APPLICATION OF GEOPHYSICAL WELL LOG ANALYSIS TO CHARACTERIZATION OF AQUIFERS IN THE SINAI REGION, REPUBLIC OF EGYPT

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CONVERSION FACTORS

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
kilometer (km)	0.6214	mile

Degree Celsius (°C) may be converted to degree Fahrenheit (°F) by using the following equation:

$$°F = 9/5(°C) + 32$$

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

ohmmeter (ohm-m)

millivolt (mV)

milligram per liter (mg/L)

microsiemen per centimeter (µS/cm)

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ABSTRACT

Geophysical well logs are analyzed for a series of boreholes penetrating unconsolidated sediments near El Arish in the northern Sinai, and for a series of deep boreholes penetrating consolidated sandstones and carbonates in the Central Sinai. Geophysical logs studied include natural gamma, caliper, long- and short-normal resistivity, spontaneous potential, and neutron porosity logs.

Combined interpretations of gamma and resistivity logs for boreholes in unconsolidated sediments indicate that multiple logs can be used to produce simultaneous coupled solutions for clay-mineral fraction and salinity along the borehole. Salinity profiles obtained from log sets in individual boreholes are compared to profiles of salinity inferred from surface-resistivity sounding. Intermediate-scale aquifer structure identified on the surface-resistivity profiles is related to the correlation of lithology between boreholes indicated by geophysical logs at two different locations covered by the surface profiles.

Combinations of gamma, resistivity, and neutron porosity logs are used to generate simultaneous solutions for clay-mineral fraction, effective porosity, and salinity in predominantly sandstone or carbonate aquifers. In some situations where useful spontaneous potential logs are available, estimates of formation-water salinity obtained from spontaneous potential logs agree with salinity values indicated by the combination of porosity and resistivity logs. In other situations where porosity logs are not available and spontaneous potential logs either were not made or seem unreliable, gamma and resistivity logs do not provide enough information to uniquely infer salinity and porosity. Detailed examination of resistivity logs indicate that borehole effects introduce significant error into long-normal logs, but the short-normal log reads close to true formation resistivity, except in situations where invasion is significant.

These preliminary results are used to develop a generalized method for assembling a data base for Sinai aquifers in which geophysical well logs can be related to the hydraulic properties of interest in aquifer models. The approach is based on correlation of interval summed indices designed to correlate with transmissivity and storage coefficient values determined from aquifer tests.

INTRODUCTION

The Sinai Resource Development Program

The Water Resource Research Institute (WRRI), Republic of Egypt has undertaken a long term program to develop the water resources of the Sinai region with the assistance of a United States Aid in Development (US-AID) project managed by Colorado State University (CSU). The U.S. Geological Survey subsequently established a cooperative research program with

CSU and WRRI in the application of geophysical well log analysis techniques to the characterization of Sinai aquifers. This program provides an opportunity to independently verify geophysical log-interpretation methods being developed for geohydrology by U.S. Geological Survey research programs. The WRRI Sinai project may yield insights into how aquifer properties determined at a few widely spaced measurement boreholes are related to large-scale aquifer properties determined from aquifer tests and verified during subsequent well-field development.

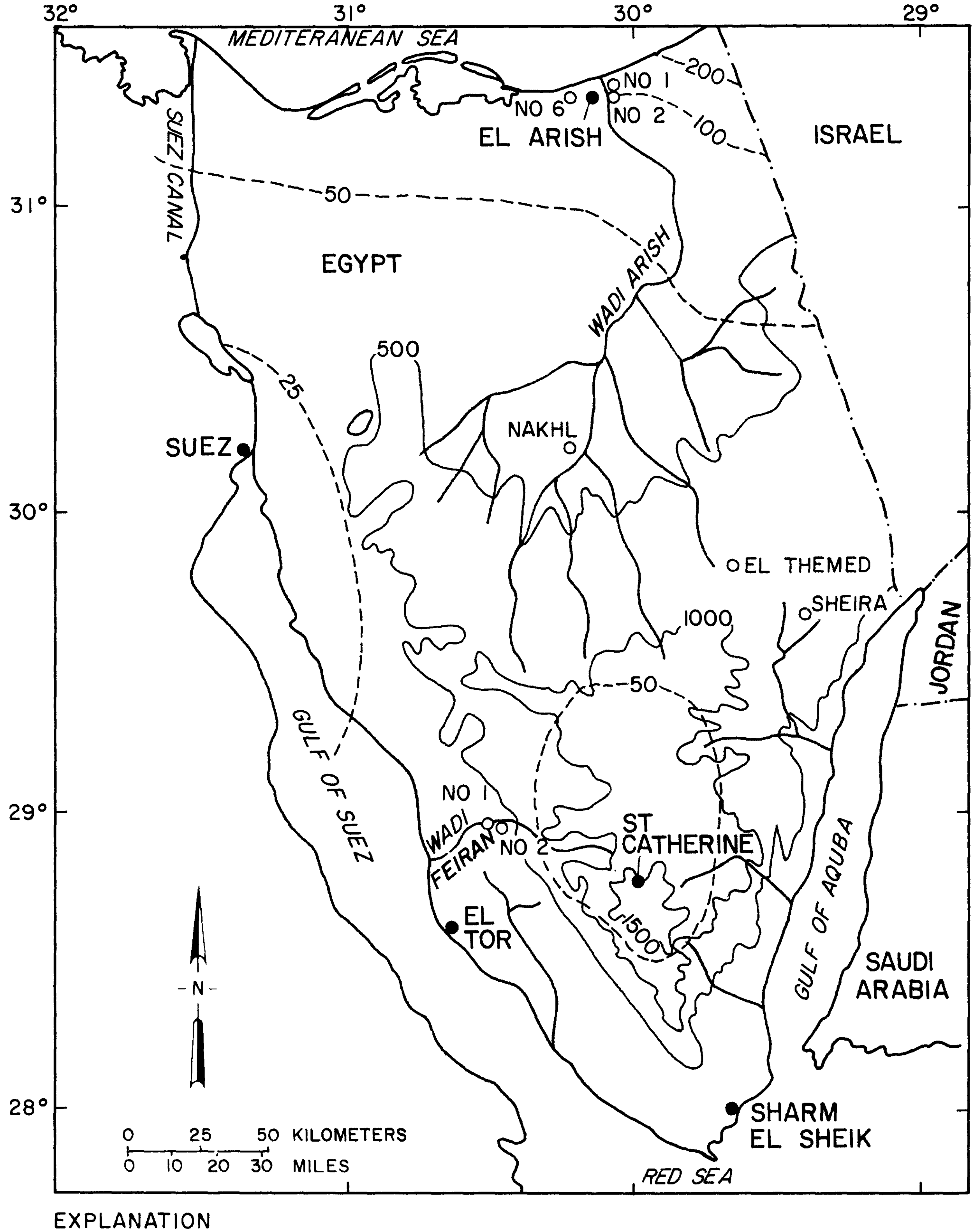
Purpose of this Report

This report presents a review of the existing log data available for boreholes in the Sinai and describes the conventional geophysical log interpretation techniques that might be applied to that well-log data base. Specific examples of the results of these techniques applied to various aquifer intervals are used to illustrate the accuracy with which the geophysical logs represent aquifer properties. These results also are used to formulate generalized aquifer-characterization methods to be used in characterizing aquifer properties. The ultimate goal is to define a consistent and reliable approach to well-log interpretation that can be applied to almost all aquifers in the Sinai region.

Geology and Hydrology of the Sinai Region

The Sinai is an arid region of desert plains and mountains located adjacent to the southeastern part of the Mediterranean Sea (fig. 1). Only the extreme northeastern corner of the Sinai region is affected by the relatively high winter rainfall associated with Mediterranean climates. With the exception of this small coastal area, yearly average rainfall in the Sinai region ranges from less than 10 to 60 mm/yr (General Meteorological Authority, Ministry of Tourism, Republic of Egypt, Unpublished data). In contrast, potential evapotranspiration ranges from 1.0 to more than 2.0 m/yr. More than half of the entire region is drained by a single watershed, Wadi Arish, which discharges into the Mediterranean at El Arish. This drainage is completely dry much of the time; discharge occurs infrequently at El Arish, and ephemeral flow occurs at various locations upstream. Wadi Arish probably provides some recharge to alluvial sediments in the wadi basin. The distribution and quantity of recharge at other locations is difficult to estimate, but cannot be large anywhere within the region.

The location of the various boreholes used in this study is indicated in figure 1, and the distribution of aquifer types in the Sinai region is shown in figure 2. Three of the boreholes mentioned in this report penetrate unconsolidated alluvial and sand dune deposits and the more calcareous and somewhat cemented sediments that are beneath them near the town of El Arish. The other boreholes in this report penetrate from 300 to 1000 m into consolidated sedimentary rocks including limestones, dolomites, sandstones, and shales (Allam and Khalil, 1989). However, there are many additional square kilometers in the Sinai underlain by fractured crystalline rocks where the potential for ground-water production, if any, remains mostly unknown.



EXPLANATION

● PRINCIPAL SETTLEMENTS

○ STUDY BOREHOLES

---25--- LINE OF EQUAL MEAN ANNUAL RAINFALL--INTERVAL, IN MILLIMETERS, VARIABLE.

—1000— TOPOGRAPHIC CONTOUR--CONTOUR INTERVAL 500 METERS. DATUM IS SEA LEVEL.

Figure 1. Location of boreholes mentioned in the text and distribution of mean annual rainfall in the Sinai Region.

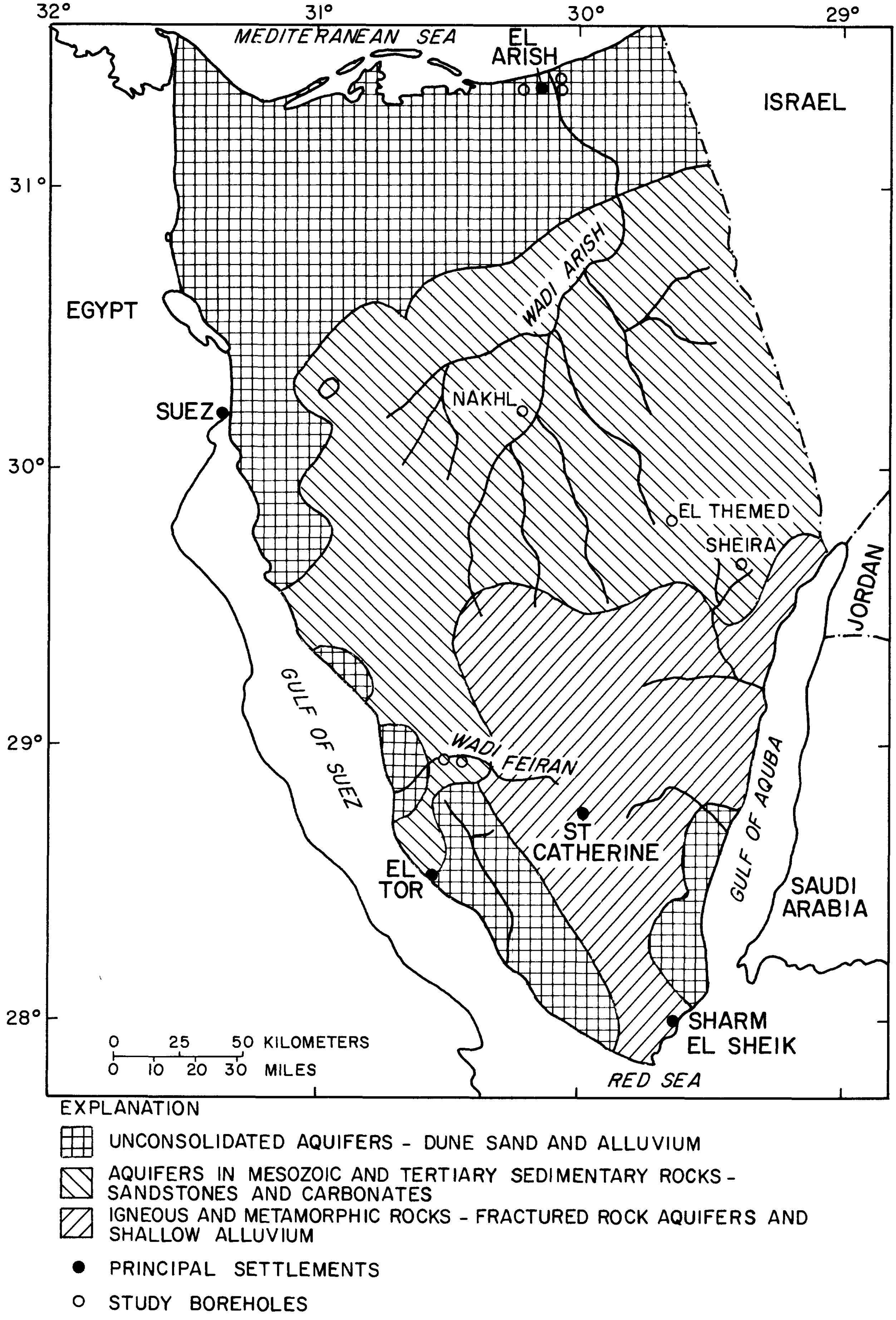


Figure 2. Distribution of aquifer types in the Sinai Region.

INTERPRETATION OF GEOPHYSICAL WELL LOGS

Description of Interpretation Techniques

The geophysical well log consists of a set of geophysical measurements made while a measuring device (the sonde) is being retrieved in the borehole. This measurement technique produces a continuous profile of the properties of the geological formation surrounding the borehole. The continuous depth scale on the log provides an important means for integrating the specific information obtained from core samples, cuttings, and water samples into the geologic column. However, the geophysical sonde measures a physical property of the formation that is different from the hydraulic properties of interest to the hydrologist. The process of geophysical log interpretation is the mathematical, statistical, or empirical process of relating the continuous geophysical measurement, or a combination of several such measurements, to one or more hydraulic properties of interest to the hydrologist.

Using the above definition for the geophysical well logs, the geophysical measurements made in boreholes can be divided into two classes: bulk properties measurements and auxiliary measurements. The bulk properties measurement includes all those geophysical measurements that can be related to a specific volume of rock surrounding the borehole. The measurement is considered to be volume averaged measurement of some bulk property of the formation (for example, gamma activity or acoustic velocity). In most situations, the measurement is not made uniformly throughout a specific volume, but integrates contributions for an extensive volume, and the extent of contribution from each element within that volume decreases with distance from the sonde. The sample volume is formally defined as the volume within that radial distance which contributes 90 percent of the measurement. In the example of the natural gamma log, 90 percent of all gamma rays detected by the sonde would originate from within that sample volume. Logs that do not measure a formation property averaged for a sample volume such as the caliper log, which measures borehole diameter, can be called auxiliary logs.

The quantitative interpretation or "inversion" of geophysical logs involves the mapping of the geophysical property measured in a specific sample volume to another hydraulic property such as porosity or permeability. Here the term "mapping" is used in the formal mathematical sense of relating one set of values to another. This mapping can be done according to a specific mathematical formula as long as a series of constraints are satisfied. In many situations this mapping amounts to the application of a series of linear relations to individual intervals of the log where background lithology remains relatively uniform. However, the process is not always that simple. Furthermore, the uniqueness theories of geophysical interpretation indicate that one cannot prove that any specific mapping is unique. In practical terms, this means that the hydrologist can never prove that any valid interpretation of a set of log data is the only possible interpretation. These arguments illustrate the importance of developing a careful formulation for geophysical log inversion based on a reasonable set of assumptions about the geophysical and hydraulic properties of the aquifers being investigated.

Geophysical Logs Routinely Used in the Sinai

A number of conventional geophysical-logging techniques have been used in the Sinai. These techniques are described in detail in such logging texts as Hearst and Nelson (1985), Tittman (1986), and Keys (1989). Unless a specific reference is cited, it can be assumed that a given interpretation technique or equation is presented in at least two of these three basic references. Typical suites of geophysical logs for representative lithologies in the Sinai are given in figure 3 (unconsolidated sediments) and figure 4 (consolidated sedimentary rocks). These include the spontaneous potential (SP), long- and short-normal resistivity, and natural gamma logs in unconsolidated sediments, and natural gamma, SP, long- and short-normal resistivity, and neutron porosity logs in consolidated sedimentary rocks. Two auxiliary logs (caliper and temperature) have been included in figure 4 because information provided by these logs can be especially helpful for the hydrologist. The SP log is listed as a bulk volume measurement because the SP log can be interpreted as a measurement of clay mineral volume fraction per unit volume if a series of specific assumptions are satisfied. The neutron porosity log has been deliberately left out of the suite for unconsolidated sediments because this log would not usually be run in an open borehole with the electric logs. The neutron porosity log is not used in this situation because the open borehole in these formations always presents the possibility of borehole-wall collapse and loss of a neutron source. In situations where the borehole is cased prior to logging, the combination of natural gamma and neutron may be used, but most electric logs cannot be made through casing.

The review of log interpretation in this report provides an outline of the the most important applications, interpretations, and quantitative inversion equations for the logs that are likely to yield useful information about aquifers of the Sinai.

