

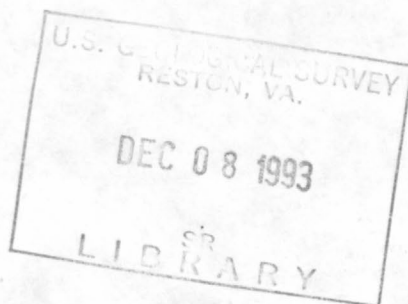
PETROPHYSICAL ANALYSIS OF GEOPHYSICAL LOGS  
NATIONAL DRILLING COMPANY-U.S. GEOLOGICAL SURVEY  
GROUND-WATER RESEARCH PROJECT FOR  
ABU DHABI EMIRATE, UNITED ARAB EMIRATES

By Donald G. Jorgensen and Mario Petricola

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U.S. GEOLOGICAL SURVEY :  
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Prepared in cooperation with the  
NATIONAL DRILLING COMPANY,  
EMIRATE OF ABU DHABI



Al Ain, Abu Dhabi Emirate, United Arab Emirates

1993

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

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# CONVERSION FACTORS

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
centimeter	0.3937	inch
cubic centimeter	0.06102	cubic inch
cubic meter	35.31	cubic foot
degree Celsius (°C)	(1)	degree Fahrenheit (° F)
gram	0.03527	ounce
kilogram	2.205	pound
meter	3.281	foot
micromho per centimeter	1.000	microSiemen per centimeter
pascal	$1.45038 \times 10^{-4}$	pound-force per square inch
square meter	10.76	square foot

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(1)  $^{\circ}\text{F} = 1.8 \times (^{\circ}\text{C}) + 32.$

The units of measurements used in this report are those that are used in the United Arab Emirates. Thus the units reported are, in general, those in which the measurement was made and customarily used in the United Arab Emirates.

PETROPHYSICAL ANALYSIS OF GEOPHYSICAL LOG, OF THE  
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By Donald G. Jorgensen<sup>1</sup> and Mario Petricola<sup>2</sup>

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 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.

<sup>1</sup> U.S. Geological Survey, Al Ain, United Arab Emirates.

<sup>2</sup> Schlumberger Middle East, Abu Dhabi, United Arab Emirates.



A research program of petrophysical logging was conducted to determine the petrophysical properties of the shallow subsurface formations. The logging included spectral-gamma (GLT) and thermal-decay-time (TDT) logs. These and the standard petrophysical 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 petrophysical 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 accordingly. 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 the Emirate of Abu Dhabi 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.

The purpose of this report is to describe the geophysical logging program conducted by the USGS and to present 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 petrophysical logging has been conducted is shown in figure 2.

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

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Figure 2.-- Abu Dhabi Emirate and surrounding area.

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#### ACKNOWLEDGMENTS

The impetus for the Ground-Water Research Project for the Emirate of Abu Dhabi 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 Mohammed Habrourh Al Suwaidi, Chairman of the National Drilling Company, and Ahmed Juma Al Dharif, General Manager of the National Drilling Company.

Petrophysical logging was done under the drilling program of the GWRP under the direction of Donald C. Signor, U.S. Geological Survey. Sidewall cores and geologic information were

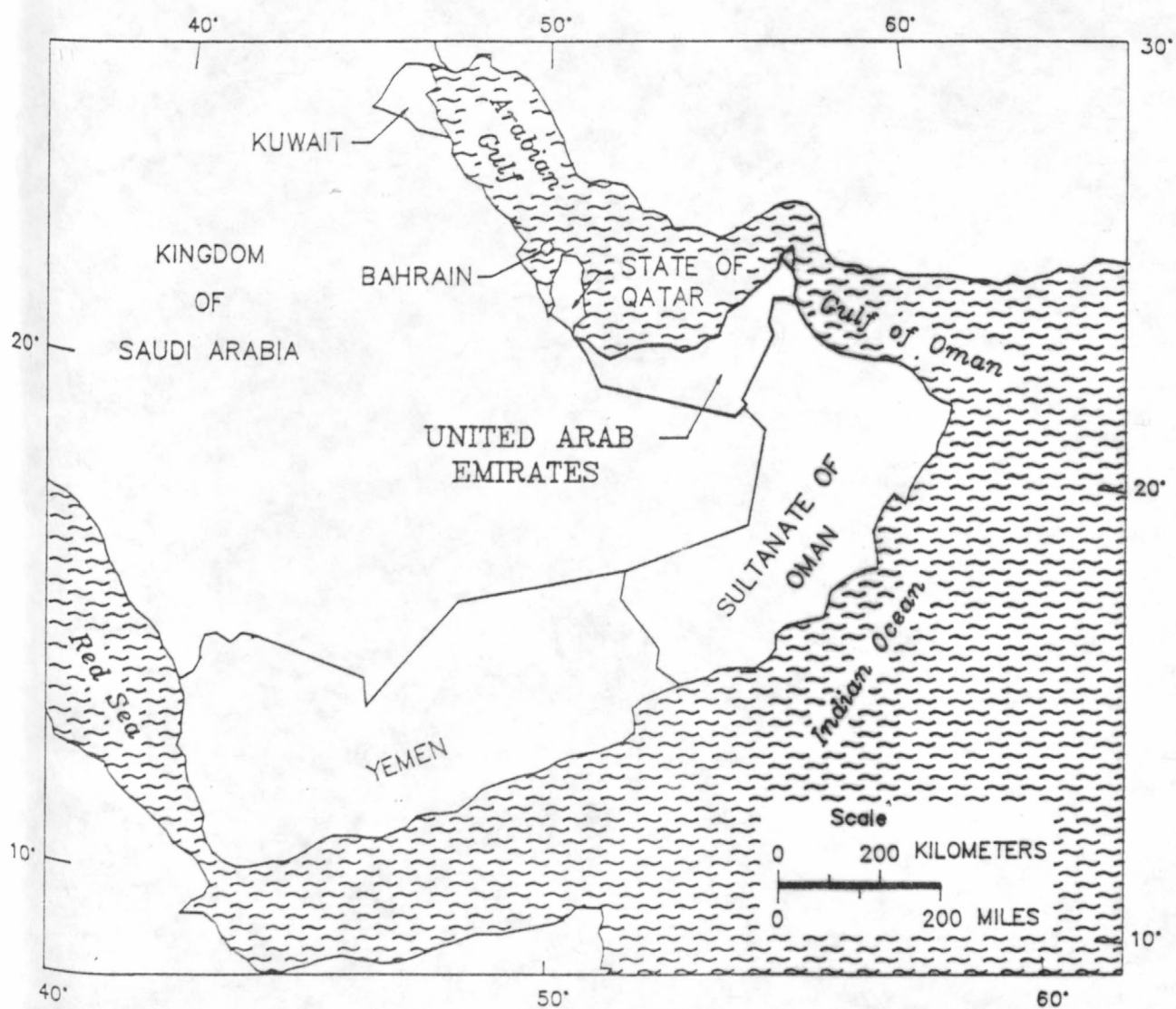


Figure 1. Arabian Peninsula and location of United Arab Emirates.



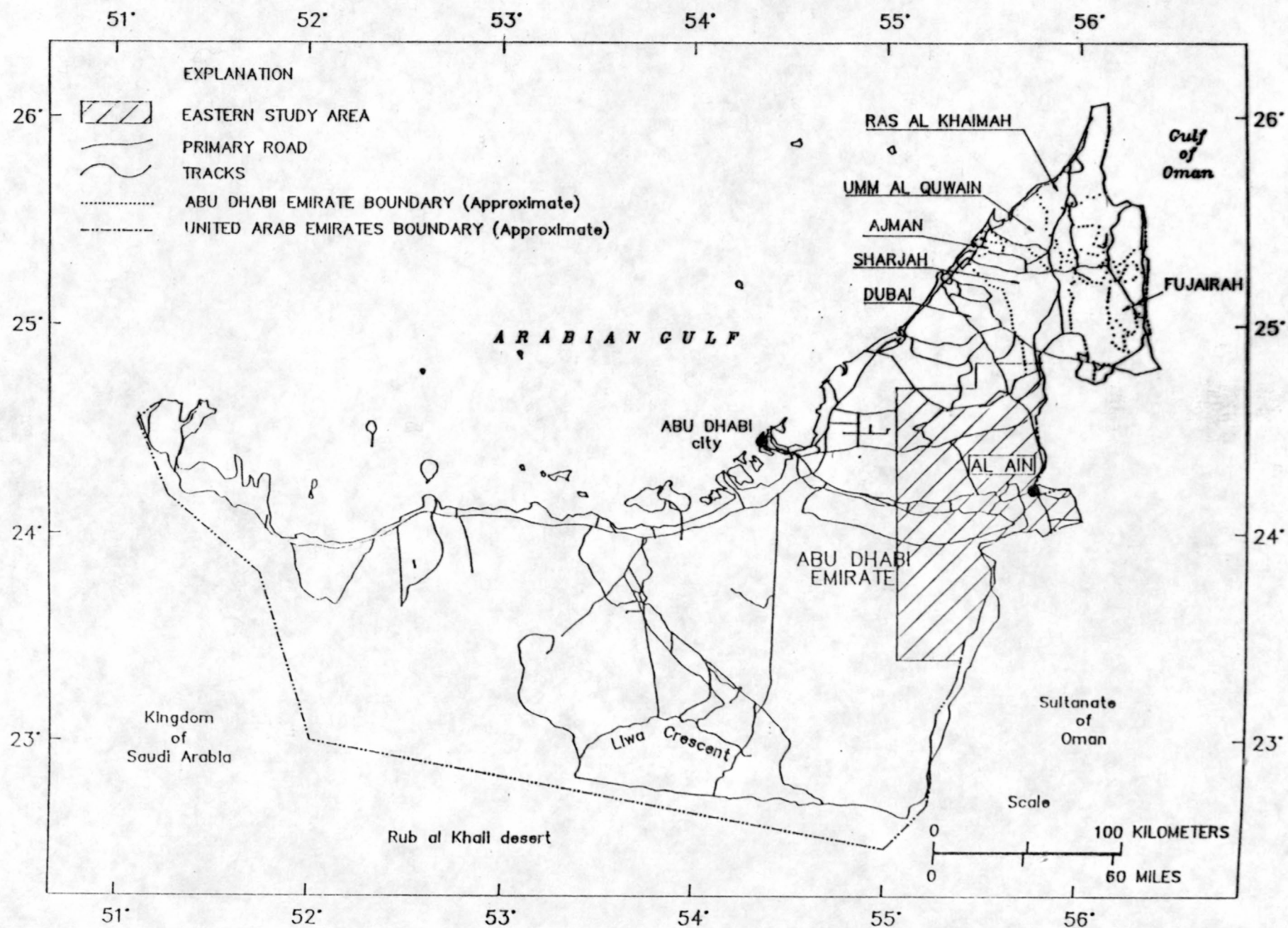


Figure 2. Abu Dhabi Emirate and location of Liwa study area.



collected as part of the geologic investigations directed by Donald G. Hadley, U.S. Geological Survey. The special petrographic analyses of sidewall cores were performed by Robertson Group plc, United Kingdom. Petrophysical logs were run by the 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 uncompact 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 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 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 geologist's 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, if 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 Schlumberger Middle East. The function, purpose, and utility of the various logs are listed in table 1.

