PROCEEDINGS
OF THE FOURTH SYMPOSIUM
ON THE GEOLOGY OF THE BAHAMAS

Editor

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Sponsored by the Bahamian Field Station

June 17 - 22, 1988

ISBN 0-935909-31-1

Printed by Don Heuer in the U.S.A.

GEOELECTRICAL SURVEY OF THE COLUMBUS LANDINGS I REGION OF SAN SALVADOR BAHAMAS

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ABSTRACT

An electrical resistivity sounding survey of Columbus Landings I (CL1) and the adjacent northern section of Columbus Landings IV (CL4), San Salvador, Bahamas, was conducted during a ten-day period in December 1987/January 1988, in order to assess the distribution of fresh groundwater of the region. An earlier groundwater hydrology investigation by Greene and Associates (1972) indicated a substantive fresh water lens in the western interior of the region, but little or no fresh water beneath the peripheral hills. Our survey utilized a Soiltest R-50/AKU Stratameter apparatus and employed the Schlumberger electrode configuration. Thirty-two field stations were established, and the resulting VES curves were inverted digitally with the USGS computer program by Zohdy (1974). The computed electrical resistivity layer models were interpreted in terms of aquifer porosities and groundwater salinities. According to World Health Organization Standards, the maximum allowable TDS content of potable water is 1500 ppm. Assuming aquifer porosity of 25%, subsurface temperatures of 25°C, and the formation resistivity factor according to the basic Archie formula, our results also indicate a major fresh water lens in the western interior of the study area, with maximum thickness possibly in excess of 100 feet. In addition, substantial fresh groundwater reserves appear to exist underneath the peripheral hills. Little or no fresh water is evident in the eastern low-lying portion of CL1.

Petrophysical laboratory analysis of twelve bedrock samples from the study area indicate very high near-surface aquifer porosities averaging approximately 30%, and a formation factor significantly different from the Archie formula. Interpretation of subsurface resistivities in terms of this formation factor substantially reduces inferred freshwater thickness at several stations.

In general, it is expected that porosities decrease with depth. We, therefore, surmise that high formation resistivities at depths in excess of 100 feet are the result not of fresh pore water, but of low formation porosities.

INTRODUCTION

This investigation is a continuation of earlier electrical resistivity work in the Columbus Landings region of San Salvador, Bahamas, by Kunze and Burke (1984) and Kunze and Weir (1987), in order to further define the distribution of fresh groundwater of that region. The investigation of the Sandy Point area by Kunze and Burke (1984) revealed a probable major freshwater lens with maximum thickness of approximately 100 feet beneath the southern hills of Sandy Point with two lesser fresh groundwater lobes extending toward the north-east and east beneath the peripheral hills of the Sandy Point peninsula. Little or no fresh groundwater was indicated in the low interior of Sandy Point. A similar peripheral distribution of fresh groundwater was indicated by electrical resistivity measurements on Sandy Hook (Kunze and Weir, 1987), although maximum peripheral fresh groundwater thicknesses there are mostly less than ten feet.

An earlier groundwater survey of the Columbus Landings region by Greene and Associates (1972), utilizing chemical water analysis and electrical conductivity measurements in test wells, revealed a substantial freshwater lens in the low interior of the northern portion of the CL4 area immediately to the north-east of the study area of Kunze and Burke (1984), and extending into CL1, with almost no fresh water beneath the peripheral coastal regions. This situation is nearly opposite to that inferred by Kunze and Burke (1984) and Kunze and Weir (1987), although the failure of Greene and Associates to locate fresh water beneath the peripheral hills may have been largely due to the fact that their test wells could not be drilled in areas with surface elevations greater than 20 feet due to equipment limitations. Thus, the present resistivity survey was undertaken to verify and clarify the distribution of fresh groundwater in the regions to the north and northeast of Sandy Point, specifically in Columbus Landings I and the northern part of Columbus Landings IV.

PROCEDURES

This study was conducted during a ten-day period in December 1987/January 1988 and utilized the Schlumberger electrode configuration with a Soiltest R-50/AKU Stratameter apparatus capable of 500 ft maximum penetration. Vertical electrical sounding (VES) curves were constructed based on current electrode half-spacings (L) ranging from 1.5 ft to 460 ft with six points per decade. Thirty-two field stations, 1000-1500 ft apart, were established along road sides throughout the 1.5 square mile study area. Station locations are shown in Fig. 1. The VES field curves were corrected for apparent resistivity off-sets caused by increases in the potential electrode spacing as described by Kunetz (1966). The corrected VES curves (Fig. 2) were inverted digitally using the USGS computer program by Zohdy (1974). Some model parameters, such as expected half-space resistivities, were specified a priori. The resulting computed resistivity layer models (Fig. 3) were interpreted in terms of groundwater salinities and aquifer porosities based on the following considerations:

