21.5	591
4	.5	10.8	536
5	.5	6.36	494
5	1	14.0	530
6	.5	4.11	461
6	1	8.99	494
8	1	3.77	373
10	1	1.82	283
10	2	4.09	308
14	1	.792	242
14	2	1.741	262
20	2	.674	210
30	2	.238	167
30	4	.499	186
40	2	.110	137
40	4	.226	140
60	4	.064	90.4
80	4	.024	61.2
100	4	.011	44.3
100	20	.057	43.1
140	4	.004	35.2
140	20	.018	27.7

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 10

Survey location: 46.18887 N, 5.75194 W (Universal Transverse Mercator)

41°43′13″ N, 086°05′45″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	3.11	85.5
4	.5	1.95	96.5
5	.5	1.29	100
5	1	2.64	99.5
6	.5	.944	106
6	1	1.91	105
8	1	1.09	108
10	1	.738	114
10	2	1.50	113
14	1	.400	122
14	2	.808	121
20	2	.410	127
30	2	.185	130
30	4	.372	129
40	2	.101	127
40	4	.203	126
60	4	.082	116
80	4	.043	108
100	4	.024	95.3
100	20	.137	103
140	4	.009	74.6
140	20	.054	81.9
200	20	.017	53.2
300	20	.004	31.7
300	40	.009	31.6

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 11

Survey location: 46.17566 N, 5.68598 W (Universal Transverse Mercator)

41°42′31″ N, 086°10′32″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	6.14	168
4	.5	3.36	166
5	.5	2.01	156
5	1	4.11	154
6	.5	1.34	151
6	1	2.71	149
8	1	1.38	137
10	1	.783	121
10	2	1.595	120
14	1	.350	107
14	2	.698	105
20	2	.302	93.9
30	2	.117	82.5
30	4	.244	84.7
40	2	.058	73.5
40	4	.125	77.8
60	4	.046	64.9
80	4	.022	55.4
100	4	.012	47.4
100	20	.066	50.4
140	4	.004	36.1
140	20	.025	39.1
200	20	.008	27.7

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 13

Survey location **46.08894 N, 5.76669 W (Universal Transverse Mercator)**

41°37′ 48″ N, 086°04′ 47″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	1.86	51.2
4	.5	1.06	52.6
5	.5	.748	58.2
5	1	1.51	57.0
6	.5	.575	64.6
6	1	1.15	63.4
8	1	.731	72.4
10	1	.513	79.8
10	2	1.08	81.7
14	1	.285	87.9
14	2	.596	89.9
20	2	.319	99.2
30	2	.145	102
30	4	.306	106
40	2	.075	94.6
40	4	.159	99.2
60	4	.057	81.3
80	4	.025	63.2
100	4	.012	49.8
100	20	.067	50.6
140	4	.004	32.3
140	20	.022	33.3
200	20	.008	25.2

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 14

Survey location: 46.06409 N, 5.72598 W (Universal Transverse Mercator)

41°36′29″ N, 086°07′44″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	0.888	24.4
4	.5	.545	26.9
5	.5	.388	30.2
5	1	.801	30.2
6	.5	.286	32.1
6	1	.587	32.3
8	1	.370	36.6
10	1	.267	41.5
10	2	.542	40.9
14	1	.163	49.0
14	2	.325	49.0
20	2	.199	62.0
30	2	.114	80.0
30	4	.248	86.0
40	2	.075	94.0
40	4	.162	100
60	4	.086	121
80	4	.051	127
100	4	.032	126
100	20	.179	134
140	4	.015	115
140	20	.082	123
200	20	.030	93.3

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 15

Survey location: 46.22566 N, 5.64961 W (Universal Transverse Mercator)

41°45′ 15″ N, 086°13′ 07″ W (latitude, longitude)

Survey azimuth: east-west

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	221	6,077
4	.5	101	5,034
5	.5	42.5	3,304
5	1	91.1	3,434
6	.5	24.9	2,796
6	1	52.0	2,860
8	1	16.2	1,606
10	1	5.48	852
10	2	12.5	947
14	1	1.00	307
14	2	2.18	328
20	2	.522	162
30	2	.172	121
30	4	.361	125
40	2	.087	109
40	4	.177	110
60	4	.064	90.1
80	4	.027	67.7
100	4	.014	54.9
100	20	.059	44.5
140	4	.004	30.8
140	20	.018	27.1
200	20	.004	12.4

Table 1. Direct current electrical-resistivity sounding data in northeastern St. Joseph County, Indiana—Continued

Survey identification: Site 16

Survey location: 46.17576 N, 5.71166 W (Universal Transverse Mercator)

41°42′31″ N, 086°08′41″ W (latitude, longitude)

Survey azimuth: north-south

AB/2 (m)	MN/2 (m)	V / I (mV / mA)	Apparent resistivity (Ωm)
3	0.5	191.7	5,271
4	.5	94.8	4,692
5	.5	58.7	4,563
5	1	116.6	4,395
6	.5	34.1	3,829
6	1	67.7	3,723
8	1	24.5	2,425
10	1	9.79	1,522
10	2	22.6	1,704
14	1	2.14	655
14	2	4.76	717
20	2	.730	227
30	2	.142	99.8
30	4	.296	102
40	2	.065	81.4
40	4	.134	83.2
60	4	.052	74.0
80	4	.026	65.4
100	4	.024	94.1
100	20	.091	68.9
140	4	.020	160
140	20	.027	41.8
200	20	.016	49

