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Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

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GEOELECTRICAL GROUND-WATER SURVEY OF THE SANDY HOOK AREA, SAN SALVADOR, BAHAMAS

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ABSTRACT

An electrical resistivity sounding survey of the Sandy Hook area was conducted during a two-week period in December 1984/January 1985 in order to explore local ground-water resources. The survey utilized the Schlumberger electrode configuration with a Soiltest R-50/AKU Stratameter apparatus. 42 field stations were established.

The resulting vertical electrical sounding (VES) curves were inverted digitally using the USGS computer program by Zohdy (1974). The computed electrical resistivity layer models were interpreted in terms of ground-water saturation and salinities subject to the following constraints: According to World Health Organization standard, the maximum allowable TDS content of potable water is 1500 ppm with a corresponding resistivity of 11.2 ohm-ft (at 25°C). Seawater resistivity (35,000 ppm, 25°C) is 0.6 ohm-ft. Inferred aquifer porosities on Sandy Hook are at least 25%. Accordingly, the expected formation resistivities on Sandy Hook are on the order of 180 ohm-ft for fresh-water limestone and 10 ohm-ft for salt-water saturated limestone.

With these constraints, our resistivity data indicate a thin (mostly less than 10 ft thick), disconnected fresh ground-water lens around the northern, eastern and southern periphery of Sandy Hook. Maximum fresh-water thickness is over 15 feet beneath the northern ridge. No fresh water is evident in the interior of Sandy Hook. Another major fresh ground-water lens with maximum thickness of nearly 100 feet is indicated near Montreal Settlement. Our VES curves also indicate one or more paleosol horizons at depth.

INTRODUCTION

The population of the Bahama Islands relies heavily on ground water for its fresh-water supplies. Fresh ground water in the Bahamas occurs mostly in the form of irregular, seasonally varying fresh-water lenses which, under suitable conditions, float in isostatic equilibrium atop denser salt water in accordance with the Ghyben-Herzberg principle (Persons, 1975; Tarbox, this volume). Few such lens configurations have been mapped in detail.

On San Salvador, parts of the Columbus Landings region in the southern part of the island were investigated by Greene and Associates (1972) who delineated several thin fresh ground-water lenses utilizing chemical and/or electrical conductivity measurements in 74 test wells. Their survey was limited to low-lying regions with elevations less than 20 feet above sea level. Kunze and Burke (1984) conducted an electrical resistivity sounding survey of Sandy Point (Columbus Landings Subdivision 4) which indicated a major previously unknown fresh-water lens with maximum thickness of nearly 100 feet beneath the peripheral hills of the peninsula. Little or no fresh water was evident in the low-lying interior of Sandy Point.

The present survey was undertaken to map in greater detail the fresh ground-water resources on and near Sandy Hook (Columbus Landings Subdivision 3). At present there are several operational water wells on Sandy Hook. Water samples from two wells near Ocean House yielded near-brackish water with total dissolved solids (TDS) of 1424 ppm and 1126 ppm respectively. In the previous engineering survey by Greene and Associates (1972) fresh ground water was indicated by three test wells on Sandy Hook; however, most Sandy Hook test wells yielded no useful data. Hence, prior to our investigation, the distribution of fresh water on Sandy Hook was largely unknown.

BACKGROUND

The electrical resistivity sounding method may be used to determine the depth to the bottom of a Ghyben-Herzberg lens due to the large resistivity contrast between fresh- and salt-water saturated rock (Bugg and Lloyd, 1976). The location of the water table is then deduced from the Ghyben--Herzberg relationship

$$h = d\left(\frac{D_s}{D_f} - 1\right) \qquad (1)$$

where h is the height of the water table above sea level, d is the depth of the lens bottom below sea level, D_s and D_f are the densities of salt water and fresh water, spectively. With normal sea-water and fresh-water densities, the ratio of d to h is about 40.

