"QUANTIFICATION OF SURFACE CONDUCTIVITY IN CLEAN SANDSTONES."

by

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This paper is to be presented at the 5th Formation Evaluation Symposium of the Canadian Well Logging Society in Calgary, May 5 - 7, 1975. Discussion of this paper is invited. Such discussion may be presented at the Symposium and will be considered for publication if filed in writing with the Technical Program Chairman prior to the conclusion of the Symposium.

ABSTRACT

Many investigators have noted that the apparent formation factor of porous materials seems to diminish as the interstitial waters become more resistive. This effect has been attributed both to the presence of "conductive solids" (usually clays) and to the existence of a concentrated layer of ions attracted to the surfaces of the rock matrix. This study was designed to determine (1) if surface conductivity in clean sandstones was an important consideration in the evaluation of fresh water aquifers and (2) if so, what parameters were necessary to evaluate the effect.

Nine cores, two of which had small percentages of clay were chosen with average grain sizes ranging from .09 to .29 mm. Resistivities were measured over a wide concentration range using solutions of NaCl, Na_2SO_4, $NaHCO_3$, and $CaCl_2$. The results were found to correlate with a simple equation that is easily applied to routine log analysis. Several examples of actual log analysis are presented and compared to measured water resistivities with an average deviation of less than 7 1/2% between the log derived values and the measured values. If surface effects were neglected in the same cases the calculated R_w could have been as much as 60% too low.

INTRODUCTION

Many investigators have noted that the apparent formation factor of porous materials will diminish as the interstitial water becomes more fresh.(1-8) This effect has been attributed both to "conductive solids" (shale or clay) and to the existence of a concentrated layer of ions adsorbed on the surface of the rock matrix. Since dry shale is a non-conductor, the two explanations are probably equivalent. The large surface areas associated with clay and shale merely enhance the effect of surface conductance when these materials are present. Alger (7) and Turcan (5) suggest the use of local formation factors in fresh water aquifers while other authors (1,6,9) have demonstrated excess conductivity with fresh water and no clay or shale (i.e., washed river sand and both crushed and polished pyrex glass). This effect is negligible, however, for clean sands saturated with typical oil field waters and the quantitative work in the literature has concentrated on shaly sands.

The western United States is now entering an era of energy development which will require large amounts of fresh water. Groundwater exploration is becoming important and many log analysts will be called upon to evaluate fresh water aquifers (R_w on the order of 10 Ω-m or more) which may be free of shale but which will still show significant reductions in the apparent formation factor. This study uses laboratory data from a series of nine sandstone cores and several salt solutions to help define the parameters a log analyst will need to make these evaluations.

DOUBLE LAYER CONDUCTIVITY

Solid surfaces in contact with an aqueous solution will attract a layer of charged ions which will in turn attract a second layer of oppositely charged ions and so on. This gives the effect of a concentrated solution near the surface and reduces the resistance to electrical flow. Winsaur and McCardell (3) present a good review of this ionic double layer conductivity in their study of shaly sands. McBain (9) used KCl solutions and polished pyrex glass to demonstrate surface conductivity on siliceous materials while Urban (1) used crushed pyrex with KCl and NaCl solutions to demonstrate the same thing. Both investigators found excess conductivity due to the double layer as high as 20 to 40 percent of the solution conductivity. Although Urban presents some formulas to predict surface conductivity, they contain variables which a log analyst would not be able to obtain; hence, a different approach was needed. Examination of Urban's data showed that an acceptable correlation for waters with R_w greater than 1 Ω-m (100 Ω-cm) was

$$C_{st} = C'_s C_w^{\alpha} \qquad (1)$$

where,

C_{st} = total surface conductivity in mho/cm per cm^2 of surface in contact with 1 cm^3 of fluid,

C'_s and α are empirically determined constants which probably depend on both the fluid and the rock,

C_w = water conductivity.

The total rock conductivity is then expressed as:

$$\frac{1}{R_{o_a}} = \frac{1}{R_o} + C'_s C_w^{\alpha} \qquad (2)$$

or

$$\frac{1}{F_a} = \frac{1}{F} + C'_s R_w^{\beta} \qquad (3)$$

where,

$R_{o_a} = F_a R_w$ = the resistivity of the saturated rock including surface effects,

$R_o = F R_w$ = the resistivity of saturated rock without surface effects,

F_a = apparent formation factor including surface effects,

F = formation factor as normally defined (no surface effects),

$\beta = 1 - \alpha$.

The following experimental work was designed to test the validity of Equation (3) and to see if C'_s and β could be predicted with the information a log analyst might have available.

EXPERIMENTAL PROCEDURE

Nine sandstone cores were selected from the Upper Jelm, Sundance, Mesaverde and Casper formations of Wyoming for resistivity measurements and five adjacent and similar cores were selected for thin section petrological examination. The properties of these are summarized in Tables I and II. All cores were 2.5 cm in length and 2.1 cm in diameter. A conventional permeability cell was altered as shown in Figure 1 to include stainless steel platinized electrodes for making resistivity measurements. A General Radio Impedance Bridge (Type 1656) was used for resistance measurements with 1-KHz AC power to minimize polarization and electroosmosis. A Beckman Model CEL-BB1 conductivity cell was employed to determine the solution resistivities.

