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EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Results of Surface Electrical Resistivity Surveys

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TEXAS DEPARTMENT OF WATER RESOURCES

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EVALUATING THE GROUND-WATER RESOURCES OF THE HIGH PLAINS OF TEXAS

Results of Surface Electrical Resistivity Surveys

By

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The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies or recommendations of the U.S. Government.

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ABSTRACT

The study was conducted as part of the Department's High Plains Aquifer Study. The Wenner configuration of electrodes as used in the "Barnes Layer Method" was employed to investigate subsurface electrical values of the High Plains aquifer to depths of 700 feet [213 meters (m)] and more. Qualitative variations in hydrologic properties are shown in terms of the aquifer's apparent formation factor and computer-calculated resistivity. In addition, the base of the Ogallala Formation was electrically sounded.

INTRODUCTION

In 1978, the Texas Department of Water Resources initiated a regional ground-water study of the High Plains aquifer. The study, utilizing Department personnel and geophysical equipment, was partially funded by the U.S. Geological Survey and its results are to be included in that agency's eight-state study of the High Plains aquifer. As part of the study, the Department conducted surface electrical resistivity soundings in selected areas of the Texas High Plains (Figure 1). These soundings represented the first use of this technique in connection with a comprehensive ground-water study of the High Plains aquifer of Texas. The results will establish a basis for future studies of the High Plains aquifer and other aquifers similarly composed of unconsolidated heterogeneous sediments.

Purpose and Scope

A major purpose of employing surface electrical resistivity or vertical electrical soundings (VES) was to determine the geographical variation in the High Plains aquifer's hydrologic properties based on the differences in geoelectrical parameters. The scope of the project included (1) conducting VES in the field, and (2) compilation and analysis of data pertaining to aquifer resistivities or formation factors to indicate trends in the aquifer's hydrologic properties. In addition, each sounding was evaluated to see if it could be used to determine the position of the base of the Ogallala Formation.

Acknowledgements

Appreciation is extended to personnel of the High Plains Underground Water Conservation District No. 1 in Lubbock and to the North Plains Water Conservation District No. 2 in Dumas for their cooperation in furnishing geo-

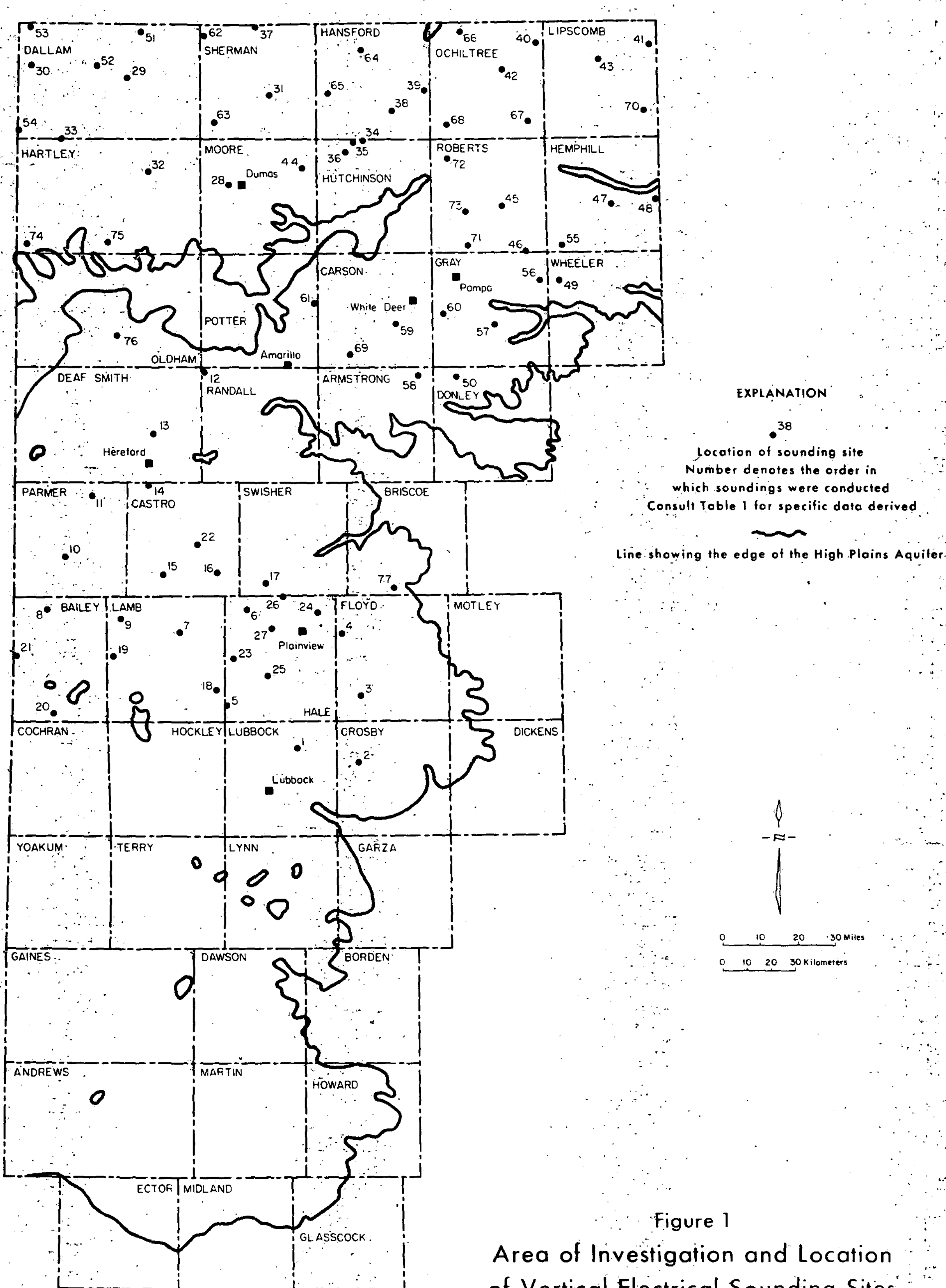


Figure 1
Area of Investigation and Location of Vertical Electrical Sounding Sites

Base from U.S. Geological Survey, 1965

hydrological data used in conducting many of the surface electrical resistivity surveys. William B. Klemt, Head of the Ground Water Studies Unit, is credited with devising the methodology for conducting the surface electrical resistivity surveys. Robert D. Price, geologist, assisted in review and editing of the manuscript. Thanks are also extended to the farmers and ranchers in the study area for permitting the surveys to be conducted on their land.

Personnel

This study was conducted under the general supervision of C. R. Baskin, P.E., Director, Data and Engineering Services Division; and Dr. Tommy R. Knowles, P.E., Chief, Data Collection and Evaluation Section of the Texas Department of Water Resources. All electrical soundings, tabulation of results, preparation of illustrations, and the writing of this report were done by Daniel A. Muller, geologist.

GENERAL GEOLOGY AND HYDROLOGY

The Ogallala Formation is the major water-bearing unit on the High Plains of Texas. It is composed of unconsolidated, fine- to coarse-grained, gray to red sand, clay, and silt. In places, it contains some quartz gravel and caliche. During Pliocene time, large quantities of eroded material from the Rocky Mountain region were transported by wind and water southeastward and deposited on the then existing surface of primarily Triassic and Permian age rocks. In certain areas, the depositional surface was composed of Cretaceous and Jurassic age sediments. The low valley areas were usually filled first by coarser materials such as gravels and coarse sand. Pebbles and cobbles of quartz, quartzite, and chert were not uncommon. Eventually, with the aid of shifting streams, the entire area was covered by Ogallala sediments until a maximum thickness of almost 900 feet (274 m) was attained in southwestern Ochiltree County (Muller and Price, 1979; Bell and Morrison, 1978).

