

A STUDY OF THE "DEPARTURE"
RECORDED ON MICROLOGS
OPPOSITE SHALE

By
Kantilal P. Desai

ProQuest Number: 10795519

All rights reserved

INFORMATION TO ALL USERS

The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if material had to be removed, a note will indicate the deletion.



ProQuest 10795519

Published by ProQuest LLC (2018). Copyright of the Dissertation is held by the Author.

All rights reserved.

This work is protected against unauthorized copying under Title 17, United States Code
Microform Edition © ProQuest LLC.

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

A thesis submitted to the faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science.

Signed: Kantilal P. Desai
Kantilal P. Desai

Golden, Colorado

Date: 23rd Oct., 1957

Approved:

John C. Hollister
John C. Hollister

Approved:

Walter H. Dumke
Walter H. Dumke

ACKNOWLEDGMENTS

A number of individuals have helped to make this work possible. I thank all who have helped in this work in any manner. I am especially grateful to Professor John C. Hollister and Dr. Walter H. Dumke, who outlined the approach to this problem and checked the results; and to Professor James Merrin for help in editing. I appreciate, also, the generosity of the Frontier Refining Company and Core Laboratories, Inc., in supplying the shale for the experiments and to Malco Refineries, Inc., in supplying the logs for the examples.

TABLE OF CONTENTS

	Page
Acknowledgments.....	iii
Introduction.....	1
Experimental Work.....	9
Equipment.....	9
Procedure.....	11
Discussion of Results.....	15
Analysis of Data From Group I.....	15
Analysis of Data From Group II.....	20
Analysis of Data From Group III.....	23
A Note on Potential.....	29
Summary.....	33
Bibliography.....	36

ILLUSTRATIONS

Figures	Page
1. Schematic Diagram of Micrologging System....	2
2. Lateral Resistivity Distribution of the Shale Formation.....	4
3. Example of Negative Departure.....	7
4. Example of Negative and Positive Departure..	8
5. Circuit Diagram for Modified Brown Resis- tance Thermometer.....	10
6. Electric Log of Lad #1.....	12
7. Set Up for Measurement of Electrical Re- sistance.....	14
 Tables	
I. Results of Resistance Measurements (Group I)	16
II. Results of Resistance Measurements and Quantitative Analysis of the Solutions..... (Group II).....	19

	Page
III. Results of Resistance Measurements and Quantitative Analysis of the Solutions (Group III).....	22
IV. Calculations for ΔR , R_s , and R_{sa}	25
 Charts	
1. Plot of Solution Concentration Against ΔR	26
2. Plot of Solution Concentration Against $\Delta R/R_s$	27
3. Plot of Solution Concentration Against $\Delta R/R_{sa}$	28

INTRODUCTION

This dissertation is a study of the cause of certain anomalous readings observed on a microlog at the level of shale formations. With this problem, a brief study was made of the potential difference that is developed when a shale sample separates saline solutions of different concentrations. (As a background for the problem, a brief review of the microlog and its behavior opposite shale sections is presented.)

A microlog is a depth record of apparent formation-resistivity measured by three electrodes one inch apart. These electrodes are mounted in an insulating pad which is pressed against the wall of the drill hole by bow springs. The electrodes are essentially in contact with the formation or with the mud cake between the pad and the formation and are shielded from direct contact with the drilling fluid. A typical micrologging system is schematically shown in figure 1.

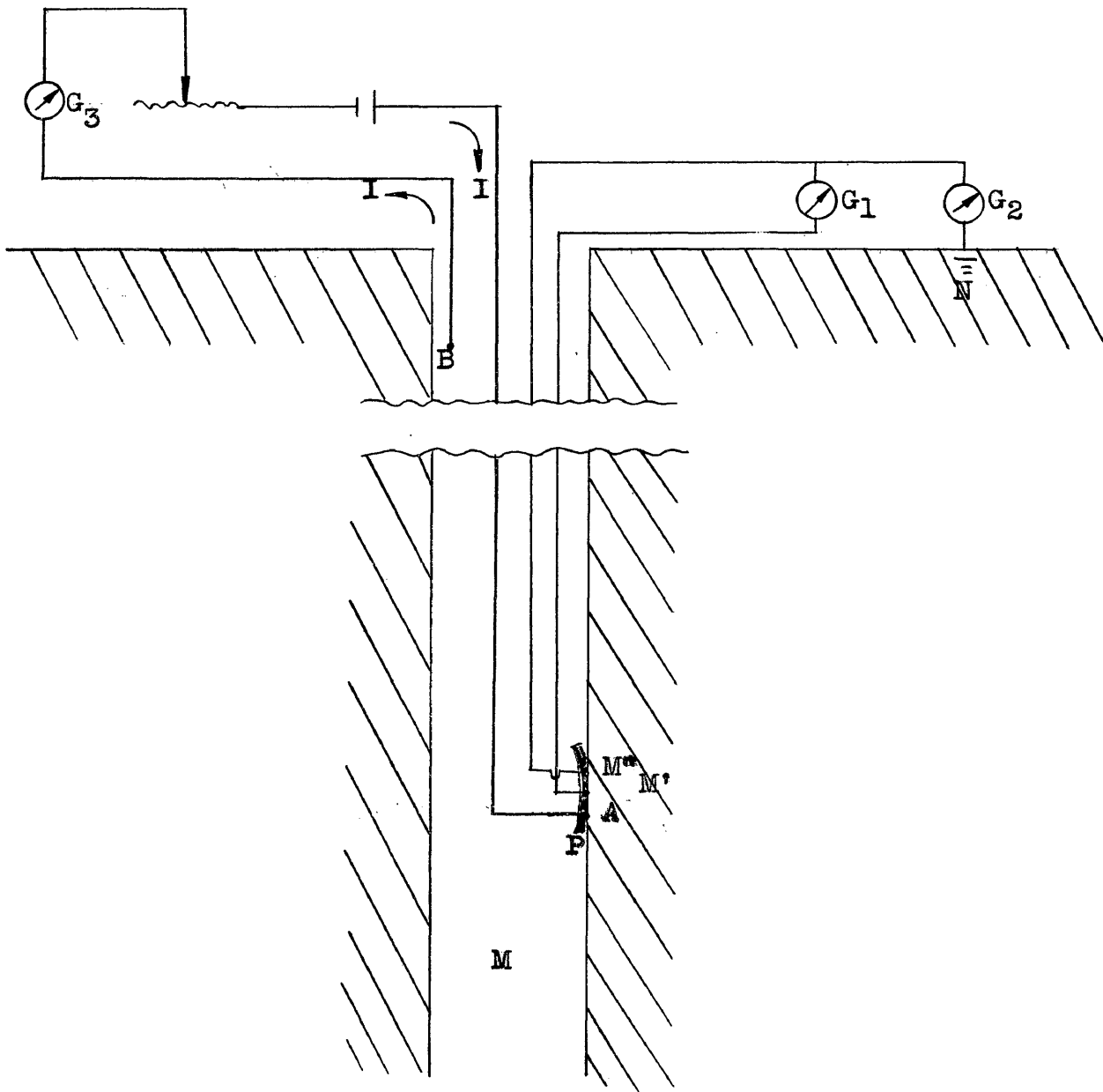


Figure 1. Schematic Diagram of Micrologging System.
 P--Pad; M--Mud; I--Current; G--Galvanometer
 A, B, M', M'', N--Electrodes

Current of known magnitude is introduced into the formation at the lower electrode A. The potential of M' relative to the reference electrode N and the potential difference between M' and M'' are measured. The instrument is calibrated so that the potential differences are read directly as resistivities. The NM' reading is affected by a greater microvolume of the formation than is the M'M'' reading. The recorded NM'' readings are called the 2" normal microlog, and the M'M'' readings, the $1\frac{1}{2}$ " lateral microlog, or microinverse log.

The difference between the apparent resistivities recorded on the 2" normal microlog and on the $1\frac{1}{2}$ " lateral microlog is called "departure" or "separation". When the longer spacing gives a larger value of resistivity, the departure is called "positive"; when a smaller, it is called "negative".

Ideally, the resistivity of a shale section is laterally uniform (see figure 2a) i. e., it should not vary with the distance from the pad. Thus both spacings should record the same resistivity value. However, in practice, both positive and negative departures are observed.