Prior to any experimental use the cores were dried at 100°C in a vacuum desicator to remove any moisture or organic matter and to render them preferentially water wet. After cooling they were mounted in the resistivity cell. Air pressure (20 psia) was used to force brine through the core. A flow of 100 to 150 pore volumes was considered to give complete saturation and the weight difference between the dry and wet cores gave the effective porosity. Although this method gave consistent porosity values, it did not give complete saturation and a vacuum saturation technique was later used to give the total porosity as reported in Table II. Porosity was not used directly in this study and the presence of a small amount of immobile gas would have little effect on the final results as long as consistent saturations were obtained.

The desired salt solutions were then flowed through the core until the core resistivity and the effluent resistivity became constant. The apparent formation factor F_a was obtained as the ratio of the core resistivity to the effluent resistivity. Grain size was visually estimated using a 50 power binocular microscope and the thin section examination was performed with a 100 power microscope. All measurements were at room temperature with the solution resistivities and all reported data corrected to 25°C using data by Davies (10) and Tower (11).

DISCUSSION OF RESULTS

Core #323 was broken during the early experimental work and is not included, but the rest of the data is presented in Figures 2, 3, 4, and 5 and Table III. The most important considerations are (1) the "goodness of fit" of the proposed equation and (2) the effect of rock and fluid properties on the experimental parameters β and C_s'.

First it should be noted that the proposed equation does fit the data very well. The average standard deviation of F_a is .3 with F_a varying over a range of approximately 2 to 20. Since it is likely that most waters of interest would be in the range of 10 to 50 Ω-m (1000 to 5000 Ω-cm) with an apparent formation factor greater than 10, this is not a large deviation.

A more difficult problem arises when the log analyst has to predict β and C_s' for a given interpretation problem. Fortunately, the data of this study indicate that these parameters are fairly constant for clean sandstones. If core #314 is disregarded, β ranges from .74 to .90 and C_s' from .8 * 10^{-4} to 1.5 * 10^{-4}. Core #314 has a β value of 1.13 which would indicate the surface conductivity decreases with increasing water conductivity ($\alpha = 1-\beta = -.13$) and the C_s' value of 0.08 * 10^{-4} is an order of magnitude less than any other core including core #407 which was cut from the same formation. A probable explanation is that the data on core #314 was obtained before the Beckman dip cell was received and the high resistivity data is considered poor. The dashed line on Figure 2 was calculated with β = .8 and C_s' = 10^{-4} and is an acceptable fit for R_w less than 100 Ω-m (10^4 Ω-cm). It should also be noted that practical interpretation for waters of higher resistivity would be a difficult problem in any case. The steepness of the F_a vs R_w curves shows a very weak dependence of rock resistivity on R_w (a slope of 45° would make R_{o_a} independent of R_w) and makes calculated values of R_w very sensitive to errors in the measured resistivity values.

Visual examination of Figures 2-4 shows that the curves seem to be unaffected by changes in the dissolved ions; hence, the log analyst can concentrate on rock properties rather than fluid properties. Cores #252 and #270 have minor amounts of clay but do not show significantly higher surface effects.

The final variable to be considered was specific surface area in contact with a unit volume of pore space, (S_ϕ). The total surface conductivity (C_{st})$^\phi$ should be equal to the specific surface area (S_ϕ) times the specific surface conductivity (C_s), where C_s is a function of C_w and the type of rock surface. Since specific surface area is a difficult quantity to measure and this study was intended for use by people who would probably not have that information, we merely noted that if we have geometric similarity, the surface area is inversely proportional to the grain size. To better quantify the surface effect we decided to hold β constant at a value of .8 and calculate C_s' for each of the cores. This data is presented in Table IV and as expected shows the trend of increasing surface conductivity with decreasing grain size. The scatter in the data makes a truly meaningful correlation impossible but Figure 6 can be used as a rough guide. The grain size classification shown below this figure is based on LeRoy (12). Attempts to apply Equation (3) to Hill and Milburn's data (4,13) suggest that C_s' would be on the order of 15 * 10^{-4} to 25 * 10^{-4} for very shaly sands. This would be a reasonable extrapolation of Figure 6 although aquifers with grain sizes less than 0.1 mm would probably be of little interest. The dashed line was drawn through the origin (infinite grain size = zero specific surface) and the best average of the data. It is possible that the ion exchange potential used by Hill and Milburn would be a good correlating parameter, but this was beyond the scope of this study.