The specific geophysical log responses indicated for lithologies of the Sinai in figures 3 and 4 are given for each of the conventional logs as follows:

1. Temperature log (auxiliary measurement)--The temperature log can be interpreted as a profile of formation thermal conductivity only under the rigorous assumption that there is no motion in the borehole fluid column, and there is a constant regional upward heat flow. In many continental regions, the expected thermal gradient ranges from 1.5 to 3.0 °C per 100 m. It is assumed that the fluid column remains unmixed (the temperature log is made first), and the log is obtained downward (that is, as the sonde is lowered into the borehole). In many applications in hydrology, naturally occurring or drilling induced differences in hydraulic head with depth drive flow along the borehole. This fluid motion is indicated by anomalies on the temperature log that can be seen as departures from the smooth vertical gradient (Keys, 1986). In other situations, loss of relatively cool drilling fluid results in anomalously low temperatures in formations where the fluid was lost (Keys and Brown, 1985). For example, the temperature log in figure 4 shows a smooth temperature gradient except for a single interval of anomalously low temperature from about 200 to 250 m in depth. This interval of anomalous temperature represents cooling of a fractured limestone interval where drilling fluid was lost during circulation. The

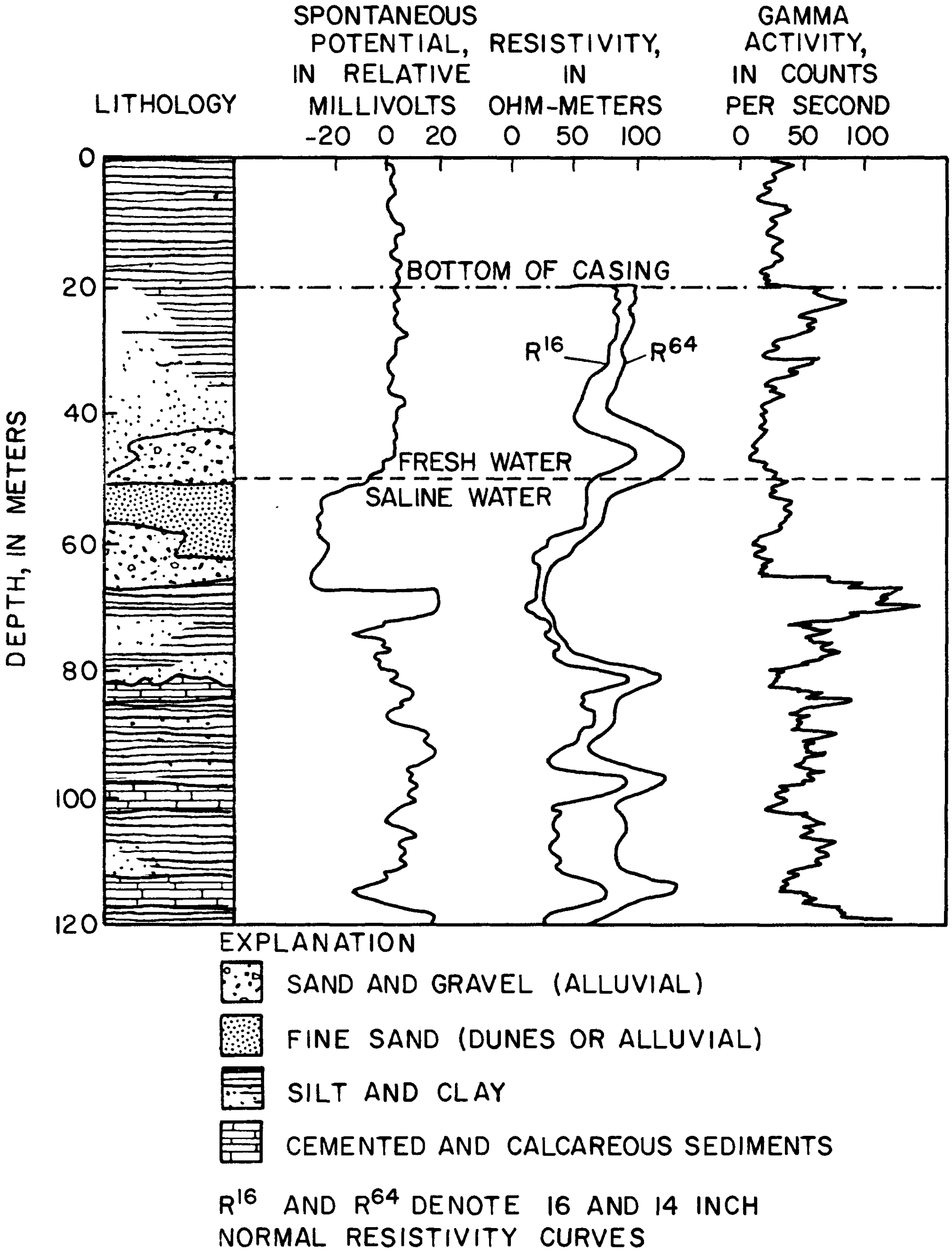
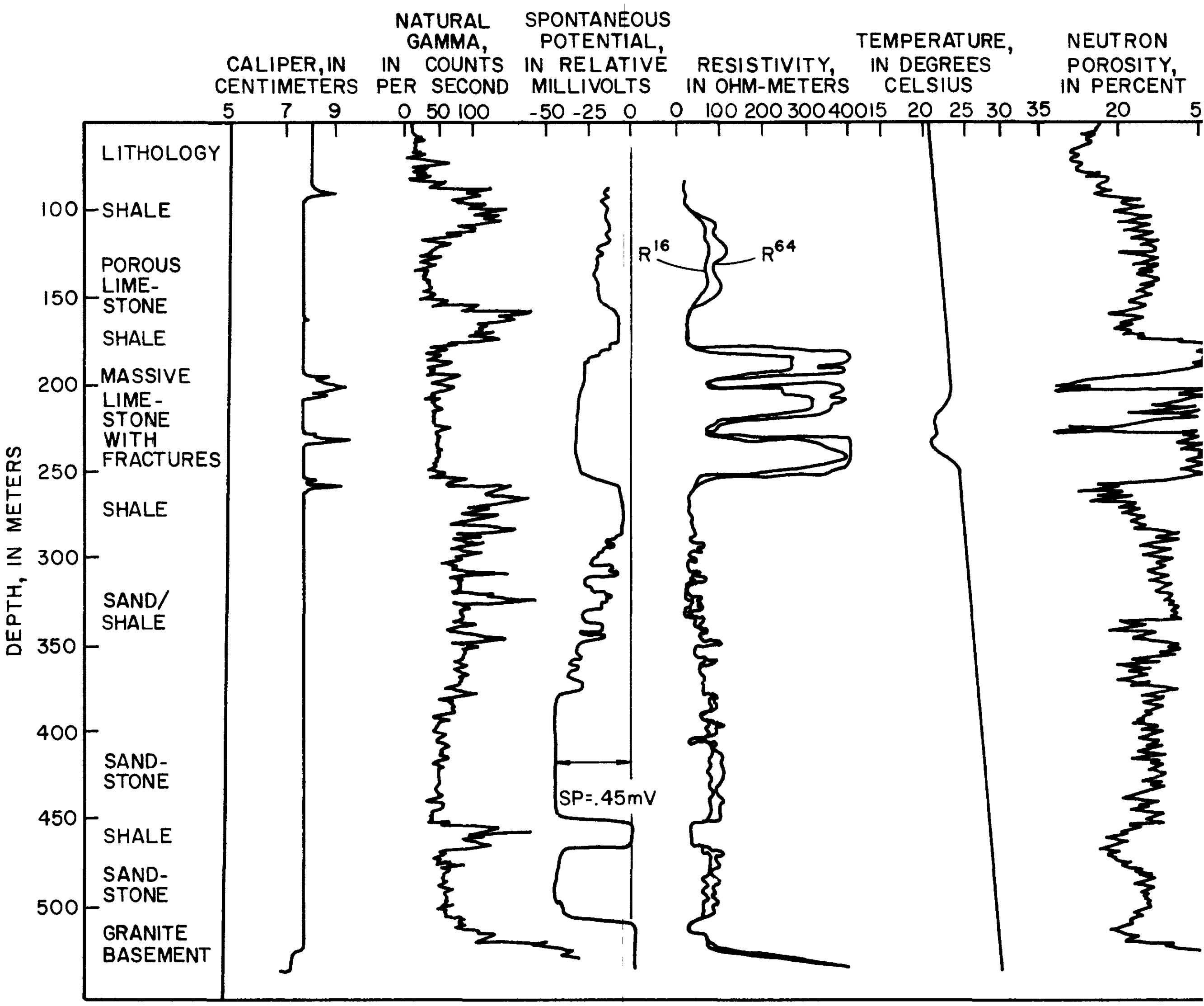


Figure 3. Typical spontaneous potential, resistivity, and natural gamma log response in unconsolidated Quaternary alluvial and sand dune sediments.



EXPLANATION

R^{16} AND R^{64} DENOTE 16 AND 64 INCH NORMAL RESISTIVITY CURVES

Figure 4. Typical caliper, natural gamma, spontaneous potential, resistivity, temperature, and neutron porosity log response in a consolidated sedimentary section.

temperature log is defined as an auxiliary log here because a bulk volume profile of thermal conductivity is not of interest to the hydrologist, whereas the indirect information about water circulation in the formation or fluid loss to permeable zones is of much greater interest.

2. Caliper log (auxiliary measurement)--The caliper log represents the borehole diameter determined from the average extension of three spring-loaded arms. The primary application of the caliper log in hydrology is to indicate those intervals where rough borehole wall or washouts have introduced large errors into such logs as the neutron porosity log, and where log response is known to be very sensitive to local borehole enlargement and "rugosity." The caliper log often is a useful indicator of fracturing (Keys, 1979). However, the thin intervals of borehole enlargement on the caliper log in figure 4 (200-250 m) only seem thin because of the vertical scale compression on the log. The caliper-log anomalies do not directly represent the mouths of fractures at the borehole wall. Instead, they represent areas of borehole wall breakage associated with the mechanical weakening at the borehole-fracture intersection. These caliper anomalies could represent fractures, bedding planes, or solution openings. Generally, caliper-log anomalies indicate the intervals where fractures intersect boreholes, and this result is expected to apply to boreholes in most of the Sinai (Keys, 1979; 1989).

3. Gamma log (bulk volume measurement)--The gamma log provides a measurement (in counts per second, CPS) that is proportional to the natural radioactivity of the formation (radioisotope concentration per unit volume). Actual counts depend upon detector size and efficiency, but often are normalized in API units, where 200 API units are defined by detector response in a specially constructed environment designed to simulate a typical shale. Sample volume for the gamma log is about 0.5 m in diameter.

The usual interpretation of the gamma log is that measured counts are proportional to the quantity of clay mineral present. This assumes that natural radioisotopes of potassium, uranium, and thorium occur as exchange ions attached to clay particles, so that the correlation is between gamma counts and cation exchange capacity (CEC); however, this relation is not always true. The primary application of gamma logs in hydrology is to assume an inverse linear correlation between gamma counts and average grain size (Keys, 1986). This relation can become invalid (1) if there are radioisotopes in the mineral grains themselves (immature sandstones or arkose), and (2) if there are differences in the CEC of clay minerals in different parts of the formations. Both of these situations are at least possible in the Sinai. The former situation would be likely in basal conglomerates composed of granitic debris, and the latter where one clay occurs as a primary sediment in shales, and another as an authigenic mineral deposited in pore spaces during diagenesis.

Another issue is the problem of nuclear statistics in gamma logging. Because nuclear disintegrations occur randomly, the gamma counts need to be averaged for a long enough time period to achieve a relatively stable count rate. Statistics determine the minimum time constant (counting period for averaging). The time constant in turn determines the maximum logging speed. If the sonde travels more than about 0.5 m (the sample volume dimension for the natural gamma log) in one time constant, the averaging of counts will degrade the vertical resolution of the log. The best way to check this is to increase the time constant, decrease the logging speed and then check to see if there is a significant change in appearance of the log for a repeat interval that has thin beds. This gamma log repeat test needs to be done for an interval where the gamma counts are relatively small in comparison with the rest of the formation (Kerford and Georgi, 1990).

The assumption of linear relationship between clay mineral fraction and measured gamma activity is used to produce a shale fraction calibration for a gamma log of the form:

$$C_{sh} = (G - G_{ss})/(G_{sh}-G_{ss}) \quad (1)$$

where C_{sh} is the shale volume fraction;
G is the measured gamma activity;
G_{ss} is the gamma activity; and
G_{sh} is the gamma activity measured in shale measured in a clean sandstone.

For example, the values for these parameters estimated from the gamma log in figure 4 would be G_{sh} = 150, and G_{ss} = 20 CPS, respectively.

4. Spontaneous potential log (bulk volume measurement under restrictive conditions)--This log measures the naturally occurring differences in voltage or electrical potential between an electrode at some depth in the borehole and a surface electrode grounded in the mud pit or adjacent moist soil. These potential differences (measured in millivolts, mV) can arise from several different sources, but conventional SP log interpretation is based on the potential differences produced when there is a difference between the solute content of the borehole fluid and that of the water saturating the formation. In order for this particular form of natural potential difference to exist, three conditions need to be satisfied: (1) There needs to be a contrast between the salinity of the borehole fluid and that of the formation water; (2) there needs to be a shale bed present; and (3) there needs to be some minimum interconnected porosity in an adjacent "clean" or clay-mineral-free formation. If these conditions are satisfied, the magnitude of the measured potential differences can be related to the salinity contrast between borehole fluid and formation waters, and the variations in SP on the log can be used as a clay mineral indicator (Alger, 1966). This second attribute of the SP log allows the log analyst to compare the SP and natural gamma logs. If the two logs indicate almost exactly the same trends, then the log analyst has a great deal of confidence that the SP log can be interpreted according to established methods. The sample volume of the SP log interpreted as a bulk clay-mineral fraction indicator depends on formation properties, but is usually 0.5 m or slightly greater in diameter.

If it is verified that the SP log indicates the same trends as the gamma log, then the measured SP values (in millivolts) can be related to the electrical conductivity values of the borehole fluid and formation waters by using the following equation:

$$SSP = - K \log (R_{mf}/R_{w}) \quad (2)$$

where the SSP is the "static spontaneous potential" defined as the maximum potential difference, or that which would develop between a clay-free sandstone and a sand-free shale; and K is a temperature-dependent constant for a sodium chloride (NaCl) solution, which is given by the formula:

$$K = 64.9 + 0.238\ T \tag{3}$$

and R_{mf} and R_w are the electrical resistivity values (inverse of conductivity values) of the borehole fluid and formation water, and the temperature, T is given in degrees Celsius. The resistivity of the borehole fluid is denoted with the subscript mf to indicate that the resistivity of interest is that of the borehole fluid or "mud" after it has been forced through the filtercake (hence the term "mud filtrate"). In almost all situations, R_{mf} is equal to or slightly less than the resistivity of the borehole fluid. Note that not only must the constant in the equation be selected for a given formation temperature, but the two resistivity values (R_{mf} and R_w) are temperature dependent, too. R_w generally is given for formation temperatures, and K and R_{mf} need to be extrapolated to that same temperature. Resistivity values given at temperature T_1 can be extrapolated to those at another temperature, T_2 according to the formula:

$$R(T_2) = R(T_1)\ (T_1+21.5)/(T_2+21.5) \tag{4}$$

where T_1 and T_2 are given in degrees Celsius. The SSP will be negative (normal SP log) when the formation water is more saline than the borehole fluid, and positive when the reverse is true, but a valid SP log will be obtained in either situation. Formation temperatures measured by a temperature log may have been affected by circulation of drilling fluid or by influx of formation waters. For this reason, formation temperature most often is estimated by linear extrapolation from yearly average temperature at the surface (taken as the temperature of near-surface ground water) to measured bottom-hole temperature (where circulation has not appreciably cooled adjacent rocks).

The single most important step in interpreting the SP log is to select a correct SSP value (Kwader, 1985). It is assumed that an interval of shale can be found because a valid SP interpretation cannot be made when such a shale is not present. However, there is no guarantee that all sandstones are completely clay-mineral free, and bed edge effects can obscure the full SP log deflection if sandstones are not thick enough. If all evidence indicates that a consistent SP value can be obtained for a shale-free sandstone, then the SSP can be read as the difference between the SP value in the sandstone and the SP value in the shale. For example, there is a consistent SP difference of about -45 mV between the sandstone and the underlying shale in the interval from 400 to 450 m in depth in figure 4.

If the probable presence of shale or clay mineral in sandstone makes an SSP value impossible to determine from the log (for example, in the depth interval from 300 to 350 m in fig. 4), then the SSP can be estimated by correcting for shale content according to the formula

$$SSP = SPa/(1-C_{sh}) \tag{5}$$

where SPa is the apparent or measured maximum SP deflection in the sandstone, and C_{sh} is the shale fraction in that sandstone determined using the gamma log, and assuming the gamma log is known to be a valid indicator of shale or clay-mineral content.

The solution of the SSP equation (2) gives a value of R_w at formation temperature if R_{mf} is known. R_w can be related to water quality by using equation 4 to relate the R_w interpretation at formation temperature to R_w at 25 °C. Generally R_w at 25 °C is related to dissolved solids in many ground waters according to the relation (Fishman and Friedman, 1989):

$$DS = \frac{0.65}{R_w} \times 10^4, \qquad (6)$$

where R_w is given in ohm-meters, and DS is given in milligrams per liter.

5. Electrical resistivity log (bulk volume measurement)--A variety of electrical sondes have been designed to measure the electrical conductivity of formations (most often expressed as resistivity in ohm-meters). The sample volume depends on both sonde configuration and formation properties. Resistivity logs most often run in the Sinai consist of the combination long and short normal resistivity logs (fig. 5). In these logs, the resistivity is proportional to the potential difference between a downhole and surface electrode when a known current is applied to the formation by the sonde. The AM spacing in the sonde is the separation between current and potential electrodes downhole. The sample volume is approximately equal to two times this spacing, and the exact value is dependent on formation properties. In the conventional long- and short-normal combination, the AM spacings are about 0.41 and 1.6 m (16 and 64 in.).

According to the theory of log interpretation, the long normal has a larger sample volume and, therefore, measures rock properties deeper into the surrounding formation. However, both long- and short-normal logs are affected by the borehole fluid and the formation, and both are dependent on bed thickness. For 20-cm diameter boreholes, the short normal reads closer to actual formation resistivity (R_t) than the long normal. This effect is illustrated in figure 5. The sample volume for both normal logs contains a combination of formation and borehole fluid. In general, the borehole fluid will be more conductive than the combination of formation water and mineral. As the ratio of formation resistivity (R_t, where the subscript denotes "true" formation values) to mud resistivity (R_m) increases and the ratio of AM spacing to borehole diameter increases, the measured resistivity (R_a, where the subscript "a" denotes apparent) approaches R_t. However, the geometrical current focusing effects of the borehole result in an overshoot (known as the departure effect), so that R_a values actually overestimate formation resistivity for some combinations of electrode spacing and formation properties. For the R_t values typical of sandstones in the Sinai (20-200 ohm-m), typical mud resistivity values (0.5-5 ohm-m) and borehole diameters (about 20 cm), figure 5 indicates that the short-normal log generally reads close to R_t.

The short-normal resistivity values might be used as reliable estimates of R_t under typical aquifer in the Sinai conditions, except that the invasion of the formation by borehole fluid can cause the short-normal log to measure the resistivity of the formation invaded by borehole fluid rather

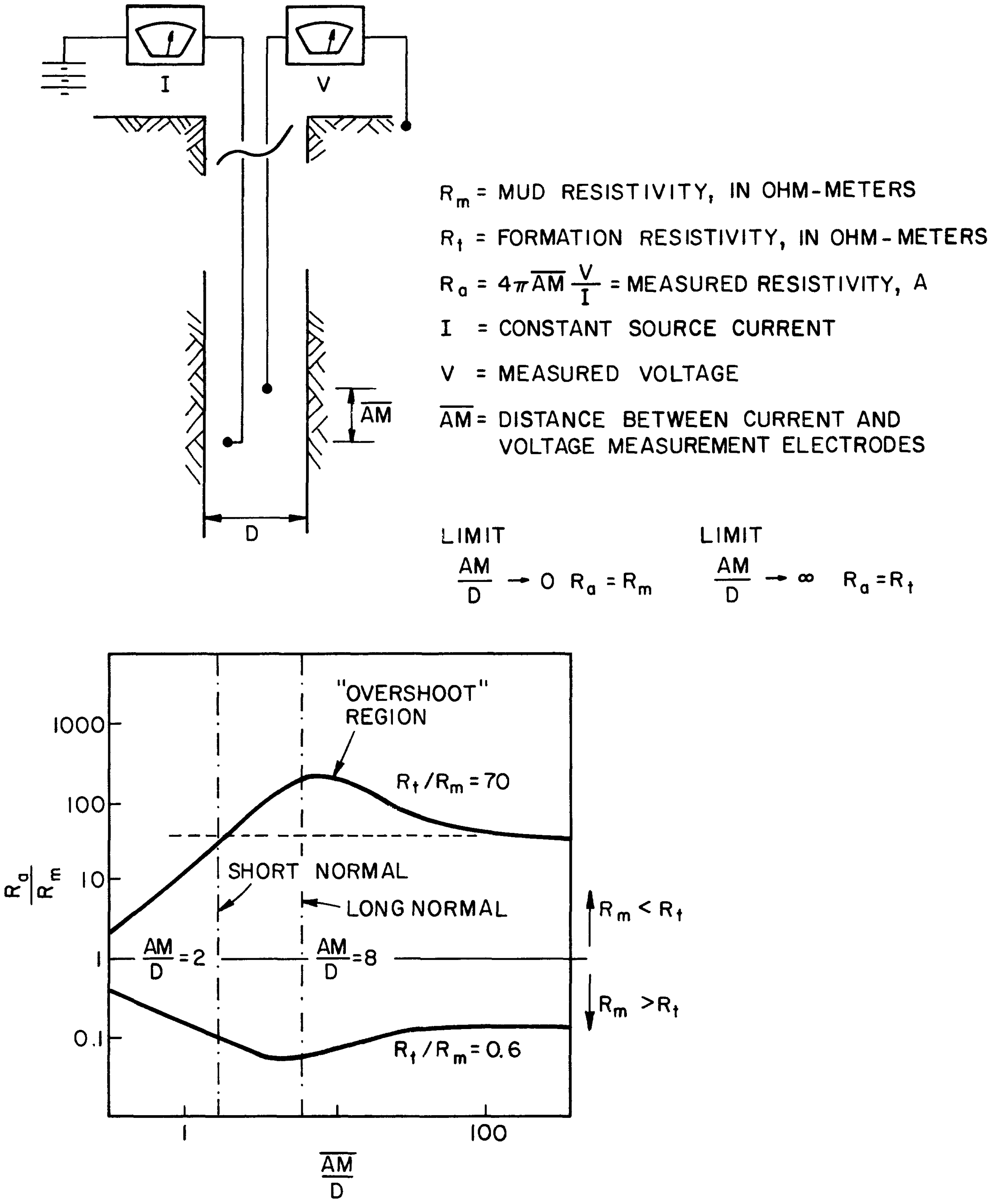


Figure 5. Effects of borehole correction on measured resistivity values for long- and short-normal measurements in a 20-cm diameter borehole; note that R_a is generally closer to R_t for the short normal.

than the formation saturated with natural ground water. The presence of invasion generally can be recognized as the indication of greater R_a values on the short-normal log than those indicated by the long normal. This effect contrasts with the expected indication of greater values of R_a for the long-normal log because of the overshoot effect in figure 5. These considerations generate two basic interpretation rules for aquifers in the Sinai:

if $R_a^{64} > R_a^{16}$	Expected departure effect; short normal more accurate for R_t.
if $R_a^{16} > R_a^{64}$	Invasion has reversed the expected departure effect; long normal more accurate for R_t.