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.



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

Type of log	Function	Purpose and utility
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.



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

Type of log	Function	Purpose and utility
Micro-resistivity	Measures resistivity of a thin section (2 to 5 centimeters) at the borehole wall.	Indicates presence or absence of mudcake, thus indicates permeability. 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.

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

Type of log	Function	Purpose and utility
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.

"Table 2 summarizes the petrophysical logs obtained at GWRP test holes. The locations of project test holes with petrophysical logs are shown in figure 3. Mylar and paper copies of the petrophysical 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"<sup>1</sup>, 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"<sup>1</sup> or "QUATTRO.PRO,"<sup>1</sup> also can be used to display petrophysical data in strip-chart form (Keys, 1986) and to analyze petrophysical data by overlay (Paillet, 1991). Copies of petrophysical 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 the Al Ain Ground Water Department. These computer interpretations indicate water salinity and lithology.

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

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Figure 3.-- Location of test holes with petrophysical logs

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<sup>1</sup> Any use of trade, product, or firm names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Government

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	SONC	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	SONC	COMPUTER INTERPRETED LOGS	TEMPERATURE	SPECIFIC CONDUCTANCE	FLOW	NEUTRON BURST THERMAL-DECAY TIME (TDT)	SPECTRAL GAMMA (GALT)
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	--	--	--	--	--

table2.dj /dt

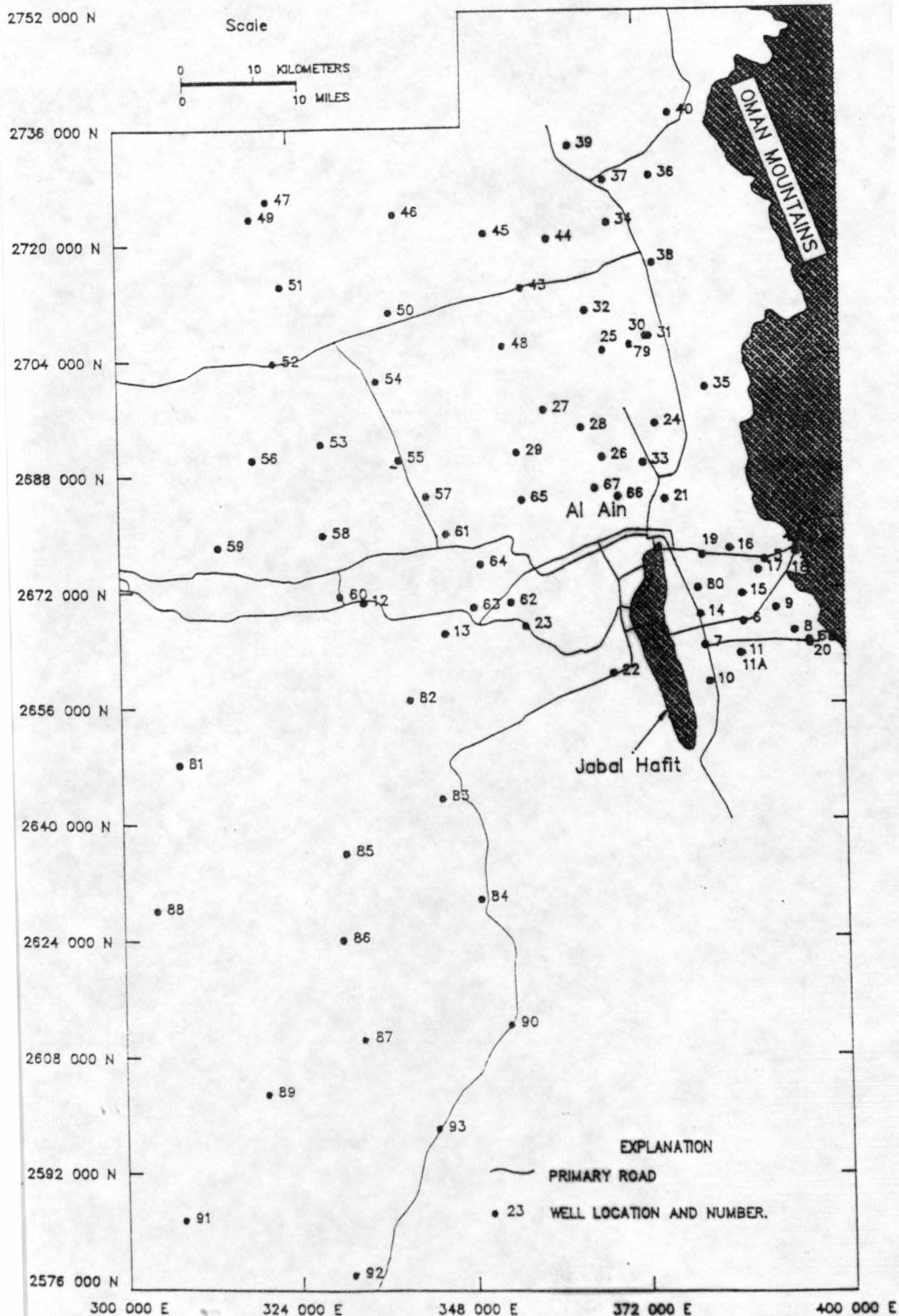


Figure 3. Location of test holes with geophysical logs.

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

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For example, figure 5 shows water salinity and lithology interpreted from petrophysical data for test hole GWP-30. Test holes for which computer-interpreted logs are available are indicated in table 2.

---

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

---

### Geologic Studies

Geophysical logs are used in several ways for geologic studies. For example, petrophysical logs are used in conjunction with drill cuttings to discern lithology, to identify formations, and to determine formation thickness. A major use of petrophysical 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



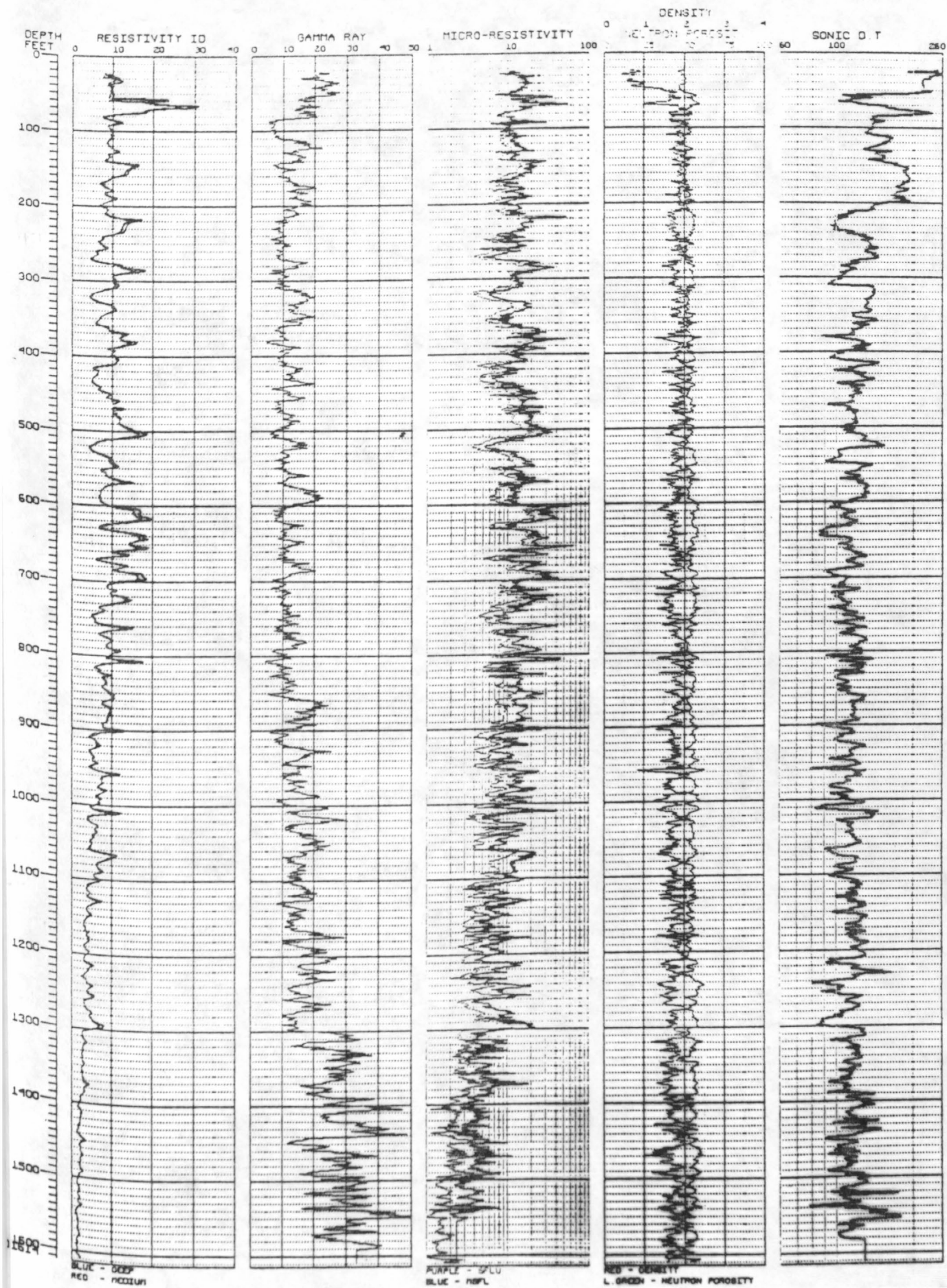


Figure 4. Petrophysical logs for well GWP-26.