Water-bearing areas of the Ogallala Formation are hydraulically connected except where the Canadian River has partially or totally eroded through the formation to separate the North and South Plains.

The saturated thickness of the Ogallala Formation ranges from a few feet to more than 525 feet (160 m). In general, the areas of greatest saturated thickness occur in the North Plains. In the South Plains, between Lubbock and Midland, the saturated zone varies from less than 50 feet (15 m) to 200 feet (61 m). Depth to water below the land surface can range from almost 400 feet (122 m) in parts of the North Plains to between 100 to 200 feet (30 to 61 m) throughout much of the South Plains.

Ogallala ground water is generally fresh, containing between 300 and 1,000 milligrams per liter (mg/l) of dissolved solids of which calcium, magnesium, and bicarbonate are the principal constituents.

Hydraulic continuity also occurs between the Ogallala Formation and the underlying Cretaceous, Triassic, and Permian formations in many areas of the High Plains. Therefore, for the purpose of this study, the High Plains aquifer will be considered to consist of the saturated sediments of the Ogallala Formation and those underlying, potable water-bearing units in hydraulic continuity with it.

RESISTIVITY SURVEYS

Electrical methods of subsurface investigation consist of determining electrical parameters and then correlating these values with the types of subsurface materials for which the values are obtained.

Basic Principles

Resistivity of the water-bearing sediments of the High Plains aquifer is a function of the percentage of the clay, sand, and gravel particles in the sediments, and the quality of the interstitial water. An increase in the clay or silt content of the aquifer causes a decrease in resistivity provided the resistivity of the interstitial water remains constant. If the aquifer is a clean sand, i. e., non-shaly, then a ratio exists such that (Alger, undated, p. 11):

$$F = R_o/R_w \quad \text{or} \quad R_o = FR_w \qquad (1)$$

Where: F = the formation resistivity factor or formation factor (dimensionless),

R_o = the resistivity of the formation in ohm-meters assuming it is saturated with water of resistivity R_w, and

R_w = the formation water resistivity in ohm-meters.

(Both R_o and R_w are corrected to 25 degrees centigrade [77°F]).

The formation water resistivity (R_w) may be determined by (Alger, undated, p. 11):

$$R_w = 10{,}000/\text{Specific conductance at 25 degrees centigrade } (77^oF).$$

Since the formation resistivity (R_o) in the above straight-line relationship of equation (1) involves a clean sand, the electric current will flow through the electrolyte or interstitial water and the sand will be perfectly insulating and non-conducting (Worthington and Barker, 1972, p. 216). However, the High Plains aquifer contains clay, silt, and sand; hence, the formation has the capability to conduct an electric current. The fresher the formation water (R_w), the more apt the current is to flow through the formation matrix or solid constituents, especially when the clay content is high. The quantity F then becomes an apparent formation factor (F_a) because the ratio R_o/R_w departs from a straight-line relationship when current passes through the formation matrix and a lower value for R_o results (Worthington and Barker, 1972, p. 217). Conversely, poor quality interstitial water tends to be a good electrolyte and the formation matrix will have less influence on R_o. Worthington and Barker (1972) studied this relationship on the Bunter sandstone of northwest England and showed it as:

$$1/F_a = 1/F + A_i R_w \tag{2}$$

Where: A_i = formation matrix coefficient (the influence of conductance through the formation).

As A_i approaches zero, F_a becomes equal to F. Substituting equation (1) into equation (2), yields:

$$1/F_a = \frac{R_w(1 + A_i R_o)}{R_o} \quad \text{or} \quad F_a = \frac{R_o}{R_w(1 + A_i R_o)} \tag{3}$$

If: R_o is understood to be the computer-interpreted formation or aquifer resistivity (Zohdy and Bisdof, 1975).

Again, as A_i approaches zero, equation (3) becomes:

$$F_a = R_o/R_w \tag{4}$$

Using the method of least squares, Worthington and Barker (1972) fitted a straight line to values of $1/F_a$ and R_w obtained from numerous samples tested in the laboratory and using electrolyte salinities of 300; 600; 1,200; 3,000; 6,000; and 12,000 parts per million (ppm). The intercept of this line on the $1/F_a$ axis defines the true formation factor. In order to determine the coefficient A_i, numerous laboratory tests of test-hole cores would be required. Such procedure is beyond the scope of this study; therefore, the apparent formation factor was determined by equation (4) by assuming that A_i goes to zero; that

R_o is the computer-interpreted formation or aquifer resistivity; and R_w is the resistivity of the interstitial water.

Assumptions

For this electrical subsurface investigation, the "Barnes Layer Method", which utilized the well-known Wenner array, was employed for the selection of electrode spacing to electrically evaluate the water-bearing zones of the High Plains aquifer and attempt to delineate the base of the Ogallala Formation (Barnes, 1954; Wenner, 1916). Furthermore, it was assumed that this method would furnish reliable data to depths of over 700 feet (213 m) even though Barnes' work was concerned with shallow depths of 18 to 50 feet (5 to 15 m), and that the complexity of the field data, due to the greater depths of investigation, could be interpreted utilizing the computer interpretive program devised by Zohdy and Bisdorf (1975). Lateral changes in soil resistivity were assumed to be negligible.

Equipment

Equipment used during the survey consisted of a main direct current (DC) power source, a rotary DC to alternating current (AC) inverter and step transformer, a main monitoring panel containing an ammeter and voltmeter, and four electrodes with connecting cable.

The power source consisted of four heavy duty 12 volt (v) storage batteries connected to provide 24 v. The rotary DC to AC inverter converted the 24 v DC to a 100 Hertz (Hz) signal for transformer step-up to 860 v. The current producing this voltage was rectified and filtered to provide ripple-free, high level direct current for surveying. In the main monitoring panel, an instrument was provided to monitor current levels ranging from 0 to 3,000 milliamperes (ma). The potentials developed were measured with a precision DC null Hewlett Packard model 419-A voltmeter with a sensitivity range from ± 3 microvolts (μv) to 1,000 v. Two steel current electrodes were mounted on reel carriers with cable sufficient to provide 1,800 m electrode separation. Two additional brass potential electrodes were similarily mounted with enough cable for 200 m separation. Auxiliary equipment included battery chargers, additional electrodes, and porcelain pots containing a solution of copper sulfate which were used as potential electrodes.

The aforementioned equipment was contained in a van that could be driven to the sites that were to be evaluated.

Method of Investigation

Selection of VES sites involved: (1) choosing sites where a maximum of aquifer saturated thickness occurred; (2) avoiding conductors such as powerlines, buried cables, pipelines, electric fences, downed wire fences or barbed wire fences with metal posts; (3) locating sites in the proximity of a water well so that a current static water level and field specific conductance of the ground water could be measured; and (4) having sites for which information on the base of Ogallala Formation and lithology of the aquifer was available. Figure 1 shows the location of the VES sites.

Following selection of the VES sites, field procedures utilized in conducting the surface electrical resistivity surveys included: (1) selecting the proper electrode spacing, (2) conducting the actual soundings, and (3) plotting the field VES curve.

