USE OF SURFACE-GEOPHYSICAL TECHNIQUES FOR GROUND-WATER EXPLORATION IN THE CANOVANAS-RIO GRANDE AREA, PUERTO RICO

By
Arturo Torres-González

U.S. Geological Survey
Water-Resources Investigations
Report 83-4266

Prepared in cooperation with the

Department of Agriculture of the
Commonwealth of Puerto Rico

San Juan, Puerto Rico
1985

UNITED STATES DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For addtional information write to:

Chief, Caribbean District, WRD
U.S. Geological Survey
GPO Box 4424
San Juan, Puerto Rico 00936
(Telephone: (809) 753-4414)

Copies of this report can be purchased from:

Open-File Services Section
Western Distribution Branch
U.S. Geological Survey
Box 25425, Federal Center
Denver, Colorado 80225
(Telephone: (303) 234-5888)

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS-Continued

TABLES

FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

For the convenience of readers who may want to use International System of Units (SI), the data may be converted by using the following factors:

Multiply the inch-pound units	By	To obtain the SI units
inches per hour (in/h)	2.54	centimeters per hour (cm/h)
feet (ft)	0.3048	meters (m)
feet per second (ft/s)	0.3048	meters per second (m/s)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
gallons per minute (gal/min)	0.06309	liters per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
ohms-feet (ohm-ft)	0.3048	ohms-meters (ohm-m)

U.S. · DEPARTMENT OF THE INTERIOR · GEOLOGICAL SURVEY

USE OF SURFACE-GEOPHYSICAL TECHNIQUES FOR GROUND-WATER EXPLORATION IN THE CANOVANAS-RIO GRANDE AREA, PUERTO RICO

By
Arturo Torres-González

ABSTRACT

Surface-geophysical techniques were used in the Canovanas-Río Grande area, Puerto Rico, for ground-water exploration. Thirteen electrical resistivity surveys complemented by two seismic refraction surveys showed that (1) the average fresh-water saturated thickness of the surficial deposits is about 50 feet, and (2) the underlying limestone formations in the study area are almost completely saturated with saline water. Driller's logs and chemical analyses of water from wells in the area verified the geophysical results.

The surficial-alluvial deposits are composed mainly of clay, silt and other fine-grained sediments of low-hydraulic conductivity. The freshwater-saltwater mixing zone throughout most of the study area is coincident with the boundary between the surficial sediments and the limestone. It occurs at an average depth of about 50 feet below land surface.

Ground-water flow seaward through the alluvial and limestone aquifer was estimated at about 0.18 million gallons per day over a 6.5 mile wide front parallel to the coast.

INTRODUCTION

An intensive program to foster agricultural development was begun in 1978 by the Department of Agriculture of the Commonwealth of Puerto Rico (PRDOA). The program included the development of a local rice industry to supplement imported rice. Alluvial valleys along the northern and western coasts of Puerto Rico are included in the proposed plan for rice cultivation. Rice is a water-intensive crop that requires large quantities of freshwater, principally for weed control. Limited information on the water resources in these areas prompted the U.S. Geological Survey to begin in 1979 a series of investigations designed to determine the availability and quality of ground water in several of the coastal valleys (fig. 1). The studies were conducted in cooperation with the Puerto Rico Department of Agriculture.

INTRODUCTION (Continued)

This report summarizes the findings of a one-year study using two surface-geophysical techniques - electrical resistivity and seismic refraction - to explore for ground water in the Canovanas-Río Grande area, east of San Juan. The study represents phase one of what was planned as a two-phase investigation into the ground-water resources of the Canovanas-Río Grande area. Initially, surface-geophysical techniques supplemented by test holes were planned to determine: 1) the thickness of unconsolidated surficial deposits and limestone formations, 2) the depth to volcanic bedrock, and 3) the inland extent of saline water into the aquifers. The second phase was designed to conduct a comprehensive investigation of the aquifer characteristics.

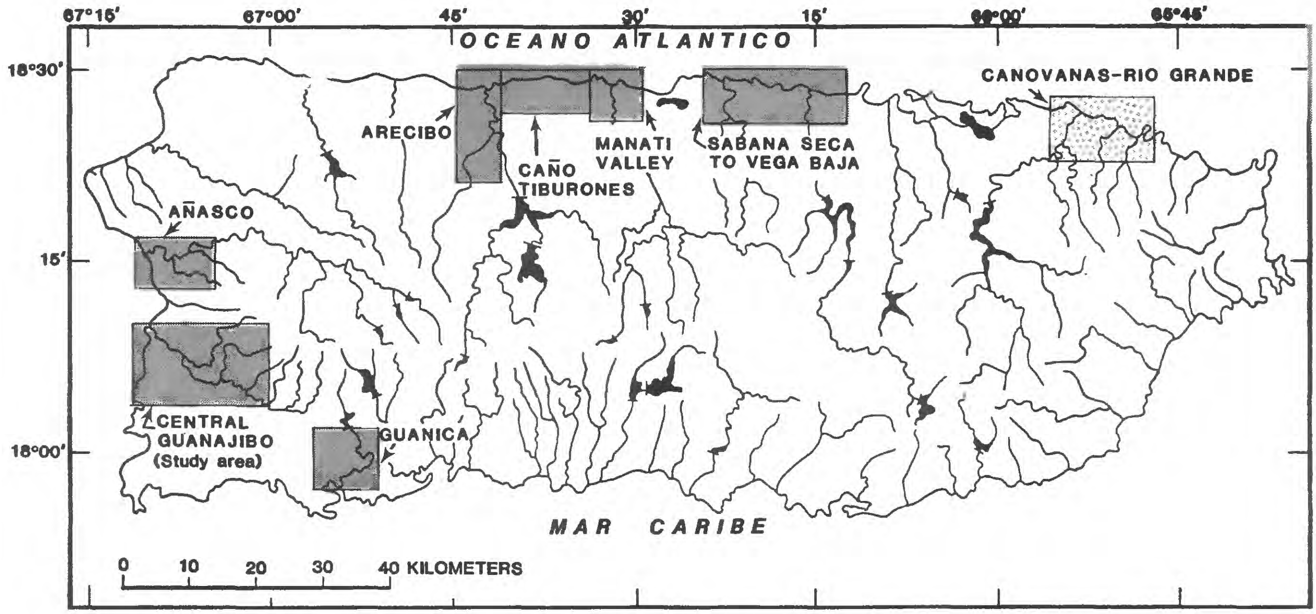


Figure 1.--Location of the Canovanas-Rio Grande study area and other coastal valleys where hydrologic investigations have been conducted.

The results of the first phase of the study showed that the quantity and quality of the ground-water resources in the Canovanas-Río Grande area were very limited; consequently the second phase of the study was not initiated.

The author gratefully acknowledges the assistance of Peter Haeni, U.S. Geological Survey. Support was also received from the Geologic Division, U.S. Geological Survey.

STUDY AREA

The Canovanas-Río Grande area lies between Río Grande de Loíza and Río Espirítu Santo on the northeastern coastal plain of Puerto Rico (fig. 1). It comprises an area of about 20 mi^2. Swamps and fossil-beach ridges dominate the topographic features of the area (fig. 2). The Canovanas-Río Grande area is approximately 25 percent swampland, the elevation of which is less than 4 feet above mean sea level.

Isolated limestone hills southwest of the area mark the eastern boundary of the north coast limestone belt. A particularly unusual feature of the area is the remarkably straight course of Río Grande de Loíza in its last four miles above its mouth. Spanish maps of the seventeenth century show the river as it is now (Monroe, 1977). Abandoned meanders adjacent to the present course suggest that it has been straightened by man.

The climate of northeastern Puerto Rico is tropical marine with only small temperature differences between summer and winter. Average-annual rainfall is about 65 in.

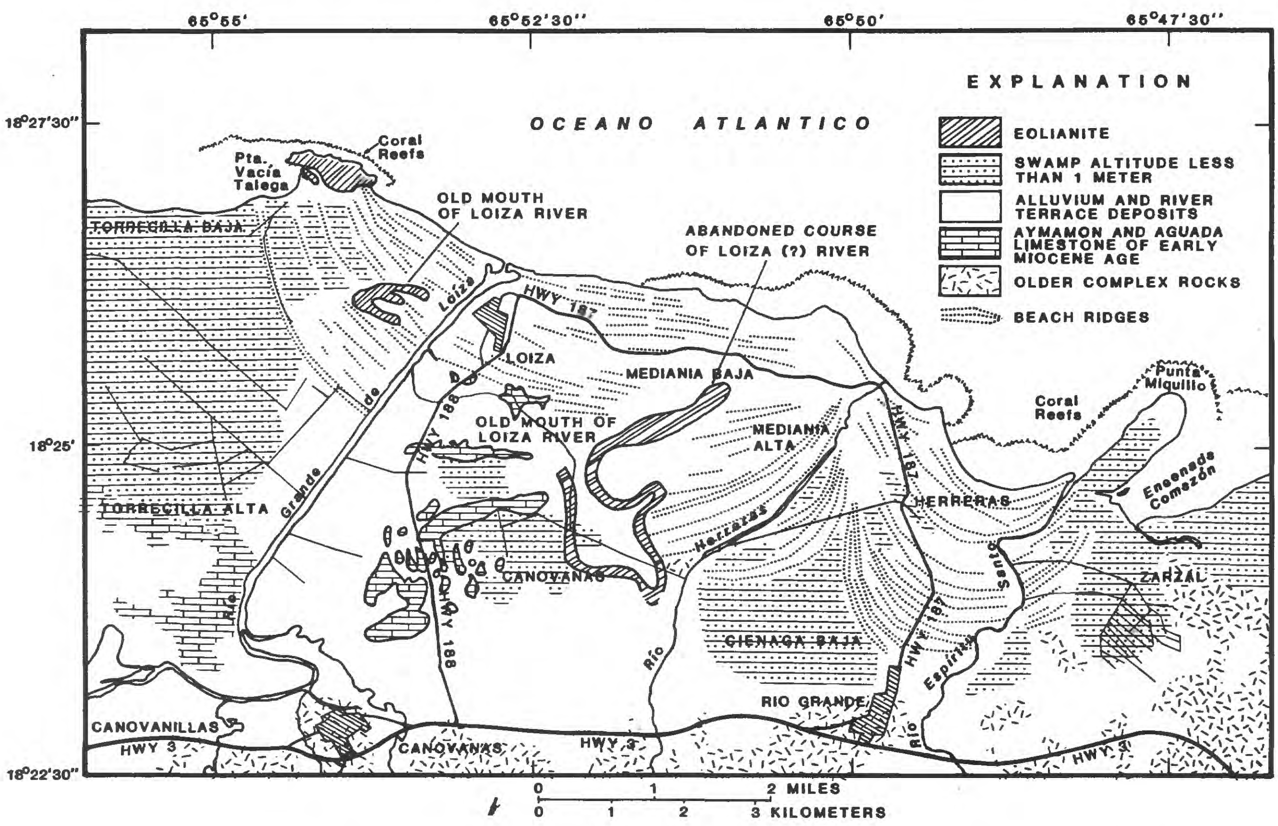


Figure 2.--Coastal topography in the Canóvanas-Río Grande area.
(Modified from Kaye, 1959.)

HYDROGEOLOGY

The hydrogeology of the Canovanas-Río Grande area has exerted the greatest influence on the occurrence, availability, and quality of the ground-water resources. Volcanic or intrusive rocks underlie the study area and are in general poor ground-water reservoirs . A thin layer of flat-lying limestone 100 to 300 ft thick, overlies an eroded basement-rock surface in the northwest half of the study area (fig. 3). The limestone apparently pinches out to the east against volcanic and intrusive rock in the vicinity of Río Herrera. The occurrence of dilute seawater has limited the usefulness of the limestone for ground-water development. The surficial-alluvial deposit averaging about 50 ft in thickness is composed mainly of clays, swamp deposits, and other fine sediments of low-hydraulic conductivity.

Ground water in the area exists only as a thin water-table aquifer containing freshwater within the alluvium and a freshwater-seawater mix within the limestone. Rainfall and seepage from Río Herrera are probably the source of freshwater in the surficial sediments. Apparently, part of this freshwater percolates into the underlying limestone formation and mixes with seawater. The alluvium probably behaves as a semi-confining bed above the limestone. At present, there are no water wells being used as a water supply in the entire area. Shallow domestic wells near the coast have been abandoned because of contamination from saltwater.