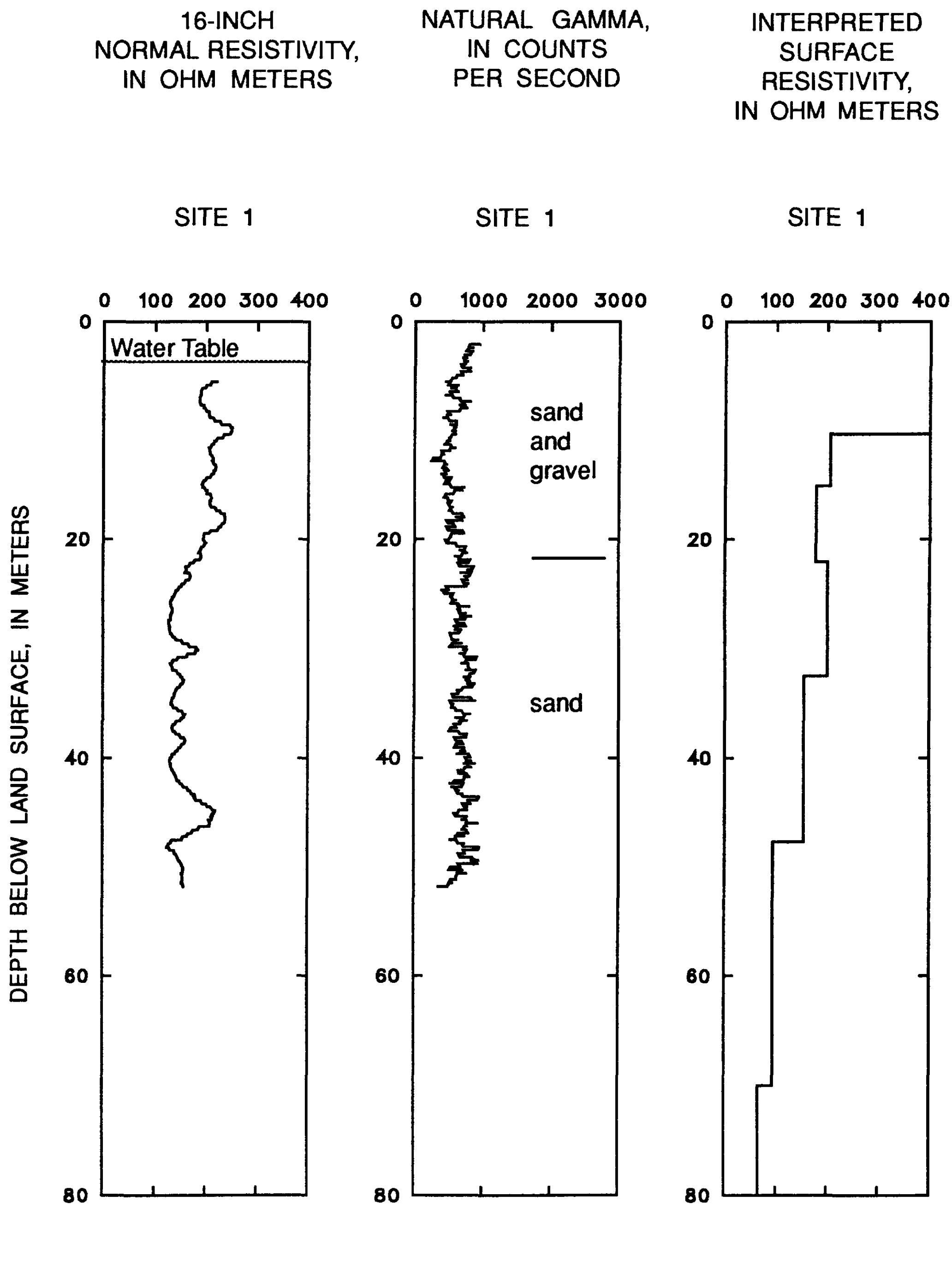

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana.