The Wenner configuration employed was the one in which two exterior steel current electrodes (A and B) and two interior brass potential electrodes (M and N) are assembled on line and at equally spaced intervals (Figure 2). At this point it should be made clear that the resistivity readings obtained in the field are not for the individual beds of the soil or aquifer material, but

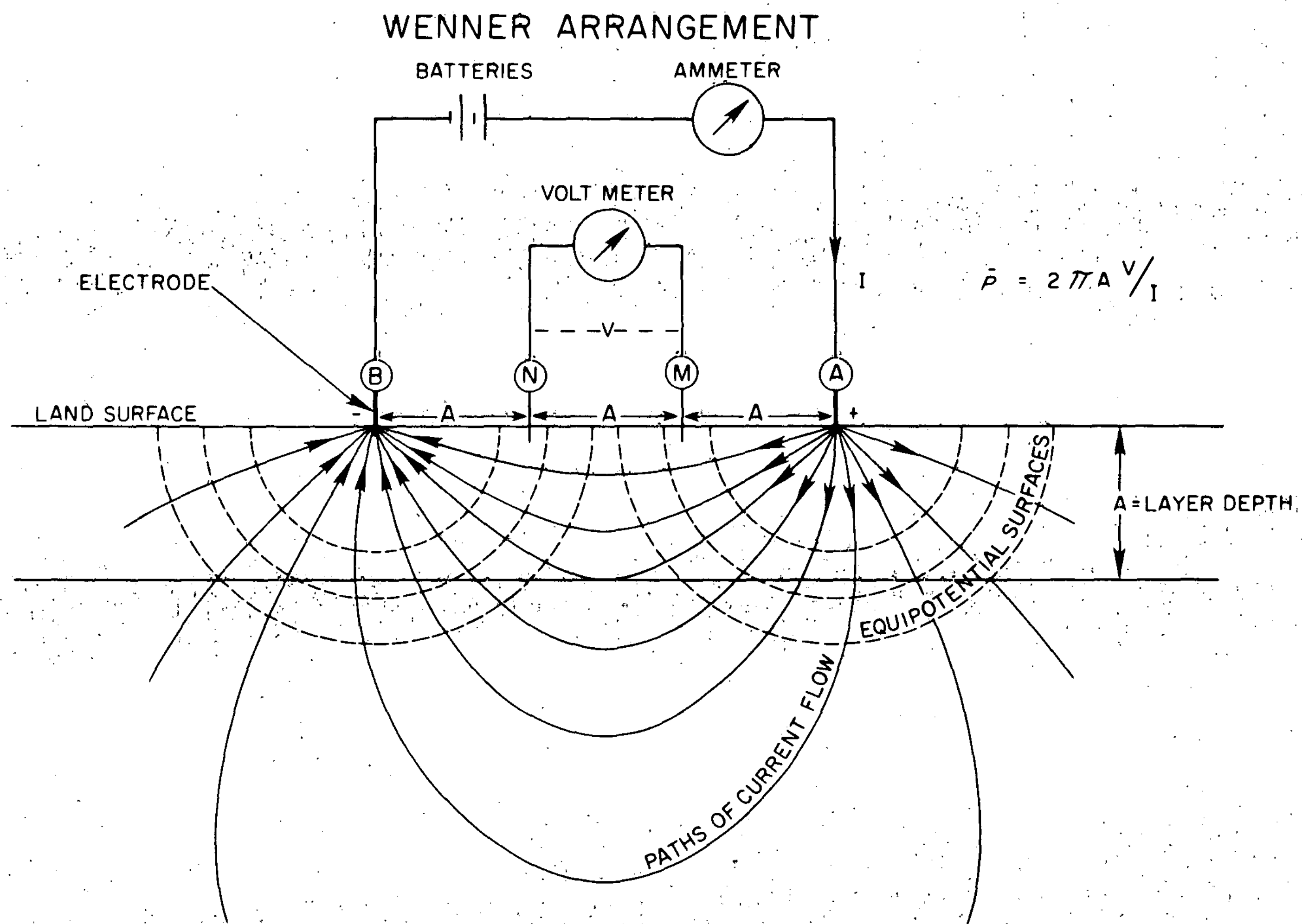


Figure 2

A Schematic Vertical Section of the Earth Showing the Wenner Configuration of Electrodes and Electric Field Lines

for the sediment mass lying between the ground surface and a depth appoximately equal to the spacing between the electrodes.

The next step consisted of spacing the electrodes at 10 meters (33 feet) or less, centered about the VES site, and taking a reading for this depth. The reading, recorded as the potential between electrodes M and N in volts at a specified current flow in amperes through electrodes A and B, represents the apparent resistivity of the top 10 meters (33 feet) of soil. These steps were continued at successive electrode spacings equivalent to the depth of the water table, base of Ogallala Formation, and a sufficient depth below the Ogallala Formation to determine the resistivity contrast between the Ogallala and the underlying sediments.

Continuing the methodology, the next step was the computation of apparent resistivity for each of the above electrode spacings using the following relationship of Ohm's law (Zohdy, Eaton, and Mabey, 1974):

$$\bar{\rho} = 2\pi A\ V/I \qquad (5)$$

Where: $\bar{\rho}$ = the apparent resistivity in ohm-meters,
A = the distance between the equally spaced electrodes in meters,
V = the potential between electrodes M and N in volts, and
I = the current flow through electrodes A and B in amperes.

The final step in the field procedure was the plotting of the field VES sounding curve on log-log graph paper as apparent resistivity versus electrode spacing.

Interpretation of Resistivity Data

Data collected in the field on apparent resistivity and shown in Table 1 were interpreted by utilization of computer programs written by Zohdy and Bisdorf (1975) for the Wenner configuration. With these programs, the field sounding curve (VES) can be interpreted by entering the apparent field resist-

Table. 1 - Summary Data Derived from Vertical Electrical Sounding Surveys

VES Number	County	Date	Elevation (ft)	Longitude (deg. min.)	Latitude (deg. min.)	Approximate Altitude of Base of Ogallala Formation (ft)	Aquifer Thickness (ft)	Resistivity of Ground Water at 77°F (R_w) (ohm-meters)	Resistivity of Aquifer at 77°F (R_o) (ohm-meters)	Apparent Formation Factor F_a
1	Lubbock	Oct. 19, 1978	3,259	101 44	33 44	2,954	100	16.67	29.47	1.77
2	Crosby	Oct. 21, 1978	3,140	101 28	33 40	2,775	230	15.72	29.47	1.87
3	Floyd	Nov. 2, 1978	3,203	101 21	33 55	2,770	188	14.20	40.19	2.83
4	Floyd	Nov. 3, 1978	3,300	101 32	34 11	2,920	178	11.79	58.94	5.00
5	Hale	Nov. 7, 1978	3,460	102 05	33 54	3,180	115	7.89	33.40	4.24
6	Hale	Nov. 8, 1978	3,580	101 59	34 16	3,291	100	12.55	71.44	5.69
7	Lamb	Nov. 18, 1978	3,651	102 18	34 11	3,350	178	14.97	29.07	1.94
8	Bailey	Nov. 18, 1978	3,900	102 55	34 16	3,705	80	11.19	48.46	4.33
9	Lamb	Nov. 19, 1978	3,750	102 13	34 13	3,549	120	11.19	26.07	2.33
10	Parmer	Nov. 20, 1978	4,050	102 48	34 27	3,620	133	17.01	80.37	4.72
11	Parmer	Nov. 29, 1978	4,050	102 42	34 43	3,525	250	16.25	61.62	3.84
12	Randall	Nov. 30, 1978	3,864	102 10	35 10	3,498	108	16.95	75.01	4.43
13	Deaf Smith	Dec. 1, 1978	3,873	102 23	34 56	3,477	205	15.70	45.81	2.92
14	Castro	Dec. 2, 1978	3,880	102 25	34 44	3,515	147	16.95	58.05	3.42
15	Castro	Dec. 3, 1978	3,773	102 22	34 24	3,373	214	17.95	48.46	2.70
16	Castro	Dec. 4, 1978	3,680	102 06	34 25	3,300	156	15.75	53.58	3.40
17	Swisher	Dec. 5, 1978	3,565	101 52	34 21	3,223	110	15.23	36.61	2.40
18	Lamb	May 16, 1979	3,506	102 07	33 56	3,216	144	9.85	28.58	2.90
19	Lamb	May 23, 1979	3,850	102 35	34 04	3,640	108	11.04	26.79	2.43
20	Bailey	May 22, 1979	3,842	102 51	33 52	3,705	35	15.63	44.65	2.86
21	Bailey	May 22, 1979	3,840	103 02	34 04	3,700	45	4.63	10.72	2.31
22	Castro	May 23, 1979	3,783	102 12	34 30	3,388	135	14.73	62.51	4.24

See footnotes at end of table.