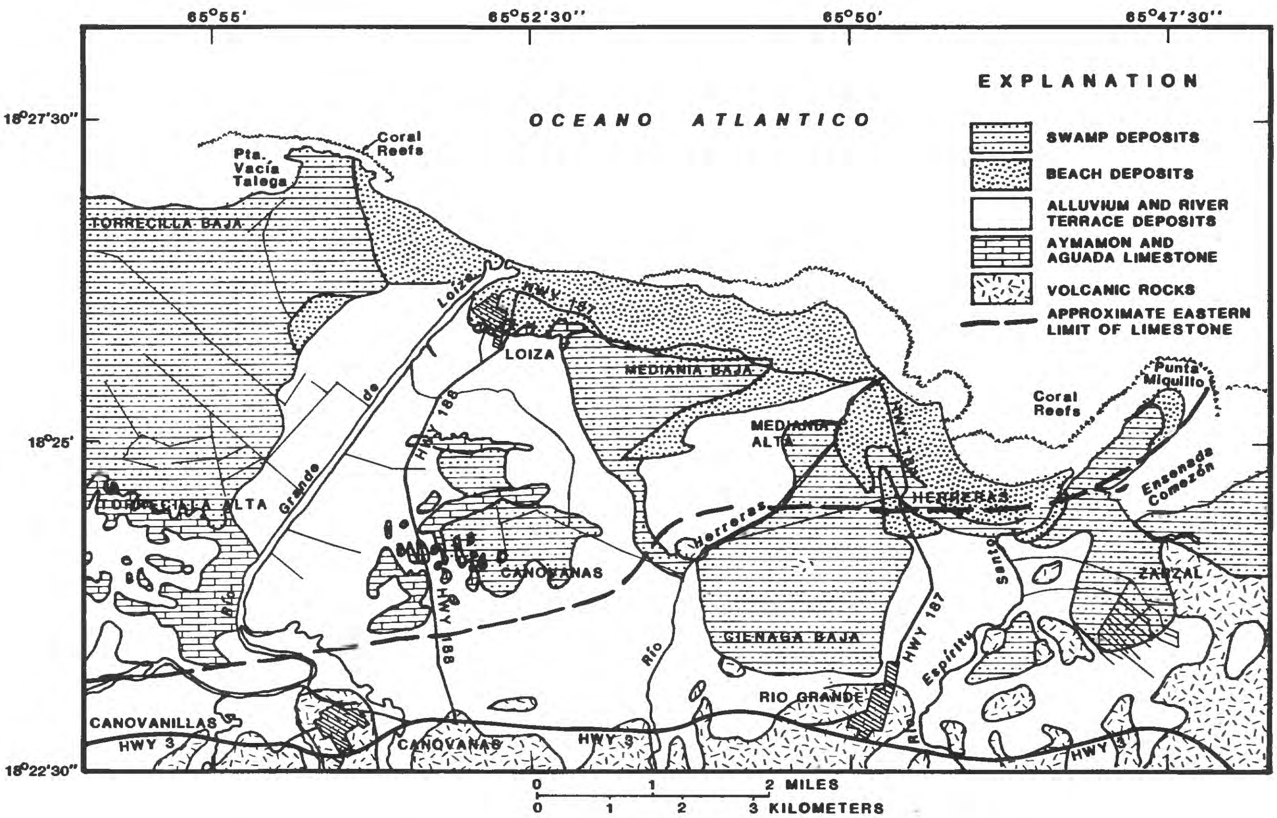


Figure 3.--Geology of the Canóvanas-Río Grande area.

HYDROGEOLOGY (Continued)

The geologic formations and their water-bearing characteristics in the Canovanas-Río Grande area are summarized in table 1. A detailed description of the geology is presented by Briggs and Akers (1965), Pease and Briggs (1972), and Monroe (1977).

SURFACE-GEOPHYSICAL TECHNIQUES IN GROUND-WATER EXPLORATION

Ground-water exploration using geophysical techniques is accomplished by measuring the physical properties of subsurface materials and interpreting the measurements in terms of relations developed (often empirical) between the physical properties and geologic conditions. Geophysical prospecting includes surface techniques (electrical, seismic, gravity, and other methods) and bore-hole techniques (caliper, temperature, electrical resistivity, fluid conductivity, neutron porosity, gamma density, and other methods).

The surface-geophysical techniques employed for ground-water studies in the Canovanas-Río Grande area were the electrical-resistivity and seismic-refraction methods. The electrical-resistivity method can be used to estimate the quality of the water contained in aquifers. It has also been used to relate aquifer resistivity to hydraulic conductivity (Heigold and others, 1979, p.338). Where such relations are known, the technique can be used to map variations in water quality and hydrologic properties of the aquifer. The seismic-refraction method can be used to define the geometry of the aquifers and to refine the resistivity solution.

Surface Electrical Resistivity

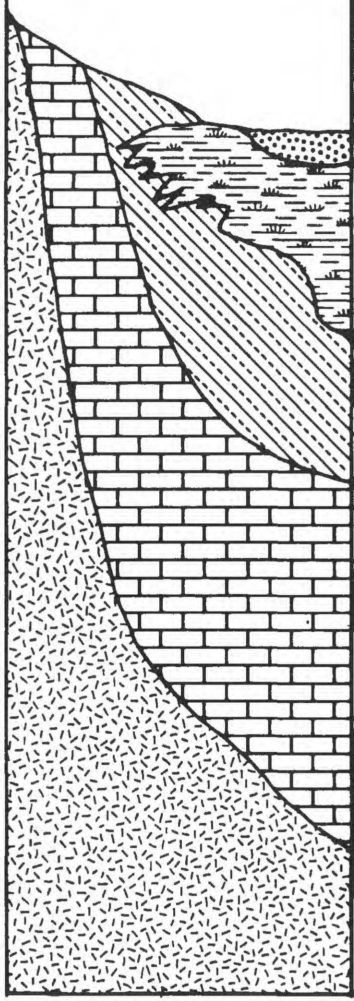
The electrical properties of most rocks in the upper part of the Earth's crust are dependent primarily upon the amount of water in the rock (saturated or unsaturated) and the salinity of the water. Saturated rocks have lower resistivities than unsaturated and dry rocks. The greater the porosity of the saturated rock, the lower its resistivity; and the higher the salinity of the saturating fluids, the lower the resistivity. The presence of clays and conductive minerals also reduces the resistivity of the rock (Zohdy, 1974, p.5).

In electrical-resistivity investigations, an electric current is introduced into the ground through two current electrodes, and the difference in electrical potential between two other electrodes is measured to determine the resistivity of the subsurface material. The distance between the electrodes, electric current, and measured potential difference can be used to made interpretations of the subsurface conditions.

There are two kinds of electrical-resistivity surveys: electrical soundings and horizontal profiling. Electrical sounding is the process by which resistivity measurements for different depth intervals are made; horizontal profiling is the process by which lateral variations in resistivity at a single depth are measured. The technique employed during this investigation was the electrical sounding method using the

Table 1. Columnar section, stratigraphic table, and water-bearing characteristics of rock units.

SECTION



GEOLOGICAL UNIT		DESCRIPTION	WATER-BEARING CHARACTERISTICS
Beach Deposits	QUATERNARY	Fine quartz grains mixed with minor quantities of shell fragments and volcanic rock fragments. Less than 30 feet thick.	Highly permeable and yield fair amount of water to domestic wells. Sea-water intrusion limits its potential.
Swamp Deposits	QUATERNARY	Black and dark-gray silt and clay with organic material. Black peaty muck of decaying plant material occurs locally. Less than 60 feet thick.	Extremely low permeability. In many places water is saline. Drainage is poor.
Stream Deposits	QUATERNARY	Mostly clay with gravel and sand in layers or lenses randomly interperced. These deposits are neither thick nor extensive.	Very low permeability. Yield small amount of water to domestic wells. Sea-water intrusion limits its potential.
Sedimentary Rocks: Aymamón Limestone Aguada Limestone Cibao Formation	TERTIARY	Aymamón.- White to very pale orange, very pure fossiliferous limestone. Exposed thickness 150-300 feet. Aguada.- Very pale orange to pink fine calcarenite and grayish orange to very pale orange clayey and chalky limestone. About 150 feet thick. Cibao.-Rubbly, very sandy limestone with gray sandy clay and fossiliferous calcareous claystone. Thickness about 110 feet.	Highly permeable where cavernous conditions exist. Wells in limestone near the salt-water marshes and swamps will yield brackish water. Sea-water intrusion limits its potential.
Volcanic or Intrusive Rocks	CRETACEOUS	Calcareous tuffaceous siltstone and sandstone, calcareous mudstone, intrusive rocks, volcanic sandstone and brecia, lava flows	Minor amounts of water could be found only along weathered and fractured zones.

Surface Electrical Resistivity (Continued)

Schlumberger electrode-configuration array, the most widely used in electrical prospecting (Zohdy and others, 1974, p. 11). Four electrodes are placed in the ground along a straight line (fig. 4) in the order AMNB, with $\overline{AB} \geq 5\,\overline{MN}$.

where: $\overline{AB}$ = current electrode spacing
$\overline{MN}$ = potential electrode spacing

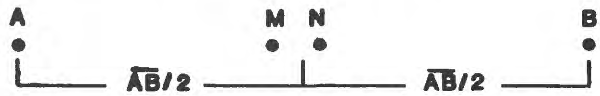


Figure 4.--Schlumberger Electrode Array.

The apparent resistivity, $\bar{\rho}$, is then calculated from the equation:

$$\bar{\rho} = \pi \frac{(\overline{AB}/2)^2 - (\overline{MN}/2)^2}{\overline{MN}} \times \frac{\Delta V}{I} \qquad (1)$$

where: ΔV = potential difference between the M and N electrodes, in volts
I = the input current, in amps

The apparent resistivity is expressed in ohm-meter squared per meter (ohm-m^2/m) or more commonly, as ohm-meters. By convention, the results are plotted on log-log paper with apparent resistivity plotted in the ordinate and the spacing $\overline{AB}/2$ plotted in either feet or meters in the abscisa.

The electrical-resistivity surveys in the Canóvanas-Río Grande area were conducted with a Soiltest R-60 DC[1], earth-resistivity meter, using the Schlumberger electrode array. The depth-limit capability of the instrument is about 300 to 400 ft. The electrode spacings used during the surveys were 3, 4.5, 5, 7, 10, 14, 20, 30, 45, 70, 100, 200, 300, 450, 700, and 1,000 ft for the current electrode ($\overline{AB}/2$) and 0.5,2,6, 20,60 and 140 ft for the potential electrodes ($\overline{MN}/2$). Once the values of apparent resistivity were plotted in the field, these were corrected by drawing a smooth curve (Zohdy and others, 1974, p. 18) for each of the soundings (fig. 5). In this study, a computer program (Zohdy, 1973) was used to calculate values of true resistivity and layer thickness from the field data (figs. 6 and 7). The bar graphs in these figures represents geoelectric layers with true resistivity in ohm-meters and their thickness in feet.