Ghyben-Herzberg Lens

Fresh groundwater in the Bahamas occurs largely in the form of irregular, seasonally varying freshwater lenses which tend to float in isostatic equilibrium atop denser saltwater in accordance with the Ghyben-Herzberg principle (Little and others, 1977; Weech, 1982; Tarbox, 1987), such that the ratio of water table elevation to lens thickness is approximately 1:40. The freshwater/saltwater interface at the bottom of the lens can, in principle, be detected by the VES

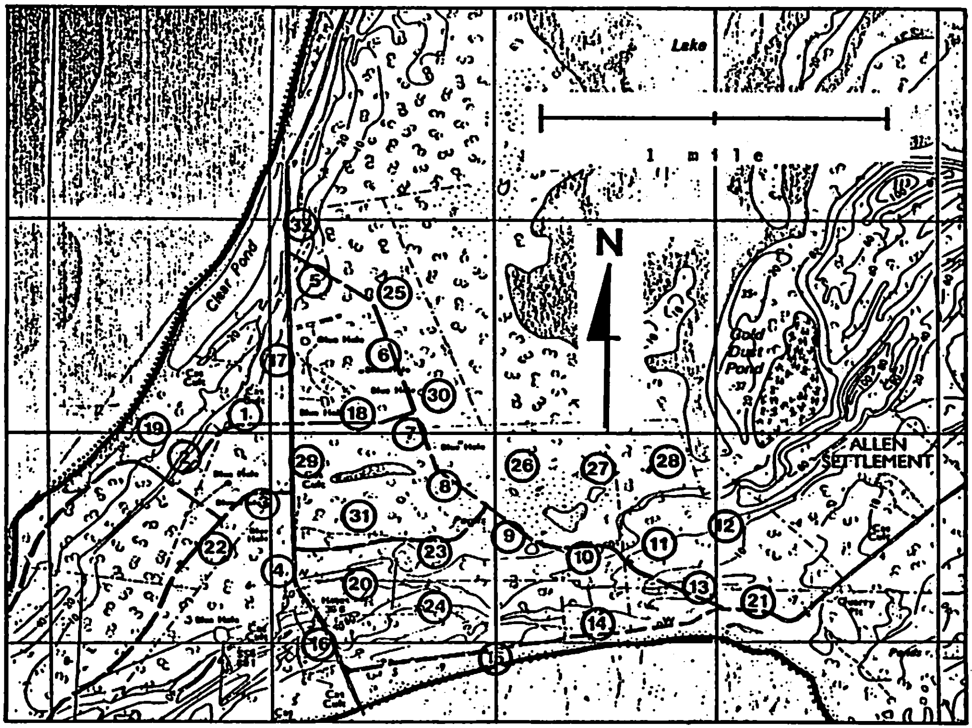

Fig. 1. Station location map. Major roads are shown as dashed lines. Contours in feet.

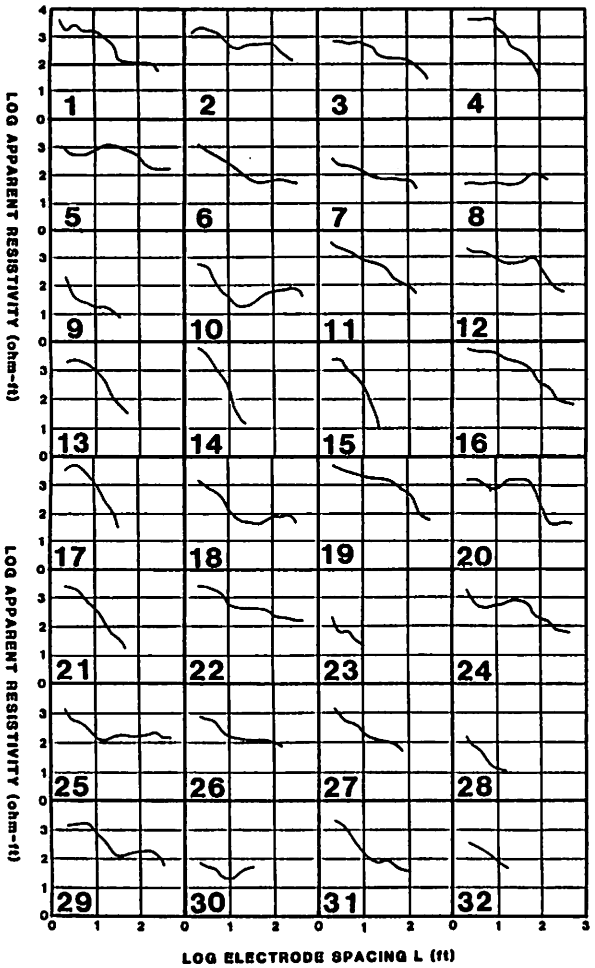

Fig. 2. Corrected VES curves for stations 1 through 32.

method due to the pronounced electrical resistivity contrast between saltwater and freshwater. Knowledge of the depth to that interface permits calculation of the total thickness of the Ghyben-Herzberg lens.

