Petrophysical Analysis of Geophysical Logs of the National Drilling Company—U.S. Geological Survey Ground-Water Research Project for Abu Dhabi Emirate, United Arab Emirates

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Prepared in cooperation
with the National Drilling
Company, Emirate of
Abu Dhabi

U.S. DEPARTMENT OF THE INTERIOR
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Petrophysical Analysis of Geophysical Logs of the National Drilling Company—U.S. Geological Survey Ground-Water Research Project for Abu Dhabi Emirate, United Arab Emirates

By DONALD G. JORGENSEN and MARIO PETRICOLA

Prepared in cooperation with the National
Drilling Company, Emirate of Abu Dhabi

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CONVERSION FACTORS

Multiply	By	To Obtain
centimeter (cm)	0.3937	inch
cubic centimeter (cm^3)	0.06102	cubic inch
cubic meter (m^3)	35.31	cubic foot
gram (g)	0.03527	ounce
kilogram (kg)	2.205	pound
meter (m)	3.281	foot
micromho per centimeter (μmho/cm)	1.000	microSiemens per centimeter
pascal (Pa)	1.45038×10^{-4}	pound-force per square inch
square meter (m^2)	10.76	square foot

Temperature in degrees (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F=1.8\times°C+32.$$

The units used in this report are those in which the measurements were made and customarily used in the United Arab Emirates.

Petrophysical Analysis of Geophysical Logs of the National Drilling Company—U.S. Geological Survey Ground-Water Research Project for Abu Dhabi Emirate, United Arab Emirates

By Donald G. Jorgensen[1] *and* Mario Petricola[2]

Abstract

A program of borehole-geophysical logging was implemented to supply geologic and geohydrologic information for a regional ground-water investigation of Abu Dhabi Emirate. Analysis of geophysical logs was essential to provide information on geohydrologic properties because drill cuttings were not always adequate to define lithologic boundaries. The standard suite of logs obtained at most project test holes consisted of caliper, spontaneous potential, gamma ray, dual induction, microresistivity, compensated neutron, compensated density, and compensated sonic. Ophiolitic detritus from the nearby Oman Mountains has unusual petrophysical properties that complicated the interpretation of geophysical logs. The density of coarse ophiolitic detritus is typically greater than 3.0 grams per cubic centimeter, porosity values are large, often exceeding 45 percent, and the clay fraction included unusual clays, such as lizardite. Neither the spontaneous-potential log nor the natural gamma-ray log were useable clay indicators. Because intrinsic permeability is a function of clay content, additional research in determining clay content was critical.

A research program of geophysical logging was conducted to determine the petrophysical properties of the shallow subsurface formations. The logging included spectral-gamma and thermal-decay-time logs. These logs, along with the standard geophysical logs, were correlated to mineralogy and whole-rock chemistry as determined from sidewall cores. Thus, interpretation of lithology and fluids was accomplished. Permeability and specific yield were calculated from geophysical-log data and correlated to results from an aquifer test.

On the basis of results from the research logging, a method of lithologic and water-resistivity interpretation was developed for the test holes at which the standard suite of logs were obtained. In addition, a computer program was developed to assist in the analysis of log data. Geohydrologic properties were estimated, including volume of clay matrix, volume of matrix other than clay, density of matrix other than clay, density of matrix, intrinsic permeability, specific yield, and specific storage.

Geophysical logs were used to (1) determine lithology, (2) correlate lithologic and permeable zones, (3) calibrate seismic reprocessing, (4) calibrate transient-electromagnetic surveys, and (5) calibrate uphole-survey interpretations. Logs were used at the drill site to (1) determine permeability zones, (2) determine dissolved-solids content, which is a function of water resistivity, and (3) design wells accord-

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[1] U.S. Geological Survey, Al Ain, United Arab Emirates.

[2] Schlumberger Middle East, Abu Dhabi, United Arab Emirates.

ingly. Data and properties derived from logs were used to determine transmissivity and specific yield of aquifer materials.

INTRODUCTION

In 1988, the National Drilling Company (NDC) of the Emirate of Abu Dhabi and the U.S. Geological Survey (USGS) joined in a cooperative agreement to exchange scientific and technical information. The NDC-USGS Ground-Water Research Project (GWRP) for Abu Dhabi Emirate is developing techniques and methodology for water-resources evaluation. The primary objective of the project is to evaluate the fresh and slightly-saline water resources of the Emirate. Accordingly, an important element of the water-resource evaluation was the drilling and geophysical logging of test holes.

Geophysical logs, when corrected for borehole environmental effects, measure in situ properties. Applications of these logs are well developed in the petroleum industry. However, applications of the logs in the ground-water environment, especially the fresh ground-water environment, are much less developed for many reasons, including cost, hole diameter, and length of logging tool. Procedures and techniques of log interpretation for ground-water investigations are only modestly developed as compared to similar efforts in the petroleum industry. Efforts have been made to modify existing techniques from the petroleum industry for use in ground-water hydrology.

This report describes the geophysical logging program conducted by the USGS and presents some of the research and new technology developed relative to petrophysical analysis of the logs. Additionally, information unique to log interpretation in the geohydrologic environment associated with ophiolitic detritus of the eastern part of Abu Dhabi Emirate is presented.

The United Arab Emirates are located on the Arabian Peninsula (fig. 1). Abu Dhabi Emirate is the largest of the seven Emirates. The study area in which test holes have been drilled and geophysical logging has been conducted is shown in figure 2.

ACKNOWLEDGMENTS

The impetus for the Ground-Water Research Project for Abu Dhabi Emirate was provided by His Highness Sheikh Khalifa Bin Zayed Al Nahayan and His Highness Sheikh Tahnoon Al Nahayan. The project has been overseen by His Excellency Mohamed Habroush Al Suwaidi, Chairman of the NDC, and Ahmed Juma Al Dharif, General Manager of the NDC.

Geophysical logging was done under the drilling program of the GWRP under the direction of Donald C. Signor, USGS. Sidewall cores and geologic information were collected as part of the geologic investigations directed by Donald G. Hadley, USGS. The special petrographic analyses of sidewall cores were performed by Robertson Group plc, United Kingdom. Geophysical logs were run by Al Ain Ground Water Department, Schlumberger Middle East of Abu Dhabi, and Hydrotechnica of Oman. Mohamed Khalifa and Fouzi Mohamed of the NDC assisted with the office interpretation of logs, and Daniel Thampan of the NDC provided the graphical display of logs.

GEOHYDROLOGIC SETTING

The relatively permeable aquifer material in the eastern Abu Dhabi Emirate is almost entirely alluvium of Quaternary age. At some locations, the slightly compacted and slightly consolidated sand and gravel layers in the upper unit of the Fars Formation of Miocene age are also water bearing. The alluvium is largely uncompacted and unconsolidated to slightly consolidated. However, at a few locations, the alluvium is well cemented. Consolidation is mostly the result of cementation, mostly by dolomitic and calcareous material. At most locations in eastern Abu Dhabi Emirate, the alluvium lies unconformably on an erosional surface that cuts across formations ranging in age from Pliocene(?) to Cretaceous. Alluvium may not be present at some locations, such as below some of the major sand dunes.

The alluvium consists mostly of clay, silt, sand, and gravel, with authigenic dolomite and calcite. In general, the clay content is substantial even in sand and gravel layers. Accordingly, most aquifer material has only slight to moderate permeability. However, some clean (relatively clay-free) deposits are found north and east of Al Ain in thin, but seemingly widespread, alluvial sand and gravel deposits. Relatively clean gravel and sand also are found in buried paleowadis. The source of the detritus for most of the alluvium is the Oman Mountains

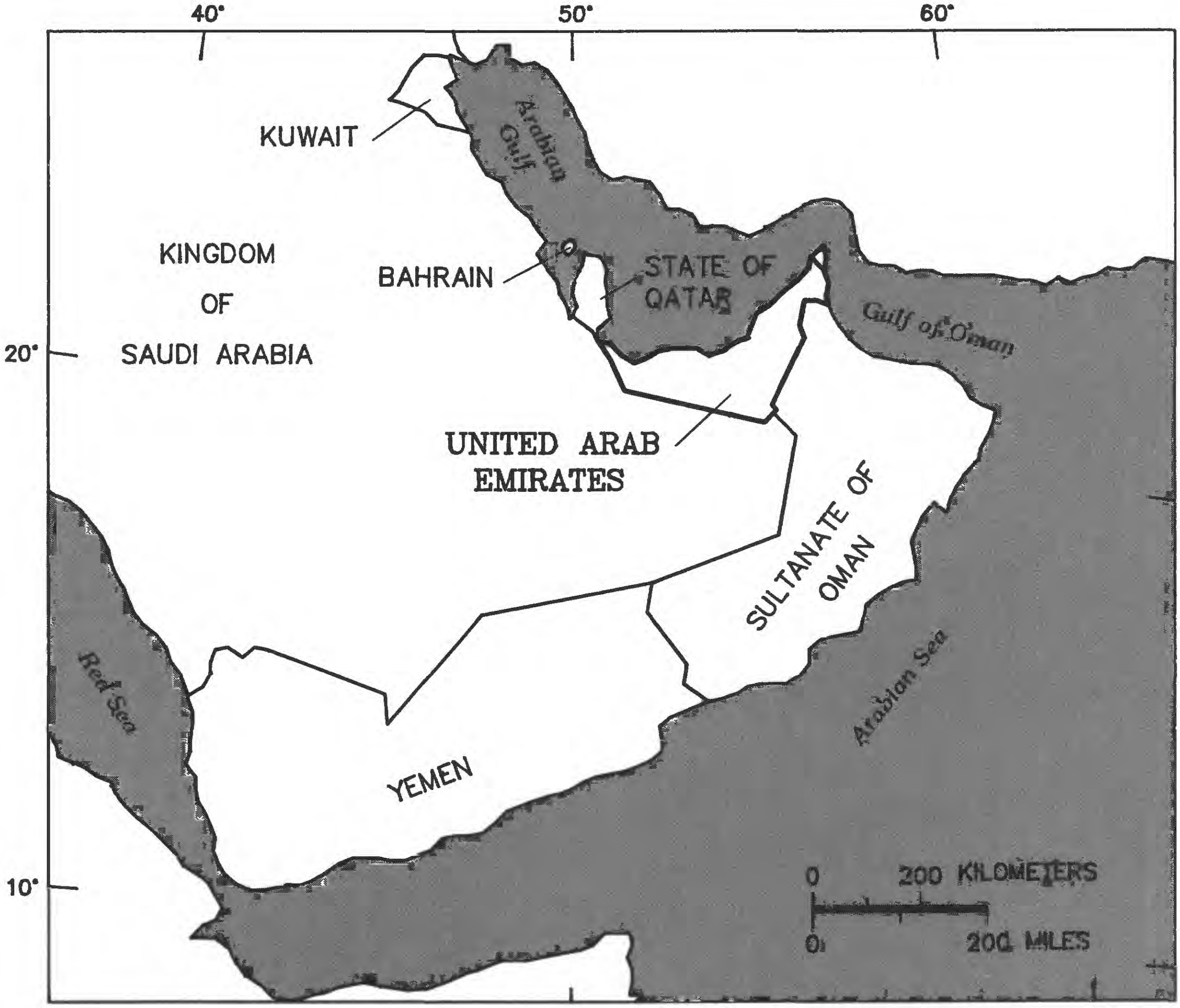


Figure 1. Arabian Peninsula and location of the United Arab Emirates.

to the east. Sediment from these mountains includes coarse detritus composed of ophiolitic material, limestone, and chert. Even the fine-grained clay is, in part, a product of the diagenesis and disintegration of the ophiolitic source rock.

BOREHOLE-GEOPHYSICAL LOGGING

Borehole-geophysical logging was a key element in many of the geologic and geohydrologic studies of the GWRP. In addition to geological logs developed on the basis of drill cuttings, geophysical logs were required because of problems related to the collection of representative drill cuttings. In general, subsurface materials were soft, and cavings from the borehole walls were common while drilling. Also, the lithologic layers penetrated were similar and repetitive, which made the formations difficult to identify uniquely from sample cuttings.

A standard suite of logs was obtained, when possible, for nearly all the project test holes and included the following:

Caliper log,
Spontaneous-potential log,
Gamma-ray log,
Resistivity or dual-induction log,
Microresistivity log,
Compensated neutron log,
Compensated density log (gamma-gamma log), and
Compensated sonic log.

Photoelectric logs, which are part of a lithodensity log, were obtained for many test holes logged by

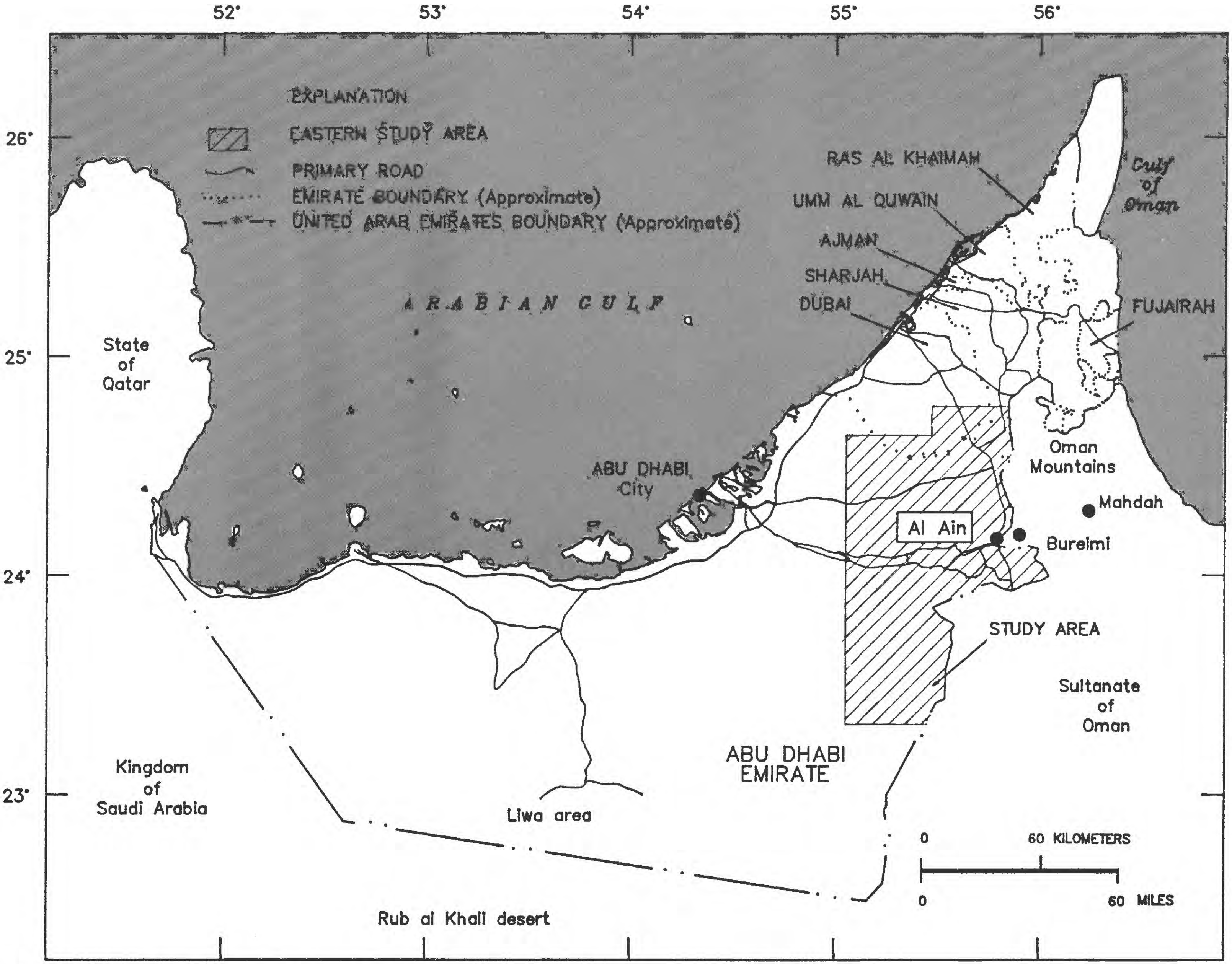


Figure 2. Abu Dhabi Emirate and surrounding area.

