UNITED STATES DEPARTMENT OF THE INTERIOR

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Prepared in cooperation with the
TEXAS BOARD OF WATER ENGINEERS
AND THE CITY OF HOUSTON

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BY

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EXPLORATORY WATER-WELL DRILLING IN THE HOUSTON DISTRICT, TEXAS

By N. A. Rose, W. N. White, and Penn Livingston

ABSTRACT

In the spring and summer of 1939 a program of exploratory drilling was undertaken in the Houston district, Tex., in conjunction with a general investigation of the water resources of the district. The main purposes of the program were to determine the thickness and character of the water-bearing sands down to a maximum depth of 2,000 feet, the chemical character of the water at different depths, and the artesian pressures and to provide additional observation wells for studying fluctuations in artesian pressure and possibilities of intrusion of salt water from the direction of the Gulf.

Thirteen deep test wells, 5½ inches in diameter and ranging in depth from 360 to 2,000 feet, were put down with a hydraulic rotary drill by the city of Houston. The combined drilling footage of all of the wells amounted to 17,460 feet, and their average depth was 1,246 feet. All were electrically logged. Samples of cuttings were collected from the drilling mud after every 20 feet of drilling. In 6 of the wells sand samples were obtained by core drilling in beds at selected horizons, about 230 feet being recovered. A total of 15 samples of sand and water were obtained from 8 wells by the drill-stem method. Side-wall sampling was attempted. Six of the test holes were cased with 3½ inch casing (inside diameter) and equipped with screens so that water-level measurements could be made and samples of water collected for chemical analyses. Selected sand samples were analyzed and tested in a field laboratory for mechanical composition, permeability, and porosity. The field and laboratory data were studied with special reference to the significance of the electrical logs.

A comparison of the electrical logs of the test wells with the driller's logs shows that, on the whole, they agree remarkably well in fixing the upper and lower limits of the thicker beds of sand and clay, but that the agreement is not so close where the beds are thin.

Varying results were obtained from attempts to correlate the second curve of the electrical log with the permeability and mechanical composition of the sand samples obtained by core drilling and drill-stem sampling. In the case of the core samples there was no apparent relationship between any of the three characteristics in well 3, but in well 5 a slight but distinct increase in the resistivity was accompaned by a large increase in permeability, and there was a general correlation between the coarseness of the sand and its permeability. In well 6 the resistivity in nearly every case varied with the permeability and coarseness of the samples. In well 6 the drilling mud was local clay enriched with Aquagel, whereas in wells 3 and 5 only local clay was used; the data obtained, however, are too meager to be used as a basis for even a tentative conclusion as to the effect of artificial mud on the correlations. In the 15 drill-stem sand samples the data show that, in general, the resistivity of sands having the same

fluid content varies with but is not proportional to the permeability, but there seems to be little or no relationship between the coarseness of the sands and either the resistivity or the permeability.

Studies of the relationship of the electrical logs to the salinity of the water indicate that increasing chloride is accompanied by decreasing resistivity. They suggest that changes in the chloride content are accompanied by large changes in resistivity when the water contains less than 100 parts per million of chloride and by relatively small changes when the chloride content is over 100 parts per million.

On the whole, the results of the test drilling from Houston tend to show that, although electrical logs give much information that is useful in the development of water wells, for the present at least these logs should be used in conjunction with driller's logs and drill-stem sampling of both sand and water in all the more promising sand horizons.

The tests indicate that an average of 600 feet of water-bearing sands occurs between the surface and a depth of 1,500 feet along the line of test wells west of Houston. A supply of water exists north of Houston in deep sands that are practically untouched by existing wells. The water contained in these sands is suitable for domestic and industrial purposes. Apparently there is no serious danger of salt-water intrusion into the water-bearing sands of the heavily pumped area in the immediate future.

INTRODUCTION

Beginning in the winter of 1930–31, whenever available funds have permitted, the Geological Survey, United States Department of the Interior, in cooperation with the Texas Board of Water Engineers, has carried out a systematic program of ground-water studies in the Houston district, Tex. Eight mimeographed reports summarizing the results of this investigation have been released to the public at various stages in the progress of the work, the first in October 1932 and the last in January 1942. These reports with illustrations and records of several thousand wells in the Houston district and adjacent region have been assembled by the Texas Board of Water Engineers in one large volume and released. The investigations show that if additional supplies of ground water are to be developed in this region they should be obtained outside of the present heavily pumped areas west and southwest of the city, or north and northeast of the city in sands that lie stratigraphically deeper than those from which most of the present ground-water supplies of the Houston district are derived.

In conjunction with the investigations the city of Houston has carried out a program of exploratory drilling. The work was started March 27, 1939, and completed August 6, 1939. Altogether, 13 deep test wells were put down, of which 9 are west of Houston along the Houston-Clodine road; 2 about 15 miles north of the city limits at Westfield; and 2 southeast of the city on the South Houston-La Porte Highway, about 3 miles east of the town of South Houston. (See fig. 11.)

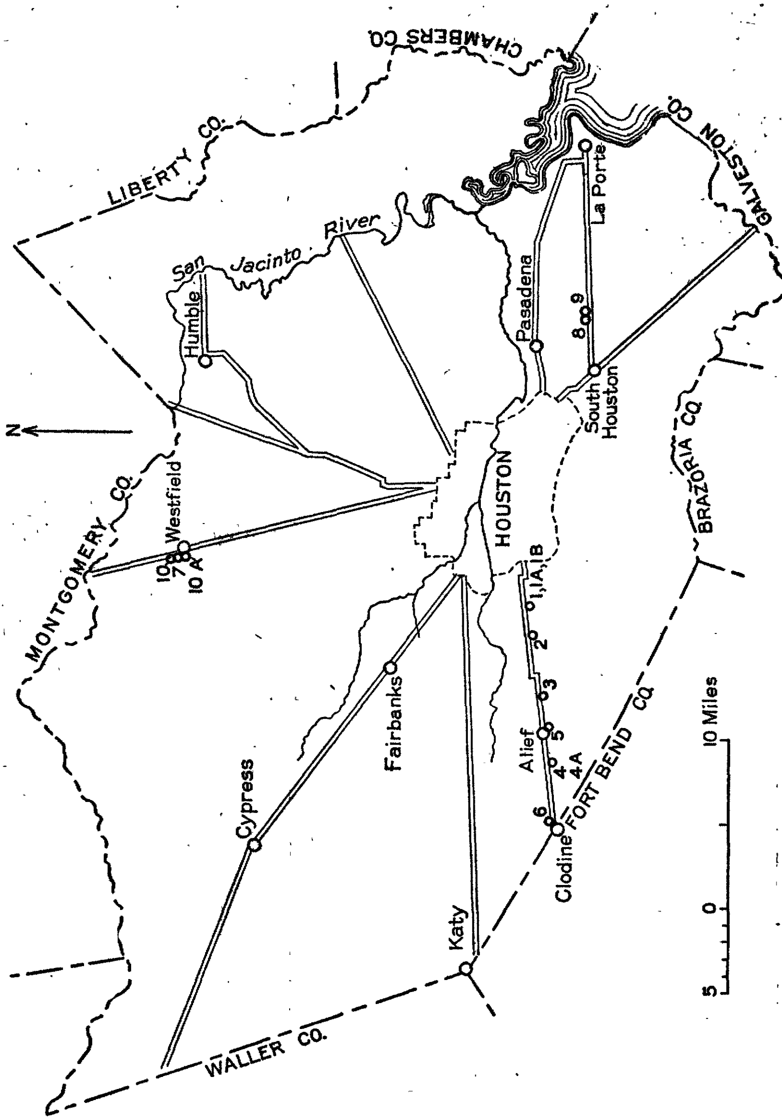

FIGURE 11.—Map of Harris County, Tex., showing location of test wells.

The drilling program had three main objectives, as follows: (1) West of Houston, to determine the thickness and character of the water-bearing sands, the chemical character of the water in them, and the artesian pressure in the sands to a maximum depth of 2,000 feet. (2) North of Houston, to determine the artesian pressure; to obtain observation wells, both in the sands at moderate depth, which correlate with the heavily pumped sands at Houston, and in the deep sands, which are undeveloped or very lightly drawn upon; and to determine the quality of the water. (3) Southeast of Houston, to determine the artesian pressure in the sands containing fresh water and the position and thickness of sands containing brackish or salty water; and by using the test holes as observation wells to obtain advance information on the possible encroachment of salt water from the direction of the Gulf of Mexico.

The test wells were put down with a hydraulic rotary drill. They were 5½ inches in diameter and ranged in depth from 360 to 2,000 feet. The combined drilling footage of all the wells amounted to 17,460 feet, and the average depth was 1,246 feet. All wells were electrically logged as soon as possible after the drilling had been completed. Samples of cuttings were taken from the drilling mud at each 20 feet of depth, and in six of the wells sand samples were obtained by core drilling in beds at selected horizons. Fifteen samples of sands and water were obtained by the drill-stem method from eight of the wells. Selected sand samples were analyzed and tested for permeability and porosity in a special laboratory set up for the purpose. Of the test holes six were provided with 3½-inch casing (inside diameter) and with screens so that periodic water-level observations could be made and the quality of the water tested from time to time. The depth of the deep test wells and their location, screen information, and distance from the city limits are given in the table that follows. The location of the wells is shown in figure 11.

Test wells in the Houston district

Well No.	Location	Distance from Houston city limits (miles)	Depth (feet)	Screen set (feet)	Width of screen opening (inches)	Remarks
1	Houston-Clodine road	2.1 W.	1,761	None		
1 A	do	2.1 W.	456	None		60 feet east of well 1.
1 B	do	2.1 W.	360	None		75 feet east of well 1.
2	do	4.1 W.	1,998	None		
3	do	8.1 W.	1,810	None		
4	do	12.1 W.	1,255	None		
4 A	do	12.1 W.	471	449–464	0.018	1,018 feet north of well 4.
5	Alief	10.1 W.	1,271	1,167–1,182	.015	
6	Clodine	15.7 W.	2,000	None		
7	At Westfield	15 N.	1,063	1,035–1,050	.021	
10	do	15 N.	815			105 feet north of well 7. Abandoned by contractor.
10 A	do	15 N.	815	778–793	.025	75 feet south of well 7.
8	Houston-La Porte Highway.	5.5 SE.	1,856	1,665–1,680	.021	
9	do	5.5 SE.	1,530	1,404–1,419	.021	40 feet east of well 8.

