"A STATISTICAL STUDY OF THE SP LOG IN FRESH WATER FORMATIONS OF WYOMING'S BIG HORN AND WIND RIVER BASINS"

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by

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ABSTRACT

Water is rapidly becoming one of the most important factors controlling the industrial development of western states, and groundwater exploration is becoming an important part of formation evaluation in these areas.

The SP curve has been the log analyst's traditional tool for the determination of water resistivity, but the published correlations of $R_{w(e)}$ vs R_w for "average fresh waters" do not extend to the resistivity of potable water. A formula presented by Gondouin, Tixier, and Simard to correct the SP for divalent cations can be used to calculate the SP from water analysis, but the problem is the converse of this. This study was an attempt to determine geographical and/or geological data that could be used to predict the quality of fresh waters using SP derived data.

Published water analyses from 100 wells in the Big Horn and Powder River Basins were used with the previously mentioned equation to calculate the equivalent SP water resistivity ($R_{w(e)}$). The resulting data was plotted against the true electrical resistivity (R_w) and was found to fall into three broad categories based on geologic age. Plots of R_w vs total dissolved solids (TDS) were found to group into the same geologic age groups. Further analysis isolated the chemical groups responsible for these patterns and suggested guidelines to be used in other areas.

The methods suggested by the study were applied to several wells where both logs and water analysis were available and resulted in an average deviation of 12.8% on R_w and 15.1% on TDS.

INTRODUCTION

Water is rapidly becoming one of the most important factors controlling the industrial and energy development of the western United States, and log analysis and formation evaluation will become an important part of groundwater exploration for these areas. Although the log analyst has usually looked to the SP log for the determination of resistivity, there are no general correlations to extend the utility of this log to water resistivities higher than 1 or 2 Ω-m. Since most potable waters will have resistivity values from 5 Ω-m to 100 Ω-m or more, the use of the SP for

fresh water evaluation depends on local correlations. If the ionic makeup of groundwaters can be established over a geologic and/or geographic unit then the SP can be used to predict water resistivity and the resistivity can be correlated with total dissolved solids. This study used published water and established log interpretation techniques to analyze SP response in three important Wyoming drainage basins. These basins are shown in Figure 1.

THEORY AND PRACTICE

The electrochemical component of the SP curve is generally based on sodium chloride solutions and expressed as the well-established equation

$$SP = -K \log \frac{R_{mf}}{R_w} \qquad (1)$$

Corrections are often made for the presence of divalent cations or high concentrations (R_{mf}/R_w not equal to a_w/a_{mf}) by means of published charts which convert the resistivities to equivalent resistivities such that

$$\frac{R_{mf(e)}}{R_{w(e)}} = \frac{a_w}{a_{mf}} \qquad (2)$$

For dilute solutions the difference between $R_{w(e)}$ and R_w is caused by the presence of divalent cations (Mg and Ca) and $R_{w(e)}$ can be considered as the resistivity of a NaCl solution which would give the same SP behavior. Alger (4) suggests that $R_{mf} = R_{mf(e)}$ because the base exchange properties of the clays in the mud will reduce the divalent ion concentration in the filtrate.

Goudouin et al. (5) have shown that the electrochemical SP can generally be expressed within 5 millivolts by:

$$SP = -K \log \frac{(a_{Na} + \sqrt{a_{Ca} + a_{Mg}})_w}{(a_{Na} + \sqrt{a_{Ca} + a_{Mg}})_{mf}} \qquad (3)$$

or if the mud filtrate is considered to act as a sodium solution

$$SP = -K \log \frac{(a_{Na} + \sqrt{a_{Ca} + a_{Mg}})_w}{(a_{Na})_{mf}} \qquad (4)$$

Alger (4) gives activity data as a function of concentration; hence, Equation (4) can be used with a water analysis to predict the SP. Our problem, however, was the converse of this; therefore, we proceeded one step further. Published water analyses (6,7) were used to predict the SP behavior from Equation (4) and this was used with Equation (2) to predict $R_{w(e)}$.

The true water resistivity R_w was taken from published values or calculated (4,8) from the analytical data and plots of R_w vs $R_{w(e)}$ were analyzed to see if definite trends could be established. These results are presented in Figures 2 and 3.