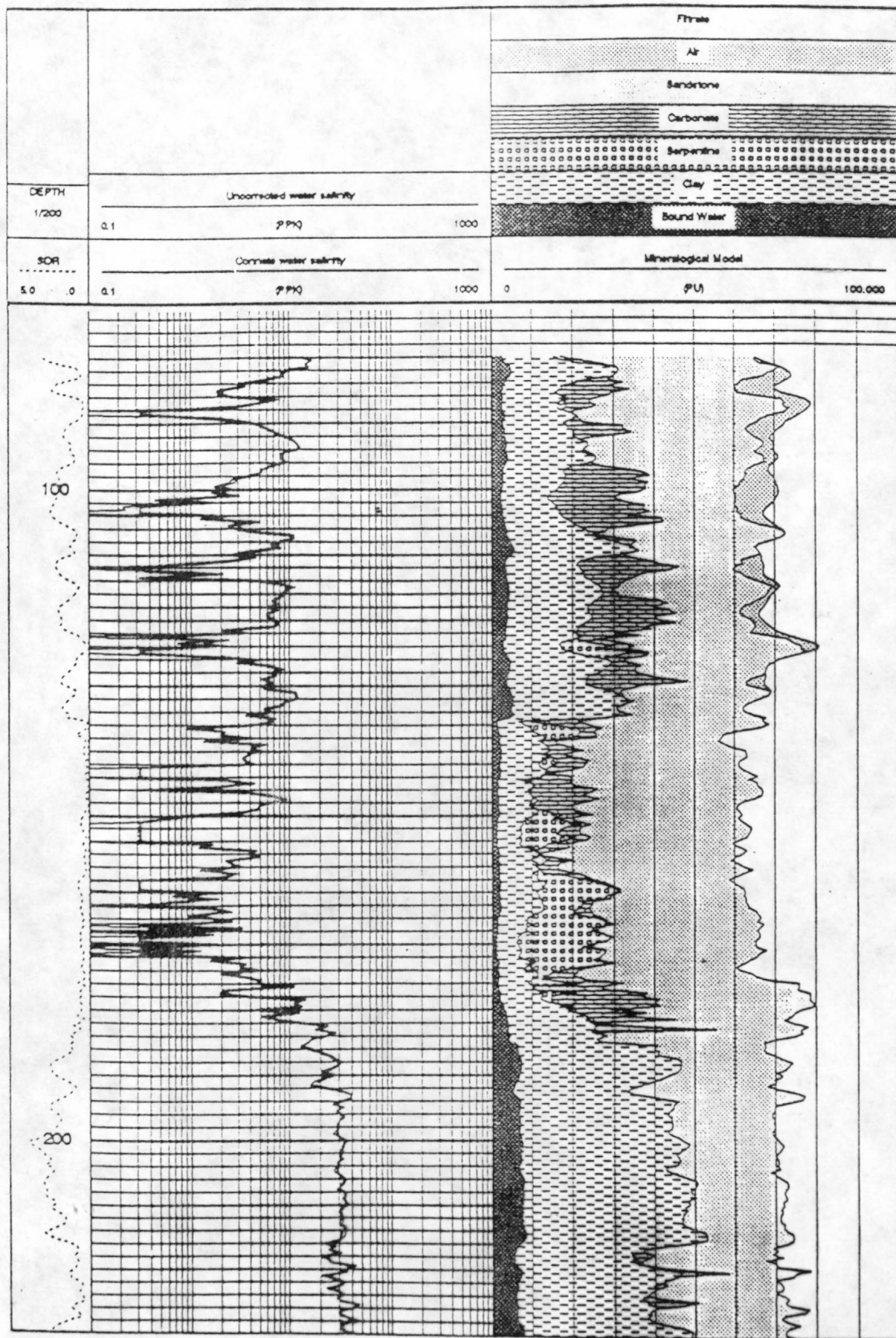


Figure 5. Computer-interpreted properties from standard suite of logs for test hole GWP-30.

versus density cross plot as described by Schlumberger (1989, 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 figure 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 usefulness in unconsolidated or slightly consolidated formations. For unconsolidated formations in the eastern study area, the compensated sonic log is a useful indicator of clay content. In the eastern study area, the natural gamma log is useful in distinguishing among formations of similar lithology that have clastic material from different sources.

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

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In the eastern part of Abu Dhabi Emirate, much of the sediment is of ophiolitic origin. This sediment has very low natural-gamma radioactivity, and 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.

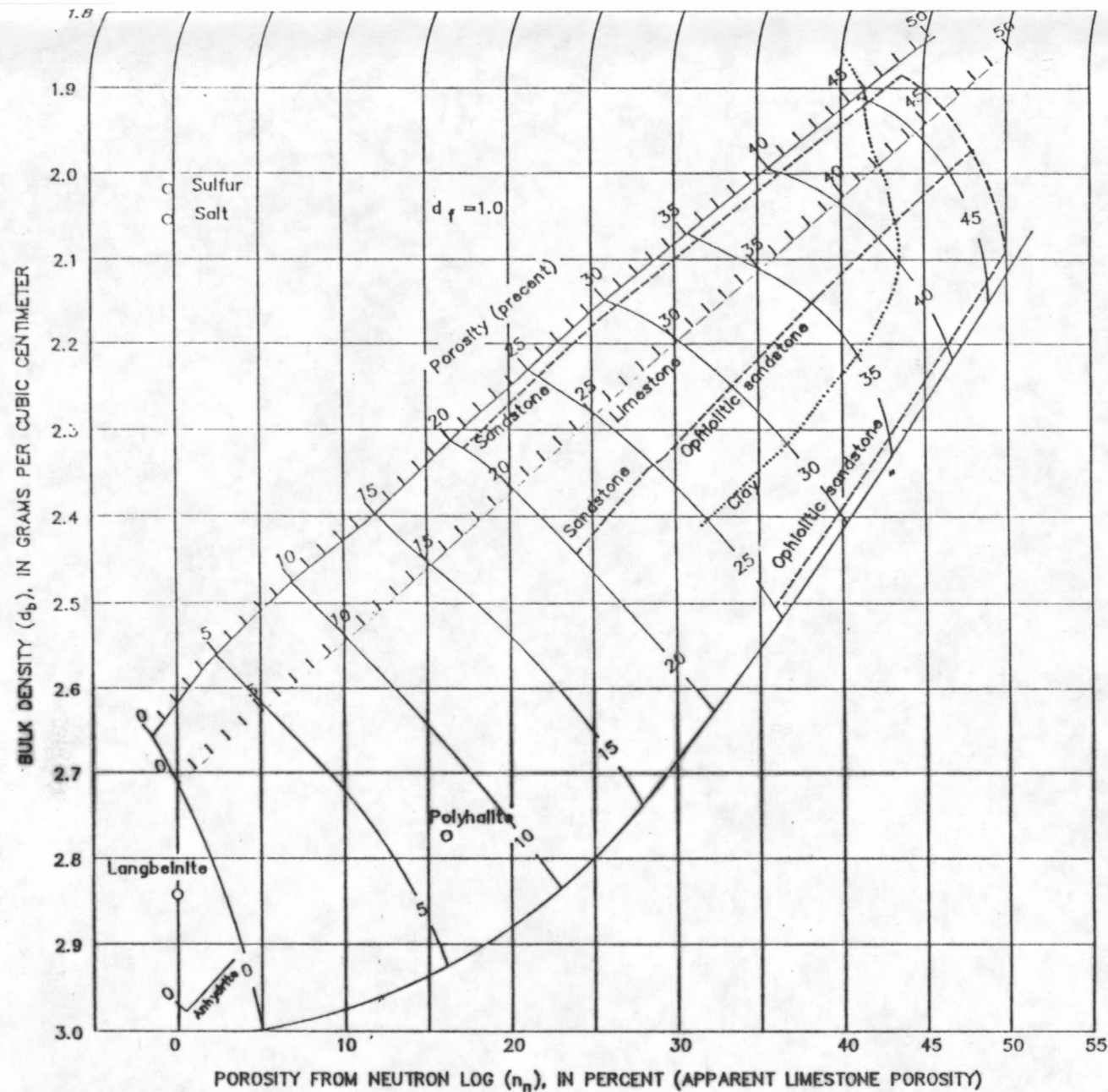


Figure 6. Lithology and porosity interpreted from cross plot of bulk density against neutron-porosity.



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

Petrophysical 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., 5 May 1989; Hadley and others, 1991). Accordingly, the seismic profile is correlated to the borehole geophysical logs, which in turn are correlated to lithology or geologic formations (fig. 8).