Table 1. Types of geophysical logs and their function, purpose, and utility (modified from Keys, 1990)

Type of log	Function	Purpose and utility
Caliper	Measures borehole diameter	Needed to evaluate borehole-diameter effects on other logs; also useful for stratigraphic correlation. Gives information necessary for hole-volume computations.
Spontaneous potential (SP).	Records potentials (voltages) that develop in the borehole.	SP is a function of the chemical activities of fluids in the borehole and adjacent rocks. Used to estimate formation water quality. Useful in locating zones of permeability. Useful in identifying clay layers and estimating clay content.
Gamma ray	Records total (naturally occurring) gamma radiation within a selected energy range.	Most extensively used nuclear log in ground-water studies. Useful for identification of lithology and stratigraphic correlation. Can be used in cased wells.
Dual induction, medium and deep or resistivity.	Measures deep and medium resistivities of the formation.	Defines bedding boundaries and assists in stratigraphic correlation. Qualitatively indicates mud invasion, a function of permeability. Can be used to estimate formation water quality.
Microresistivity	Measures resistivity of a thin section (2–5 cm) at the borehole wall.	Provides high resolution of thin lithologic layers. Can be used to estimate formation water quality when used in conjunction with deep-resistivity measurements.
Compensated neutron	Provides a record of neutron interactions that occur in the vicinity of a borehole. Interactions are related to quantity of hydrogen (principally water) present.	Measurement of porosity, water content, and material characteristics, which allow lithology determinations (in conjunction with density and sonic logs). Useful in determining water levels. Can be used in cased holes.
Compensated density (gamma-gamma).	Measures radiation received at a detector from a gamma source in the same probe.	Gamma-radiation attenuation is proportional to the bulk density of rocks. Gives information on density and lithology and allows porosity analysis.
Compensated sonic	Measures acoustic-energy travel velocity through fluids and surrounding rocks.	Identifies lithology and measures porosity. Can be used in conjunction with neutron and density logs for porosity and lithology determinations. Useful in determining water levels.

Schlumberger Middle East. The function, purpose, and utility of the various logs are listed in table 1.

Table 2 summarizes the geophysical logs obtained at GWRP test holes. The locations of project test holes with geophysical logs are shown in figure 3. Mylar and paper copies of the geophysical logs are stored in project files. The mylar copies can be used to make blueprints. Digital data for each log (in ASCII format) are entered into the project's computer data bases. Specialized commercial computer programs, such as LOGGER, are available to output the digital data into strip charts. For example, figure 4 shows several logs for test hole GWP-26 created from digital data in the project data base. Commercial computer spreadsheet programs and associated graphics, such as LOTUS 1–2–3 or QUATTRO.PRO, also can be used to display geophysical data in strip-chart form (Keys, 1986) and to analyze geophysical data by overlay (Paillet, 1991). Copies of geophysical logs for most project test holes are shown in a separate publication. Computer-interpreted logs are available for test holes logged by Schlumberger Middle East and for some of the test holes logged by Al Ain Ground Water Department. These computer interpretations indicate water salinity and lithology. For example, figure 5 shows water salinity and lithology interpreted from geophysical data for test hole GWP-30. Test holes for which computer-interpreted logs are available are indicated in table 2.

Geologic Studies

Geophysical logs are used in several ways for geologic studies. For example, geophysical logs are used in conjunction with drill cuttings to discern lithology, to identify formations, and to determine formation thickness. A major use of geophysical logs is correlation. Typical log responses are correlated to lithology as determined by both log analyses and by correlation with drill cuttings. When the typical log responses to the different lithologies of an area are known, lithology can be implied by noting the log response. In this manner, formations can be identified and correlated from borehole to borehole.

Lithology, such as sandstone, limestone, and dolomite, can be determined from cross plots of neutron porosity and bulk density (Schlumberger, 1989, fig. 6–7). The photoelectric factor versus density cross plot as described by Schlumberger (1989,

Table 2. Summary of geophysical logs obtained for project test holes

[--, no log obtained]

Ground-Water Project test hole number	Caliper	Spontaneous potential	Gamma ray	Resistivity or induction	Microresistivity	Neutron	Density	Sonic	Computer interpreted logs	Temperature	Specific conductance	Flow	Neutron burst thermal-decay-time (TDT)	Spectral gamma (GLT)
1	--	--	X	--	--	--	--	--	--	--	--	--	--	--
2	--	--	X	--	--	--	--	--	--	--	--	--	--	--
3	--	X	X	X	--	--	--	--	--	--	--	--	--	--
4	--	--	X	--	--	--	--	--	--	--	--	--	--	--
5	--	--	X	--	--	--	--	--	--	--	--	--	--	--
6	X	X	X	X	--	X	X	X	--	X	X	X	--	--
7	X	X	X	X	--	X	X	X	--	X	X	--	--	--
8	X	X	X	X	--	X	X	X	--	--	--	--	--	--
9	X	X	X	X	--	X	X	X	--	--	--	--	--	--
10	X	X	X	X	--	X	X	--	X	--	--	--	--	--
11	X	X	X	X	--	X	X	--	X	--	--	--	--	--
11A	X	--	X	X	X	--	--	--	--	--	--	--	--	--
12	X	X	X	X	X	X	X	X	X	--	--	--	--	--
13	X	--	X	--	--	X	X	X	--	--	--	--	--	--
14	X	X	X	X	--	X	X	X	--	--	--	--	--	--
15	X	X	X	X	--	X	X	X	--	--	--	--	--	--
16	X	X	X	X	X	X	--	--	X	--	--	--	--	--
17	X	X	X	X	X	X	--	--	X	--	--	--	--	--
18	X	X	X	X	X	X	X	X	--	--	--	--	--	--
19	--	X	X	X	--	--	--	--	--	--	--	--	--	--
20	X	X	X	X	X	X	X	X	X	--	--	--	--	--
21	X	X	X	X	X	X	X	X	X	--	--	--	--	--
22	X	X	X	X	X	X	X	X	--	--	--	--	--	--
23	X	X	X	X	X	X	X	X	X	--	--	--	--	--
24	X	X	X	X	X	X	X	X	X	--	--	--	--	--
25	X	X	X	X	X	X	X	X	X	--	--	--	--	--
26	X	X	X	X	X	X	X	X	X	--	--	--	--	--
27	X	X	X	X	X	X	X	X	X	--	--	--	--	--
28	X	X	X	X	X	X	--	--	--	--	--	--	--	--
29	X	X	X	X	X	X	X	X	X	--	--	--	--	--
30	X	X	X	X	X	X	X	X	X	--	--	--	X	X

Table 2. Summary of geophysical logs obtained for project test holes—Continued

Ground-Water Project test hole number	Caliper	Spontaneous potential	Gamma ray	Resistivity or induction	Microresistivity	Neutron	Density	Sonic	Computer interpreted logs	Temperature	Specific conductance	Flow	Neutron burst thermal-decay-time (TDT)	Spectral gamma (GLT)
31	X	X	X	X	X	X	X	X	X	--	--	--	--	--
32	X	X	X	X	X	X	X	X	X	--	--	--	--	--
33	X	X	X	X	X	X	X	X	X	--	--	--	--	--
34	X	X	X	X	X	X	X	X	X	--	--	--	--	--
35	X	X	X	X	X	X	X	X	X	--	--	--	--	--
36	X	X	X	X	X	X	X	X	X	--	--	--	X	X
37	X	X	X	X	X	X	X	X	X	--	--	--	--	--
38	X	X	X	X	X	X	X	X	X	--	--	--	--	--
39	X	X	X	X	X	X	X	X	X	--	--	--	--	--
40	X	X	X	X	X	X	X	X	X	--	--	--	--	--
41	X	X	X	X	X	X	X	X	X	--	--	--	--	--
42	X	X	X	X	X	X	X	X	X	--	--	--	--	--
43	X	X	X	X	X	X	X	X	X	--	--	--	--	--
44	X	X	X	X	X	X	X	X	X	--	--	--	--	--
45	X	X	X	X	X	X	X	X	X	--	--	--	--	--
46	X	X	X	X	X	X	X	X	X	--	--	--	--	--
47	X	X	X	X	X	X	X	X	X	--	--	--	--	--
48	X	X	X	X	X	X	X	X	X	--	--	--	--	--
49	X	X	X	X	X	X	X	X	X	--	--	--	--	--
50	X	X	X	X	X	X	X	X	X	--	--	--	--	--
51	X	X	X	X	X	X	X	X	X	--	--	--	--	--
52	X	X	X	X	X	X	X	X	X	--	--	--	--	--
53	X	X	X	X	X	X	X	X	X	--	--	--	--	--
54	X	X	X	X	X	X	X	X	X	--	--	--	--	--
55	X	X	X	X	X	X	X	X	X	--	--	--	--	--
56	X	X	X	X	X	X	X	X	X	--	--	--	--	--
57	X	X	X	X	X	X	X	X	X	--	--	--	--	--
58	X	X	X	X	X	X	X	X	X	--	--	--	--	--
58	X	X	X	X	X	X	X	X	X	--	--	--	--	--
60	X	X	X	X	X	X	X	X	X	--	--	--	--	--
61	X	X	X	X	X	X	X	X	X	--	--	--	--	--

Table 2. Summary of geophysical logs obtained for project test holes—Continued

Ground-Water Project test hole number	Caliper	Spontaneous potential	Gamma ray	Resistivity or induction	Microresistivity	Neutron	Density	Sonic	Computer interpreted logs	Temperature	Specific conductance	Flow	Neutron burst thermal-decay-time (TDT)	Spectral gamma (GLT)
62	X	X	X	X	X	X	X	X	X	--	--	--	--	--
63	X	X	X	X	X	X	X	X	X	--	--	--	X	X
64	X	X	X	X	X	X	X	X	X	--	--	--	--	--
65	X	X	X	X	X	X	X	X	X	--	--	--	--	--
66	X	X	X	X	X	X	X	X	X	--	--	--	--	--
67	X	X	X	X	X	X	X	X	X	--	--	--	X	X
81	X	X	X	X	X	X	X	X	X	--	--	--	--	--
82	X	X	X	X	X	X	X	X	X	--	--	--	--	--
83	X	X	X	X	X	X	X	X	X	--	--	--	--	--
84	X	X	X	X	X	X	X	X	X	--	--	--	--	--
85	X	X	X	X	X	X	X	X	X	--	--	--	--	--
86	X	X	X	X	X	X	X	X	X	--	--	--	--	--
87	X	X	X	X	X	X	X	X	X	--	--	--	--	--
88	X	X	X	X	X	X	X	X	X	--	--	--	--	--
89	X	X	X	X	X	X	X	X	X	--	--	--	--	--
90	X	X	X	X	X	X	X	X	X	--	--	--	--	--
91	X	X	X	X	X	X	X	X	X	--	--	--	--	--
92	X	X	X	X	X	X	X	X	X	--	--	--	--	--
93	X	X	X	X	X	X	X	X	X	--	--	--	--	--

fig. 6–4, p. 59) also is useful. However, a cross plot of bulk density versus neutron porosity for the lithologic types that characterize the alluvium and other terrestrial environments typical of the eastern study area is the most useful. (See fig. 6.) Sonic cross plots of neutron porosity versus travel time are useful in determining lithology for consolidated formations; however, the sonic-neutron cross plots developed for consolidated rocks and reported in most references on logging are of limited value in unconsolidated or slightly consolidated formations. For unconsolidated formations in the eastern part of Abu Dhabi Emirate, the compensated sonic log is a useful indicator of clay content. Also, the natural gamma log is useful in distinguishing among formations of similar lithology that have clastic material from different sources.