As far as this writer knows, no worker has investigated the cause of departures recorded on microlog in front of shale formations. Some workers have speculated about the cause of "departures". For example, Doll (1950, p. 157)

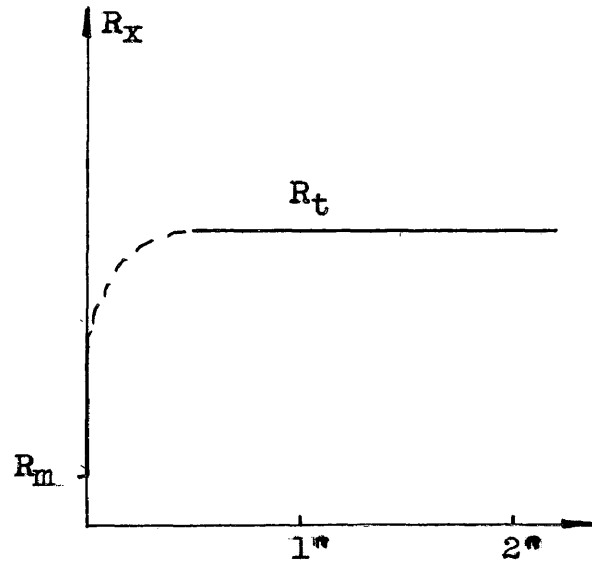
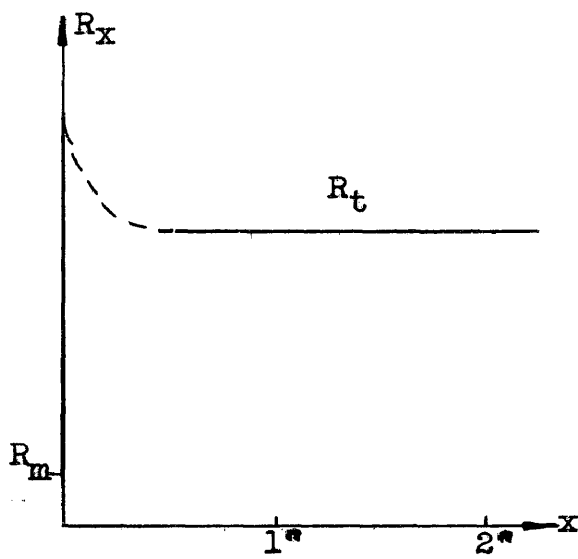
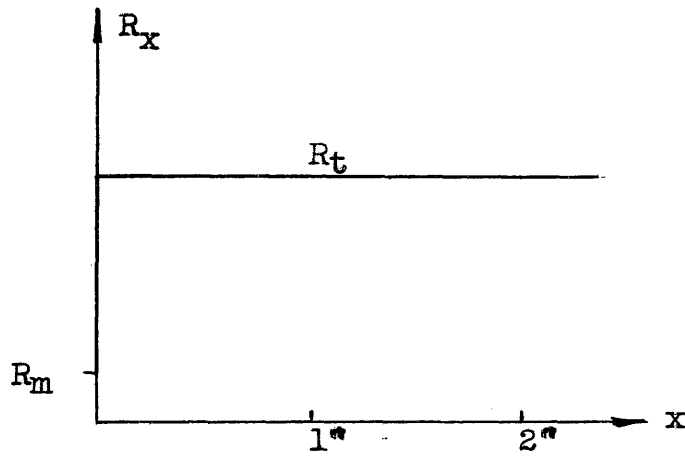


Figure 2. Lateral Resistivity Distribution of the Shale Formation.

x = Lateral distance from the pad
 R_x = Specific resistivity of ground at distance x
 R_t = True resistivity of the formation
 R_m = Resistivity of the mud

writes:

For intermediate values of the resistivity, and because of the limited dimensions of the pad, a separation between the microresistivity curves is sometimes observed on impervious beds, but, in that case, the separation is negative.

Maurice Martin (1955, p. 110) writes that cavings are most often encountered at the level of shale beds. He further states that if the caving is deep, the two readings are equal to the mud resistivities, while if the caving is not very deep, a positive separation is observed which may be interpreted erroneously as indicating permeable streaks. He also writes:

When there is no caving in the shales, the pad again is separated from the formations by a thin mud film. The reading is equal to, or more often smaller than, the resistivity of the shales. The separation may be negative, zero, or slightly positive. This behavior of the microlog at the level of shales is not entirely explained. It is assumed that the occurrence of a negative separation may be due to the anisotropy of the shales.

Martin's explanation is debatable. It is hard to believe that the anisotropy of shale is the dominant cause of departures. Departures may be explained on the basis of ionic diffusion between the mud filtrate and the connate water. This diffusion hypothesis proposes that when drilling mud comes in contact with shale, ions diffuse from the connate water to the mud filtrate or from the mud filtrate to the connate water depending upon their relative concentrations. The diffusion process does not significantly

affect the resistivity of drilling fluid, because of its relatively large volume and high diffusion rate, but it does affect the resistivity of a very thin layer of the shale formation. Thus the resistivity of the shale is not in the ideal form shown in figure 2a, but takes the form shown in figure 2b or 2c.

When a shale has a highly saline water, the ions diffuse from the connate water to the mud filtrate, and the resistivity distribution takes the form shown in figure 2b. As a result, a negative departure is recorded on the microlog (see figure 3). When shale has a lower concentration connate water, the ions diffuse from the mud filtrate to the connate water and the resistivity distribution takes the form shown in figure 2c. As a result, the microlog shows a positive departure (see figure 4).

The following sections of this thesis describe the experimental work done to test the validity of the hypotheses of ionic diffusion; discuss the results of this work; and indicate the application of these results to the problem of determining the salinity of connate water within shales. Finally, a section is devoted to a note on potential that is developed when a shale separates NaCl solutions of different concentrations.

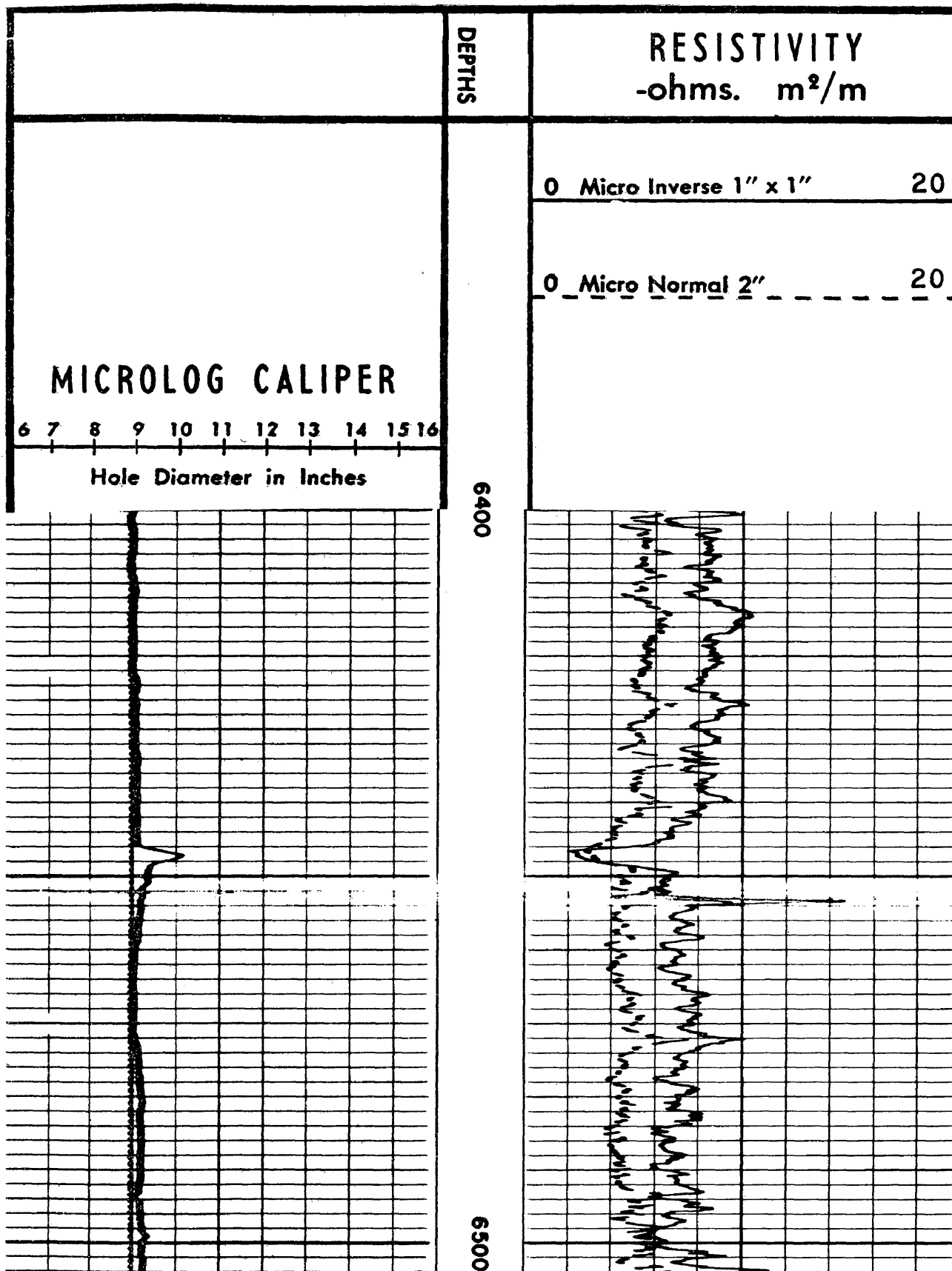


Figure 3. Example of Negative Departure. From Ko-wach #2 of Malco Refining Inc., Moffat County, Colorado. Concentration of the connate water is unknown. Concentration of the mud filtrate is 1500 ppm NaCl.