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

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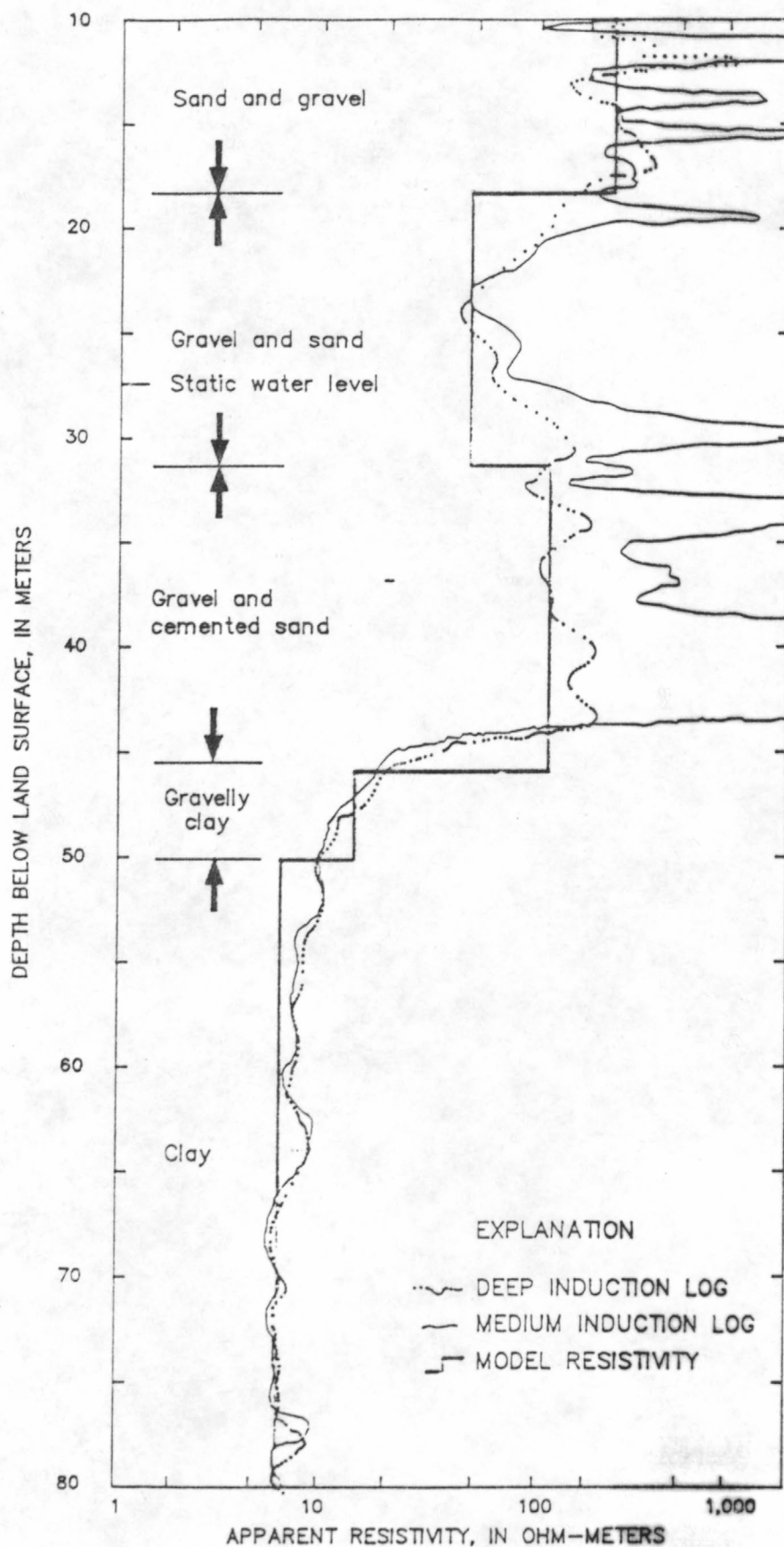


Figure 7. Geophysical logs of test hole GWP-18 and interpreted resistivity from transient - electromagnetic survey (after Fitterman and others, 1991).

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

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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).

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

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### 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.

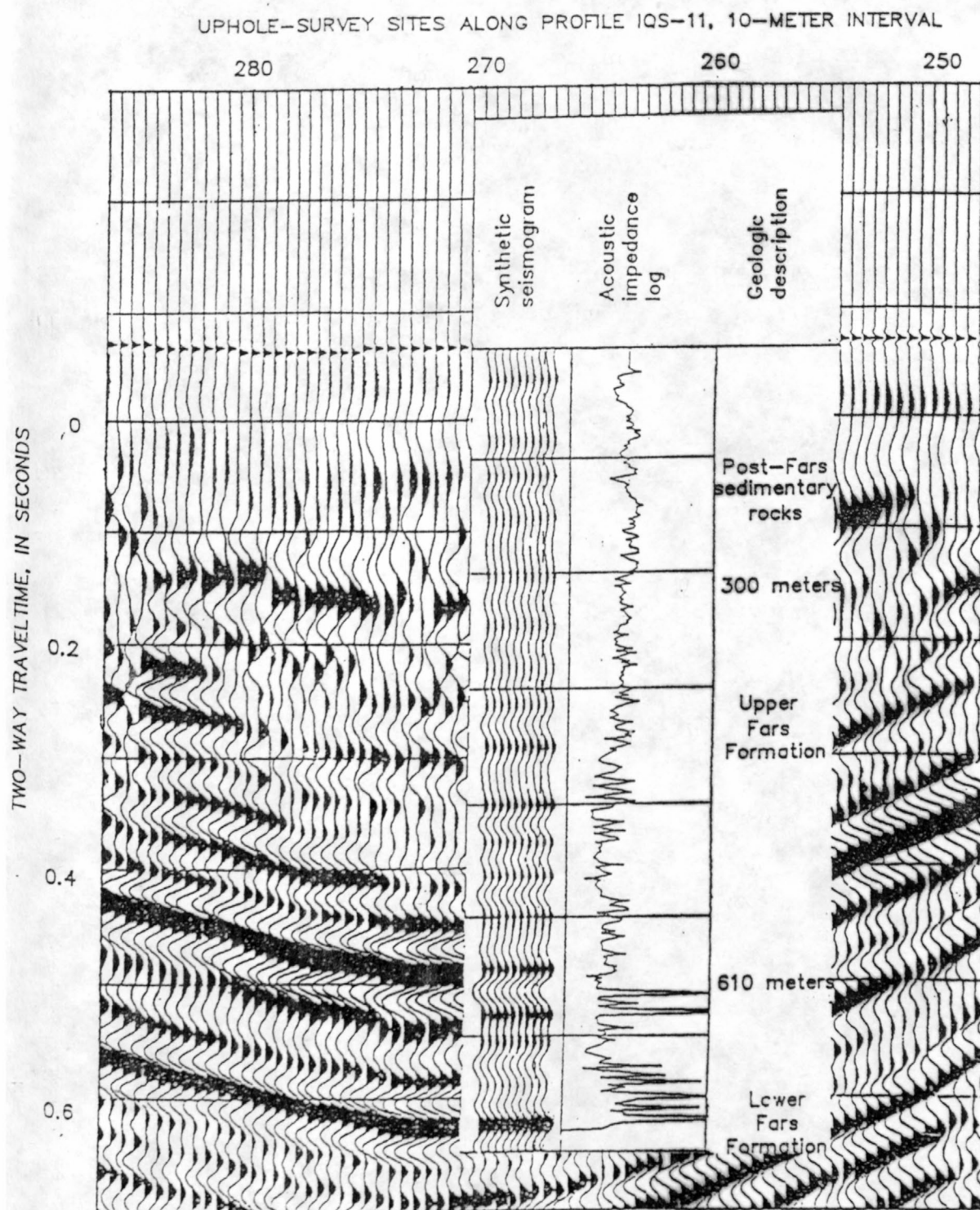


Figure 8. Reprocessed seismic data and synthetic seismogram of test hole GWP-7, Al Jaww Plain (after Menges and others, 1991).