Formation Factor

Formation resistivity (R_O) of saturated rocks is proportional to pore water resistivity (R_W) with the proportionality constant defined as the formation resistivity factor (F):

$$R_O = FR_W \tag{1}$$

F, in turn, is a function of rock porosity (Φ):

$$F = \frac{a}{\Phi^m} \tag{2}$$

where "a" and "m" are characteristic constants. For well-cemented carbonates, F is given by the so-called basic Archie formula:

$$F = \frac{1}{\Phi^2} \tag{3}$$

This relationship should be valid for the deeper aquifers of San Salvador (e.g. marine units 1, 2, and 3 of Little and others, 1977).

A previous petrophysical investigation of the electrical behavior of surface rock samples from San Salvador by Weir and Kunze (1988) yielded a different functional relationship:

$$F = \frac{0.57}{\Phi^{2.4}} \tag{4}$$

The Archie relationship, however, gives comparable results for F in the porosity range of 20%-32%. Hence, the basic Archie formula may also be applicable to porous, near-surface aquifers on San Salvador (e.g. marine unit 4 of Little and others, 1977).

A similar petrophysical analysis of twelve bedrock samples from the present study area (CL1) is described in the appendix. The resulting formation factor is

$$F = \frac{1.07}{\Phi^{2.3}} \tag{5}$$

This equation yields F-values significantly larger than those obtained with the Archie or other commonly used formulas. Therefore, our initial formation resistivity evaluation utilized equation 3, with a subsequent check using equation 5.

Porosity

Helium porosity tests of representative San Salvador lime-stones by Weir and Kunze (1988) showed porosities ranging from 8.2% to 36.1% with an RMS porosity value of 23.5%.

Table 1 shows the results of additional Helium porosity tests performed on twelve bedrock samples from the current study area (CL 1). These porosities range from 8.9% to 39.0% with an RMS value of 30.3%. Little and others (1977) estimate porosities of the shallowest Bahamian aquifers (marine unit 4) to attain values of 40%-50%. Deeper units have reduced porosities due to conversion of aragonite to calcite with its concomitant specific volume increase of 8%, and the introduction of additional cements. For example,