The electrical resistivity ρ_R of saturated carbonate rocks is a function of rock porosity ϕ and pore-water resistivity ρ_W . According to the basic Archie relationship:

$$\rho_R = \rho_w / \phi^2 \qquad (2)$$

The pore-water resistivity ρ_W, in turn, depends on water temperature and salinity. The mean annual temperature of San Salvador is approximately 25°C. According to World Health Organization standards, the TDS content of potable water may not exceed 1500 ppm. Hence, according to Nomogram G-9 (Schlumberger, 1984), the minimum resistivity of potable water (1500 ppm TDS) at 25°C is 11.2 ohm-ft. The corresponding resistivity of sea water (35,000 ppm TDS) is 0.60 ohm-ft.

Helium porosity tests on rock samples from different localities of San Salvador indicated porosities ranging from 8% to 36% with an RMS value of 23.5%. These indurated surface rocks, however, may not be representative of the largely unconsolidated, Holocene materials of Sandy Hook (Titus, 1984), whose porosities are probably substantially higher. Table 1 shows theoretical rock resistivities calculated from equation 2 for aquifers of different porosities. Note that the resistivities of salt-water and fresh-water aquifers differ by a factor of about 18, and that there is no overlap between

TABLE 1. ROCK RESISTIVITIES AT 25 °C

Porosity (%)	Fresh-water aquifer (ohm-ft)	Salt-water aquifer (ohm-ft)
10	1120	60
15	500	27
20	280	15
25	180	10
30	120	7
35	90	5
40	70	4

Fresh-water values are minimum values.

resistivities of salt-water and fresh-water aquifers for the expected range of porosities.

In this study, in view of the largely unconsolidated nature of Sandy Hook, resistivity values corresponding to 25% porosity were chosen to differentiate between fresh-water (180 ohm-ft) and salt-water aquifers (10 ohm-ft).

PROCEDURES

This study utilized the Schlumberger electrode configuration with Soiltest R-50/AKU Stratameter resistivity meters. Vertical electrical sounding (VES) curves were constructed based on current electrode half spacings (L) ranging from 3 to 300 feet with six points per decade. VES curves were inverted with the USGS computer program by Zohdy (1974).

The field work was conucted during a two week period in December 1984/January 1985. Thirty-nine field stations were established at convenient sites the along road-sides throughout Columbus Landings Subdivision 3. Three additional stations were established near Montreal Settlement. Station locations are shown in Figure 1. Station elevations were estimated based on the 1972 Bahamas Government topographic map of San Salvador. Maximum station elevation error is estimated to be 5 feet.