---

[1] The use of Brand names is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

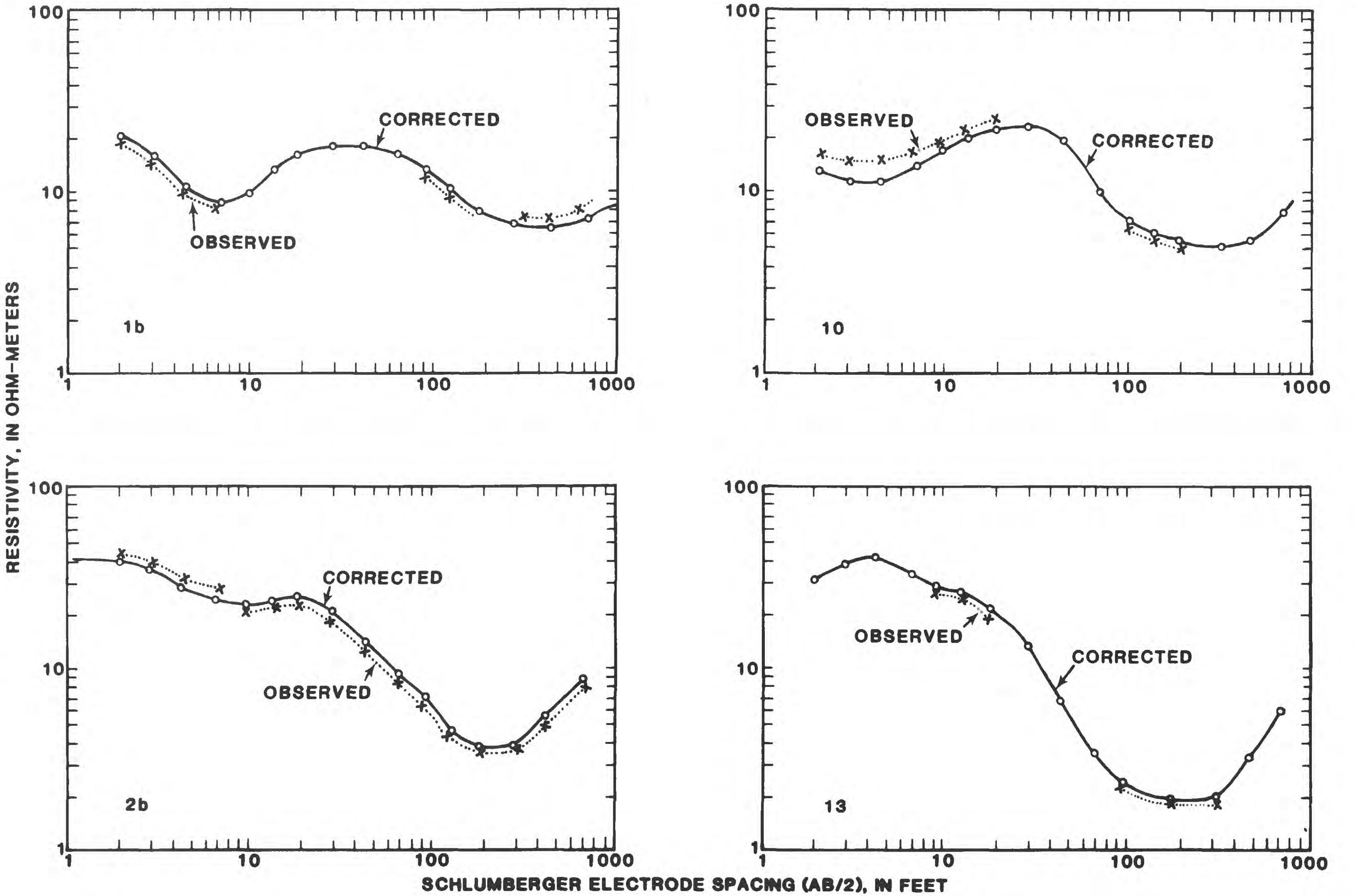


Figure 5.--Schlumberger sounding curves 1b, 2b, 10, and 13 in the Canóvanas-Río Grande area.
(Observed field data and smoothed curve used for test interpretations.)

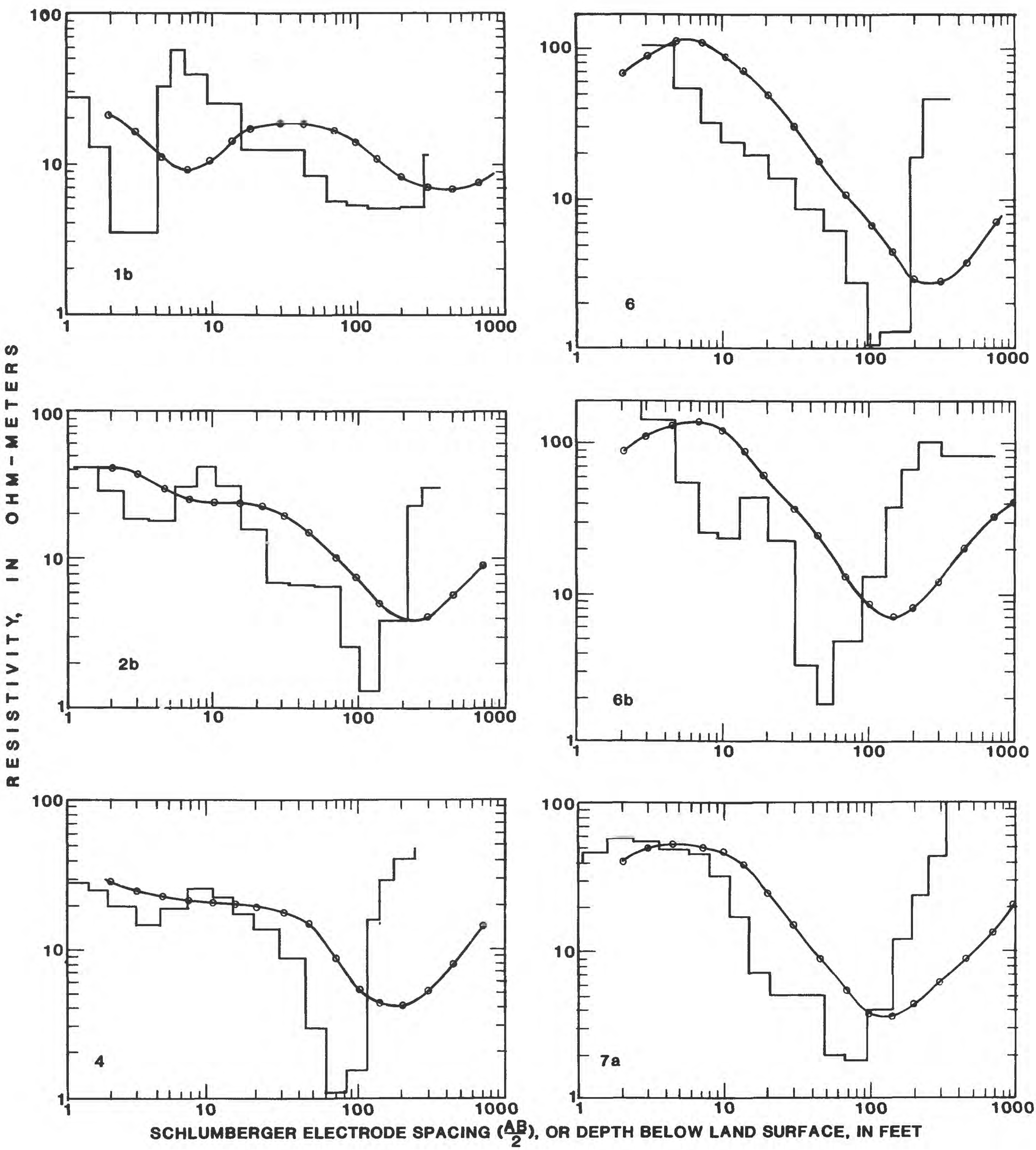


Figure 6.--Smoothed curves: 1b, 2b, 4, 6, 6b, and 7a.

(Layering calculated from Zohdy computer program, 1973.)
(See fig. 11 for location of test sites.)

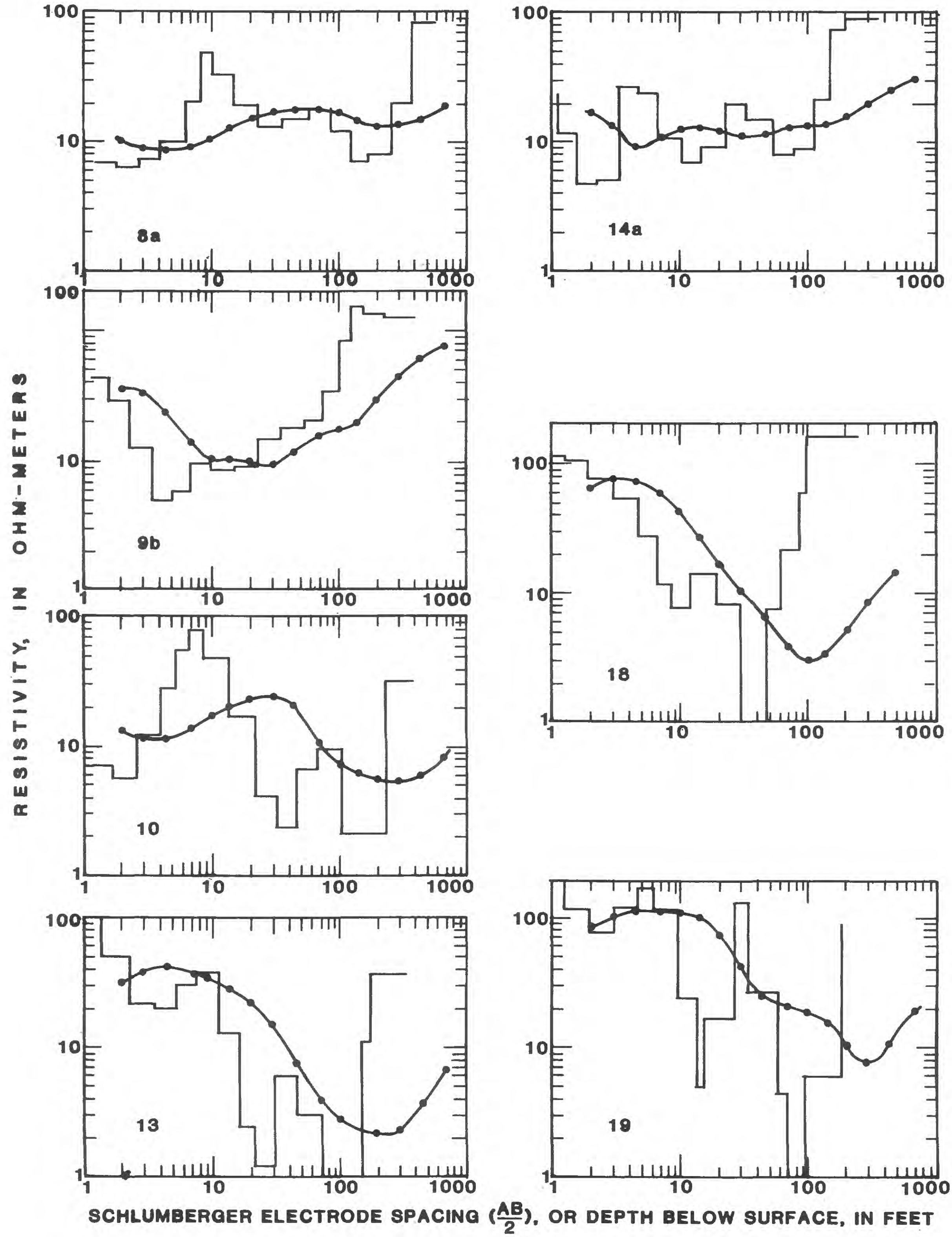


Figure 7.--Smoothed curves: 8a, 9b, 10, 13, 14a, 18, and 19.
(Layering calculated from Zodhy computer program, 1973.)
(See fig. 11 for location of test sites.)

Formation Resistivity Factor

The apparent resistivity ($\bar{p}$) as measured by the instrument and the true resistivity adjusted by the computer (Ro) represents the resistivity of the water-saturated rock. Archie (1942, p. 54) showed that the resistivity of the water with which the rock is saturated (Rw) is related to Ro, for non-shaly unconsolidated formations, by the expression:

$$F = {}^{Ro}/_{Rw}$$

where:

F is the formation resistivity factor
Ro is the true resistivity of a water-saturated formation
Rw is the resistivity of the water with which the formation is saturated.

The formula has wide application in estimating Rw from values of Ro because the formation factor is constant over a wide range of water salinities in the same rock material. However the formation factor varies with differences in intergranular relations such as the degree of cementation, porosity, grain size, and sorting.

For applications in non-clastic formations such as consolidated limestones, the derivation of the formation factor is more closely approximated by the expression: $F = a\,\phi^{-m}$;

where, a is a proportionality constant (0.6 to 1.5) related to the rock type. For limestone, a value of a = 1.0 is appropriate (Schlumberger, 1958, p. 11);
ϕ is the porosity of the rock expressed as a decimal between 0 and 1;
m is the cementation exponent. Generally, m = 2 is used for carbonate rocks (MacCary, 1980, p. 4).

Empirical relations between ϕ, F, Ro, and Rw can be developed for all rock classifications, whether consolidated or not, if limestone porosities are estimated macroscopically.

In general, the formation factor of consolidated formations decreases with increasing porosities (Schlumberger, 1962, p. C-9), which also occurs when the grain size of unconsolidated sediment becomes smaller and smaller (gravel to sand to clay, figure 8) (Croft, 1971, p. B266). In limestone, the porosity increases with size of the solution openings which reduces the size of interconnecting "grains". Macroscopically, the porous limestone has a small grain size which produces a smaller formation factor.