Although R_w itself can be a meaningful number, its value is improved if it can be related to dissolved solids. For example, Figure 4 shows that $R_w = 4$ Ω-m could represent dissolved solids ranging from 700 ppm Na_2CO_3 to 2200 ppm $Ca(HCO_3)_2$. A second series of plots (Figures 5,6,7) were constructed to relate R_w to total dissolved solids (TDS).

DISCUSSION OF RESULTS

Although the results of this study are strictly applicable only to northern Wyoming (and the extension of the Powder River Basin into Montana) the following discussion will point out several ion groups that could be used to extend the correlation to other areas.

TDS AND R_w

Figure 4 is a plot of total dissolved solids vs specific conductance for several common salts and will be used later as a base to compare with the curves of Figures 5, 6, and 7. Conductance rather than resistivity was chosen as the abcissa in order to linearize the plots, although resistivity values are given on Figure 4. All values are at 25°C (77°F) and the resistivity in Ω-m is given by:

$$R_w = \frac{10,000}{\text{Specific Conductance}} \qquad (5)$$

Three general groupings were found which correlate very nearly with geologic age. Figure 5 presents data for the Madison limestone (Mississippian Age) and the Tensleep sandstone (Pennsylvanian Age). The solid line is a fourth order least squares polynomial with standard deviation of 16 ppm. Calcium and magnesium are the predominate cations with the calcium content approximately four times the magnesium content. The sodium content is very low. No definite trends could be established for the anions, but a comparison of Figures 4 and 5 show that the water is probably changing from a sulfate water at the lower concentrations to a bicarbonate water at high concentrations. Chloride was nearly absent. White (10) suggests nearly the same correlation when he says sulfate waters generally predominate near the surface, bicarbonates at intermediate depth and chlorides at further depths.

Figures 6 and 7 present the data for the Cretaceous and Tertiary Ages and show

some overlap. The Fort Union formation is Lower Tertiary, but seems to group with the Cretaceous period, while the Lance formation is Upper Cretaceous and groups with the Tertiary period. The data scatter is somewhat worse for these figures than for Figure 5. The standard deviations are 38 (fourth order polynominal) and 71 (second order polynomial) ppm for Figures 6 and 7 respectively. Sodium is the predominate cation in both figures and, in fact, the data for both figures lie nearly on the Na_2SO_4 line throughout much of the range. The Cretaceous waters begin to deviate toward the bicarbonates at higher salinities while the Tertiary waters follow the Na_2SO_4 line. Chloride was again nearly absent. The lines on all three figures are above the sodium chloride line and for a given R_W the NaCl charts would be low for total dissolved solids.

R_w - $R_{w(e)}$ Relationships

Figures 2 and 3 show that the data for R_w - $R_{w(e)}$ fall into the same three general classifications and the same comments as above hold for ion assemblage. The scatter is greater than for the previous figures and the slope for the Carboniferous period is steep enough to make R_w sensitive to errors in $R_{w(e)}$. For example, a change from $R_{w(e)}$ = 1 Ω-m to $R_{w(e)}$ = 2 Ω-m for this figure changes R_w from 4.3 to 17.9 Ω-m. The other two ages would be much less sensitive. All lines lie well above the sodium chloride line (R_w - $R_{w(e)}$) and use of this line would give very low values for R_w. The standard deviations for $R_w = f(R_{w(e)})$ are 2.7, 1.8, and 2.1 Ω-m respectively for third order polynomial fits.

FIELD APPLICATIONS

The preceding correlations are applied by reading the SP and using conventional interpretation charts to calculate $R_{w(e)}$ at 25°C (77°F). The low values of SP common to fresh water aquifers might make corrections for streaming potential necessary and this should be considered.

Lynch (1) has presented a field curve for streaming potential which we utilized by assuming a pressure differential due to an 8.6#/gal formation pressure gradient and the given mud weight. R_w is read from Figure 2 or 3 and TDS from Figure 5, 6 or 7. Several examples are shown in Table I and the average deviation (12.8% for R_w and 15.1% for TDS) is considered acceptable. It should be noted, however, that the calculated R_w is low in all but one case and TDS is high in all cases. This indicates a consistent bias and the possibility that a better correlation could be made. Perhaps

the streaming potential was not properly handled or perhaps Equation (4) has a consistent bias.