RESULTS AND INTERPRETATION

Inversion of the 42 VES curves shown in

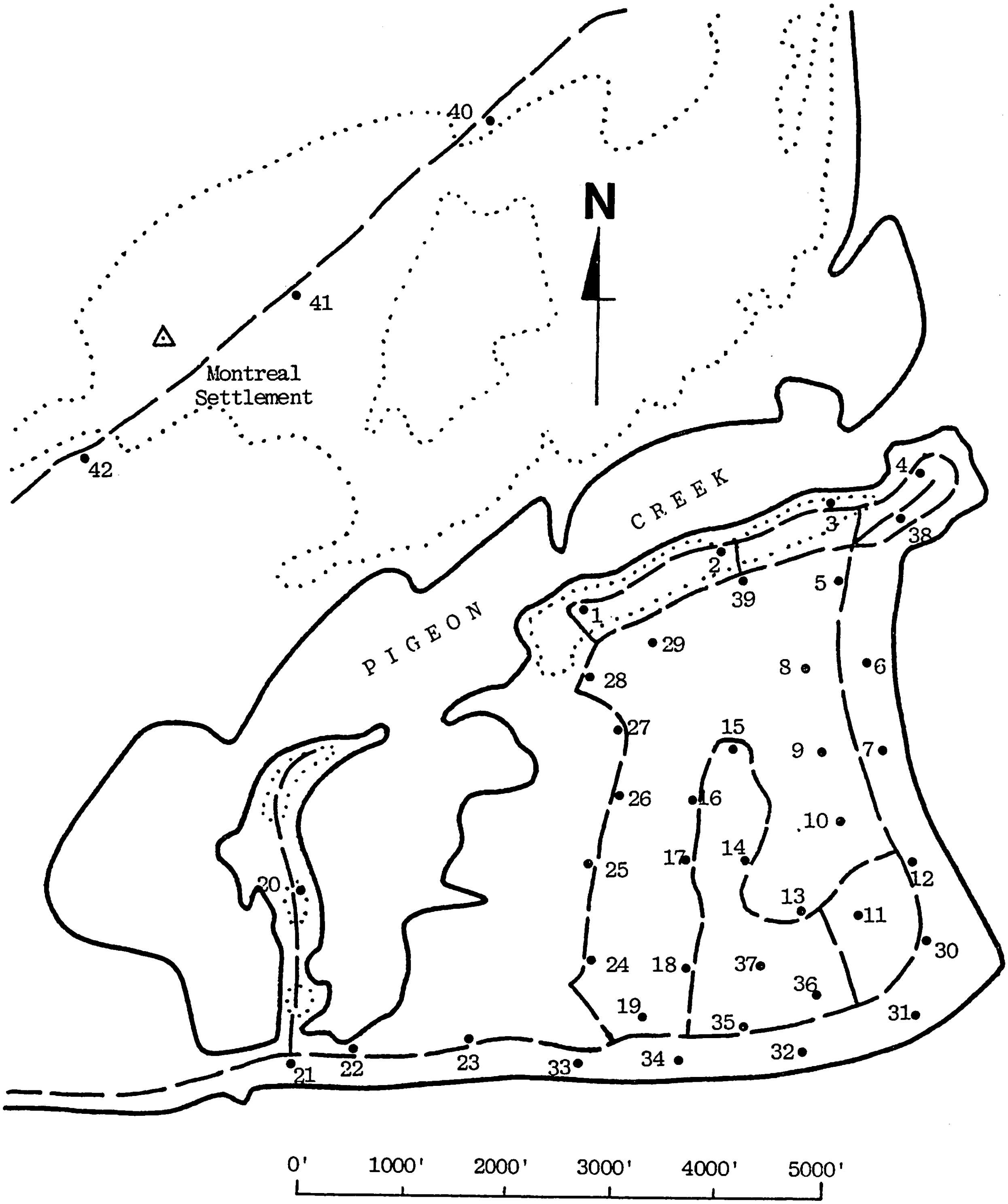

Fig. 1. Sandy Hook region with station locations (large dots). Dashed lines indicate major roads., dotted lines represent the 20 ft contour. Hill crest (108 ft) shown by triangle.