The specific surface area for these cores was estimated to be on the order of 50,000 cm^2 per unit pore volume (Kozeny equation (14) and Helander's work (8)). Hence, the specific surface conductivity at infinite dilution is approximately 2 * 10^{-9} mho/cm per cm^2 of surface in contact with 1 cm^3 of fluid. This is in good agreement with Urban's work (1) where he measured C_s = 3 * 10^{-9} mho/cm/(cm^2/cm^3) for 0.00012N NaCl in contact with pyrex glass particles.

FIELD EXAMPLES

If good values of R_{o_a} and F can be obtained from logs, the application of Equation (3) is straight forward. β can be taken as 0.8 and C_s' as 10^{-4} for an average clean sand (use Ω-cm for R_w) or if cutting data is available to estimate the grain

size, C_s' can be selected from Figure 6.

The equation

$$R_w = R_{o_a}\left[\frac{1}{F} + C_s' R_w^{\beta}\right] \qquad (4)$$

is most easilty solved by trial and error. Estimate a value of R_w for the right hand side. Calculate a new value from the equation and use the new value in the right hand side. Four or five iterations should give acceptable convergence. Table V shows the results of applying this method to five wells for which we had both good logs and good water analysis. Note that the second well is producing from a limestone formation (The Madison) and the agreement between measured and calculated water resistivity is still excellent.

CONCLUSIONS

It can be concluded that:

1. Surface conductivity can materially reduce the apparent formation factor and cause pessimistic evaluations of water quality with water resistivities as low as 3 Ω-m.

2. This effect is present in clean sands and is not significantly changed by minor amounts of clay. Analysis of a single well also indicates similar effects for clastic limestone reservoirs.

3. The type of salt in the water has little or no effect on the magnitude of surface conductivity over the range of concentration studied. This may not be true at higher concentrations, but would not be an important consideration in clean sands.

4. Due to the difficulty of accurately estimating specific surface areas (both for the experimental work and in actual log analysis) no definite correlation was established between surface conductivity and either grain size or specific surface, although some guidelines are suggested. The cation exchange capacity looks like a possible correlating parameter.

5. Temperature effects were not studied, but the suggested method gave good results in wells as deep as 2800 feet.

6. Although the results of this study indicate that very few variables are necessary to evaluate R_w in fresh water aquifers, further studies should be made to evaluate clastic limestones and temperature effects and to extend these results to shaly sands.

ACKNOWLEDGEMENT

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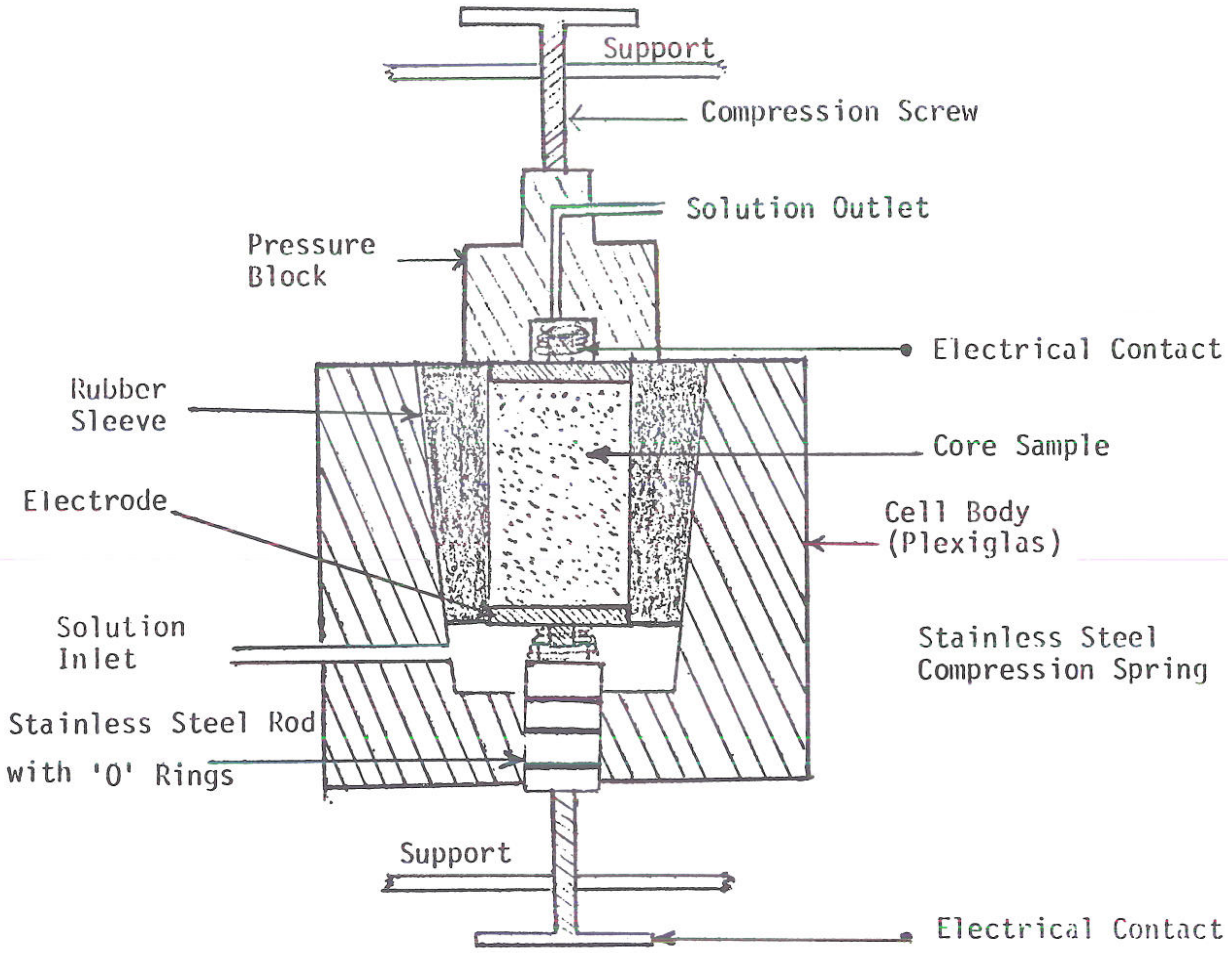