CONCLUSIONS

1. Bicarbonates and sulfates of sodium and calcium predominate in most of the fresh water of northern Wyoming and must be accounted for if SP is to be used for log interpretation.

2. Acceptable correlations for R_W and TDS can be established with published data on water analysis although a consistent bias toward low R_W values from actual logs suggests that better results are possible.

3. Isolation of certain groups of anions and cations show promise of "quick look" techniques to extend this study to other geologic or geographical areas.

4. Although $R_{w(e)}$ vs R_w curves in the literature show a strong temperature dependence, this effect was not investigated. The 25°C (77°F) data reported should be near the temperature of most aquifers. In high temperature aquifers the calculated R_W would probably be too low if the procedures of this paper are used.

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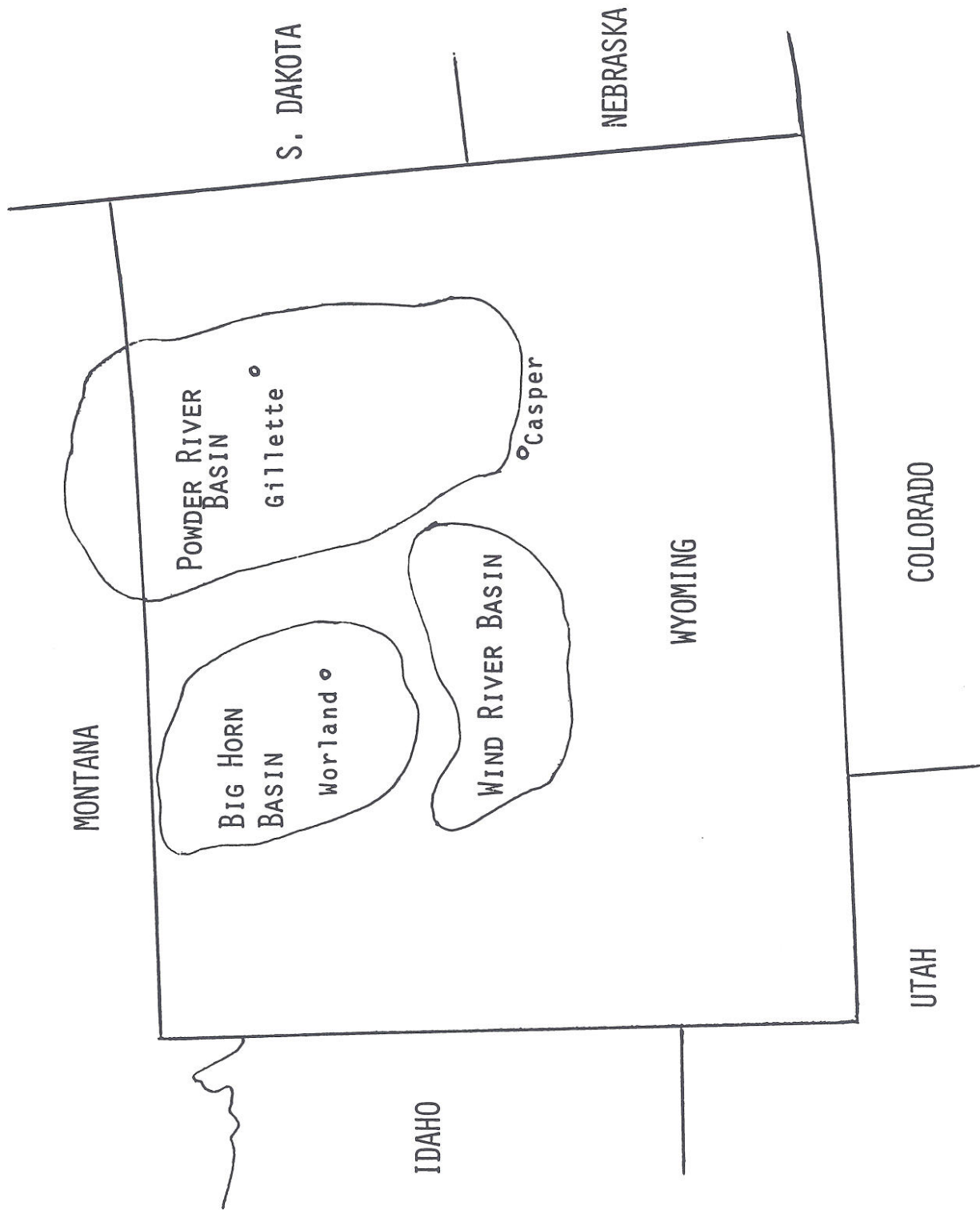10. White, D. E., "Saline Waters of Sedimentary Rocks," *USGS* Prof. Paper, April 1964, p. 342.
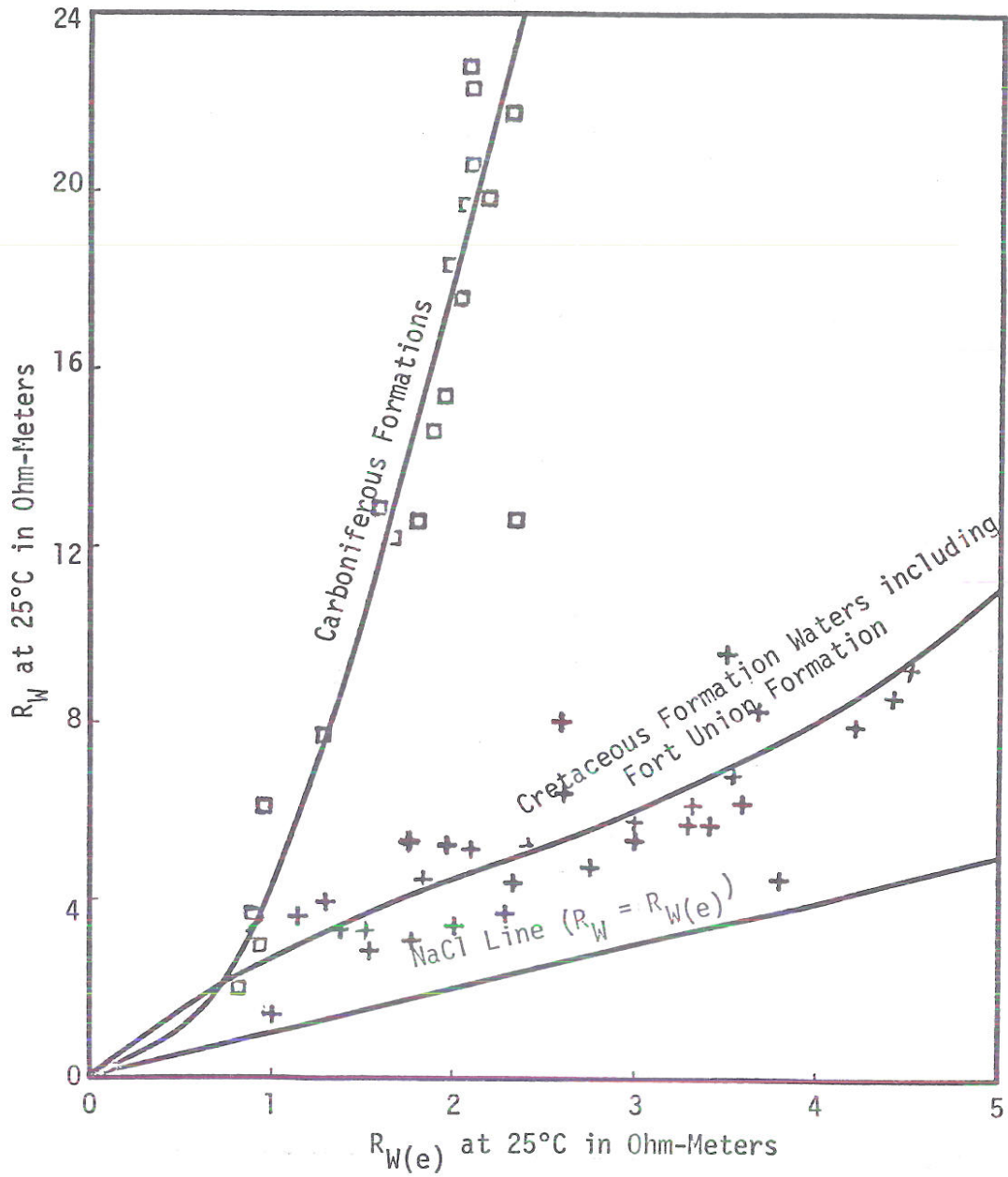
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Figure 1. Location Map