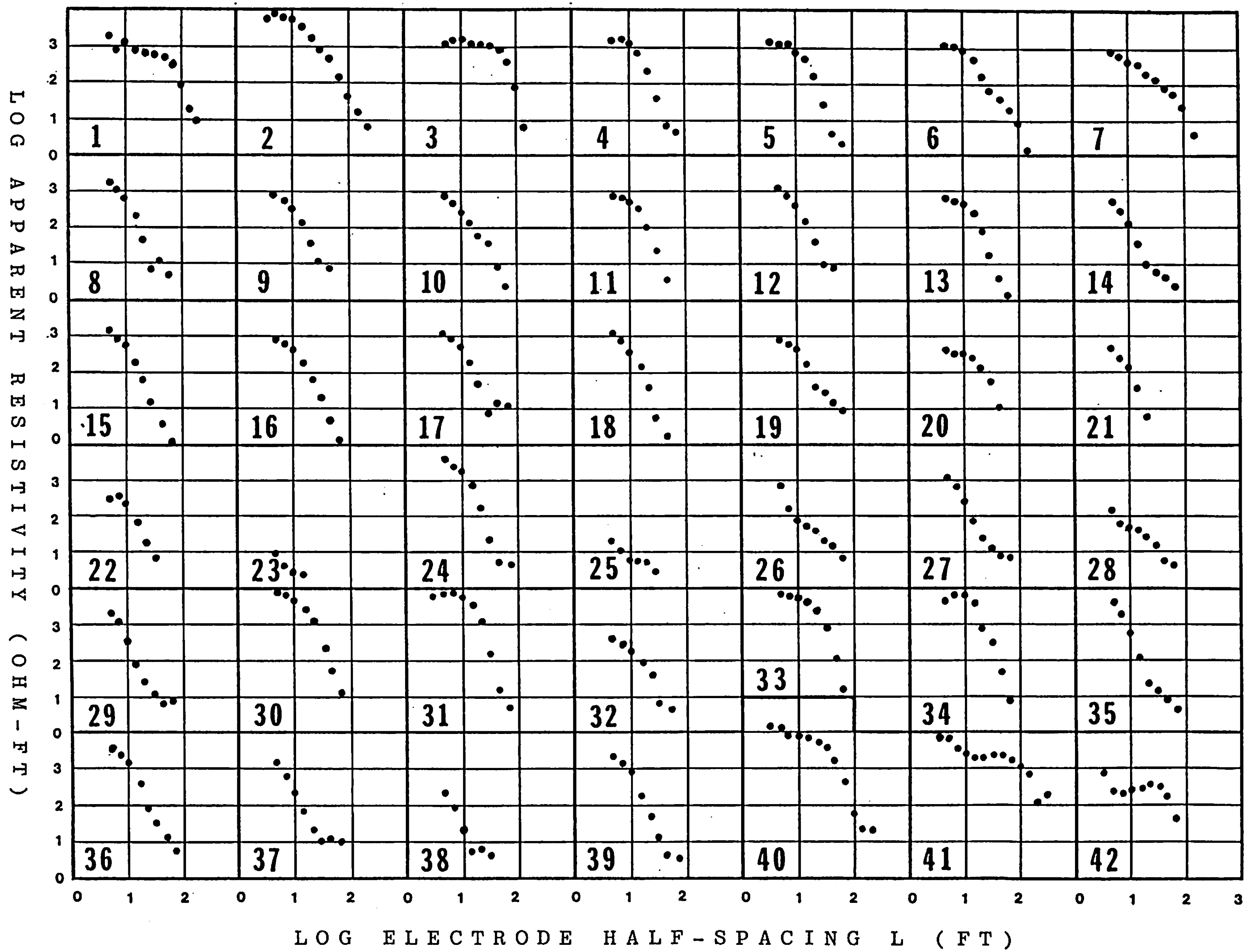

Fig. 2. VES curves for stations 1 through 42.