Unless formation waters are unusually saline (>5000 mg/L DS), invasion would produce a relatively small increase in short-normal resistivity.

Once the normal resistivity log measurement has been interpreted to correct the measured resistivity values (R_a) to give the formation resistivity (R_t), the electrical conductivity of the formation can be related to the physical properties of the formation. These corrections can only be applied where beds are thick enough to avoid thin-bed effects (thickness greater than 6 AM spacings). The fundamental assumption is that current is carried through the formation by two parallel paths: one through the pore spaces and one through the conductive clay minerals present in the formation. This assumption relates the total conductivity to the resistivity values along the two paths according to the equation:

$$\sigma = 1/R_t = (1-C_{sh})/R_p + C_{sh}/R_{sh} \qquad (7)$$

where σ is conductivity of the formation in siemens per meter, R_p is the resistivity of the saturated pore network, R_{sh} is the resistivity of the shale, and C_{sh} is the volume fraction of clay mineral or shale present in the formation. This equation clearly applies to those situations where clay or shale is present as distinct thin beds, and does not apply to situations where clay mineral is present as dispersed or disconnected deposits (such as authigenic clays in pore spaces).

In many situations, aquifers are assumed to be free of clay mineral, and total conductivity is related to the inverse of the resistivity of the network of pore spaces. However, it remains unclear how the resistivity of such a tortuous network of pores might be related to the resistivity of the water saturating those pores. A property of the pore network, formation factor (F), is defined according to the following equation:

$$F = R_t/R_w \qquad (8)$$

where R_t is the resistivity of the saturated formation, and R_w is the resistivity of the saturating fluid. It has been determined by empirical studies that the formation factor can be related to porosity (ϕ) in saturated formations by the equation known as Archie's law (Archie, 1942):

$$F = 1/\phi^n \qquad (9)$$

where n is known as the cementation exponent. In general, n is found to vary from 1.3 to 2.0, fall in the range from 1.3 to 3.0, and averages about 1.5 (Jorgensen, 1989). The best fit to various data sets indicates that n may be as low as 1.2 in sandstones. The cementation exponent is somewhat greater than 2.0 in carbonates. A comprehensive study of numerous sandstone reservoirs done by the petroleum industry determined that the following relation, known as the Humble Equation, produced the best fit for these data (Winsaur and others, 1952):

$$F = 0.62/\phi^{2.15} \tag{10}$$

In this report, the generalized version of Archie's law (eq. 9) is used and n = 2.0 because both sandstone and carbonate aquifers are of interest, and little data are available with which to define the cementation exponent by the usual empirical methods. It also is convenient to use an integer for the cementation exponent because square roots are much easier to use in the inversion of the interpretation equations.

One final note of caution is needed in discussing Archie's law and its application in hydrology. The neglect of the mineral conduction term in equation 7 requires that the ratio of mineral conduction (either conduction by the mineral proper or solid-state conduction along the mineral surface) to pore space conduction be very small. In aquifers saturated with fresh or brackish water, the pore-space conductivity becomes small, and the ratio of pore to mineral conductivity may not be small even if the minerals are not very conductive. In the situation where all mineral grains are nonconductive, surface conduction mechanisms associated with the pore fluid-solid interface become important when pore-fluid salinity is minimal. Experimentation with clean, mature sandstones indicates that such mineral-grain surface effects cannot be neglected when R_w becomes greater than about 10 ohm-m, corresponding to about 500 mg/L of dissolved solids at 25 °C (Biella and others, 1983). In the Sinai, most waters produced from deep sedimentary aquifers have salinity values ranging from 800 to 4000 mg/L in dissolved solids, so that Archie's law can be used whenever the formation is assumed to be free of clay minerals.

In application of Archie's law to sandstone, two inversion relations are important. When porosity is known from the neutron porosity log, then the equation can be solved for water quality.

$$R_w = \frac{R_t}{F} = R_t \phi^n \tag{11}$$

If R_w is considered known from either water sampling or interpretation of the SP log, then Archie's law can be solved for porosity under the assumption that n = 2:

$$\phi = (R_w/R_t)^{1/2} \tag{12}$$

In both of these equations, the porosity (ϕ) is expressed as a volume fraction, so conventional expression of porosity in percent requires multiplication by 100.

6. Neutron log (bulk volume measurement)--The neutron logging sonde uses a source of relatively energetic neutrons to measure the ability of the formation to slow and absorb neutrons. The neutron log measures the rate at which neutrons are backscattered to a detector located from 20 to 50 cm uphole from the source. If this detector is shielded from slow or thermal neutrons, then the rate at which neutrons are detected (given in counts per second) is inversely correlated with the amount of water in the formation. However, the relation is nonlinear. The following relation can be used to express the neutron counts at the detector to the saturated porosity of the adjacent formation:

$$N = A - B \log (\phi) \qquad (13)$$

Where N is the neutron log measurement in counts per second, A and B are calibration constants, and ϕ is porosity given in percent. The sample volume for the epithermal neutron sonde is about 1 m in diameter when typical source-to-receiver spacings are used. The constants in equation 13 often are determined for a particular sonde in a borehole of a certain diameter by measuring the neutron sonde counts in specially designed calibration pits. These constants can be used only in situations where boreholes have the same diameter and the lithology is the same as that in the calibration pits. However, further empirical studies of neutron log response can be used to adjust the values of A and B to suit the specific value of borehole diameter and lithology type of interest. For single-detector epithermal neutron logs, diameter corrections can be large (several percent porosity or more), whereas lithology corrections are small (generally less than 1 or 2 percent porosity).

A hypothetical example of the calibration process can be given to illustrate how the constants A and B might be evaluated. For example, assume that the sonde output is 1,000 CPS in a calibration pit where the surrounding formation has a known porosity of 3 percent (limestone 1). The sonde output then is measured at 500 CPS in a second calibration pit where the porosity is 20 percent (limestone 2). These two count rates can be used to set up a pair of simultaneous equations for A and B:

LIMESTONE 1: $1{,}000 = A - B \log (3) = A - 0.48B$

LIMESTONE 2: $500 = A - B \log (20) = A - 1.3B$

Subtracting the two equations gives:

SOLUTION: $500 = (1.3-0.48)\,B \qquad B = 500/.82 = 610$

$1{,}000 = A - 0.48B \qquad A = (1{,}000 + 293) = 1{,}293$

By using these calibration constants, a measured neutron log response of 700 CPS would correspond to:

$$\log (\phi) = (A - 700)/B = .97$$
$$\phi = 9.3 \text{ percent}$$

In hydrogeology, one of the most important considerations in neutron log interpretation is distinguishing between effective and noneffective porosity. The neutron log detects the hydrogen present in water in the formation whether that water is free to move in interconnected pores or tightly bound as water of hydration associated with clays and other minerals. Shales and clay deposits have apparent (noneffective) porosities ranging from 20 percent for relatively indurated shales to 60 percent or more for Quaternary lacustrine clays. The clay mineral response of neutron logs almost always overwhelms the smaller porosity variations in sandstones and granular carbonates. For this reason, the following shale correction often is applied to calibrated neutron logs:

$$\phi_{nc} = \phi_n - C_{sh}\, \phi_{nsh} \quad (14)$$

where ϕ_{nc} is the corrected neutron porosity, ϕ_n is the uncorrected neutron porosity (calibrated neutron log response), C_{sh} is the clay mineral volume fraction (from eq. 1) and ϕ_{nsh} is the apparent neutron porosity of a thick shale section. For example, the neutron log in figure 4 indicates that the thick shale near 450 m in depth has an apparent porosity of 30 percent. This value for ϕ_{nsh} would be used in addition to C_{sh} determined from the gamma log to estimate the effective porosity (ϕ_{nc}) from the total porosity (ϕ_n) shown in figure 4.

Other Potentially Useful Geophysical Logs

Several other geophysical logs, which are currently not run in the Sinai, could be of use in further defining aquifer properties. One of these, the fluid conductivity log, is relatively inexpensive to run and provides important information about water stratification within the borehole. The fluid conductivity log measures the electrical conductivity in the borehole fluid column, and is therefore considered an auxiliary measurement. This log is normally run before the borehole is disturbed, with measurements made while lowering the sonde, as in the temperature log. When water samples are obtained after an extended production period and production zones are well-defined in terms of specific screened intervals, the water quality analysis can be directly related to formation waters in the aquifer. When an open borehole has not been pumped, or where there is natural movement under ambient hydraulic-head differences between formations, water quality may vary along the borehole. Profiles of borehole fluid conductivity provide an indication of how water sampled at specific depths relates to the water in other parts of the borehole. The distribution of fluid conductivity also provides an indication of zones where fluid is entering and exiting the borehole under ambient hydraulic head conditions.

A geophysical log closely related to the fluid conductivity log is the single-point resistance log. The differential version of this log most commonly used in ground-water applications measures the potential difference between two electrodes spaced several centimeters apart on the body of a cylindrical probe. This potential difference cannot be expressed as a bulk resistivity of the formation around the borehole, but single-point resistance measurements, expressed in ohms, depend upon borehole fluid salinity and the resistivity of the borehole wall rocks. The single-point resistance log has the advantage of not being distorted by extremely thin beds, a common problem with normal resistivity logs (Keys, 1979). One of the most important thin beds in hydrogeology would be the thin layer of altered rock surrounding permeable fractures. Although the single point resistance log does not provide a direct, quantitative measurement of borehole fluid conductivity, the single-point resistance measurement contains qualitative information about borehole fluid salinity, borehole wall enlargements, and fractures or thin beds. Like the fluid conductivity log, this log is inexpensive, easy to run, and could contribute to the geophysical logging program in the Sinai.

In the logging completed to date in the Sinai, the primary porosity log has been the neutron log. Other porosity logs are valuable, and they can contribute to porosity measurements in different ways. The acoustic logging probe measures the effective acoustic velocity of the formation around the borehole. This velocity can be calibrated in porosity units by using information about the acoustic velocity of the minerals present in the formation. The acoustic logging system is relatively complex and requires some experience in its application. However, this logging system has the advantage of not using a radioactive source, and acoustic logs can be run quickly because nuclear statistics and time constants are not involved. The acoustic log requires the same sort of clay-mineral correction as used for the neutron log. Although not expected to make a major contribution in the Sinai logging program, the acoustic logging system could be an effective alternative to neutron logging in deeper, consolidated formations.

Another potentially useful logging system for hydrologic applications in the Sinai is the gamma-gamma or density logging system. In this logging system, energetic gamma rays are produced by a radioactive source such as cesium or cobalt, and the backscattered gamma rays or photons are measured for some distance uphole are measured. This logging system usually is provided in the form of a compensated system, where gamma rays are counted at two different source-to-receiver spacings. This approach enables the log to be compensated to some extent for the effects of the gaps between the tool body and the formation caused by borehole wall rugosity. The main advantage in using this system in the Sinai would be the production of porosity logs that are relatively insensitive to clay minerals. This also is a relatively sophisticated logging system to use, and one that involves a radioactive source. However, the source generally is not as strong as that used for neutron logging, and the compensated density log sometimes provides more accurate porosity data than the neutron log in consolidated formations. In unconsolidated formations, a primary control of formation permeability is the absence of clay mineral, so the accentuated clay mineral response of the neutron log is an advantage (if it can be correctly quantified), and the neutron log is probably the porosity log of choice when logging unconsolidated sediments through casing.

Unconsolidated Sediments in the El Arish Area

Identification of Aquifers and Saline Water

One of the important concerns about ground water in the El Arish area is the possibility of saline water intrusion associated with ground-water withdrawal because production wells are located within a few kilometers of the Mediterranean Sea. Geophysical logs can provide an indication of the depth at which saline formation waters occur in the vicinity of boreholes. Saline water is indicated on resistivity logs by the increased conductivity of pore spaces filled with saline water in comparison with pores saturated with fresh or brackish water, assuming a constant porosity. However, local decreases in formation resistivity can be related to either increases in pore water salinity or increases in clay content or porosity. For this reason it is difficult or impossible to uniquely attribute variations in formation resistivity to changes in pore water salinity on the basis of electrical measurements alone. The dependence of formation resistivity on clay-mineral content and salinity of pore waters indicates that a second, independent geophysical log is required to provide an indication of lithology, so the effects of salinity on electric log response can be separated from those of clay minerals.

An example of the use of two geophysical logs to interpret the clay-mineral content and salinity of pore waters in unconsolidated sediments is shown in figure 6. In this borehole located near El Arish, the gamma and short-normal logs indicate that formation resistivity varies because clay-mineral content and pore water salinity vary with depth. In the upper part of the borehole, ground water is relatively fresh, and small resistivity values correspond to clay-rich intervals. It also is apparent that resistivity values decrease overall with depth as ground water becomes more saline.

There is a general correspondence between clay-rich sediments identified on the lithology log and the large local gamma values and small resistivity values on the logs in figure 6. The small discrepancies between the depths and thickness of lithologic units identified on the lithologic log and those indicated on the gamma and short normal logs are attributed to the time lag required for cuttings to be carried to the surface. In general, the continuous depth scale on the geophysical logs provides a more detailed and accurate depth profile of the sediments along the borehole than the set of descriptions given by the driller on the basis of cuttings carried to the surface. The combination of continuous depth profile provided by the geophysical logs and direct lithologic information provided by the driller's log presents a unique description of the stratigraphy along the borehole that would not be available from either geophysical or driller's logs alone.

The depth at which the contact between fresh and saline waters occurs can be shown by overlaying the reversed resistivity (short-normal) log on the gamma log (fig. 6). In the upper part of the borehole, the two logs almost coincide because the response of both logs is controlled primarily by clay mineral content. Near 39 m in depth, the trend in the reversed short-normal log begins to depart from that of the gamma log. This departure indicates the depth where increased pore fluid salinity begins to

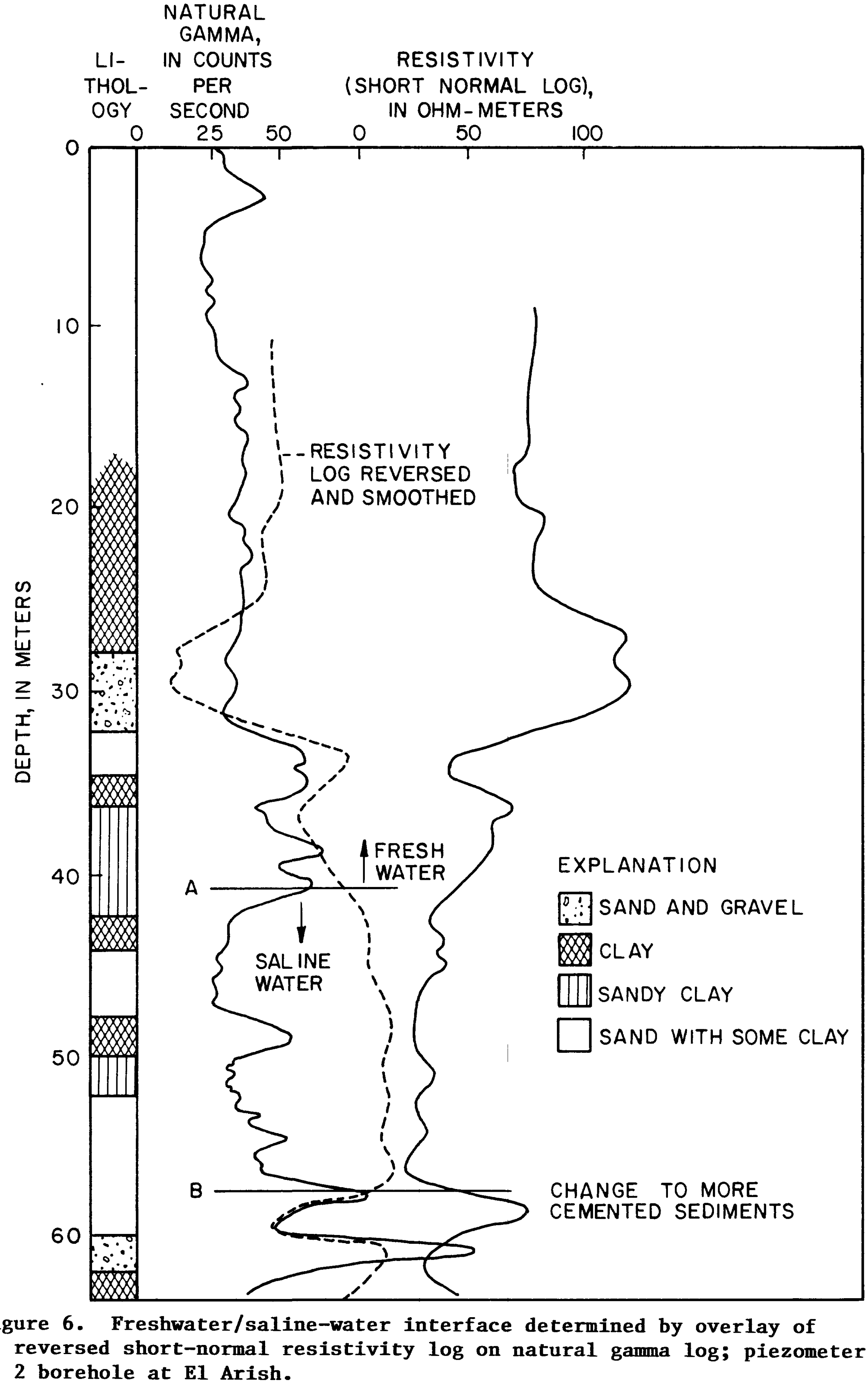


Figure 6. Freshwater/saline-water interface determined by overlay of reversed short-normal resistivity log on natural gamma log; piezometer no. 2 borehole at El Arish.

become significant. The combination of electric and gamma logs indicates that there is an abrupt increase in pore fluid salinity immediately below the clay zone identified by the driller's log about 42.5 m in depth (A in fig. 6). Still further down the borehole, a second change in the relation between short-normal and gamma logs is indicated at about 58 m (B in fig. 6). At this depth, large resistivity values again are indicated on the normal log. These large values could indicate a return to less saline water conditions or to substantial increase in the cementation of the sediments (in the form of both a decrease in porosity and increase in interstitial clay). The latter is interpreted as more likely, because the driller's log indicates penetration into older, more calcareous sediments known to underlie the unconsolidated sediments near El Arish.