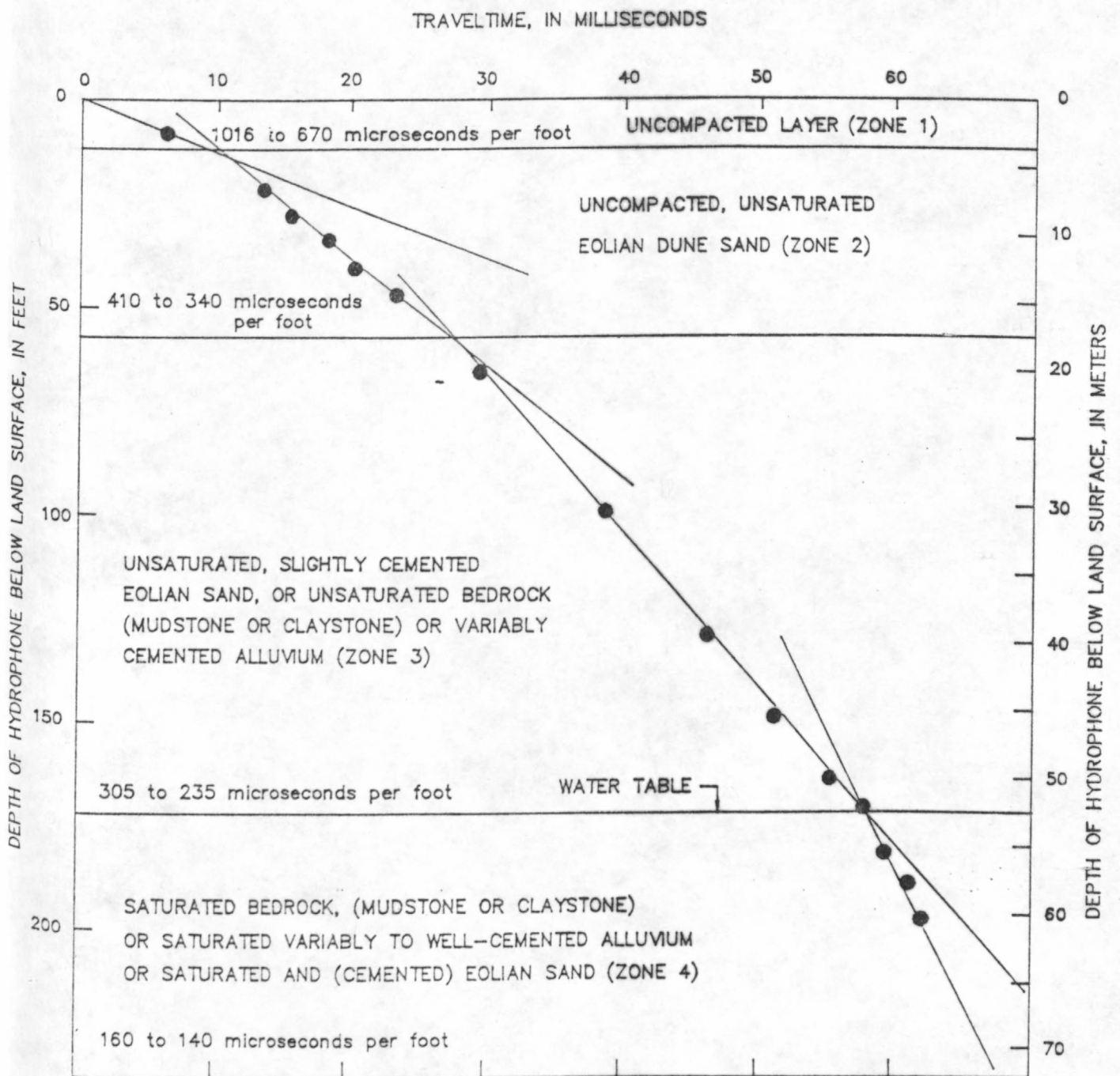


Figure 9. Hydrologic interpretation of velocity layers derived from an uphole survey (modified from Woodward and Menges, 1990).



## Use of Logs at Drill Site

Geophysical logs were obtained from the mud-filled test holes at the completion of drilling. The diameter of the drilling bit used is 8-1/2 inches. 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  $\mu\text{s}/\text{ft}$  (microseconds per foot) 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 greater resistivity than equivalent partially saturated material.

Table 3. Typical compensated sonic-log travel times in 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

### 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 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 candidates for well-screen sections. Other permeability indicators, such as spontaneous potential and the 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 which 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 resistivity can be made from petrophysical logs (Jorgensen, 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.

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

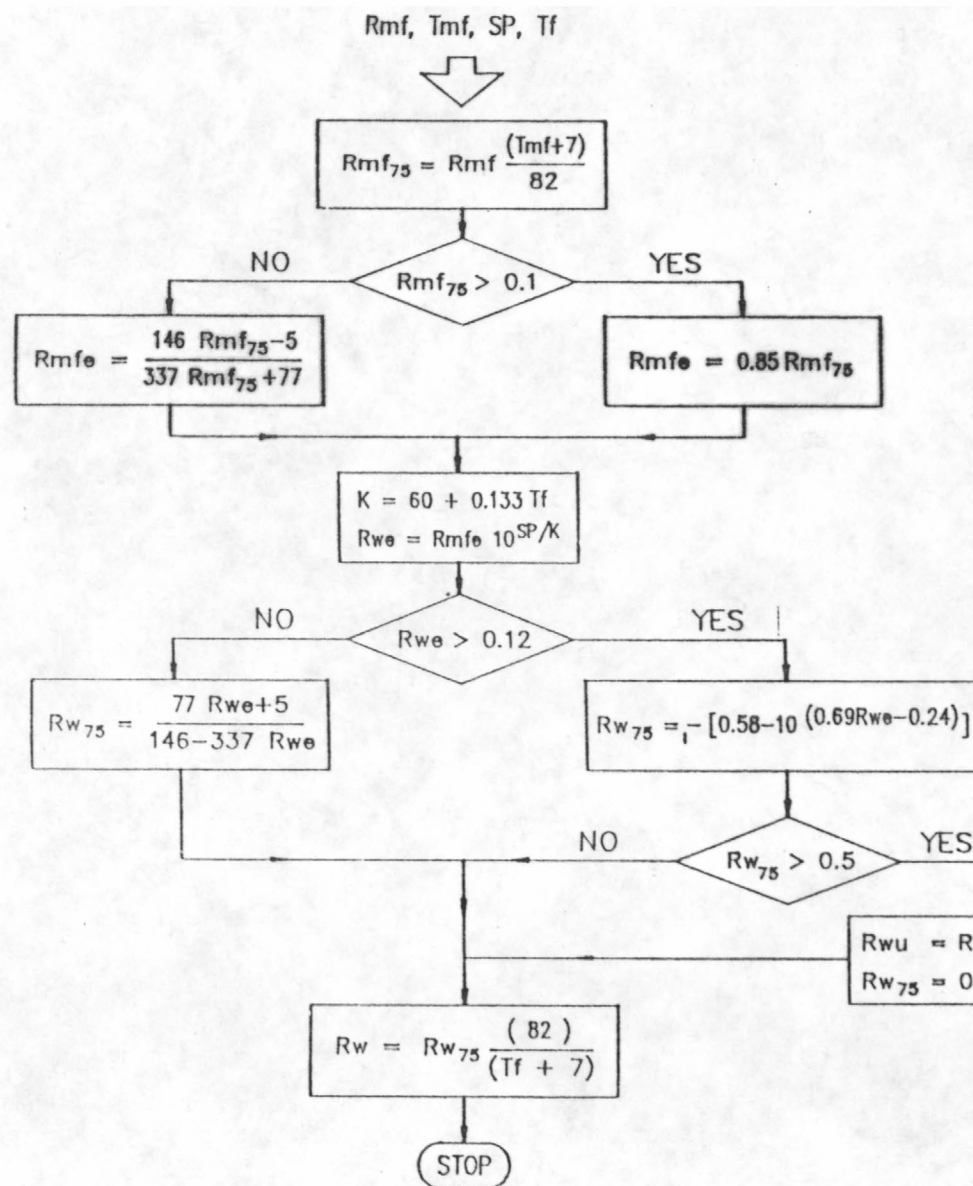
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Figure 11.-- Porosity-resistivity cross plot (after Jorgensen, 1989).

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#### EXPLANATION

K Spontaneous potential constant at a specific temperature

Rmf Resistivity of mud filtrate, in ohm-meters

Rmfe Resistivity of mud filtrate equivalent, in ohm-meters

Rmf<sub>75</sub> Resistivity of mud at 75°F, in ohm-meters

Rw Resistivity of water, in ohm-meters, at formation temperature

Rwe Resistivity of water equivalent, in ohm-meters

Rw<sub>75</sub> Resistivity of water at 75°F, in ohm-meters

Rwu Resistivity of water uncorrected, in ohm-meters

SP Spontaneous potential, in millivolts

Tf Temperature of formation, in degrees Fahrenheit (°F)

Tmf Temperature of mud filtrate, in degrees Fahrenheit (°F)

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

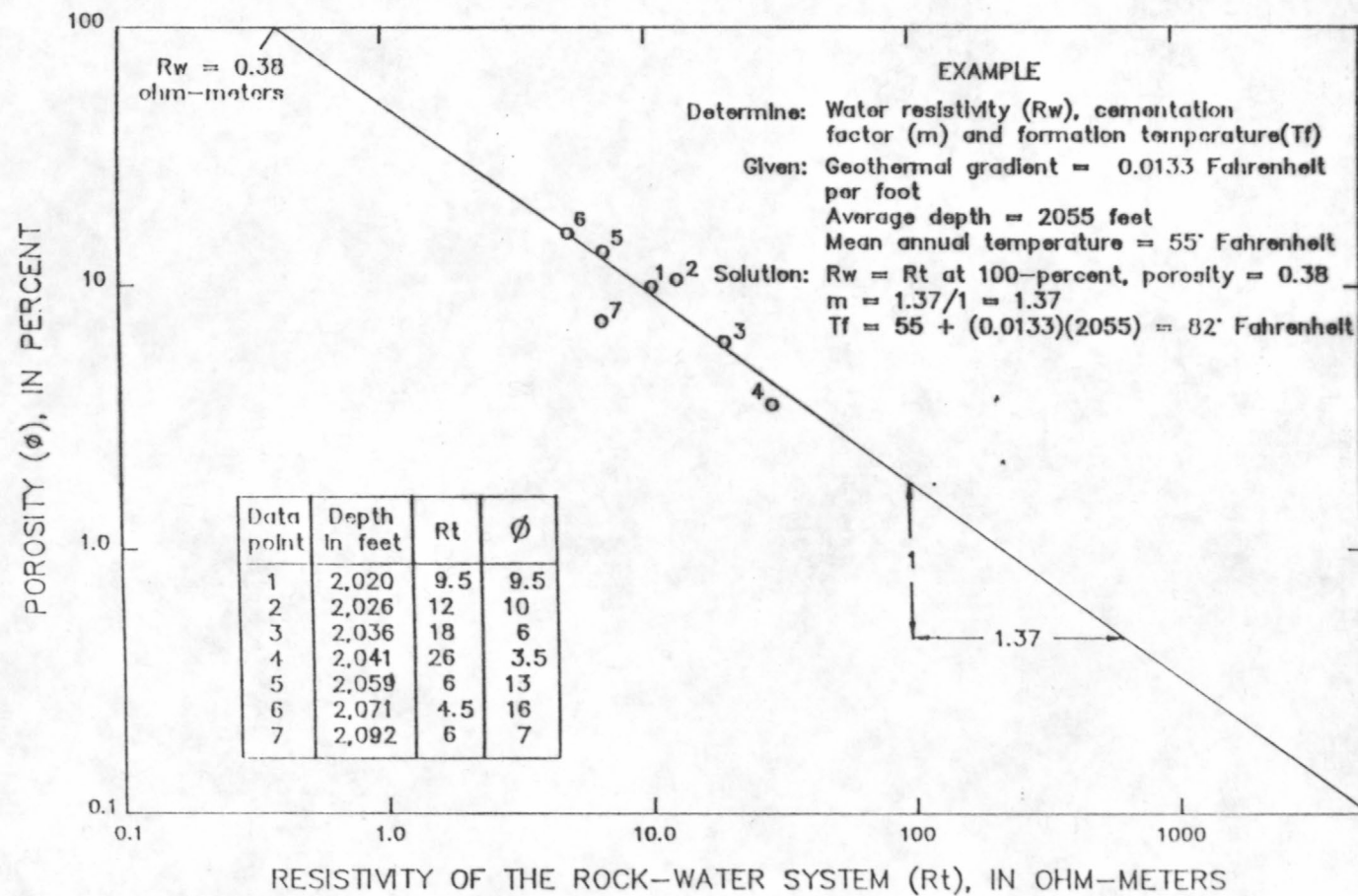


Figure 11. Porosity – resistivity cross plot (from Jorgensen, 1989).