EQUIPMENT AND METHODS USED IN DRILLING WELLS AND MAKING TESTS

The test wells were put down with a truck-mounted rotary drilling rig, the essential parts of which were drilling rods, rotary table, circulating mud pump, power-driven hoisting drum, and a 28-foot folding mast. The rotary table and hoisting drum were driven by the truck motor. An auxiliary six-cylinder motor, mounted directly behind the truck cab, furnished power for the pump. A 5½-inch fishtail bit with two jet openings was used, screwed to the lowest member of the drill stem. The drill rods were 2⅜ inches in outside diameter. This rig was designed for drilling to a maximum depth of 2,000 feet.

Rotary drilling is accomplished by rotating in the hole a drill stem to the bottom end of which is attached a bit or cutting tool that grinds or breaks up the material at the bottom of the hole. This material is carried away by drilling mud, which is pumped from a slush pit at the surface down through the drill stem to the bottom of the well, passes out through openings in the bit and thence upward through the space between the drill pipe and walls of the hole to the surface, where it passes through a ditch in which the sand and other coarse material removed from the hole settle out, and back to the slush pit, for recirculating. Except for a section that extends a short distance below the surface, no casing is used in the hole during operations, and the drilling mud is depended upon to keep the walls of the well from caving.

In connection with the drilling operations at Houston a sluice box approximately 1 foot wide and 12 feet long was placed in the ditch leading from the well to the slush pit. Wood cleats were nailed to the bottom of this box to serve as baffles to collect samples of the sand, silt, and clay brought up with the drilling mud. Samples of this material were collected in cloth bags, and the sluice box was cleaned out after each 20 feet of drilling.

Field tests for chloride were run on all water used in making up the drilling mud and on the mud itself after each 100 feet of drilling. A specially designed low-pressure filter was used to obtain clear samples of water from the drilling mud.

The weight of the mud was determined by means of a Mudwate hydrometer, and its viscosity through the use of a Marsh funnel viscosimeter. These determinations were made at the start of each test hole and repeated after every 100 feet of drilling.

Coring operations were carried out at selected horizons in an effort to obtain undisturbed samples of the water-bearing sands. The cores were 2 inches in diameter and were packed in shallow, hinged-top boxes, 5 feet long and 1 foot wide, divided longitudinally by partitions. The more friable cores were coated with paraffin to prevent crumbling.

In most of the wells samples of the water and sand from at least one water-bearing horizon were obtained by the drill-stem method. Each hole was electrically logged as soon as possible after the drilling was completed.

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Six of the holes were cased with 3½-inch casing (inside diameter), and 15 feet of bronze wire-wrapped screen was placed opposite the sand that was considered the most important from the standpoint of water sampling and water-level observations. The other seven test holes were abandoned.

In a cased well the casing and screen were first set, then the drilling mud was pumped out and the well thoroughly washed by flushing with clear water. It was then equipped with an air-lift pump and alternately pumped for 15 to 20 minutes and shut down for 5 to 10 minutes until it yielded clear water, the time required ranging from 24 to 48 hours. At the close of the pumping operations water samples were taken for chemical analysis, and after the top of the air line had been capped to keep out dirt and debris the well was ready to serve as an observation well for periodic measurements of water levels and for water sampling.

The drilling personnel was made up of a foreman and four crews, each consisting of a driller and two helpers. The work was continuous, each crew working 8 hours a day and 40 hours a week, with an extra, or "swing" crew, taking the remaining 8-hour period needed to complete the week. An engineer from the city water department was at the place of drilling continually. This arrangement proved very satisfactory, because orders and decisions could be given to meet conditions as they arose. A representative of the Federal Geological Survey also was present or quickly available at all times to serve in an advisory capacity in matters pertaining to coring, sampling of the water-bearing sands, and correlation of the strata penetrated by the drill.

A routine procedure was adhered to. At the end of each shift the driller gave to the city representative a detailed log of the formations encountered during the shift. This log was based mainly on the action of the drilling rig. Well cuttings were collected and studied by the senior author. An engineer of the city water department, under the direction of C. R. Harvill, kept a detailed progress report of all the drilling operations, including the drill-stem tests, coring, and electrical logging surveys.

The test drilling was done by the Core Drilling Co. under a contract with the city of Houston. Part of the funds were furnished by the city and part by the Public Works Administration. The work was done on a unit basis, the number of units of drilling, coring, electrical logging, and the like being specified within certain minimum and maximum limits. The maximum depth of the test wells was specified at 2,000 feet. A table showing the cost of various units is given below.

Cost of test drilling

	Number of holes	Number of feet	Unit cost	Total cost
Drilling (5½ in.)	12	16,131.0	$0.85	$13,711.35
Coring (2 in.)	6	229.5	4.00	918.00
Electrical logging	15	20,651.3	.10	2,065.13
Drill-stem tests	8	(1)	215.00	3,226.00
Casing (3½ in.)	6	6,512.2	.85	5,535.37
Water pipe (1 in.)	6	1,157.8	.10	115.78
Wire-wrapped bronze screen	6	90.0	3.50	315.00

1 15 tests.

CORING

In formulating plans for the exploratory drilling it was decided that samples of the water-bearing sands should be obtained chiefly by coring and that these samples should be tested for their mechanical composition and permeability. In this way information regarding the water-bearing qualities of the sands might be obtained, which not only would be of value in itself but also would be useful in interpreting the electrical logs, especially with reference to the degree of correlation between the resistivity and permeability of the sands.

To obtain the cores a conventional coring tool with nonrotating inner barrel was used with various types of core catchers and bits. The first attempts resulted in almost complete failure, apparently because the parts failed to fit properly when the coring tool was assembled. Later this trouble was overcome. At the first test-well location well 1 was drilled to a depth of 1,761 feet and electrically logged to determine the position of the sand horizons. Then supplementary hole 1A was put down, 60 feet away, to a depth of 456 feet, and attempts were made to core successively all the more important sands, the positions of which were indicated by the log of well 1. In this hole, however, only 34 feet of core was recovered out of 161 feet attempted. A second offset hole, 1 B, was drilled 75 feet from well 1 to a depth of 355 feet to obtain core samples from the most important beds missed in the first offset hole. In this hole 26 feet of core was recovered out of 31 feet attempted.

After the completion of well 1 B the procedure of putting down offset holes to obtain cores was discontinued, and cores were taken from the regular test holes as the drilling proceeded. With this plan of operation the selection of horizons for coring proved difficult. In some cases the choice was based on the log of the preceding test hole or other available logs of water wells or oil tests in the area. In other cases the decision was made at the well after the drill bit had penetrated a few feet into a bed of sand. The results were only partly successful, as considerable useless material was cored and some important sand beds were missed. From the standpoint of cost, however, this method proved more satisfactory than the offsetting method.

According to the city's records, 229½ feet of core was recovered by the core barrel out of a total of 417 feet attempted. A careful study of the cores in the laboratory showed, however, that in many wells several inches of cuttings had settled at the bottom of the hole before the core was taken, and this material formed the upper part of the segment removed. The total length of core as determined in the laboratory was 200 feet. Approximately 50 feet of the recovered material consisted of sand that apparently was undisturbed and unaffected by the invasion of drilling mud, but the remainder consisted of clay or of mud-contaminated and disarranged sand.

An opportunity to try a side-wall sampler was offered by the Schlumberger Well Surveying Corporation. In this method of coring, a bullet consisting of a hollow cylinder that serves as a core barrel is fired into the side of the well by means of a powder charge. The device is capable of carrying from 6 to 18 bullets, which are fired separately and at any desired depth by an electrically heated wire that ignites the powder charge. The retrieved cores are ¾ inch in diameter and from 1½ to 2½ inches long, depending on the type of bullet. The recovery of samples by this method in oil wells at the present time is said to be approximately 70 percent.

A six-bullet tool was used at test well 3, two bullets each being fired at depths of 360, 670, and 900 feet. No samples were recovered. The reason for this may have been that the device was developed for coring in oil tests at comparatively great depths, where the rocks are more compact and better cemented than are the unconsolidated fresh-water sands. Perhaps in a short time this side-wall sampler and other similar devices that are now being used successfully in the oil industry will be adapted to coring at shallow depths.

DRILL-STEM TESTS

Drill-stem tests to obtain water and sand samples were made with the Howco tester and performed by the Halliburton Oil Well Cementing Co. The tester consists of a narrow metal barrel about 10 feet long, which is attached to the drill stem in the same way as the drill bit. The apparatus is equipped with an inlet valve that can be opened or closed from the surface, a heavy sleeve of rubber that serves as a packer, and an anchor of adjustable length. When the depth at which sampling is desired has been determined the anchor is adjusted so that it touches the bottom of the hole when the testing barrel is opposite the sand to be sampled. The weight of the drill stem causes the rubber sleeve to expand, sealing off the mud above it. Then the valve, which has been closed while the apparatus was being lowered into the well, thus preventing drilling mud from entering the pipe, is opened, and drilling mud, water from the sand in the isolated section, and considerable quantities of the sand, enter the empty drill pipe under pressure. The valve usually is allowed to remain open from 10 to 20 minutes and is then closed. The packer is freed by removing the weight of the drill stem from the barrel, and the entrapped fluid is brought to the surface. In some of the deeper holes drilled during the exploratory work near Houston sufficient water entered the tester to fill several hundred feet of drill stem, and the upper part of the water column was usually contaminated with the drilling fluid. This muddy water was disposed of, and the water in the remaining sections emptied into barrels. The last two barrels of water thus obtained were considered to be true samples of the formational water. The water in these barrels was allowed to stand overnight to permit the suspended sand, silt, and other material to settle out, after which samples were taken for chemical analysis. The bottom lengths of drill pipes usually contained a large amount of sand, representative samples of which were taken to the laboratory for mechanical analyses and tested for permeability and porosity.