A second example of the interpretation of natural gamma and normal resistivity logs is illustrated in figure 7. Both logs indicate the vertical distribution of clay mineral in the clay-rich intervals described in the lithologic log. However, the spontaneous potential log for this borehole also seems valid, and generally indicates the same distribution of clay minerals as the gamma log. The correlation between the gamma and SP logs indicates that SSP values for relatively clay-free intervals can be used to infer variation in the salinity of formation water with respect to the salinity of the borehole fluid. Both the SP and resistivity logs indicate a downward increasing trend in formation water salinity. The overlay of the reversed short normal log on the gamma log and the negative relative spontaneous potentials indicate that formation waters are more saline than the borehole fluid in the sand bed at about 43 m in depth (A in fig. 7). The formation water seems to become more saline in the deeper sand bed that extends from 46 to 52 m in depth (assuming ϕ is approximately the same in "clean" zones; B in fig. 7), and may become even more saline in the coarsest beds within the interbedded sand and clay extending from 54 to 65 m in depth. In general, the logs indicate that aquifer water becomes saline in a series of steps within permeable beds separated by clay-rich intervals rather than there being a single, saltwater-freshwater interface. The logs also indicate that the close correlation between SP and gamma logs breaks down at about 64 m in depth (C in fig. 7), where another lithologic aspect (calcareous cementation) becomes a factor in the relation between geophysical measurements and sediment properties.

Correlation of Geophysical Well Logs with Surface Resistivity Surveys

Surface resistivity surveys provide horizontal maps of the average subsurface resistivity and vertical profiles of resistivity variations with depth. These surveys present the same difficulties to the log analyst as electric logs in differentiating resistivity variations associated with variations in water quality from resistivity variations associated with the distribution of clay minerals in the subsurface. Geophysical logs provide a means for calibrating the depths inferred for various resistivity layers interpreted from the surface surveys. Even more importantly, the geophysical logs provide multiple measurements that yield the information needed to determine clay-mineral fraction and formation water salinity. This information can be useful in developing unique interpretations for surface resistivity data.

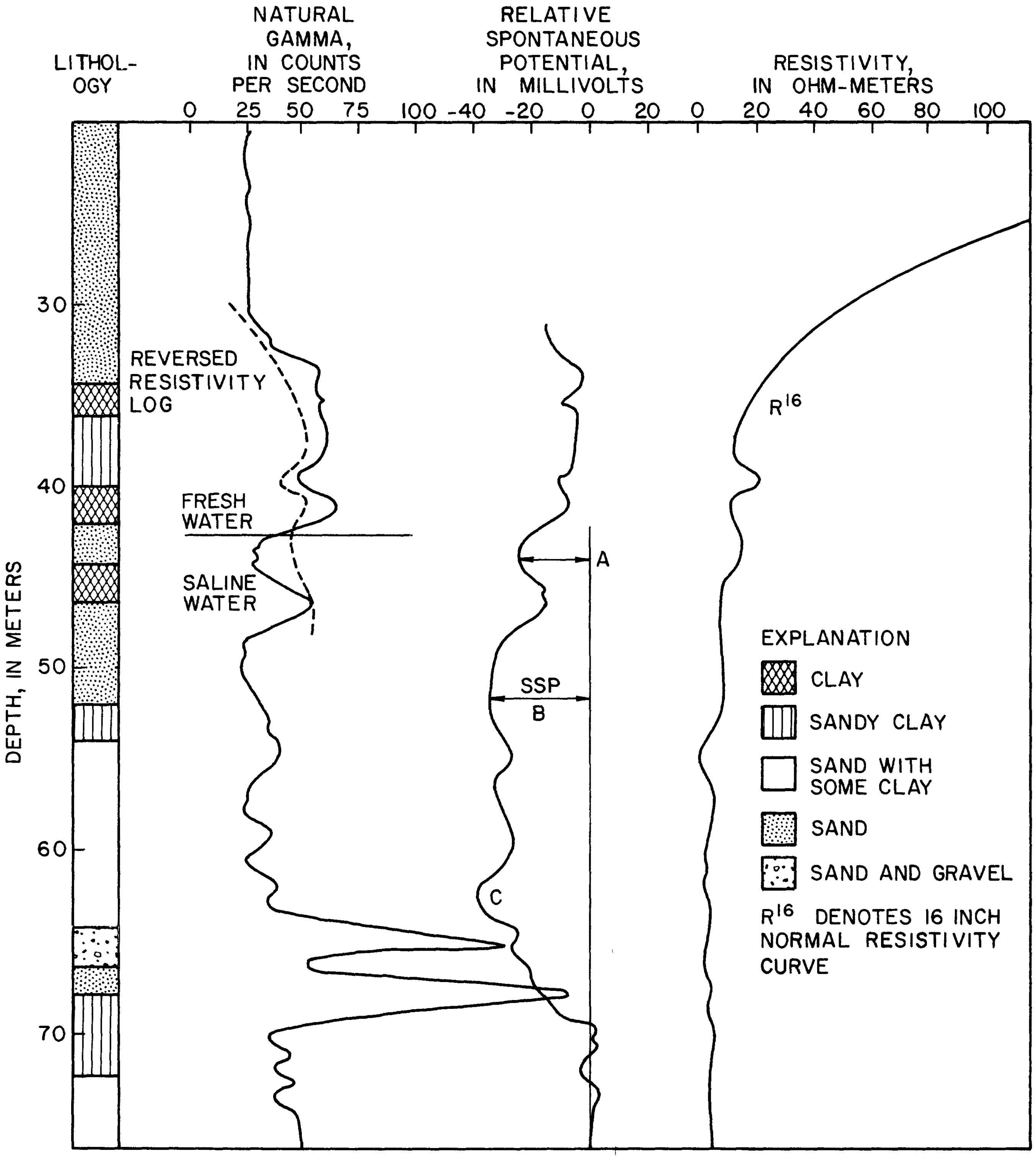


Figure 7. Freshwater/saline-water interface determined by a combined resistivity, natural gamma, and spontaneous potential log analysis; piezometer no. 6 borehole at El Arish.

Probably the single greatest difficulty in relating well-log-derived information to the surface resistivity survey is the difference in scales of investigation. The well logs provide measurements averaged for a small volume adjacent to the borehole, whereas the surface resistivity surveys provide information averaged over a scale of 100 m or more. One approach to the scale problem is to correlate the geophysical logs from two or more boreholes located within the surveyed area. An example of such correlation is illustrated for the El Arish area in figures 8 and 9. Two surface resistivity profiles and the distribution of resistivity layers along those profiles are shown in figure 8. The depths of the resistivity layers have already been adjusted to agree with the resistivity profiles obtained from the geophysical logs. Comparison of the lithology indicated by the gamma logs from two boreholes located along one of the surface resistivity profiles is illustrated in figure 9. The correlation of the logs for a separation of about 470 m indicates that clay-rich intervals within the main aquifer are continuous for at least that distance.

Comparison of this result with the distribution of formation water salinity indicated in figures 6 and 7 demonstrates that the internal structure within the aquifer exerts an important control on the distribution of salinity in the aquifer. For example, the resistivity profile in figure 8 indicates a smoothly rising freshwater-salinewater interface, whereas the two geophysical logs located 470 m apart along that profile indicate that the same clay-rich layer separates freshwater-saturated sand layers above the clay from sand saturated with saline water below the clay. The profile of formation water salinity inferred from figure 7 indicates that the saline water extends much higher in the aquifer than would be inferred from the resistivity profile in figure 8. Both of these results indicate that the dynamics of saline-water intrusion in the El Arish area may not be as simple as inferred from the surface resistivity profiles. However, these results are based on the detailed analysis of geophysical logs from only three boreholes. A larger number of boreholes need to be logged and the geophysical interpretation related to the surface survey results before a meaningful evaluation of the pattern of saline-water intrusion indicated by the resistivity profiles can be made.

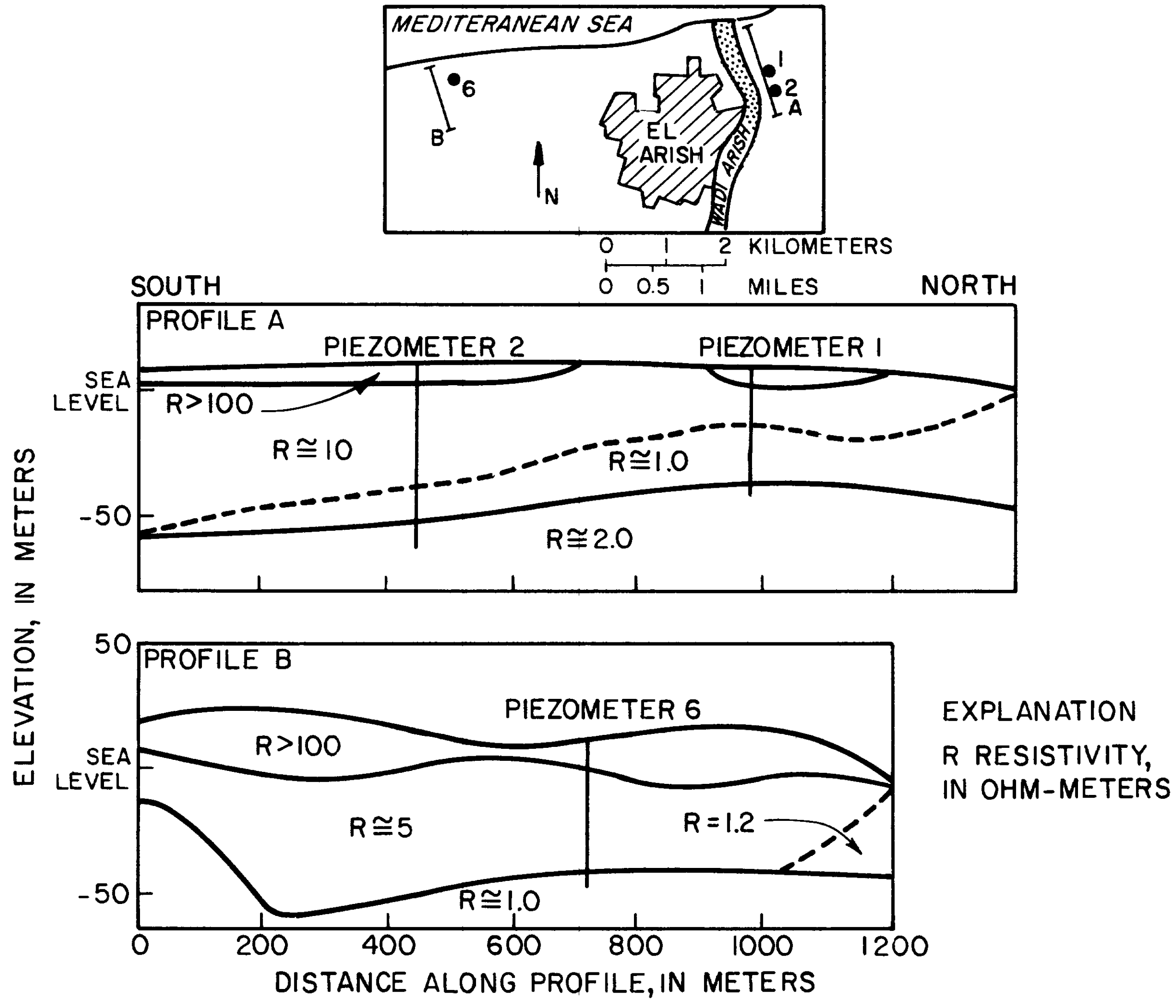


Figure 8. Surface-resistivity profiles A and B near El Arish, northern Sinai. The depths of the resistivity layers at piezometers 1,2, and 6 have been adjusted to agree with geophysical logs.

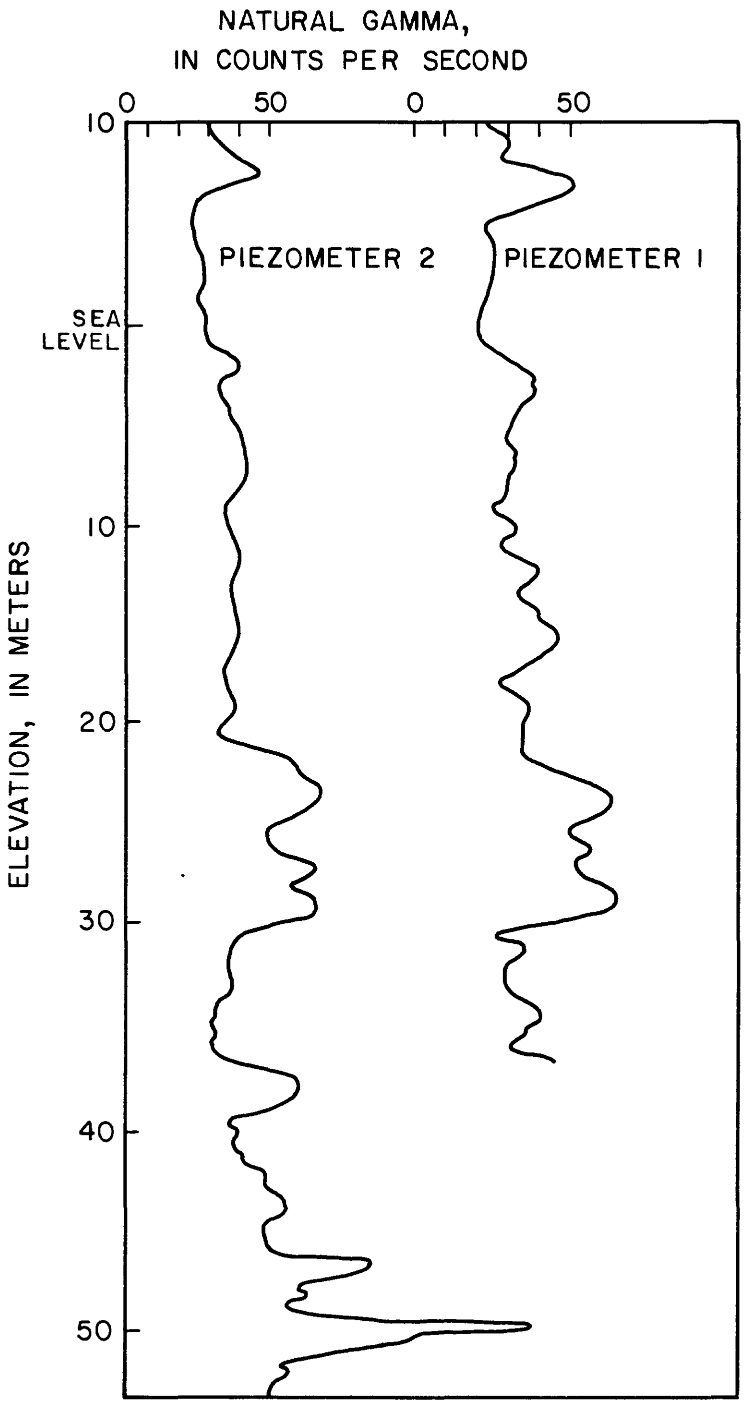


Figure 9. Correlation of natural gamma logs from piezometer no. 1 and piezometer no. 2 boreholes near Wadi Arish illustrating lateral continuity of sediments encountered by boreholes; the boreholes are about 470m apart.

Examples of Geophysical Log Interpretation for Consolidated Sedimentary Rocks in the Central Sinai

Wadi Feiran Borehole No. 2

An example of a relatively complete suite of geophysical logs from a borehole penetrating a thick series of consolidated sedimentary rocks in the interior of the Sinai is given for the Wadi Feiran borehole no. 2 in figures 10 and 11. Inspection of the sandstone-shale sequence of sediments in figure 10 indicates several thick intervals where clay-mineral content appears relatively low, and permeable sandstones might be developed into productive aquifers. The natural gamma log provides a simple and direct means for identifying relatively clay-mineral free or "clean" intervals. Furthermore, the SP log almost exactly parallels the gamma log which indicates that a normal spontaneous potential had developed before logging. The consistency of the SP log is significant, because the development of a normal spontaneous potential is a direct indication of the presence of clay minerals, whereas the natural gamma log indirectly indicates clays by measuring radioisotopes which may be attached at ion exchange sites. In particular, the lowermost sandstones in figure 10 could be derived from immature sediments, which indicates that formation gamma activity might be related to more than just CEC of clay minerals in shales. The consistency of the gamma and SP logs reinforces the interpretation that the intervals A, B, and C in figure 10 correspond to thick, clay-free sandstone aquifers.

Once the sandstones are identified in the Wadi Feiran borehole no. 2, the hydrologist is concerned with the permeability of these sandstones and the quality of water they contain. Geophysical logs cannot provide a direct indication of permeability, but the permeability of some granular formations is known to increase with effective porosity. The neutron porosity log in figure 10 (calibrated on the basis of diameter-corrected values in a limestone calibration environment) indicates the relative porosity of the sandstones, but the noneffective porosity of clay minerals is superimposed on the variation of effective porosity in the sandstones. The relatively smooth caliper log in figure 10 indicates that borehole diameter enlargements have not invalidated the neutron porosity log in any of the potential aquifers. A more useful indication of sandstone porosity is obtained by applying the clay-mineral correction of equation 14 to the neutron log in figure 10, by using the gamma log to produce the clay-mineral fraction according to equation 1. The gamma and linearized but uncorrected neutron logs are compared to a linearized and corrected neutron log in figure 11. The combination of linearized porosity scale and correction for the neutron log makes the porosity and permeability distribution in the sandstones easier to interpret. In the corrected log, sandstones A and B stand out as intervals of relatively large porosity values, whereas the shale beds in sandstone C substantially decrease the permeability of that interval. Note that the porosity of the lower half of sandstone A seems relatively small in the porosity log in figure 10, but stands out as intermediate in porosity on the corrected neutron log in figure 11.