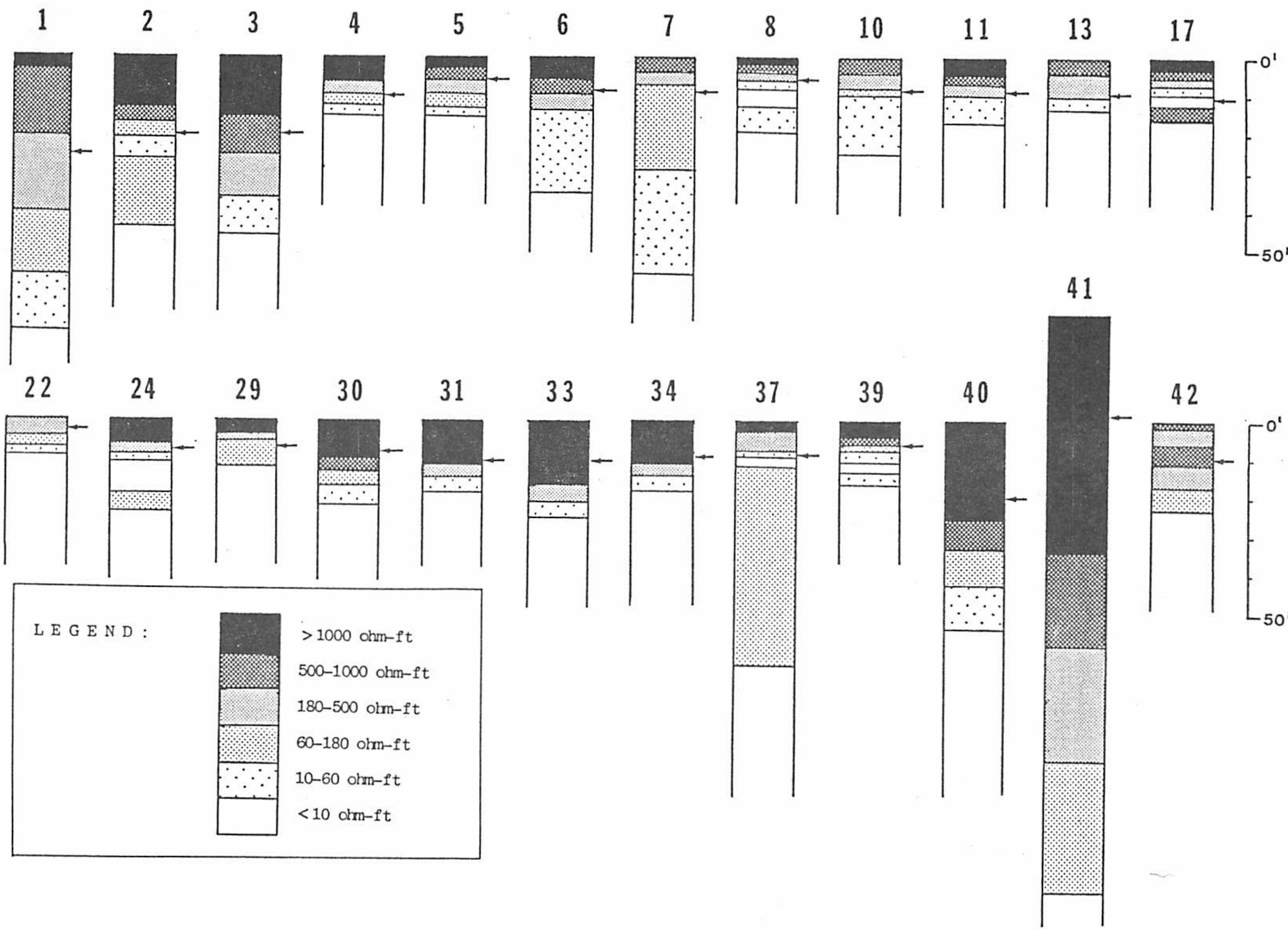

Fig. 3. Computer generated resistivity layer models for selected stations. Arrows indicate sea level.

Figure 2 yielded resistivity layer models for all stations. Figure 3 depicts those 24 layer models which indicate fresh or brackish ground water below sea level (aquifer resistivities greater than 180 or 60 ohm-ft, respectively). The corresponding fresh-water Ghyben-Herzberg lens parameters are listed in Table 2. The lens bottom represents the depth above which rock resistivities are greater than 180 ohm-ft. The resulting fresh-water lens configuration and thickness on Sandy Hook is shown in Figure 4. In view of the uncertainties in station elevations, fresh ground water thicknesses are probably uncertain by at least 5 feet. Nevertheless, it appears that Sandy Hook has a thin, disconnected fresh-water lens extending around the northern, eastern and southern periphery of the peninsula with maximum thicknesses on the order of 15 feet underneath the northern ridge. The northern part of the fresh water lens may be disrupted by tidal pumping through cave systems in the vicinity of stations 2 and 39. The patchy eastern and southern portions of the fresh-water lens are generally less than 10 feet thick and are located near or beneath the highest, youngest beach ridges of Sandy Hook.

TABLE 2. GHYBEN-HERZBERG LENS PARAMETERS

Station	Elevation	Lens Bottom (below surface)	Lens Bottom (below S.L.)	Lens Thickness (rounded)
1	25	40.4	15.4	16
2	20	17.3	0	
3	20	36.4	16.4	17
4	10	10.0	0	
5	6	10.0	4.0	4
6	8	14.1	6.1	6
7	8	7.3	0	
8	6	6.5	0.5	1
9	8	5.4	0	
10	8	6.9	0	
11	8	9.6	1.6	2
12	10	4.8	0	
13	10	10.2	0.2	0
14	13	4.8	0	
15	11	6.1	0	
16	10	6.9	0	
17	11	6.8	0	
18	10	6.8	0	
19	11	6.2	0	
20	20	9.3	0	
21	10	4.6	0	
22	2	4.7	2.7	3
23	6	0	0	
24	8	8.8	0.8	1
25	8	0	0	
26	12	2.4	0	
27	8	5.7	0	
28	8	0	0	
29	7	4.6	0	
30	8	12.8	4.8	5
31	10	13.7	3.7	4
32	8	6.8	0	
33	10	20.6	10.6	11
34	10	13.9	3.9	4
35	8	4.7	0	
36	8	6.2	0	
37	8	7.6	0	
38	12	2.8	0	
39	7	6.7	0	
40	19	32.6	13.6	14
41	25	114.6	90.6	93
42	10	17.3	7.3	7