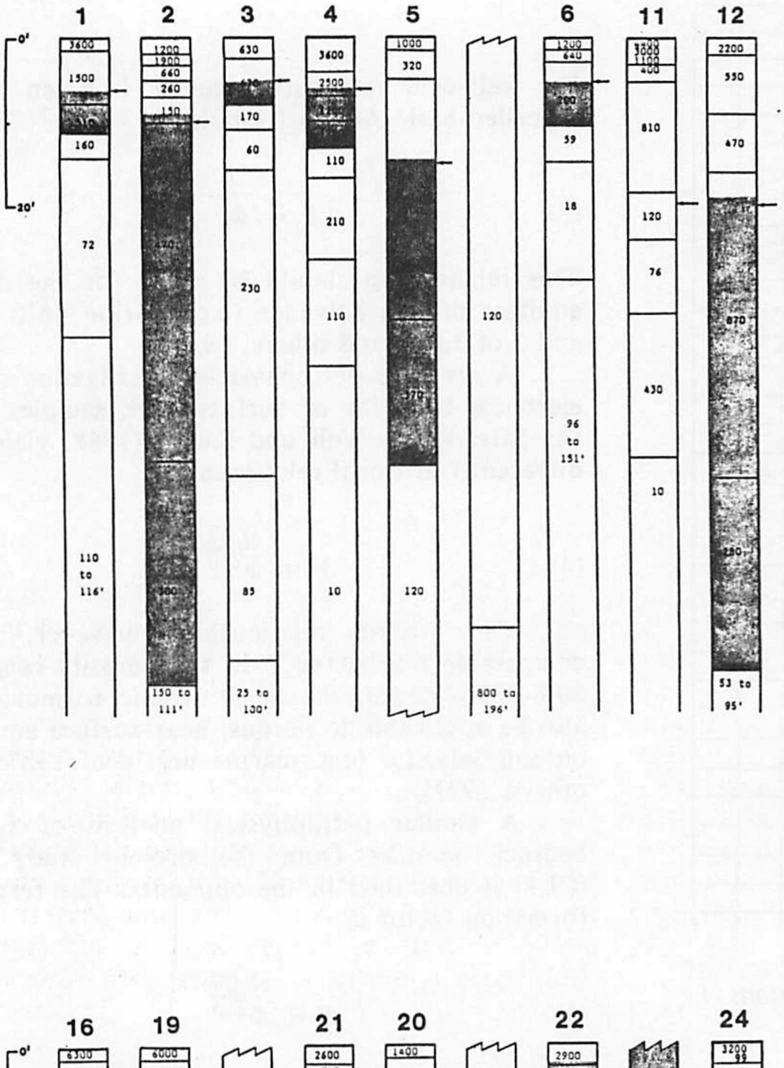

Fig. 3. Computer generated resistivity layer models for selected stations. Sealevel is shown by arrows. Shaded regions indicate possible fresh ground-water. Discussion in text.

Table 1. Rock Sample Data

Site #	Nearest Station	Type	Porosity
1	5	Bioclastic LS	34.5/28.5%
2	10	"	32.5/35.8%
3	25	"	32.6/27.4%
4	30	"	30.5/26.7%
5	16	Eolianite	38.8/39.0%
6	32	Bioclastic LS	11.8/8.9%

the aragonite conversion effect could reduce a 30% porosity by as much as 5.6%. Tightly cemented thin micritic layers or paleosols may have porosities on the order of 5% (Persons, 1975) or less. Nevertheless, most Bahamian subsurface formations appear to be very porous or cavernous to a depth of at least hundreds of feet (e.g. Spencer, 1967), and it is reasonable to assume that the bulk porosity of most Bahamian aquifers is on the order of 25% or more. This porosity value was chosen for initial resistivity model evaluation.

Groundwater Salinity and Resistivity

According to World Health Organization (1963) standards, the maximum allowable total dissolved solids (TDS) content of drinking water is 1500 ppm (Bouwer, 1978), with corresponding resistivity of 11.2 ohm-ft (at 25°C). The resistivity of seawater (35,000 ppm TDS) at 25°C is 0.6 ohm-ft. Consequently, according to the Archie formula and assuming formation porosities averaging 25%, the formation resistivity of freshwater aquifers should be at least 180 ohm-ft, and that of seawater saturated aquifers on the order of 10 ohm-ft. Equation 5 predicts 290 ohm-ft and 16 ohm-ft for freshwater and seawater aquifers, respectively. Whatever the formation factor or the formation porosity, the bottom of a GhybenHerzberg freshwater lens should be marked by an 18-fold or greater resistivity contrast.

RESULTS AND INTERPRETATION

Freshwater Resources

Fig. 3 shows fourteen selected resistivity layer models computed with the USGS inversion program by Zohdy (1974). Not shown are models with resistivities too low to be compatible with a fresh groundwater lens (stations 7, 8, 9, 10, 13, 14, 15, 17, 18, 23, 25-32). In Fig. 3, sealevel is indicated by arrows, and potential freshwater bearing layers are shaded. In general, the shaded regions represent minimum resistivities of 180 ohm-ft extending downward from the inferred water table. At station 22, this column includes a narrow layer of resistivity of 160 ohm-ft. This layer, if real, might represent a high-porosity freshwater layer. In accordance with equations 1 and 3:

$$(6) \qquad R_0 = R_w/\Phi^2$$

and the porosity Φ corresponding to some formation resistivity R_0 is given by:

$$(7) \qquad \Phi = (R_w/R_0)^{0.5}$$

Thus, if R_0 and R_w are 160 ohm-ft and 11.2 ohm-ft respectively, Φ is 26.5%, a quite typical value. If equation 5 is used, then

$$(8) \qquad \Phi = (1.07\ R_w/R_0)^{0.435}$$

and Φ is approximately 32.5%. This value is high, but not unreasonable for near-surface layers. Accordingly, we interpret this layer to be part of a freshwater lens. A similar situation exists at station 21, where a 120 ohm-ft layer overlies a potential freshwater bearing layer. The necessary porosity, in this case, is 30.5% (equation 7) or 37% (equation 8). These values are unusually high, hence the Ghyben-Herzberg lens indicated is probably brackish (with lower porosities).