The salinity of water in sandstones A and B can be estimated by using the SSP values read from the SP log for the Wadi Feiran borehole no. 2. The SSP values estimated from the SP log in figure 10 are about -35 and -40 mV in sandstones A and B. Mud resistivity is given as 6.2 ohm-m at 19 °C. No

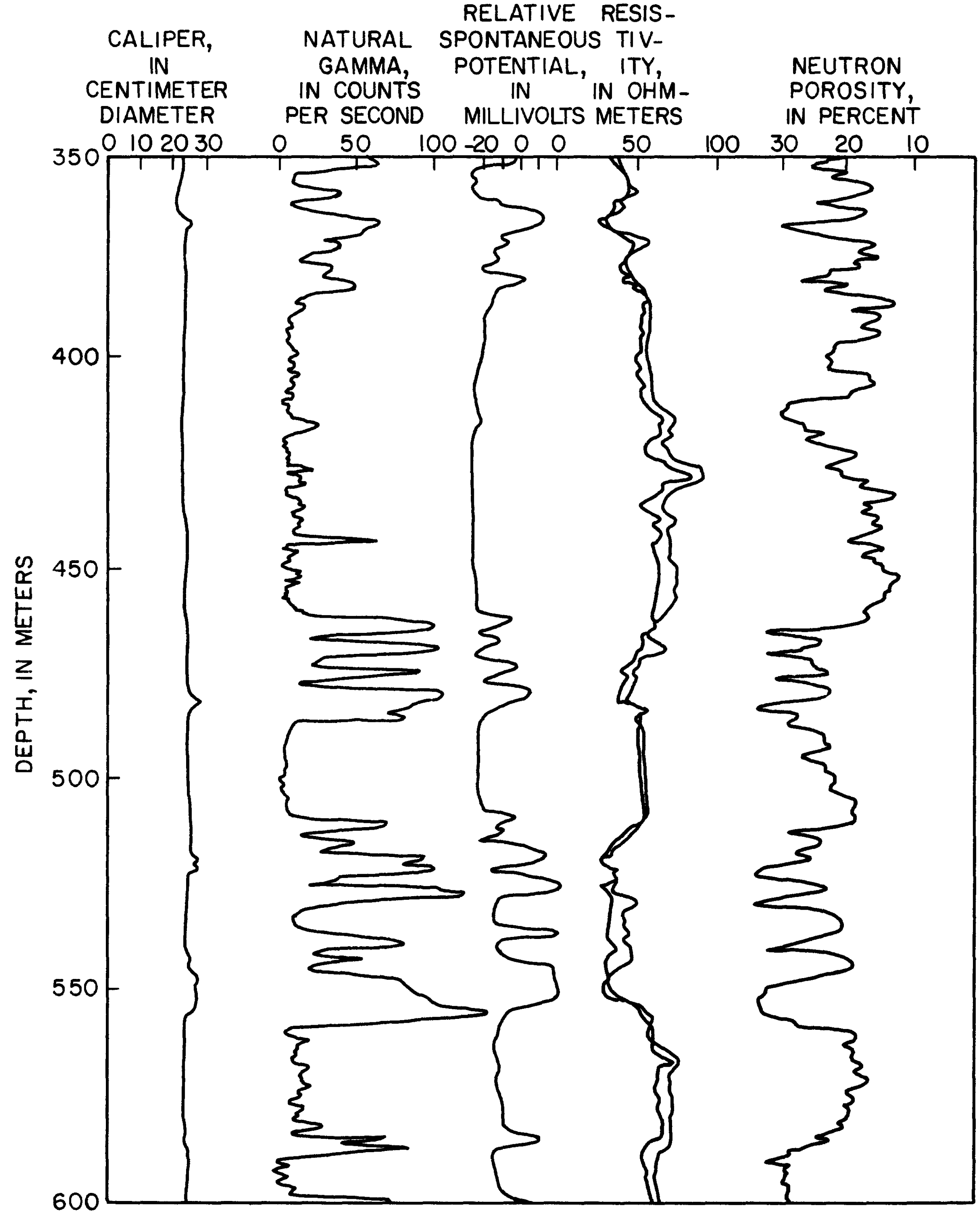


Figure 10. Caliper, natural gamma, spontaneous potential, long- and short-normal resistivity, and neutron porosity logs for the sandstone aquifer interval in Wadi Feiran borehole no. 2.

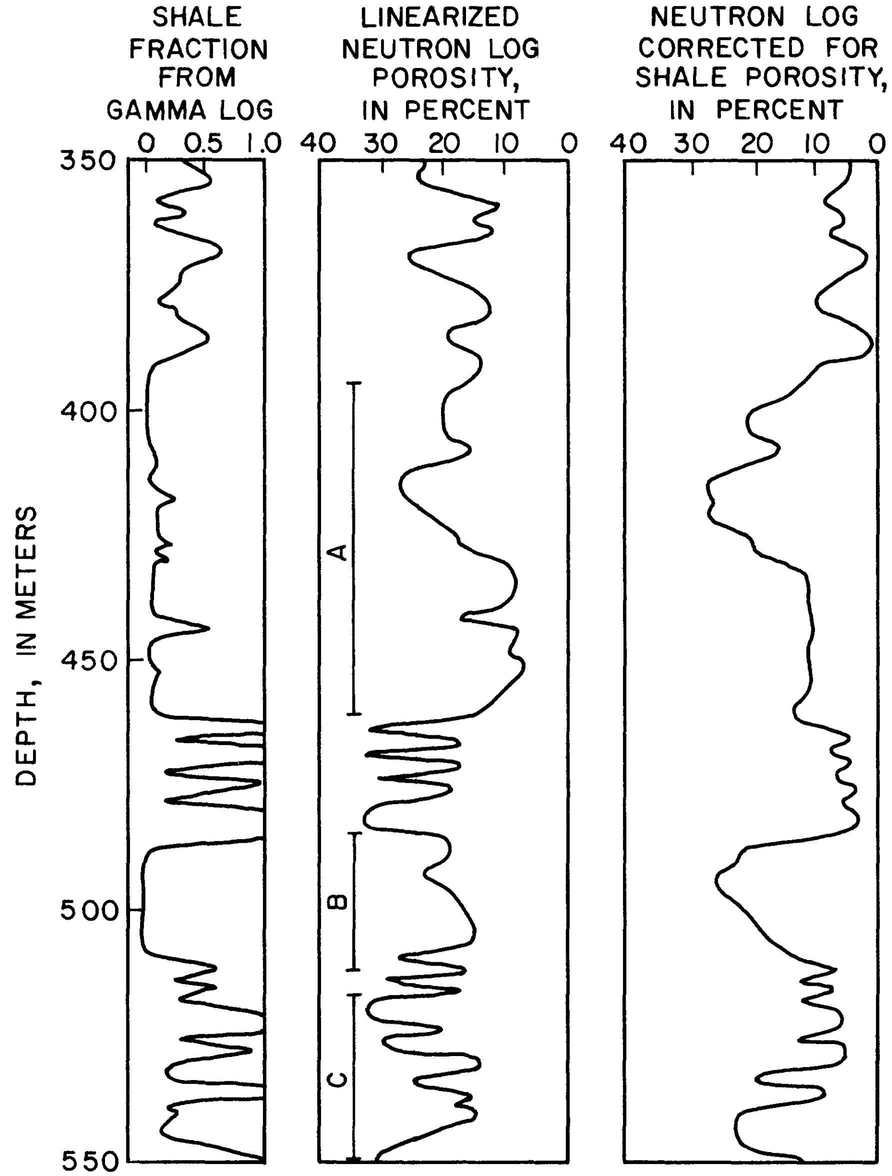


Figure 11. Shale fraction determined from gamma log and then used to correct linearized neutron porosity log for sandstone interval in Wadi Feiran borehole no. 2.

borehole temperature log is given, but formation temperature can be estimated on the basis of yearly average temperatures for shallow ground water and a typical geothermal gradient. This procedure gives an estimated temperature of 30 °C for the two sandstones. At this temperature, the value for R_m becomes 4.5 ohm-m and it is assumed that $R_{mf} = R_m$. Substitution of these values in the interpretation (equation 2) for SSP_m values gives estimates of R_w at 30 °C of 1.45 and 1.25 ohm-m, respectively. Translating to standard conditions of 25 °C and application of equation 6 gives estimates of dissolved solids of 4,300 and 5,000 mg/L (equivalent NaCl).

The long- and short-normal resistivity logs also can be used to interpret the quality of aquifers A and B, but the interpretation is more complicated because formation resistivity (R_t) depends on formation water salinity (R_w), porosity, and clay content. In this situation there are enough logs other than resistivity to interpret porosity and R_w, and this information can be used to check on the consistency of the interpretation in comparison with the resistivity logs. The consistency is checked by using Archie's law in figure 12, where the resistivity R_t predicted by using equation 9 is compared to the short-normal resistivity, R_a^{16}, is a close approximation to R_t on the basis of the normal log departure curves shown in figure 5. For example, at 385 m in depth in figure 10, porosity (uncorrected neutron log) is about 18 percent and R_w is calculated from the SP log to be about 1.45 ohm-m. Using these values, R_t is predicted to be about 45 ohm-m. This compares to a measured short-normal resistivity value of about 50 ohm-m. The average value of R_t predicted for sandstone A is almost the same as the R_a measured by the short normal (fig. 12). The consistency with which both porosity and SP logs, and normal electric logs give the same resistivity increases confidence that porosity and salinity have been accurately interpreted from the geophysical logs. The differences in the measured and predicted R values in figure 12 can be attributed to differences in sample volume and secondary lithology effects on the short-normal resistivity values and neutron porosity measurements.

Even though the complete suite of geophysical logs illustrated in figure 10 can be interpreted to give a consistent indication of formation properties and water quality, the values of R_w calculated from the logs do not agree with R_w calculated on the basis of the specific conductance of water samples after extensive pumping from sandstones A and B. The measured specific conductance of water samples is 1150 µS/cm, corresponding to R_w about 8.0 ohm-m at 25 °C. The independent verification that resistivity, porosity, and SP logs all indicate about the same value for R_w lends confidence that the geophysical logs are being correctly evaluated. One possible source of error is that the measured R_m may not be representative of the water in the borehole when the logs were made. The close correlations of the SP and gamma logs indicate that the water in the borehole was considerably fresher than formation water during logging, which resulted in a normal SP value (negative in sandstones). If formation waters are characterized by an R_w of about 8.0 ohm-m at 25 °C, then R_{mf} would have to be at least 15 ohm-m to produce the observed spontaneous potentials. An alternate possibility is that the SP log was inadvertently plotted with reversed signs, in the expectation that SP values are supposed to be negative in sandstones. In that situation, the SP log in figure 10 would indicate that borehole fluid was more saline than formation waters. By using the measured SSP values and the measured salinity values for formation

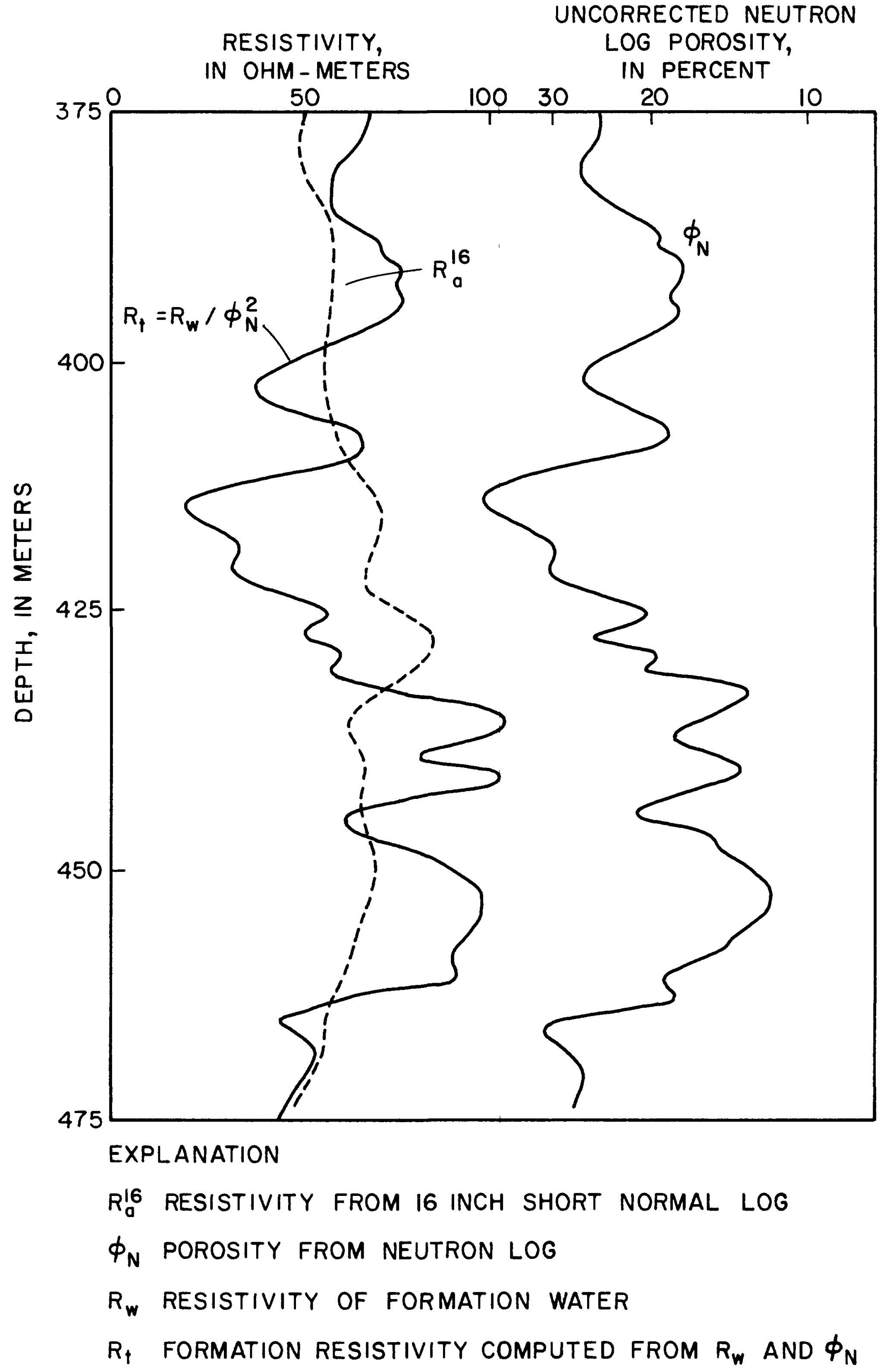


Figure 12. Comparison of resistivity given by short-normal log with resistivity calculated using porosity from the neutron log, R_w, from the spontaneous potential log, and Archie's Law: for sandstone interval A in Wadi Feiran borehole no. 2.

water, Rm would be less than 2.5 ohm-m at the surface. This value is very different from that reported with the logs. Furthermore, reversed signs on the SP log would be a very serious error, and one that an experienced logging contractor would not be likely to make. Also, none of the SP logs obtained in other Sinai boreholes indicated a reversed SP, so that it seems unlikely that the Wadi Feiran borehole no. 2 would be the only example where borehole fluids are much more saline than formation waters. The saline drilling mud also would have affected mud properties in a way that probably would have been noted by the driller.

A thick interval of carbonate sediments lies above the sandstone aquifers in Wadi Feiran borehole no. 2. The geophysical logs obtained in these carbonates are illustrated in figure 13. The natural gamma and SP logs indicate that several carbonate intervals are relatively free of clay minerals and contain at least enough porosity to enable a measurable SSP to develop. The neutron log indicates substantial porosity in some of these carbonates. However, almost all of the carbonate intervals where the neutron log indicates large porosity values correspond to substantial borehole enlargements indicated on the caliper logs. Most of the intervals with large porosities indicated by the neutron log apparently represent the effects of these enlargements rather than intergranular porosity. Unless these enlargements are interpreted as secondary porosity, the logs do not provide any positive evidence to indicate that these carbonates could be aquifers. The geophysical logs do not sample a large enough volume of rock to indicate whether the potential for secondary permeability is important in the local circulation of ground water. Because of the scale problem in interpreting secondary permeability from geophysical well logs, the log analyst needs to learn from experience and other geological sources of information whether a particular formation is likely to produce water from fractures or solution openings.

Wadi Feiran Borehole No. 1

The Wadi Feiran borehole no. 1 provides a second example of geophysical log analysis for deep sedimentary aquifers (fig. 14). This suite of logs is nearly identical to that for Wadi Feiran borehole no. 2, except that the neutron porosity log was originally given in counts per second (direct backscatter neutron count measurement) rather than being calibrated in percent porosity. The neutron log shown in figure 14 has been given an approximate onsite calibration as described by MacCary (1980). This calibration is based on experience with geophysical logs from similar formations (in this situation, the calibrated logs for Wadi Feiran borehole no. 2). Inspection of the log indicates neutron counts obtained in a thick shale section (corresponding to a porosity of 30 percent) and a thick carbonate (above the interval illustration in fig. 14) characterized by very large resistivity values (corresponding to a porosity of less than 5 percent). This allows porosity values to be assigned to neutron counts using equation 13 and inversion for the constants A and B using the 30 and 5 percent porosity values, but such a calibration probably includes an error of as much as several percent porosity.

The SP log in figure 14 indicates a single, thick sandstone interval from 250 to 330 m in depth. The gamma and SP logs generally indicate the same trends, except for a thin interval of large natural gamma activity

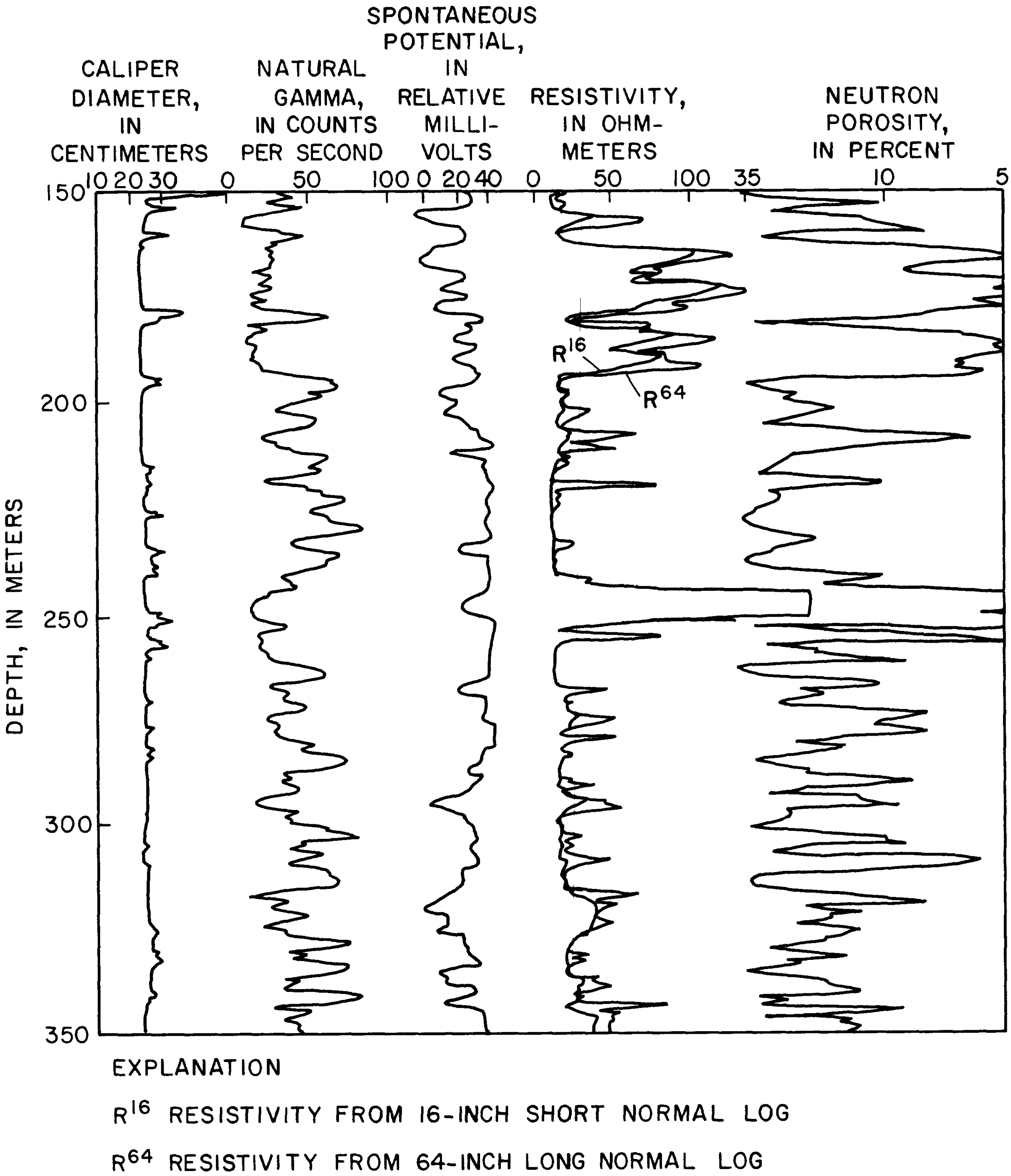


Figure 13. Caliper, natural gamma, spontaneous potential, long- and short-normal resistivity, and neutron porosity logs for the carbonate aquifer interval in the Wadi Feiran borehole no. 2.