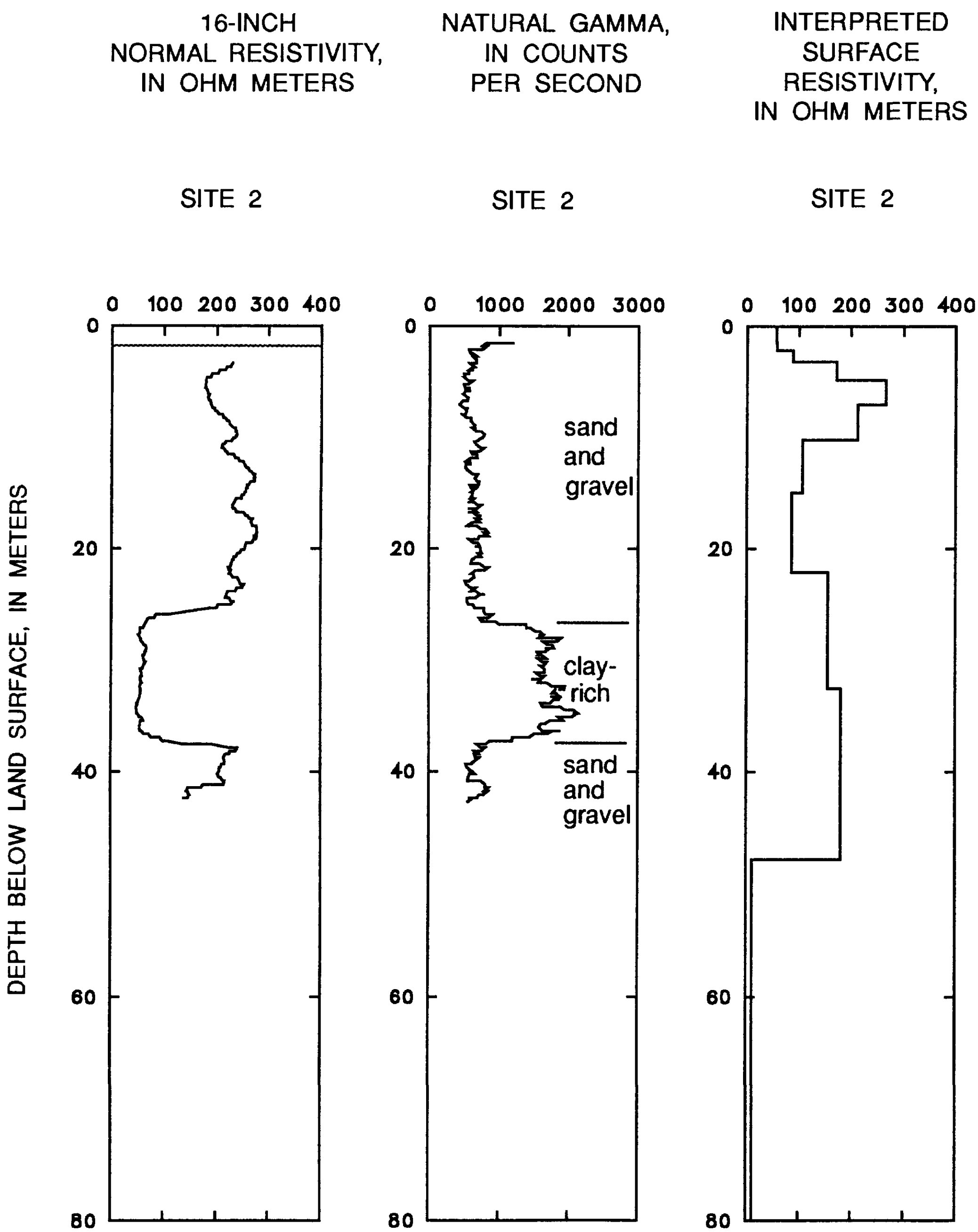

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

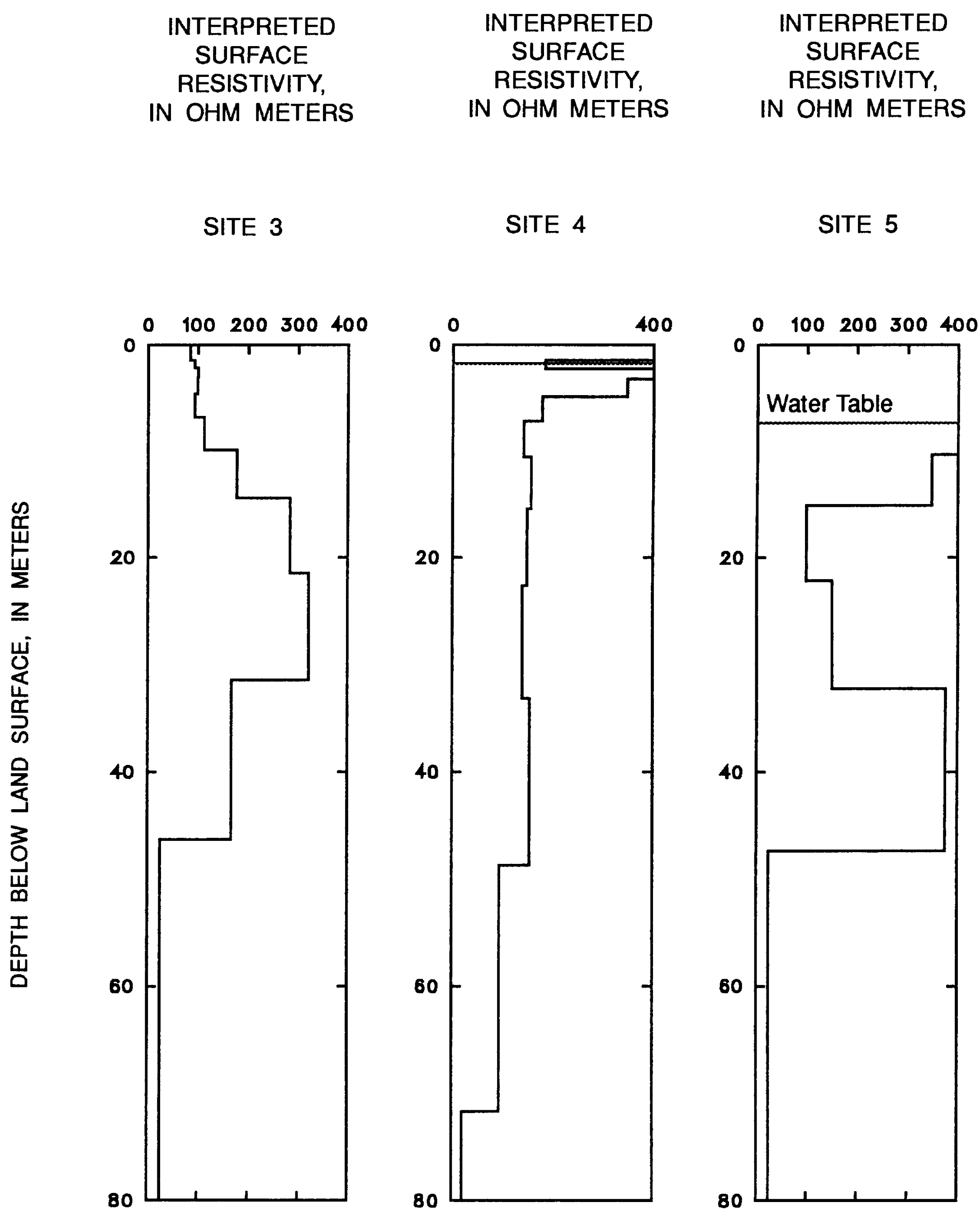

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

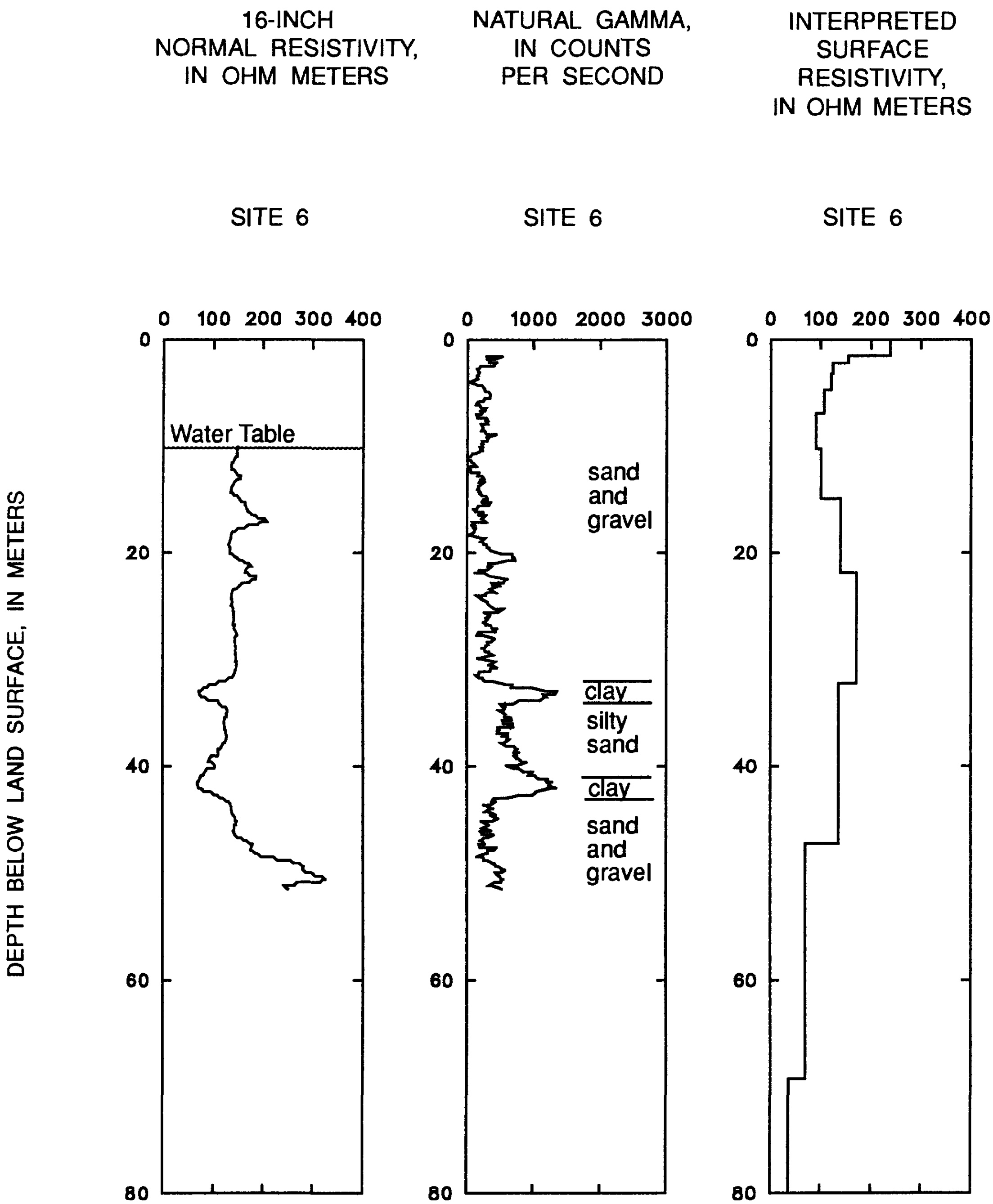