Devices were used in conjunction with the drill-stem tester for registering temperature and pressure, but, being calibrated for the wide ranges in both temperature and pressure that occur in deep oil tests, they did not register accurately enough to give information of much practical use in the comparatively shallow holes put down in the Houston investigation.

ELECTRICAL LOGGING

In 1928 the Schlumberger Well Surveying Corporation started the development of a series of procedures for studying in place the resistance of the beds penetrated by drill holes before the casing is placed and for interpreting the results in terms of the character of the beds and the nature of the liquids or gases contained in them. This procedure is called "electrical coring" or "electrical logging." At present electrical logs are obtained in most oil tests put down in Texas and in many water-well tests. The logging units are mounted on trucks and provided with enough cable for testing wells several thousand feet deep. The cable is a multiple conductor and supports the electrode carrier, which is usually about 3 inches in diameter and from 10 to 15 feet long. Electrical measurements are recorded as the carrier is lowered into or withdrawn from the well. The measurements are calibrated to show the units of resistivity of the different beds.

It should be borne in mind that these resistivity values are not the actual resistivity of the material logged but the apparent resistivity, which approaches the true resistivity only when the electrode spacing is much less than the thickness of the bed. Figure 12, reproduced

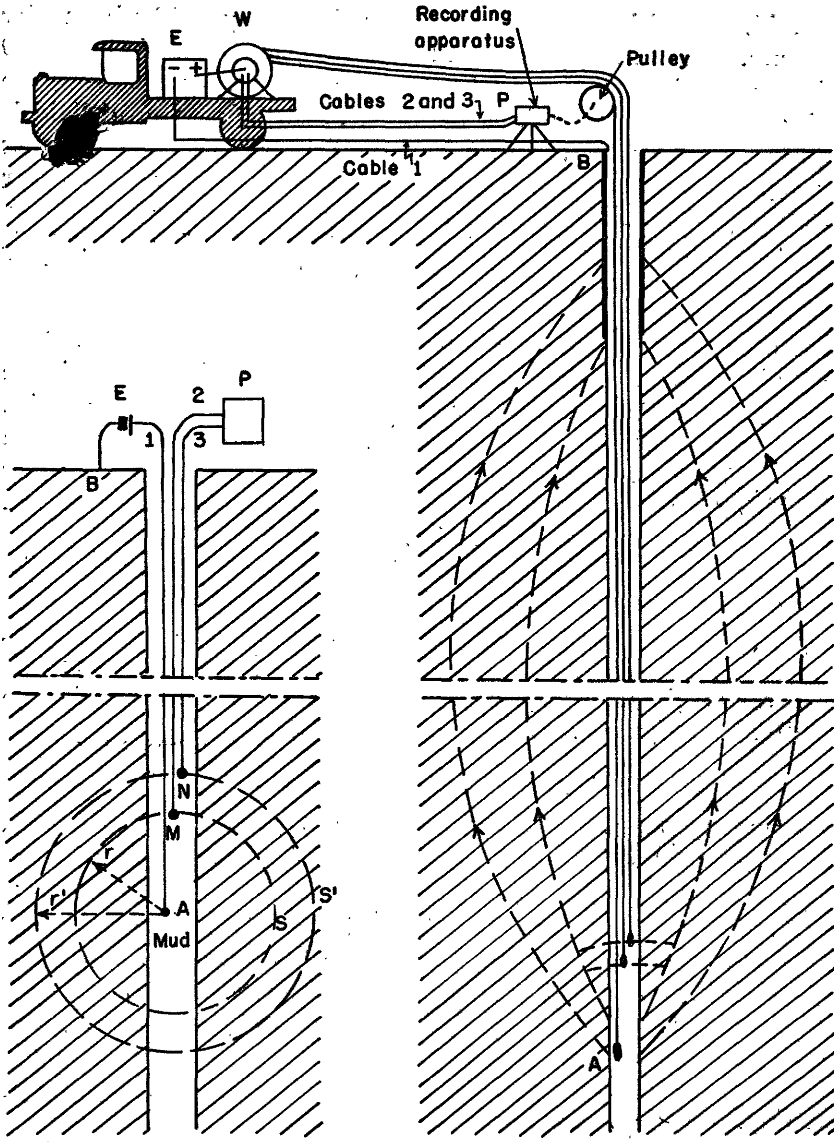


FIGURE 12.—Diagram showing schematically the arrangement of electrodes used in electrical logging. (After Schlumberger.)

from a sketch by Schlumberger and Leonardon,[1] shows schematically a three-electrode logging device and illustrates its operation. Three electrodes, A, M, and N, attached to three conductors 1, 2, and 3, as shown in the sketch at the left in figure 12, are lowered into the well.

[1] Schlumberger, C. and M., and Leonardon, E. G., Electrical coring: A method of determining bottom-hole data by electrical measurements: Am. Inst. Min. Eng. Trans., vol. 110, p. 240, 1932.

A current is passed from a battery E through conductor 1 to electrode A and thence back through the earth to the battery, which is grounded at B. In order to measure the differences of potential between M and N, the insulated conductors 2 and 3, to which they are attached, are connected to the terminals of potentiometer P, at the surface. Then, knowing the values of r, r', the intensity i of the current, and the potential difference V between M and N, the apparent resistivity of the formation in the region between S and S′ of the measuring device A M N may be calculated.

In practice the conductor cables are woven together into a single cable, which is wound up on a winch mounted on a truck, as shown at the right in figure 12. From the winch, cable 1 is connected with battery E, which is grounded through the surface casing, and cables 2 and 3 are connected with the potentiometer. The resistivity of the rocks is expressed by the Schlumberger Well Surveying Corporation in ohms per meter square meter (ohms m^2m), a unit suitable for practical purposes, giving figures between one and several thousands.

The distance between the electrodes governs the distance that the currents penetrate beyond the bore of the well, and by adding more electrodes, more curves can be obtained. In the Houston program three resistivity curves were obtained with each log, which, according to the electrical logging company, represented resistances at 3, 6, and 10 feet, respectively. The electrode separation should be large enough to allow the current to penetrate beyond the part of the beds invaded by the drilling mud, thus determining more nearly the true resistivity of the formation.

In addition to readings of the resistivity, the apparatus gives values for the earth current or natural "self potential," that occurs spontaneously in the drilled hole. These readings are obtained by means of a potentiometer in a circuit consisting of an insulated cable leading from one of the moving electrodes to the fixed electrode or ground at the surface near the well.

Values for the resistivity and self-potential in a well, can be obtained with simple electrical instruments, but in order to make quick commercial surveys, devices are used that automatically record the value optically, photographically, and mechanically. The recording apparatus is much too complicated to describe in this paper.

The brief explanation given below of the use of electrical logging in differentiating between rocks is taken largely from a paper by Mathieu and associates.[2]

The resistance of a formation to the passage of an electric current is used in electrical logging to differentiate the geologic formations,

[2] Mathieu, J. L., and others, Houston Geological Society Study Group, Electrical well logging: Am. Assoc. Petroleum Geologists Bull., vol. 23, No. 9, pp. 1297–1298, 1939.

because this property varies widely from one formation to another. This difference is not dependent upon the mineralogic make-up of the rock but on its physical characteristics and the solutions it contains. In general, the resistivity curves may be classified in four groups, as given below:

1. High resistivity in permeable formations that contain in their interstices fluids, such as fresh water, sulfur water, or oil and gas, that have a more or less high resistance to the passage of electric currents.

2. Low resistivity in permeable formations that contain in their interstices saline water, which is electrically conductive.

3. High resistivity in nonpermeable formations, generally dense, compact rocks with low porosity, which contain only small amounts of water and are therefore poor conductors; examples are anhydrite, coal, lignite, rock salt, and the like.

4. Low resistivity in nonpermeable formations, such as shales and clays, which usually contain in their minute pore spaces considerable amounts of water that is mineralized and is therefore a good electrical conductor.

The first electrical log consisted only of a resistivity curve, but in the course of making logging surveys new and important phenomena have been discovered, and the more modern logs have four curves—a self-potential curve and three resistivity curves. The self-potential curve is based on measurements of the minute voltages spontaneously generated in the hole itself.

The recorded potential is assumed to be the algebraic sum of two components—(1) the electromotive force established by the infiltration between the drilling mud column and the fluids in the permeable formations, acting across the mud cake, and (2) the electro-chemical potential which occurs wherever there is a difference in the salt content of the drilling fluid and the water in the formation.

The electrical logs of the Houston test drilling shown in plates 12–14 consist of three graphs, or curves as they are generally called, plotted on the same vertical scale and a comparable horizontal scale. At the extreme left is the first or self-potential curve which aids in distinguishing between permeable and less permeable beds and in determining the type of solutions contained in them. The next curve to the right is the second or normal resistivity curve, which records the resistance to a current that is supposed to penetrate laterally not more than 3 feet from the drill hole. In the opinion of some geologists this amount of penetration is inadequate and may lead to misinterpretation of the graph, because in permeable beds the resistivity is affected by invasion of the drilling mud. The third curve, which closely parallels the second, is shown by a dotted line. It is supposed to record the resistance at a maximum lateral penetration of about 6 feet, which is probably more than the drilling mud usually penetrates. A fourth curve not shown on these electrical logs was obtained with a greater electrode spacing and is said to represent a penetration laterally of about 10 feet. The resistivities shown in this curve are supposed to be those of the rocks penetrated by the well, modified slightly, if at all, by the effects of the invasion of the drilling mud into the sands. It is possible, however, that mud invasion may modify the values somewhat if the sands are highly permeable. All the curves are subject to limitations and need to be interpreted with care.

Plates 12–14 show the first, second, and third curves recorded in the logs of the six test wells along the Houston-Clodine road, near South Houston, and the two at Westfield. Plate 15 shows these curves in their relation to the beds from which the drill-stem samples were taken.