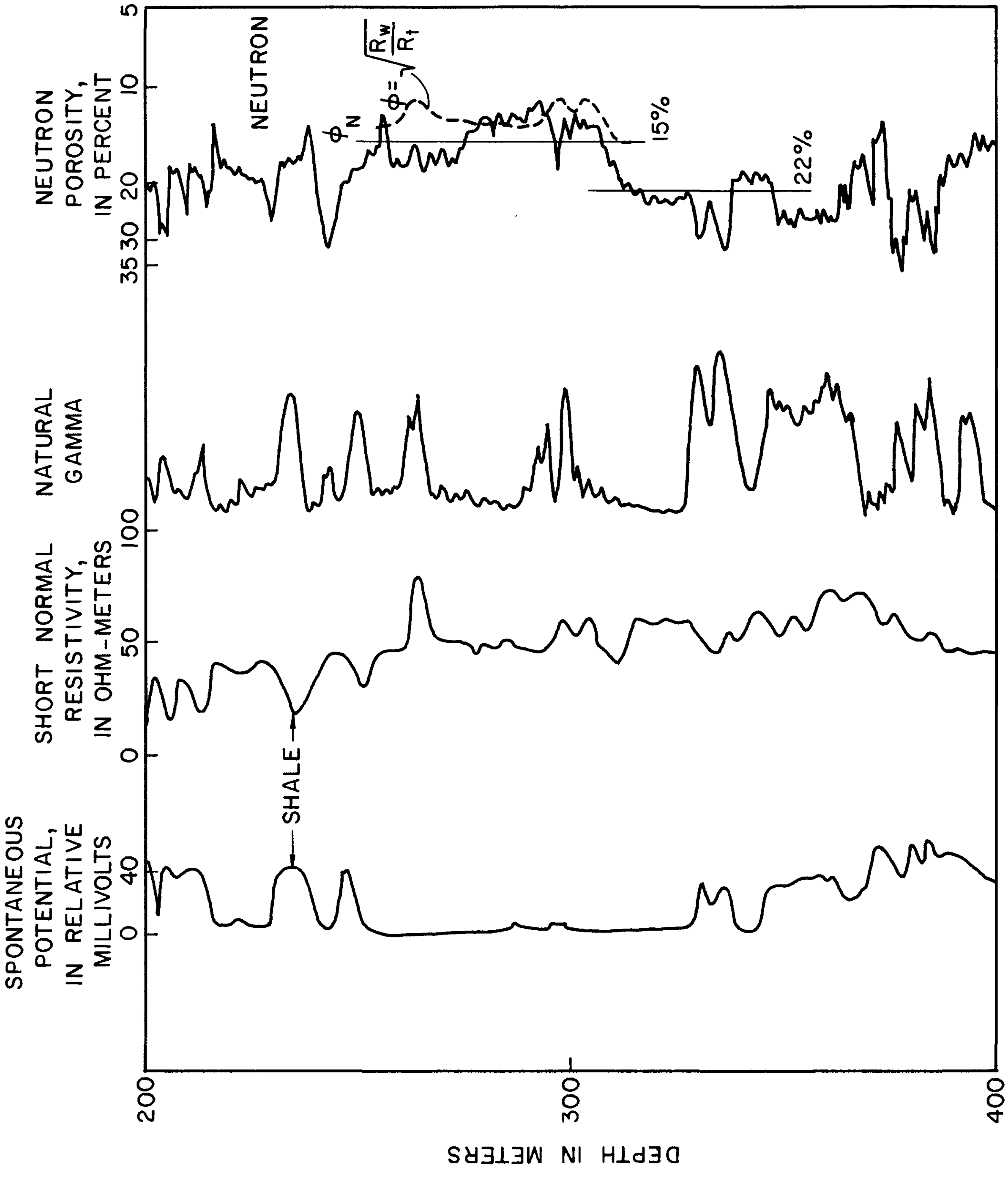


Figure 14. Spontaneous potential, short-normal resistivity, natural gamma, and neutron porosity logs for Wadi Feiran borehole no. 1 illustrating consistency of porosity measured by the neutron log and porosity determined from electrical logs for a thick sandstone interval.

values near 280 m in depth. There is no corresponding clay-mineral indication at this depth on the SP log, while the resistivity log indicates a very large resistivity value. On the basis of these data, the gamma high at 280 m in depth is interpreted as an interval where the sandstone has been cemented with silica containing trace quantities of a natural radioisotope such as uranium. With the exception of this one thin interval, the neutron log indicates an average porosity of about 15 percent for the upper part of the sandstone that increases to more than 20 percent in the lower part of the sandstone. Mud resistivity values were not obtained with the geophysical logs, so that the SP log cannot be used to calculate R_w. However, the SP log indicates a normal SP, so that formation waters are more saline the borehole fluid. Assuming mud conditions similar to those recorded in Wadi Feiran borehole no. 2, the measured SSP of -40 mV corresponds to an R_w of about 1.5 ohm-m. By using this value for R_w, the short-normal log can be transformed into a predicted porosity (using equations 8 and 9). These predicted porosity values agree within a few percent with those from the approximate calibration of the neutron log. Nevertheless, measured R_w values from water samples obtained during aquifer testing indicate water resistivity values similar to those obtained in Wadi Feiran Borehole No. 2. If the R_w value of 8.0 ohm-m is used to predict porosity from the short-normal resistivity data, then predicted porosity values are about 40 percent. Even after allowing for the inaccuracy of the calibration of the neutron log, these porosity predictions seem much too large to be consistent with the neutron porosity log in the sandstone aquifer.

Nakhel Borehole

The Nakhel borehole intersects a series of consolidated sedimentary rocks similar to those that occurred with the Wadi Feiran boreholes. However, the geophysical logs in the Nakhel borehole were obtained by a logging contractor who furnished the resistivity and neutron logs in the form of corrected and calibrated data sets. No details on the exact methods for calibration and borehole correction are given with the data, but it is assumed that the standard procedures described for compensated sondes by Hearst and Nelson (1985) and Tittman (1986) were used. The resistivity and porosity data calculated from the normal and neutron logs by the contractor are illustrated in figure 15 for carbonate and shale (A) and sandstone and shale (B) intervals. Both intervals indicate the effects of borehole fluid invasion. In these plots, the resistivity curve labeled R_t would be similar to the long normal shifted slightly to the left to allow for borehole effects, and the curve labeled R_{xo}, which is the interpreted resistivity of the formation saturated with borehole fluid, would be similar to the short-normal resistivity curve. In this situation R_{xo} trace (analogous to the short normal resistivity log) is to the right of the R_t trace (analogous to the long-normal resistivity log. This is the opposite of what would be expected from borehole effects alone. This reversal of the expected relation of the normal resistivity logs indicates that relatively saline formation water has been replaced by relatively fresh borehole fluid in the vicinity of the borehole. If the resistivity of the borehole fluid were known and then corrected to account for formation temperature, then R_w could be calculated from the pair of equations:

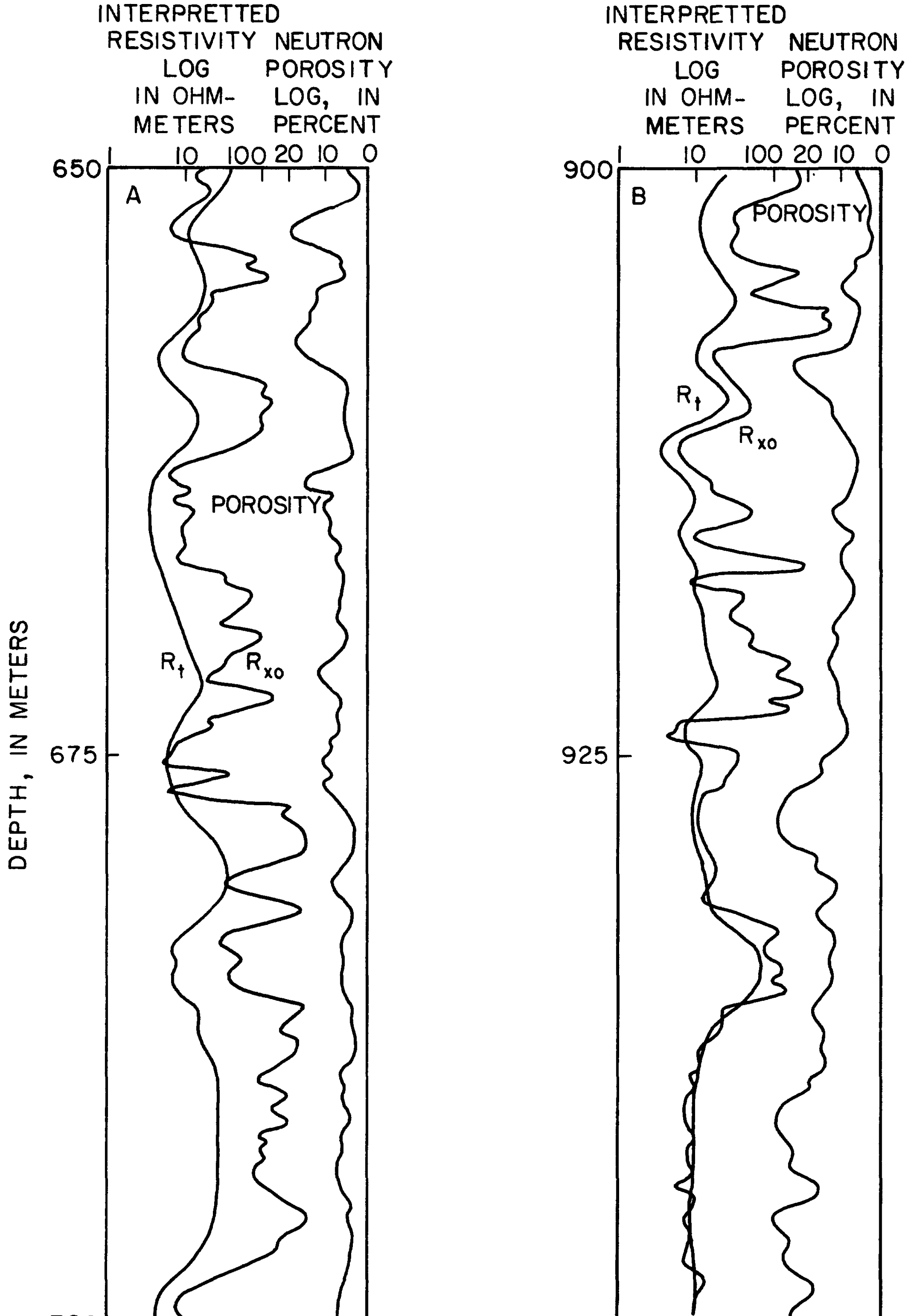


Figure 15. Interpreted resistivity and neutron porosity logs for the Nakhel borehole illustrating effect of borehole fluid invasion in (A) carbonate aquifer and (B) sandstone aquifer.

$$R_{xo} = R_{mf} F \quad \text{and} \quad R_w = R_t/F, \text{ or}$$
$$R_w = (R_t R_{mf})/R_{xo} \qquad (15)$$

However, the formation factor can be estimated directly from the calibrated porosity log, giving:

$$R_w = R_t/F = R_t \phi^2 \qquad (16)$$

For example, application of this equation to the logs in figure 15 at a depth of about 940 m where porosity is about 15 percent and resistivity is about 15 ohm-m gives a value of 0.6 ohm-m for R_w. By correcting back to a standard temperature and using equation 6, this water resistivity translates to a dissolved-solids concentration of about 6500 mg/L. Such relatively saline water would have been expected from the relatively small formation resistivity values for this interval.

The details of the trend in separation between R_{xo} and R_t curves in figure 15 also are worth noting. Inspection of the figures indicates that the two resistivity plots are farthest apart when porosity is in the range of 3-5 percent. This situation commonly occurs when loss of drilling fluid to the formation is controlled by the establishment of a layer of deposits filtered from the borehole fluid known as filter cake on the borehole wall. So little permeability exists in this layer that it effectively controls the rate at which fluid can move from the borehole into the formation. When the loss rate is controlled in this manner, the permeability of the filter cake determines the rate at which fluid invades the formation. There will be more volume to fill adjacent to the borehole when the formation is very porous, and the lateral extent of invasion is inversely proportional to porosity. This is an important point because log analysts sometimes attempt to correlate invasion with permeability. In the Nakhel borehole, the geophysical logs indicate that the most pronounced invasion effects are associated with the relatively impermeable zones (low porosity) of the formation because the greatest depths of invasion are associated with smaller porosity values. This is the standard interpretation of invasion given in most well logging texts, but deepest invasion can correspond to the most permeable intervals in boreholes where mudcake does not limit infiltration into the formation. In the Nakhel borehole, the geophysical logs can be interpreted by using a standardized model for invasion effects, where the most pronounced invasion effects are not associated with the most productive zones in the aquifer.

El Themed Borehole

The geophysical log suites for several boreholes penetrating consolidated sedimentary rocks in the Sinai are restricted to only normal resistivity and SP logs. In general, these logs do not provide enough information to evaluate potential aquifers. Only when the log analyst can develop confidence that the SP log reliably indicates the clay-mineral or shale volume fraction of the formation is it possible that the two logs can be inverted to determine porosity and water quality. Verification that the SP log is indicating clay-mineral volume fraction is especially difficult to demonstrate when there is no gamma log with which to compare the SP log. However, in at least a few situations there is some confidence (usually based on the consistency of the SP log in comparison to the gamma log in sets of well logs from adjacent boreholes in the same formations) that the SP log alone can be used as a bulk-volume measurement. In those situations, the SP log can be used as an independent indicator of lithology, SSP values can be used to determine R_w, and then the resistivity log can be used to solve for formation porosity.

An example of log interpretation based primarily on the SP log is given by the logs for the El Themed borehole (fig. 16). In this example there is no recorded value for R_{mf}, so that R_w cannot be directly determined from the SSP values read from the SP log. However, the SP log indicates the lithology and water quality of the formation, whereas the resistivity log reflects lithology, porosity, and water quality. A simple graphical overlay technique shows how the lithology dependence of the SP log can be used to distinguish between the effects of lithology and porosity on the resistivity log, assuming a uniform value for R_w. In figure 16, the reversed short normal log is overlaid on the SP log. In the interval where the two logs nearly coincide the variations in formation resistivity are apparently related to clay-mineral fraction. In other intervals (A, B, and C) the two curves separate, which indicates that resistivity is decreased by ionic conduction in interconnected pore spaces if R_w is constant. These are probably permeable intervals where water would be expected to flow into the borehole during pumping. Two intervals (D and E) appear to be as clay-mineral free as intervals A, B, and C, but the resistivity logs indicate that these intervals are tightly cemented. There is a shift in the SP curve toward the left near 480 m in depth that may have been caused by the pen drive slipping when the log went off scale to the left, or by a change in water quality associated with that large SP log deflection. In either situation, the overlay of the resistivity log needs to be shifted to compensate so the curve separation near F on figure 16 probably does not represent formation permeability.

Sheira Borehole

The geophysical log suites presented for the Wadi Feran, Nakhel, and El Themed boreholes can be interpreted to solve for lithology, water quality, and porosity by inverting a consistent set of interpretation equations obtained from established logging literature. There is no guarantee that there will always be enough geophysical log data available to define such a quantitative interpretive solution. In the general situation where the lithologic description on the driller's log is limited to one or two components, quantitative interpretation often requires three independent measurements to determine mineral grain type, water quality, and porosity.

An example of the problems that occur when insufficient data are available to carry out the interpretation is given by the logs for the Sheira borehole. Caliper, natural gamma, SP, and long- and short-normal resistivity logs for the shale and sandstone sequence overlying granitic basement rocks in the lower part of the Sheira borehole are shown in figure 17. Although this seems to be an adequate suite of logs with which to interpret formation properties, considerable uncertainty remains after the logs are analyzed. The natural gamma log indicates a thick interval of relatively low gamma activity apparently corresponding to a sandstone

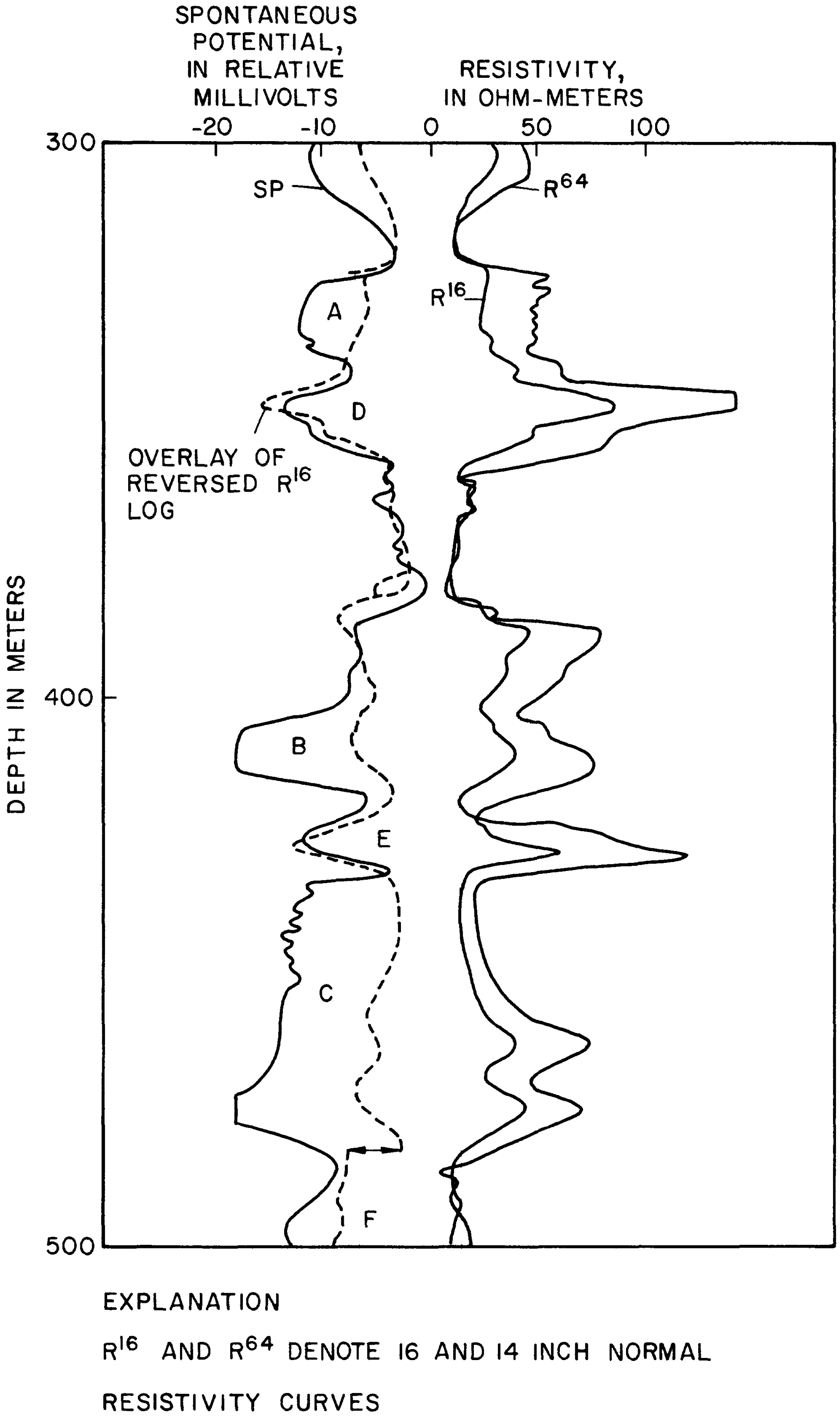


Figure 16. Resistivity log overlay on SP log used to indicate intervals of relatively large porosity values (A, B, and C); F indicates apparent shift in shale baseline; Interval shown consists of carbonate and shale sediments in the El Themed borehole.