The cross-plot method of estimating water resistivity is difficult to apply to logs from 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, and the method has only limited applicability. Additionally, because clay is present in most zones, the "clean" formation assumption of the Archie equations (Archie, 1942) are not met. (The reader is referred to Worthington and Johnson [1991] for a review of the "clayey, freshwater aquifer" problem in geophysical logging).

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

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

where  $R_t$  is the true resistivity [ohm·meter (ohm·m)], and  $R_w$  is the resistivity [ohm·m] of the formation water, at in-situ temperature.

The second formation-factor equation is as follows:

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

where  $R_{xo}$  is the resistivity [ohm·m] of the flushed zone,  
usually determined from a microresistivity log, and  
 $R_{mf}$  is the resistivity [ohm·m] of the mud filtrate.

Combining the two formation-factor equations yields the following:

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

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 have been used at several test holes in the eastern 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:

$$F = \theta^{-m} \quad , \quad (4)$$

where  $\theta$  is the effective or interconnected porosity  
exclusive of retained water on the pore walls [a  
decimal], and  
 $m$  is the cementation exponent.



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:

$$R_w = R_t \theta^m \quad . \quad (5)$$

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 degrees Fahrenheit, to dissolved solids (DS). The relation is as follows:

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

where DS is the dissolved-solids content [parts per million],

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

SC is specific conductance [microSiemens per centimeter at 25 degrees Celsius]

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:

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

where  $R_{w77}$  is resistivity [ohm·m] of water at 77 degrees Fahrenheit.

$R_{w77}$  is calculated from the following equation:

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

where  $R_w$  is from equation 3 or 5, and

$T_f$  is formation temperature [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) 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:

$$T = K_1 b_1 + K_2 b_2 + \dots K_n b_n , \quad (9)$$

where  $K$  is the hydraulic conductivity of the permeability zone [ $m \cdot s^{-1}$ ] ,

$b_1$  is the thickness of permeability zone 1 [ $m$ ], and 1,2,...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 exist. The artesian storage coefficient ( $S_a$ ) is related to the specific storage ( $S_s$ ) by the following equation:

$$S = S_a = S_s B , \quad (10)$$

where  $B$  is the thickness of the aquifer [ $m$ ].

For individual permeability zones the equation is:

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

where  $S_s$  is specific storage of a permeability zone [ $m^{-1}$ ], and

1, 2,...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:

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

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:

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

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

Estimates of specific yield for the aquifers in the eastern 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 hydrologic investigations. An important feature of the program was 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 are 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 petrophysical 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 figure 3 for locations.) In addition to the standard suite of logs obtained at GWRP test holes, a spectral-gamma log, termed "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:

$$\Sigma_L = (\Sigma_o) (1-\theta-V_c) + (\Sigma_c) V_c + (\Sigma_f) \theta, \quad (14)$$

where  $\Sigma_L$  is the TDT measurement [capture cross-sectional units (c.u.)] ,

$\Sigma_o$  is the capture cross section for matrix other than clay [c.u.] ,

$\theta$  is porosity excluding clay-bound water [decimal] ,

$V_c$  is volume of wet clay [decimal] ,

$\Sigma_c$  is the capture cross section for clay [c.u.] , and

$\Sigma_f$  is the capture cross section of the fluid in the invaded zone [c.u.] .

Values for  $\Sigma_c$  and  $\Sigma_o$  can be obtained from published tables of log properties of minerals; values of  $V_c$  and  $\theta$  can be determined by independent log analysis.

If the invaded zone is not permeable (there is no invasion),  $\Sigma_f$  will be equal to  $\Sigma_w$ , which is the capture cross section of the formation water. If the zone is totally flushed,  $\Sigma_f$  will equal  $\Sigma_{mf}$ , 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:

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

where  $V_{mf}$  is the volume of mud filtrate [decimal] , and

$V_{wir}$  is the volume of water not flushed as  
"seen" by the TDT tool [decimal] .

Values for  $\Sigma_{mf}$  and  $\Sigma_w$  are functions of salinity and can be obtained from published tables.  $V_{mf}$  is probably a good estimate of specific yield, and  $V_{wir}$  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:

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

and  $\Sigma_f$  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 figure 12.) The minerals included in the interpretation were a mix of minerals identified from cross plots and minerals recognized in sidewall cores.

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

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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-



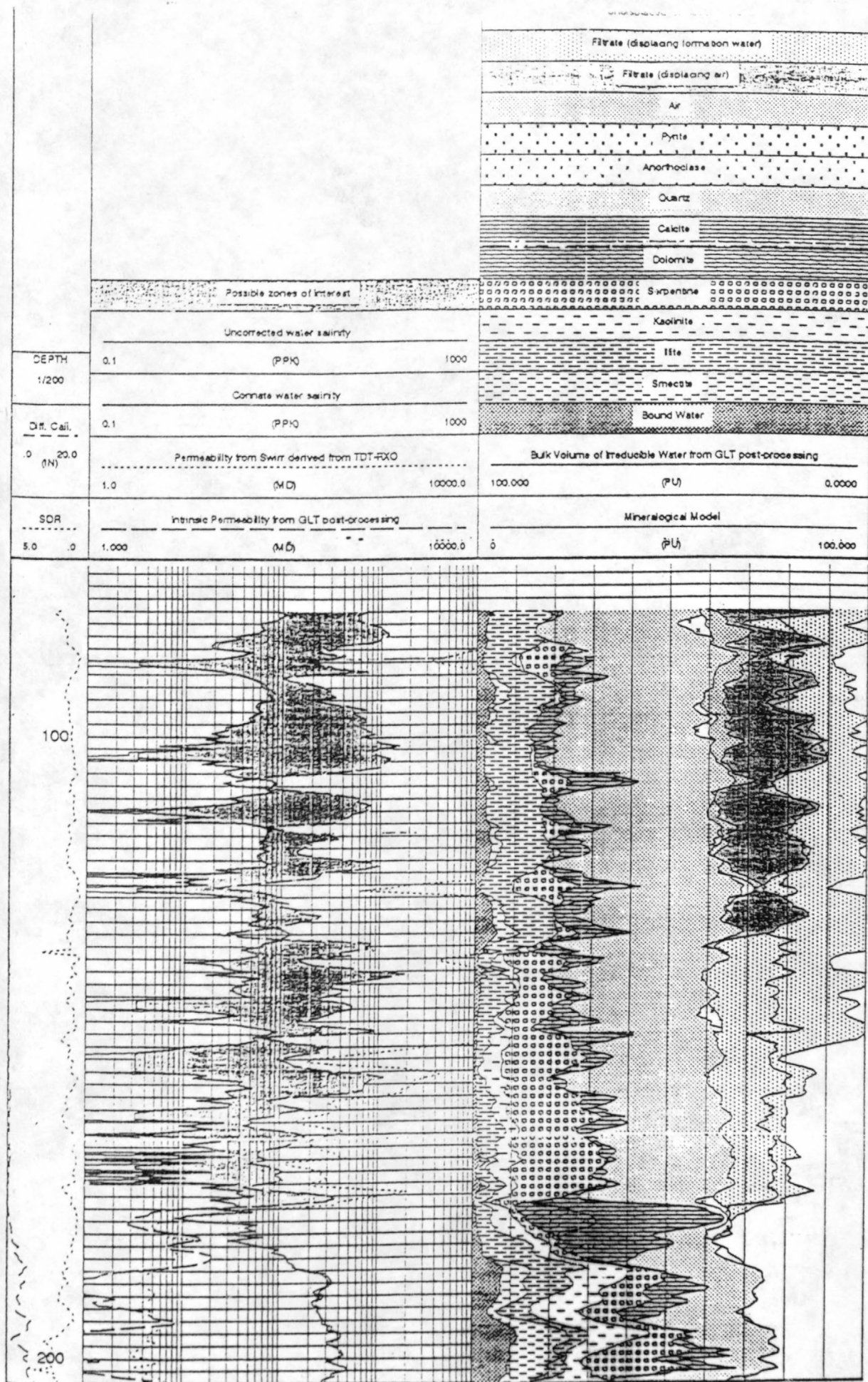


Figure 12. Computer-interpreted properties from research logging at test hole GWP-30 (Schlumberger Geochemical Analysis).

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 figure 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 figure 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 termed 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 petrophysical-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.