Figure 1. Cross Section of the Resistivity Cell

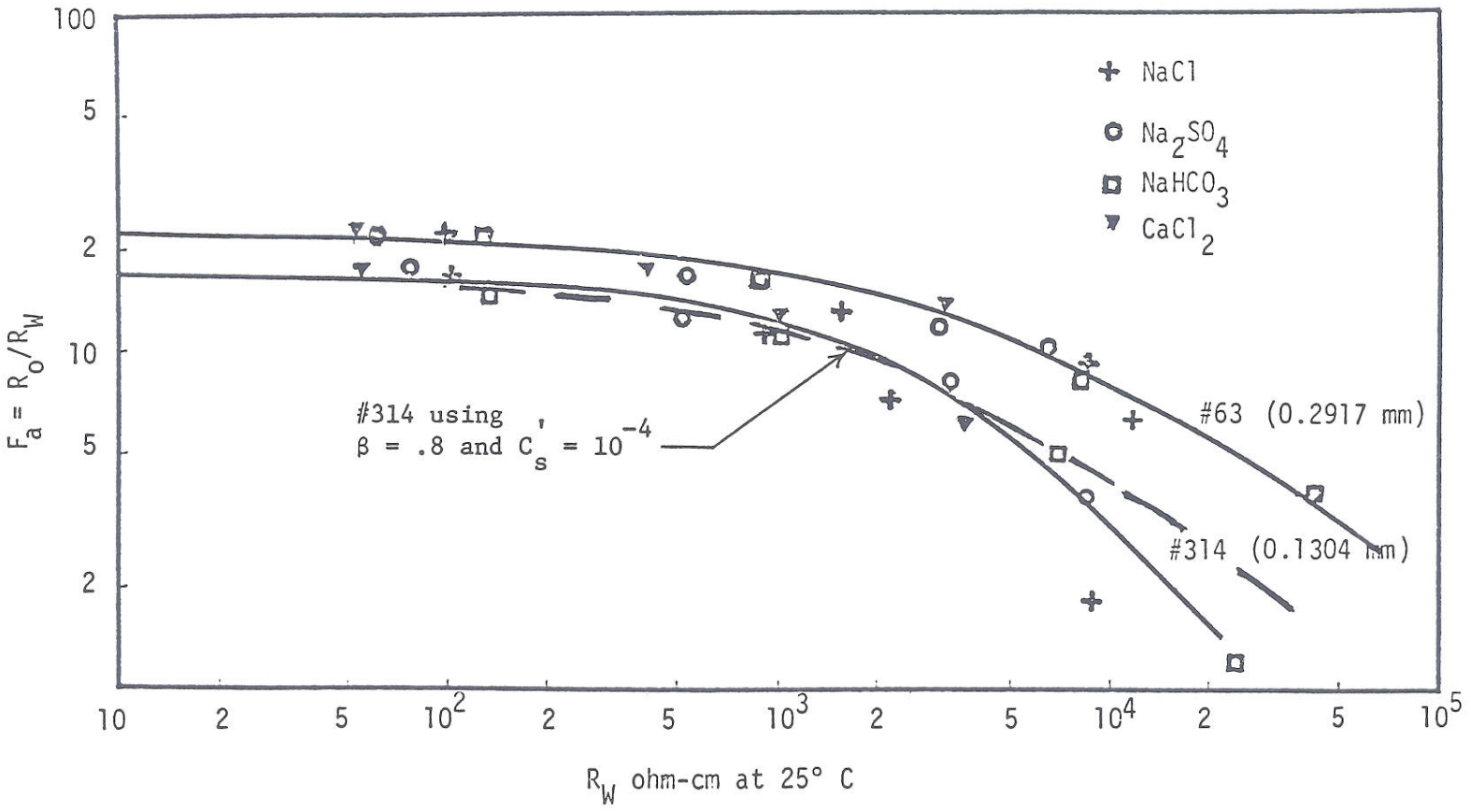

Figure 2. Relationship of Formation Resistivity Factor and R_w for Experimental Cores #63 and #314