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

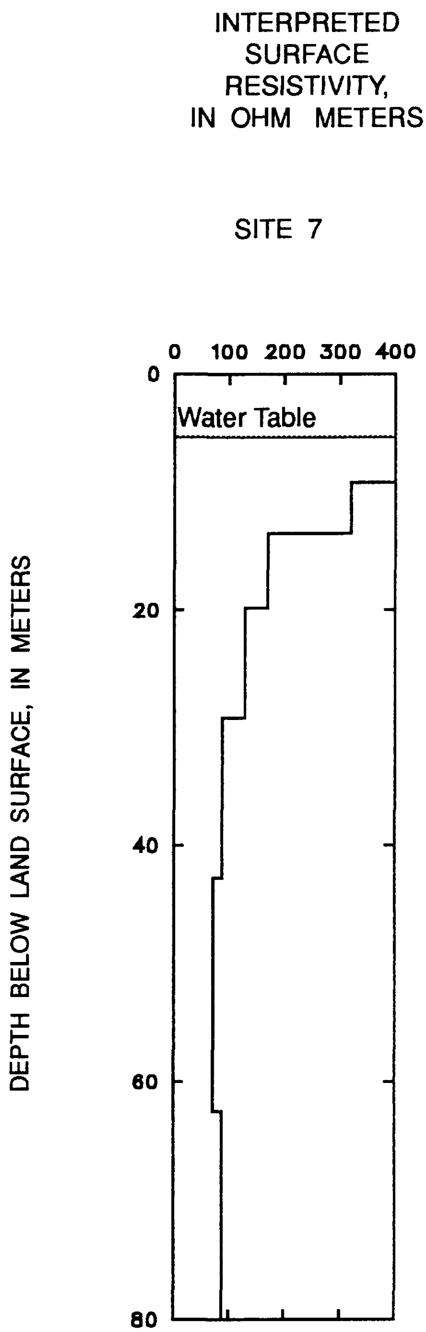

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

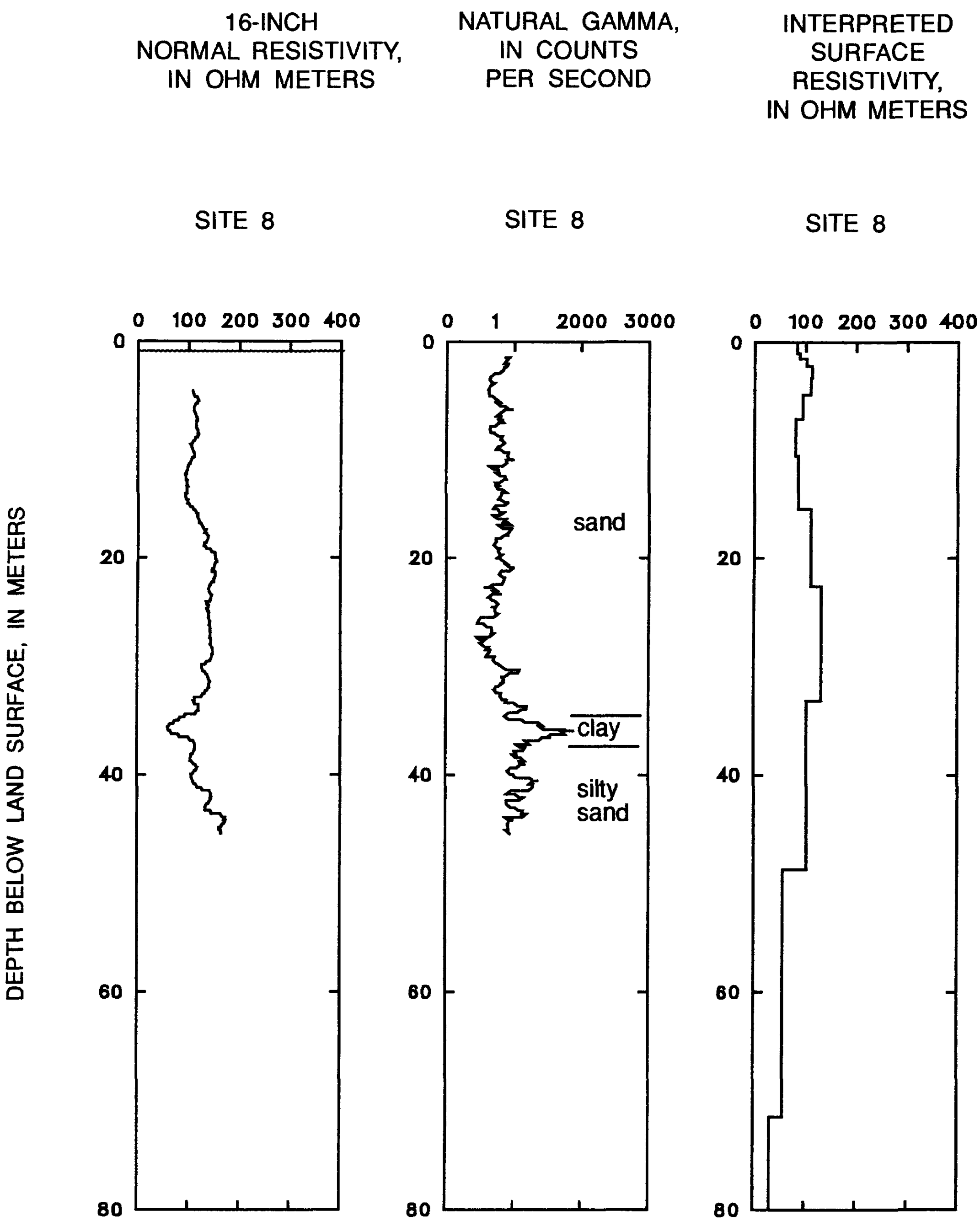

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

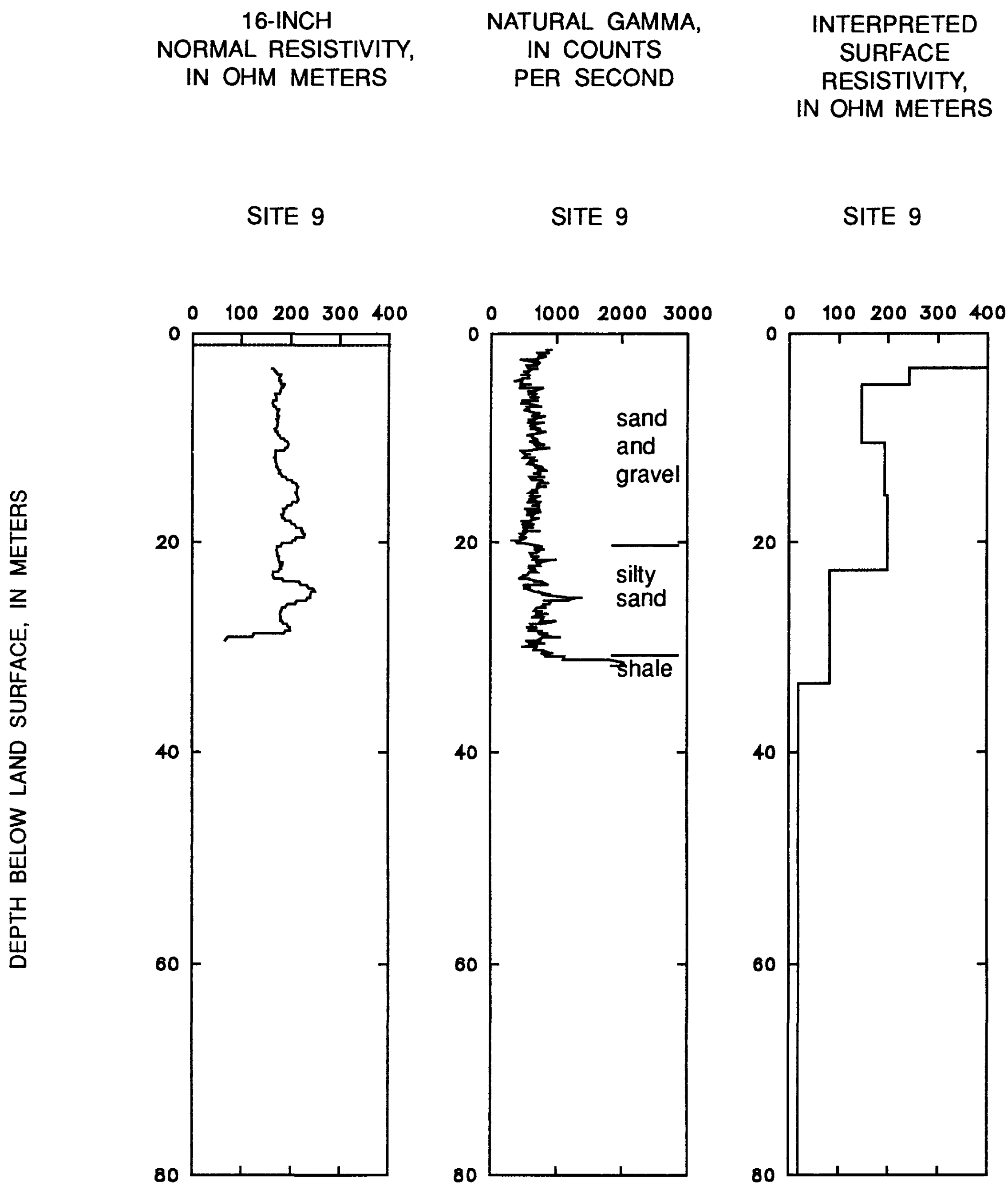