Table. 1 - Summary Data Derived from Vertical Electrical Sounding Surveys -- Continued

VES Number	County	Date	Elevation	Longitude		Latitude		Approximate Altitude of Base of Ogallala Formation	Aquifer Thickness	Resistivity of Ground Water at 77°F (R_w)	Resistivity of Aquifer at 77°F (R_o)	Apparent Formation Factor F_a
			(ft)	(deg.	min.)	(deg.	min.)	(ft)	(ft)	(ohm-meters)	(ohm-meters)	
23	Hale	May 24, 1979	3,495	102	02	34	03	3,150	193	12.30	40.19	3.27
24	Hale	May 29, 1979	3,360	101	39	34	15	3,014	175	14.06	35.72	2.54
25	Hale	May 30, 1979	3,410	101	54	34	01	3,060	160	14.79	49.12	3.32
26	Hale	May 30, 1979	3,500	101	48	34	18	3,150	150	15.65	40.19	2.57
27	Hale	June 27, 1979	3,465	101	52	34	12	3,130	147	15.08	26.79	1.78
28	Moore	June 29, 1979	3,625	102	07	36	03	2,937	375	15.43	22.33	1.45
29	Dallam	July 10, 1979	4,125	102	32	36	17	3,678	126	22.78	49.12	2.16
1/ 30	Dallam	July 11, 1979	4,580	102	59	36	20	4,300	185	16.56	16.90	1.02
31	Sherman	July 16, 1979	3,505	101	49	36	13	3,005	287	20.20	24.11	1.19
32	Hartley	July 17, 1979	3,940	102	25	35	55	3,475	85	17.54	26.43	1.51
33	Hartley	July 18, 1979	4,330	102	50	36	03	3,851	280	20.00	62.51	3.13
2/ 34	Hutchinson	July 24, 1979	3,220	101	25	36	03	2,840	180	21.65	120.56	5.57
2/,3/ 35	Hutchinson	July 25, 1979	3,195	101	27	36	02	2,870	225	22.22	24.11	1.09
36	Hutchinson	July 26, 1979	3,235	101	29	36	00	2,875	180	22.22	58.05	2.61
37	Sherman	July 31, 1979	3,485	101	54	36	30	3,150	145	17.01	47.80	2.81
2/ 38	Hansford	Aug. 1, 1979	3,150	101	16	36	08	2,724	215	16.37	66.04	4.03
39	Hansford	Aug. 7, 1979	3,085	101	07	36	15	2,310	425	15.60	58.05	3.72
40	Ochiltree	Aug. 8, 1979	2,875	100	33	36	25	2,395	250	11.36	24.11	2.12
41	Lipscomb	Aug. 9, 1979	2,490	100	02	36	24	2,190	280	15.36	12.68	0.83
42	Ochiltree	Aug. 10, 1979	2,910	100	45	36	20	2,335	275	9.09	50.40	5.54
43	Lipscomb	Aug. 11, 1979	2,720	100	17	36	22	2,310	246	15.67	28.58	1.82
44	Moore	Aug. 12, 1979	3,360	101	41	35	56	2,894	220	23.26	40.19	1.73

See footnotes at end of table.

Table. 1 - Summary Data Derived from Vertical Electrical Sounding Surveys -- Continued

VES Number	County	Date	Elevation (ft)	Longitude (deg. min.)	Latitude (deg. min.)	Approximate Altitude of Base of Ogallala Formation (ft)	Aquifer Thickness (ft)	Resistivity of Ground Water at 77°F (R_w) (ohm-meters)	Resistivity of Aquifer at 77°F (R_o) (ohm-meters)	Apparent Formation Factor F_a
45	Roberts	Aug. 20, 1979	3,010	100 45	35 47	2,485	225	20.00	32.15	1.61
46	Roberts	Aug. 21, 1979	3,050	100 39	35 37	2,500	250	20.00	44.65	2.23
3/ 47	Hemphill	Aug. 22, 1979	2,575	100 14	35 47	2,260	125	23.81	4.47	0.19
48	Hemphill	Aug. 23, 1979	2,430	100 01	35 49	2,230	50	15.38	98.23	6.39
49	Wheeler	Aug. 24, 1979	2,700	100 29	35 31	2,600	50	25.51	21.43	0.84
50	Donley	Aug. 25, 1979	3,205	100 58	35 10	2,700	200	24.57	80.37	3.27
1/,2/ 51	Dallam	Sept. 5, 1979	4,090	102 28	36 28	3,926	65	14.35	42.25	2.94
1/,2/ 52	Dallam	Sept. 6, 1979	4,225	102 40	36 20	4,071	20	16.61	17.75	1.07
1/,2/ 53	Dallam	Sept. 19, 1979	4,705	102 59	36 28	4,687	-	24.39	-	-
2/ 54	Dallam	Sept. 20, 1979	4,505	103 02	36 03	4,095	-	23.64	48.22	2.04
2/ 55	Hemphill	Sept. 24, 1979	2,905	100 29	35 38	2,183	-	-	-	-
2/ 56	Gray	Sept. 25, 1979	2,800	100 34	35 30	2,500	200	18.55	98.23	5.30
2/ 57	Gray	Sept. 26, 1979	3,005	100 48	35 19	2,687	30	27.62	64.30	2.33
2/ 58	Armstrong	Sept. 27, 1979	3,100	101 10	35 09	2,850	100	20.00	62.51	3.13
59	Carson	Oct. 2, 1979	3,350	101 17	35 20	2,820	200	19.92	37.51	1.88
60	Gray	Oct. 3, 1979	3,300	101 03	35 23	2,775	175	18.87	83.05	4.40
61	Potter	Oct. 4, 1979	3,500	101 38	35 25	2,900	150	23.53	33.04	1.40
62	Sherman	Oct. 10, 1979	3,785	102 09	36 27	3,350	150	18.05	8.93	0.49
63	Sherman	Oct. 11, 1979	3,700	102 06	36 09	3,190	250	18.94	71.44	3.77
64	Hansford	Oct. 12, 1979	3,200	101 25	36 24	3,200	200	18.87	66.08	3.50
65	Hansford	Oct. 16, 1979	3,355	101 33	36 13	2,865	285	18.73	52.69	2.81
66	Ochiltree	Oct. 17, 1979	2,950	100 58	36 28	2,550	225	15.20	44.65	2.94

See footnotes at end of table.