In the eastern part of Abu Dhabi Emirate, much of the sediment is of ophiolitic origin. This sediment has very low natural gamma radioactivity; thus, the gamma-ray log is not useful as a clay indicator. The 0- to 1,300-foot interval of the gamma-ray log for test hole GWP-26 shown in figure 4 is an example of the low gamma radioactivity. Because of the substantial clay content in nearly all of the shallow material in the area, determination of the static spontaneous potential is difficult. The spontaneous potential is only slightly developed and is of limited use as a clay indicator in the study area. The reason for the only slightly developed

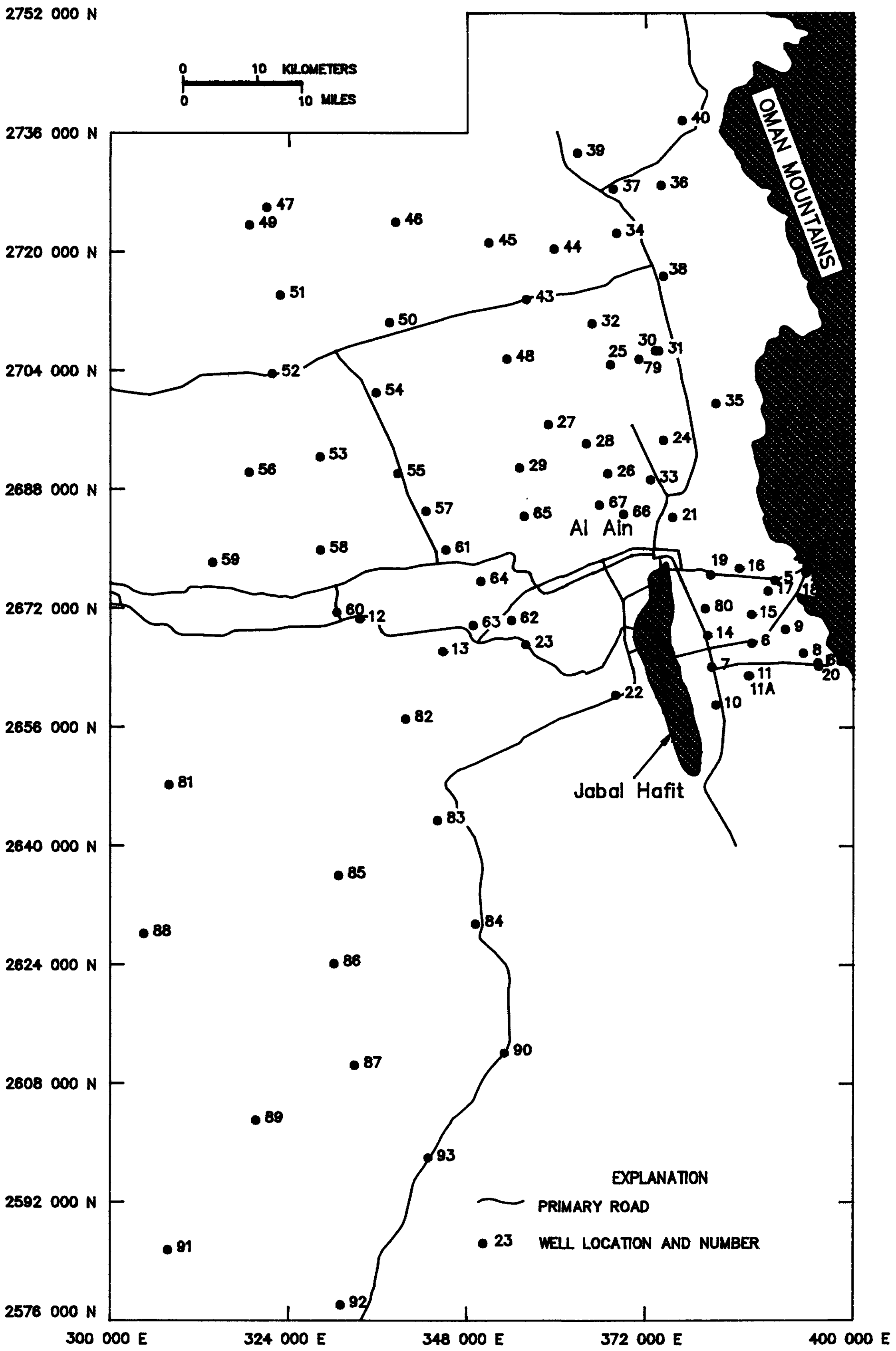


Figure 3. Location of test holes with geophysical logs.

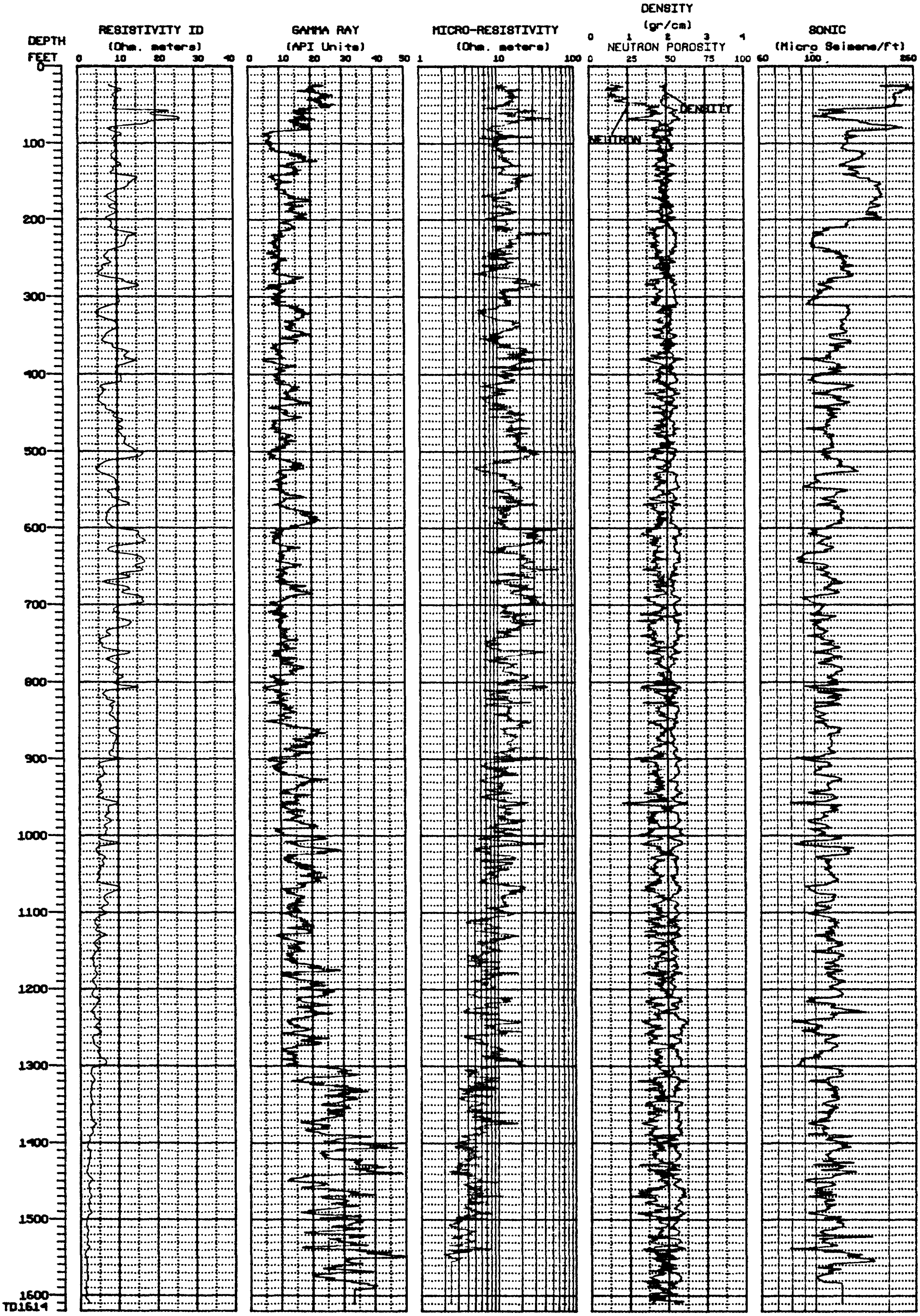


Figure 4. Geophysical logs for test hole GWP-26.

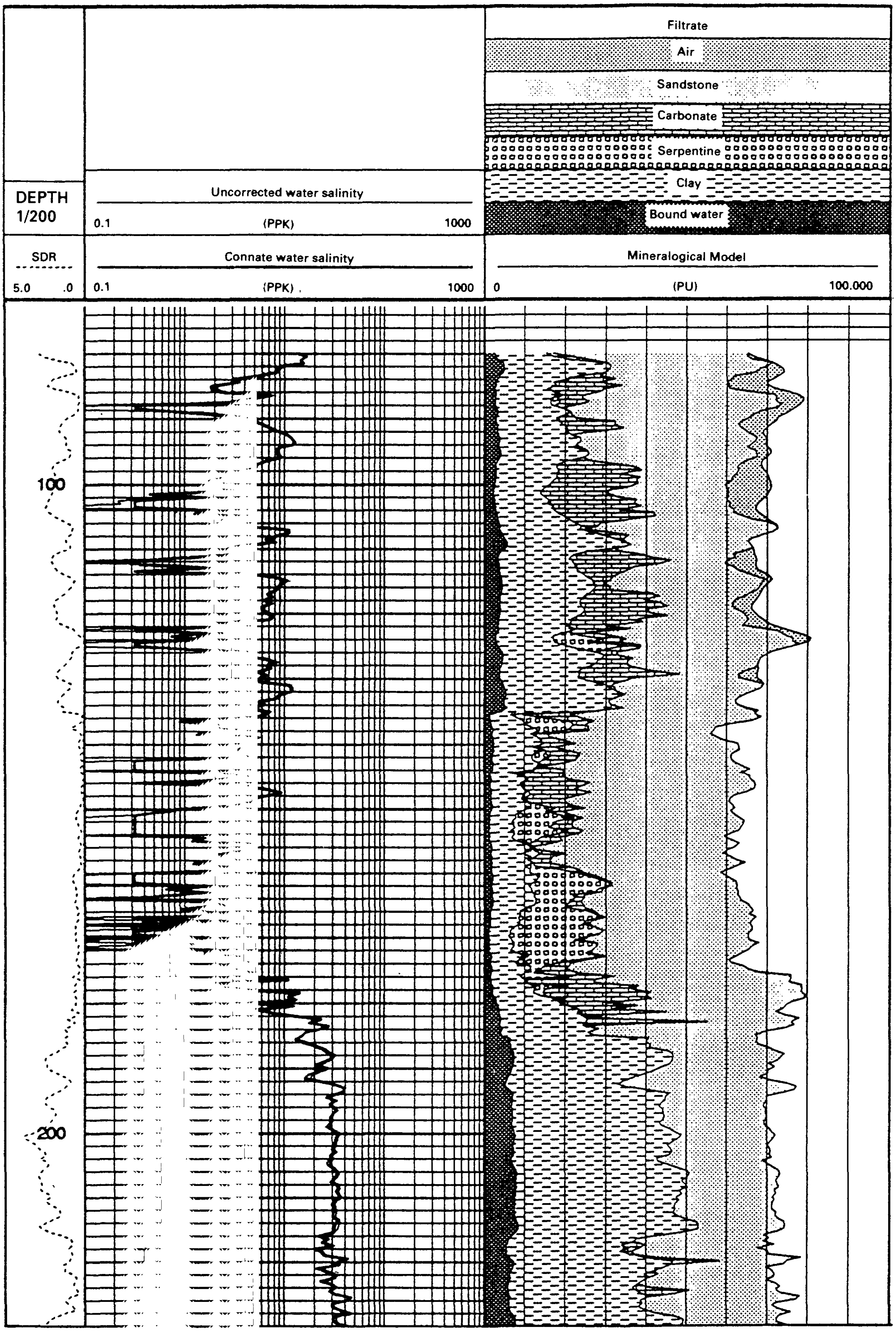


Figure 5. Logs of computer-interpreted properties from standard suite of logs for test hole GWP-30.

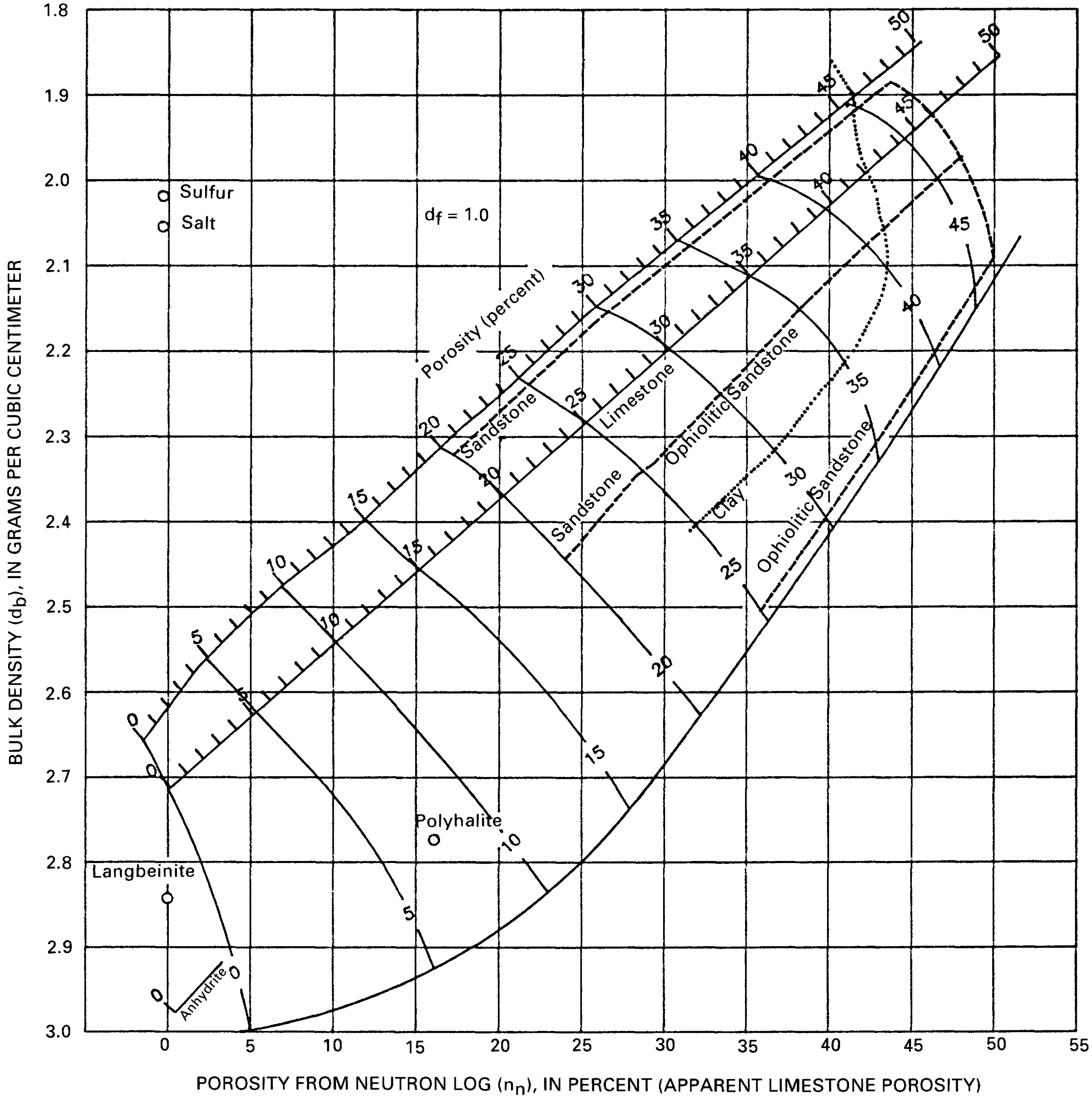


Figure 6. Lithology and porosity interpreted from cross plot of bulk density against neutron-porosity.

spontaneous potential may be indirectly related to the clay-mineral properties of the sediment.

Geophysical logs also are used to correlate data collected by surface-geophysical investigations of subsurface formations. For example, resistivity values from logs (fig. 7) are correlated to resistivity of subsurface layers as interpreted from data from transient-electromagnetic surveys (Fitterman and others, 1991). The correlation of the deep induction log to transient electromagnetic layers (fig. 8) is exceptionally good.