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

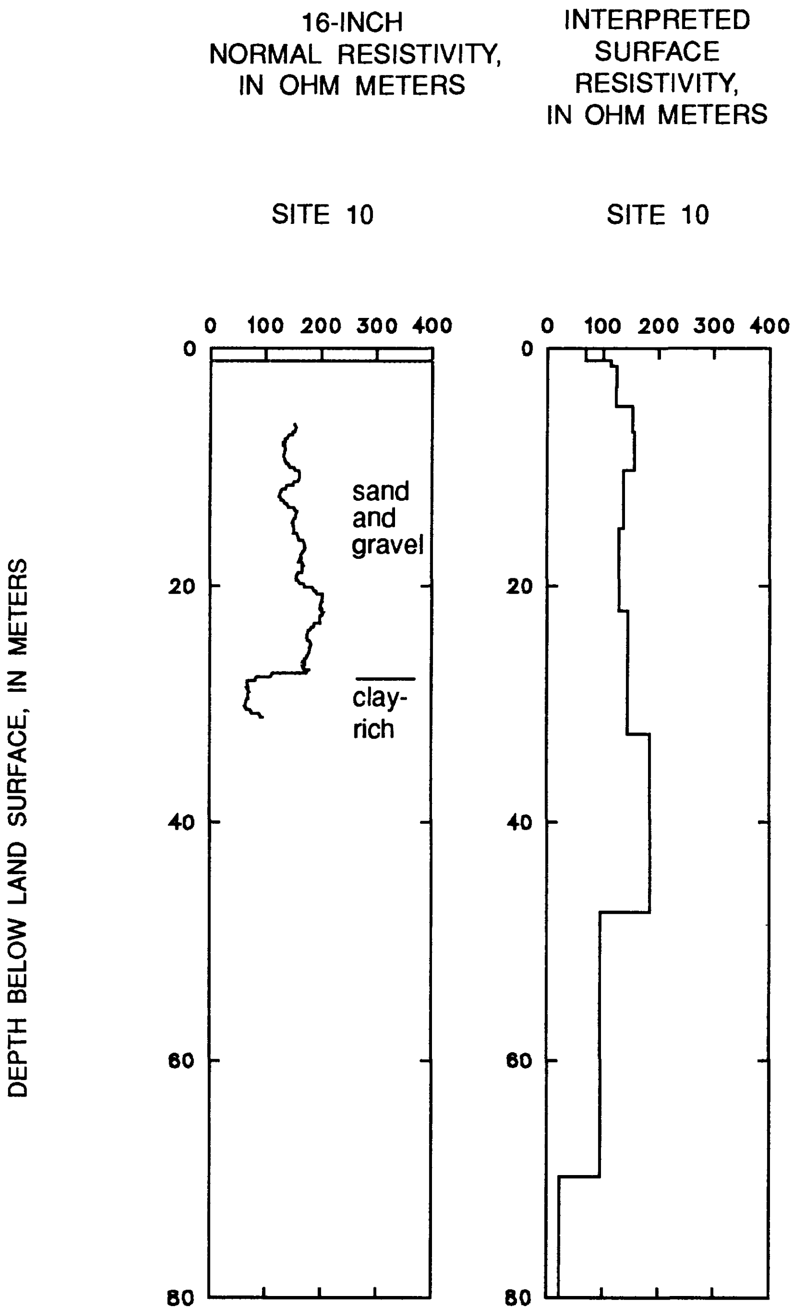

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

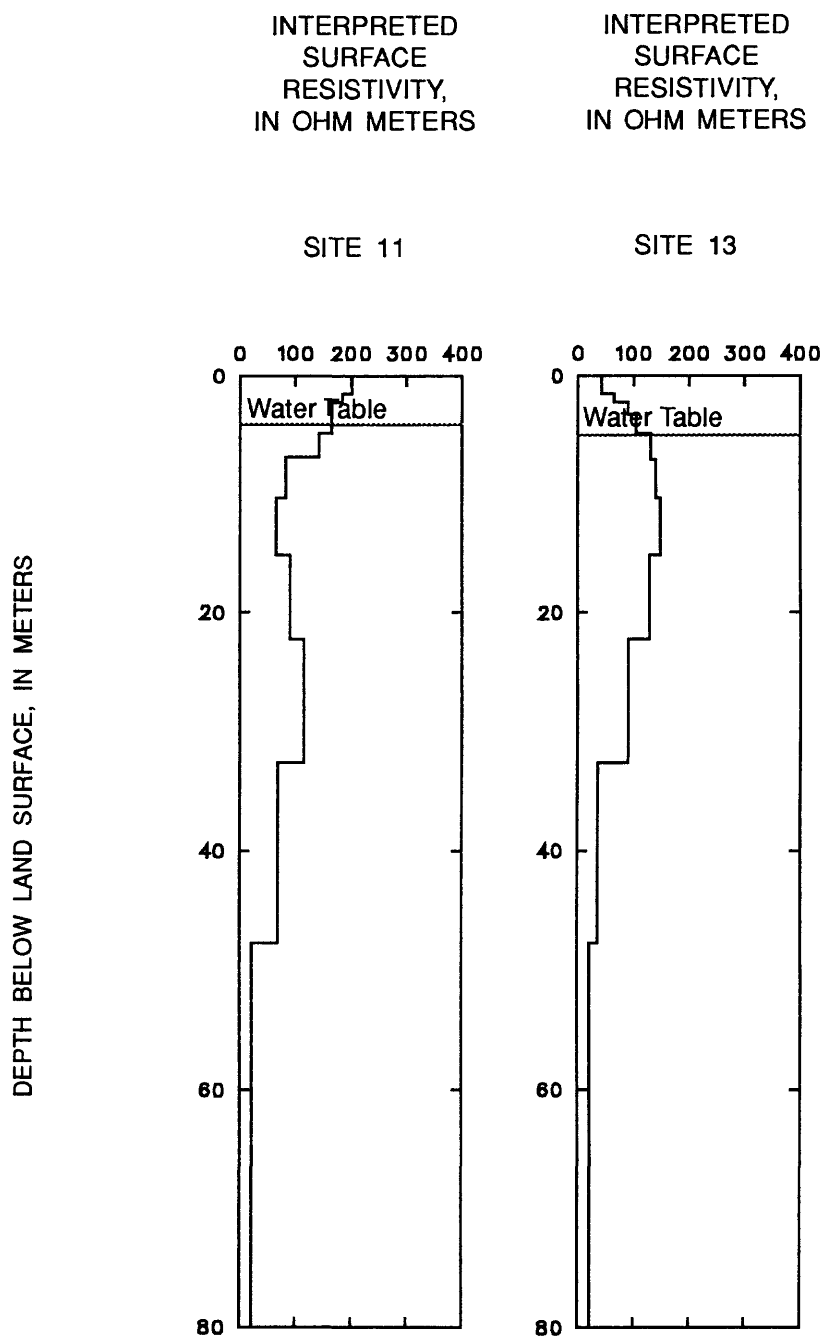

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