Table. 1 - Summary Data Derived from Vertical Electrical Sounding Surveys -- Continued

VES Number	County	Date	Elevation (ft)	Longitude (deg. min.)	Latitude (deg. min.)	Approximate Altitude of Base of Ogallala Formation (ft)	Aquifer Thickness (ft)	Resistivity of Ground Water at 77°F (R_w) (ohm-meters)	Resistivity of Aquifer at 77°F (R_o) (ohm-meters)	Apparent Formation Factor F_a
67	Ochiltree	Oct. 18, 1979	2,850	101 38	36 06	2,255	375	18.66	31.26	1.67
68	Ochiltree	Oct. 19, 1979	3,095	101 01	36 06	2,505	200	11.43	49.12	4.30
3/ 69	Carson	Oct. 20, 1979	3,460	101 19	35 14	3,015	125	20.20	205.39	10.17
2/ 70	Lipscomb	Oct. 24, 1979	2,610	100 03	36 09	2,240	210	13.23	66.08	4.99
71	Roberts	Oct. 25, 1979	3,205	100 54	35 39	2,545	240	20.20	62.51	3.09
2/ 72	Roberts	Oct. 25, 1979	2,700	101 01	35 59	2,525	125	-	-	-
2/ 73	Roberts	Oct. 27, 1979	3,050	100 56	35 48	2,525	375	20.20	17.86	0.88
2/ 74	Hartley	Oct. 28, 1979	4,100	102 59	35 40	3,985	100	21.65	35.91	1.66
2/ 75	Hartley	Oct. 28, 1979	3,790	102 36	35 41	-	-	-	-	-
2/ 76	Oldham	Oct. 29, 1979	4,050	102 33	35 18	3,811	25	-	-	-
2/ 77	Briscoe	Oct. 30, 1979	3,200	101 16	34 21	3,013	-	-	-	-

1/ Ogallala Formation dry, saturated zone is in underlying Cretaceous or Jurassic sediments.

2/ Primary purpose of sounding was to electrically sound the base of the Ogallala Formation.

3/ Electrical obstructions affect the results of the sounding.

ivities in the following two ways: (1) all of the observed apparent resistivities and their corresponding electrode spacings are entered; and (2) the field sounding curve is digitized and entered at the rate of six equally spaced points per log cycle.

The program solution to the field VES curve is interpreted in terms of thicknesses, depths, and resistivities as a detailed layering in which the number of layers equals the number of points entered on the sounding curve plus six additional layers corresponding to an automatic extension of the left branch of the sounding curve through one logarithmic cycle. Additionally, there is a reduced layering which is a geoelectric equivalent of the detailed layering solution but with fewer layers. This resultant resistivity layering of the subsurface is then entered into another computer program as depths and corresponding resistivity to give a solution as a calculated sounding curve in terms of electrode spacing and corresponding apparent resistivities. It was during this procedure that adjustments were made to the entered resistivity of the layers, especially the resistivity of the saturated layer or aquifer, so that the computer solution would be a curve matching the field VES curve. This final resistivity of the aquifer (R_o) and the formation water resistivity (R_w), adjusted to 25 degrees centigrade (77^{o}F), were then used to calculate the apparent formation factor using equation (4). The formation water resistivity (R_w) and temperature (aquifer temperature assumed equal to water temperature) were determined from field tests of ground water from wells near the VES site or obtained from available data and reports.

Formation water resistivities (R_w) and aquifer resistivities (R_o) were adjusted for temperature (25^{o}C or 77^{o}F) using data from the American Public Health Association and others (1971, p. 324-325) and Schlumberger Limited (1973, p. 9), respectively (Table 1). The temperatures used to make these adjustments at each applicable VES site ranged from 60 to 68^{o}F (16 to 20^{o}C).

These temperatures were as follows: (1) 60°F or 16°C at site 74; (2) 64°F or 18°C at sites 30, 41, 51, and 52; (3) 66°F or 19°C at sites 9, 37, 38, and 42; (4) 67°F or 19°C at sites 5, 7, 8, 13, 15, and 32; and (5) 68°F or 20°C at the remaining VES sites where data were sufficient to make the adjustment.

RELATIONSHIP BETWEEN RESISTIVITY AND HYDROLOGY OF THE HIGH PLAINS AQUIFER

Base of the Ogallala Formation

As previously discussed, the High Plains aquifer includes the saturated rocks of the Ogallala Formation and underlying potable water-bearing sediments that are in hydrologic continuity. Generally, the computer-interpreted resistivities of the saturated zone of the Ogallala Formation are greater than those in the underlying Jurassic, Triassic, or Permian sediments (Figures 3, 4, and 5). In areas where Cretaceous rocks may underlie the Ogallala Formation, resistivities can be higher than in areas where only the Ogallala is saturated. Soils and overburden may contain different proportions of sand, silt, clay, and caliche; consequently, resistivities can range from less than 10 to 400 ohm-meters and more, depending upon the moisture content. In northwestern Dallam County where the Ogallala is not saturated and is underlain by the Dakota Sandstone and Purgatoire Formation (shale) of Cretaceous age, electrical resistivity surveys were conducted to investigate the base of the Ogallala Formation and the underlying Cretaceous sediments.

The position of the base of the Ogallala Formation was successfully determined at most sites using electrical layering contrasts suggested by the geoelectrical model (Figures 3, 4, and 5). Agreement was generally noted down to depths of 150 to 200 meters (492 to 656 feet) where comparisons could be made with drillers' logs in nearby wells. However, where there was an absence of