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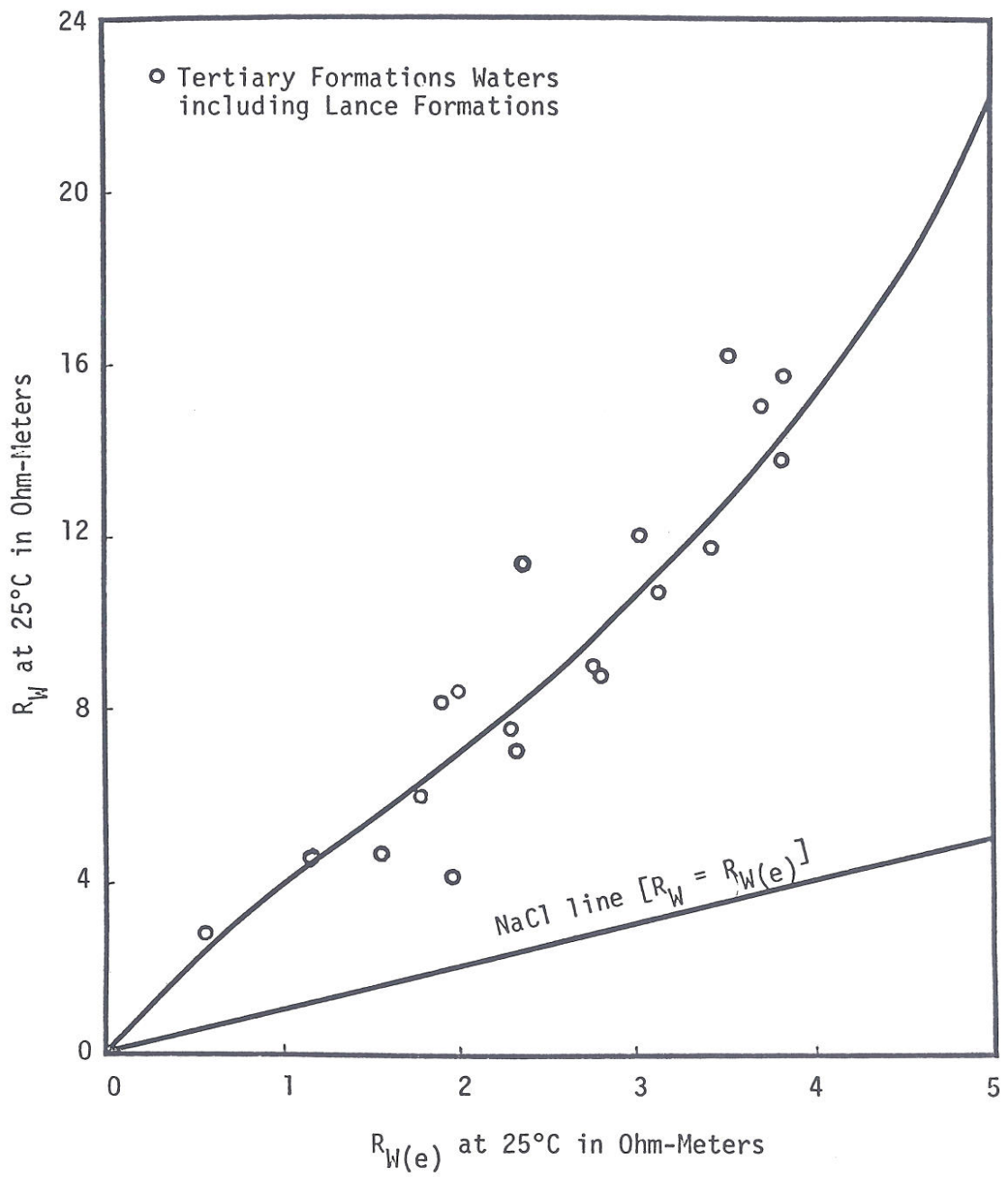Figure 2. R_W Vs. $R_{W(e)}$ Relationship for Formation Waters