Table 2. Ghyben/Herzberg Lens Parameters

Station	Elevation (feet)	Rel. depth to lens bottom (feet)	Lens thickness (feet)
1	6	11.0	5
2	10	77.2	69
3	5	8.0	3
4	6	12.8	7
5	15	50.6	36
6	5	10.6	6
7	5	-	-
8	5	-	-
9	6	-	-
10	8	-	-
11	20	-	-
12	20	75.3	57
13	8	-	-
14	5	-	-
15	6	-	-
16	25	109.5	87
17	6	7.1	1
18	5	-	-
19	18	45.4	28
20	20	36.8	17
21	6	-	-
22	5	245.5	247
23	6	-	-
24	20	28.3	9
25	4	-	-
26	6	-	-
27	6	7.2	1
28	7	-	-
29	5	7.5	3
30	4	-	-
31	5	5.9	1
32	10	-	-

The Ghyben-Herzberg lens parameters corresponding to Fig. 3 are listed in Table 2. Lens thicknesses are computed by subtracting station elevation from the relative depth to lens bottom and multiplying the result by 1.025 in accordance with the Ghyben-Herzberg relationship. Station elevations are estimated from the 1972 Bahamas Government map of San Salvador and may be in error by ± 5 feet.

More significant errors, no doubt, are introduced by our lack of knowledge of the applicable formation resistivity factor and actual subsurface porosities, as well as by deviations of the actual subsurface from the ideal horizontal layer model. Furthermore, the logarithmic increments of electrode spacings lead to a progressive loss of resolution of subsurface features with increasing depth and electrode spacing. Resolution is also affected by the electrical equivalence of high-resistivity layers of equal transverse resistance (given by the product of layer thickness and layer resistivity) between low-resistivity layers, or of low-resistivity layers of equal longitudinal conductance (given by the ratio of layer thickness to layer resistivity) between high-resistivity layers. Thus, thin low-porosity micritic layers tend to masquerade as much thicker, less resistive, layers in computed resistivity models. The VES curve inversion program used also tends to miss existing or generate non-existing layers of intermediate resistivity between high and low resistivity layers. Consequently, the exact position of the bottom of a freshwater lens may not be identifiable in the computed resistivity models. In fact, only two stations (20 and 21) show the expected diagnostic 18-fold or greater resistivity decrease at depth marking the freshwater/saltwater boundary. Thus the dimensions of the inferred freshwater layers may be greatly in error.

There is significant change in the results if the formation resistivity factor of equation 5 is used. In that case no freshwater is indicated at stations 6 and 24 (unless aquifer porosities are at least 29%), the freshwater column at station 12 is reduced to 33 ft (unless aquifer porosity is at least 25.5%, a quite reasonable value), the freshwater column at station 16 is also reduced to 33 ft (unless aquifer porosity is at least 31%), and at station 22 it is reduced to 19 ft (unless porosity exceeds 27%).

A significant problem is presented by the high resistivity values of the computed layer model of station 22. This station is located near station 31 of Greene and Associates (1972) which indicated a substantial thickness of high-quality fresh groundwater, and a unusually thick freshwater column was therefore expected. However, the initial estimate of 247 ft for the freshwater lens thickness at that site is totally unrealistic. In general, even the most massive Bahamian freshwater lenses are rarely more than 100 ft thick (Cant, 1988). Additional doubts are raised by the fact that station 22 is situated only about 1500 ft from Station 23 of Kunze and Burke (1984) which indicated no freshwater. Finally, according to the Ghyben-Herzberg relationship the water table elevation corresponding to such a lens thickness should be 6 ft above sea level, yet the surface elevation in that area is estimated to be only 5 ft above sea level. Hence, the high subsurface resistivities at station 22 must have another explanation, such as anomalously low subsurface porosity. To explain the model resistivities in terms of seawater saturation requires a porosity of 4.9% for the 250 ohm-ft layer, and 4.3% for the 320 ohm-ft layer (according to equation 7). If equation 8 is utilized, the corresponding porosities are 7.5% and 6.7% respectively. Although these porosity values are not unreasonable, the great thickness of the inferred low porosity layers is unusual. Considering the electrical equivalence of high resistivity layers of equal transverse resistance, the computed 54 ft thick layer of 320 ohm-ft might in reality represent a 4 ft freshwater saturated micritic layer of resistivity 4300 ohm-ft and 5.1% porosity 133 ft below sealevel. Such micritic layers are known to occur at the bottom of at least some freshwater lenses (Persons, 1975; Weech, 1982). Alternately, the bottom of the freshwater lens may be represented by the 930 ohm-ft layer at a depth of 19 feet below sealevel. In either case, the resistivity values at Station 22 remain somewhat enigmatic.

If the deep subsurface porosities are, in fact, significantly lower than 25%, then our interpretation of station 16 is also in error. Specifically, the 180 ohm-ft layer is more likely to represent a saltwater bearing layer with porosity of 5.8% (or 8%) than a freshwater layer with 25% porosity. In that case the bottom of the freshwater lens at that site is 32 feet below sealevel, and the lens is approximately 33 feet thick.