Note: All values in feet

These general findings are largely supported by the spotty results of the engineering survey by Greene and Associates (1972). The one major discrepancy is their discovery (in May, 1972) of fresh water in the interior of Sandy Hook near our station 15. Perhaps transient fresh-water lenses form in the interior during the May-October rainy season. Another problem is presented by the two operational water wells containing potable water (with salinities of 1126 and 1424 ppm) immediately next to station 39 where resistivity readings do not indicate fresh water. One explanation may be the distortion of the current flow-line pattern by the adjacent northern ridge which leads to reduced current densities near the potential electrodes and, in turn, to lower calculated apparent resistivities. A similar reduction in current density at station 39 may be caused by the additional current deflection into the highly conductive, salt-water saturated interior of Sandy Hook.

In addition, there are some indications that the sub-surface porosity on Sandy Hook is significantly higher than 25%. According to the land resource study by Little and others (1977), Unit 4, the major aquifer in the Bahamas which may also underlie Sandy Hook, has a porosity of 40-50%. In our study, minimum layer resistivities encountered at depth were commonly on the order of 3 ohm-ft or less. Such low values could be the result of either hypersaline pore water or of high porosities. Specifically, according to equation 2, a rock resistivity value of 3 ohm-ft requires a porosity of 45% if the pore fluid is sea water of 35,000 ppm salinity (at 25°C). If the pore fluid is fresh water, such a highly porous rock should have a bulk resistivity of 54 ohm-ft. In that case, station 39 results indicate 1-2 feet of fresh water, and the isopach values of Figure 4 should be increased by some five feet and