Increasing resistivity is indicated in curves 2 and 3 by a swing of varying amplitude to the right, and decreasing resistivity by a swing in the opposite direction. In unconsolidated deposits, such as those encountered in the test wells, very high resistivity in all cases probably indicates sand containing fresh water, and very low resistivity indicates clay, a mixture of silt and clay, or sand containing highly mineralized water. The interpretation of the intermediate resistivities, however, is generally conceded to be more difficult. In comparison with beds containing fresh water, beds containing brackish or salty water generally give low resistivity values in sand and high values for the self-potential (indicated by an abrupt swing of curve 1 toward the left). Salt or brackish water is also supposed to be indicated when the resistivity values recorded in curve 3 are abnormally low in comparison with those in curve 2. In the Houston program, as previously explained, the electrical logs were checked as fully as practicable by means of the driller's logs, core drilling, and drill-stem tests.

DRILLING MUD

The drilling mud serves to carry away the cuttings and to keep the sides of the drill hole from caving in. It also helps to confine water to the beds in which it occurs and to lubricate and cool the drill pipe and bit. Two kinds of drilling mud were used, mud made from clay obtained at or near the test holes and mud from local clay to which was added Aquagel, a drilling clay prepared from processed bentonite containing a high percentage of gel-forming colloids. In drilling shallow holes local mud ordinarily meets the requirements, but in deep wells mud made from local clay may fail to support the sides of the hole and it may become necessary to improve the properties of the mud and give it better performance. There are several kinds of commercial clay on the market, each of which is reported to have special advantages in drilling. Aquagel was mixed with the local clay in wells 1A, 1B, 4, 6, 7, and 10.

LABORATORY DETERMINATIONS

A laboratory was set up in the abandoned North Side city pumping plant in Houston for the purpose of making mechanical analyses and for testing the permeability and porosity of sand from core and drill-stem samples. The laboratory was equipped with a mechanical shaker, a set of United States standard sieves, portable permeameter, balances, electrical hot plate, sample pans, and other equipment.

All cores that were badly impregnated with drilling mud were discarded. Some of the slightly contaminated cores were studied, however, after the outside mud-invaded portion had been scraped off. The sections selected for testing were divided into lengths of approximately 6 inches and broken down, care being taken to avoid crushing the sand grains. Each large drill-stem sample was well mixed, and from it smaller samples were selected for testing. Both the core and drill-stem samples were thoroughly dried on a hot plate and divided into two parts, one of 100 grams for mechanical analysis and another of 200 to 300 grams for permeability and porosity tests. The methods used are discussed below.

MECHANICAL ANALYSES

A set of 10 sieves was used for the mechanical analyses, the openings being as follows:

Mesh	*Size of opening (millimeters)*	*Mesh*	*Size of opening (millimeters)*
20	0.84	70	0.210
30	.59	80	.170
40	.42	100	.149
50	.297	120	.125
60	.250	More than 120	Less than .125

Each sample was shaken by hand until examination of the residue on each screen indicated that the core had been completely disintegrated. The sieves were then shaken in the mechanical shaker for 20 minutes. The parts of the material retained on each screen and that passing all the screens were weighed separately and calculated as percentages of the total sample. These data were plotted on block diagrams (histograms). The diagrams giving the results of analyses of core samples from wells 3, 5, and 6 are shown in figures 13 and 14 and plate 16, respectively. The results of the mechanical analyses of the drill-stem samples are given in the table that follows.

Mechanical analyses of sand samples from drill-stem tests

Test well No.	Depth of sample below surface (feet)	Percent by weight of particles having diameter (mm.) of—									
		More than 0.84	0.84 to 0.59	0.59 to 0.42	0.42 to 0.297	0.297 to 0.250	0.250 to 0.210	0.210 to 0.170	0.170 to 0.149	0.149 to 0.125	Less than 0.125
1A	438– 467	4.4	8.6	33.0	34.9	8.9	4.9	0.7	0.7	0.4	2.4
	1,009–1,031	--------	.1	.6	2.5	4.1	17.0	13.5	18.5	9.8	33.7
	1,437–1,464	--------	--------	.6	7.9	7.2	26.9	15.7	19.9	12.3	10.0
2	1,653–1,669	--------	--------	3.3	26.3	25.5	30.5	7.4	3.6	0.9	1.3
	1,808–1,820	--------	--------	1.0	15.3	18.7	32.5	10.2	10.3	5.3	5.4
	1,943–1,998	--------	--------	.3	2.0	4.1	24.7	20.3	23.4	10.5	13.4
3	1,766–1,810	.3	.2	.4	1.7	4.6	21.5	10.5	18.2	17.7	24.7
4	1,203–1,230	--------	.2	3.3	35.3	25.8	19.3	5.7	6.2	3.4	2.3
6	1,684–1,704	.3	1.0	8.6	39.3	18.4	16.6	5.7	7.0	2.2	1.2
	1,970–2,000	--------	--------	.1	4.4	8.8	27.7	14.8	19.3	11.0	13.7
7	583– 617	.2	.6	8.5	33.7	21.2	21.9	5.4	3.8	1.7	3.0
	1,193–1,222	--------	.1	.3	1.5	3.2	17.6	12.3	24.2	20.7	20.0
8	1,666–1,706	--------	.1	.3	3.4	9.8	46.0	18.3	12.8	2.7	6.3
	1,832–1,850	--------	.2	2.4	14.5	14.6	29.6	13.5	13.8	6.5	5.0
9	1,506–1,526	--------	--------	.1	2.0	4.4	22.2	12.8	16.2	13.8	28.4

PERMEABILITY TESTS

The permeability determinations were made with a permeameter of the discharging type. This apparatus[3] consists of a brass cylinder that has a screen at its base. The bottom of the cylinder is connected to a graduated manometer by means of a copper U-tube. The manometer extends above the top of the percolation cylinder and serves as a reservoir. The sample is well tamped in the percolation cylinder and the manometer and U-tube are filled with water. The water percolates upward through the sand and flows over the edge of the cylinder, and as this takes place the water level in the graduate tube lowers continuously at a decreasing rate. The coefficient of permeability may be determined from the time necessary for the meniscus in the manometer to move from one graduation to the next. This coefficient is defined as the flow in gallons per day through a square foot of cross section under unit hydraulic gradient at 60° F. The coefficients of permeability as determined from the tests ranged from about 1 to 50 in the core samples (see figs. 13 and 14 and pl. 16) and from 40 to 800, averaging about 275, in the drill-stem samples. (See table below and pl. 15.)

Coefficient of permeability of drill-stem samples obtained in Houston test drilling

Well No.	Depth of sample below surface (feet)	Coefficient of permeability	Well No.	Depth of sample below surface (feet)	Coefficient of permeability
1A	438– 467	800	6	1,684–1,704	80
	1,009–1,031	120		1,970–2,000	40
	1,437–1,464	285	7	583– 617	195
2	1,653–1,669	375		1,193–1,222	135
	1,808–1,820	340	8	1,666–1,706	200
	1,943–1,998	260		1,832–1,850	340
3	1,766–1,810	75	9	1,506–1,526	170
4	1,203–1,230	530			

[3] Fishel, V. C., and Stringfield, V. T., Apparatus for testing the permeability of samples of unconsolidated sediments in the field: U. S. Geol. Survey, April 19, 1937. [Mimeographed.]

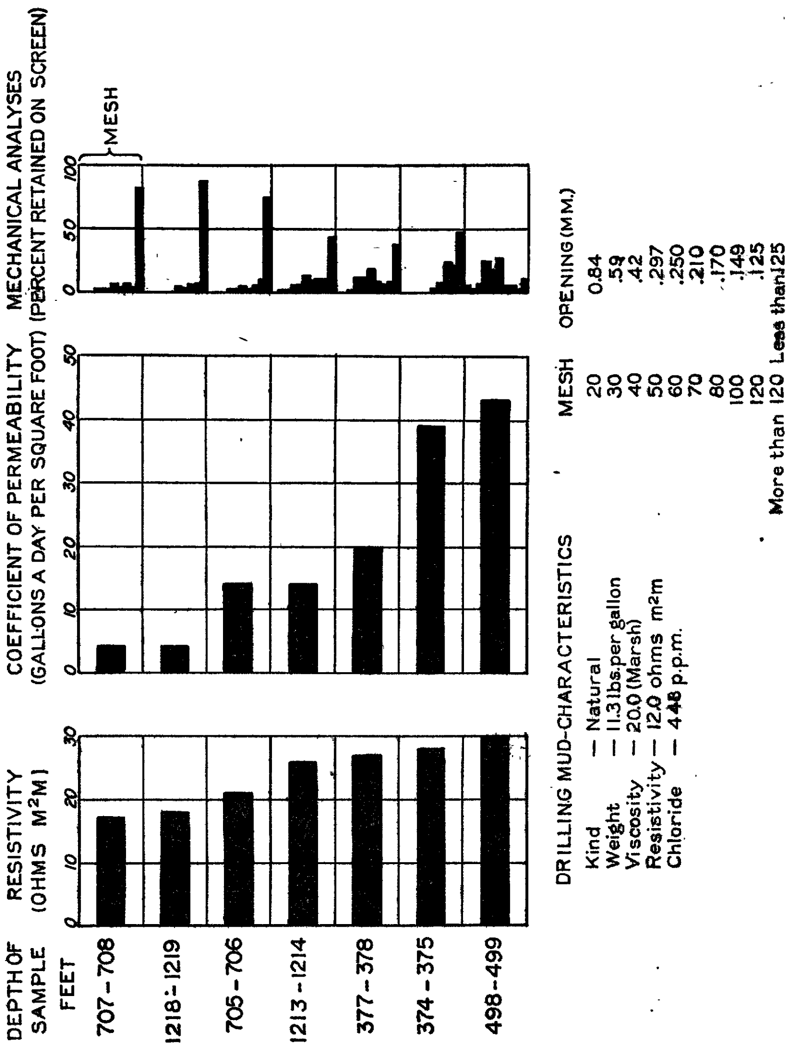


FIGURE 18.—Diagram showing for well 3 relation between resistivity recorded in electrical log (second curve) and permeability and grain sizes of core samples.