These modified results were used to construct the freshwater isopach map shown as Fig. 4. This map also includes stations 1, 13, 17, 18, 19, 20, 22, 23, 24, 26, 27, and 28 of Burke and Kunze (1984) whose resistivity layer models were reinterpreted according to the slightly different criteria of this paper.

High-Resisitivity Layers at Depth

Table 3 lists pertinent parameters of high-resistivity layers computed by the VES inversion program at twenty stations. As discussed previously, these layers probably represent electrically equivalent low-porosity thin micritic zones or paleosols. They tend to cluster about depths of 20 ft, 30 ft, 60 ft, 90 ft, and 150 ft below sealevel, and may be equivalent to paleosols at 25 ft, 55 ft and 90 ft reported by Little and others (1977). Supko (1977) reports buried paleosols on San Salvador at 51 ft, 81 ft, and 107 ft below sealevel with dolomite below 111 ft (34 m). Rodriquez and others (1988) report a prominent reflector on San Salvador 30-38 m below the surface. This reflector as well as the paleosols of Supko (1977) at 81 ft or 107 ft might correspond to our high-resistivity layer at approximately 90 ft, but, in view of the low resolution of our electrical subsurface models, meaningful correlation is not possible. Alternately, these high-resistivity layers may, of course, represent extended zones of intermediate to low porosities.

Other Correlations

Eight stations were located near blueholes, lakes or wells containing water of known salinity. If the adjacent groundwater has the same salinity, then it is possible to calculate subsurface porosity from the model subsurface resistivity (R_0) using equation 7 or 8. Table 4 lists the pertinent data and the results of such a calculation using equation 7. Inferred near-surface aquifer porosities range from 3.4% to 54.7% and average around 19%. It is, however, unlikely that such surface water has exactly the same salinity as the pore water in the surrounding rock - especially if porosities and permeabilities are low. Hence the low-porosity results are particularly suspect.

SUMMARY AND CONCLUSIONS

Our data indicate a very inhomogeneous subsurface with greatly varying porosities. Near-

Table 3. High Resistivity Layers at Depth

Station	R_o (ohm-ft)	Abs. depth range (ft)	Avg. depth (ft)
1	91	12 - 101	56
3	230	11 - 47	29
4	210	11 - 20	16
5	800	136 - 181	159
6	100	24 - 146	85
8	410	24 - 47	35
10	110	7 - 220	114
11	430	13 - 29	21
16	200	138 - 229	183
18	110	62 - 133	97
19	240	69 - 116	92
20	250	66 - 91	78
22	320	106 - 160	133
25	180	7 - 187	97
27	90	9 - 29	19
29	160	9 - 118	63
30	420	5 - 8	6
31	140	5 - 36	20

Table 4. Porosity Estimates from Salinity and Resistivity Data

Station	R_o (ohm-ft)	Sample Site	Salinity	R_w (ohm-ft)	Porosity
3	667 173 60.4	B.H. #2	23 ppt	0.855	3.4% 7.0% 11.9%
18	93.7 33.5 22.5	B.H. #3	21 ppt	0.92	10.0% 16.6% 20.2%
23	11.2	Pond	38 ppt	0.55	22.2%
25	91.2	B.H. #5	22-25 ppt	0.79-0.89	9.3-9.9%
30	7.5 92.4	B.H. #6	13 ppt	1.48	44.4% 12.7%
31	38.8 25.3	Well	15.5 ppt	1.25	17.9% 22.2%
32	35.8	Clear Pond	35 ppt	0.60	12.9%
15	8.0 1.0	French Pond	70 ppt	0.305	19.5% 54.7%

Salinity data provided by James Teeter, The University of Akron surface porosities tend to be very high (perhaps averaging near 30%), but porosities of many of the deeper strata appear to be quite low (5% or less). Such low-porosity regions at depth may represent well cemented limestones or dolomites without caverns. Elsewhere cavernous regions in otherwise low-porosity formations increase the formation bulk porosity affecting resistivity measurements. Because of these porosity variations, estimation of groundwater salinity by the resistivity method is problematic, if not impossible. For example, low-porosity, seawater saturated layers have similar resistivities as high-porosity, freshwater aquifers. This may be the reason for the unrealistic results at station 22. Another major problem hampering the interpretation of resistivity data is the lack of resolution of the deeper layers. As a result of this, the freshwater/saltwater transition zone, which is commonly only a few feet wide (Little and others, 1977), is usually poorly defined or occasionally missed altogether in the computed resistivity layer models. Consequently, the freshwater lens thicknesses depicted in Fig. 4 may be greatly in error - especially the larger values.