It is possible to derive the formation factor for a particular water-saturated rock or sediment from adjusted values of Ro measured by earth resistivity or from borehole logs and corresponding measurements of RW.

Formation Resistivity Factor (Continued)

The resistivity of the water (Rw) must be measured for water samples withdrawn from wells completed in the same rock or sediment for which Ro has been determined. The formation factor can then be used with adjusted values of Ro at other locations within the same formation, and corresponding values of Rw can be estimated.

Under fresh-water conditions, the true resistivity values are influenced by material types (Table 2). The effect of the material type on the value of Ro is particularly significant where the material is dry, moist, or saturated with water of low dissolved solids (high resistivity). But where Rw is low (saline water), with respect to the material type, the resistivity of the material type is negligible in its influence upon Ro.

It is important to recognize that a low value of true formation resistivity (5.0-10.0 ohm-m) does not necessarily mean that saline water exists in a formation. A clay matrix containing freshwater will have a low Ro because of its intergranular relationships.

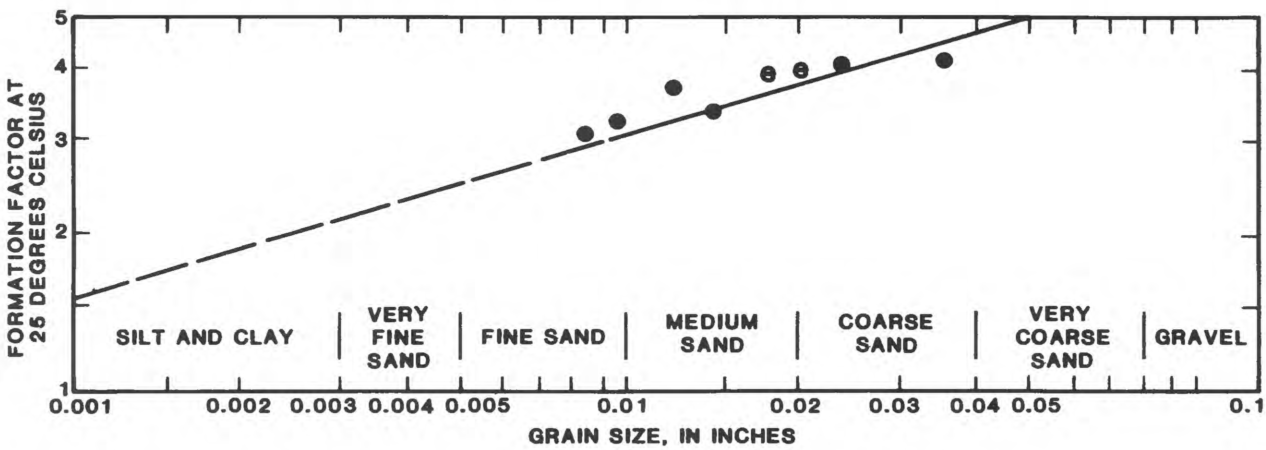


Figure 8.--Relation of grain size to formation resistivity factor.
(Modified from Alger, 1966.)

Seismic Refraction

Seismic refraction is often used as a reconnaissance tool in newly explored areas. This method is effective in estimating the saturated thickness of aquifers under certain geologic conditions.

The Seismic-Refraction Method consists of measuring, at known points along the surface of the ground, the travel times of compressional waves generated by an impulsive energy source (fig. 9). The energy source could be either a hammer blow, a seisgun projectile impact, or an explosive charge. The seismic waves are detected by geophones placed at a known distance from the energy source.

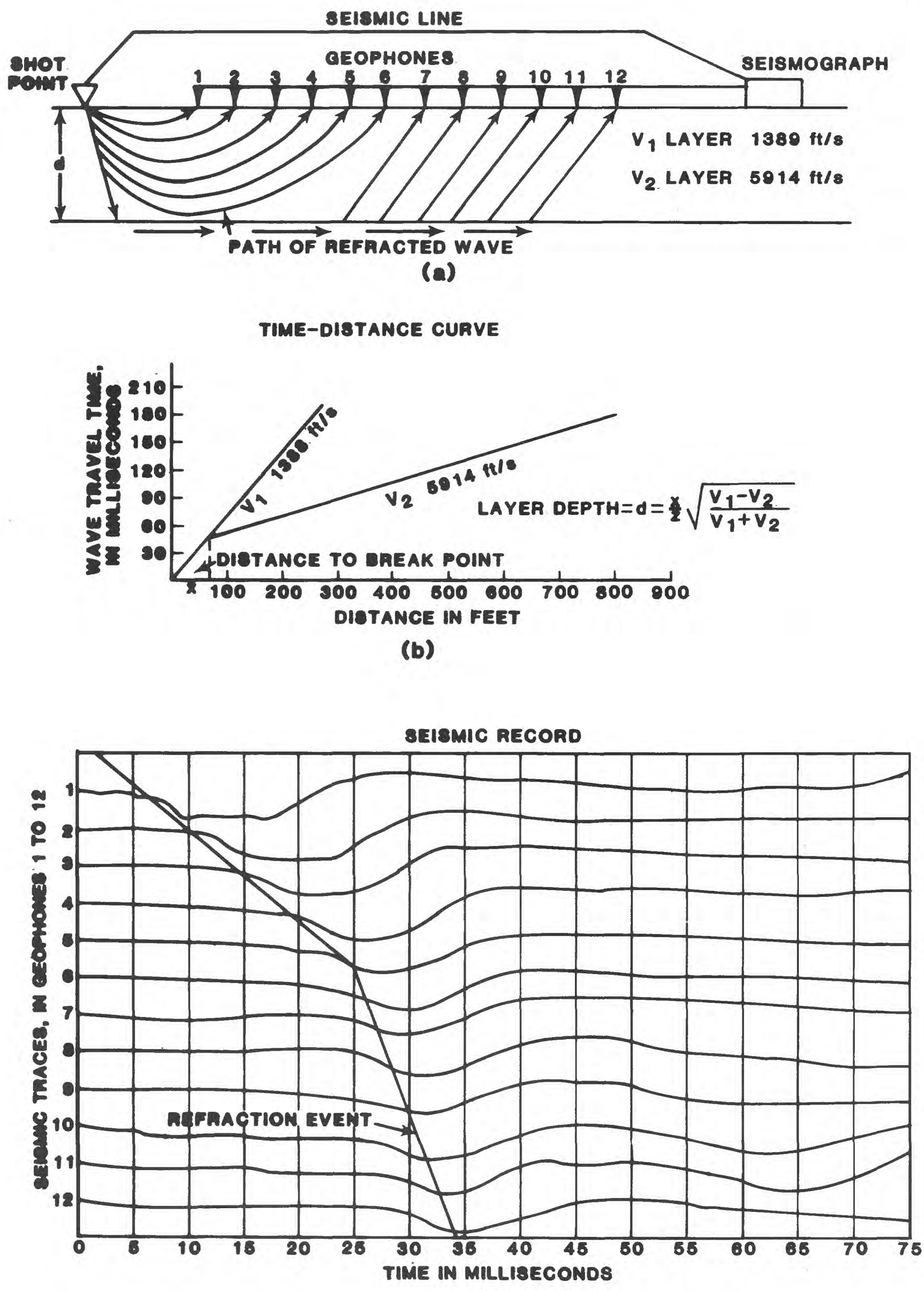


Figure 9. Elements of refraction method of seismic exploration, (a) seismic line, (b) time-distance curve, and (c) seismic record.

Table 2. Range of resistivity values in earth materials.
(Modified from Soiltest, 1968)

Range of values in ohm-meters	Type of material
1 to 3	Wet to moist clayey sloils.
3 to 15	Wet to moist silty clay and silty soils
15 to 30	Moist to dry silty and clayey soils
20 to 150	Moist to dry gravelly clays and clayey gravels; wet to moist limestone, sandstones and conglomerates; decomposed igneous rocks; saturated clean sand, sand and gravel; enter-layered gravel and silt.
150 to 1,000	Dry limestone, sandstones and conglomerate.
1,000 to 2,500	Dry clean sand and gravel; slightly fractured igneous rock.
2,500 +	Undecomposed massive bedded and hard igneous rock.

Seismic Refraction (Continued)

Seismic waves propagate in solids as patterns of particle deformation traveling through the materials with velocities that depend upon their elastic properties and densities (Dobrin, 1976, p. 26). Faster seismic velocities are recorded in hard rock or strongly cemented materials, and lower velocities are recorded in weathered or fractured rocks and loose unconsolidated sediments (fig. 10). For the seismic-refraction method to be usable, it is necessary for layer velocities to increase with depth (Sander, 1978, p. 394).

The propagation of seismic energy through subsurface layers is described by essentially the same rules that govern the propagation of light rays through transparent media (Redpath, 1973). The fundamental law that describes the refraction of light rays is Snell's Law, and this together with the phenomenon of "critical incidence", is the physical foundation of seismic-refraction surveys. For a more detailed description in seismic refraction refer to Redpath (1973), Dobrin (1976), and Saayman (1978).

The seismic-refraction data collected during the course of this study was analysed with the computer program of Scott, and others (1972). This program generates a two-dimensional model representing a layered system.

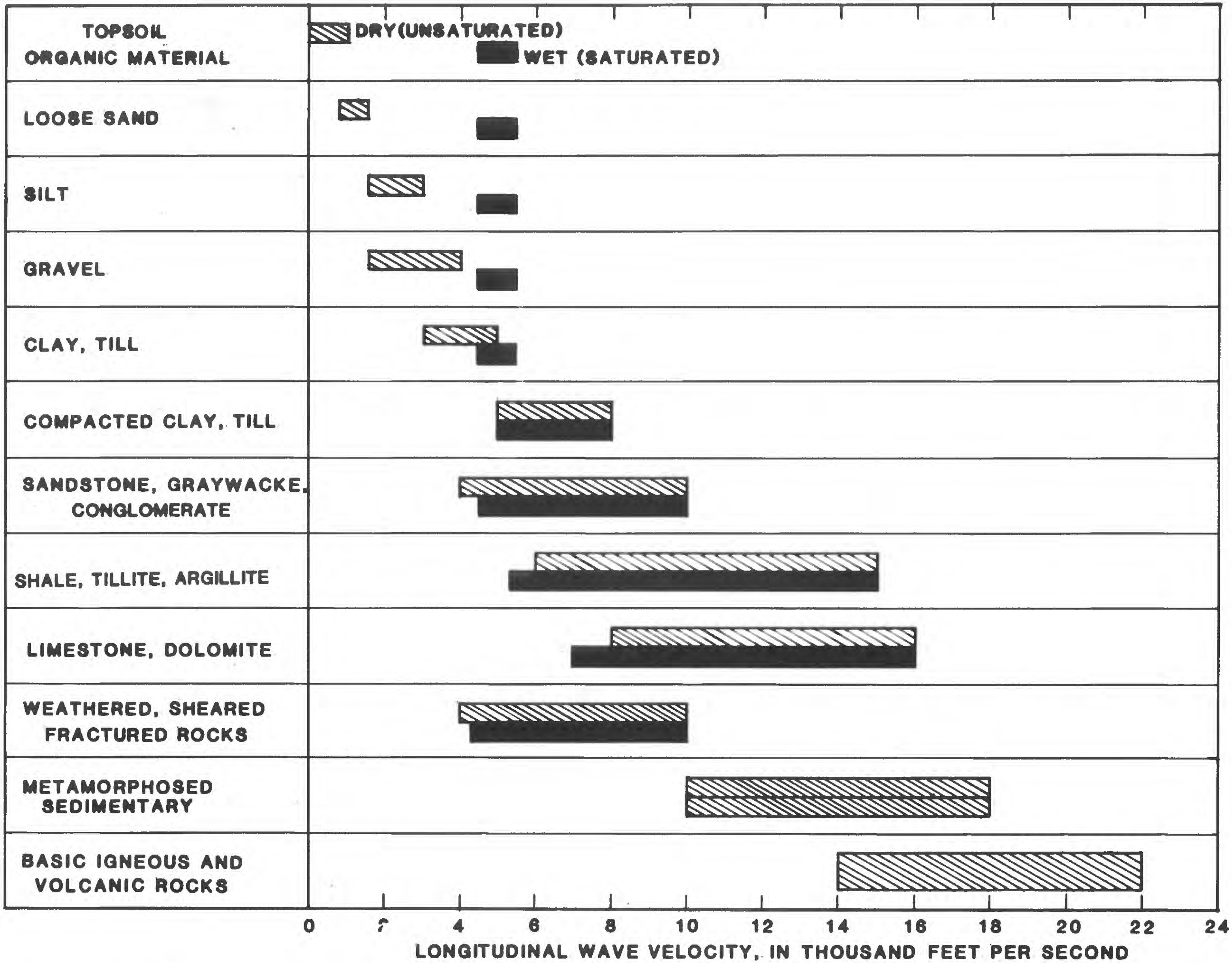


Figure 10.--Range of seismic velocities in typical earth materials under different moisture conditions. (Modified from Huntec (70) Limited.)