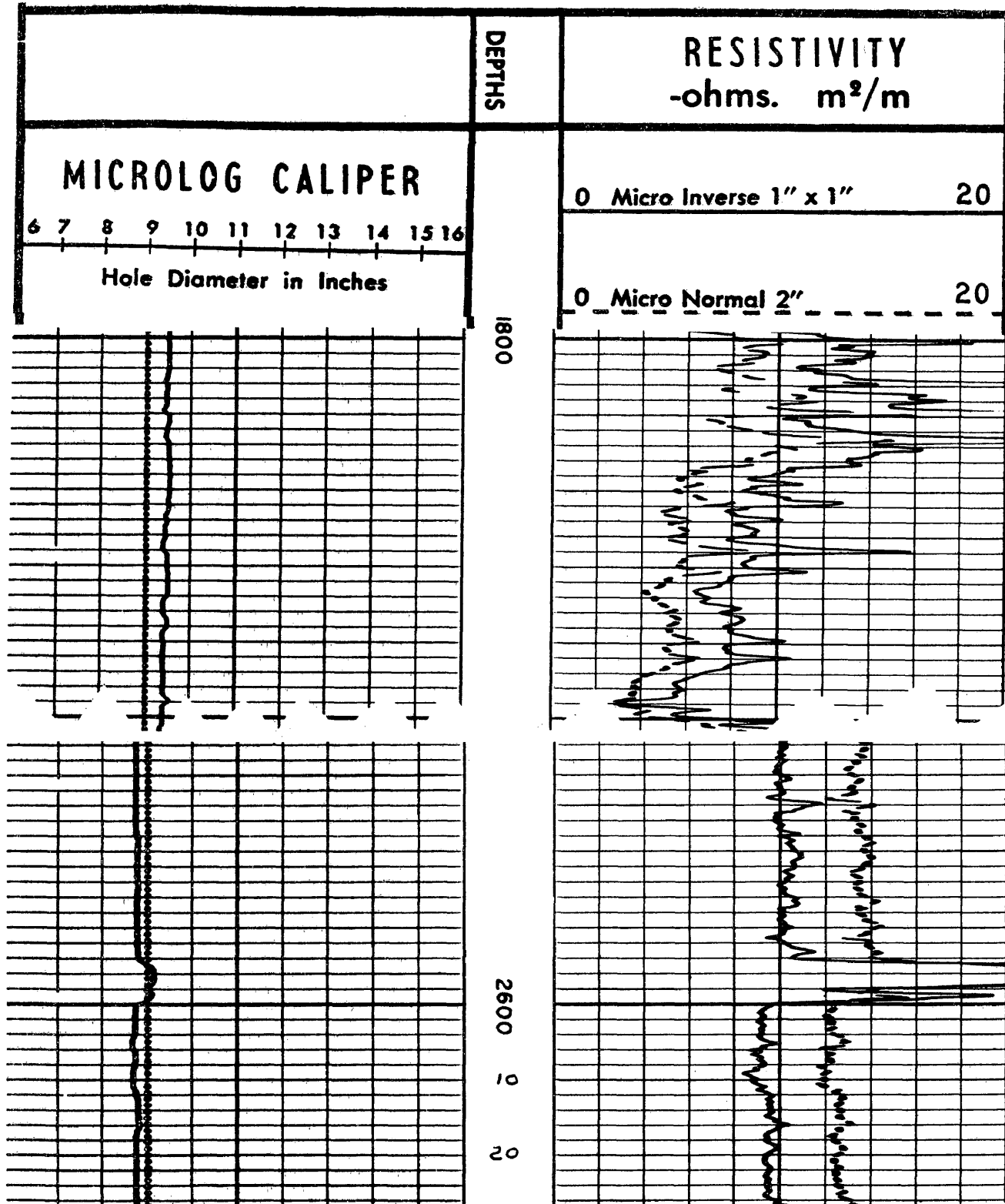


Figure 4. Example of Negative and Positive Departure. From Kowach #1 of Malco Refining Inc., Moffat County, Colorado. Concentration of the connate water is not known; concentration of mud filtrate is 2,000 ppm NaCl. Note that the negative departure is opposite the shale of the low resistivity, while the positive departure is opposite the shale of high resistivity. There is no caving.

EXPERIMENTAL WORK

Three sets of experiments were carried out using the same instruments and practically the same procedure for each. In each set the variation in resistance of the shale sample with time was continuously recorded. In the second and third set, samples of the solutions were taken at the beginning and at the end of the experiments and quantitatively analysed for Na, K, and Cl. The equipment used and the procedure followed in these experiments are discussed below.

Equipment

A modified Brown Resistance Thermometer, model 9161, was used to record the resistance continuously. Figure 5 shows a schematic diagram of the measuring circuit. To eliminate the effect of polarization at the platinum electrodes, the batteries used in the original circuit were replaced by a transformer to supply 6.3 volts at 60 cycles.

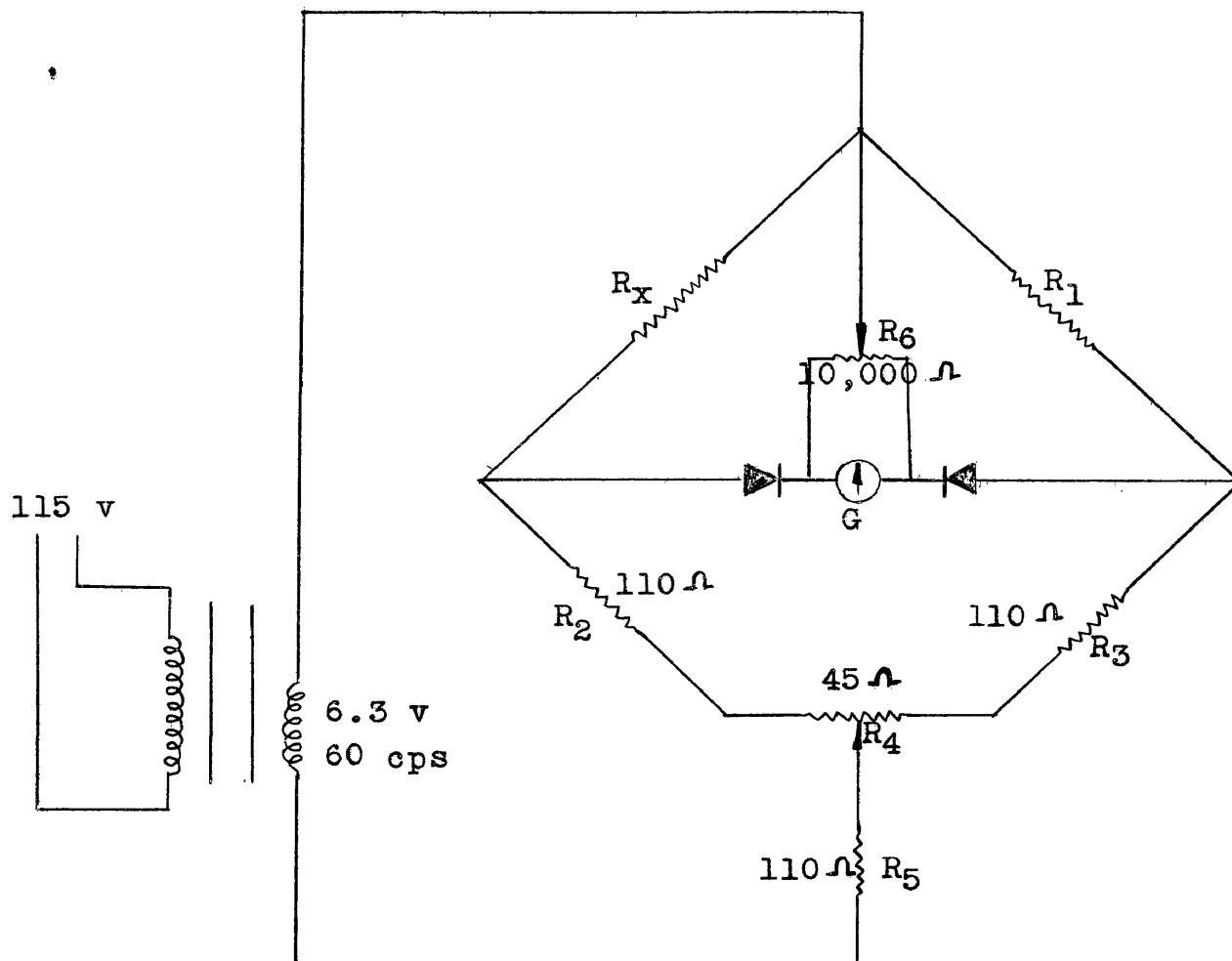


Figure 5. Circuit Diagram for Modified Brown Resistance Thermometer, Model 9161. R_x --unknown resistance (see figure 7); G --galvanometer; \blacktriangleright -- germanium diode; R_1 --standard resistance.

Since the galvanometer would not respond properly to ac in the Wheatstone bridge circuit, two germanium diodes were employed as half wave rectifiers in the galvanometer circuit. The resistance R_6 was used for the zero adjustment of the galvanometer. R_1 is a standard resistance whose value was selected so that the readings would be recorded in the central portion of the chart. The instrument was calibrated with the help of the standard resistance box.

Other equipment used for measuring resistance was platinum electrodes, lucite cups, and a motor-driven circulating pump.