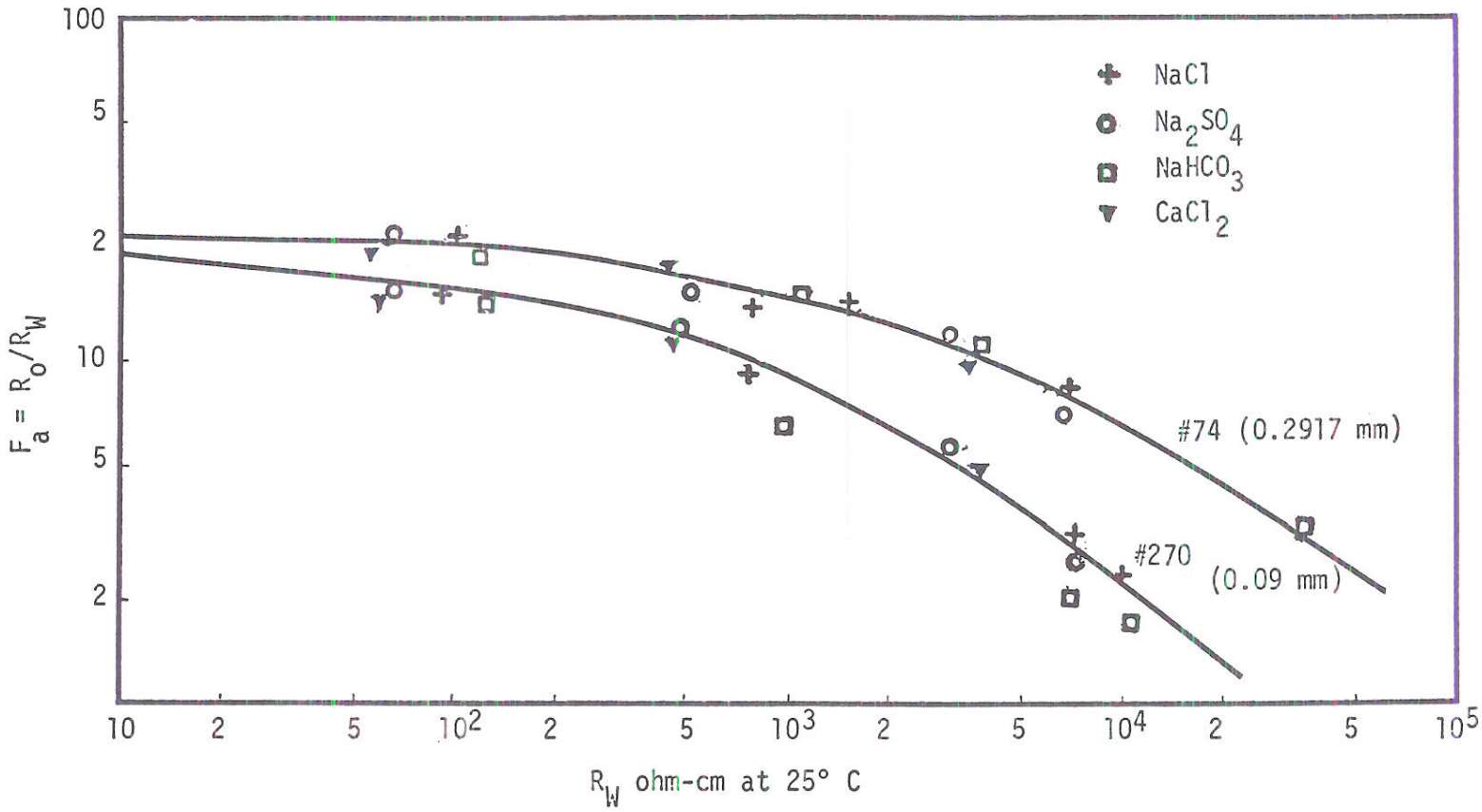

Figure 3. Relationship of Formation Resistivity Factor and R_w for Experimental Cores #74 and #270