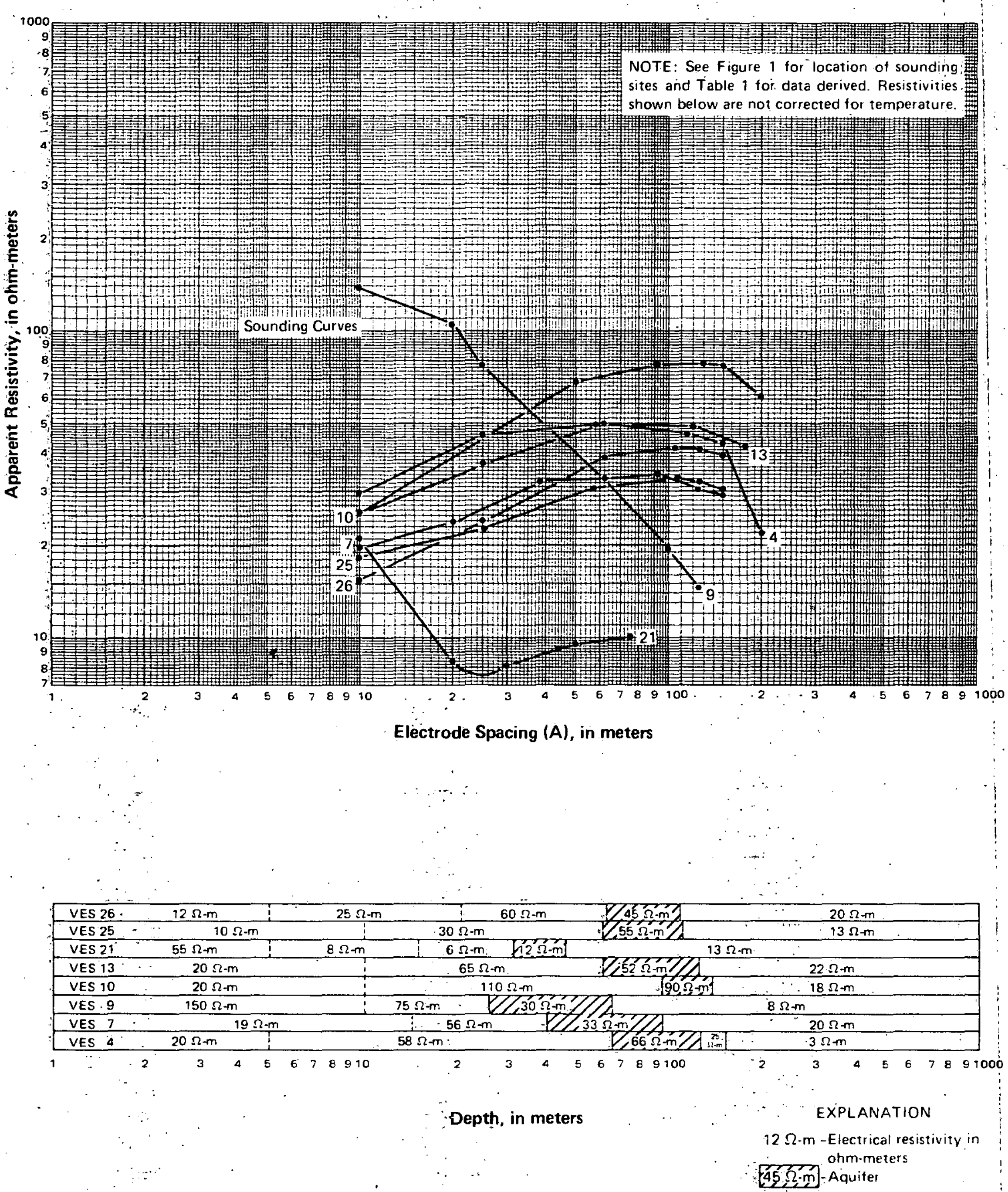
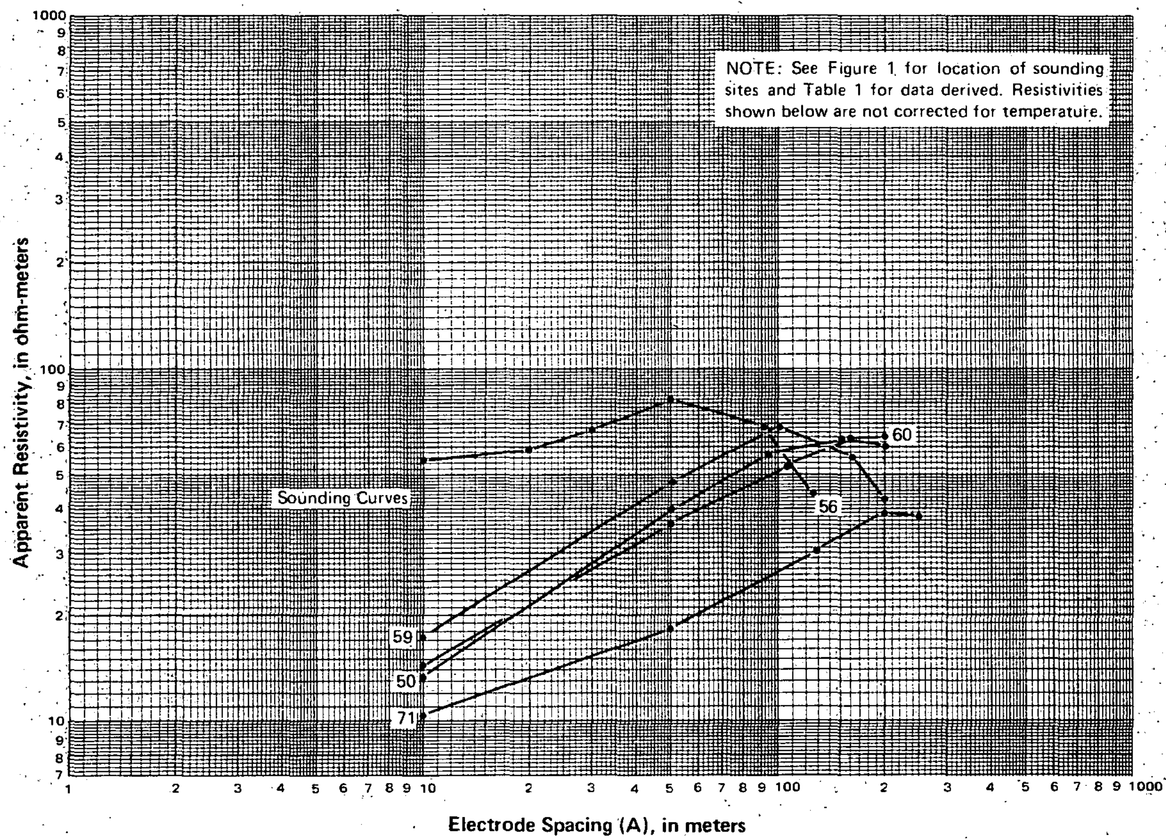
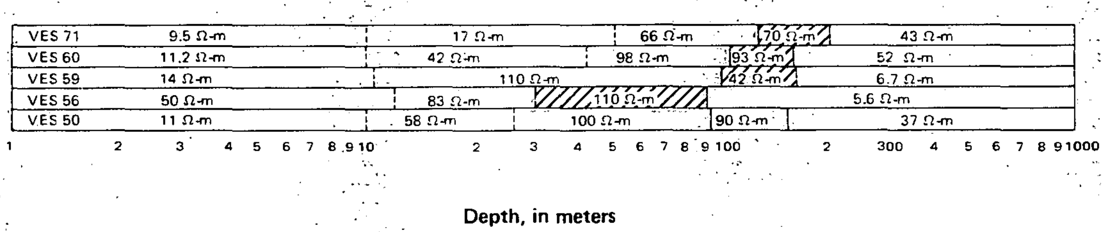


Figure 3

Representative Vertical Earth-Resistivity Sounding Curves and Computer Interpreted Electrical Layering of the South Plains (Plainview-Hereford Area) of Texas





EXPLANATION

12 Ω-m—Electrical resistivity in ohm-meters

45 Ω-m—Aquifer

Figure 4

Representative Vertical Earth-Resistivity Sounding Curves and Computer Interpreted Electrical Layering of the South Plains (White Deer-Pampa Area) of Texas