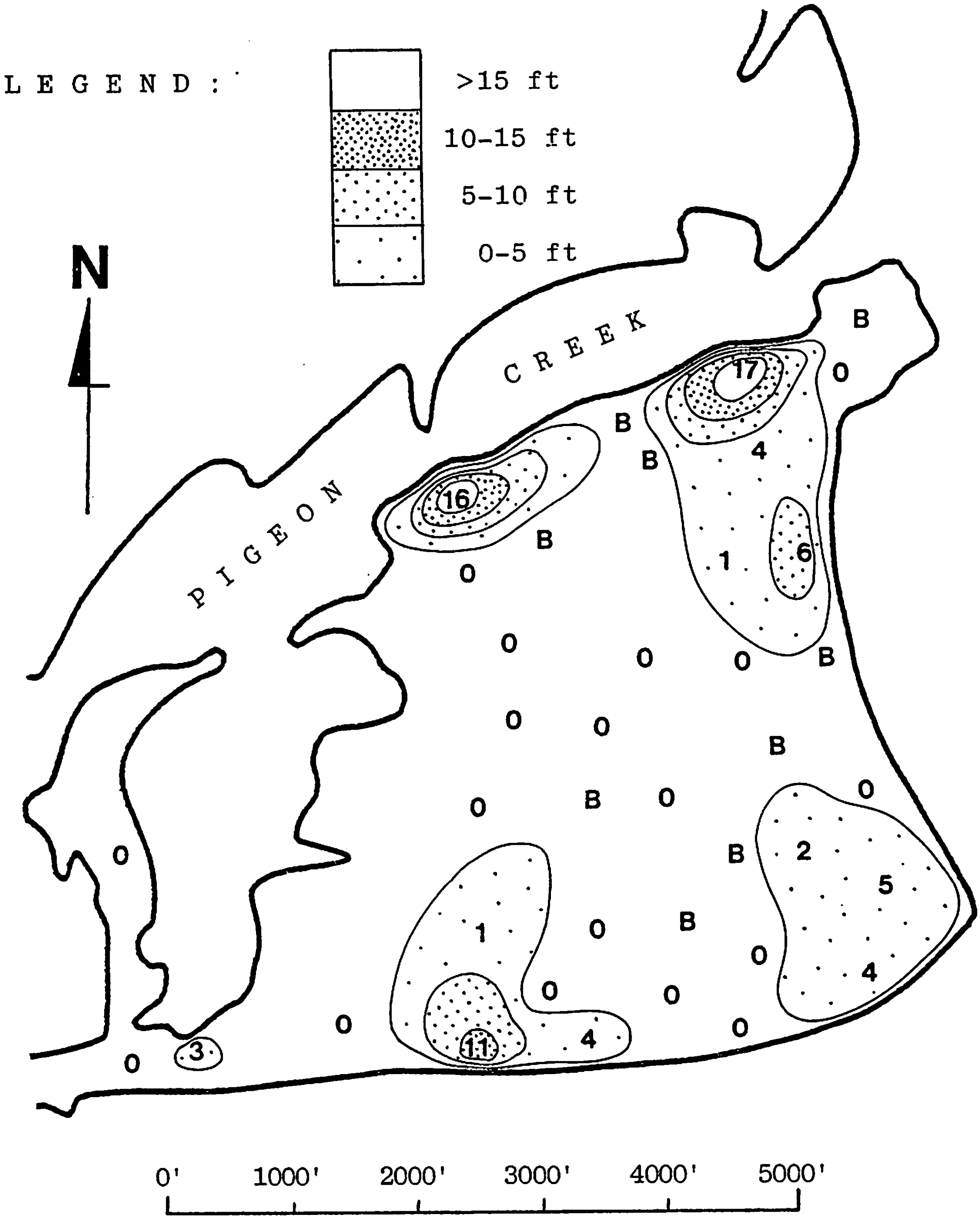

Fig. 4. Fresh-water lens isopach map. Station values in feet. B denotes stations with brackish ground-water lens.

TABLE 3. HIGH-RESISTIVITY LAYERS AT DEPTH

Station	Layer depth range below S.L. (ft.)
2	7-24
6	15-27
8	8-13
9	4-12
17	1-5
19	2-10
24	12-16
25	3-9
27	1-13
29	1-6
37	4-56
39	7-10

contours extended to include stations marked B.

The resistivity measurements along the east coast road near Montreal Settlement (stations 40, 41, and 42) indicate a major fresh-water lens with maximum thickness of at least 93 feet (station 41). This surprising result is supported by the occurrence in a dug well near station 41 of excellent fresh water with a TDS content of 389 ppm (55 ppm chlorinity).

Many stations on Sandy Hook show evidence of high-resistivity layers at depth beneath layers of lower resistivities. These stations and the corresponding high-resistivity layer depths (below sea level) are listed in Table 3. Most of these depths are clustered around 10 feet below sea level. In view of the fact that a prominent paleosol is present at that depth throughout much of the Bahamas (Little and others, 1977), it appears that at least some of the high-resistivity layers at depth represent low-porosity paleosols. Other prominent paleosols occur at depths of 25 and 40 feet; these may be indicated at stations 6 and 37. Similar possible paleosols were apparent in the resistivity models of Sandy Point by Kunze and Burke (1984).

CONCLUSIONS

A perennial fresh ground-water lens exists around the northern, eastern and southern periphery of Sandy Hook. This lens is mostly less than 10 feet thick and is probably discontinuous. Its extent may vary with the seasons. The interior of Sandy Hook contains no permanent fresh ground water. Maximum lens thicknesses (10-20 feet) occur near or beneath the highest topography. A major fresh-water lens with maximum thickness on the order of 100 feet is present in the Montreal Settlement area near a high (103 feet) eolianite ridge. A previous resistivity survey by Kunze and Burke (1974) also found a strong correlation between fresh ground-water thickness and topographic elevation on Sandy Point. A possible reason for this situation is the inhibition of evapotranspiration of ground water due to the greater depth to the water table in elevated terrain. It, therefore, appears likely that on San Salvador, and possibly throughout the Bahamas, major fresh ground-water lenses develop beneath all prominent ridges except where disrupted by tidal pumping through cave systems.

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