POROSITY DETERMINATIONS

The samples used in the permeability determinations were tested for porosity by the following method: The sample was oven dried, then packed in the cylinder of the permeameter and weighed. The permeability test was made, and the cylinder and the saturated sample were reweighed. The difference between the weight of the dried sample and cylinder and that of the saturated sample and cylinder represented the amount of water contained in the pore spaces of the sample. The porosity (P) expressed as a percentage, is determined by the formula $P=100\frac{w}{V}$, in which V is the volume of the cylinder, in this case 133 cubic centimeters, and w is the weight of the water in

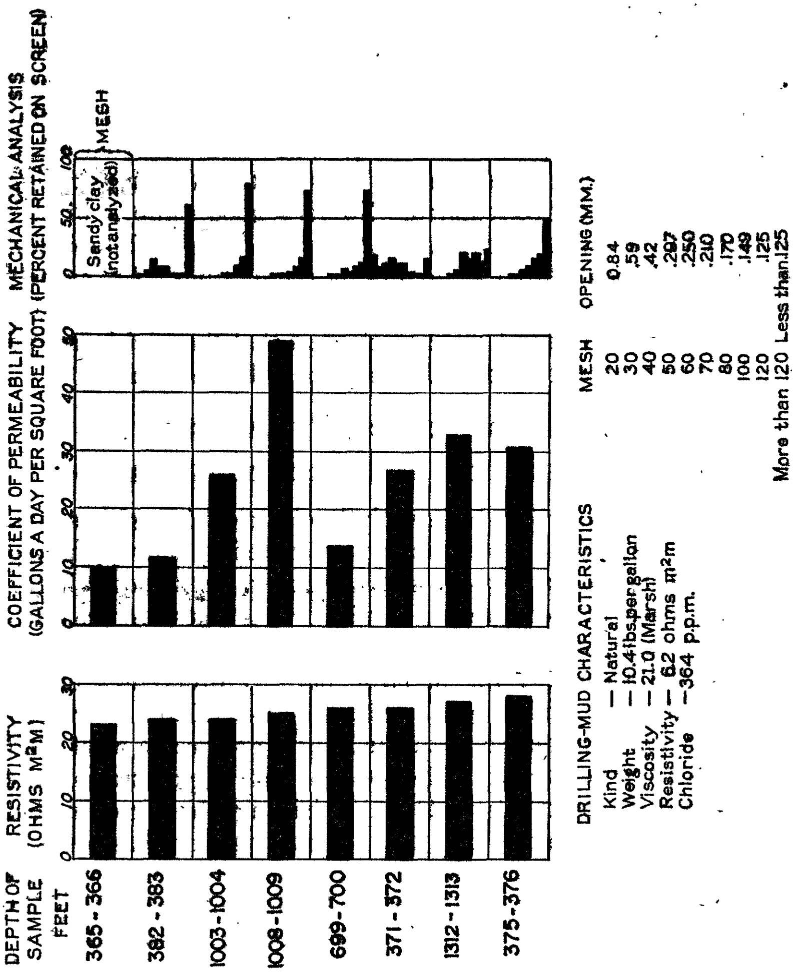


FIGURE 14.—Diagram showing for well 5 relation between resistivity recorded in electrical log (second curve) and permeability and grain sizes of core samples.

grams. The results of the porosity tests of the drill-stem samples are shown in plate 15.

MICROSCOPIC EXAMINATION OF CUTTINGS

Approximately 800 samples of cuttings collected at intervals during the drilling operations were examined under a binocular microscope. The color, texture, and type of material contained in each sample was described, and a log of each test hole was compiled. These logs, however, were unsatisfactory and could not be correlated closely with either the drillers' logs or the electrical logs. Depth was estimated on the basis of the time required for the material to reach the surface.

The formations drilled near Houston are of different geologic ages, but constitute a thick series of interbedded sands and clays with essentially the same sedimentary and lithologic character. As the shape and composition of the sand grains were essentially the same at all depths, these characteristics did not serve to distinguish individual beds or horizons. Despite the fact that many of the samples obviously came from beds of clay, all contained considerable amounts of fine sand, which probably represented that part of the sand from all of the overlying formations which was too fine to settle out of the drilling mud and was therefore recirculated. No very good samples of clay were obtained from the cuttings. Most of them had fine sand imbedded in them and had been altered in texture by the drilling. Apparently the clay cuttings were pulverized by the drill and in part were added to the circulating mud, as indicated by the fact that the mud increased materially in weight when the drill was in thick beds of clay.

COMPARISONS AND CORRELATIONS

COMPARISON OF ELECTRICAL LOGS WITH DRILLERS' LOGS

A comparison of the drillers' logs with the electrical logs shows that, on the whole, they agree remarkably well in fixing the upper and lower limits of the thicker beds of sand and clay, but the correlation is not so close where the beds are thin. It is obvious that the correlation is closer in some wells or parts of wells than in others. This, it is believed, can be accounted for in large part by differences in the experience of the well drillers employed on the job. The driller must depend mostly upon the action of the drilling rig to decide what kind of material is being penetrated. He notes the rate of penetration, the power necessary to rotate the tools while drilling, the force exerted by the pump to circulate the mud, and the cuttings that are brought up by the drilling mud. After he becomes acquainted with the action of the rig and the formations encountered, his log becomes more reliable as a means of differentiating the formations penetrated.

CORRELATION OF SECOND CURVE OF ELECTRICAL LOGS WITH STUDIES OF CORE SAMPLES

The main purpose of the core drilling and laboratory testing of the core materials was to study the relation between the permeability and mechanical character of the sands obtained in the core drilling and the resistivity recorded by the electrical log at the same depth.

The data obtained from wells 3, 5, and 6 were selected for this study because of the large amount of coring done in them and the high percentage of core recovered. In figures 13 and 14 and plate 16 the coefficients of permeability and the mechanical analyses of the core samples obtained at different depths in these wells are compared graphically with the resistivity recorded in the second curve of the electrical log. It should be noted that the resistivity values are plotted in the order of magnitude and not according to the depths of the observations, the lowest resistivity being at the top of the diagram and the highest at the bottom. In well 3 (fig. 13) there was no apparent relationship between any of the three quantities. The permeability and coarseness of the sand samples varied within fairly wide limits, but not in harmony with each other, and the resistivity was practically the same opposite all the sand beds sampled. In well 5 (fig. 14) a large increase in the permeability was accompanied by a slight but distinct increase in the resistivity, and there was a general correlation between the coarseness of the sand and its permeability. In well 6 (pl. 16) the resistivity recorded in the second curve in nearly every case varied with the permeability and coarseness of the samples.

Considerable thought has been given to the question of why the correlation between the permeability, size of grain, and electrical resistivity recorded in the second curve was so much closer in well 6 than in either well 3 or 5. Aquagel mixed with local clay was used in drilling well 6, but local clay alone was used in wells 3 and 5. The explanation may lie, in part, in that fact. When drilling mud penetrates into a formation it tends to reduce the resistance in the permeable beds and therefore to diminish the difference between the resistances of the various formations. Hence, sand and clay should be more easily distinguished when a processed bentonite, such as Aquagel, is used because the penetration of mud thus fortified is almost negligible.

Under all the above conditions it is conceivable that a closer correlation between permeability and resistivity may be revealed if a good processed bentonite is used in the drilling mud. The data obtained on this subject in the present investigation, however, are too meager to be used as a basis for even a tentative conclusion. Further studies of the effect of using artificial mud are needed.

In plate 15 are shown the results of the laboratory test of 15 drill-stem samples of water and sand obtained from 8 wells during the drilling program. At the right of the diagram are given the chloride content of the water samples, in parts per million; the permeability of the sand, in gallons per day; the porosity of the sands, in percent by volume; and mechanical analyses, indicated by histograms. At the left of the figure are shown the self-potential curve and the second and third curves of the electrical logs, including the part opposite the beds from which the drill-stem samples were taken. At the center of the diagram is shown graphically the thickness of the beds sampled by the drill-stem method.

The correlation and study of these data lead to the conclusion that, in general, the resistivity recorded opposite the beds varied with the permeability of the sands from these beds but the magnitude of the resistivity was not directly proportional to the permeability of the material, small differences in the chemical character being neglected. As shown in plate 15 the highest permeability and nearly the highest