Sonic and density logs are used to construct an acoustic-impedance log, which is the basis of a synthetic seismogram and can be correlated to seismic profiles (Dennis Woodward, U.S. Geological Survey, oral commun., May 5, 1989; Hadley and others, 1991). Accordingly, the seismic profile is correlated to the borehole-geophysical logs, which

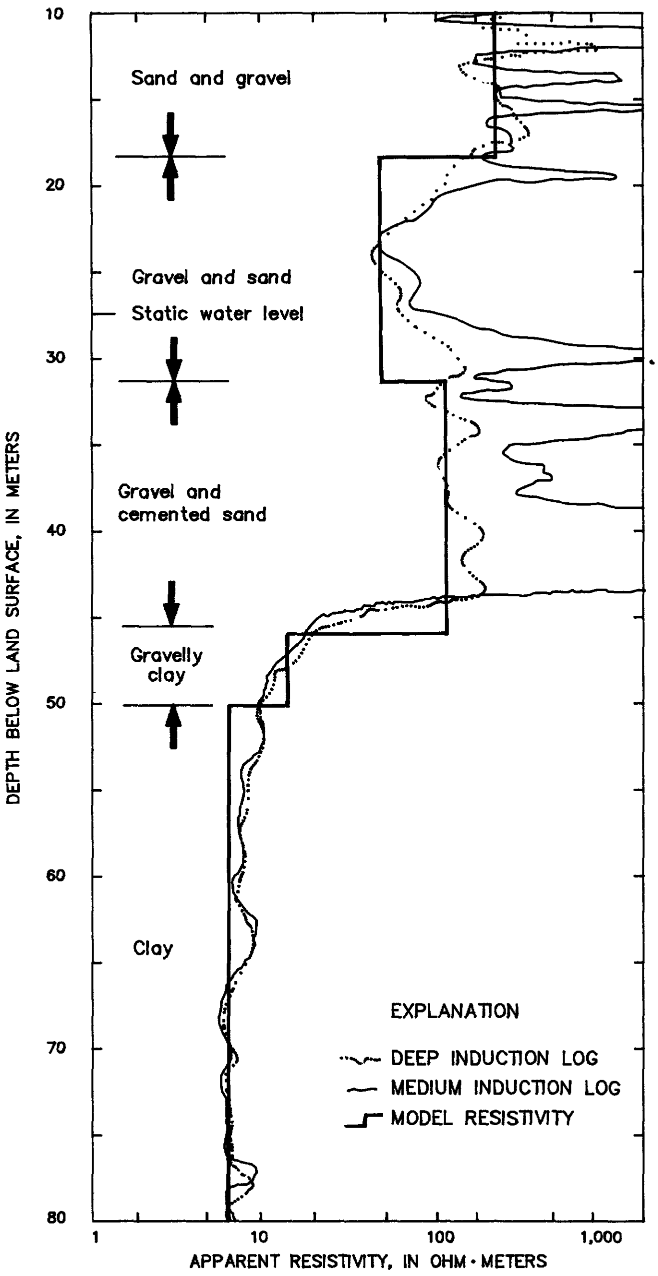


Figure 7. Geophysical logs of test hole GWP-18 and interpreted resistivity from transient electromagnetic survey (after Fitterman and others, 1991).

in turn are correlated to lithology or geologic formations (fig. 8).

Sonic logs also are used to determine typical sonic velocities in different subsurface lithology. These sonic velocities then are used to interpret lithology from velocity data. For example, velocity data from uphole seismic surveys (fig. 9) generally can be used to determine not only the geologic units but also if the units are saturated (Woodward and Menges, 1991).

Geohydrologic Studies

Geophysical logs are used in numerous ways including the differentiation of geohydrologic units, such as aquifers and confining layers. Geohydrologic units are composed of one or more permeability zones. A permeability zone is a thickness of subsurface material with a characteristic permeability, whether it be large or slight.

Use of Logs at Drill Site

Geophysical logs were obtained from the mud-filled test holes, which were drilled with an 8½-inch bit. Copies of the geophysical logs were made at the drill site for use by the site geohydrologist in identifying the water table, permeable zones, and water resistivity. This information was needed to design the well.

The compensated sonic log was very useful in locating the water level in most test holes because the sonic velocity in most partially saturated material is slow. Transit times greater than 225 microseconds per foot (μs/ft) are typical for partially saturated material (table 3).

The neutron log also was useful in estimating the water saturation including the water table. In general, partially saturated material is indicated by very slight porosity on the neutron log because the unsaturated pores have little water (small quantity of hydrogen). For example, the neutron-porosity logs for test hole GWP-26 (fig. 4) indicate that the partially saturated zone extended from ground level to about 50 feet. The deep induction log also may be useful in determining the water level because saturated permeable material has a lesser resistivity than equivalent partially saturated material.

Determination of Permeable Zones

Qualitative interpretations of permeable zones, which will yield water easily to a well, can be made from the logs at the drill site by inspection of the resistivity (or induction) log and the sonic log. In most clastic material, permeability is primarily an inverse function of clay content. The sonic log of test holes in the eastern study area is a better clay indicator than the gamma-ray log or the spontaneous-potential log, which are the usual clay indicators. Most permeable aquifer material, such as sand and gravel, is resistive and can be identified on the resistivity log. However, water resistivity and clay

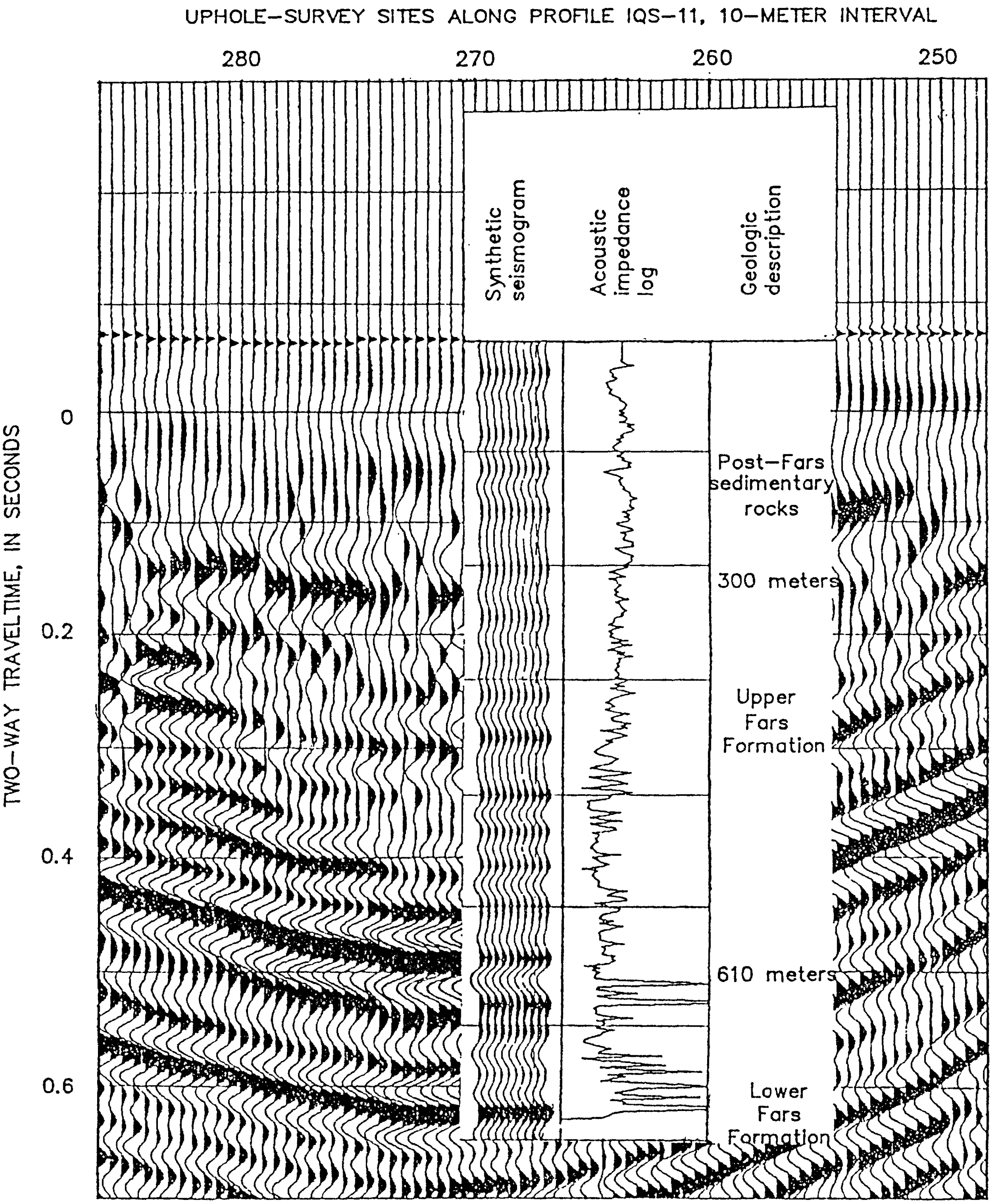


Figure 8. Reprocessed seismic data and synthetic seismogram of test hole GWP-7, Al Jaww Plain.

conductivity also affect resistivity. Accordingly, the site geohydrologist (using the log of the drill cuttings as a reference) examines the resistivity log for zones of relatively larger resistivity. These zones then are checked on the sonic log to qualitatively evaluate clay content. If the zones are generally resistive and are interpreted as relatively clay free, they probably are permeable zones and are candidates for well-screen sections. Other permeability indicators, such as spontaneous potential and the

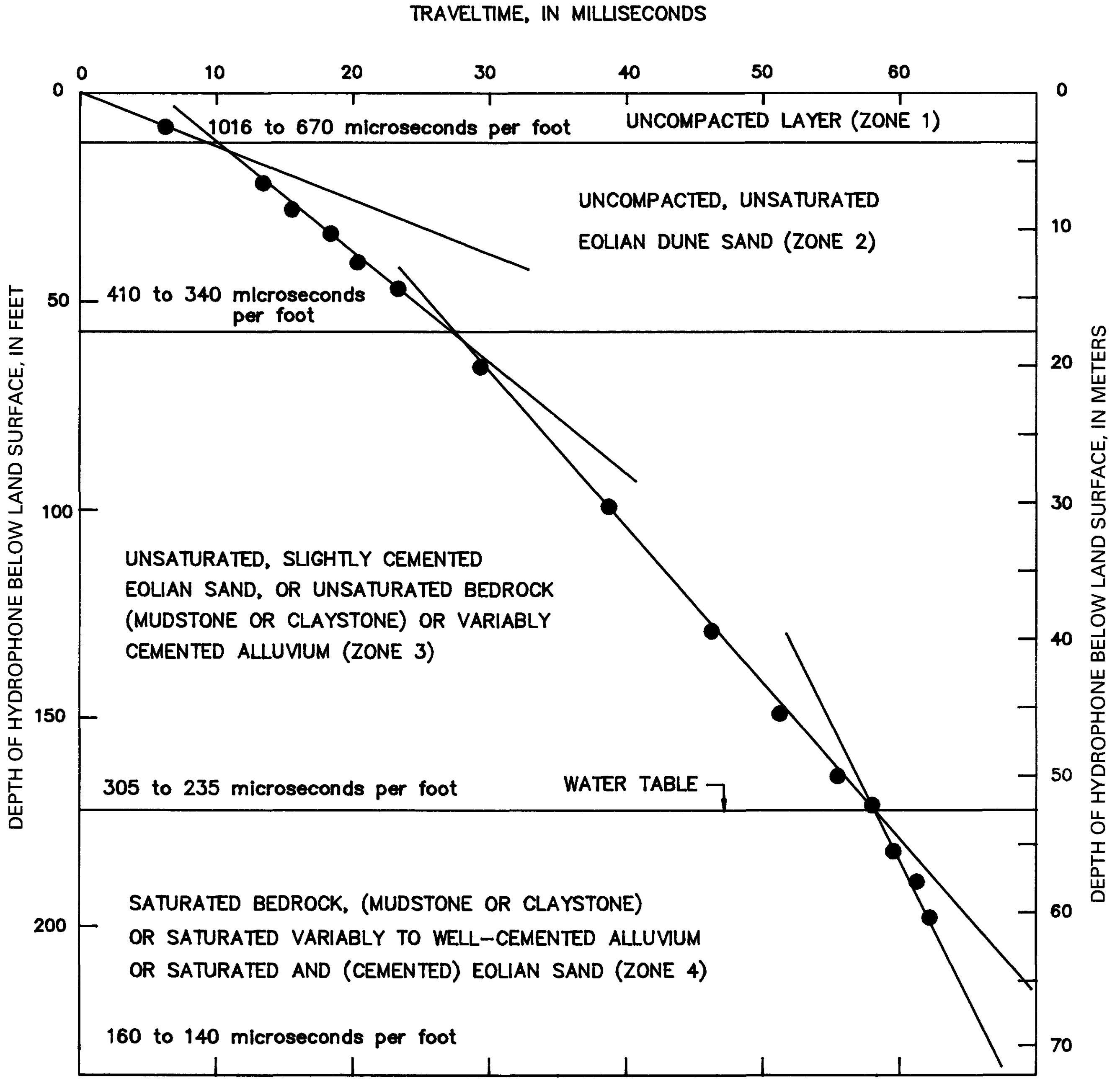


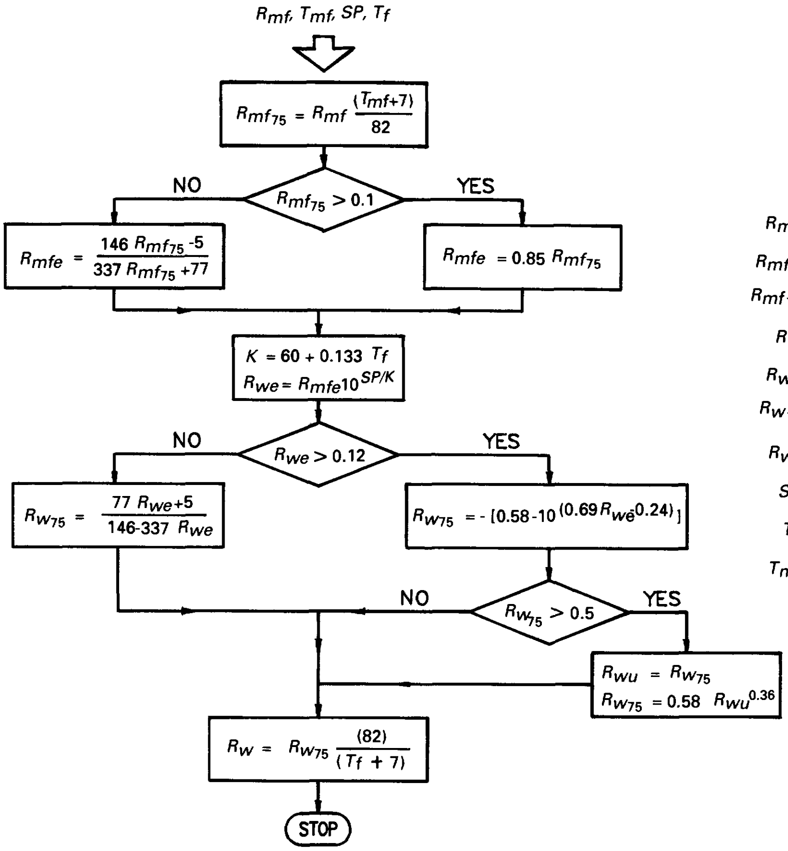
Figure 9. Hydrologic interpretation of velocity layers derived from an uphole survey (modified from Woodward and Menges, 1991).

presence of mud cake, also are used to identify probable permeable zones to the degree possible.