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

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

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A special mud system was used in drilling the four project test holes where research petrophysical 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



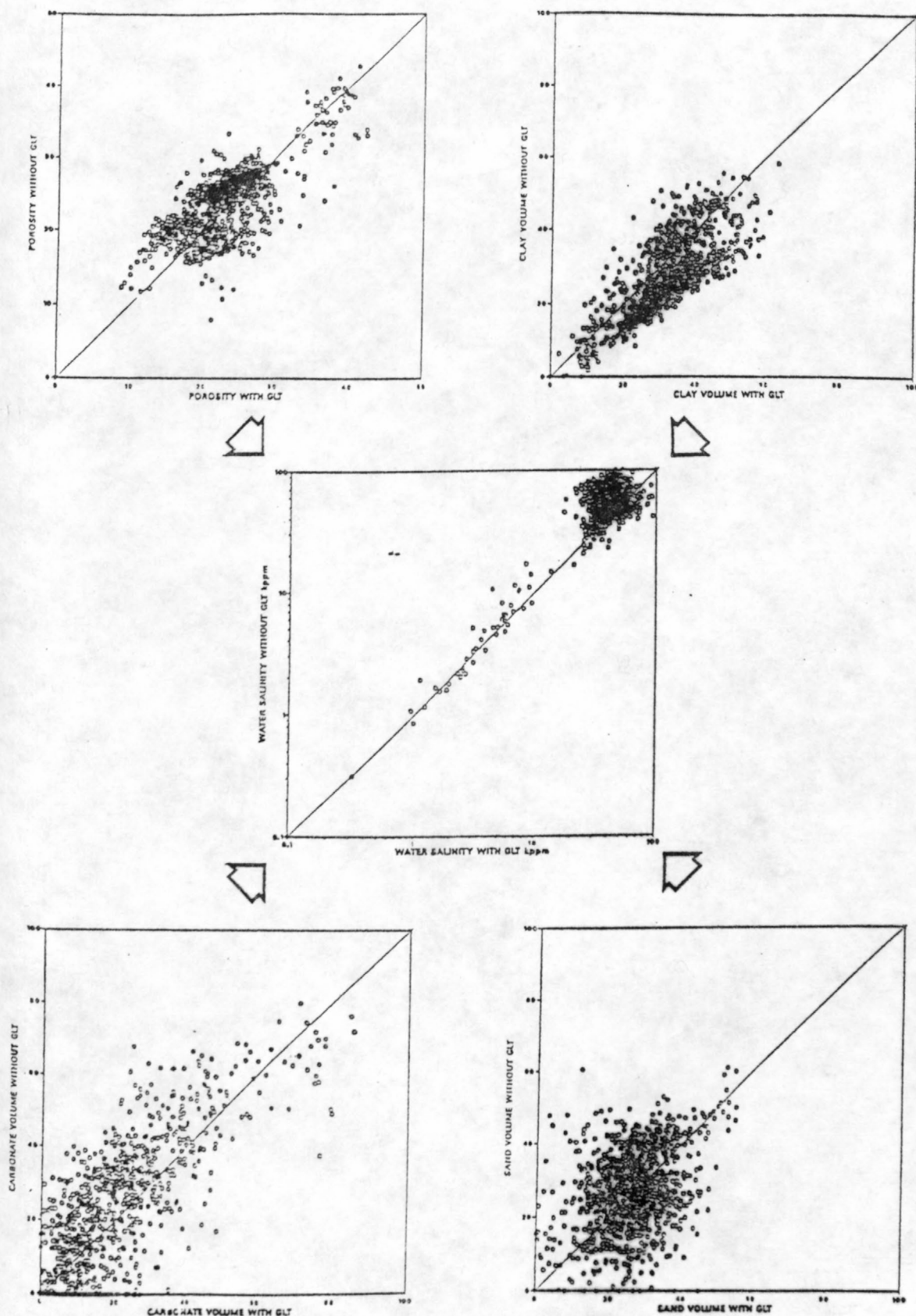


Figure 13. Cross plots of log interpretations for test hole GWP-30, with and without a geochemical logging tool log (GLT). (volumes in percent, water salinity in parts per thousand).



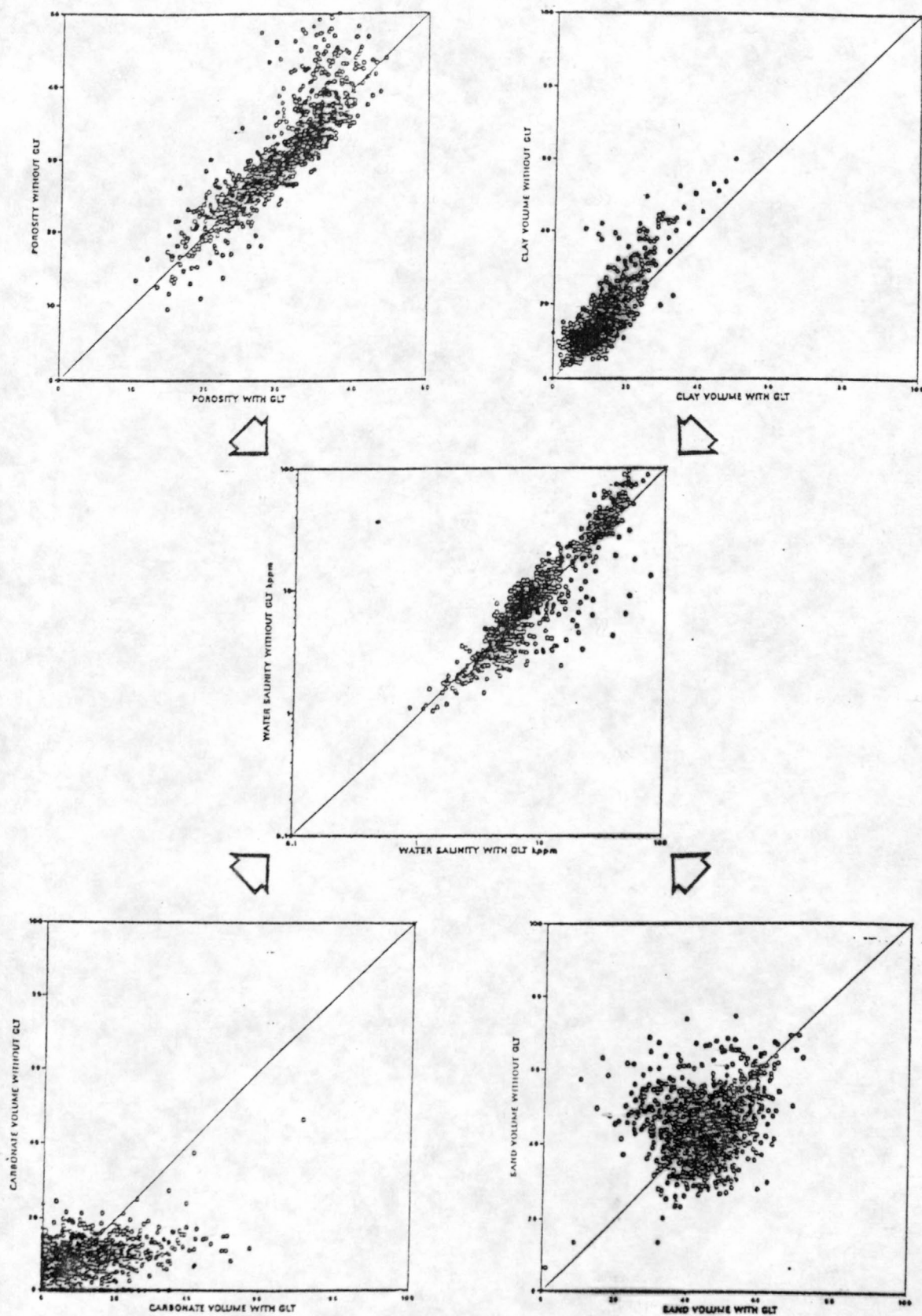


Figure 14. Cross plots of log interpretations for test hole GWP-67, with and without a geochemical logging tool log (GLT). (volumes in percent, water salinity in parts per thousand).

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 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 post-processing 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 and specific yield 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 petrophysical logs used in the project. (See figures 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, in particular kaolinite 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 the purpose of 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 dual-water 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 eastern 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 relations is:

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

where  $C_{weq}$  is the conductivity of an equivalent water

assuming clay-free conditions [ $\text{ohm}^{-1} \cdot \text{meter}^{-1}$ ] ,

$C_{fw}$  is the conductivity of far water [ $\text{ohm}^{-1} \cdot \text{meter}^{-1}$ ] ,

$V_{fw}$  is volume of far water [decimal] ,

$C_{bw}$  is conductivity of bound water [ $\text{ohm}^{-1} \cdot \text{meter}^{-1}$ ] , and

$V_{bw}$  is volume of bound water [decimal] .

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

$$1/C_{weq} = \phi_t^m / C_t , \quad (19)$$

where  $\phi_t$  is total porosity [decimal], and

$C_t$  is the reciprocal of  $R_t$  [ $\text{ohm}^{-1} \cdot \text{meter}^{-1}$ ] .

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 (eq. 3 and eq. 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 Emirate of Abu Dhabi. 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 (equations) literature. A

research program of petrophysical 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 specific yield and intrinsic permeability that were calculated using the petrophysical log analysis were correlated to values obtained from an aquifer test conducted at test hole GWP-30. A model of water resistivity was made and correlated to the whole-rock chemistry of the aquifer.

Petrophysical log analysis was used in both geologic and geohydrologic investigations. Petrophysical 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.

Petrophysical 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 a newly developed program termed LOGAN2. Estimates of the following geohydrologic properties were obtained: volume of clay, volume of free water, volume of retained water on clay, 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, values for hydraulic conductivity, transmissivity, and specific yield were derived.

A computer interpretation of the standard suite of petrophysical 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 was used to develop effective interpretation techniques for the interpretation of a limited suite of logs in many other boreholes inspite of the unusual properties of sediments encountered by those boreholes.