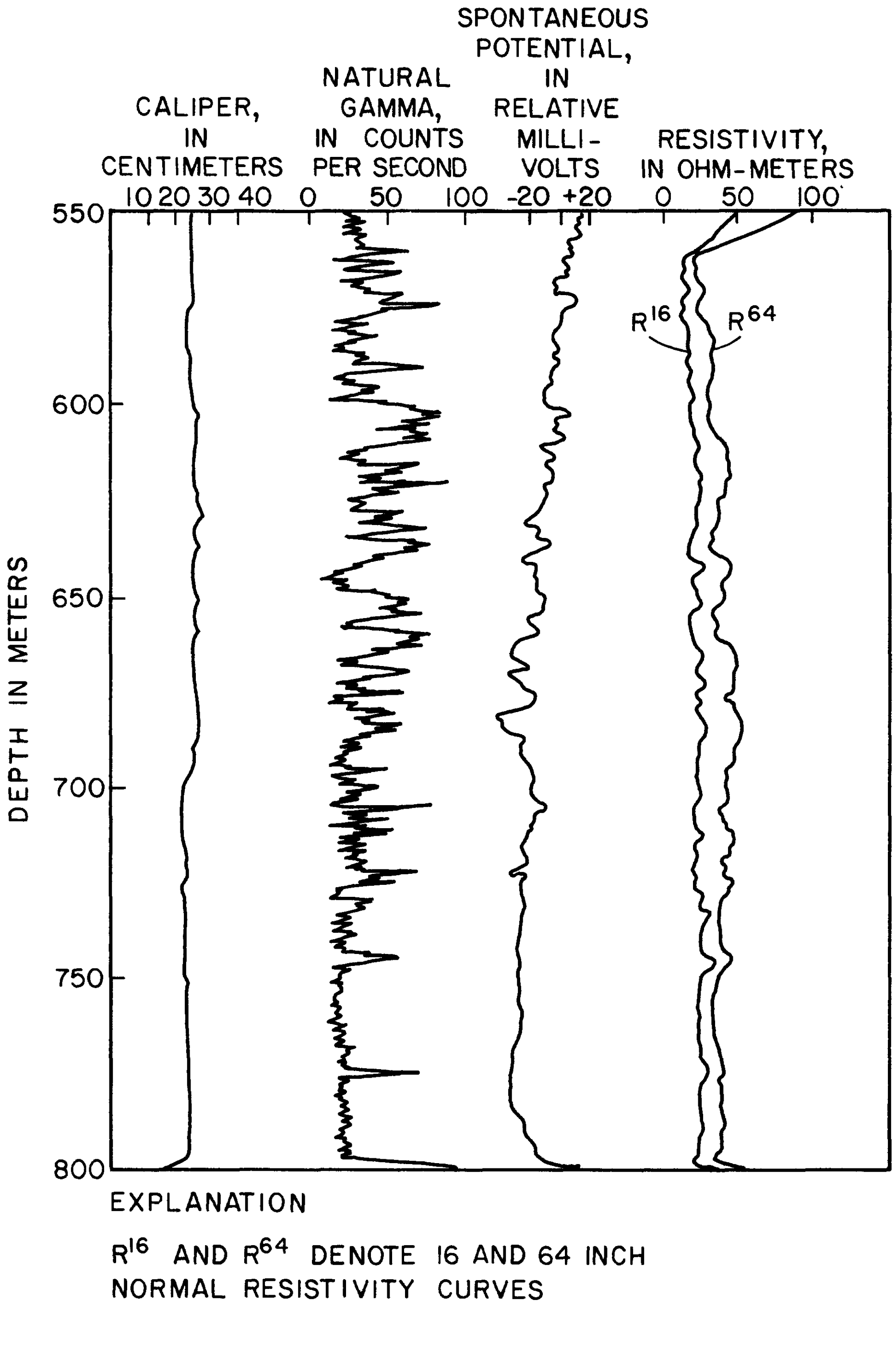


Figure 17. Caliper, natural gamma, spontaneous potential and resistivity logs for the sandstone aquifer in the Sheira borehole.

aquifer indicated on the driller's log (700 to 800 m in depth in fig. 17). Inspection of the SP log indicates that this log is not a reliable indicator of water-quality contrast between formation waters and borehole fluid. The SP log does not correlate very well with the natural gamma log, and there is a consistent drift to the left with increasing depth. Furthermore, the long- and short-normal resistivity logs do not indicate relatively small resistivity values corresponding to the two large values of gamma activity at 745 and 775 m in depth. This observation indicates that gamma activity may not be a reliable indicator of clay-mineral content at this depth in the borehole. The location of the sandstone aquifer at the base of a thick sedimentary sequence and overlying granitic basement indicates that the observed pattern of natural gamma activity may be related to immature sediments and not clay-mineral distribution, or to former clay-mineral rich zones that have been altered to more indurated sediments in a process that removed natural radioisotopes.

The resistivity values in the sandstone interval in the Sheira borehole given by the short normal resistivity log range from 20 to 30 ohm-m. These are relatively small resistivity values for saturated sandstone, but somewhat large for shales. Although the SP log does not seem reliable in this sandstone, the SP log in overlying sediments seems to correlate somewhat better with the natural gamma log. In those overlying sediments, the SP log indicates normal SP values, which correspond to relatively more saline water in the formation if the SP log can be taken as a reliable indicator of water quality in that interval. The cessation of the correlation between the SP log and the natural gamma log at depths greater than 700 m in depth could be explained by an alteration or induration of clay minerals in shales such that the membrane properties of these shales have been destroyed.

The observed separation of long- and short-normal resistivity volume in figure 17 indicates long normal resistivities consistently greater than short normal resistivity values. For the usual conditions of $R_w < R_m < R_t$, short normal resistivity values are expected to be somewhat less than long normal resistivity values. Furthermore, the ratio of long and short normal resistivities is expected to increase as R_t increases. The observed increase of this ratio with R_t is plotted for both the Sheira borehole and the Wadi Feiran borehole no. 1 in figure 18. The increases in the long- to short-normal resistivity ratio are shown to follow the expected trend, but plot along curves associated with lesser mud resistivity values than those recorded with the log data. An alternative explanation for the separation of the resistivity curves is that the formation has been saturated by relatively more saline drilling mud. However, the SP log in figure 17 (if it can be relied upon) indicates a normal SP log at depths less than about 700 m, which corresponds to $R_m > R_w$.

The preceding discussion of the geophysical logs for the basal sandstone in the Sheira borehole indicates that a number of different interpretations are possible. The important result is that there are not enough reliable and mutually consistent logs to solve for the properties of the sandstone. The resistivity logs could be interpreted as functions of lithology, porosity, and water quality. However, there is a question about how well the gamma log indicates lithology and the SP log cannot be used to estimate the R_w independent of the resistivity log. No porosity log is

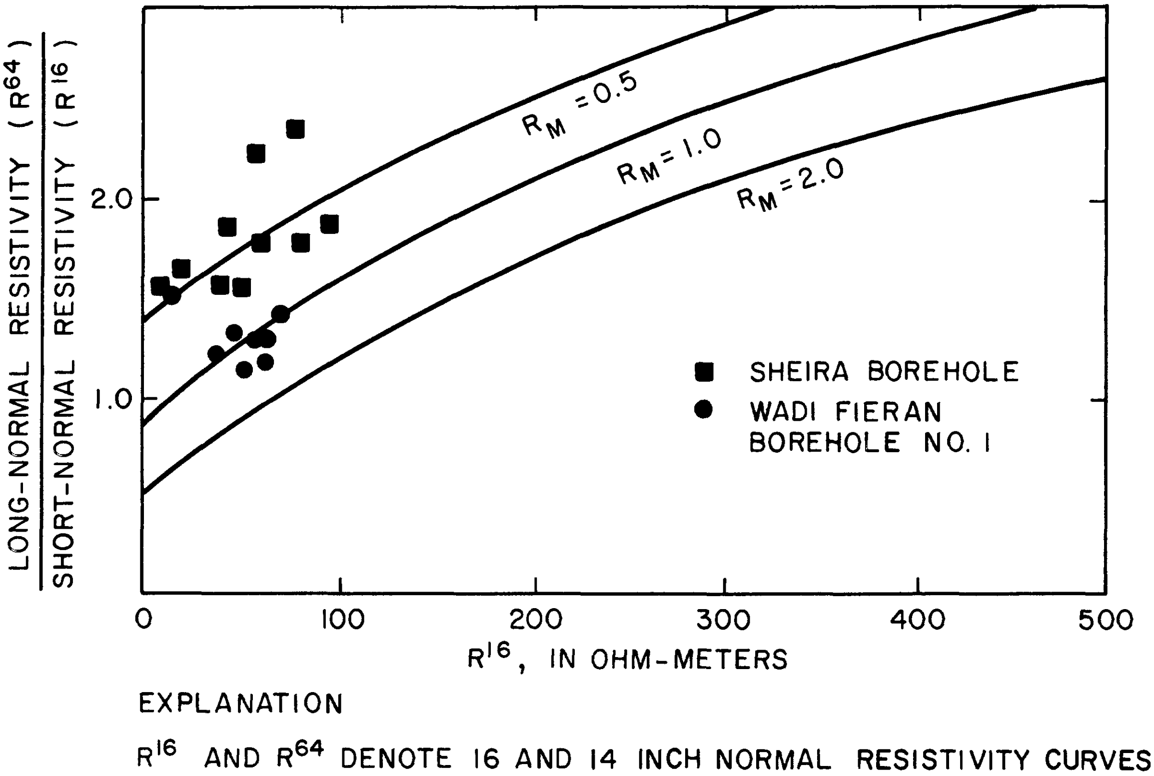


Figure 18. Long- and short-normal resistivity values compared to those predicted from normal log departure curves for various values of mud resistivity in a 20-cm diameter borehole.

available to provide an independent measurement of porosity. As a result there is one probably valid measurement, the resistivity log, that depends upon three different variables: lithology, porosity, and water quality. Even if the gamma log is assumed to be a reliable indicator of lithology, there are still only two measurement equations with which to solve for three unknowns. In this situation, several different aquifer properties could produce the combination of geophysical logs obtained for the basal sandstone in the Sheira borehole.

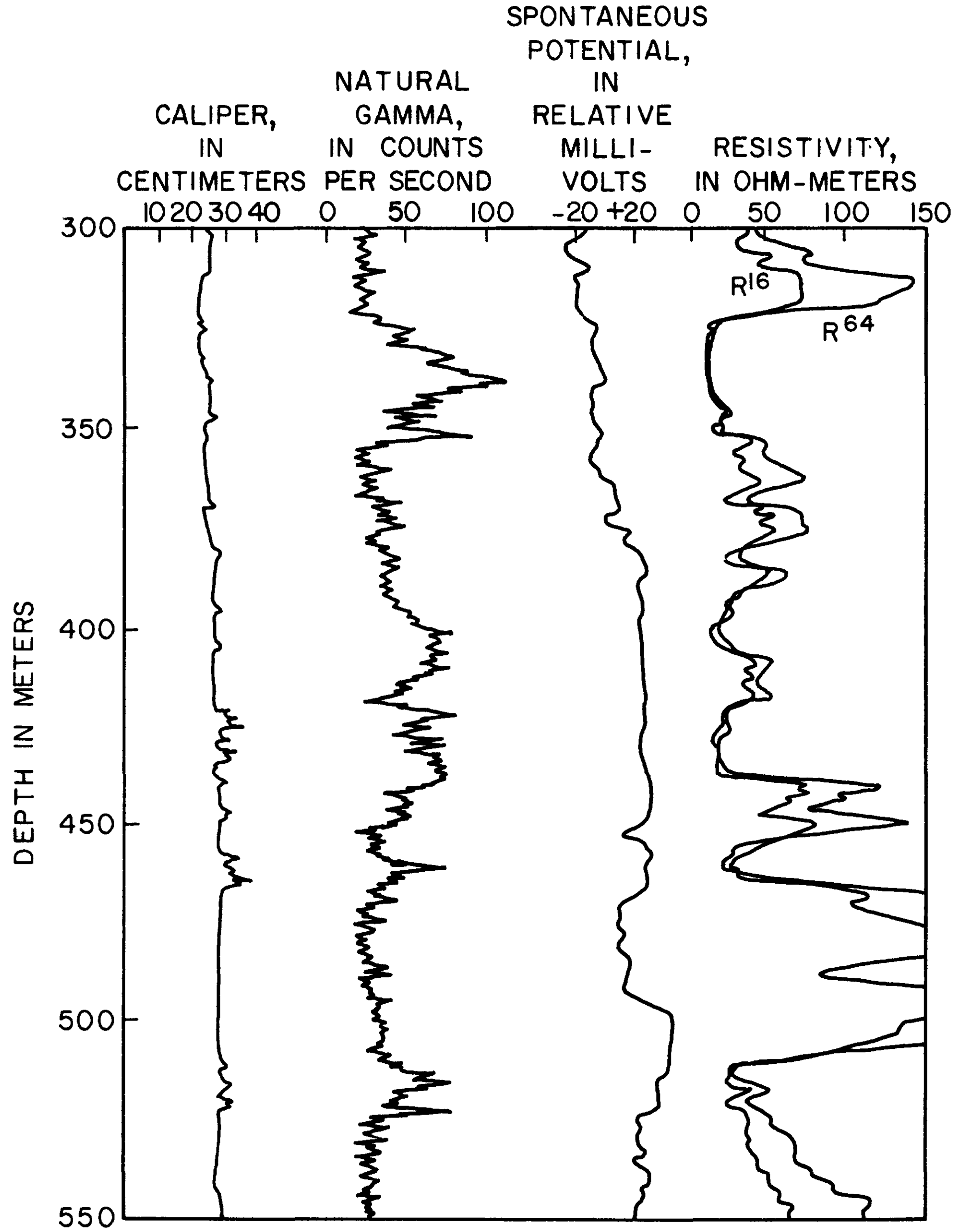
With the information available there are several equally probable alternative explanations for the relatively small resistivity values for the sandstone interval from 700 to 800 m in depth in figure 17 that can be made (on the basis of geophysical log interpretation alone):

1. Saline formation water in otherwise typical sandstone. The small formation resistivity values are associated with unusually large salinity values for Sinai sandstones. The gamma log inversely correlates with permeability even though induration or diagenesis has destroyed the membrane properties of shales.

2. Brackish formation water in permeable sandstone. The small formation resistivity values are associated with unusually high permeability for Sinai sandstones. Immature sediment grains are the reason for the lack of correlation between resistivity and gamma logs, and lack of shale membranes is the reason for the unusual SP log.

3. Disseminated clay minerals in relatively impermeable formation. Authigenic clays deposited in pore spaces contribute to electrical conductivity, which is the reason for the small resistivity values. Clay mineral-effect accounts for the SP log not indicating typical sandstone response, and lack of radioisotopes in the system is the reason for the lack of correlation between the gamma log and disseminated clays.

The sediments overlying the sandstones in the Sheira borehole consist of an alternating series of carbonates and shales. Geophysical logs obtained in these sediments are illustrated in figure 19. Comparison of the natural gamma, SP, and resistivity logs in figure 19 indicates that there is one interval that seems to be predominantly carbonate, moderately electrically conductive, and characterized by a typical clay-free lithology response on the SP log. Although there were important questions about the reliability of the SP log deeper in this borehole, there seems to be some correlation between gamma and SP logs in the interval from 330 to 380 m in figure 19. The combination of SSP of about -20 mV, short normal resistivity values of about 50 ohm-m, and relatively low gamma activity in the interval from 350 to 380 m indicate that this interval may be characterized by an average porosity of about 15 percent and a water quality of about 3000 mg/L dissolved solids. However, the lack of additional information means that this combination of sediment properties is only one of several possible combinations that would produce the observed log response. The same geophysical log analysis indicates that another carbonate interval, from 430 to 520 m in depth, is characterized by about the same water quality but porosity values are less than 5 percent. The interpretation indicates the possibility (but only the possibility) of a relatively thin (30 m) carbonate aquifer containing water of marginal quality in the Sheira borehole.



EXPLANATION

R^{16} AND R^{64} DENOTE 16 AND 14 INCH NORMAL RESISTIVITY CURVES

Figure 19. Caliper, natural gamma, spontaneous potential, and resistivity logs for the carbonate aquifer in the Sheira borehole.

Formulating Generalized Log Interpretation Methods

Generalized interpretation methods for the quantitative inversion of geophysical well log data are based on the simultaneous solution of coupled interpretation equations that relate the geophysical measurement at each point along the borehole to a physical property of interest to the hydrologist. One simple example of this process is the calibration of a neutron porosity log. In this situation the geophysical measurement (backscattered neutrons in counts per second) is known to be related to formation porosity. The neutron counts are related to formation porosity using equation 13, which involves two calibration constants. The unstated assumption in this process is that only one geophysical measurement can be solved for only one unknown by using a single inversion equation. Application of equation 13 requires that the lithology or mineral grain type is known, and that porosity is solved as the single unknown. The logging industry routinely addresses this issue by using other logs to identify lithology, and then having a particular set of the constants A and B for each possible mineral grain type; subsequent corrections are made to account for borehole diameter. Standard interpretation methods are used to estimate values for the constants for mixtures of lithologies.

The log interpretation process is generalized by allowing for more than one lithology, porosity, and water quality as unknowns in the interpretation equations, and then solving a set of more than one such equation by the mathematical techniques used to yield solutions to simultaneous coupled equations. Site geology and hydrology indicate how many unknowns are present; the number of geophysical measurements made determines the number of equations to be used. In some situations, the two numbers are equal, and the equations yield definite solutions. However, there will be other situations where there are not enough measurements to solve for the unknowns (underdetermined case) or more measurements than there are unknowns (overdetermined).

Underdetermined Interpretation Methods

Underdetermined interpretation problems in borehole geophysics result in the log analyst being unable to make a unique interpretation. One way in which to present such an indeterminate interpretation is to list the alternate interpretations, as was done for the Sheira borehole. Each alternative results from the application of an additional constraint on the data set. For example, the assumption of a given value for R_w in the interpretation of the resistivity log for the Sheira borehole enables Archie's law to be solved for porosity for each measurement of formation resistivity. Every different assumed value for R_w yields a different solution for porosity. In the treatment of the Sheira data, two different values of R_w were assumed, in addition to two different lithologies. In the generalized interpretation method of log analysis, the treatment of indeterminate interpretation problems requires the addition of one or more interpretation equations or conditions to make the number of equations match the number of unknowns. Each assumption is listed with the description of the associated solution, and the probability of each alternative is related to the probability of the assumption used to realize that alternative.