Determination of Water Chemistry and Resistivity

Water quality is of concern to the geohydrologist in designing a well. In general, it is desirable to screen the most permeable sections that contain water with the least dissolved-solids content because this best fits the usual objectives of obtaining adequate water of the best quality. Also, for wells from which water samples for chemical analyses are to be collected, it is desirable to screen only those zones that have the same water chemistry. Accordingly, for the design of most wells, it is necessary to identify not only the permeable zones that will yield water to the well, but also the water chemistry in each of the zones.

The resistivity of the formation water is related to water chemistry. Estimates of water resist ivity can be made from geophysical logs (Jorgensen,



EXPLANATION

K	Spontaneous potential constant at a specific temperature
R_{mf}	Resistivity of mud filtrate, in ohm · meters
R_{mfe}	Resistivity of mud filtrate equivalent, in ohm · meters
$R_{mf_{75}}$	Resistivity of mud at 75°F, in ohm · meters
R_w	Resistivity of water, in ohm · meters, at formation temperature
R_{we}	Resistivity of water equivalent, in ohm · meters
$R_{w_{75}}$	Resistivity of water at 75°F, in ohm · meters
R_{wu}	Resistivity of water uncorrected, in ohm · meters
SP	Spontaneous potential, in millivolts
T_f	Temperature of formation, in degrees Fahrenheit (°F)
T_{mf}	Temperature of mud filtrate, in degrees Fahrenheit (°F)

Figure 10. Spontaneous-potential method of calculating water resistivity (after Jorgensen, 1991).

Table 3. Typical compensated sonic-log travel times in the eastern study area

[>, greater than]

Material	**Travel time (microseconds per foot)**
Partially saturated formations	>225
Clay	170–225
Water or freshwater mud	190
Sand and gravel, clean	50–130
Limestone and marl	45–70
Dolomite, sandstone, anhydrite, or gypsum	45–60

1989, 1990, 1991). Methods of estimating water resistivity include the spontaneous-potential method (fig. 10), the cross-plot method (fig. 11), the microresistivity method, and the cementation-exponent method. In the eastern study area, the spontaneous-potential method generally does not work satisfactorily because the potential between adjacent lithology is slight in the clay-rich clastic sediment. Sediment that is partially ophiolitic in origin has slight spontaneous-potential contrasts.

The cross-plot method of estimating water resistivity is difficult to apply to logs of test holes in the eastern study area because most of the permeable sections contain some clay. The cross-plot method assumes that water resistivity is constant within the permeability zone and that substantial porosity differences exist within the zone. These conditions are seldom met in the eastern study area; thus, the method has only limited applicability. Additionally, because clay is present in most zones, the clean formation assumption of the Archie equations (Archie, 1942) is not met. (The reader is referred to Worthington and Johnson (1991) for a review of the clayey, freshwater aquifer problem in geophysical logging.)

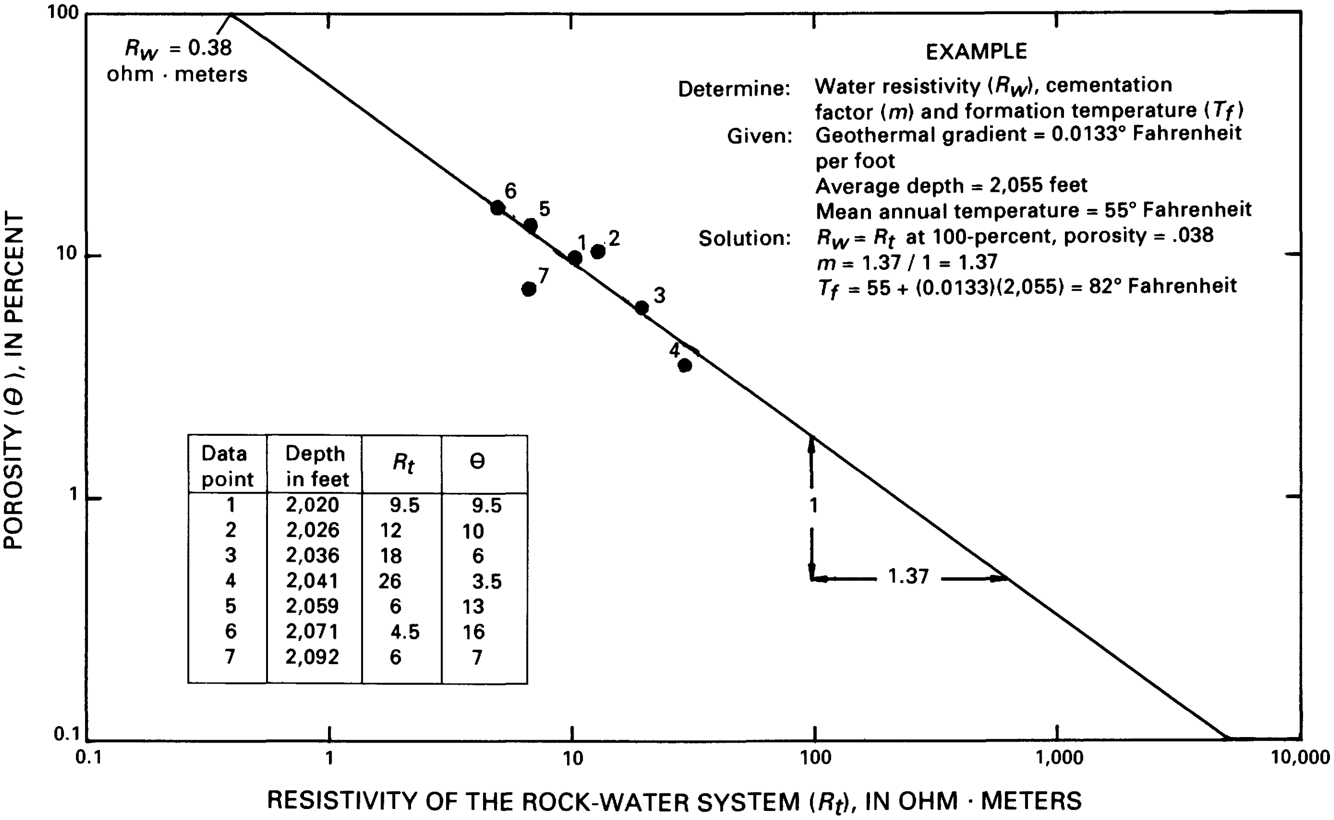
Even though the clay-free assumption was not met, the microresistivity method was useful for estimating the water resistivity in most test holes in the study area if there was some invasion of the drilling fluid. The microresistivity method uses two different equations for the formation factor (F). The first formation-factor equation is as follows:

$$F=R_t/R_w, \qquad (1)$$

where

R_t is the true resistivity, in ohm·meters, and

R_w is the resistivity, in ohm·meters, of the formation water, at in situ temperature.



Data point	Depth in feet	R_t	Θ
1	2,020	9.5	9.5
2	2,026	12	10
3	2,036	18	6
4	2,041	26	3.5
5	2,059	6	13
6	2,071	4.5	16
7	2,092	6	7

EXAMPLE

Determine: Water resistivity (R_w), cementation factor (m) and formation temperature (T_f)
Given: Geothermal gradient = 0.0133° Fahrenheit per foot
Average depth = 2,055 feet
Mean annual temperature = 55° Fahrenheit
Solution: $R_w = R_t$ at 100-percent, porosity = .038
$m = 1.37 / 1 = 1.37$
$T_f = 55 + (0.0133)(2{,}055) = 82°$ Fahrenheit

Figure 11. Porosity-resistivity cross plot (after Jorgensen, 1989).

The second formation-factor equation is as follows:

$$F \approx R_{xo} / R_{mf}, \qquad (2)$$

where

R_{xo} is the resistivity, in ohm·meters, of the flushed zone, usually determined from a microresistivity log, and

R_{mf} is the resistivity, in ohm·meters, of the mud filtrate.

Combining the two formation-factor equations yields the following:

$$R_w \approx R_t R_{mf} / R_{xo}. \qquad (3)$$

Values of R_t generally are read from a deep induction log and R_{xo} values from a microresistivity log. The R_t and R_{xo} values are measured at the in situ formation temperature (T_f). Because the temperature of the mud filtrate (T_{mf}) affects the resistivity, R_{mf} measurements should be corrected to in situ temperature (T_f) prior to use in equations 2 and 3.

The spontaneous-potential and the microresistivity methods were used at several test holes in the study area. Each method requires a value of R_{mf}, which is not always available. If R_{mf} is not available, the cementation-exponent method may be used. This method also is based on the formation-factor concept and uses the following Archie (1942) equation:

$$F = \phi^{-m}, \qquad (4)$$

where

ϕ is the effective or interconnected porosity exclusive of retained water on the pore walls (decimal), and

m is the cementation exponent (dimensionless).

The cementation exponent relates to the tortuosity of the flow path and the pore-throat dimension. The cementation exponent (fig. 11) is the negative reciprocal of the slope of the line defined by a log-log cross plot of porosity and resistivity. Combining equations 1 and 4 yields the following equation:

$$R_w = R_t \, \phi^m. \qquad (5)$$

Because R_t is at in situ formation temperature (T_f), R_w is calculated at in situ temperature. Empirically, it was determined that R_w could be estimated using log-derived neutron-porosity values of porosity and by using an assumed cementation exponent (m) of 1.35.

Knowing R_w at T_f from equation 5, it remains to correlate resistivity to water chemistry. This is done by relating specific conductance (SC), which is the inverse of the resistivity of water at 77°F, to dissolved solids (DS). The relation is as follows:

$$DS \approx (P)(SC), \qquad (6)$$

where

DS is the dissolved-solids content, in parts per million,

P is proportional factor determined for the water of concern, and

SC is specific conductance, in microSiemens per centimeter at 25°C.

For most ground water in the eastern study area, P is approximately 0.67, which is the value often used for water from aquifers worldwide. Specific conductance is computed from the following equation:

$$SC=10{,}000/R_{w77}, \qquad (7)$$

where

R_{w77} is resistivity, in ohm·meters, of water at 77° F.

R_{w77} is calculated from the following equation:

$$R_{w77}=(R_w)(T_f+7)/84, \qquad (8)$$

where

R_w is from equation 3 or 5, and

T_f is formation temperature, in degrees Fahrenheit.

The geohydrologist at the drill site, after identifying the permeable zones and after calculating estimates of dissolved-solids content of the formation water, designs the well such that a screen is placed in the borehole opposite the permeable zones having the required water quality.

Transmissivity

Estimates of transmissivity, T, in meters squared per second are derived from hydraulic-conductivity estimates. The transmissivity of an aquifer is the sum of the transmissivities of the individual permeability zones (zone with a characteristic permeability, large or small) as indicated by the following equation:

$$T=K_1b_1+K_2b_2+\ldots K_\mathrm{n}b_\mathrm{n}, \qquad (9)$$

where

K is the hydraulic conductivity of the permeability zone in meters per second,

b_1 is the thickness of permeability zone 1, in meters, and

$1,2,\ldots n$ refer to the first, second, and nth permeability zones.

Hydraulic conductivity based on intrinsic permeability and water properties can be estimated (appendix G) for each zone. Intrinsic permeability was determined for each permeability zone using a computer program, LOGAN2, as described in appendix C. The thickness of each permeability zone can be determined from the logs, especially the resistivity logs. Accordingly, estimates of transmissivity can be calculated using equation 9.

Aquifer Storage Coefficient

The storage coefficient (S) of an aquifer is derived from the storage coefficient of the individual permeability zones. The storage coefficient is a function of compressibility of the aquifer and delayed yield. If the aquifer is confined (artesian), delayed yield does not exit. The artesian storage coefficient (S_a) is related to the specific storage (S_s) by the following equation:

$$S=S_a=S_sB, \qquad (10)$$

where

B is the thickness of the aquifer, in meters.

For individual permeability zones the equation is:

$$S=S_{s,1}b_1+S_{s,2}b_2+\ldots S_{s,n}b_n, \qquad (11)$$

where

$\mathrm{S_s}$ is specific storage of a permeability zone, in meters^{-1}, and

$1, 2,\ldots n$ are subscripts that relate to the first, second, and nth permeability zones.

Using equation 11, the storage coefficient for a confined aquifer can be calculated using S_s values determined from log data (appendix F) and thickness values determined from the resistivity logs. For water-table conditions, delayed yield (S_y), which is water derived from drainage of the water table (also called drainage), is included in the computation of the storage coefficient as follows:

$$S=S_y+S_a. \qquad (12)$$

For usual water-table conditions, S_a is much smaller than S_y, and S is approximately equal to S_y.

For a water-table aquifer consisting of several individual permeability zones, the specific yield (appendix D) for the aquifer, assuming the water table includes each of the zones, is given by the following equation:

$$S_y=(S_{y,1}b_1+S_{y,2}b_2+\ldots S_{y,n}b_n)/B, \qquad (13)$$

where B is the sum of the thickness of the individual permeability zones (b_1, b_2,...b_n).

Estimates of specific yield for the aquifers in the study area can be calculated using equation 13. Estimates of S_y for individual permeable zones (appendix D) can be calculated from the computer program LOGAN2 using log data and thickness values determined from the resistivity logs.

Research Borehole-Geophysical Logging

A research borehole-geophysical-logging program was designed to provide new and detailed information for both geologic and geohydrologic investigations. An important feature of the program is that it can provide additional and improved data in less time and at less cost than obtaining similar data using other methods, such as complete coring. In addition, the research program provided information that can be correlated to other data-gathering techniques, such as computer interpretations of the standard suite of geophysical logs obtained for nearly all project test holes.

For geologic investigations, information regarding lithology, rock chemistry, and mineralogy variations with depth are needed. In reference to geohydrology, information on specific yield, water chemistry, lithology, mineralogy, and permeability variations with depth also is needed. One method of collecting the needed data would be to core a test hole continuously. Continuous coring while drilling in unconsolidated material is slow, difficult, and expensive. A program of research geophysical logging in conjunction with a program of special testing, including sidewall coring, was developed to reduce costs and improve data-collection efficiency.