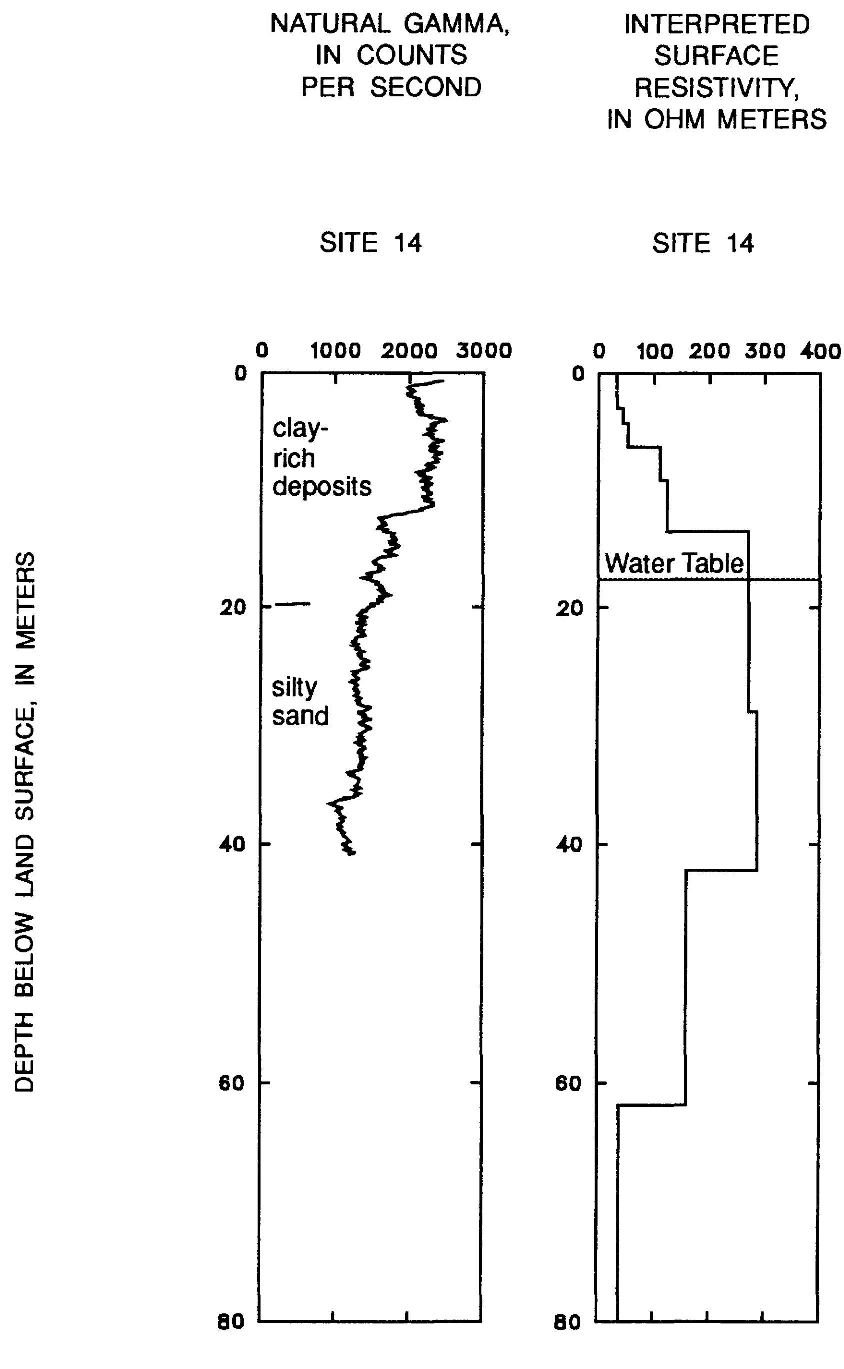

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

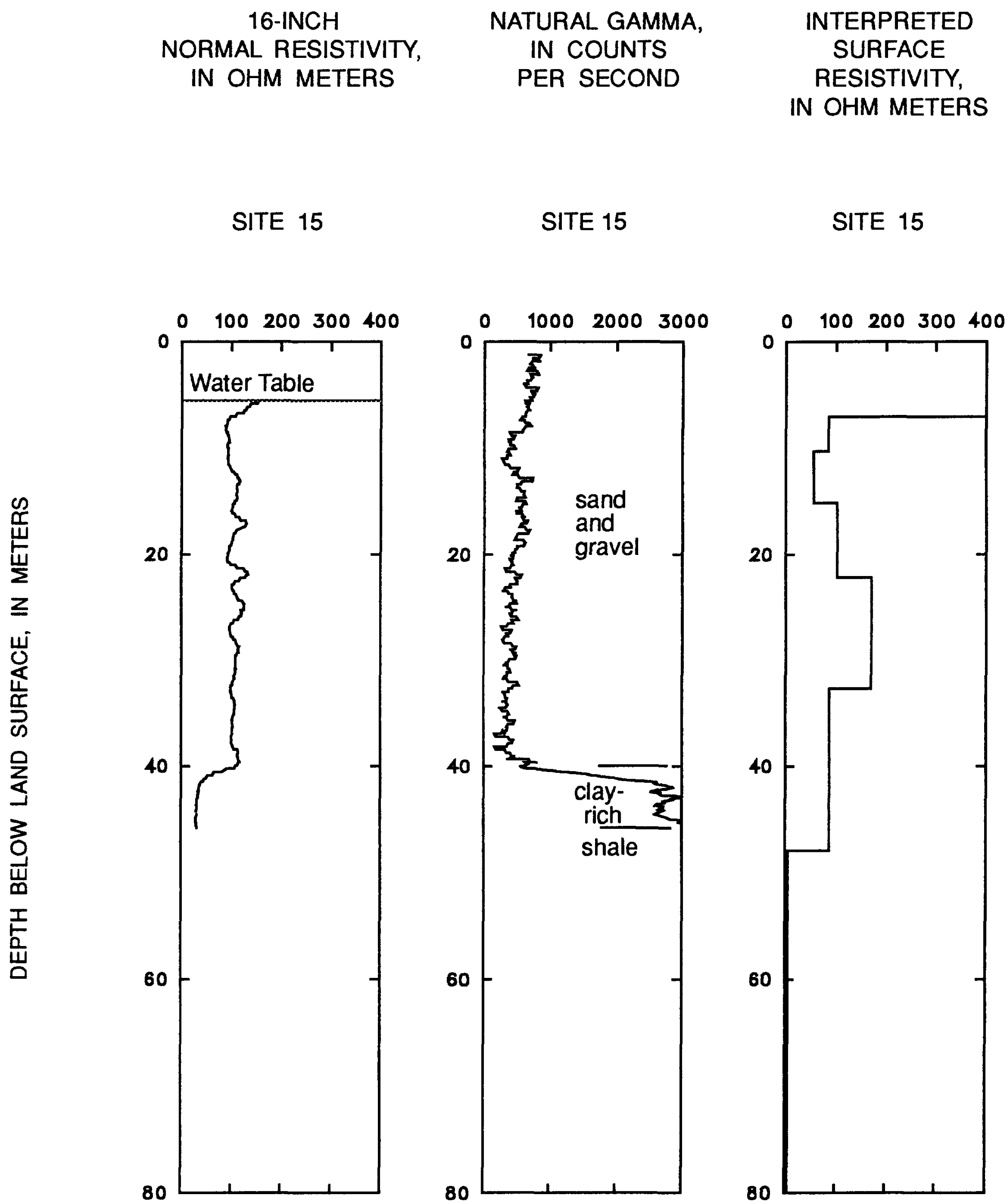

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

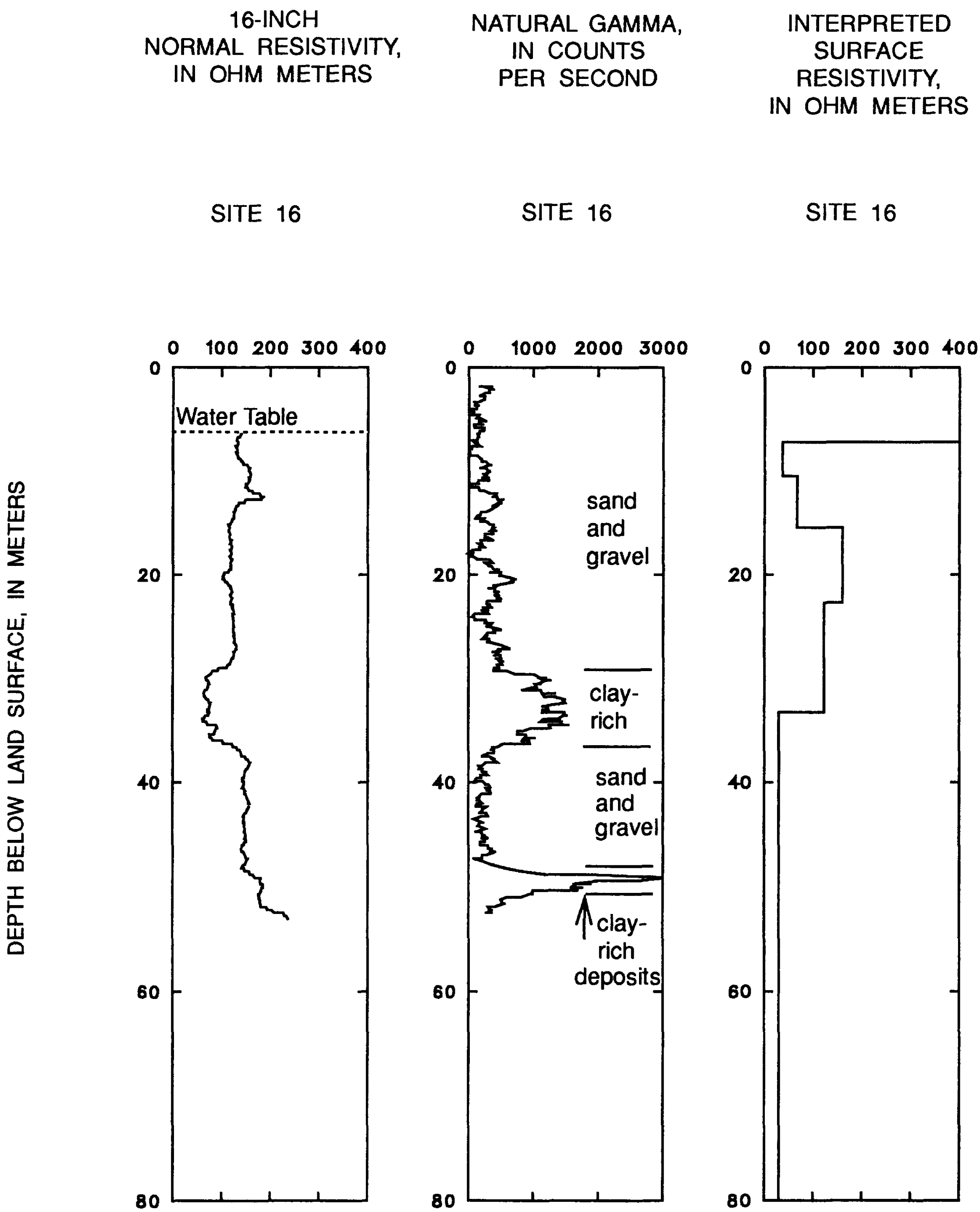