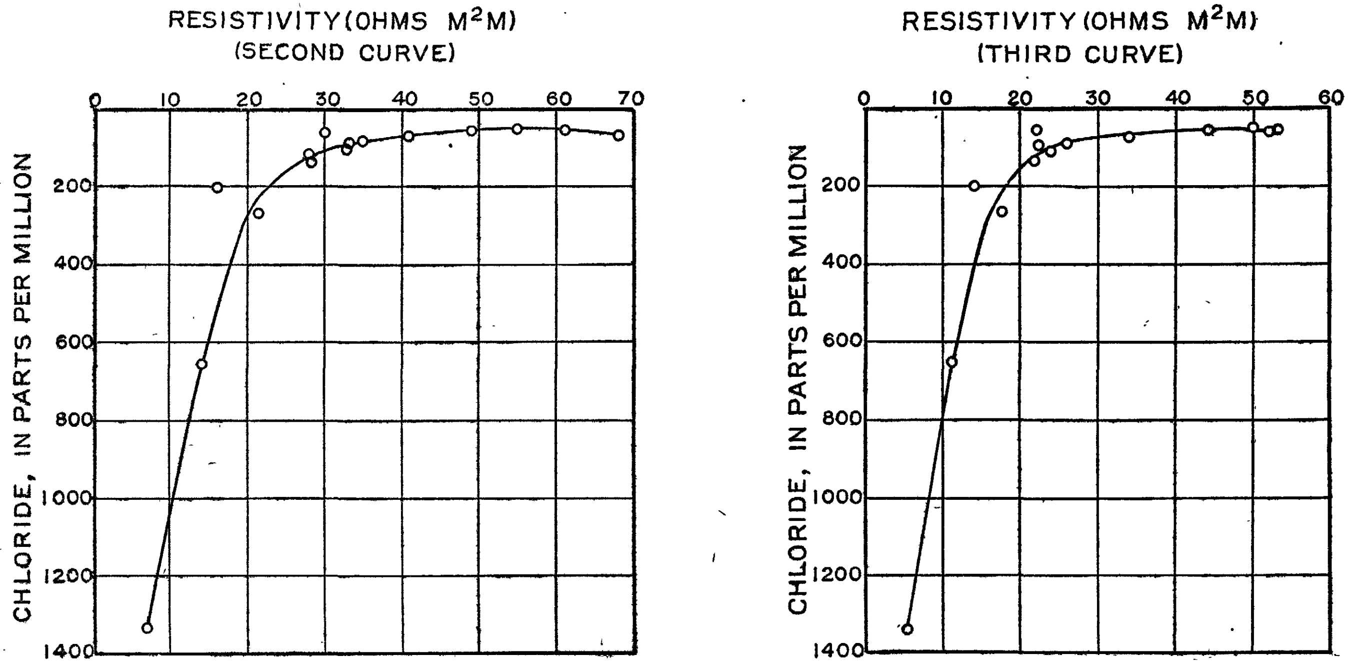
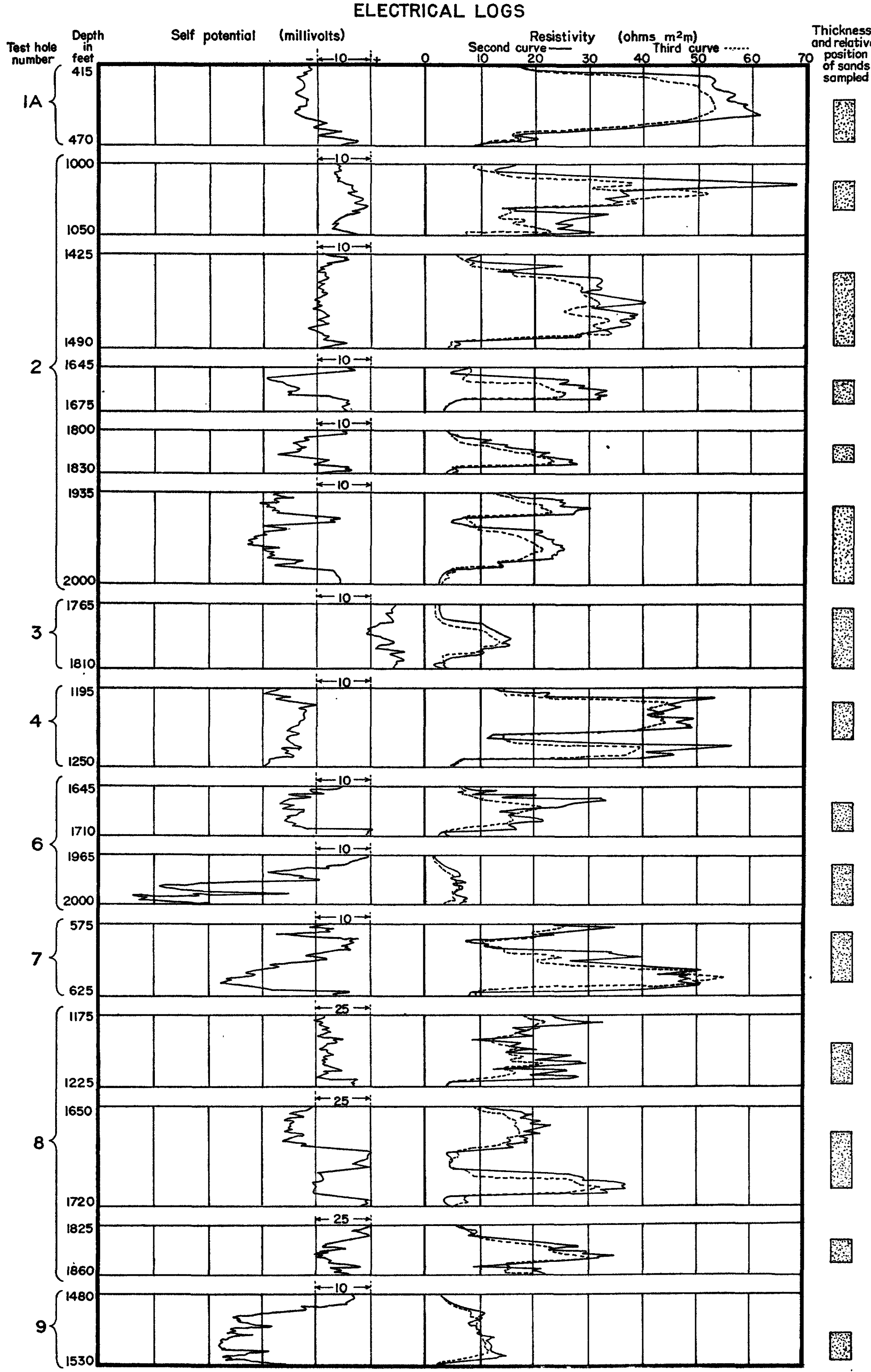


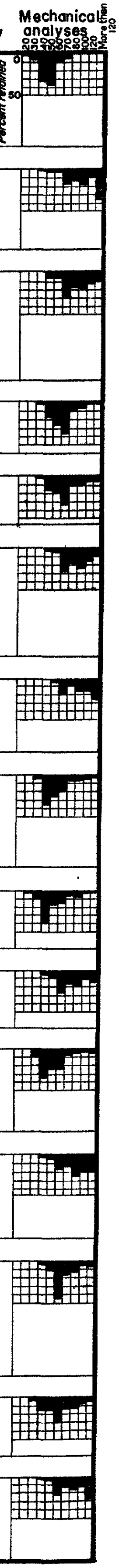
FIGURE 15.—Relation of chloride in water obtained from test wells by drill-stem sampling to resistivity recorded at the same depths by the electrical log.

ELECTRICAL LOGS

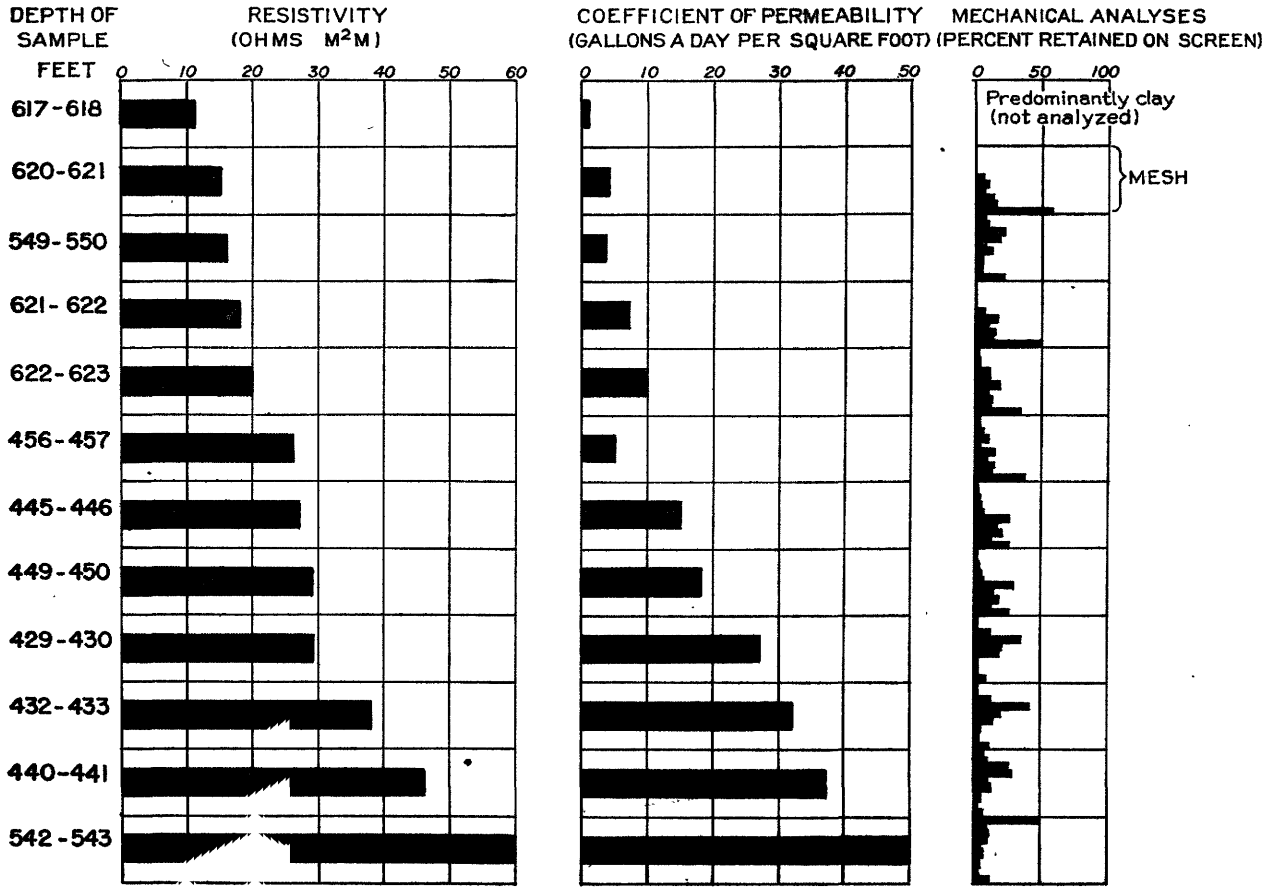


LABORATORY DETERMINATIONS

Test hole number	Depth in feet	Cl p.p.m.	Coefficient of permeability g.p.d./sq.ft.	Porosity (percent by volume)
1A	415–470	54	800	40.5
2	1000–1050	62	120	38.2
2	1425–1490	73	285	41.2
2	1645–1675	89	375	40.5
2	1800–1830	111	340	40.0
2	1935–2000	133	260	40.9
3	1765–1810	199	75	44.6
4	1195–1250	54	530	34.9
6	1645–1710	97	80	37.7
6	1965–2000	1281	40	36.6
7	575–625	51	195	36.6
8	1175–1225	51	135	40.5
8	1650–1720	290	200	39.2
8	1825–1860	89	340	37.7
9	1480–1530	652	170	40.5



RELATION OF ELECTRICAL LOG TO CHARACTER OF WATER AND SAND IN DRILL-STEM SAMPLES.