Procedure

The shale used in most of these experiments was cored in 1948 from the Mesa Verde group of Rio Blanco County, Colorado, and was provided by the Frontier Refining Company from its Lad No. 1 well. A portion of the electric log for this well is given in figure 6. Samples whose thickness varied from 1.5 cm to 11.9 cm were cut from the shale that was cored between depths of 5770 and 6340 feet. In experiments 11, 12, and 13, the samples of the sandy mudstone were used. In an attempt to compensate for connate water losses, some samples were soaked in 50,000 ppm NaCl solution for a time varying from 17 hours to 4

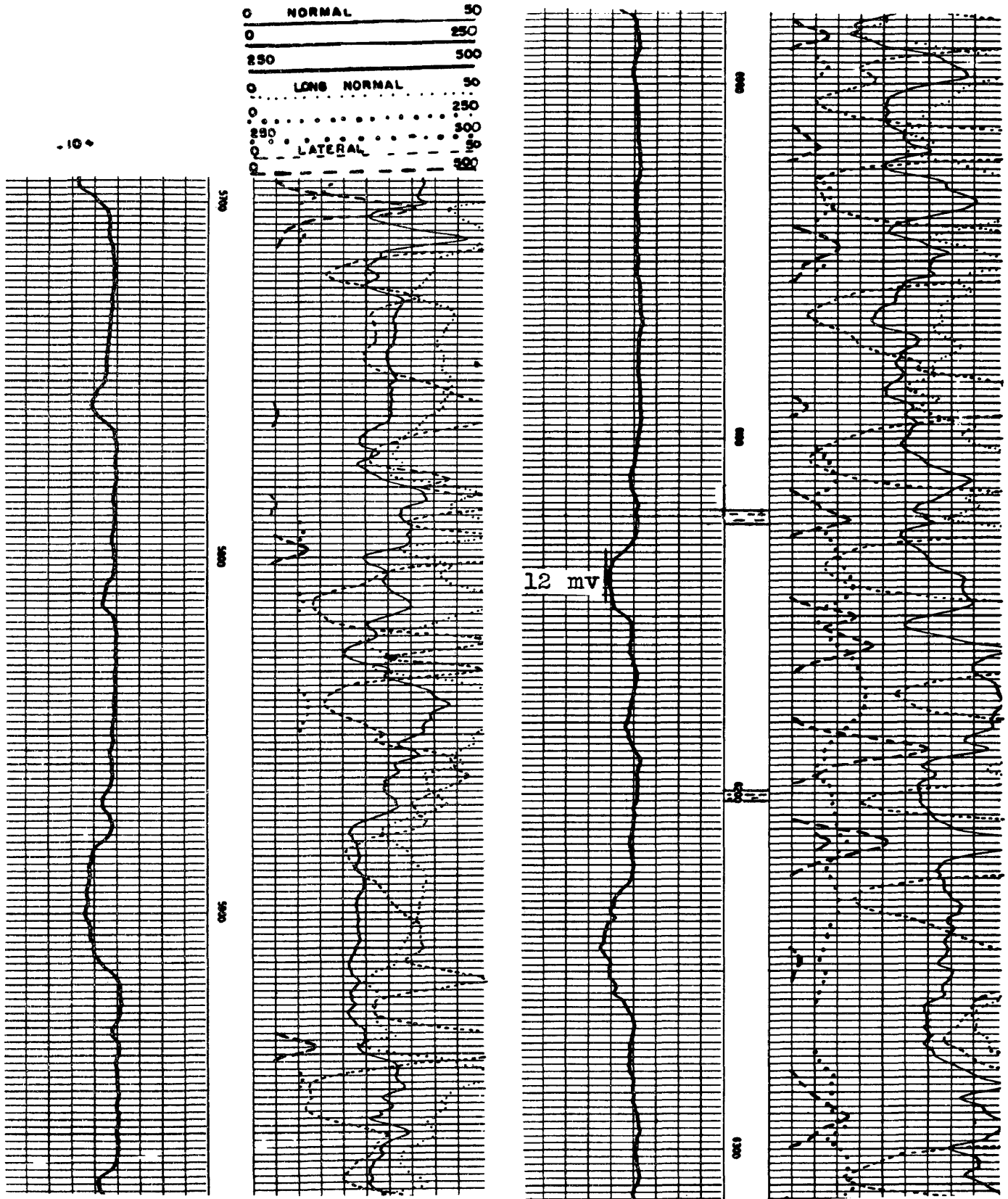


Figure 6. Electric Log of Lad #1, Frontier Refining Company, Rio Blanco County, Colorado. In groups I and II, shale samples taken between depths 5770 to 6340 feet were used. In group III the shale samples (---) taken between the depths 6120 to 6124 and 6199 to 6202 were used. The mud resistivity was 1.05 ohm-meters at formation temperature of 125°F.

months; some were soaked in distilled water for 165 hours. Some samples were tried without soaking. In a few experiments, the frozen shale from the Dakota group of the Denver-Julesburg Basin was used.

A rubber gasket ring was cemented to the open end of each lucite cup (see figure 7) to prevent the saline solution leakage, which causes erroneous readings. The shale sample was clamped between two lucite cups, which were then filled with NaCl solutions; next the platinum electrodes were connected to the recording device as shown in figure 7. R_x in figure 7 corresponds to unknown resistance in figure 5. Continuous recording of R_x was made for time that varies from a few minutes to 150 hours. In some experiments, solution C" was circulated by means of a motor-driven circulating pump system.

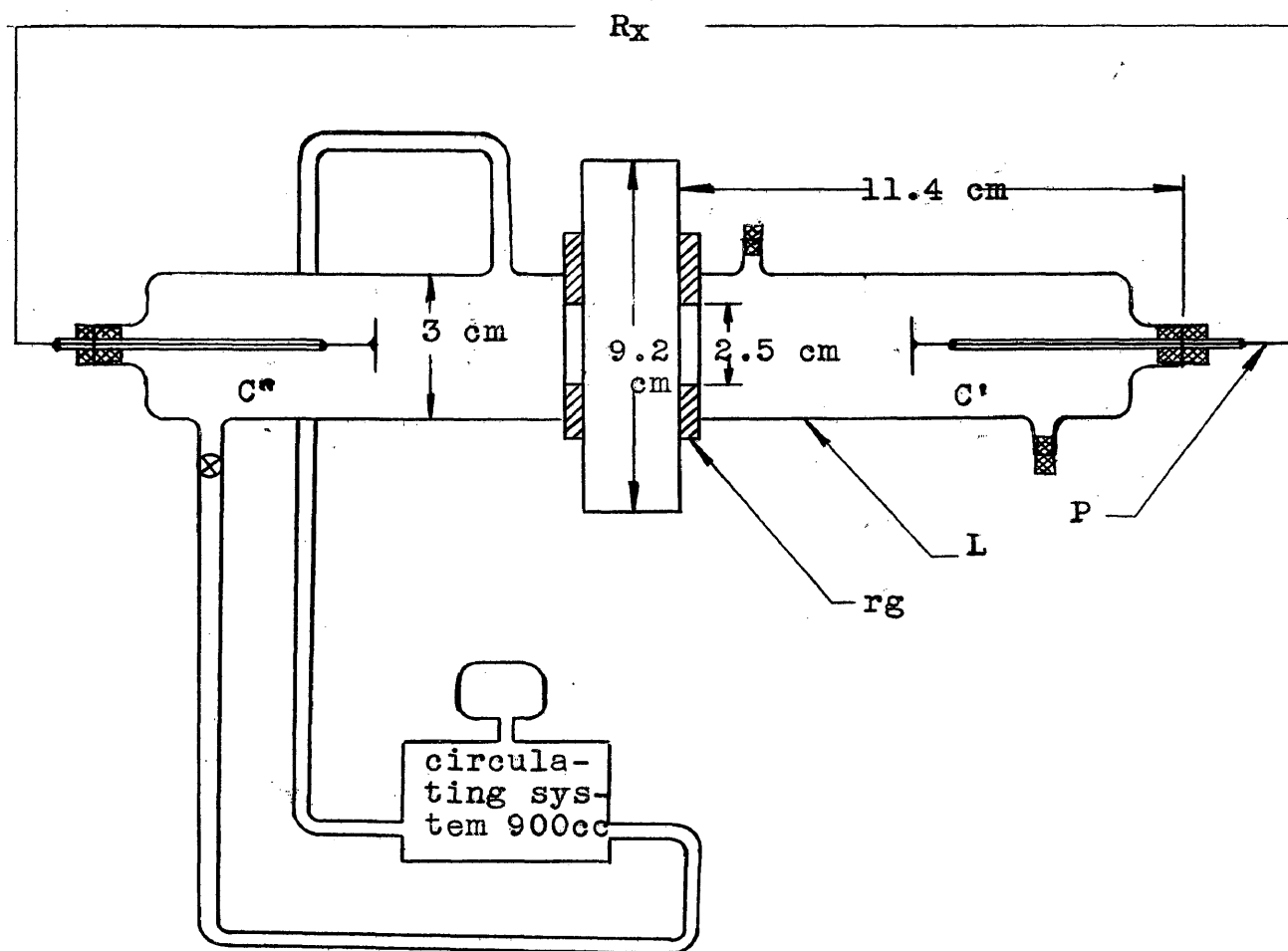


Figure 7. Set up for Measurement of Electrical Resistance. C' --high concentration solution; C'' --low concentration solution; L --lucite cup; P --platinum electrode; rg --rubber gasket ring; R_x --unknown resistance (see figure 5).

DISCUSSION OF RESULTS

Data from the three groups of experiments performed to test the hypothesis of ionic diffusion are presented in Tables I, II, and III, and are discussed in the following paragraphs.