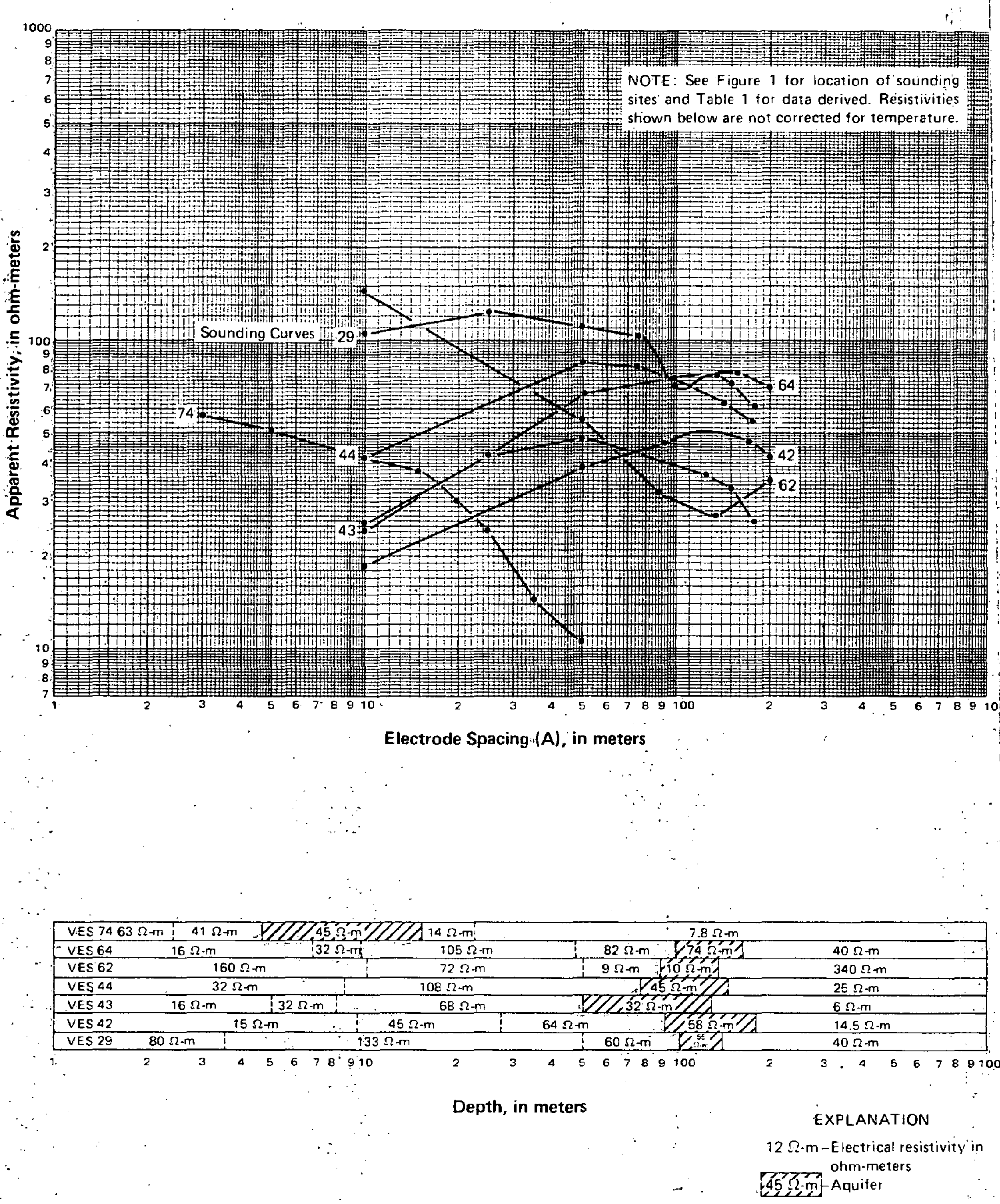


Figure 5

Representative Vertical Earth-Resistivity Sounding Curves and Computer Interpreted Electrical Layering of the North Plains of Texas

geoelectrical contrast between the Ogallala Formation and the underlying sediments, the base of the Ogallala was not well discerned.

Relation of Apparent Formation Factor (F_a) and Formation or Aquifer Resistivity (R_o) to Hydrologic Properties

The apparent formation factor (F_a) and formation or aquifer resistivity (R_o) of the water-bearing sediments of the High Plains aquifer are a function of the percentage breakdown of the clay, sand, and gravel particles, and the quality of the interstitial water. An increase in the clay or silt content in the aquifer causes a decrease in the formation or aquifer resistivity providing the resistivity of the interstitial water remains constant. The apparent formation factor also decreases with an increase in clay content. Equation (4) also allows for water quality changes affecting this parameter. As the clay or silt content in the stratigraphic sediments of the aquifer increases, intergranular permeability and effective porosity or specific yield decrease. Therefore, variations in the hydrologic properties or lithology of the stratigraphic sediments due to different clay or silt content can be qualitatively represented by the geophysical parameters of apparent formation factor and formation or aquifer resistivity.

Following determination of the apparent formation factors (F_a) and formation or aquifer resistivities (R_o), Figures 6 and 7 were constructed to show the lateral variation in formation factors and formation or aquifer resistivities, respectively. These figures also indicate variations in lithofacies within the High Plains aquifer, as the properties mapped generally have an inverse relationship to clay or silt content. The areas of best permeabilities and specific yields (and lowest clay content) are indicated by the highest apparent formation factors and formation or aquifer resistivities.

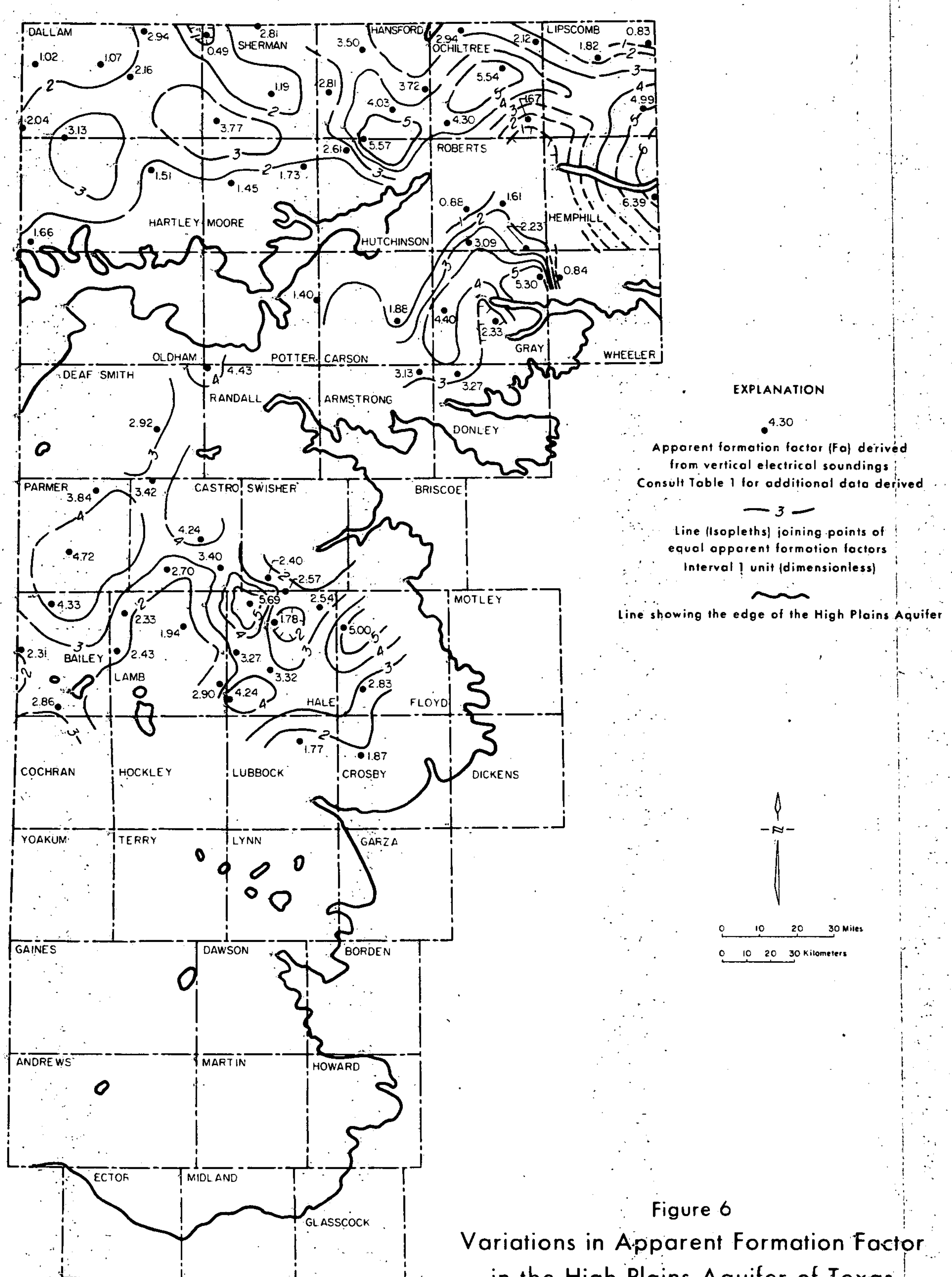


Figure 6
Variations in Apparent Formation Factor in the High Plains Aquifer of Texas