DRILLING-MUD CHARACTERISTICS

Kind	— Aquagel
Weight	— 10.6 lbs. per gallon
Viscosity	— 24.0 (Marsh)
Resistivity	— 8.2 ohms m²m
Chloride	— 56 p.p.m.

MESH	OPENING (MM.)
20	0.84
30	.59
40	.42
50	.29
60	.25
70	.210
80	.170
100	.149
120	.125
More than 120	Less than .125

DIAGRAM SHOWING FOR WELL 6 THE RELATION BETWEEN RESISTIVITY RECORD IN ELECTRICAL LOG (SECOND CURVE) AND PERMEABILITY AND GRAIN SIZES OF CORE SAMPLES.

resistivity were recorded in well 1A at 413 to 470 feet, and the next highest permeability and a high resistivity in well 4 at 1,195 to 1,200 feet. The lowest permeability and lowest resistivity as well as the highest chloride content were found in well 6 at 1,965 to 2,000 feet. The results in the other wells seem to show similar relationships, with two exceptions, well 2 at 1,000 to 1,050 feet and well 7 at 575 to 625 feet. There seems to have been little or no relationship between the coarseness of the sands and either the permeability or resistivity.

CORRELATION OF ELECTRICAL LOGS WITH SALINITY OF THE WATER

In figure 15 the chloride in water from all the drill-stem water samples is plotted against the maximum resistivity recorded in the second and third curves opposite the beds from which the samples were taken. A study of these graphs seems to point to the conclusion that even a moderate increase in the chloride in the water tends to reduce the resistivity of the beds as recorded by the electrical logs.

As already noted the permeability of the water-bearing beds, the character of the drilling mud, and other factors affect the resistivity, and for most of the wells sampled only a part of these data are available. The most complete records were obtained in wells 8 and 9 and are given below.

A comparison of the values shown in the first, third, and fourth lines of the table tends to show that the resistivity at those depths was affected more by the salinity of the water than by the permeability of the sand. (See fig. 15.)

Relation of the resistivity to chloride content of water from test wells 8 and 9

Depth of sampling (feet)	Chloride content (parts per million)	Permeability (gallons per day)	Resistivity (ohms m²m)	
			2d curve	3d curve
1,198–1,222	47	135	30	25+
1,399–1,414	208		26	22
1,506–1,526	645	170	14+	12
1,666–1,706	268	200	23+	18
1,832–1,850	82	340	34	31

The effect of the chloride content on the electrical log can be seen in the logs of test wells 8 and 9. (See fig. 15.)

In plate 15 the maximum resistivity recorded in the second or third curve of the electrical log is plotted against the chloride content of the water at that depth as shown by the drill-stem samples from all the test wells. For the most part the salinity of these samples was low, being less than 100 parts per million in nine of them, but ranging from 111 to 1,330 parts per million in the remaining six. The graphs indicate that increasing chloride content is accompanied by decreasing resistivity and that when the chloride concentration in the water is less than 100 parts per million, changes in the chloride content are accompanied by relatively large changes in resistivity but that when the chloride concentration is more than 100 parts per million, changes in chloride content are accompanied by smaller changes in resistivity. The two graphs in plate 15 are similar but the third curve shows that resistivity between these electrodes is influenced more by changes in chloride content.

The presence of saline water is also revealed by a marked negative trend in the self-potential curve. In oil-exploration work this has been found helpful as a means of differentiating between sands and clay in beds containing a high concentration of salt water, where the resistivity values are usually so low that practically no difference is recorded between sand and clay beds. An example of this is shown at a depth of 1,970 to 2,000 feet in test well 6 at Clodine.

The quality of the water is shown by the analyses that follow.

Analyses of water from city test wells, Houston, Tex.

[Parts per million. Analyses for wells 1A, 2 (1,653–1,669 ft., 1,808–1,820 ft., and 1,943–1,998 ft.), 4, 4A, 5, 8 (1,661–1,676 ft.), 9 (1,399–1,414 ft.), and 10A by A. J. Hartsook, Rice Institute; other analyses by E. W. Lohr, Geological Survey. All samples were collected in 1939. Drill-stem samples except as otherwise indicated.]

Well No.	Date of collection	Depth of sample below surface (feet)	Total dissolved solids	Silica (SiO_2)	Iron (Fe)	Iron and aluminum oxide ($Fe_2O_3+Al_2O_3$)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Total hardness as $CaCO_3$[a]
1A	Apr. 7	438– 467	520	12		1	23	3	120	0	267	36	54			70
	Apr. 14	1,009–1,031	379	10	0.02		15	4.4	[a] 131	0	304	7.8	57	0.8	0.0	[a] 56
	Apr. 15	1,437–1,464	[b] 424	12	.02		11	4.0	[a] 170	0	384	4.1	65	1.0	.1	[a] 44
2	Apr. 19	1,653–1,669	808	49		5	10	1	213	0	427	1	89			29
	Apr. 20	1,808–1,820	1,099	287		61	10	1	219	24	378		111			29
	Apr. 22	1,943–1,998	838	56		7	7	1	233	18	374	1	133			22
3	May 2	1,766–1,810	713				15	4.4	272	0	421	8	204	2.5		[a] 55
4	May 5	1,203–1,230	381	4		3	17	2	93	3	180	24	54			51
4A[c]	May 13	461– 476	425	18		1	63	8	36	0	243	6	45			190
5[c]	May 13	1,172–1,187	395	14		5	31	7	66	0	216	17	41			106
6	May 22	1,684–1,704	550	38	.06		9.9	2.5	196	0	378	14	96	.6	.0	[a] 35
	May 25	1,970–2,000	2,629	19	.01		102	15	855	0	141	172	1,330	1.9	.0	[a] 316
	May 29	583– 617	265	24	.05		47	6.4	39	0	186	6.3	48	.4	.0	[a] 144
7	June 1	1,037–1,052	415	17	.14		12	3.5	147	3.9	278	15	78	1.1	.0	[a] 44
	June 8	1,193–1,222	494	13	.13		7.0	3.0	[a] 178	20	362	16	47	1.4	.20	[a] 30
8	June 13	[c] 1,661–1,676	1,353	12		2	5	1	422	30	582	2	286			16
	June 10	1,666–1,706	997	14	.05		6.1	2.3	[a] 397	7.9	594	.8	268	3.4	.0	[a] 25
	June 14	1,832–1,850	613	16	.05		5.2	1.9	[a] 243	12	495	1.1	82	2.2	.0	[a] 21
9	June 18	[c] 1,399–1,414	960	7		2	4	1	303	24	414	1	208			14
	June 18	1,506–1,526	1,649	14	.10		10	5.2	[a] 647	4.9	643	.6	645	2.5	.0	[a] 46
10A	Aug. 6	[c] 780– 795	390	4		1	15	2	99	12	211	10	41			46

[a] Calculated.
[b] Some precipitation as $CaCO_3$ apparently occurred before the determination of total solids was made.
[c] Sample from completed well.

CONCLUSIONS

The test drilling near Houston shows that electrical logging of wells gives much information that is useful in developing water wells but that under certain circumstances it may not be possible to interpret all parts of the curves correctly. For the present, at least, these logs should, therefore, be used in conjunction with carefully kept driller's logs and drill-stem sampling of both water and sand in all the more promising sand horizons.

The following conclusions have been reached regarding the most effective methods of test drilling in this area: The test wells should be drilled by rotary method. They should be of small bore but preferably not less than 5½ inches and should be put down as quickly and economically as practicable. The drilling contractor should have had experience with the water-bearing formations of the area. His equipment should be up to date, heavy enough for rapid deep drilling, and adequate in other respects. The drillers' log should be accurately kept and the drilling contract should provide that the well will not be accepted unless this is done. As drilling progresses samples of water and sand should be obtained by the drill-stem method from each sand of sufficient thickness to justify testing. To do this and to keep from overlooking sands which may be potential sources of supply, a ground-water hydrologist or water-supply engineer should be in constant attendance at the drilling rig. He should have authority to stop the drilling at any time and order a drill-stem test made. Electrical logs should be run in all test wells. When it is essential to determine the artesian pressure in sands at different depths, a test well should be cased in each important sand and the well developed by pumping it until the water becomes clear. The wells thus cased should be protected and used as permanent observation wells. In the Houston district and in areas having similar conditions the information obtained by coring is not likely to be sufficient to justify the cost and the delay involved in making cores, and the collection of drill-cutting samples is likely to yield very little productive information.

Regarding ground-water conditions in the area explored, the following conclusions are drawn: Water-bearing sands having an average thickness of 600 feet occur between the surface and a depth of 1,500 feet along the line of test wells from the western city limits of Houston to Clodine. A supply of water is available north of Houston in deep sands that are practically untouched by existing wells. The water contained in these sands is suitable for domestic and industrial purposes. The occurrence of fresh water in the deep sands in the vicinity of South Houston tends to show that salt-water encroachment from down dip through the sands tapped by wells in the heavily pumped area may not be very serious so far as the immediate future is concerned.