Research borehole-geophysical logging and special testing, including sidewall coring, were conducted at project test holes GWP-30, -36, -63, and -67. (See fig. 3 for locations.) In addition to the standard suite of logs obtained at GWRP test holes, a spectral-gamma log, the geochemical logging tool (GLT) log, was obtained. The GLT log proved to be useful in determining clay volume and mineralogy, and in making permeability estimates. Measurements of aluminum, silicon, calcium, iron, sulfur, potassium, uranium, and thorium were possible with the GLT log. The measured quantities of these elements can be correlated with the mineralogy expected on the basis of the analyses of sidewall cores and existing background information, which in turn can be correlated with estimates of whole-rock chemistry.

The second research log obtained in addition to the standard suite of logs was a thermal-decay-time (TDT) log. The TDT log measures the rate of decay of the thermal-neutron population around two detectors after a neutron burst has been emitted by a neutron generator. This measurement is affected primarily by the element chlorine, which is the most common thermal-neutron absorber in the subsurface. The depth of investigation of the TDT measurement is relatively shallow, less than 1 foot. Therefore, it is considered to be an invaded-zone measurement when obtained from an uncased hole.

The GLT and TDT logs allowed an independent determination of specific yield and irreducible water saturation when it was assumed that the volume of formation water that is replaced by mud filtrate approximately equals the specific yield. The governing equation for TDT response is as follows:

$$\Sigma_L=(\Sigma_o)(1-\phi-V_c)+(\Sigma_c)V_c+(\Sigma_f)\phi, \qquad (14)$$

where

Σ_L is the TDT measurement, in capture cross-sectional units, (c.u.),
Σ_o is the capture cross section for matrix other than clay, in c.u.,
ϕ is porosity excluding clay-bound water (decimal),
V_c is volume of wet clay (decimal),
Σ_c is the capture cross section for clay, in c.u., and
Σ_f is the capture cross section of the fluid in the invaded zone, in c.u.

Values for Σ_c and Σ_o can be obtained from published tables of log properties of minerals; values of V_c and ϕ can be determined by independent log analysis.

If the invaded zone is not permeable (there is no invasion), Σ_f will be equal to Σ_w, which is the capture cross section of the formation water. If the zone is totally flushed, Σ_f will equal Σ_{mf}, which is the capture cross section of the mud filtrate. Any intermediate situation will give a corresponding intermediate capture cross section as indicated by the following equation:

$$\Sigma_f=[(\Sigma_{mf})(Ꝟ_{mf})+(\Sigma_w)(Ꝟ_{wir})]/(Ꝟ_{mf}+Ꝟ_{wir}), \quad (15)$$

where

$Ꝟ_{mf}$ is the volume of mud filtrate (decimal), and

$Ꝟ_{wir}$ is the volume of water not flushed as measured by the TDT tool (decimal).

Values for Σ_{mf} and Σ_w are functions of salinity and can be obtained from published tables. $Ꝟ_{mf}$ is probably a good estimate of specific yield, and $Ꝟ_{wir}$ is probably a good estimate of the irreducible water saturation (retained water, but not clay-bound water). Irreducible water saturation (S_{wir}) can be approximated by the following equation:

$$S_{wir}\approx Ꝟ_{wir}/(Ꝟ_{mf}+Ꝟ_{wir}), \quad (16)$$

and Σ_f is given by the following equation:

$$\Sigma_f=(\Sigma_{mf})(1-S_{wir})+(\Sigma_w)(S_{wir}). \quad (17)$$

In practice, S_{wir} is calculated using equation 17.

The lithology encountered in each of the research test holes was interpreted from geophysical logs using a comprehensive borehole environmental model. (See fig. 12.) The minerals included in the interpretation were a mix of minerals identified from cross plots and minerals recognized in sidewall cores. For example, three types of clay were included in the mineralogical model. Smectite and kaolinite were identified repeatedly in sidewall cores from all of the research test holes, whereas illite was identified clearly on cross plots of thorium versus potassium and aluminum versus potassium. An iron-rich serpentine was included to account for the large iron content of the ophiolitic sand. Quartz and calcite were included because they were recognized in cuttings, in cores, and on cross plots of calcium versus silicon. Dolomite was included to reconcile large calcium content from GLT logs with a slight photoelectric index. Anhydrite (not shown in fig. 12) was included to account for the large sulfur and calcium measurements. Pyrite was included to account for the substantial sulphur and iron measurements. Anorthoclase was included because it was reported in cores and because it was necessary to account for the aluminum GLT measurements. Finally, anorthite (not shown on fig. 12) was included because of its repeated occurrence in sidewall cores.

All the expected logging-tool properties were taken from existing tables or were calculated using special Schlumberger-designed geochemical computer programs, GEOCHEM and SNUPAR. These two programs calculate the theoretical logging-tool response properties for any mineral that can be described in terms of its chemical formula or its weight composition. Although the chemical formula of common clays can vary substantially, log responses of typical compositions obtained from a laboratory study performed at the Schlumberger-Doll Research Center were found to agree with the log responses observed in the four research geophysical-logging test holes.

In addition to the minerals, the borehole environmental model also accounted for mud filtrate and formation water, which are the fluids that fill the pore space in the invaded zone. The proportion of fluids was determined by analysis of data from the TDT and the shallow resistivity logs if these logs were not adversely affected by environmental conditions in the borehole. Because, in the zones of interest for this study, the capture cross section of the formation water remains quite constant and substantially less than the capture cross section of the mud filtrate, exact values of formation water salinity were not required for a good estimate of specific yield.

A special mud system was used in drilling the four project test holes where research geophysical logs were obtained. For the purpose of GLT logging, a freshwater mud is preferable because the large chlorine content of saline mud reduces the fraction of the spectrum available for elements other than chlorine. Therefore, only a small fraction of the spectrum is left for the other elements, which increases the statistical variance of the other measurements. However, a very saline mud is favorable to the acquisition of a good quality TDT log because as much contrast as possible between formation-water and mud-filtrate salinity is desirable for determining the specific yield. A mud salinity of 50,000 to 60,000 parts per million sodium chloride was used and provided a satisfactory compromise.

GLT-log processing includes post-processing computations of permeability and bulk volume of irreducible water from mineralogy. This processing was designed originally for the mineralogy of clastic sediment found in a typical formation encountered

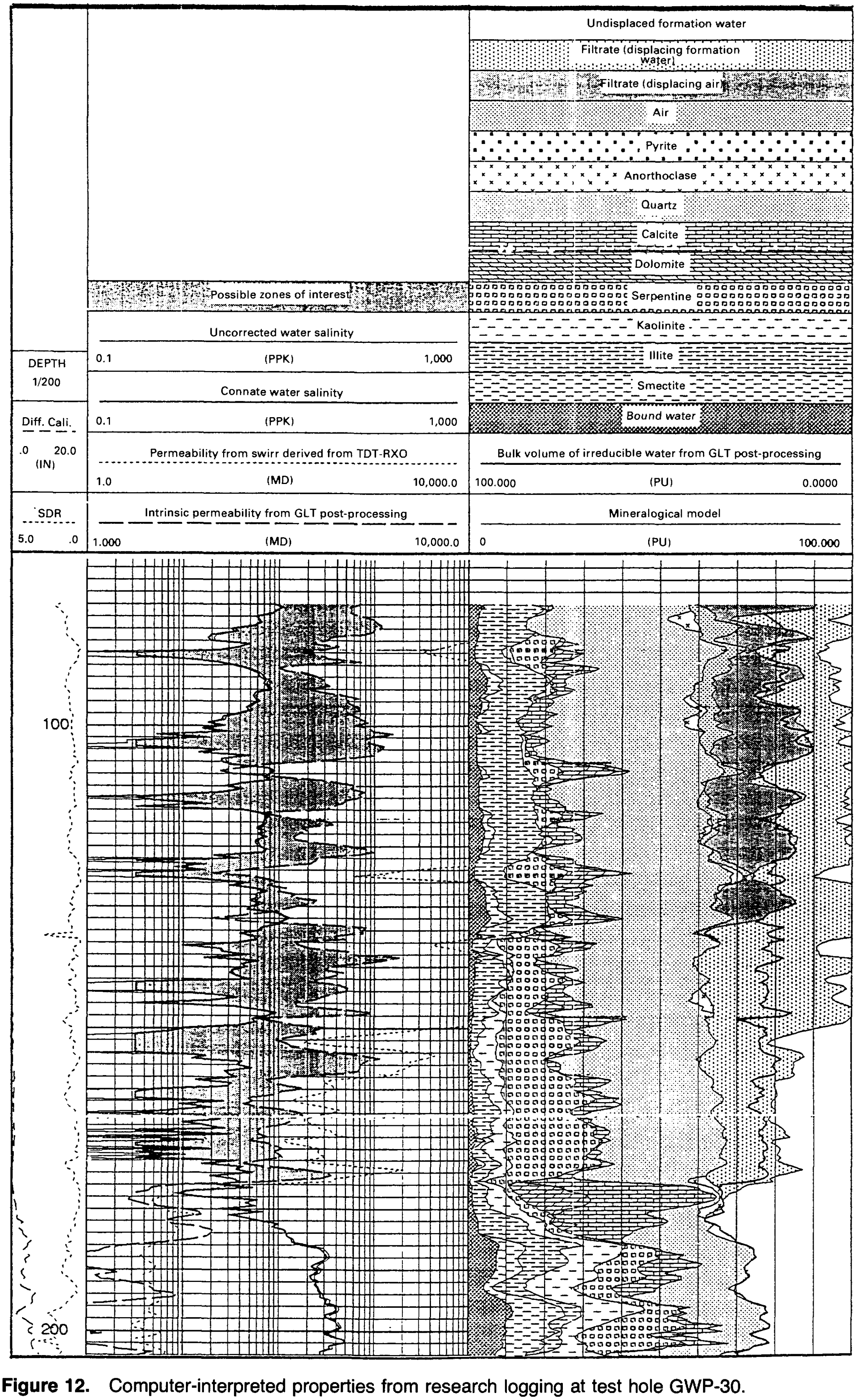


Figure 12. Computer-interpreted properties from research logging at test hole GWP-30.

in exploration for petroleum and did not account for the presence of ophiolitic material. Therefore, it was necessary to evaluate the effect of ophiolitic material on the computed permeability values. Because the same postprocessing also used a relation between porosity and permeability to derive a bulk volume of irreducible water, it was possible to estimate the effect of serpentine, the principal ophiolitic material, by comparing the bulk volume of irreducible water derived from mineralogy to the volume of unmoved formation water computed from the TDT log. An independent check on permeability and specific yield consisted of comparing the log-derived permeability for test hole GWP-30 to values determined from an aquifer test on a well constructed in that test hole. The comparison was favorable.

Computed-Interpreted Lithology

Computer-interpreted lithology determinations are made for test holes logged by Schlumberger Middle East (table 2). The borehole environmental model using the standard suite of logs has seven components: filtrate, air, sandstone, carbonate, serpentine, clay, and bound water (fig. 5). The model was developed to correlate information from the research-logging program to the data collected from the standard suite of geophysical logs used in the project. (See figs. 13 and 14.)

To optimize the interpretations for wells without GLT logs, both borehole environmental models were applied to the four test holes where research logs were available. Cross plots of the results obtained from both models were made. Figure 14 shows the same cross plots for test hole GWP-67 as were displayed for test hole GWP-30 in figure 13. Considering the difficulties in determining clay volume from standard methods, the match for clay volume and porosity is excellent. The match for carbonate and sand is not as good as the match for clay volume and porosity. However, the range is correct and shows small carbonate content and fairly large sand content (almost 50 percent of the total volume). These interpretations are reasonable considering the complex lithology.

Test hole GWP-30 was very rugose, and accordingly, a lesser quality match as compared to GWP-67 is expected. Indeed, it can be observed that there is more scatter around the 45° line for porosity and clay volume for this test hole than for test hole GWP-67. Part of the discrepancy in clay volume is attributed to the presence of kaolinite throughout a large part of the hole. Kaolinite is extremely difficult to recognize with standard logs, particularly when kaolinite is in combination with other clay types, which was found to be the case in test hole GWP-30. The match for carbonate and sand is not as good as that for porosity and clay volume, but the range is correct and shows that this test hole contains larger quantities of carbonate but less sand than test hole GWP-67. It should be emphasized that for the computation of water salinity, the main properties of interest are porosity and clay content, which explain the good match obtained in the center plot (fig. 13), particularly in the slight salinity range. For this comparison, sand includes ophiolitic material because the simplified borehole environmental model correctly computes the volume of this material only when it is present in a substantial quantity; whereas, the GLT log can measure even very limited quantities of such material. Overall the matches obtained here should greatly increase the confidence in the environmental elements determined for test holes using the simplified borehole environmental model.

Water Resistivity

The conductivity of water, which is the inverse of the resistivity of water, also was determined as part of computer-interpreted logs for test holes using a dual-water model. The model is especially useful in interpreting water resistivity of clayey sand. The dual-water model has proven useful in determining the effects of variable mineralogy, which is the case for the study area where at least three different types of clay with different mineralogy and ionic-exchange capacity were modeled.