RESULTS OF GEOPHYSICAL EXPLORATIONS

In the Canovanas-Río Grande area 13 surface-electrical resistivity and two seismic-refraction surveys were conducted (fig. 11). The resistivity surveys were designed to determine the inland extent of saline water in the water-table aquifer and the seismic surveys were designed to determine the thickness of subsurface formations and the depth to bedrock. Four test holes (fig. 11) were drilled to verify the geophysical data.

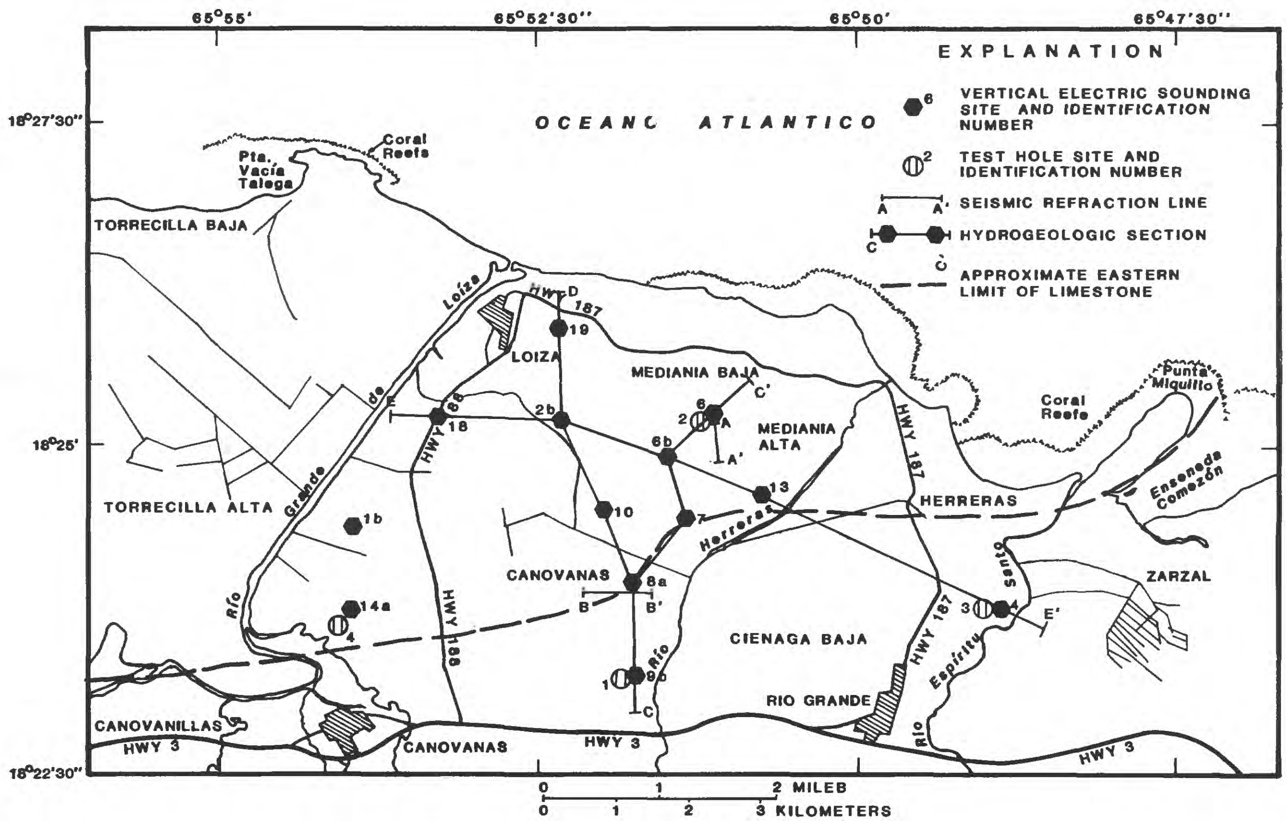


Figure 11.--Location of electrical resistivity, seismic refraction, and test hole sites.

Surface-Electrical Resistivity

Unconsolidated material example

The electrical-resistivity surveys showed sites of low resistivity (fig. 12, sites 4, 6, and 8a). At site 4, a layer with a resistivity value of 1.2 ohm-m extends from about 60 ft to about 80 ft below land surface. The driller's log for this site describes the existence of a clay and shell deposit underlain by volcanic rock. The usefulness of the formation-resistivity factor ($F = {}^{Ro}/Rw$) can be demonstrated from the data at site 4. Using the true calculated resistivity value (Ro) of 1.2 ohm-m and assuming a formation factor of 2.0 for the sandy-clay and shell deposit (fig. 8), the resistivity of the water (Rw) is:

$$Rw = {}^{Ro}/F = {}^{1.2}/2.00 = 0.6 \text{ ohm-m}$$

Because resistivity is the reciprocal of specific conductance (electrical conductivity of a water sample at 25°C, expressed in micromhos per centimeter) both can be related by the following expression (fig. 13):

$$\text{Specific Conductance} = \frac{10,000}{Rw} = \frac{10,000}{0.6} = 16,666 \text{ mho/cm}$$

A specific conductance of 16,666 mho/cm in north-coast water wells in Puerto Rico represents water having approximately 5,200 milligrams per liter (mg/L) chloride (fig. 14). To verify the results obtained from the resistivity survey, a water sample was taken from test hole 3 (screened from 55 to 60 ft), adjacent to resistivity site 4. It had a specific conductance of 20,000 μmho/cm. This represents water having approximately 6,250 mg/L chloride (fig. 14). The resistivity data is indicative that at site 4, saline water occurs from a depth of 45 ft downward.

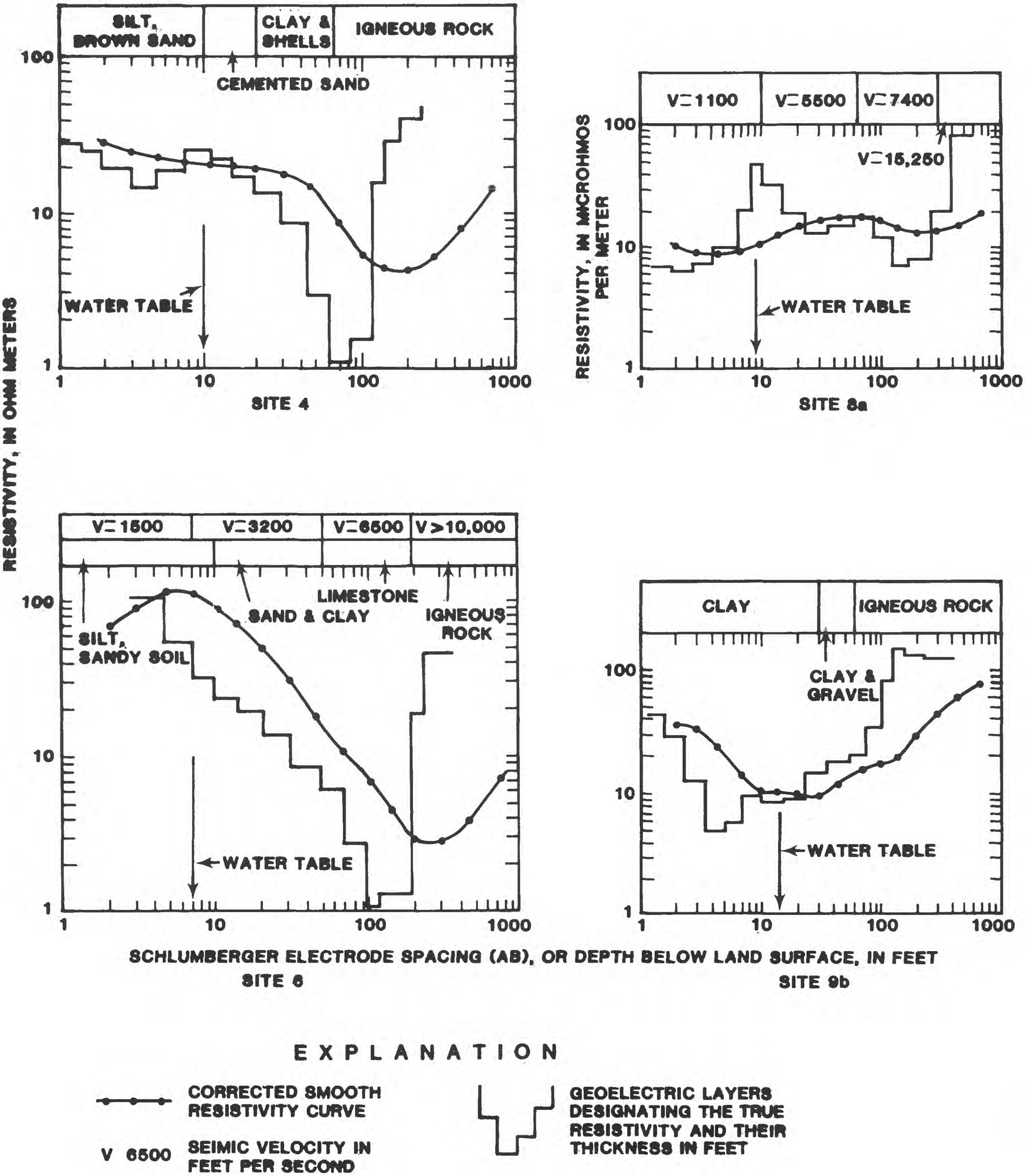


Figure 12. Comparison of electrical resistivity data with drillers records and seismic refraction results.

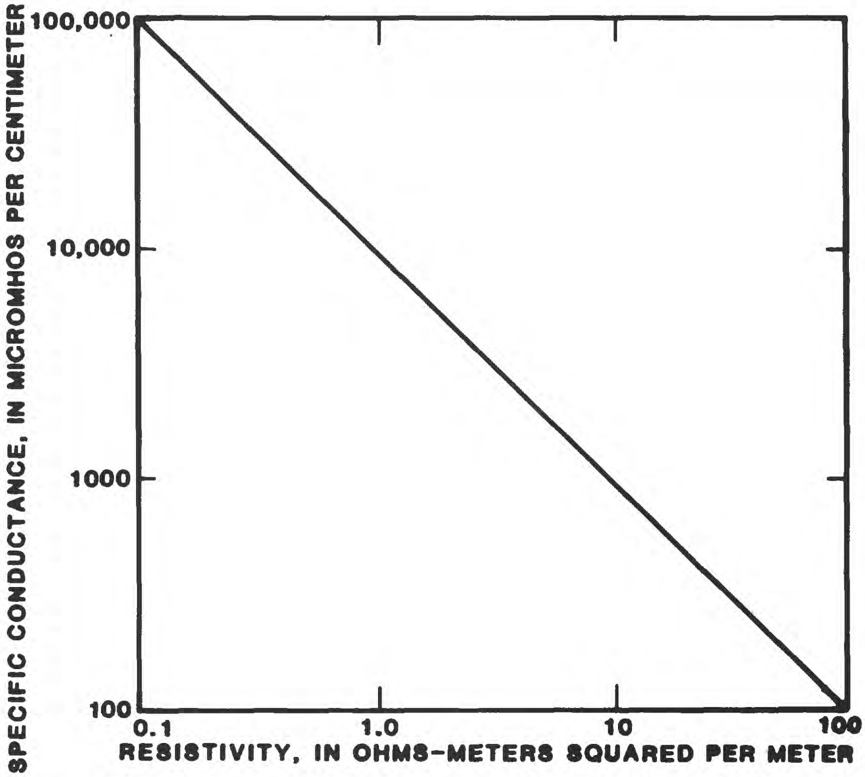


Figure 13.--Conversion graph for resistivity and specific conductance. (Turcan, 1966.)