Analysis of Data From Group I

In the first set, the first four experiments were performed with C' (see figure 7) as 50,000 ppm NaCl solution and C'' (see figure 7) as 5,000 ppm NaCl solution. It was assumed that in salinity C' would be close to the connate water and C'' close to the mud filtrate. C'' was circulated to correspond to the circulating mud. In all these experiments, a decrease in resistance with time was observed, which suggested that there was ionic diffusion from the solutions C' and C'' to the connate water, or that there was higher ionic diffusion from the solution C' to the connate water compared to that from the connate water to the solution

TABLE I
RESULTS OF RESISTANCE MEASUREMENTS (GROUP I)

Experi- ment no.	Thick- ness of the sam- ple in cm	Sample soaked in 50,000 NaCl for hours	NaCl in ppm		Resistance in Ohms						Remarks		
			solu- tion C'	solu- tion C"	0 hr.	1 hr.	5 hrs.	10 hrs.	20 hrs.	50 hrs.		100 hrs.	150 hrs.
1	2.6	-----	50,000	5,000	8,380	8,000	6,400	5,500	4,680	3,550	3,000	2,800	medium gray carbona- ceous shale
2	2.5	17	50,000	5,000	4,100	4,000	3,860	3,700	3,450	3,100	-----	-----	medium gray carbona- ceous shale
3	2.0	26	50,000	5,000	8,650	8,400	7,000	6,200	5,900	4,600	4,000	3,500	medium gray silty shale
4	3.0	4 months	50,000	5,000	1,440	1,435	1,410	1,400	1,390	1,520	1,520	-----	medium gray carbona- ceous shale
4a	Replace 50,000 by 357,000 ppm NaCl solution				1,520	1,250	1,200	1,200	-----	-----	-----	-----	
5	11.9	-----	50,000	50,000	16,000	14,200	13,000	12,450	12,100	12,000	-----	-----	medium gray sandy shale
6	3.0	84	5,000	5,000	3,130	3,080	2,840	2,750	-----	-----	-----	-----	sandy shale
7	3.0	84	5,000	5,000	2,140	2,240	2,300	2,300	-----	-----	-----	-----	medium gray silty shale
8	9.9	118	5,000	5,000	2,120	2,300	2,780	3,180	3,820	4,800	5,000	-----	medium gray silty shale
9	3.0	95	500	500	4,470	4,600	4,850	5,180	-----	-----	-----	-----	sandy shale
10	10.0	95	500	500	3,570	3,780	3,830	3,880	4,000	-----	-----	-----	medium gray silty shale
Resistance in Ohms													
After													
0 min. 15 min. 30 min. 132 min													
11	1.8	-----	5,000	5,000	-----	375	370	370	-----	-----	-----	-----	
12	1.6	-----	5,000	5,000	-----	280	280	-----	-----	-----	-----	-----	
13	1.5	-----	5,000	5,000	-----	265	265	-----	-----	-----	-----	-----	sandy mudstone

In the first four experiments, solution C" was circulated.

C". It was also observed that when the circulation was stopped and restarted, the sample exhibited a somewhat higher resistance than could be expected if circulation had not been stopped. This observation can be explained on the ground that when circulation was stopped, the shale received comparatively fewer ions since the volume of the reacting solution C" was changed from 1,000 cc to 85 cc (see figure 7). But this explanation does not satisfy the observations made in experiment 4. While the circulation was stopped, the resistance value was higher than the value observed at the starting time; no satisfactory explanation for this can be put forward.

Experiment 4a shows that the rate of decrease in resistance is very high when a 50,000 ppm NaCl solution is replaced by a 357,000 ppm NaCl solution. This behavior is in accordance with the principle that the rate of diffusion is higher when the concentration gradient is higher.

By this time it was realized that the two different solutions would have different effects on the change in resistance; so it was decided to use C' and C" of the same concentration. At the same time, the circulation of the solution C" was stopped.

In experiment five, 50,000 ppm NaCl solution was used; a decrease in resistance with time was observed, which

suggests that the connate water has lower concentration than the 50,000 ppm NaCl solution. In experiments six, seven, and eight, 5,000 ppm NaCl solution was used. In experiment 6, a decrease in resistance with time was observed, while in experiment 7, and 8, an increase in resistance with time was observed. This difference in behavior may be attributed to the difference in the soaking effect on the samples. Sandy shale was used in experiment 6 and silty shale was used in experiment 7 and 8; these samples were soaked in 50,000 ppm NaCl solution. It seems that after soaking, the concentration of the connate water of the first sample was less than 5,000 ppm NaCl while that of the other two samples was more than 5,000 ppm NaCl. In experiments nine and ten, 500 ppm NaCl solution was used, and an increase in resistance with time was noted. This increase suggests that the connate water has higher concentration than the 500 ppm NaCl solution. In experiments eleven, twelve, and thirteen, 5,000 ppm NaCl solution was used. It was observed that the resistance decreases with time and reaches a constant value within 15 minutes. This behavior may be explained on the assumption that the samples, which were of dry sandy mudstone, became fully saturated in a few minutes; thus the resistance reached an early constant value. To further demonstrate that

TABLE II

RESULTS OF RESISTANCE MEASUREMENTS AND QUANTITATIVE ANALYSIS OF THE SOLUTIONS (GROUP II)

Experi- ment no.	Thick- ness of sample in cm	Sample soaked in 50,000 ppm for hours	NaCl in ppm origi- nal so- lution	ppm final solu- tion	Resistance in Ohms					Remarks	
					0 hrs.	1 hr.	5 hrs.	10 hrs.	15 hrs.		20 hrs.
14	1.7	—	49,533	49,345	608	526	498	432	—	—	frozen shale
15	2.1	—	49,533	49,207	4,850	4,850	4,800	4,570	3,980	3,610	medium gray silty shale
16	3.0	183	50,021	48,531	2,200	1,940	1,640	1,390	1,370	1,370	sandy shale
17	3.0	219	50,021	48,954	1,108	1,013	930	892	835	825	medium gray silty shale
18	1.8	—	5,005	5,044	9,680	9,500	9,050	8,800	7,900	7,600	dark gray carbonaceous shale
19	1.0	—	5,005	4,980	693	635	566	554	—	—	frozen shale
20	1.5	—	5,005	5,005	811	800	804	798	780	755	frozen shale
21	3.0	84	495	657	5,900	5,850	5,660	5,460	5,075	4,975	medium gray silty shale
22	2.0	26	495	516	14,400	13,400	11,250	10,400	10,000	9,550	medium gray silty shale
23	3.0	48	53	109	12,820	12,680	11,610	11,160	10,380	—	dark gray silty carbonaceous shale
24	1.8	—	53	79	11,870	11,640	11,240	10,980	—	—	frozen shale
25	3.0	183	53	69	15,200	15,200	15,000	14,650	—	—	sandy shale

the decrease or increase in resistance is the direct result of the ionic diffusion from the solution to the connate water, or from the connate water to the solution respectively, a second set of experiments was performed.

Analysis of Data From Group II

In this second set the solution was sampled in the beginning and at the end of the experiments and quantitatively analysed for Na, K, and Cl; these results are given in table II. Analysis shows that there are fewer than 2ppm of K present in any of the experiments, so it is not listed in the table. In the analysis of Na and Cl, it was recognized that greater accuracy is achieved by determining Cl for the 2,000 or more ppm NaCl solutions and Na for the 500 and 50 ppm NaCl solutions; and from these values the concentration of NaCl can be calculated. Thus, in experiments 14 through 20, the values of NaCl were calculated from the Cl values, while in experiments 21 through 25 the Na values were used to calculate the NaCl values.

The results of the quantitative analysis in table II show that in experiments 14, 15, 16, 17, and 19, the decrease in resistance is associated with ionic diffusion from the solution to the shale sample. In experiments 23, 24, and 25, chemical analysis shows that ions diffused from connate water to the solution, but the overall resistance decreased. This

overall decrease is explained as follows: as the ions diffused from the connate water to the solution, the resistance of the shale increased, at the same time the resistance of the adjacent solution decreased as its salinity increased. It can be shown by calculations that the increase in the resistance of shale was masked by the decrease in the resistance of the solution.

In experiment 18, the decrease in resistance is apparently associated with ionic diffusion from connate water to the solution, but the change in the concentration of the solution is so negligible that the change is within analytical error. Experiment 20 shows a decrease in the resistance of the shale sample. It is reasonable to expect a decrease in resistance of a frozen shale with temperature rise.

Results observed in experiments 21 and 22 cannot be explained on the basis of ionic diffusion. Results obtained from these two experiments must be attributed to the peculiarity of the samples, or to experimental error. Somewhat unsatisfactory results observed in the experiments may be due to variation in the samples. Samples were taken from the Mesa-Verde cores, as well as from the Dakota group cores; there is variation in the period for which they were soaked in 50,000 ppm NaCl solution. In order that the experimental results could be better correlated, a third set of experiments was performed.

TABLE III
RESULTS OF RESISTANCE MEASUREMENTS AND QUANTITATIVE ANALYSIS OF THE SOLUTION (GROUP III)

Experi- ment no.	NaCl in origi- nal so- lution	NaCl in ppm final solu- tion	Resistance in Ohms After						Remarks	
			0 hrs.	1 hr.	5 hrs.	10 hrs.	15 hrs.	20 hrs.		24 hrs.
26	49,624	49,583	775	748	702	675	642	635	632	
27	49,624	49,456	807	807	795	782	770	755	755	
28	9,933	9,892	1,065	1,065	1,060	1,058	1,028	1,013	1,013	medium gray, silty
29	4,957	4,986	1,250	1,250	1,265	1,300	1,325	1,325	-----	shale from the depth
30	4,957	4,981	1,280	1,280	1,280	1,315	1,340	1,360	-----	of 6120-6124 feet
31	2,013	2,080	1,475	1,510	1,560	1,600	1,600	1,612	1,627	
32	2,013	2,051	1,520	1,558	1,590	1,597	1,602	1,605	1,605	
33	49,624	49,436	870	836	728	647	599	561	540	
34	49,624	49,560	792	734	647	598	544	509	490	
35	4,927	5,099	1,265	1,265	1,302	1,370	1,375	1,380	1,420	medium gray, carbona- ceous shale from the
36	2,013	2,036	2,025	2,025	2,105	2,164	2,145	2,170	2,200	depth of 6199-6202
37	2,013	2,036	1,850	1,850	1,860	1,918	1,920	1,940	1,950	feet

In each experiment in this group, the sample tested was 2 cm in thickness and had been soaked in distilled water for a period of 165 hours.