In the dual-water model, the formation conductivity is considered to be the result of the parallel conductance of bound water (conduction is by ion exchange) with the conduction due to far water (free water plus retained water), where conduction is by mobile ions. This relation is

$$C_{weq}=(C_{fw}V_{fw}+C_{bw}V_{bw})/(V_{fw}+V_{bw}), \qquad (18)$$

where

C_{weq} is the conductivity of an equivalent water assuming clay-free conditions, in $\text{ohm}^{-1}\cdot\text{meters}^{-1}$,

C_{fw} is the conductivity of far water, in $\text{ohm}^{-1}\cdot\text{meters}^{-1}$,

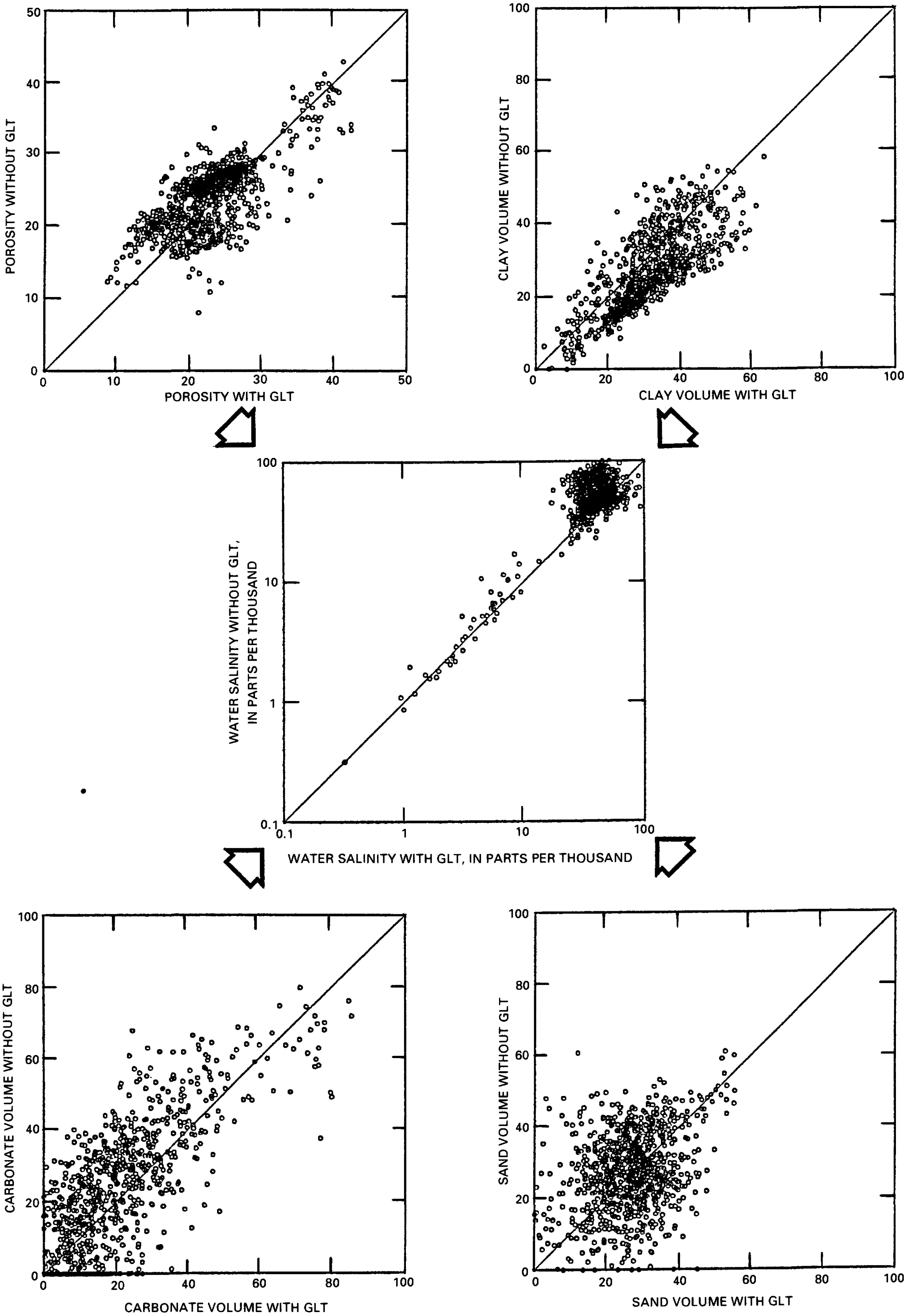


Figure 13. Cross plots of log interpretations for test hole GWP-30, with and without a geochemical logging tool (GLT) log.

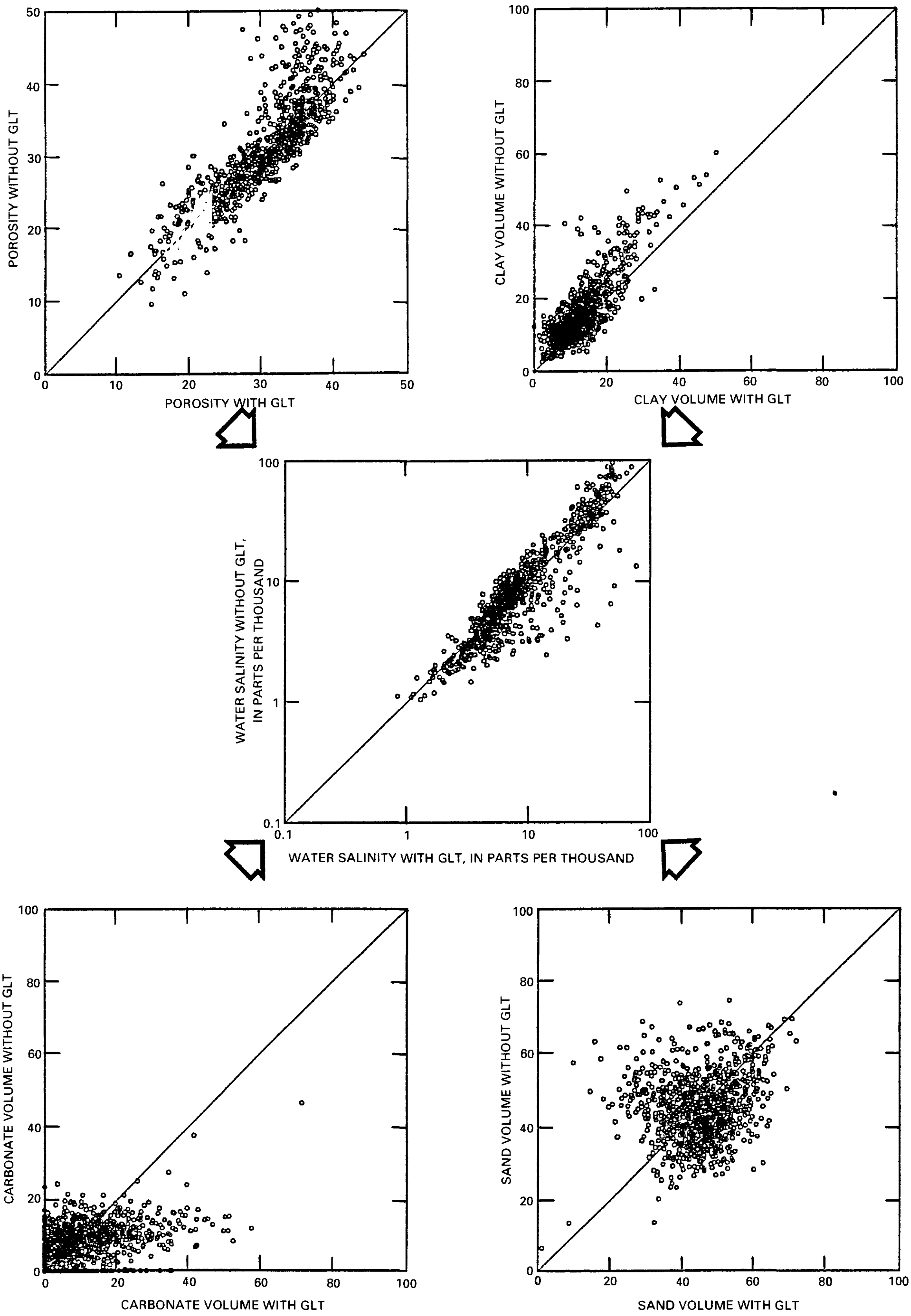


Figure 14. Cross plots of log interpretations for test hole GWP-67, with and without a geochemical logging tool (GLT) log.

$\cancel{V}_{fw}$ is volume of far water (decimal),
C_{bw} is conductivity of bound water, in $\text{ohm}^{-1}\cdot\text{meters}^{-1}$, and
$\cancel{V}_{bw}$ is volume of bound water (decimal).

The dual-water model assumes the Archie (1942) equations apply. Equation 5 can be written as follows:

$$1/C_{weq}=\phi^{m}_{t}/C_{t}, \tag{19}$$

where

ϕ_t is total porosity (decimal), and
C_t is the reciprocal of R_t, in $\text{ohm}^{-1}\cdot\text{meters}^{-1}$.

Values of R_t can be determined from a deep induction log. By combining equations 18 and 19, the conductivity of far water (C_{fw}) at downhole temperature can be computed. Because C_{bw} is itself a function of C_{fw} and temperature, a one-step iteration is required to solve for C_{fw}.

The cementation exponent (m) was assumed to be 2. Smaller apparent m values are valid when corrections for the clay content are not made. Cementation exponents greater than 2 (based on the dual-water model) were inferred by testing Archie equations (eqs. 3 and 4) for m knowing C_{mf}. Larger values of m correlated with large calcite presence in the matrix.

SUMMARY

A program of geophysical logging was implemented for the Ground-Water Research Project for the Abu Dhabi Emirate. The logging program is an integral part of the geologic and hydrogeologic investigations. Geophysical logging was needed to determine the lithology and hydrogeologic properties of sediments in potential aquifers. Distinguishing lithology in the eastern study area on the basis of drill cuttings is very difficult because the alluvium and other shallow formations consist of layers of similar and repetitive lithology and because cavings of the soft subsurface material were common while drilling.

A standard suite of geophysical well logs was obtained at project test holes. This suite includes caliper, spontaneous-potential, gamma-ray, resistivity (dual-induction), microresistivity, compensated neutron, compensated density, and compensated sonic logs. Additionally, photoelectric logs were obtained in most of the test holes logged by Schlumberger.

Interpretation of formation properties using these logs is difficult because of the nature of the eastern Abu Dhabi Emirate sediment. Specifically, the source of a substantial part of the clastic sediment is ophiolites or altered ophiolitic material transported from the adjacent Oman Mountains. This clastic sediment has nontypical petrophysical properties, which make log interpretation difficult and which invalidate standard empirical relationships published in the literature. A research program of borehole-geophysical logging was conducted to determine the properties of the shallow subsurface formations. The program included special coring and logging at four project test holes, GWP-30, -36, -63, and -67. Drill cuttings were collected and a log was made at the drill site. In addition to the standard suite of logs, a spectral-gamma (GLT) log and a thermal-decay-time (TDT) log were obtained. After logging was completed, the geophysical logs and the sample logs were used to identify lithologic and permeability zones (zones with a characteristic permeability) in the test holes. Sidewall cores were collected from selected lithologic and permeability zones.

The sidewall cores were analyzed in the laboratory for mineralogy, whole-rock chemistry, and other properties. The mineralogy and whole-rock chemistry of the sidewall cores were correlated to measurements of aluminum, silicon, calcium, iron, sulfur, potassium, uranium, and thorium from the GLT log. A borehole environmental model based on sidewall-core analyses and drill cuttings was developed. Results of the GLT log were related to the model. The TDT log was interpreted as to irreducible water saturation and specific yield. Values of intrinsic permeability that were calculated using the geophysical-log analysis were correlated to values obtained from an aquifer test conducted later at test hole GWP-30. A model of water resistivity was made and correlated to the whole-rock chemistry of the aquifer.

Geophysical-log analysis was used in both geologic and geohydrologic investigations. Geophysical-log analysis was used in geologic studies to identify formations, to determine lithology, and to calibrate seismic profiles using a synthetic seismogram, which was constructed from the compensated density and compensated sonic logs. The compensated sonic log was one source of information used to define typical velocities for different lithologies. The velocity data were used to interpret uphole seismic surveys. Resistivity logs were used to correlate borehole resistivity to resistivity determined by surface transient electromagnetic surveys.

Geophysical-log analysis was used at nearly all test hole sites to design wells. Resistivity logs and other logs were used to locate probable permeable zones in the test hole, and the compensated sonic log was used to evaluate clay content of the probable permeable zones. Formations with significant clay content have slight permeability and do not yield water easily to wells; clean formations with interconnected porosity have significant permeability and yield water to wells. Water resistivity, which is a function of water chemistry, also was calculated at the drill site using Archie (1942) equations. In general, permeable zones with similar water resistivity were designated as sections to be screened.

Permeability zones were analyzed one zone at a time by using the newly developed computer program LOGAN2. Estimates of the following geohydrologic properties were obtained: volume of clay, volume of free water, volume of retained water, volume of matrix other than clay, density of matrix other than clay, density of the matrix, irreducible water saturation, intrinsic permeability, specific yield, modulus of elasticity of the matrix, and specific storage. From these properties, estimated values for hydraulic conductivity, transmissivity, and specific yield were derived.

A computer interpretation of the standard suite of geophysical-logs for lithology and water resistivity was made for most logged test holes. The lithologic model for this interpretation was correlated to the borehole environmental model developed for the research logging. In this way, the results of the intensive analysis of research and standard logs in a few boreholes were used to develop effective techniques to interpret a limited suite of logs in many other boreholes despite the unusual properties of sediments encountered by those boreholes.

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APPENDIXES

APPENDIX A. ESTIMATING VOLUMES AND DENSITIES USING LOGAN2

A conceptual model of the saturated material was developed that assumes subsurface material below the water table consists of three components—water-filled porosity, clay, and material other than clay.

Determining volume of clay is important because clay has pronounced effects on permeability and other geohydrologic properties such as specific yield. The gamma-ray log and the spontaneous-potential log were not satisfactory clay indicators for test holes in the study area. Therefore, a special program (LOGAN2) was developed to determine volume of clay ($Ꝟ_c$). The program is largely based on the difference between the porosity for a clay as calculated from a neutron log and the porosity calculated from a density log.

Geohydrologic properties that can be estimated from LOGAN2 include volume of free water ($Ꝟ_{fw}$), volume of retained water ($Ꝟ_{rw}$), volume of clay ($Ꝟ_c$), volume of matrix other than clay ($Ꝟ_o$), density of matrix other than clay (ρ_o), density of the matrix (ρ_m), irreducible water saturation (S_{wi}), intrinsic permeability (k), specific yield (S_y), modulus of elasticity of the matrix (E_m), and specific storage (S_s). From these properties, it is possible to estimate hydraulic conductivity (K), transmissivity (T), and specific yield (S_y) of an aquifer that consists of multiple permeability zones.

Because the occurrence of clay and its relation with water are complex and not completely known and because terms used in reference to clay and water may be used differently by various investigators, terms used in this appendix are defined specifically as follows:

Dry clay is clay excluding retained water or water adhering to the clay. Dry clay includes H_2O or OH internal to the clay.

Retained water is water that does not drain easily from a saturated medium. Large quantities of water are retained by clay minerals; however, only small quantities of water are retained on a coarse-grained matrix, such as sand or gravel.

Free water is water that will drain by gravity from the pores of a saturated medium. Free water occupies the effective porosity and is analogous to specific yield.

Effective porosity is the ratio of the volume of free water to the total volume.

Bound water is water that is very tightly held (bound) to the internal and external surface areas of the clay minerals and is considered part of the matrix. The amount of bound water is a function of the mineralogy of the clay.

Volume of clay includes the volume of water bound to the clay surface. Volume of the clay as used herein can be considered the volume of wet clay.

The determination of geohydrologic properties from geophysical logs requires that relations be established among the properties measured by the logs. This was especially difficult in the eastern study area. The responses measured by the gamma and spontaneous-potential logging tool were inadequate for evaluating volume of clay. Thus, a new interpretive technique using the compensated neutron and compensated density logs was developed to determine the volume of clay and other properties.