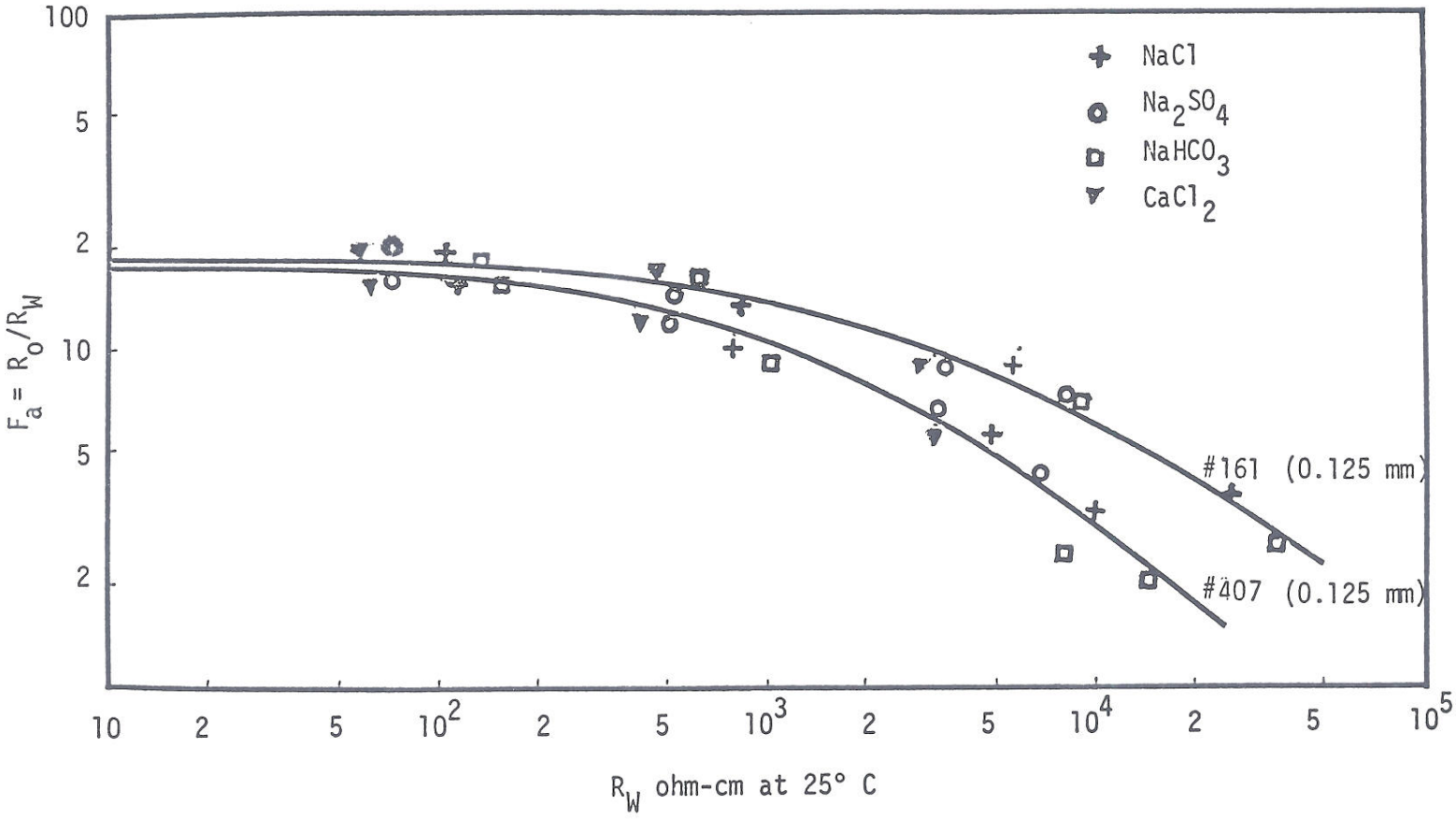

Figure 4. Relationship of Formation Resistivity Factor and R_W for Experimental Cores #161 and #407