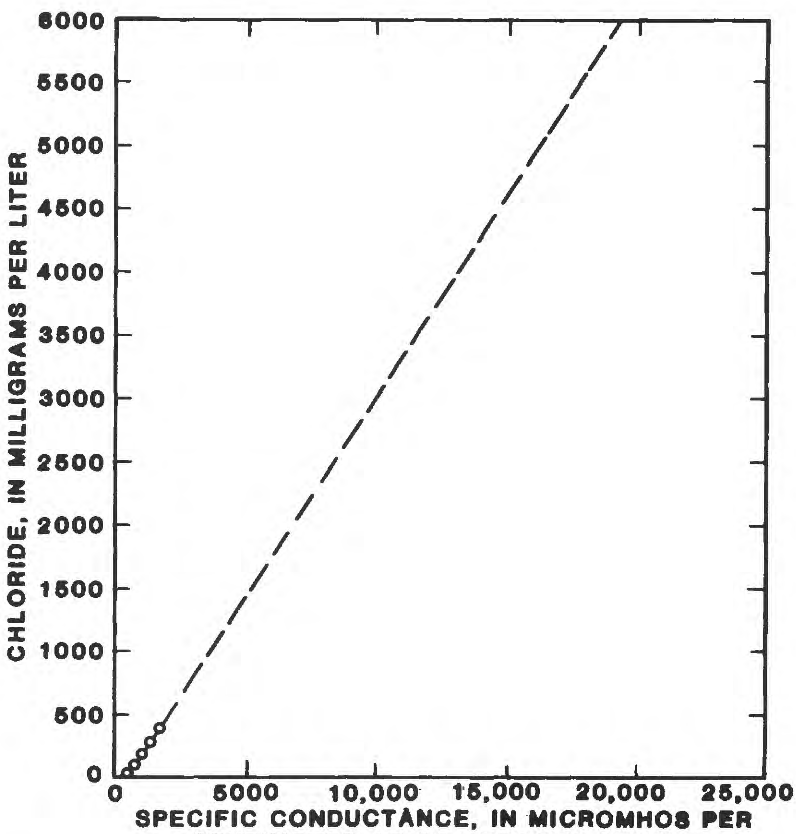


Figure 14.--Conversion for specific conductance and chloride for north coast water wells in Puerto Rico. (Zack, personal communication, 1982.)

Limestone Examples

At test-hole 2, adjacent to resistivity site 6 (fig. 12), limestone was found at a depth of 55 ft. The true resistivity of the limestone (Ro) decreased from 6 ohm-m at 55 ft to 1 ohm-m at about 100 ft.

The average porosity of the limestones in the north coast of Puerto Rico is about 0.17 (Giusti, 1978, p. 40). This value was derived from the primary porosity of the limestones and does not consider the effect of secondary porosities (solution cavities). Localized cavernous conditions in this aquifer could increase the porosity value of the limestone from 0.17 to as much as 0.50 or more. For the purpose of this study a porosity value (Ø) of 0.45 for the cavernous limestone was assumed and a cementation exponent (m) of 2 (MacCary, 1980, p. 4). The computed formation resistivity factor ($F=1/Ø^m$) equals 4.94. The resistivity of the water at depths of 55 ft and 100 ft is then,

$$Rw_{55} = \frac{Ro}{F} = \frac{7}{4.94} = 1.42 \text{ ohm-m}$$

$$Rw_{100} = \frac{Ro}{F} = \frac{1}{4.94} = 0.20 \text{ ohm-m}$$

These numbers are equivalent to specific conductance values of 7,000 and 50,000 umho/cm (fig. 13). A water sample from test hole 2, 70 ft deep and screened from 65 to 70 ft in the limestone, contained very salty water (26,000 umho/cm). The resistivity data was therefore indicative of saline water occurring in the limestone at this site.

At site 8a (fig. 12), limestone occurs at a depth of about 50 ft based on the results of seismic line B-B'. The true resistivity of the limestone, at this depth, is about 18 ohm-m. Assuming the same values of porosity and formation factor (Ø=0.45 and F=4.94) for the limestone, the resistivity of the water Rw at this depth is 3.64 ohm-m, which is equivalent to a specific conductance of about 2,700 umho/cm (750 mg/L of chloride, figs. 13 and 14). However, at depths of about 85 and 125 ft respectively, the resistivity of the limestone drops to 12 and 7 ohm-m respectively, indicating salinity changes in the water. The resistivity of the water at these depths is 2.42 and 1.41 ohm-m, which represents specific conductances of 4,000 and 7,000 umho/cm, respectively. At this site the freshwater-saltwater mixing zone starts at a depth of about 50 feet or less and becomes progressively saltier with depth.

Ground-water quality improves south of site 8a. At site 9b (fig. 11), the computed resistivity value (Ro) for the saturated clay and gravel deposit at a depth of 60 ft is 20 ohm-m (fig. 12).

With a formation resistivity factor ($F= {}^{Ro}/Rw$) of 2.00 (fig. 8), the resistivity of the water (Rw) is,

$$Rw = {}^{Ro}/F = {}^{20}/2 = 10 \text{ ohm-m}$$

which corresponds to a specific conductance of 980 umho/cm (fig. 13). The specific conductance of a water sample collected from test hole 1 (fig. 11) (screened at a depth of 60 ft), was 840 umho/cm. This value represents water having approximately 140 mg/L chloride (fig. 14).

Limestone Examples (Continued)

The electrical-resistivity surveys (fig. 11) and the concept of the formation resistivity factor, were used to map the areal extent of saline ground-water zones in the Canovana-Río Grande area (figs. 15a and b). The areas on the maps with true resistivity values of 5 ohm-m or less are probably saturated with saline water. Areas with resistivity values ranging from 5 to 20 ohm-m and at depths less of 50 ft describe clay and silt deposits with alternating layers of sand and gravel at some locations. These areas probably do not contain saline waters. At depths greater than 50 ft, where limestone is known to occur, these values of true resistivity (5-20 ohm-m) indicate saline-water zones. True resistivity values ranging between 20 to 150 ohm-m indentify areas of: 1) dry-unsaturated clay and clay-sand deposits, 2) fresh-water saturated sands, gravels and limestone and 3) weathered zones in the volcanic bedrock. Values of true resistivity above 150 ohm-m are typical of poorly permeable limestones and volcanic bedrock. Dry unsaturated sand deposits near the shoreline produced values of true resistivity as high as 1,000 ohm-m.

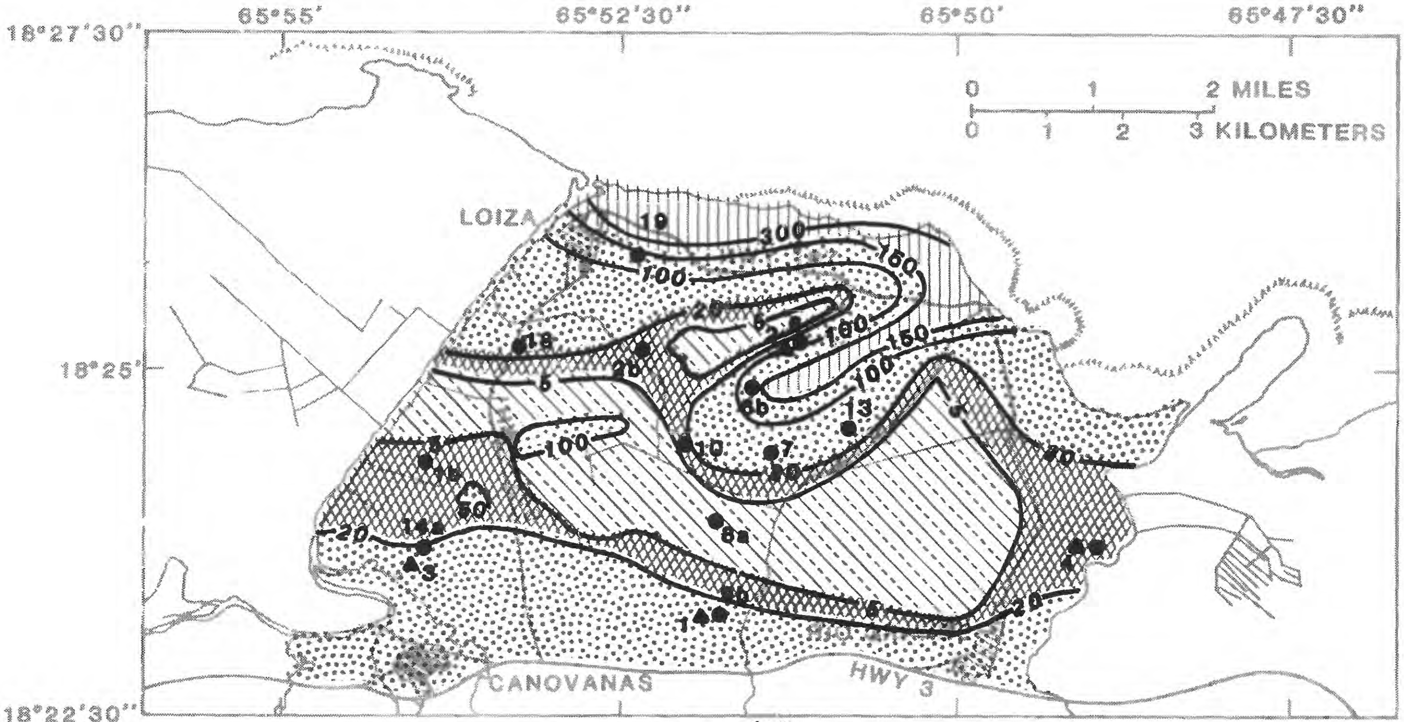
Seismic Refraction

The seismic-refraction surveys (fig. 11) were conducted to complement the electrical-resistivity surveys. Seismic-refraction profiles (figs. 16 and 17), derived from the surveys, present thickness and seismic velocities in the layers.

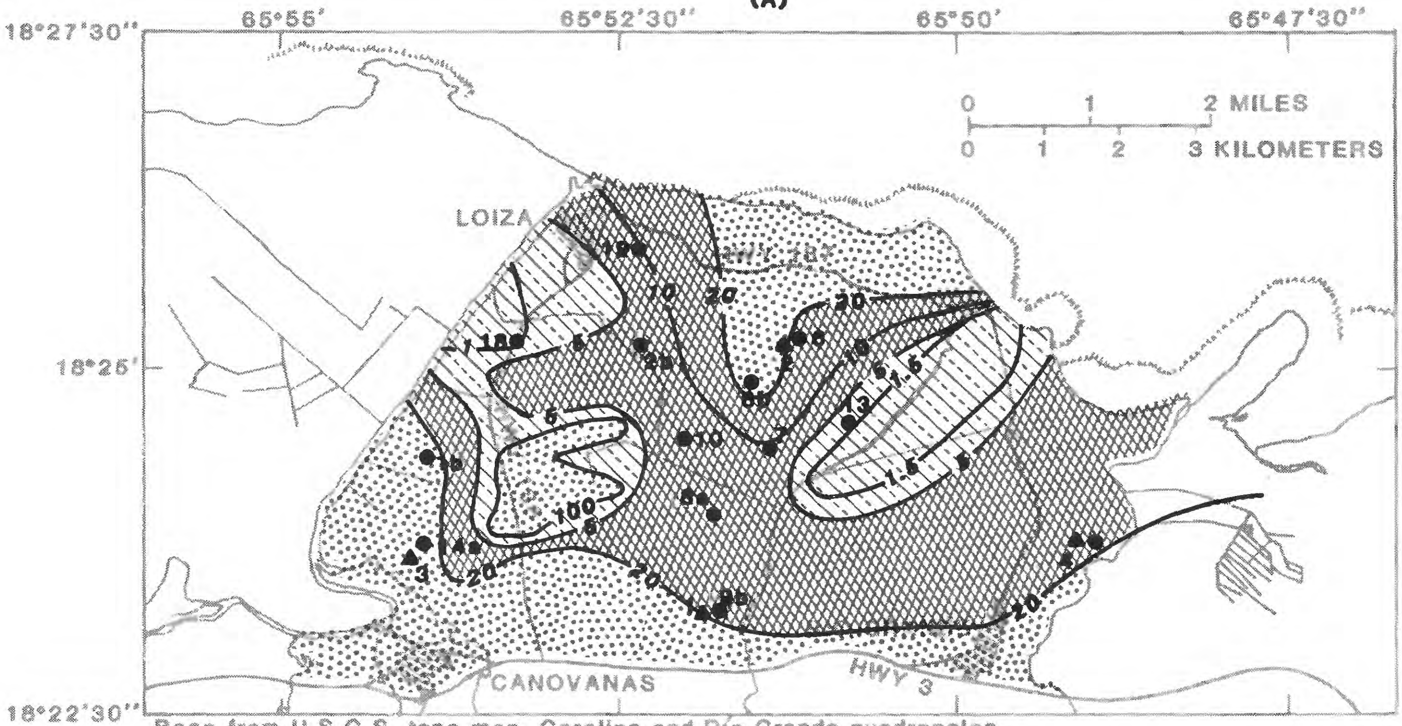
Four layers having different seismic velocities were identified in seismic line A-A' (fig. 16). The seismic velocity in the upper layer was 1,600 ft/s. This layer is approximately 10 ft thick and represents unsaturated surficial deposits. The second layer averages 50 ft thick and represents the saturated part of the surficial deposits. The seismic velocity in this layer ranges between 4,000 and 5,000 ft/s. The third layer is about 190 ft thick and has a velocity of 7,000 ft/s, a typical velocity for limestone (fig. 10). The lowest layer identified extended from approximately 250 ft below land surface and its computed velocity was 15,000 ft/s, typical of volcanic bedrock (fig. 10). The results of seismic line A-A' were compared to driller's log of test-hole 2 and resistivity survey at site 6 (fig. 12), where depth to the limestone (layer 3) was 55 ft. This value is comparable to the one obtained with the seismic results (50 ft).