The neutron log, in general, measures hydrogen content. Because most hydrogen in subsurface material is associated with water-filled pore space, it is common in geophysical logging to interpret neutron logs in terms of porosity. The equation for neutron porosity of a water-saturated formation can be stated as follows:

$$\phi_N \approx Ꝟ'_{hw}+Ꝟ_{bw}+Ꝟ_{rw}+Ꝟ_{fw}, \qquad \text{(A-1)}$$

where

ϕ_N is the neutron porosity if no other hydrogen is present in addition to hydrated hydrogen and free or retained water (decimal),

$Ꝟ'_{hw}$ is apparent volume of hydrated water within the matrix and is proportional to hydrogen content (decimal),

$Ꝟ_{bw}$ is the volume of bound water (decimal),

$Ꝟ_{rw}$ is the volume of water retained (decimal), and

$Ꝟ_{fw}$ is the volume of the free (nonretained) water and is equivalent to effective porosity (decimal).

A gamma-gamma log or density log records the bulk density of the matrix and the fluid-filled pores. In reference to the model for clay and water used here, it is assumed that bound water is part of the clay matrix; that is, the clay is wet clay. The water-filled pore space includes both retained water and free water. Bulk density from the gamma-gamma log can be converted to porosity values (ϕ_D) by the following equation:

$$\phi_D=(\rho_m-\rho_b)/(\rho_m-\rho_f), \qquad \text{(A-2)}$$

where

ϕ_D is gamma-gamma porosity (decimal),

ρ_m is density of matrix, in grams per cubic centimeter,

ρ_b is bulk density of the matrix and the water-filled pores, in grams per cubic centimeter, and

ρ_f is density of the fluid (water), in grams per cubic centimeter.

Values of ρ_m for specific clays can be measured in the laboratory or can be estimated from published tables if the mineralogy of the matrix is known, such as by examination of drill cuttings. Density values of matrix material for the eastern study area were obtained from published tables or were determined empirically by using LOGAN2 and are listed in table A–1. Values of ρ_b are

Table A–1. Typical density values or range of values for matrix materials in the eastern study area

Lithology	Density, ρ (grams per cubic centimeter)
Gravel, ophiolitic	2.9–3.1
Anhydrite	2.98
Sand, ophiolitic	2.85–3.0
Dolomite or magnesite	2.85
Sand, ophiolitic and calcareous	2.8–2.85
Silt and very fine sand	2.6–2.75
Calcite or limestone	2.71
Clay	2.3–2.45
Gypsum	2.35

obtained from the density log, and values ρ_f for water can be calculated (Jorgensen, 1989) or obtained from published tables if salinity and temperature are known. In general, $\rho_f \approx 1.0$ for fresh ground water near land surface.

It follows from equation A–2 and the related assumption given that the porosity calculated includes both retained and free water:

$$\phi_D \approx \mathcal{V}_{fw} + \mathcal{V}_{rw}, \tag{A–3}$$

where ϕ_D is porosity calculated using data from a gamma-gamma log (decimal).

Volume of Clay ($\mathcal{V}_c$)

Subtracting the density-based porosity (equation A–3) from the neutron-based porosity (equation A–1) produces the following:

$$\phi_N - \phi_D = \mathcal{V}'_{hw} + \mathcal{V}_{bw} \tag{A–4}$$

In reference to clay, it can be related:

$$\mathcal{V}_c \approx (\phi_N - \phi_D)/\phi_{CNL}, \tag{A–5}$$

where

ϕ_{CNL} is the response of a compensated neutron logging tool for the wet clay (decimal).

Typical values of ϕ_{CNL} are 0.30 for illite, 0.37 for kaolinite, 0.44 for montmorillonite, and 0.52 for chlorite. Values of ϕ_{CNL} empirically determined for the eastern study area by trial and error using LOGAN2 ranged from 0.30 to 0.52, with 0.41 being typical. Equation A–5 is a good estimator of $\mathcal{V}_c$ as long as the ϕ_{CNL} for other nonclay minerals of the matrix are approximately zero.

Volume of Bound and Retained Water for Clay ($\mathcal{V}_{bw}$, $\mathcal{V}_{rw}$)

Both the volume of bound water for clay ($\mathcal{V}_{bw,c}$) and the volume of retained water for clay ($\mathcal{V}_{rw,c}$) are closely related to the mineralogy. (In general, volume of bound water is negligible for most nonclay minerals.) The relations are as follows:

$$\mathcal{V}_{bw,c} \approx \mathrm{P}_{\mathrm{bw}} \mathcal{V}_c, \tag{A–6}$$

where

P_{bw} is a proportional factor relating bound water and the clay (decimal), and

$$\mathcal{V}_{rw,c} \approx P_{rw} \mathcal{V}_c \;, \tag{A–7}$$

where

P_{rw} is a proportional factor relating retained water and the clay (decimal).

On the basis of analyses of research logging and the use of LOGAN2, P_{bw} ranged from about 0.1 to 0.5, with 0.2 being typical. Values of P_{rw} ranged from about 0.3 to 1.3, with typical values of about 0.9. Values of P_{bw} and P_{rw} are functions of the clay mineralogy.

Volume of Matrix Other Than Clay ($\mathcal{V}_o$)

The volumetric equation for a unit volume of saturated material is as follows:

$$\mathcal{V}_t = \mathcal{V}_c + \mathcal{V}_{rw} + \mathcal{V}_{fw} + \mathcal{V}_o = 1, \tag{A–8a}$$

where

$\mathcal{V}_t$ is total volume.

Solving equation A–8a for volume of matrix other than clay produces the following:

$$\mathcal{V}_o = 1 - \mathcal{V}_c - \mathcal{V}_{rw} - \mathcal{V}_{fw}. \tag{A–8b}$$

Density of Matrix Other Than Clay (ρ_o)

The density of a unit volume of material is given by the following equation:

$$\rho_b \mathcal{V}_t = \rho_c \mathcal{V}_c + \rho_{rw} \mathcal{V}_{rw} + \rho_{fw} \mathcal{V}_{fw} + \rho_o \mathcal{V}_o. \tag{A–9a}$$

Noting that $\mathcal{V}_t = 1.0$, $\rho_{rw} \approx 1.0$, $\rho_{fw} \approx 1.0$, and $\phi_{fw} \equiv \mathcal{V}_{fw}$, equation A–9a reduces to the following:

$$\rho_o \approx (\rho_b - \mathcal{V}_{rw} - \mathcal{V}_{fw} - \rho_c \mathcal{V}_c)/\mathcal{V}_o. \tag{A–9b}$$

Density of Matrix (ρ_m)

Equations A–2, A–5, A–7, A–8b, and A–9b can be solved iteratively using an estimate of density of matrix (ρ_m) to determine ρ_o. An initial estimate for ρ_m of 2.71 is often used. The resulting calculated value of ρ_o can be compared to a value of ρ_o measured in the laboratory or estimated from the mineralogy of the drill cuttings. If the calculated ρ_o does not match the measured or estimated ρ_o, a new value of ρ_m is assumed, and the equations are solved again. This iterative procedure is continued until the calculated ρ_o matches the estimated or measured ρ_o. The iterative procedure of solving equations A–2, A–5, A–7, A–8b, and A–9b is the major component of the computer program LOGAN2.

Because determination of volume of clay is essential to the successful solution of the set of equations, an independent estimate of $\mathcal{V}_c$ is made for a sand-clay lithology using the following equation:

$$\mathcal{V}_c \approx ((\Delta t_L - \Delta t_{sd})/(\Delta t_c - \Delta t_{sd}))(1-\phi), \qquad \text{(A–10)}$$

where

Δt_L is transit time from log, in microseconds per foot,

Δt_{sd} is transit time for clay-free sand, in microseconds per foot, and

Δt_c is transit time for clay, in microseconds per foot.

The iterative solution of equations A–2, A–5, A–7, A–8b, and A–9b can also be performed such that $\mathcal{V}_c$ from the model compares to the $\mathcal{V}_c$ estimated from equation A–10. This technique works best with a lithology of only sand and clay.

Estimates of $\mathcal{V}_c$, $\mathcal{V}_o$, ρ_o, and ρ_m were obtained using LOGAN2. The program requires input of data read from the standard suite of geophysical logs used in the Ground-Water Research Project. The first step of collecting the data is to separate the log into permeability zones or lithologic zones. The program has a distinct advantage because it requires the user to evaluate the results at each iteration and to make changes to the petrophysical properties assumed initially, such as density of liquid and typical logging-tool responses. Thus, properties are adjusted or evaluated for each permeability or lithologic zone, not for the entire logged section, which probably is not homogeneous.

Values of properties, such as volume of clay, density of matrix, and volume of free water, are used to estimate other geohydrologic properties, including irreducible water saturation (S_{wi}), intrinsic permeability (k), specific yield (S_y), modulus of elasticity of matrix (E_m), specific storage (S_s), and hydraulic conductivity (K).

APPENDIX B. ESTIMATING IRREDUCIBLE WATER SATURATION (S_{wi})

Irreducible water saturation for clay is the ratio of the volume of retained water ($\mathcal{V}_{rw}$) to the volume of retained and free water as indicated by the following equation:

$$S_{wi,c} = \mathcal{V}_{rw}/(\mathcal{V}_{rw} + \mathcal{V}_{fw}). \qquad \text{(B–1)}$$

Equation B–1 is based on an approximation of $\mathcal{V}_{rw}$ for a clay. However, coarser grained material, such as silt, sand, or gravel, also has some retained water. Accordingly, equation B–1 can be modified to include an approximation for the nonclay component of the matrix as follows:

$$S_{wi} \approx (S_{wi,c})(\mathcal{V}_c) + (S'_{wi,o})(\mathcal{V}_o), \qquad \text{(B–2)}$$

where

$S'_{wi,o}$ is the apparent irreducible water saturation for other than clay (decimal).

Values of $S'_{wi,o}$ for sand and gravel typically range from 0.02 to 0.1 (Eckis and Gross, 1934; Poland and others, 1939; Smith, 1961; Morris and Johnson, 1967; and Lohman, 1972).

APPENDIX C. ESTIMATING INTRINSIC PERMEABILITY (k)

Several empirical equations are available for estimating intrinsic permeability from porosity and irreducible water saturation. The following equation reported by Timur (1968) was selected because of its simplicity:

$$k \approx 1\times 10^4 \phi^{4.5}/S_{wi}^{\,2}, \qquad \text{(C–1a)}$$

where

k is intrinsic permeability (millidarcies).

Intuitively, the porosity of concern in relation to irreducible water saturation would be ϕ_D as follows:

$$k \approx (1\times 10^4)(\phi_D^{4.5})/S_{wi}^{\,2}. \qquad \text{(C–1b)}$$

APPENDIX D. ESTIMATING SPECIFIC YIELD (S_y)

By definition, free water is analogous to specific yield as indicated by the following equation:

$$S_y = \mathcal{V}_{rw} + \mathcal{V}_{fw} - \mathcal{V}_{rw}. \qquad \text{(D–1)}$$

Noting the definition of irreducible water saturation is:

$$S_y = \mathcal{V}_{rw} + \mathcal{V}_{fw} - S_{wi}(\mathcal{V}_{rw} + \mathcal{V}_{fw}). \qquad \text{(D–2)}$$

Combining equations A–3 and D–2 yields:

$$S_y \approx \phi_D - S_{wi}\phi_D. \qquad \text{(D–3)}$$

APPENDIX E. ESTIMATING MODULUS OF ELASTICITY OF MATRIX (E_m)

The dynamic modulus of elasticity (E_m) is related to the density (ρ) and sonic velocity (V) by the following general equation:

$$V = (E_m/\rho)^{0.5}, \qquad \text{(E–1)}$$

if Poisson's ratio is assumed to be 0.5.

If the sonic velocity is assumed to be approximately equal to compressional velocity, the sonic log can be used to estimate the modulus of elasticity. (The relation between compressional velocity and modulus of elasticity is complex and beyond the scope of this report. Refer to Entwisle and Mc Cann (1990) for detailed discussion.)

Sonic logs are a record of transit time, which is the inverse of velocity as indicated by the following equation:

$$\Delta t = 1/V. \qquad \text{(E–2)}$$

An equation commonly used to relate transit time from a sonic log to porosity is as follows:

$$\Delta t = (\phi/V_w) + (1-\phi)/V_m, \qquad \text{(E–3)}$$

where

ϕ is porosity (decimal),

V_w is velocity of the compressional wave in water, in meters per second, and

V_m is velocity of the compressional wave in the matrix, in meters per second.

Because equation E–3 was developed for consolidated materials, its applicability to the slightly consolidated material common in the eastern study area has not been evaluated specifically. Other equations that relate sonic velocity to porosity also exist (Schlumberger, 1989).

Assuming the porosity of interest is the porosity related to the retained water and free water (ϕ_D), combining equations E–1 and E–3 yields the following:

$$\Delta t = \frac{\phi_D}{(E_w/\rho_w)^{0.5}} + \frac{(1-\phi_D)}{(E_m/\rho_m)^{0.5}}, \qquad \text{(E–4)}$$

where

E_w is bulk modulus of elasticity of water, in pascals),

ρ_w is density of water, in kilograms per cubic meter,

E_m is modulus of elasticity of the matrix, in pascals, and

ρ_m is density of the matrix, in kilograms per cubic meter.

Equation E–4 can be used to estimate the modulus of elasticity.

APPENDIX F. ESTIMATING SPECIFIC STORAGE (S_s)

Specific storage of a water-saturated formation (without dissolved gases) is a measure of the compressibility due to water and matrix per unit thickness. Jorgensen (1980) provides the following equations:

$$S_s=S_{sw}+S_{sm}, \qquad \text{(F–1a)}$$

where

$$S_s=\frac{\phi\,\rho_w\,g}{E_w}+\frac{\rho_m g}{E_m}, \qquad \text{(F–1b)}$$

where

S_{sw} is specific storage related to water compressibility, in meters^{-1},

S_{sm} is specific storage related to the compressibility of the matrix, in meters^{-1}, and

g is gravity, in meters per second squared.

For most aquifers S_{sw} is small (in the order of 1×10^{-6} m^{-1}), and equation F–1b reduces to the following:

$$S_s\approx\rho_w g/E_m. \qquad \text{(F–1c)}$$

Assuming $\rho_w\approx1\times10^3$ $kg\cdot$m^{-3} and g=9.807×10^3 m·s^{-2}, equation F–1c simplifies to the following:

$$S_s\approx9.807\times10^3/E_m. \qquad \text{(F–1d)}$$

APPENDIX G. ESTIMATING HYDRAULIC CONDUCTIVITY (K)

Hydraulic conductivity of the various permeability zones is calculated by using values of intrinsic permeability estimated from LOGAN2. Hydraulic conductivity is related to intrinsic permeability as follows:

$$K=(k\rho_w g)/\mu_w, \qquad \text{(G–1)}$$

where

K is hydraulic conductivity, in meters per second,

k is intrinsic permeability, in square meters,

ρ_w is density of water in situ, in kilograms per cubic meter,

g is gravity, in meters per second squared, and

μ_w is viscosity of water, in pascal·seconds.

Values of ρ_w and μ_w are dependent on temperature and salinity.

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