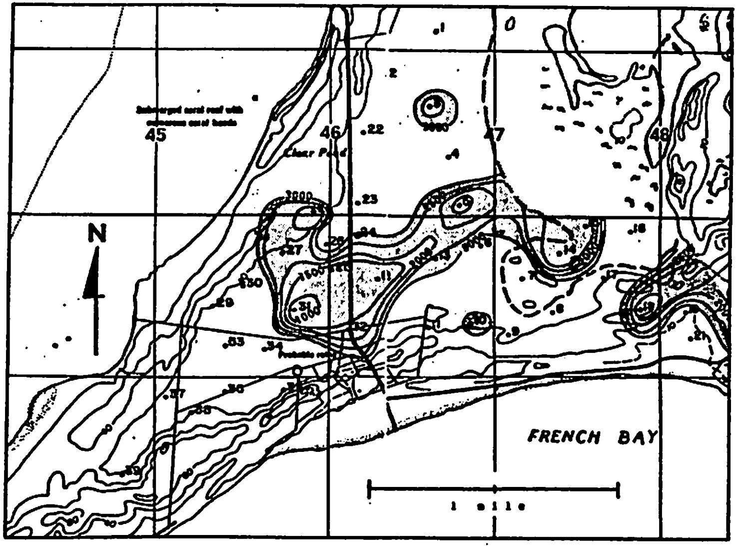

Fig. 5. Freshwater lenses (shaded) determined by Greene and Associates (1972). Freshwater conductivity isolines in micromho/cm. Discussion in text.

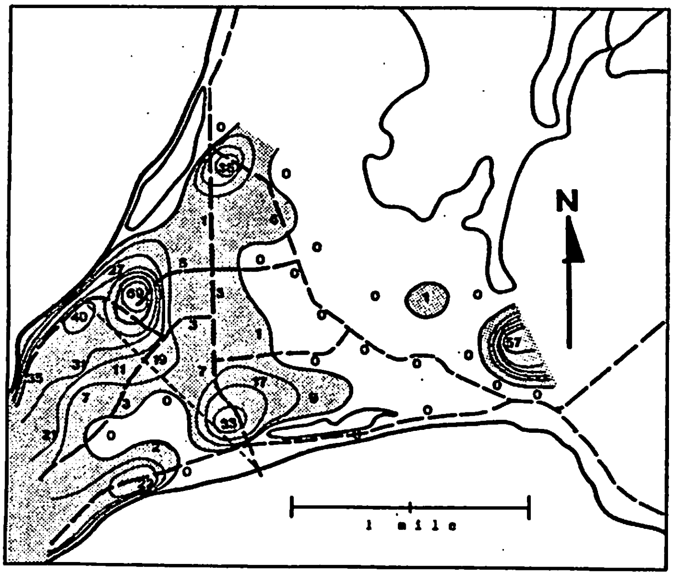

Fig. 4. Inferred fresh groundwater isopach map. Shaded area indicates freshwater lens. Numbers indicate freshwater thicknesses (in feet). Contour interval is ten feet. Major roads are shown as heavy dashed lines. Thin dashed line is study area boundary.

In spite of these uncertainties, certain trends in the interpreted fresh groundwater distribution are unmistakable. As in previous investigations on San Salvador (Kunze and Burke, 1984; Kunze and Weir, 1987), there is a definite tendency for fresh groundwater to underly peripheral hills and topographic highs, with generally lesser freshwater accumulations in the low interior. A similar distribution of fresh groundwater on San Salvador was inferred by Davis and Johnson (1988). There is, however, the possibility of an anomalously thick freshwater lens in the western part of the low-lying interior which may reach a maximum thickness on the order of 100 ft near station 22, but the freshwater/saltwater interface at that station is not defined in the corresponding resistivity layer model. We conclude that freshwater thickness at that site must be at least 19 ft. There appears to be almost no fresh groundwater in the eastern part of CL1 except underneath the easternmost hills. The freshwater lens as indicated in Fig. 4 (shaded) bears little resemblance to that of Greene and Associates (1972) as shown in Fig. 5. The isolines represent equal well-water conductivities (in micromho/cm) and are strongly correlated with measured freshwater thicknesses. The maximum conductivity of freshwater as defined by the World Health Organization (1500 ppm TDS), corresponding to a resistivity of 11.2 ohm-ft, is 2930 micromho/cm. The 1500 micromho/cm line corresponds roughly to the 15 ft freshwater isopach line of Greene and Associates (1972). Thus the freshwater lens depicted by Fig. 5 (shaded) is confined largely to the low interior of the study area and attains a maximum thickness of perhaps well over 20 ft near our station 22. As discussed earlier, no test wells were established in the higher, hilly regions; consequently Fig. 5 does not show most of the freshwater present there. However, the freshwater lens beneath the easternmost hills is evident and confirms our results. On the other hand, our results show virtually none of the fresh groundwater detected by Greene and Associates (1972) in the low-lying eastern interior of CL1. The fact that all surface water recently tested in that region (Table 4) was brackish supports our results. We, therefore, conclude that, on San Salvador, relatively stable major freshwater lenses tend to occur beneath hills and highlands, and that the few freshwater lenses that develop in low-lying areas tend to be unstable and ephemeral. Nevertheless, special conditions - such as the absence of caves - may permit development of a major freshwater lens anywhere on the island.