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## 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 eastern study area. Therefore, a special program (LOGAN2) was developed to determine volume of clay ( $V_c$ ). The program is 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 ( $V_{fw}$ ), volume of retained water ( $V_{rw}$ ), volume of clay ( $V_c$ ), volume of matrix other than clay ( $V_o$ ), density of matrix other than clay ( $\rho_o$ ), density of the matrix ( $\rho_m$ ), 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 petrophysical logs requires that relations be established among the properties measured by the logs. This is 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 petrophysical logging to interpret neutron logs in terms of porosity. The equation for neutron porosity of a water-saturated formation can be stated as follows:

$$\theta_N \approx V'_{hw} + V_{bw} + V_{rw} + V_{fw} , \quad (A-1)$$

where  $\theta_N$  is the neutron porosity if no other hydrogen is present in addition to "hydrated" hydrogen and free or retained water [decimal],

$V'_{hw}$  is apparent volume of hydrated water within the matrix and is proportional to hydrogen content [a decimal],

$V_{bw}$  is the volume of bound water [decimal] ,

$V_{rw}$  is the volume of water retained [decimal], and

$V_{fw}$  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 herein, 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 ( $\phi_D$ ) by the following equation:

$$\theta_D = (\rho_m - \rho_b) / (\rho_m - \rho_f) , \quad (A-2)$$

where  $\theta_D$  is gamma-gamma porosity [a decimal] ,  
 $\rho_m$  is density of matrix [grams per cubic centimeter ( $\text{gr}\cdot\text{cm}^{-3}$ )] ,  
 $\rho_b$  is bulk density of the matrix and the water-filled pores [ $\text{gr}\cdot\text{cm}^{-3}$ ], and  
 $\rho_f$  is density of the fluid (water), [ $\text{gr}\cdot\text{cm}^{-3}$ ].

Values of  $\rho_m$  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  $\rho_b$  are obtained from the density log, and values  $\rho_f$  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.

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

Lithology	Density, $\rho$ (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	2.60-2.75
Calcite or limestone	2.71
Clay	2.3-2.45
Gypsum	2.35

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

$$\theta_D \approx \Psi_{fw} + \Psi_{rw} , \quad (A-3)$$

where  $\theta_D$  is porosity calculated using data from a gamma-gamma log [a decimal].

### Volume of Clay ( $V_c$ )

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

$$\theta_N - \theta_D = V'_{hw} + V_{bw} \quad (A-4)$$

In reference to clay, it can be related:

$$V_c \approx (\theta_N - \theta_D) / \phi_{CNL} , \quad (A-5)$$

where  $\theta_{CNL}$  is the response of a compensated neutron logging tool for the wet clay [decimal].

Typical values of  $\phi_{CNL}$  are 0.30 for illite, 0.37 for kaolinite, 0.44 for montmorillonite, and 0.52 for chlorite. Values of  $\phi_{CNL}$  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  $V_c$  as long as the  $\phi_{CNL}$  for other non-clay minerals of the matrix are approximately zero.

### Volume of Bound and Retained Water for Clay ( $V_{bw}$ , $V_{rw}$ )

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

$$V_{bw,c} \approx P_{bw} V_c , \quad (A-6)$$

where  $P_{bw}$  is a proportional factor relating bound water and the clay [decimal], and

$$V_{rw,c} \approx P_{rw} V_c , \quad (A-7)$$

where  $P_{rw}$  is a proportional factor relating retained water and the clay [decimal].

In the eastern study area 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. Of course, values of  $P_{bw}$  and  $P_{rw}$  are functions of the clay mineralogy.

#### Volume of Matrix Other Than Clay ( $V_o$ )

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

$$V_t = V_c + V_{rw} + V_{fw} + V_o = 1 , \quad (A-8a)$$

where  $V_t$  is total volume.

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

$$V_o = 1 - V_c - V_{rw} - V_{fw} . \quad (A-8b)$$

#### Density of Matrix Other Than Clay ( $\rho_o$ )

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

$$\rho_b V_t = \rho_c V_c + \rho_{rw} V_{rw} + \rho_{fw} V_{fw} + \rho_o V_o . \quad (A-9a)$$

Noting that  $V_t = 1.0$ ,  $\rho_{rw} \approx 1.0$ ,  $\rho_{fw} \approx 1.0$ , and  $\theta_{fw} \equiv V_{fw}$ , equation A-9a reduces to the following:

$$\rho_o \approx (\rho_b - V_{rw} - V_{fw} - \rho_c V_c) / V_o . \quad (A-9b)$$



### Density of Matrix ( $\rho_m$ )

Equations A-2, A-5, A-7, A-8b, and A-9b can be solved iteratively using an estimate of density of matrix ( $\rho_m$ ) to determine  $\rho_o$ . An initial estimate for  $\rho_m$  of 2.71 is often used. The resulting calculated value of  $\rho_o$  can be compared to a value of  $\rho_o$  measured in the laboratory or estimated from the mineralogy of the drill cuttings. If the calculated  $\rho_o$  does not match the measured or estimated  $\rho_o$ , a new value of  $\rho_m$  is assumed, and the equations are solved again. This iterative procedure is continued until the calculated  $\rho_o$  matches the estimated or measured  $\rho_o$ . 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  $V_c$  is made for a sand-clay lithology using the following equation:

$$V_c \approx ((\Delta t_L - \Delta t_{sd}) / (\Delta t_c - \Delta t_{sd})) (1 - \phi), \quad (A-10)$$

where  $\Delta t_L$  is transit time from log [microseconds per foot] ,

$\Delta t_{sd}$  is transit time for clay-free sand  
[microseconds per foot] , and

$\Delta t_c$  is transit time for clay [microseconds per foot].

The iterative solution of equations A-2, A-5, A-7, A-8b, and A-9b can be performed such that  $V_c$  from the model compares to the  $V_c$  estimated from equation 10. This technique works best with a lithology of only sand and clay.

Estimates of  $V_c$ ,  $V_o$ ,  $\rho_o$ , and  $\rho_m$  were obtained using LOGAN2. The program requires input of data read from the standard suite of petrophysical 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 ( $V_{rw}$ ) to the volume of retained and free water as indicated by the following equation:

$$S_{wi,c} = V_{rw} / (V_{rw} + V_{fw}) \quad (B-1)$$

Equation B-1 is based on an approximation of  $V_{rw}$  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 non-clay component of the matrix as follows:

$$S_{wi} \approx (S_{wi,c}) (V_c) + (S'_{wi,o}) (V_o), \quad (B-2)$$

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, 1939; 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:

$$k \approx 1 \times 10^4 \theta^{4.5} / S_{wi}^2, \quad (C-1a)$$

where  $k$  is intrinsic permeability [millidarcies].

Intuitively the porosity of concern in relation to irreducible water saturation would be  $\phi_0$  as follows:

$$k \approx (1 \times 10^4) (\theta_0^{4.5} / S_{wi}^2) \quad (C-1b)$$

## APPENDIX D

### Estimating Specific Yield ( $S_y$ )

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

$$S_y = V_{rw} + V_{fw} - V_{rw} . \quad (D-1)$$

Noting the definition of irreducible water saturation:

$$S_y = V_{rw} + V_{fw} - S_{wi} (V_{rw} + V_{fw}) . \quad (D-2)$$

Combining A-3 and D-2 yields:

$$S_y \approx \phi_D - S_{wi} \phi_D . \quad (D-3)$$

:

## APPENDIX E

### Estimating Modulus of Elasticity of Matrix ( $E_m$ )

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

$$V = (E_m / \rho)^{0.5} , \quad (E-1)$$

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. The reader is referred to Entwistle and McCann [1990] for detailed discussion.)

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

$$\Delta t = 1/V . \quad (E-2)$$



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

$$\Delta t = (\theta/V_w) + (1-\theta)/V_m , \quad (E-3)$$

where  $\theta$  is porosity [decimal] ,

$V_w$  is velocity of the compressional wave

in water, [meters per second ( $m \cdot s^{-1}$ )], and

$V_m$  is velocity of the compressional wave in the matrix [ $m \cdot s^{-1}$ ].

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 ( $\phi_p$ ), combining equations E-1 and E-3 yields the following:

$$\Delta t = \frac{\theta_p}{(E_w/\rho_w)^{0.5}} + \frac{(1-\theta_p)}{(E_m/\rho_m)^{0.5}} , \quad (E-4)$$

where  $E_w$  is bulk modulus of elasticity of water [pascal],

$\rho_w$  is density of water [kilograms per cubic meter ( $kg \cdot m^{-3}$ )],

$E_m$  is modulus of elasticity of the matrix [pascal], and

$\rho_m$  is density of the matrix [ $kg \cdot m^{-3}$ ].

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) provided the following equations:

$$S_s = S_{sw} + S_{sm} , \quad (F-1a)$$

$$\text{where } S_s = \frac{\theta \rho_w g}{E_w} + \frac{\rho_m g}{E_m} , \quad (F-1b)$$

where  $S_{sw}$  is specific storage related to water compressibility [ $m^{-1}$ ],

$S_{sm}$  is specific storage related to the compressibility of the matrix [ $m^{-1}$ ], and

$g$  is gravity [ $m \cdot s^{-2}$ ].

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

$$S_s \approx \rho_w g / E_m . \quad (F-1c)$$

Assuming  $\rho_w \approx 1 \times 10^3 kg \cdot m^{-3}$  and  $g = 9.807 \times 10^3 m \cdot s^{-2}$ ,

equation F-1c simplifies to the following:

$$S_s \approx 9.807 \times 10^3 / E_m . \quad (F-1d)$$

## 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:

$$K = (k \rho_w g) / \mu_w , \quad (G-1)$$

where  $K$  is hydraulic conductivity [ $m \cdot s^{-1}$ ] ,

$k$  is intrinsic permeability [ $m^2$ ] ,

$\rho_w$  is density of water in situ [ $kg \cdot m^{-3}$ ] ,

$g$  is gravity in [ $m \cdot s^{-2}$ ] , and

$\mu_w$  is viscosity of water [pascal  $\cdot$  s] .

Values of  $\rho_w$  and  $\mu_w$  are dependent on temperature and salinity.

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