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

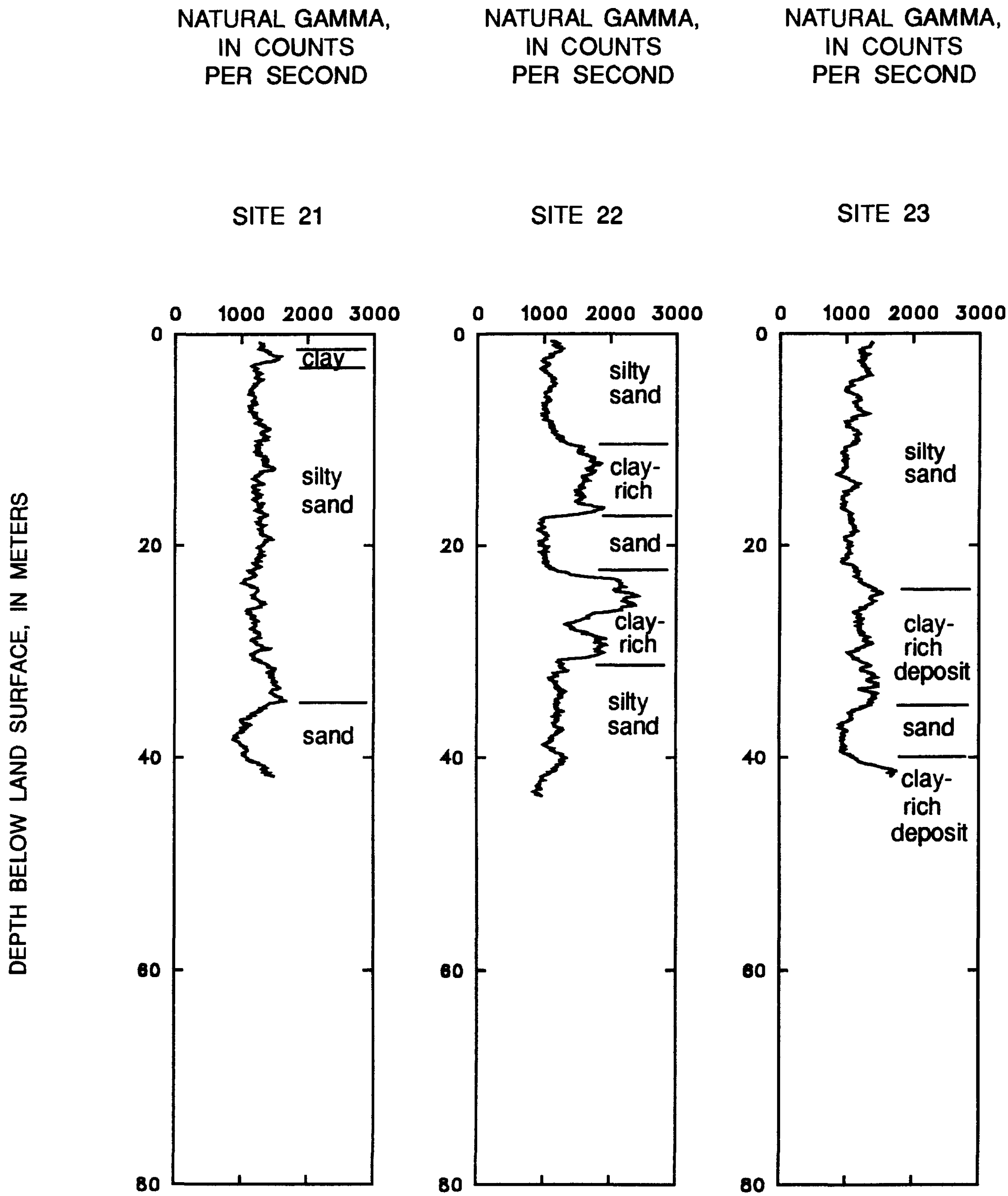

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

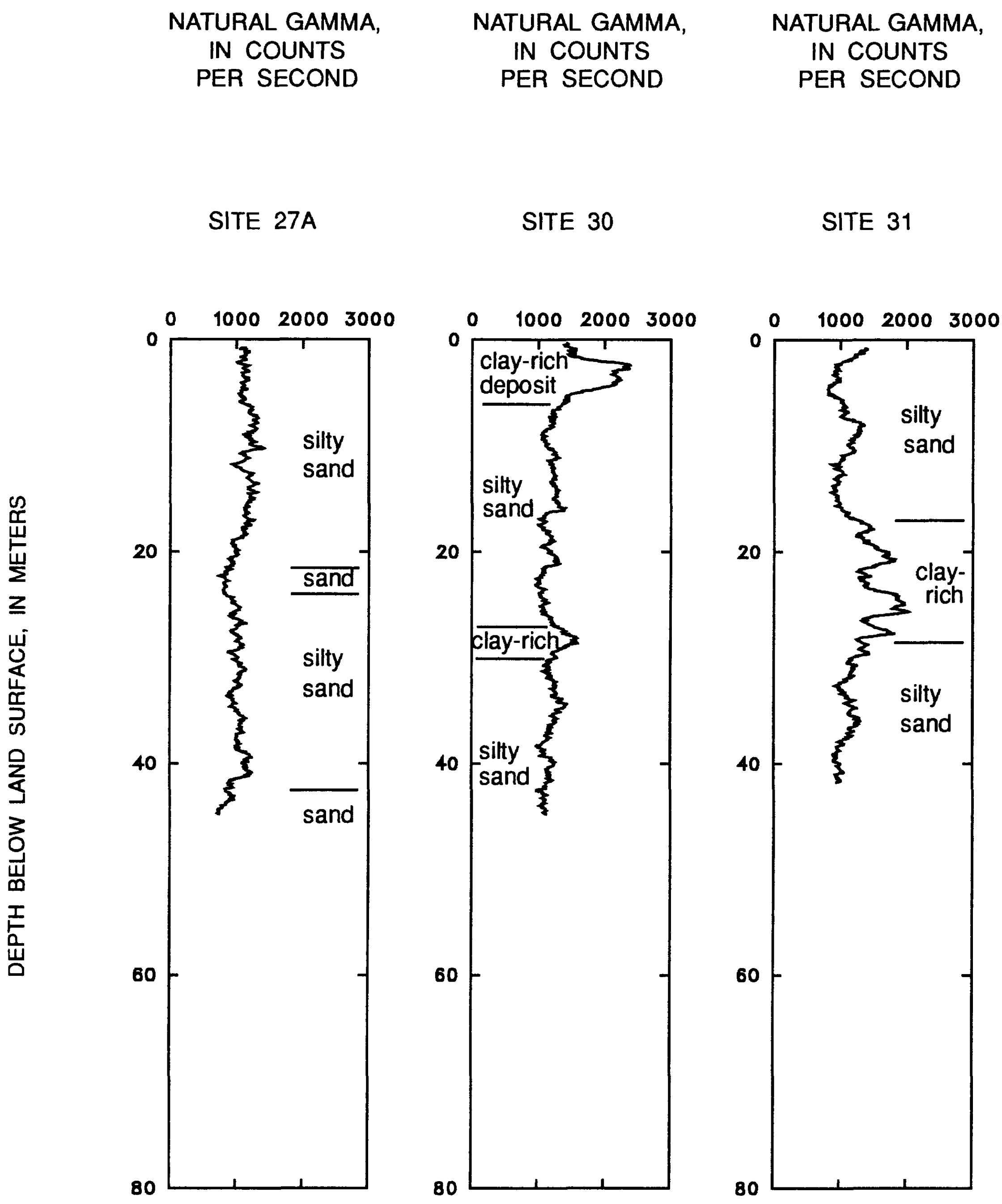

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

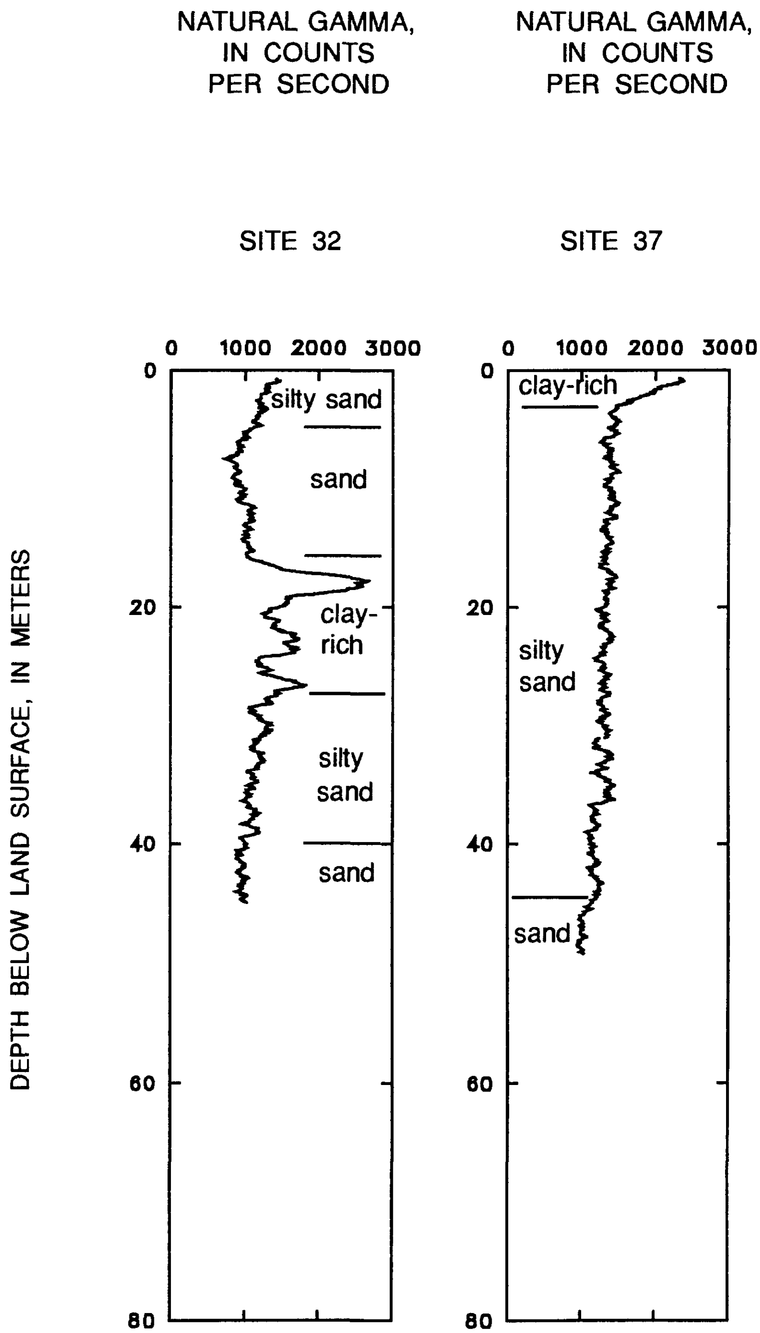