Base from U.S. Geological Survey, 1965

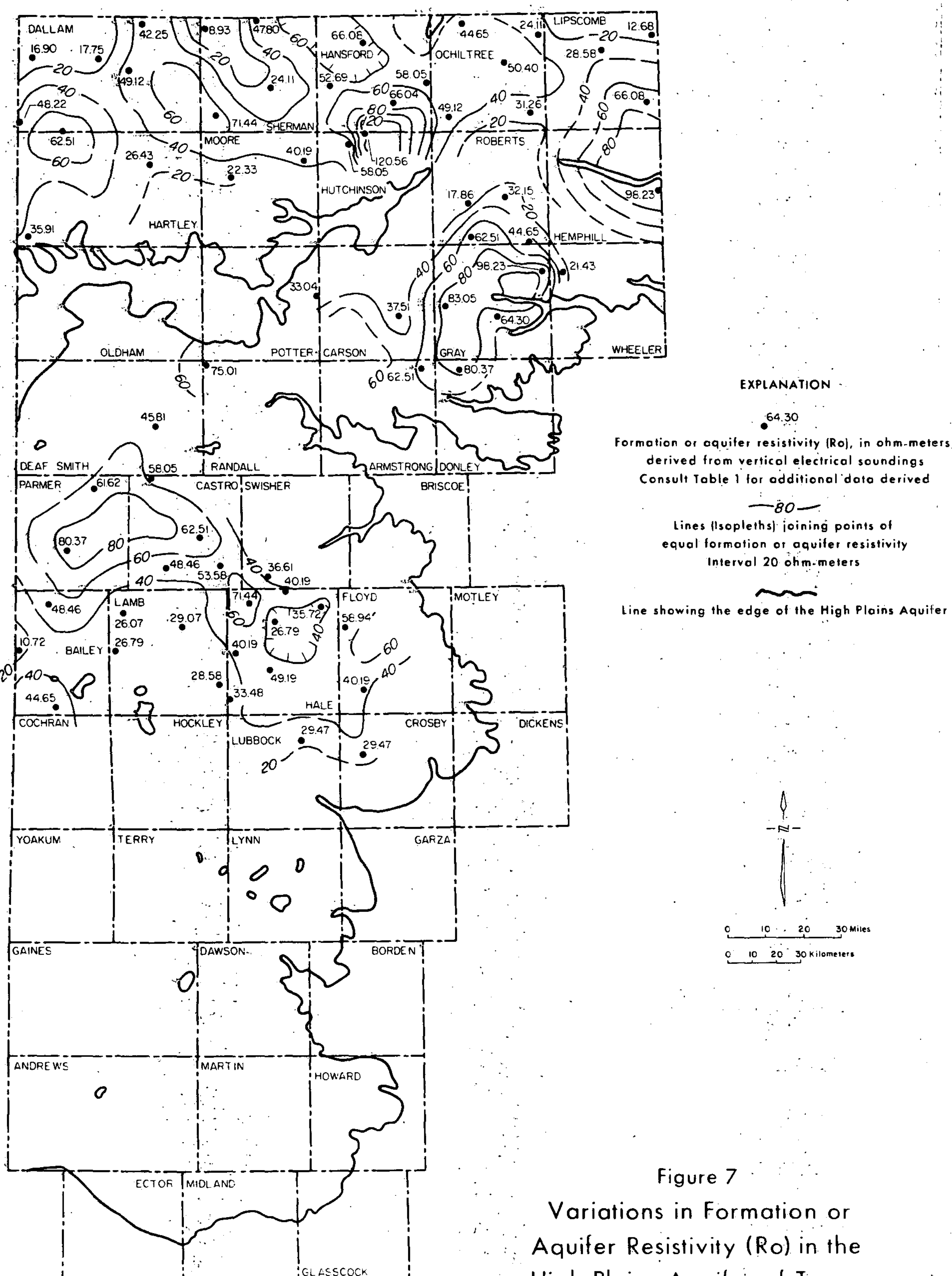


Figure 7
Variations in Formation or Aquifer Resistivity (Ro) in the High Plains Aquifer of Texas

Base from U.S. Geological Survey, 1965

Inspection of Figures 6 and 7 indicates the following with respect to the apparent formation factor and aquifer resistivity isopleths (lines): (a) a noticeable trend of high values extending from northern Hartley and southern Dallam Counties eastward into southern Sherman, Hansford, Ochiltree, and Lipscomb Counties; (b) a prominent, circular high in southwestern Gray County; and (c) a northwest to southeast trend of high values through Parmer, Castro, Hale, and Floyd Counties. An anomaly is shown in north-central Hale County at VES 27. In this instance, the apparent formation factor of 1.78 is low in comparison to surrounding values. Cretaceous sediments which underlie the major portion of southeastern Hale County might influence these respective sounding results.

The above delineated trends indicate favorable areas in which wells would encounter the best aquifer permeabilities and highest specific yields. Examination of Figures 3, 4, and 5 will allow the reader to determine representative aquifer thicknesses in such areas.

SUMMARY

This first attempt by the Department of Water Resources to apply surface electrical resistivity techniques to the High Plains aquifer of Texas appears to have successfully shown that the methods are practicable for indicating the regional variations in the hydrologic properties that control aquifer performance. Permeability, specific yield, and in a general way, variations in overall lithology, were qualitatively shown. Areas of high apparent formation factor (F_a) and high formation or aquifer resistivities (R_o), both of which correspond well with the known areas of high permeability and specific yield, are shown on Figures 6 and 7, respectively.

In most cases, determination of the position of the base of the Ogallala Formation was possible using the resistivity method as determined by geoelectrical modeling.

LIMITATIONS

By its very nature, the surface electrical resistivity method of investigation is restricted to supplying data that support other forms of geohydrological information such as test hole data, water-level measurements, and laboratory analyses. The results of this study are qualitative in nature since laboratory tests were not conducted to determine the effect of clays within the heterogeneous Ogallala Formation and the degree to which current flows through the formation matrix. Quantitative results could be obtained only if the Ogallala Formation were a clean sand or if the effect of its clay were known.

SELECTED REFERENCES

Alger, R. P., (undated), Interpretation of electric logs in fresh water wells in unconsolidated formations: Schlumberger Well Surveying Corporation, Houston, Texas, 25 p. (Presented at Soc. of Prof. Well Log Analysts Symposium, 1966).

American Public Health Association, and others, 1971, Standard methods for the examination of water and wastewater, 13th ed.: Washington, D.C., Am. Public Health Assoc., 874 p.

Barnes, H. E., 1954, Electrical subsurface exploration simplified: Roads and Streets, v. 97, p. 81-84.

Bell, A. E., and Morrison, S., 1978, Analytical study of the Ogallala aquifer in Lubbock County, Texas: Texas Dept. Water Resources Rept. 216, 63 p.

Muller, D. A., and Price, R. D., 1979, Ground-water availability in Texas - estimates and projections through 2030: Texas Dept. Water Resources Rept. 238, 77 p.

Schlumberger Limited, 1973, Log interpretation charts: Houston, Tex., Schlumberger Ltd., 92 p.

Wenner, F., 1916, A method of measuring earth resistivity: U. S. Bureau of Standards Bull., v. 12, p. 469-478.

Worthington, P. F., and Barker, R. D., 1972, Methods for the calculation of true formation factors in the Bunter sandstone of northwest England: Eng. Geol., v. 6, p. 213-228.

Zohdy, A. A. R., Eaton, G. P., and Mabey, D. R., 1974, Application of surface geophysics to ground-water investigations: Techniques of Water-Resources Investigations of the United States Geological Survey, book 2, chap. D1, 116 p.

Zohdy, A. A. R., and Bisdorf, R. J., 1975, Computer programs for the forward calculation and automatic inversion of Wenner sounding curves: U. S. Geol. Survey, Denver, Colo., duplicated rept., 9 p.