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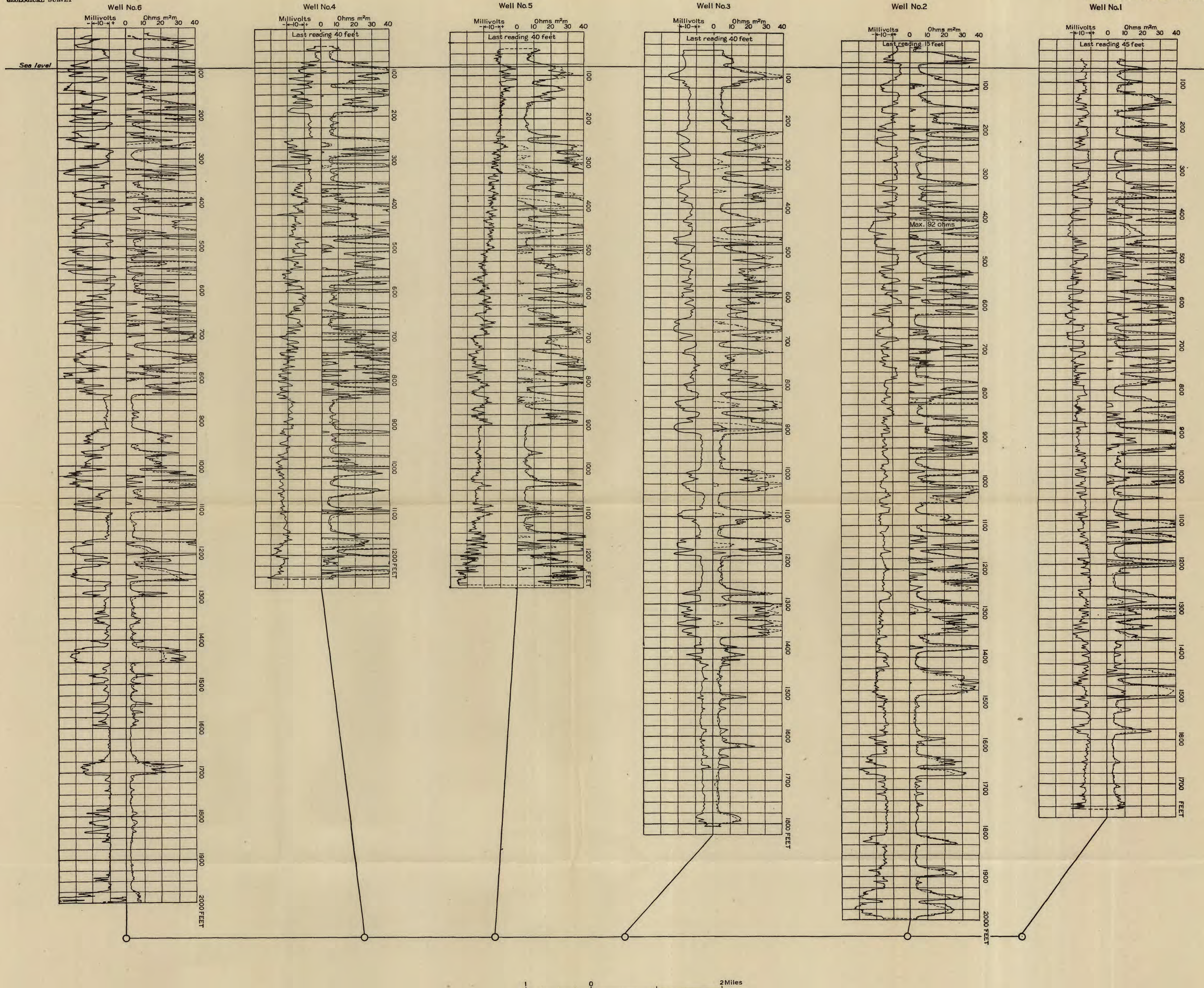

ELECTRICAL LOGS OF TEST WELLS ALONG HOUSTON-CLODINE ROAD.

○ represents location of well.

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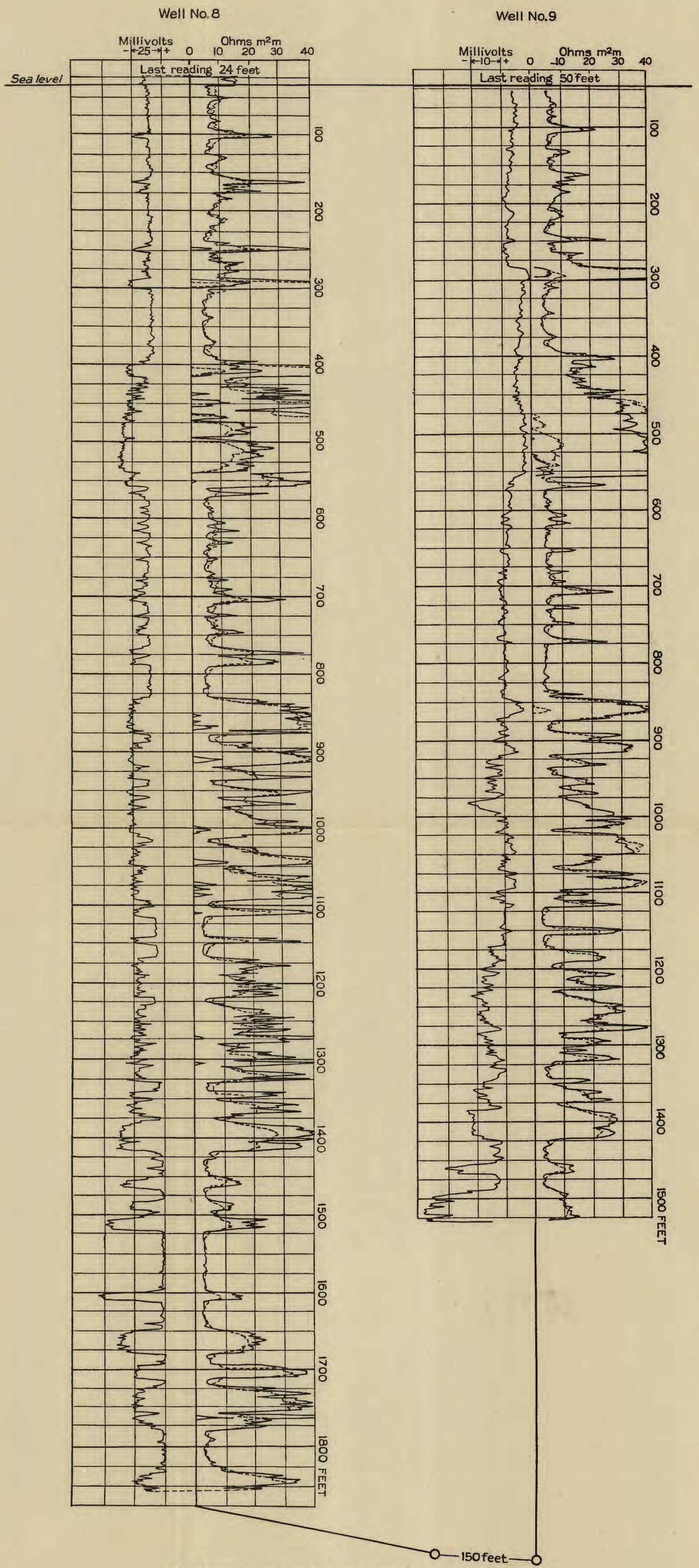
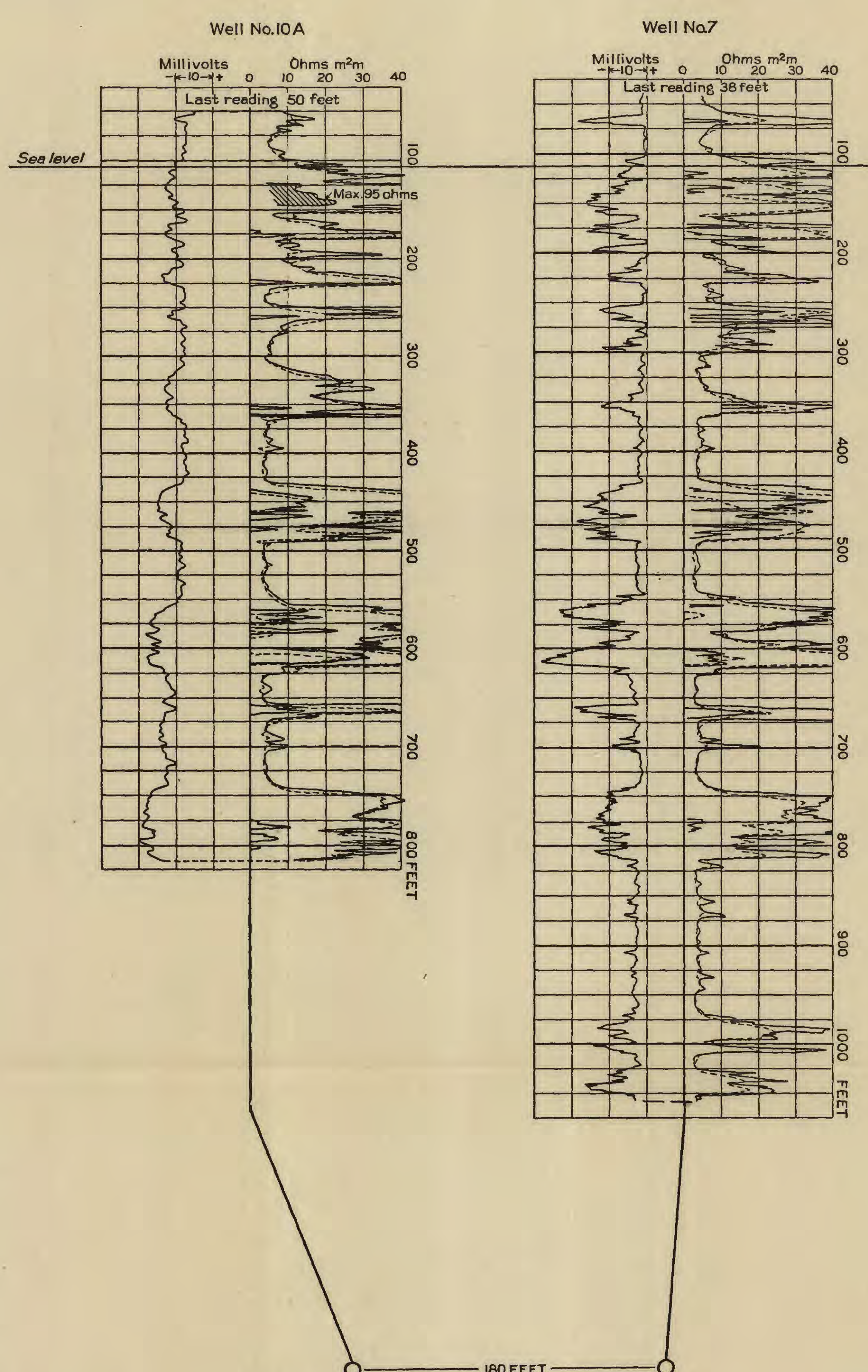


ELECTRICAL LOGS OF TEST WELLS NEAR SOUTH HOUSTON.



ELECTRICAL LOGS OF TEST WELLS AT WESTFIELD.

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