Analysis of Data From Group III

To keep all the conditions as uniform as possible, the samples for the experiments 26 through 32 were cut from a core of the Mesa Verde shale taken from the depth of 6120-6124 feet, and the samples for the experiments 33 through 37 were cut from a core of the Mesa Verde shale taken from the depth of 6199-6202 feet. All the samples were 2 cm thick and soaked in distilled water for 165 hours in order to return moisture to dry samples without changing their original saline content. The samples were removed from the distilled water, which was then analysed; the analysis showed a negligible amount of leaching of NaCl from the samples. The samples were kept covered with a wet towel; and each sample was kept at room temperature for two hours before it was in the experiment. In all these experiments, solutions were analysed for Cl, and from that NaCl was determined. Results of these experiments are given in table III.

In experiments 26 through 37, the change in the resistance of the solutions is negligible; thus the recorded change in the overall resistance is essentially the change in the resistance of shale samples. In experiments 26, 27, 28, 33, and 34, the decrease in resistance is associated with ionic diffusion from the solution to the connate water. In experiments 29, 30, 31, 32, 35, 36, and 37,

the increase in resistance is associated with ionic diffusion from the connate water to the solution. Thus, experiments 26 through 37 satisfied the hypothesis of ionic diffusion.

From the data obtained in experiments 26 through 37, an attempt is made to determine, graphically, the concentration of the connate water in the shale (see Charts 1, 2, 3). The solution concentration is plotted against ΔR , $\Delta R/R_s$, and $\Delta R/R_{sa}$ where,

ΔR (starting overall resistance) (ending overall resistance)

R_s starting resistance of shale sample, i. e.,
(starting overall resistance) (resistance of the solution)

R_{sa} average value of R_s

The scattering of the data observed in the above plots may be due to change in resistance of the shale formation (see figure 6), but plots still show that the concentration of the connate water is approximately 6,000 to 7,000 ppm NaCl. The concentration of the connate water calculated from the electric log data (see figure 6) is 5,900 ppm NaCl. This result shows that the hypothesis of ionic diffusion may not only explain the cause of the departures, but it may also be useful in determining the NaCl concentration of the connate water in the shale formation.

TABLE IV
Calculations for R , R_s , and R_{sa}

Solution NaCl ppm	ρ in ohm-meters	R ohms
50,000	0.13	26
10,000	0.56	112
5,000	1.15	230
2,000	2.62	530
$R = \rho K$ where $K = 200$ per meter		

Ex. no.	R of solution	Start- ing R of set up	Ending R of set-up	ΔR	R_s Resis- tivity of sam- ple	$\Delta R/R_s$	R_{sa}	$\Delta R/R_{sa}$
26	33	775	632	-143	749	-.191		-.156
27	33	807	755	- 52	781	-.067		-.057
28	141	1,065	1,013	- 52	953	-.055	912 [†]	-.057
29	289	1,250	1,325*	/ 75	1,020	/ .074		/ .083
30	289	1,280	1,360*	/ 80	1,050	/ .076		/ .088
31	665	1,475	1,627	/ 152	945	/ .161		/ .169
32	665	1,520	1,605	/ 85	990	/ .086		/ .093
33	33	870	540	-330	840	-.394		-.305
34	33	792	490	-302	766	-.395		-.277
35	289	1,265	1,420	/ 155	1,035	/ .150	1,091 [†]	/ .142
36	665	2,025	2,200	/ 175	1,495	/ .128		/ .160
37	665	1,850	1,950	/ 100	1,320	/ .076		/ .092

*These experiments were run for 20 hours; the rest of the experiments were run for 24 hours.

†From this value of R_{sa} , the calculated resistivity of the shale is close to the resistivity of the shale formation as recorded on the electric log (see figure 6).