Results of seismic line B-B' were very similar to seismic line A-A' (fig. 17); seismic velocities indicated that the same layers existed at seismic line B-B'. It was therefore concluded that at this site limestone is expected to occur also at a depth of about 50 ft and volcanic bedrock about 280 ft below land surface. These results were compared with the resistivity survey at site 8a (fig. 12).

Results of the surface resistivity and seismic-refraction techniques were combined to obtain hydrogeologic sections of the Canovanas-Río Grande area (fig. 18). The average freshwater-saturated thickness of the surficial deposits (alluvium, sand, clay) is about 50 ft. The limestone seems to be almost completely saturated with saline water. A small fresh water saturated limestone zone apparently exists only in the southeastern corner of the study area.



(A)



Base from U.S.G.S. topo map, Carolina and Rio Grande quadrangles.

(B)

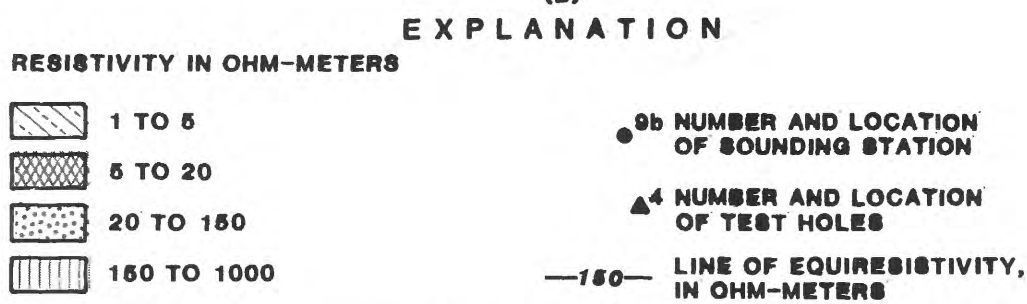


Figure 15a.--True resistivity of the area for different depths of exploration: (A) 2 feet, (B) 30 feet.

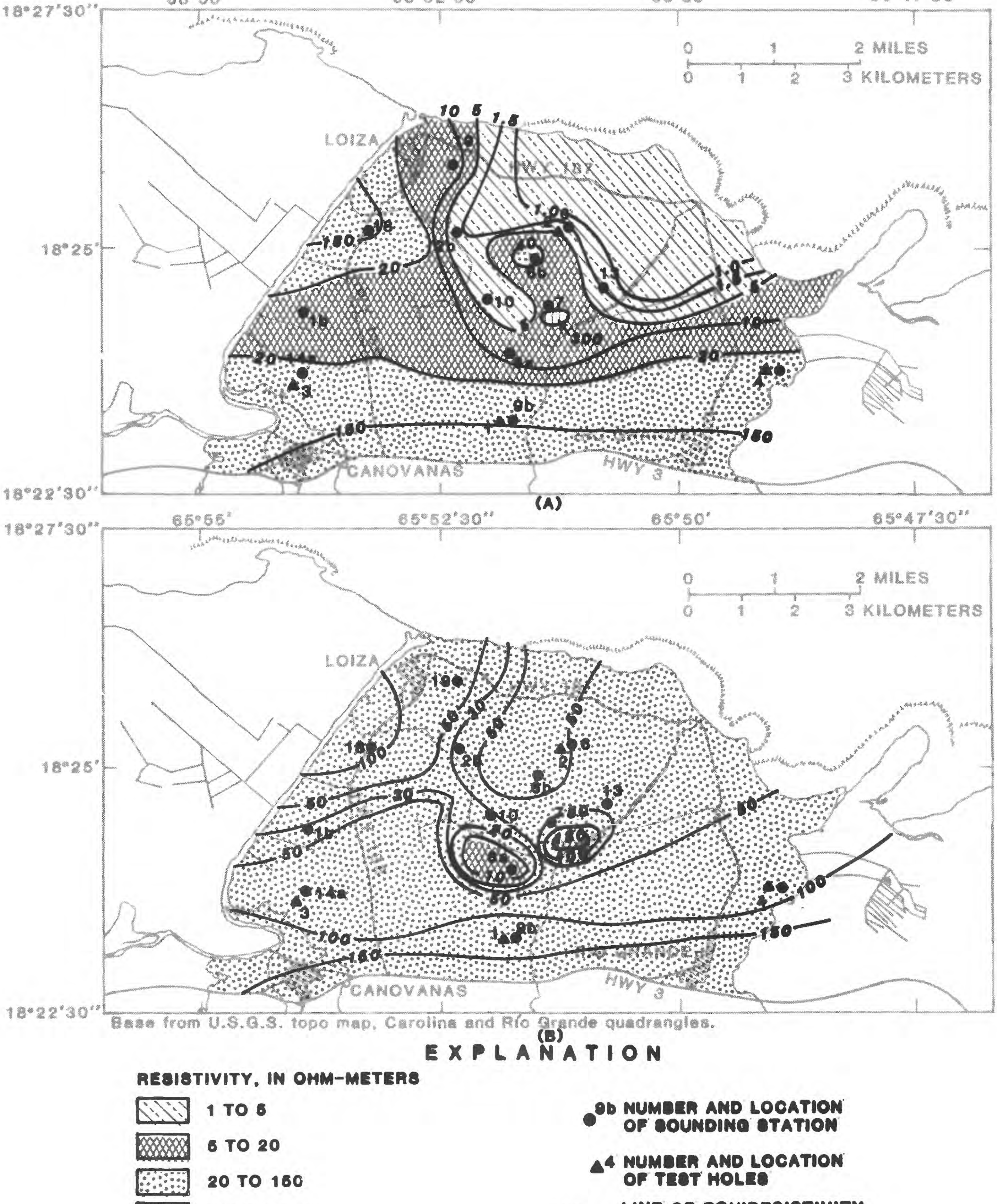


Figure 15b.--True resistivity of the area for different depths of exploration: (A) 140 feet, (B) 250 feet.

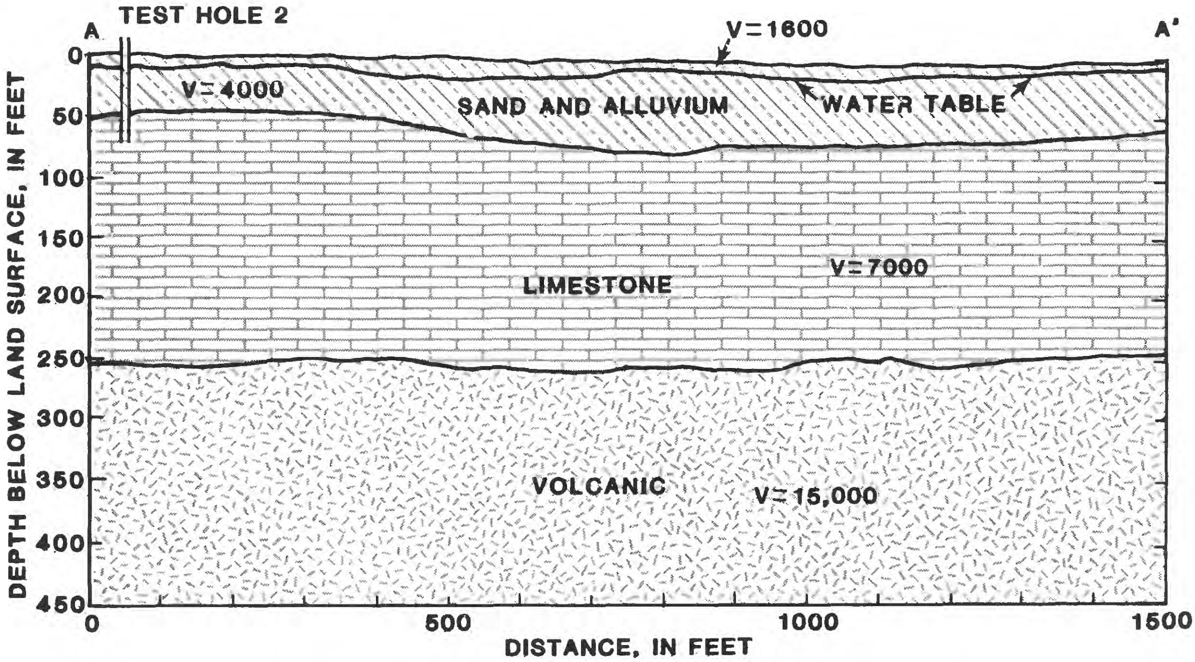


Figure 16.--Seismic refraction profile A-A'.

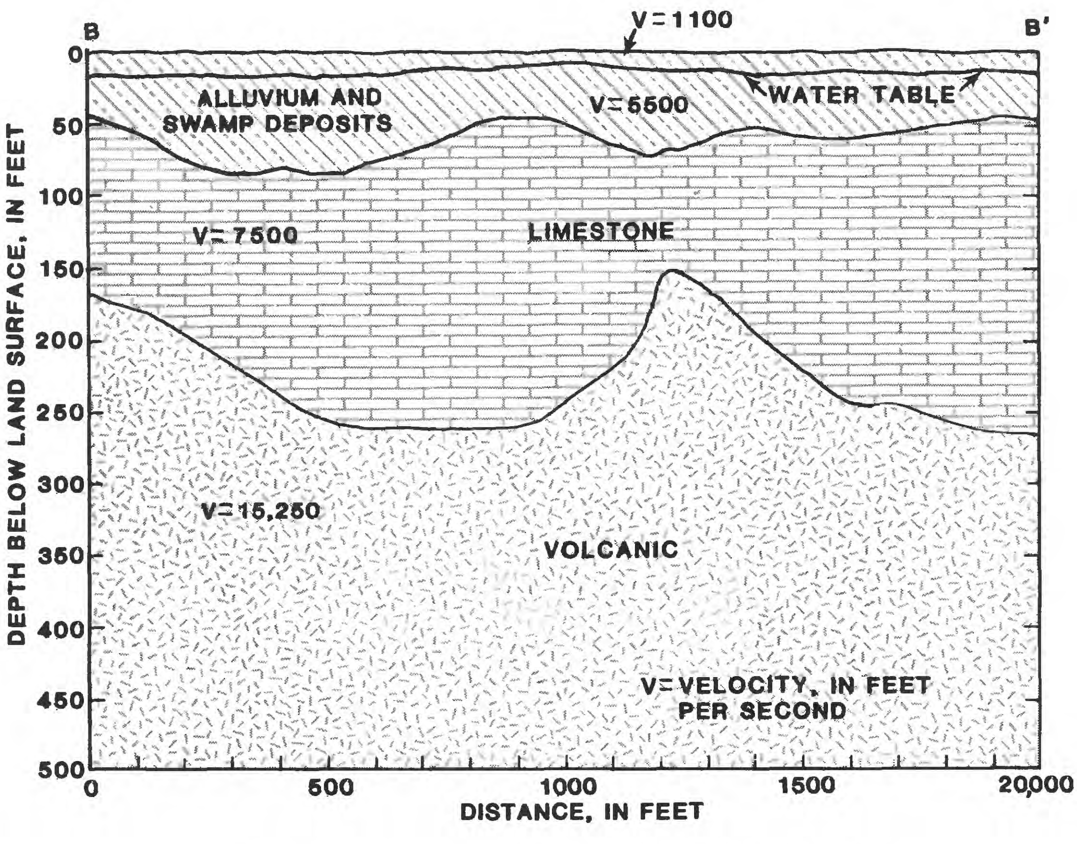


Figure 17.--Seismic refraction profile B-B'.