ACKNOWLEDGEMENTS

We wish to thank the College Center of the Finger Lakes, Bahamian Field Station for providing logistical support. We also wish to express our appreciation to the Standard Oil Production Company, Dallas, Texas, for kindly providing use of their laboratory facilities. Thanks are also due to Jim Teeter for furnishing pertinent water salinity and temperature data, to Tom Quick for analysing water samples, and to Roger Bain for petrological analysis of our rock samples. Financial support for this research was received from the Research (Faculty Projects) Committee of the University of Akron.

APPENDIX

Determination of Formation Resistivity Factor

Twelve bedrock samples from the CL1 area were analysed at the Standard Oil Production Laboratory, Irving, Texas for porosity and rock resistivity (R_0) while saturated with an NaCl solution of known resistivity R_w (0.184 ohm-m). Procedural details are described by Weir and Kunze (1988). Knowledge of R_0 and R_w permits calculation of corresponding formation factors (F):

Table 5. Geoelectrical parameters of rock samples

Sample	R_0 (ohm-m)	F	Porosity (%)
1a	2.20	12.0	34.5
1b	3.22	17.5	28.5
2a	3.26	17.7	32.5
2b	2.28	12.4	35.8
3a	2.48	13.5	32.6
3b	3.03	16.5	27.4
4a	3.03	16.5	30.5
4b	3.98	21.6	26.7
5a	1.84	10.0	38.8
5b	1.62	8.8	39.0
6a	25.65	139.4	11.8
6b	54.55	296.5	8.9

(9) $$F = R_0/R_w$$

The twelve measured resistivity (R_0) and porosity (Φ) values as well as corresponding calculated formation factors (F) are listed in table 5.

The formation factors are functionally related to rock porosities in accordance with equation 2.

$$F = \frac{a}{\Phi^m}$$

This relationship may be written in logarithmic form as:

(10) $$\log F = \log a - m \log \Phi$$

A plot of log F versus log Φ thus represents a straight line with slope "-m" and intercept "log a", permitting determination of the parameters "a" and "m" of equation 2.

Fig. 6 is the logarithmic plot of the twelve F and Φ values (actually log F versus -log Φ). The best fitting least squares line has a slope "m" of 2.30±0.08 and intercept "log a" of 0.028±0.046. The parameter "a", therefore, is equal to 1.07 ± 0.11. Hence, based on our samples, the formation factor F for shallow aquifers in the CL1 area is given by:

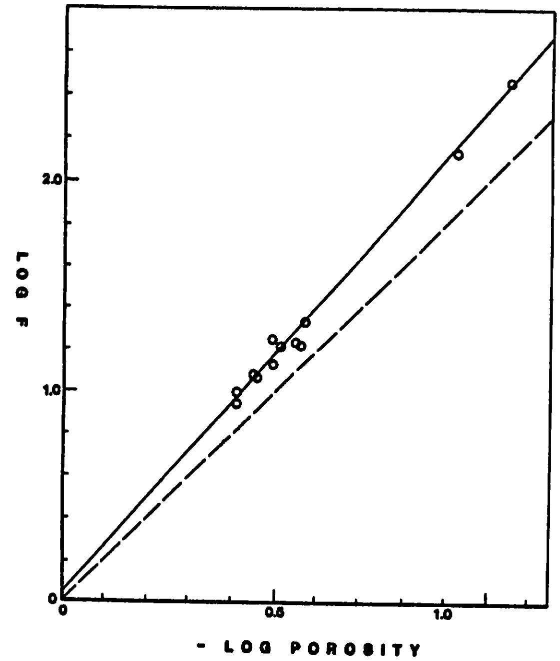

Fig. 6. Scatter plot and least squares trend (solid line) of sample log F versus -log Φ values. The dashed line represents the basic Archie relationship.

(11) $$F = \frac{1.07}{\Phi^{2.3}}$$

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