CHART 1

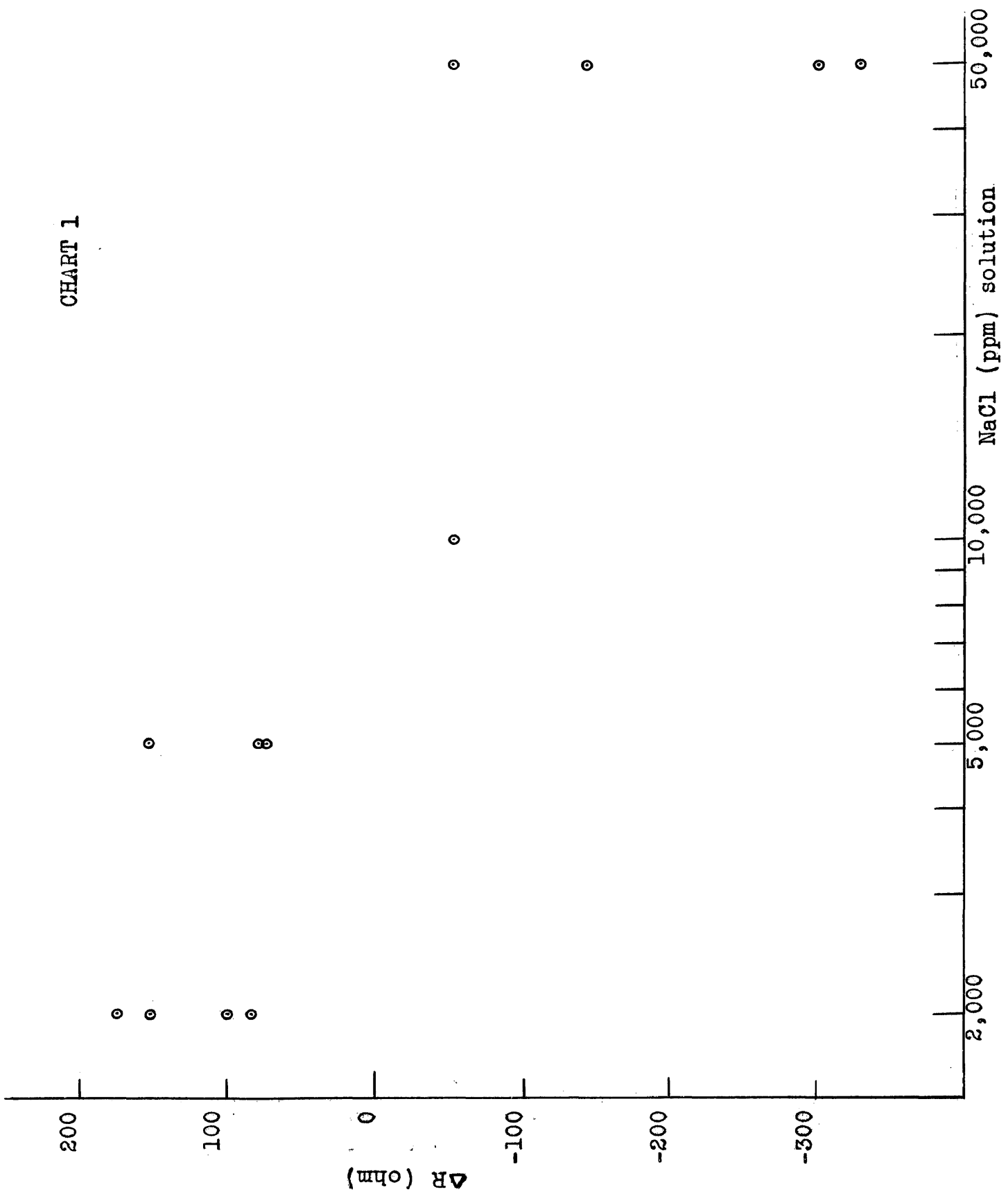


CHART 2

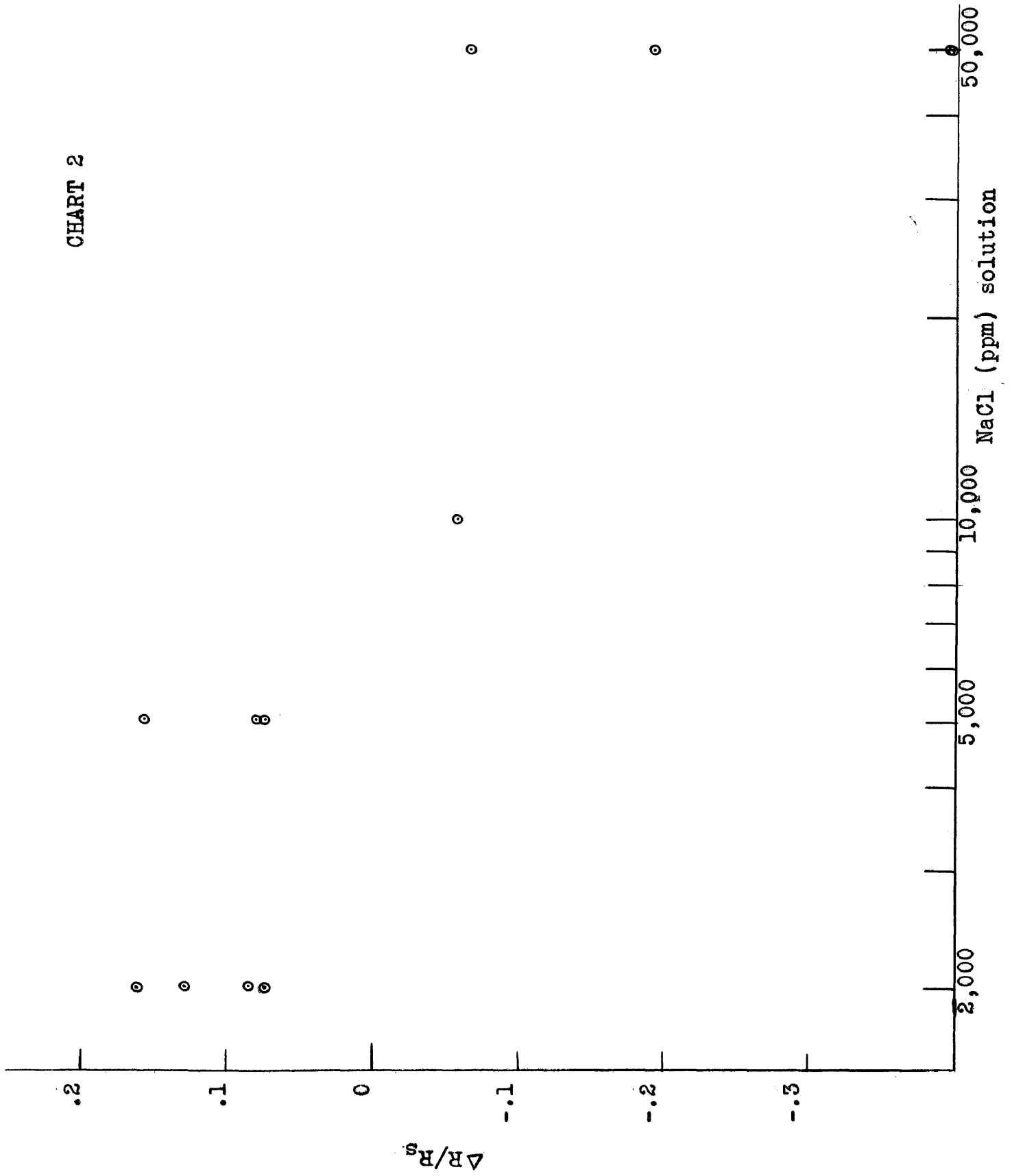
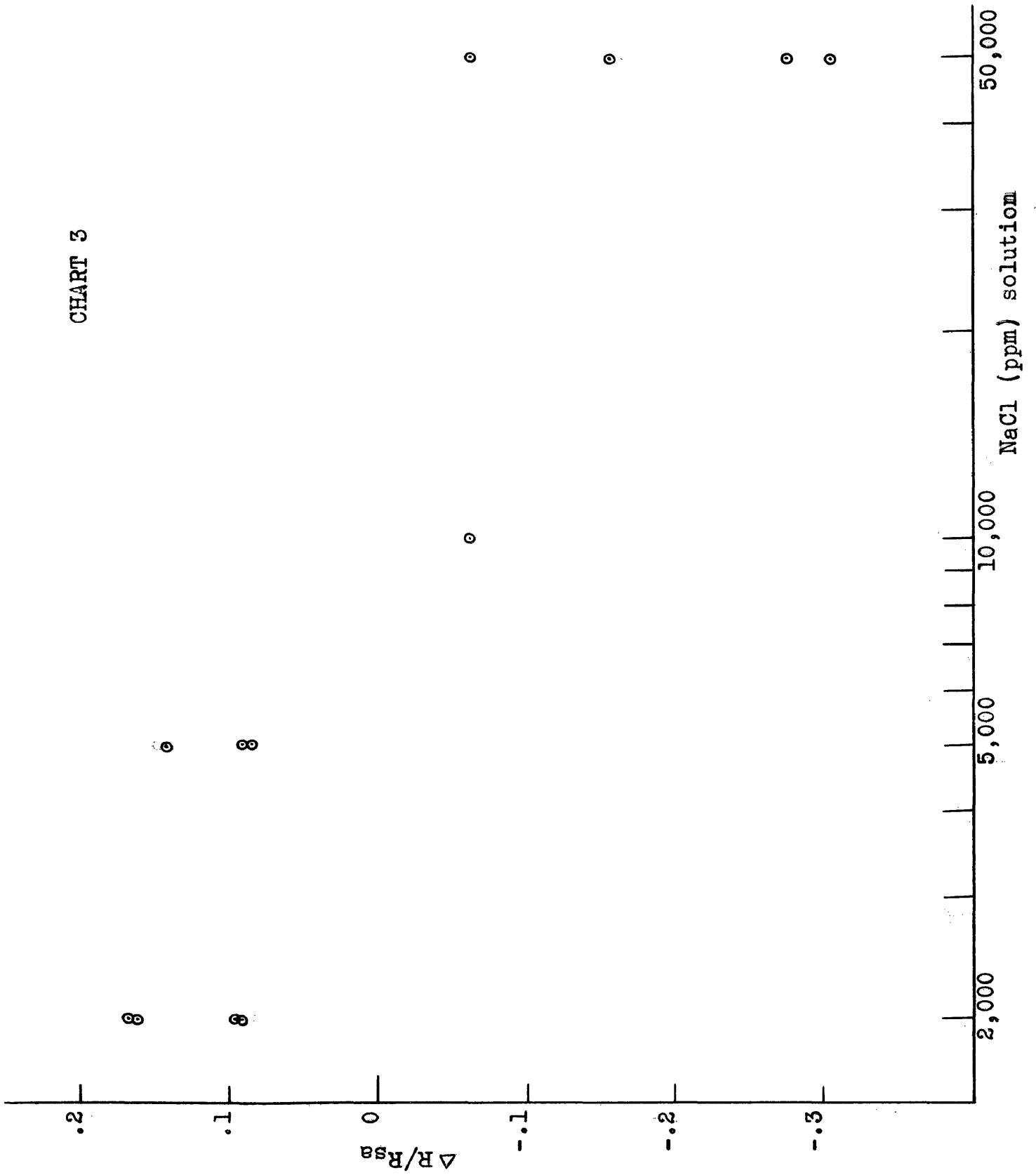


CHART 3



A NOTE ON POTENTIAL

Numerous workers have studied the cause of the potential observed in a bore hole. C. and M. Schlumberger and Leonardon (1934) jointly published a paper in which they reasoned that the S. P. (spontaneous potential) was due to an electrokinetic phenomenon called the streaming potential. In a second paper, they stated that under certain circumstances the electrochemical phenomenon could play a dominant role in development of S. P. Mounce and Rust (1944) published the results of their experimental works. They showed that when the sandstone separated two electrolytes, the developed potential is very small, and no current was observed to flow in the system. But when shale separated salt water and fresh water, the developed potential was of the magnitude of 100 to 150 mv; and the current was flowing from the shale to the fresh water, from the fresh water to the salt water, and from the salt

water to the shale. Wyllie and Patnode (1950) published a discussion of their experimental work on the electrochemical component of the S. P. They stated that the natural shale is semi-permeable. Thus, when it separates two electrolytes, the developed potential satisfied the Nernst equation. The Nernst equation for NaCl solutions is given by

$$V = \frac{RT}{F} \ln \frac{a'}{a''}$$

where V is the developed potential, R is the gas constant, T is the absolute temperature, F is Faraday's constant, and a' and a'' are the activities of the two solutions. McCardell, Winsauer, and Williams (1953) studied the cause of the potential that is developed when shale separates two electrolytes of different concentrations. They explained that shale has a characteristic of adsorbing negative ions when in contact with saline solutions; thus phase boundary potentials between shale and the solutions in contact are developed. A diffusion potential is developed because of ionic diffusion through shale from high concentration solution to low concentration solution. They believed that the diffusion potential is negligible in the case of pure shale. Their expression for the phase potential E_p is:

$$E_p = - \frac{KT}{e} \ln \left[\frac{n_0}{2n} + \sqrt{1 + \left(\frac{n_0}{2n}\right)^2} \right]$$

where

k is Boltzman's constant

T is absolute temperature

ϵ is the charge of a univalent ion

n is the concentration of the univalent positive or negative ions in the external solution far away from the phase boundary where the potential is defined to be zero and

n_0 is the concentration of the fixed negative charges on the surface of the shale particles

Gondouin, Tixier, and Simard (1957) presented a modified equation for the potential and demonstrated its use when a number of ions other than Na and Cl ions are present. Their equation is based upon the assumption that shale is semi-permeable.

The experimental results described in previous sections show that the shale used is permeable to both Na and Cl ions; so an attempt was made to see what type of potential would be developed when this shale separates NaCl solutions of two different concentrations. A number of experiments were performed where shale separated either 1N and .1N or .01N and .001N NaCl solutions. Standard 1.0N calomel electrodes were used to measure the potential, and the high-impedance Brown potentiometer was used to record the potential

In all the experiments in which shale separated 1N and .1N NaCl solutions, the developed potential ranged

from 50 to 56 mv. According to the Nernst equation, the developed potential should be 55 mv. When shale separated .01N and .001N NaCl solutions, the developed potential varied from minus 30 to plus 56 mv. To study the cause of such behavior, solutions were analysed at the beginning and at the end of the experiments. It was found that there was extensive K and Cl ions diffusion from calomel electrodes to the solutions. To avoid the effect of calomel electrodes, platinum, silver chloride, and lead electrodes were tried, but all gave erratic results.