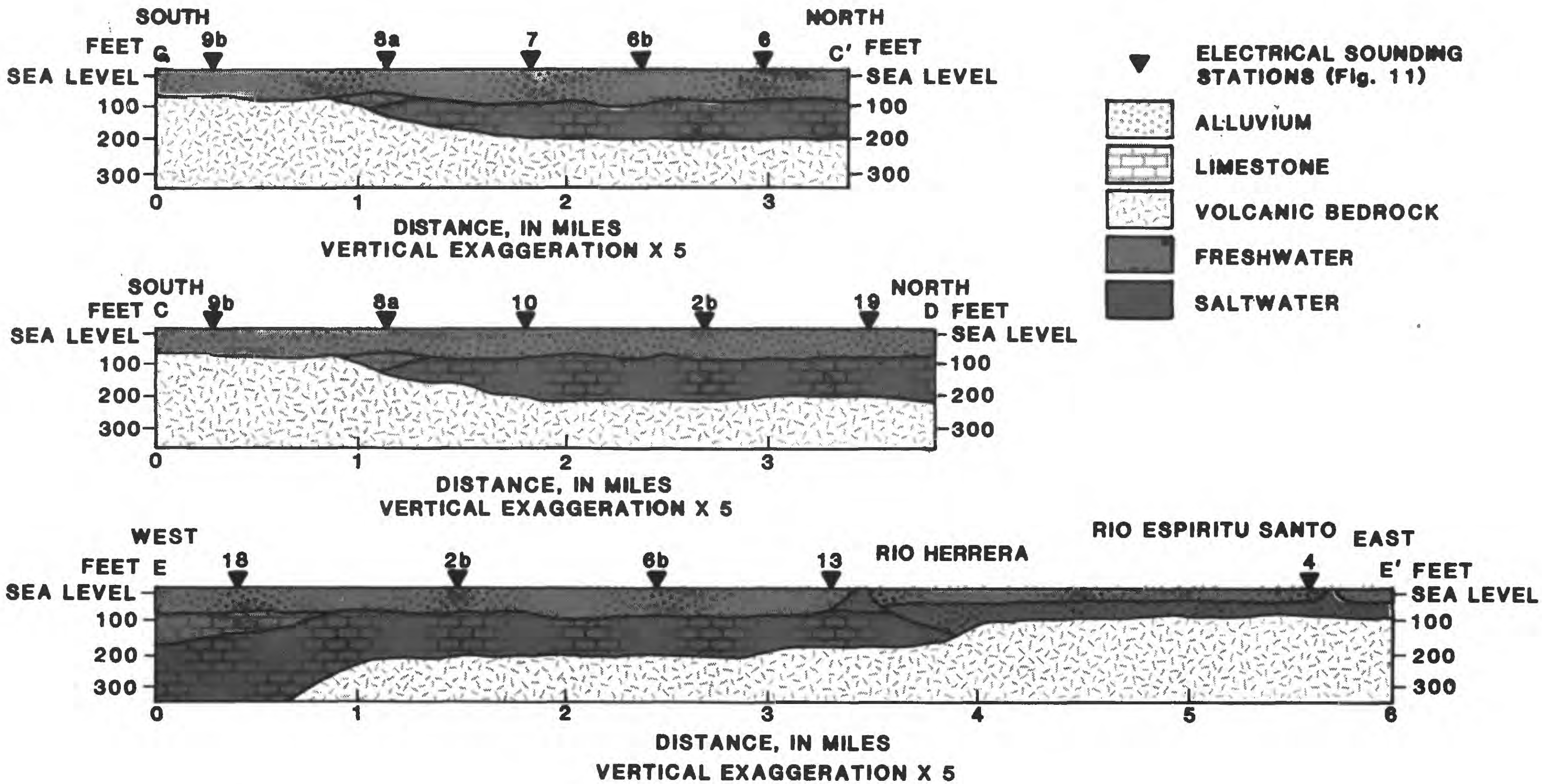


Figure 18.--Hydrogeologic sections of the Canóvanas-Río Grande area based on electrical resistivity and seismic refraction data. (See fig. 11 for location of sections.)

THE POTENTIAL FOR GROUND-WATER DEVELOPMENT

The geology and ground-water quality of the Canovanas-Río Grande area have limited the potential of the aquifer for ground-water development.

The volcanic rocks outcroping at the southern boundary of the study area are poor aquifers. These rocks will only conduct water if joints and fractures exist; in general, volcanic rocks yield less than 10 gal/min to wells (Briggs and Akers, 1965).

The unconsolidated sediments in the coastal plain (swamp, beach and alluvial deposits, fig. 3) that comprise the surficial aquifer are fine grained and yield less than 50 gal/min to wells (McGuinness, 1948). Small supplies of water with acceptable quality can be obtained from shallow wells almost anywhere in this deposit except in the swampy area. Seawater enters through existing rivers and canals and deteriorates the quality of the adjacent ground-water system when pumping wells are installed. Wells drilled close to the rivers and canals will yield saline water through induced recharge.

The Aymamón and Aguada limestones are productive aquifers, but in certain areas of the north coastal plain, like the Canovanas-Río Grande area, they usually yield saline water. In addition, sea-water intrusion is likely to occur in these limestones under pumping condition. Direct ground-water recharge to the limestones has been limited because their outcrop area is small. Fresh-water seepage from surficial material is probably the major source of recharge to the limestone. The amount of this recharge is slight, however, because the fine-grained sediments, overlying the limestone are unable to transmit large quantities of water, particularly under small hydraulic head. What fresh-water head occurs in the surficial sediments is insufficient to flush the seawater from the limestone. Sea-water intrusion is known to occur in the surficial aquifer near existing rivers and drainage canals when nearby wells are pumped.

The freshwater-saltwater mixing zone occurs at about 50 ft below land surface in the Canovanas-Río Grande area aquifer system. Its location is roughly coincident with the base of the surficial sediments. In test-hole 4, the mixing zone was encountered at a depth of about 45 ft. In test-hole 2, at a depth of about 50 ft, and in resistivity site 8a (fig. 11) it was estimated at 50 ft below land surface. Significant ground-water withdrawals would induce sea-water intrusion into fresh-water wells in a relatively short time.

An estimate of the ground-water flow seaward through the study area was made using Darcy's Law. An approximate potentiometric gradient and an average value of hydraulic conductivity for the surficial deposits and limestone were estimated from field data. A thickness of 50 ft was assumed for the fresh-water zone in the surficial aquifer. The discharge was estimated as follows:

THE POTENTIAL FOR GROUND-WATER DEVELOPMENT (Continued)

$$Q = TIL = KbIL$$

where Q = Flow, in cubic feet per day
T = Transmissivity, in feet squared per day
K = Hydraulic conductivity, in feet per day
b = Thickness of aquifer, in feet
I = Gradient of potentiometric surface (dimensionless)
L = Width of aquifer under consideration, in feet.

The study area is 6.5 mi wide; the average potentiometric gradient estimated from wells is 0.0007, and the hydraulic conductivity of the combined surficial deposits and limestone is 20 ft/d. The computed discharge is:

$$Q = KbIL = 20 \times 50 \times 0.0007 \times 34{,}320 = 24{,}024 \text{ ft}^3/\text{d} \text{ (0.18 Mgal/d)}.$$

The amount of flow through the area is not necessarily available for withdrawal. Even under optimal conditions of pumpage, probably less than 50 percent of the flow could be withdrawn without incurring upconing or lateral encroachment of saltwater.

CONCLUSIONS

Results of the surface-electrical resistivity and seismic-refraction surveys indicate that the geology and ground-water quality of the area limit the potential of the aquifer for ground-water development.

The surficial-alluvial deposits are of low hydraulic conductivity and the only productive aquifer; the limestone, is generally saturated with saline water. Sea water enters the limestone through rivers and canals in response to pumping and deteriorates the quality of the adjacent ground-water system. Wells drilled close to the river and canals will yield saline water through induced recharge. The freshwater salt-water mixing zone is located approximately 50 ft below land surface and is roughly coincident with the boundary between the surficial sediments and the limestone. Significant ground-water withdrawals are expected to induce sea-water intrusion to fresh-water wells in a relatively short period of time.

SELECTED REFERENCES

Alger, R.P., 1966, Interpretation of electric logs in fresh-water wells in unconsolidated formations: Society of Professional Well Log Analysts Trans., Seventh Annual Logging Symposium, sec. CC, p. 1-25.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir characteristics: Am. Inst. Mining Metal. Engineers Trans., v. 146, p. 54-62.

Briggs, R.P., and Akers, J.P., 1965, Hydrogeologic map of Puerto Rico and adjacent islands: U.S. Geological Survey Hydrologic Investigations Atlas HA-197.

Croft, M.G., 1971, A method of calculating permeability from electric logs: U.S. Geological Survey Prof. Paper 750-B, p B265-B269.

Dobrin, M.B., 1976, Introduction to Geophysical Prospecting McGraw-Hill Book Company, 630 p.

Giusti, E.V., 1978, Hydrogeology of the Karst of Puerto Rico: U.S. Geological Survey Professional Paper 1012, 68 p.

Heigold, P.C., Gilkeson, R.H., Cartwright, K., and Reed, P.C., 1979, Aquifer transmissivity from surficial electrical methods: Ground Water, v. 17, no. 4, July-August, 1979, p. 338-345.

HUNTEC (70) Limited, revised 1972, FS-3 Facsimile seismograph operator's manual, 25 Howden Road, Seeborough, Ontario, Canada, 96 p.

MacCary, L.M., 1980, Use of geophysical logs to estimate water-quality trends in carbonate aquifers: U.S. Geological Survey Water-Resources Investigations 80-57, 23 p.

McGuinness, C.L., 1948, Ground-water resources of Puerto Rico: Puerto Rico Aqueduct and Sewer Authority, duplicated report, p 328-335.

Monroe, W.H., 1977, Geologic Map of the Carolina Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Investigation Series Map I-1054.

Pease, M.H. Jr., and Briggs, R.P., 1972, Geologic map of the Río Grande Quadrangle, Puerto Rico: U.S. Geological Survey Miscellaneous Geologic Investigation Map I-733.

Redpath, B.B., 1973, Seismic refraction exploration for engineering site investigations: U.S. Army Engineer Waterways Experiment Station, Explosive excavation Research Laboratory, Livermore, California, Technical Report E-73-4, 51 p.

Saayman, C.M., 1978, Fundamentals of the Seismic Method-Important factors concerning its engineering applications and prerequisites for optimum utilization: Bulletin of the Association of Engineering Geologists, v. XV, no. 1, 1978.

SELECTED REFERENCES (Continued)

Sander, J.E., 1978, The blind zone in seismic ground-water exploration: v. 16, no. 6, Ground water professional paper 394-397.

Schlumberger Wells Surveying Corporation, 1958, Introduction to Schlumberger well logging, p 11-13.

Schlumberger Well Surveying Corporation, 1962, Log interpretation chart book, p. C9-C10.

Scott, J.H., Tibbetts, B.L., and Burdick, R.G., 1972, Computer analysis of seismic refraction data: Department of Interior, Bureau of Mines, RI-7595, 95 p.

Soiltest, Inc., 1968, Earth resistivity manual, 2205 Lee Street, Evanston, Illinois, 53 p.

Turcan, Jr., A.N., 1966, Calculation of water quality from electrical logs theory and practice: Water Resources Pamphlet No. 19, Department of Conservation, Louisiana Geological Survey and Lousiana Department of Public Works, 23 p.

Zohdy, A.A.R., 1973, A computer program for the automatic interpretation of Schlumberger sounding curves over horizontally stratified media: U.S. Geological Survey NTIS.PB-232-703, 11p.

Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Application of surface geophysics to ground-water investigations: U.S. Geological Survey TWRI, Book 2, Chapter D1, 116 p.