Overdetermined Interpretation Methods

Overdetermined interpretation problems occur when there are more geophysical measurements than unknowns, and these occurred for the Wadi Feiran boreholes where there were four unknowns (clay, quartz sand, porosity, and formation water salinity), four measurements (natural gamma, SP, resistivity, and neutron porosity), and five equations. The fifth equation is derived from the observation that the two lithologic components and porosity have to sum to 100 percent of the rock because it is assumed that no other minerals or fluids besides clay, quartz and water are present. Mathematical theory dictates that the equation cannot be solved because values for four unknowns cannot be determined that satisfy five independent equations. The practical solution to this problem is to minimize the residual, where the residual is defined as the amount by which substitution of the four solution values determined using any four of the equations fails to satisfy the fifth equation. This was done in an indirect way in the Wadi Feiran borehole no. 2 analysis by solving four of the equations for the four unknowns (clay, quartz sand grains, porosity and R_w) and then considering how well the solution for these four unknowns satisfied the fifth equation (measured R_t compared to R_t predicted by equations 8 and 9). In the Wadi Feiran example, the computed values for the unknowns fit the fifth equation very well, at least on the average for a sandstone where clay mineral was shown mostly absent. A formal mathematical approach to this interpretation problem would be to vary the interpretation slightly by testing alternate values for G_{ss} and G_{sh} in equation 1 or the cementation exponent, n, in equation 9, for example, until the average difference between measured resistivity values and that calculated from Archie's law is made as small as possible. The minimum size of the residual (expressed in the Wadi Feiran example as the percent difference between the measured and predicted resistivities) is a useful measure of the potential error in the interpretation. Therefore, overdetermined interpretation situations are preferred because they provide not only a quantitative solution to the geophysical interpretation, but also a quantitative measure of the probable error in the interpretation.

Generalized Solution for Unconsolidated Aquifers in the Sinai

The suite of geophysical logs obtained in unconsolidated sediments near El Arish consists of natural gamma, resistivity, and SP logs. These logs apparently represent the minimum set of logs required to solve for two lithologies, porosity, and salinity. In at least some situations the SP log will not be available, will appear unreliable, or will not develop because of insufficient water-quality contrast between the borehole fluid and formation waters. Porosity then is formally removed from the list of unknowns, and the formation is divided into three unknowns: impermeable clay, permeable sand and gravel, and salinity. The gamma log is used to solve for lithology, separating the formation into clay and nonclay fractions. The resistivity log is used to solve for salinity using the known clay-mineral fraction. This solution was done graphically for the El Arish piezometer boreholes by overlaying the reversed resistivity log on top of the gamma log. This could be done mathematically by solving the gamma log for clay-mineral fraction using a linear relationship between gamma activity and clay content. Then resistivity values could be assumed for the clay mineral present, and the parallel conduction model (eq. 7) and Archie's law (eq. 9) for R_w. A hidden difficulty in this approach is produced by the possibility of more than one clay mineral, and other sand and gravel lithologies. Formal treatment of these possibilities results in more unknowns than equations. In figure 6, the change in relation between reversed resistivity and gamma logs could be explained as either freshwater in the lower aquifer, or calcareous cementation of the sands. Either alternative would explain the relatively larger resistivity value measured by the long- and short-normal logs. The limited log suite available indicates that there is no solution to this inherently underdetermined problem using geophysical logs alone. The logical approach to the log interpretation in unconsolidated sediments in the Sinai is to use the resistivity, SP, and natural gamma combination to solve for clay, sand, and water quality in individual lithologic units, and then to change the interpretation equations in each unit as required to make the best fit to the data. The inherently underdetermined nature of this interpretation problem indicates the importance of having as much additional information on the geological environment as possible to minimize the uncertainty. Accurate and detailed driller's logs are an important contribution to geophysical log interpretation in this situation.

Generalized Solution for Consolidated Sedimentary Rocks in the Sinai

The suite of geophysical logs obtained for deep, consolidated sedimentary rocks in the interior of the Sinai varies from a relatively limited suite of logs that includes natural gamma and long- and short-normal resistivity logs to a relatively complete suite that includes caliper, natural gamma, SP, long- and short-normal resistivity, temperature, and neutron porosity logs. As many different types of geophysical logs as possible need to be obtained because of the lack of uniqueness inherent in the interpretation of geophysical data and the interpretation difficulties associated with underdetermined inversion problems. The additional cost of running one or two additional geophysical well logs is almost always small in comparison with drilling costs and the costs of mobilizing the logging crew to obtain a limited suite of logs. More specific reasons for obtaining as many geophysical logs as possible in consolidated sediments are related to the possible effects of sedimentary environment on porosity and permeability through cementation and authigenic pore deposits. In contrast, the hydraulic properties of shallow, unconsolidated deposits are mostly determined by particle size distributions and related factors that can be correlated with such lithologic variables as clay fraction determined from the natural gamma log. The relation between lithology and porosity and permeability can sometimes be more complicated for consolidated sediments, which makes independent verification of the assumptions used in geophysical log interpretation more important for these sediments. In the instance of consolidated sedimentary aquifers in the Sinai, the information about the consistency and probable degree of error in quantitative interpretation provided by minimized residuals indicates that overdetermined interpretations are to be sought whenever possible.

The examples of geophysical log interpretation from the Wadi Feiran, Nakhel, El Themed, and Sheira boreholes indicate that the combination of natural gamma, SP, resistivity, and neutron porosity logs provide an overdetermined interpretation for the four variables: mineral grain, clay-mineral fraction, porosity, and water quality. When inspection of the data set for these boreholes confirmed that all four logs are reliable, the interpretation results indicated that the residual for standard interpretation equations was very small, even without additional effort to improve calibration of log data. These results lend considerable confidence to the overall interpretation. The caliper and temperature logs contribute indirectly to the interpretation by indicating that logs are reliable because the values on the log are not affected by rugosity and washouts, and by providing formation temperature values to use in the interpretation of resistivity and SP logs.

In at least one situation, the Sheira borehole, inspection of the SP and gamma logs indicated that either these logs were unreliable, or some unusual lithologic conditions were making the standard interpretation equations invalid. In this example it would have been very helpful to have had an overdetermined interpretation situation by having a neutron porosity log available. If that were the situation, then several different assumptions could have been tried and the consistency of the analysis could have been checked by comparing the magnitude of residuals. In the absence of a neutron porosity log, one could only list several different alternatives and then speculate about the probability of the assumptions leading to each of those alternatives being valid.

Relating Geophysical Log Interpretation to the Hydraulic Properties of Aquifers

None of the geophysical measurements provided by logs give a direct indication of the hydraulic properties of interest to the hydrologist. In evaluating aquifer tests or implementing regional models of aquifers, the hydrologist is interested in transmissivity (T) and storage coefficient (S) of aquifers. The estimation of these hydraulic properties from geophysical log data involves not only the interpretation of the geophysical data, but also the scale problem that relates the detailed description of the aquifer within a meter of the borehole to the larger scale average of aquifer properties that determines well productivity. One objective of geophysical well log analysis for Sinai aquifers is to develop a generalized method for relating aquifer properties interpreted at the borehole to interval-averaged quantities that can be correlated to T and S for the aquifer as determined from standard aquifers tests, and that would be suitable to be used in defining regional aquifer models.

The fundamental aquifer properties that are determined from well log interpretation are water quality, lithology, and porosity. Water quality is given in the form of specific conductance of formation water:

$$\sigma = (1/R_w) \times 10^4 \quad \mu S/cm \qquad (17)$$

where R_w is given at the standard temperature of 25 °C. The log analyst can then either accept the approximate relation between formation water conductance and dissolved-solids concentration given by equation 6, or consult empirical data that relates the specific conductance of local ground water with measured solute content.

Transmissivity is defined as the vertically integrated hydraulic conductivity of the aquifer. The hydraulic conductivity of the formation adjacent to the borehole depends upon the effective porosity of a formation. Numerous investigations indicate that hydraulic conductivity can be related to permeability if the tortuosity of pore passages and the distribution of average pore sizes are taken into account (Bear, 1972). The non-linear relation between porosity and permeability is discussed for a well-sorted sandstone by Bredehoeft (1964) and many other similar studies. A general consideration of the relationship between porosity and permeability given by Jorgensen (1988) indicates that hydraulic conductivity is proportional to the cube of porosity divided by a specific pore volume surface area factor. This specific volume would be expected to decrease with increasing porosity. As a result, the integrated hydraulic conductivity of each 10-m interval of aquifer is expected to be proportional to the quantity:

$$D_i = (1-C_{sh})\ \phi^3 /(1 - \phi^2) \qquad (18)$$

where D_i is a transmissivity score, C_{sh} is the average clay-mineral volume fraction for the interval, and ϕ is the average interval porosity for the relatively shale-free beds within the interval expressed as a volume fraction. This form of average porosity is used in equation 19 because Jorgensen (1988) derived the $\phi^3/(1-\phi^2)$ dependence for relatively clay-mineral-free sandstones and carbonates. An alternative method for developing an interval-averaged transmissivity score is based on the relation between natural gamma activity and the product of gamma activity and density given by Alger and Harrison (1989):

$$\begin{aligned} A_1 &= C_{sh}(1-0.62\ \phi) \\ D_i &= 10^{-m_1 A_1} \end{aligned} \qquad (19)$$

where C_{sh} is given by equation 1, the term (1-0.62 ϕ) is taken as proportional to bulk density (that is, assuming average mineral grain density is 2.62 g/cm³), and m_1 is an exponent that needs to be determined from the regression of the factor A_1 against measured hydraulic conductivity (laboratory tests run with core samples). In correlating core test data with logs, the core test data need to be depth averaged to account for sample volume differences between core tests and geophysical log measurements. The values of D_i over the thickness of each aquifer then would be summed to obtain a total transmissivity score, D_o:

$$D_o = \sum_{i=1}^{n} D_i b_i \qquad (20)$$

where b_i is the vertical thickness of each subinterval.

The values for D_o then could be correlated with aquifer transmissivity determined from a number of aquifer tests to determine the best choice for the exponent m_1 and to calibrate the well-log derived transmissivity scores D_o in terms of the aquifer-test-derived values for transmissivity, T.

A similar procedure would be followed for determining a storage coefficient score, E_o based on the porosity and lithology of the aquifer. In this derivation, the storage coefficient of the aquifer is assumed to be nearly proportional to average porosity in shale-free beds, and the proportion of aquifer within an interval is estimated from an interbedded sandstone or carbonate and shale model:

$$E_i = (1-C_{sh})\phi$$

$$E_o = \sum_{i=1}^{n} E_i b_i \tag{21}$$

E_i is the storage coefficient score for a 10 m interval, C_{sh} is the average clay-mineral volume fraction within that interval, ϕ is the average interval porosity, and b_i is the thickness of each subinterval. The relationship between porosity and storage coefficient is obvious for unconfined aquifers, but may not seem so obvious for confined aquifers. For fully confined aquifers, water released from storage is derived from aquifer compression. Geophysicists often assume that formation compressibility is a linear function of porosity. This assumed relationship is reflected in equation 21. As in equation 20, the values for E_i are summed over the aquifer, and the total E_o is correlated with values of S derived from aquifer tests.

The parameters D_o and E_o defined using equations 18 through 21 are presented as a logical way in which to produce interval-averaged quantities that would be expected to correlate with transmissivity and the storage coefficient on the basis of established relation between sediment properties and aquifer hydraulics. These representations will work only as long as the assumptions involved in deriving the correlations given by Jorgensen (1988) and Alger and Harrison (1989) are valid. The unit interval of 10 m is selected as an interval large enough to average aquifer properties, yet small enough that the summation of several such units can indicate some of the internal structure of the aquifer. The log analyst might consider averaging log-derived properties over intervals in the 5 to 20 m range, based on bed boundaries identified on the logs rather than rigorously enforcing the 10 m unit thickness.

In the hydrogeological literature, transmissivity and storage coefficient are known to depend in a complex way on grain-size distribution and lithology rather than just effective porosity. Both grain-size distributions and lithology are considered indirectly through the "shale factor" incorporated in equations 18, 19, and 21. The objective is to come up with a log-derived quantity that can be correlated with aquifer properties of interest. The best approach may vary from the direct inverse correlation between gamma log and T and S, to the sophisticated combinations of log parameters suggested by Alger and Harrison (1989).

Another important consideration in using equations 18 through 21 is that the derivation of those equations considers only primary, intergranular porosity as the source of aquifer permeability and storage. Solution openings and fractures can cause aquifer transmissivity values to be orders of magnitude greater than those associated with primary porosity in sediments. All of the geophysical-log and aquifer-test data currently (1990) available do not indicate that fractures and solution openings are an important contribution to water production from sandstones in the Wadi Feiran, Nakhel, El Themed, and Sheira boreholes. However, geophysical logs indicate that average primary porosity values are smaller and fractures and solution openings more frequent in overlying carbonates. The porosity logs indicate that a few thin carbonate intervals might be capable of producing water from primary porosity alone, but fracture permeability or solution openings could be important or dominant in carbonate aquifers in the Sinai.

Additional Studies and Procedures to Augment and Improve the Geophysical Well-Log Data Base for the Sinai

The experience derived from the analysis and interpretation of geophysical well-data from the various Sinai boreholes described in this report indicate that certain improvements in data-base management and several additional areas of study could greatly improve the ability to apply well-log analysis to hydrologic studies.

1. Log headings and standardized log scaling procedures. The results of the geophysical-log analysis described in previous sections of this report indicate certain procedures could greatly improve the effectiveness of the data base. The geophysical log data available for the Sinai consists of analog records (strip charts) and copies of those records. The routine digitization of well log data for Sinai boreholes will not occur for some time. The use of analog charts as primary records indicates that: (1) log scales be optimized as logs are recorded, because scale changes are difficult or impossible to make after recording; and (2) a standardized format or log header be used to record calibration data, log scales, and well site-specific data such as surface elevation, drill bit diameter, and mud resistivity. In a number of cases, repeatedly copied logs had unreadable calibration and scale data, and mud resistivity values had been lost. These data are critical in the quantitative interpretation of logs. Keys (1989) discusses log headers in detail and gives an example of a generalized well-log header to be used to record this information. Implementation of such a standardized log-heading record would increase the effectiveness of the Sinai logging program.

Optimization of geophysical log scales often is relegated to the experienced logging operator, who uses his experience to set scales for logs based on the measured properties of formations. Often typical values for log scales can be estimated from log response on the trip into the borehole; however, two general procedures would seem to improve resolution for long- and short-normal logs. These procedures are that both long- and short-normal logs be plotted on a logarithmic rather than linear scale, and that designations other than ink color be used to identify the two resistivity traces so the two traces can be distinguished on copies of logs. The logarithmic resistivity scale improves resolution because the log analyst is most interested in distinguishing the response of different formations for relatively small resistivity values (R_t<100 ohm-m). The short-normal log generally can be distinguished from the long normal log by the better resolution of the short normal log for thin beds. However, this is not always the situation, and proper interpretation of resistivity logs can depend upon identifying whether the long or short normal measures a larger resistivity. Hand annotation or some other method for consistently identifying the two resistivity curves on log copies could improve the interpretation of copied logs.

2. Structure of unconsolidated aquifers at El Arish and elsewhere. The generally low mineral resistivity of sediments in unconsolidated aquifers in the north Sinai indicates that surface resistivity surveys are useful in mapping aquifer properties and in identifying regional patterns of saline-water intrusion from the adjacent Mediterranean Sea. Preliminary comparison of three geophysical logs of boreholes located on resistivity profiles obtained near El Arish indicate that the single-aquifer-layer model used in the resistivity analysis actually is divided into distinct subunits by laterally extensive clay layers or lenses. The log analysis further indicates that these layers may be important in controlling the rate at which saline water moves into the aquifer during pumping. However, these conclusions are based on the study of a very limited number of boreholes. A substantially greater number of boreholes need to be compared to the resistivity profiles before the importance of internal aquifer structure can be evaluated by comparing the detailed profiles of aquifer properties given by the logs to the larger scale, vertically averaged profiles given by the surface resistivity analysis.

3. Verifying R_w and water quality measurements. The consistency with which geophysical log analysis results in estimates of formation water quality (R_w) that are much smaller than those indicated by measurement of the electrical conductivity of recovered water samples needs to be studied further. Several sources for this difference are possible, including incorrect values for R_m, significant differences between R_m and R_{mf}, and production of water from local openings that produce water of much lower salinity than that saturating the rest of the formation. Further analysis of the resistivity of water samples and the relation between that resistivity and values of R_w determined by analysis of SP and resistivity logs could make a major contribution to the geophysical log interpretation program in the Sinai.

4. Lithology, formation factor, and formation properties. Although expensive and time consuming, careful analysis of the petrophysical properties of sedimentary rocks can identify relations between rock properties that can be measured by conventional geophysical logs and those of interest to the hydrogeologist. Two specific areas of interest were identified in the preliminary analysis of geophysical logs from the Sinai: (1) the relation among formation factor, cementation exponent, and permeability; and (2) the extent of and probable geophysical log indications of authigenic clays in pore spaces. The quantitative measurement of typical sandstone and carbonate cementation exponents using established petrophysical methods (Winsauer and others, 1952) for Sinai aquifers would improve the precision with which geophysical logs can be interpreted. Preliminary estimates of the cementation factor could be made using crossplots of neutron porosity and R_t interpreted from normal resistivity logs. The presence of dispersed clays is not accounted for by conventional interbedded sand and shale models for the interpretation of resistivity logs. Geophysical and lithologic indicators of disseminated clays, such as those that may have complicated the analysis of the resistivity logs from the Sheira boreholes, would be useful in the interpretation of geophysical logs from the Sinai. The difference in values of a given log, crossplots, and petrophysical analysis might indicate the importance of disseminated clays.

5. Clay-mineral studies. Much of the conventional geophysical log interpretation described in this report is based on the application of interpretation of clay-mineral fractions, and correction of porosity and resistivity log measurements for clay-mineral effects. The precision of these corrections could be improved with a quantitative study of the clay-mineral types that are present in Sinai aquifers, the differences in CEC between different clay minerals, and the geochemical conditions under which these clays lose their membrane properties.

SUMMARY

A review of conventional geophysical log interpretation techniques indicates that the combination of caliper, temperature, natural gamma, long- and short-normal resistivity, spontaneous potential (SP), and porosity logs can be used to characterize the lithologic and hydraulic properties of aquifers in the Sinai. Natural gamma, SP, and resistivity logs are the only logs that can routinely be made in uncased boreholes in unconsolidated sediments, but this suite of logs cannot be used to distinguish between saline formation water and electrically conductive clay-mineral-rich sediments saturated with freshwater.

Natural gamma, SP, resistivity, and neutron logs, in addition to indirect information about aquifer properties provided by caliper and temperature logs, can be used to define the lithology, porosity, and salinity of saturating waters for consolidated sedimentary rocks. In situations where reliable driller's logs limit the number of possible rock types present, this suite of logs provides a quantitative estimate of the consistency of the interpretation in the form of the minimized residual produced by the standard application of mathematical inversion methods for overdetermined inversion problems. In situations where one or more of these logs are not available, or some of the logs are considered unreliable, the residual error estimation is not provided, or not enough information may be available in the geophysical logs to provide a single interpretation. This problem most often is indicated by the lack of information required to determine whether vertical variations in formation resistivity are related to variations in formation permeability, variations in formation water salinity, or variations in clay-mineral fraction. Several examples of this analysis applied to geophysical logs from the Sinai indicate that this residual is very small, and that the logs accurately define aquifer properties. In at least one situation, the analysis indicates that authigenic clay-mineral deposits and alteration of sediment properties subsequent to deposition may invalidate application of standard interpretation methods.

Additional review of log data and application of conventional interpretation techniques to those data indicate that the geophysical log data base would be much more effective if information about log scales, calibration data, mud resistivity, and other data are recorded in a standardized log header attached to each geophysical log. Further study of the petrophysical properties of Sinai sediments such as clay-mineral type, variation of cation exchange capacity (CEC) with clay-mineral type, and the relation between formation factor and permeability would improve the precision with which Sinai logs can be interpreted.

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