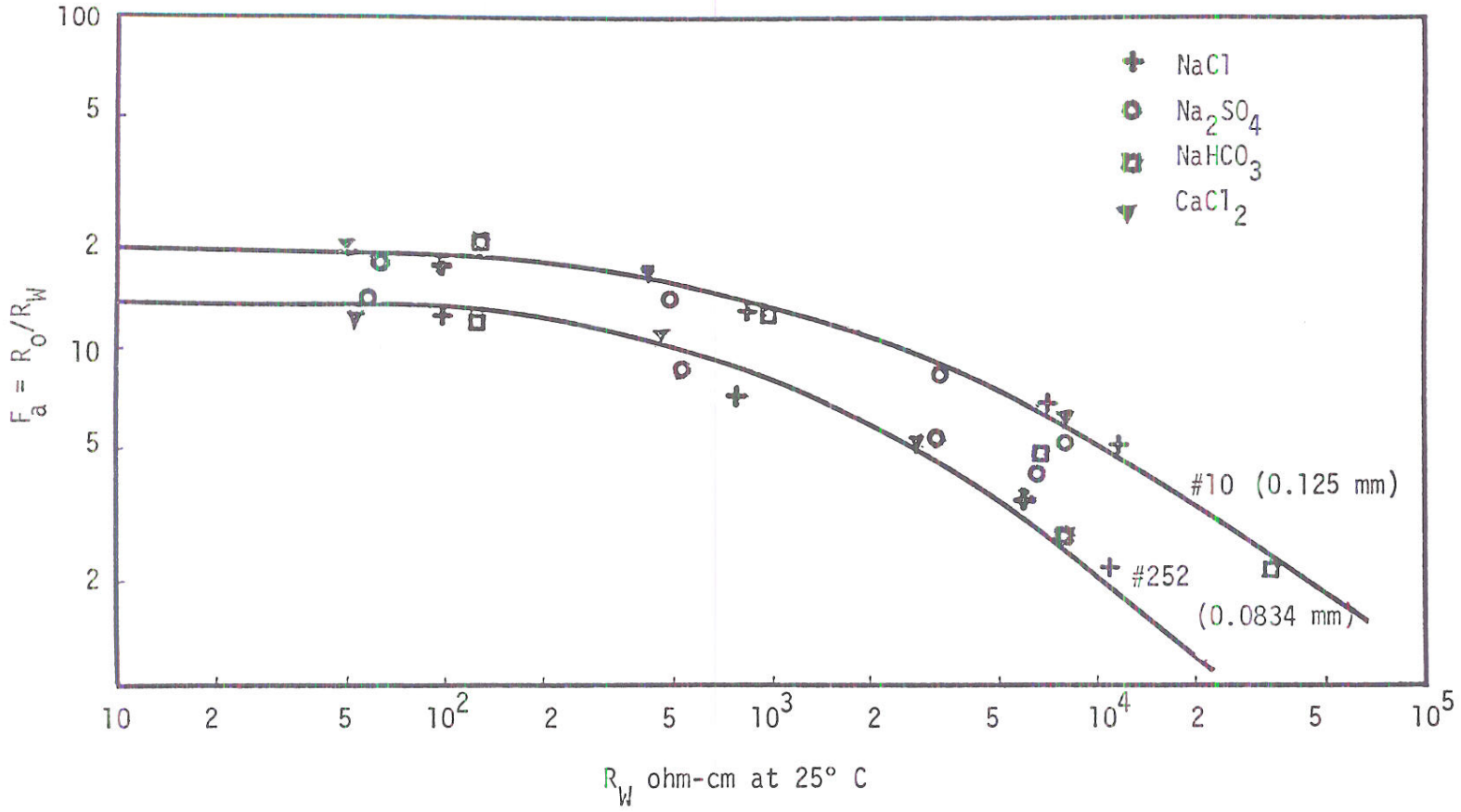

Figure 5. Relationship of Formation Resistivity Factor and R_w for Experimental Cores #10 and #252