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

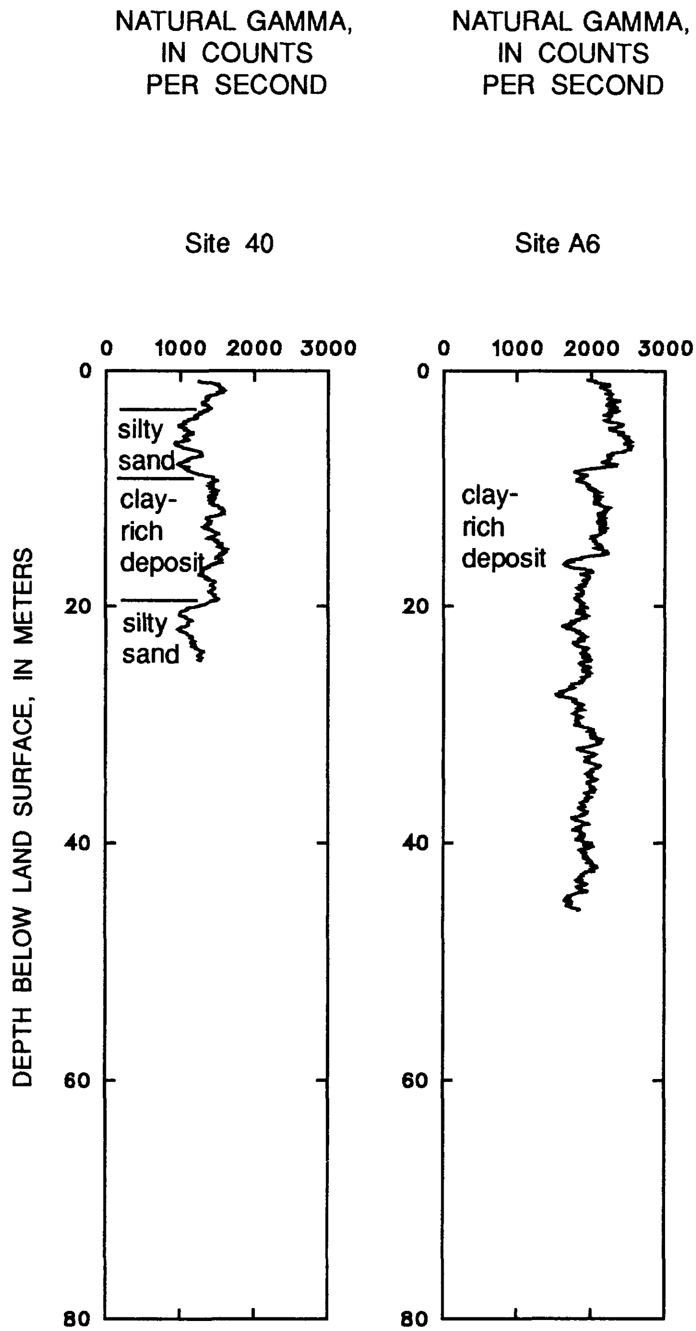

Figure 2. Geophysical logs and inverse models, northeastern St. Joseph County, Indiana—Continued.

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