SUMMARY

The hypothesis of ionic diffusion is presented to explain a "separation" recorded on a microlog at the level of shale formation. This hypothesis proposes that when drilling mud comes in contact with shale, there is ionic diffusion between connate water and a drilling fluid. This process of ionic diffusion affects the resistivity distribution of a shale formation (see figure 2a, 2b, and 2c). When a shale has a highly saline water, the ions diffuse from the connate water to the mud filtrate and create a thin layer of shale formation comparatively more resistive; thus a negative separation is recorded (see figure 2b and 3). When shale has lower concentration connate water, the ions diffuse from the mud filtrate to the connate water and create a thin layer of

shale formation comparatively less resistive; thus a positive separation is recorded (see figure 2c and 4).

A number of experiments were performed to test the validity of the hypothesis. The results obtained in most of the experiments indicated a decrease with time in the resistance of a shale sample when a solution of comparatively high salinity was in contact with the sample, and conversely an increase with time in the resistance with an adjacent solution of comparatively low salinity. This is in accordance with the hypothesis of ionic diffusion. It may be possible to determine the NaCl concentration of the connate water in the shale formation by plotting change in resistance of shale against the concentration of the solution used in the experiment (see charts 1, 2, and 3).

In the course of the experiments, two interesting points were observed. It was found that if the shale cores have become partially dehydrated, it is advisable to soak them in distilled water in order to restore to some extent the moisture they have lost and thus facilitate the diffusion of ions without greatly changing the original salinity of interstitial water. It was also noted that the shale resistivity, calculated from the average measured resistance of the samples, is close to the resistivity of the shale formation as recorded on the electric log (see figure 6).

Some experiments were performed to study the potential that is developed when shale that is permeable to both Na and Cl ions, separates NaCl solutions of different concentrations. It was observed that the developed potential satisfied the Nernst equation when the shale separated 1N and 0.1N NaCl solutions but apparently did not hold for dilute solutions.

It is recognized that further experimental work is necessary to test the ionic diffusion hypothesis, which if established as a theory will increase our understanding of the electric log.

BIBLIOGRAPHY

- Archie, G. E., 1950, Introduction to Petrophysics of Reservoir Rocks: Am. Assn. Petroleum Geologists Bull., v. 34, p. 943.
- Arps, J. J., 1953, The Effect of Temperature on the Density and Electrical Resistivity of Sodium Chloride Solution: Jour. Pet. Tech., Sec. 1, Tech. Note 195, v. 5, no. 10, Oct., p. 17.
- Bacon, L. O., 1949, Formation Clay Minerals and Electrical Logging: Producers Monthly, v. 13, no. 3, Jan., p. 18.
- Berg, J. W. Jr., 1952, Conductivity Study of Aqueous KAO-LIN NaCl Mixtures: Producers Monthly, v. 16, no. 3, Jan., p. 36.
- Blum, H. A., and Martin, J. L., 1955, Log Interpretation Problem in Low Resistivity Sands: Jour. Pet. Tech., August, p. 10.
- Cook, J. C., 1950, Characteristics of Reservoir Models by Resistivity Logging: Producers Monthly, v. 14, no. 5, March, p. 24.
- DeWitte, L., 1950, Relations Between Resistivities and Fluid Contents of Porous Rocks: Oil and Gas Jour., v. 49, no. 16, August 24, p. 120.
- Doll, H. G., 1949, The SP Log: Theoretical Analysis and Principles of Interpretation: AIME Trans. Pet. Branch, v. 179, p. 146.

- Doll, H. G., 1950, The Microlog-A New Electrical Logging Method For Detailed Determination of Permeable Beds: A. I. M. E. Transactions, v. 189, T. P. 2880, p. 155.
- Doll, H. G., Sauvage, R. and Martin, M., 1952, Application of Micrologging to Determination of Porosity: Part I, Oil and Gas Jour., v. 51, no. 17, Sept. 1, p. 90.
- Doll, H. G., Sauvage, R. and Martin, M., 1952, Application of Micrologging to Determination of Porosity: Part II, Oil and Gas Jour., v. 51, no. 18, Sept. 8, p. 86.
- Dunlap, H. F. and Hawthorne, R. R., 1951, The Calculation of Water Resistivities From Chemical Analyses: Jour. Pet. Tech., v. 3, no. 3, Tech. note 67, March, p. 17.
- Gondouin, M., Tixier, M. P., and Simard, G. L., 1957, An Experimental Study on the Influence of the Chemical Composition of Electrolytes on the SP Curve: Jour. Pet. Tech., v. 9, no. 2, February, p. 58.
- Guyod, Hubert, 1951, Principles of Microlog Interpretation: Oil and Gas Jour., v. 50, no. 31, Dec. 6, p. 102.
- Hamilton, R. G., 1952, Common Fallacies in Electrical Log Interpretation: World Oil, v. 134, no. 5, April, p. 141.
- Holmes, C. R., 1954, Some Factors Related to the Measurement of the Electrical Properties of Porous Sandstones: Producers Monthly, Nov., p. 21.
- Howell, B. F., Jr., 1953, Electrical Conduction in Fluid-Saturated Rocks, World Oil, v. 136, no. 2, Feb., p. 113, part I.
- Howell, B. F., Jr., 1953, Electrical Conduction in Fluid-Saturated Rocks, World Oil, v. 136, no. 4, March, 1953, p. 142, part II.
- Howell, B. F. Jr., 1953, Review of Well Logging Research at the Pennsylvania State College: Producers Monthly, April, p. 51.

- Howell, B. F. Jr. and Cervik, J., 1956, Comparison of X-Ray Diffraction and K-Factor Studies of the Clay Content of Artificial Cores: Producers Monthly, February, p. 36.
- Jakosky, J. J. and Hopper, R. H., 1937, The Effect of Moisture on the Direct Current Resistivities of Oil Sands and Rocks: Geophysics, v. 2, no. 1, January.
- Jones, P. J., 1944, Characteristics of Electrical Logs: Oil and Gas Jour., v. 43, no. 33, Dec. 23, p. 75.
- Keller, G. V., 1951, The Role of Clays in the Electrical Conductivity of the Bradford Sand: Producers Monthly, February, p. 23.
- Kornfeld, J. A., 1951, Why Clay Content Affects Permeability of Reservoir Sand: Oil and Gas Jour., Oct. 25, p. 147.
- Kozary, M. T., 1949, Streaming Potentials in Electrical Well Logging: Producers Monthly, v. 13, no. 4, Feb., p. 14.
- Martin, M., 1955, With the Microlog---You Can Be Sure:
Part I, Oil and Gas Journal, v. 54, no. 20, Sept. 19, p. 108-111.
Part II, Oil and Gas Journal, V. 54, no. 25, Oct. 24, p. 106-109.
- Mounce, W. D. and Rust, W. M., Jr., 1949, Natural Potentials in Well Logging: A. I. M. E., v. 155, p. 49.
- McBain, J. W., 1950, Colloid Science: D. C. Heath and Company, Boston.
- McCardell, W. M. and Winsauer, W. O., 1953, Ionic Double-Layer Conductivity in Reservoir Rock: Jour. Pet. Tech., T. P. 3565, v. 5, no. 5, May, p. 129.
- McCardell, W. M. and Winsauer, W. O., Williams, M., 1953, Origin of the Electric Potential Observed in Wells: T. P. 3500, Jour. Pet. Tech, v. 5, no. 2, February, p. 41.
- Pullen. M. W., 1929, Tentative Method for Making Resistivity Measurement of Drill Cores and Hand Specimens of Rocks and Ores: Information Circular No. 6141, Bureau of Mines, June.

Richardson, J. G., Perkins, F. M. Jr., and Osoba, J. S., 1955, Differences in Behavior of Fresh and Aged East Texas Woodbine Cores, Jour. Pet. Tech., T. P. 4056, v. 7, no. 6, June, p. 86.

Schlumberger, C. and M and Leonardon, E. G., 1936, Electrical Coring; A Method of Determining Bottom-hole Data by Electrical Measurements: A. I. M. E., v. 110, p. 237.

Schlumberger, C. and M. and Leonardon, E. G., 1936, A New Contribution to Subsurface Studies by Means of Electrical Measurements in Drill Holes: A. I. M. E., v. 110, p. 273.

Ward, S. H., 1953, A Method for Measuring the Electrical Conductivity of Diamond Drill Core Specimens: Geophysics, v. 18, no. 2., April, p. 434.

Wyllie, M. R. J., 1949, A Quantitative Analysis of the Electrochemical Component of the SP Curve, Jour. Pet. Tech., v. 1, no. 1, Jan., p. 17.

Wyllie, M. R. J., 1948, Some electrochemical Properties of Shales: Science, Dec. 17, v. 108, no. 2816, p. 684.

Wyllie, M. R. J. and Patnode, H. W., 1950, The Development of Membranes Prepared from Artificial Cation-Exchange Materials with Particular Reference to the Determination of Sodium-Ion Activities: Jour. of Phys. and Colloid Chemistry, v. 54, no. 2, Feb., p. 204.