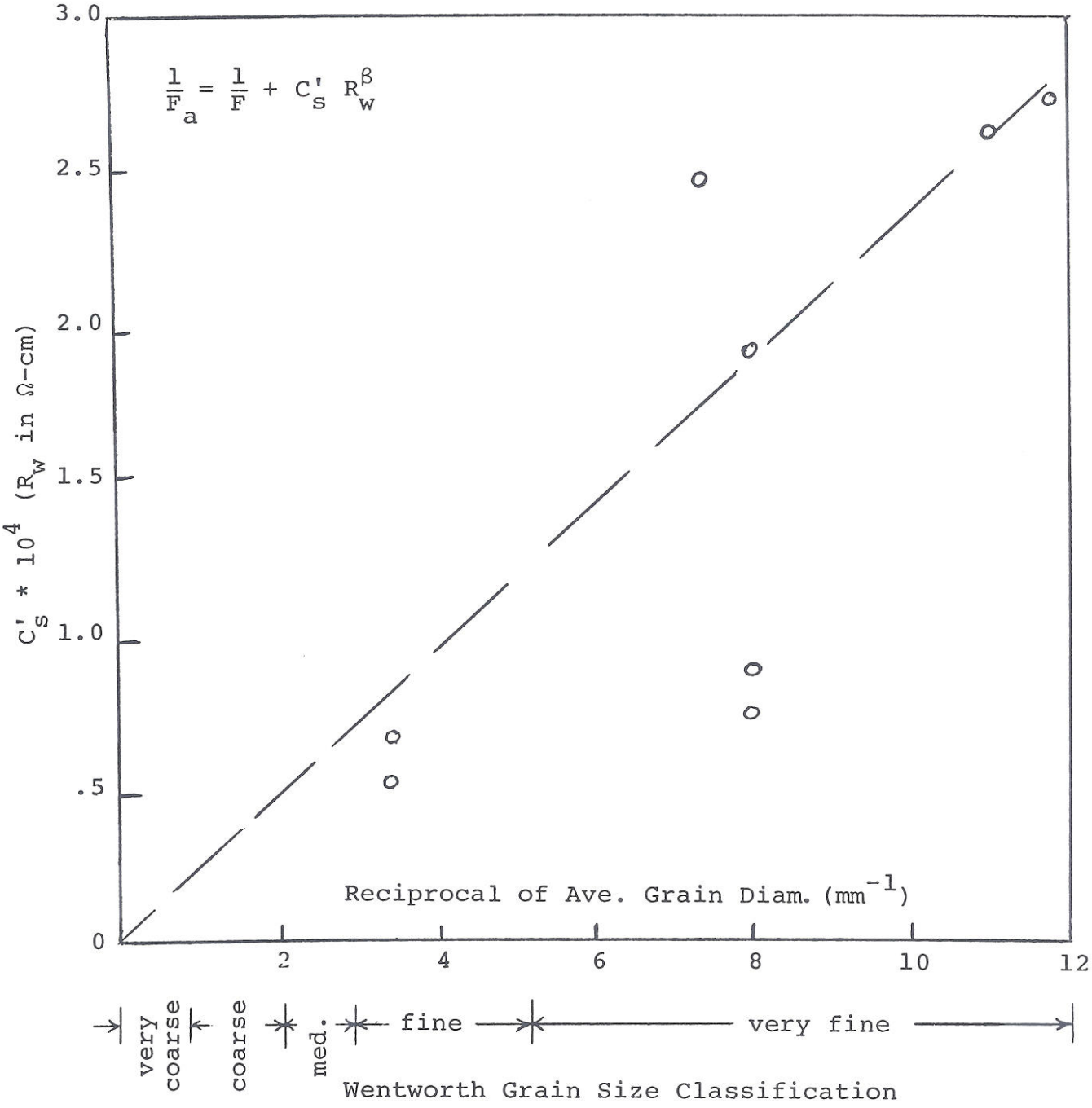

Figure 6. Surface Conductivity Parameter C_s' vs. Grain Size

Table I. Classification and Petrology of Core Formations.

Type	Formation	Cores used for experimental work	Cores used for petrology	Appearance under the microscope
1.	Upper Jelm	#10	#2	Fine sandstone Dolomite cement, very small Rhombohedral crystals projecting into open pores Detrital grains - well rounded to subrounded quartz, some feldspar Porosity fair, ave grain size >.1 mm Clay content none.
2.	Sundance	#63,74,161	#65	Very fine sandstone Dolomite, fine angular crystals Detrital grains; quartz and some feldspar Low porosity, grain size <.1 mm No clay content visible.
3.	Mesaverde	#252,270	#248	Very fine sandstone Calcite (isolated patches) Clay borders on sand grains Clay content distinct Detrital grains; magnetite Quartz dominant, some chert and feldspar Average grain size <.1 mm.
4.	Casper (Tensleep or Minnelusa)	#314,323, 407	#315,408	Very fine sandstone Both cemented by Calcite Large intergrowths of Sparry Calcite Detrital grains: Angular chert, feldspar, mica along with quartz Porosities of both low Clay content not distinct Average grain size <.2 mm Ilmenite (iron oxide) stains on core #408

TABLE II

PROPERTIES OF CORES

Core #	Total Porosity Percent	Effective Porosity Percent	Permeability Millidarcys	Average Grain Size Millimeters
10	18.30	15.45	23.11	0.125
63	19.361	14.58	26.43	0.2917
74	17.63	15.98	18.617	0.2917
161	20.963	18.56	23.42	0.125
270	18.84	15.48	47.67	0.090
314	19.259	16.4	16.53	0.1304
323	19.422	13.85	80.37	0.167
407	19.283	17.81	13.09	0.125
252	21.16	18.47	41.0	0.0834

TABLE III

CALCULATED VALUES OF FORMATION FACTOR
AND SURFACE CONDUCTIVITY PARAMETERS

EXPERIMENTAL CORES

Core #	F	β	Minimum Standard Deviation	Surface Conductivity Parameter, $C_s' \times 10^{-4}$
10	21.267	0.751	0.293	1.456
63	23.232	0.753	0.168	0.806
74	23.172	0.739	0.240	1.252
161	19.051	0.773	0.388	0.962
252	14.845	0.898	0.329	1.057
270	19.287	0.858	0.397	1.543
314	16.964	1.133	0.548	0.079
407	18.223	0.851	0.278	1.161

TABLE IV

SURFACE CONDUCTIVITY OF EXPERIMENTAL CORES

USING CONSTANT VALUE OF β

Core Sample	Average Grain Size, mm	$C'_s \times 10^4$ Surface Conductivity Parameter
63	0.2917	0.495
74	0.2917	0.665
161	0.125	0.727
10	0.125	0.878
407	0.125	1.879
314	0.1304	2.496
270	0.090	2.647
252	0.0834	2.744

TABLE V

EXAMPLES OF LOG INTERPRETATIONS

County and Well Location	Formation and Depth	Formation Resistivity (Ω-m)	F	F_a	R_w at 25°C without surface effects	R_w at 25°C with surface effects β=.8, C_s'= 10^{-4}	Measured R_w at 25°C
Natrona 39N 79W Sec 11	Frontier 2100 ft	35	14	11.8	2.5	3.0	2.8
Washakie 47N 89W Sec 6	Madison 2835 ft	1300	156	63	9.7	24.0	25.3
Campbell 55N 75W Sec 9	Fort Union 1095 ft	45	12	10.5	4.1	4.7	5.1
Albany 16N 73W Sec 33	Tensleep 800 ft	380	24	8.2	17.2	42.8	38.5
Weston 45N 61W Sec 29	Lakota 930 ft	40	8.7	7.6	4.5	4.7	4.8