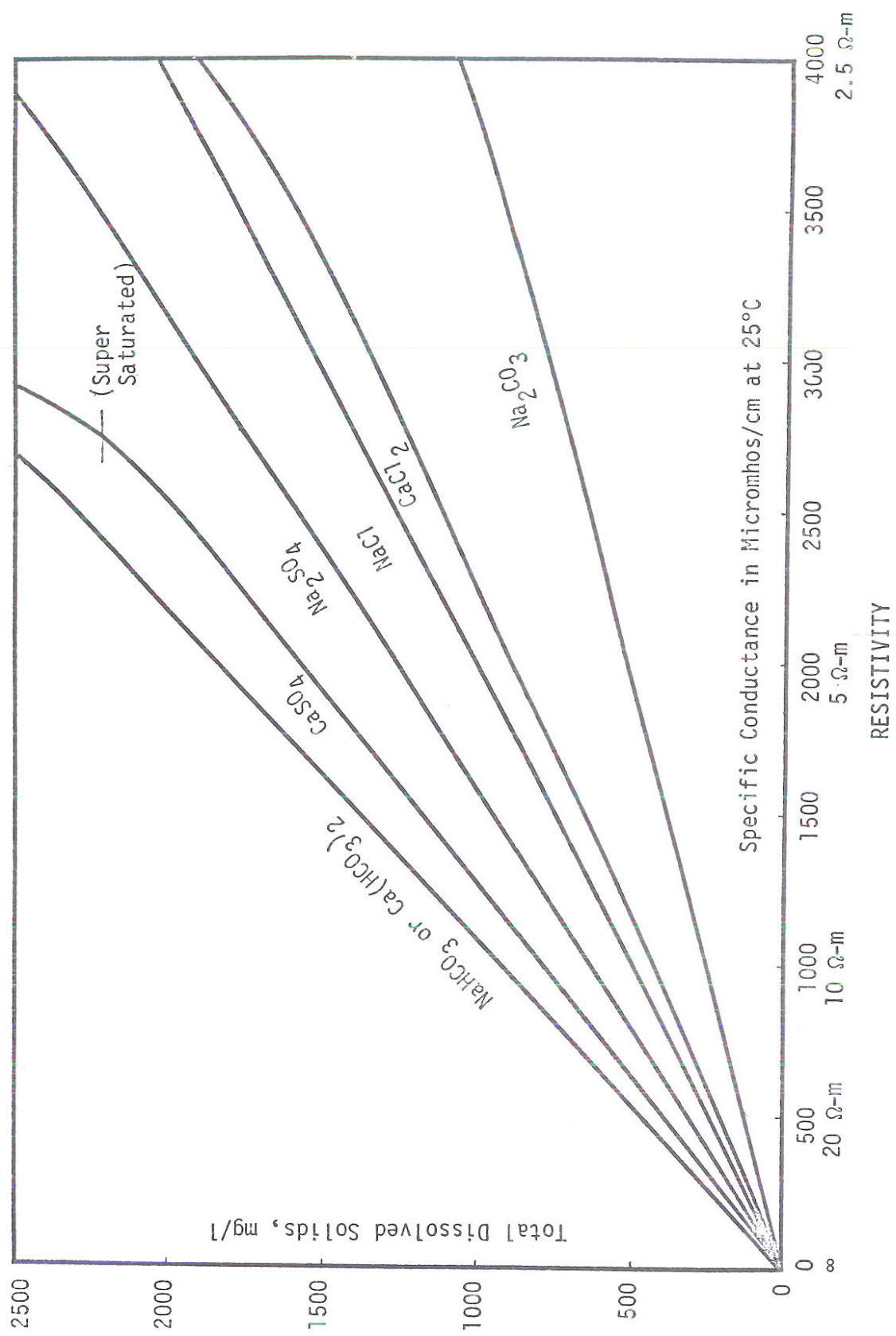Figure 3. R_W Vs. $R_{W(e)}$ Relationship for Formation Waters

The chart axes and labels read:
- Y-axis: R_W at 25°C in Ohm-Meters, with values 0, 4, 8, 12, 16, 20, 24
- X-axis: $R_{W(e)}$ at 25°C in Ohm-Meters, with values 0, 1, 2, 3, 4, 5
- Legend: o Tertiary Formations Waters including Lance Formations
- NaCl line [$R_W = R_{W(e)}$]

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Figure 4. Relationship of TDS and Specific Conductance for Dilute Solutions [Reference Davies (8), Tower (9)]
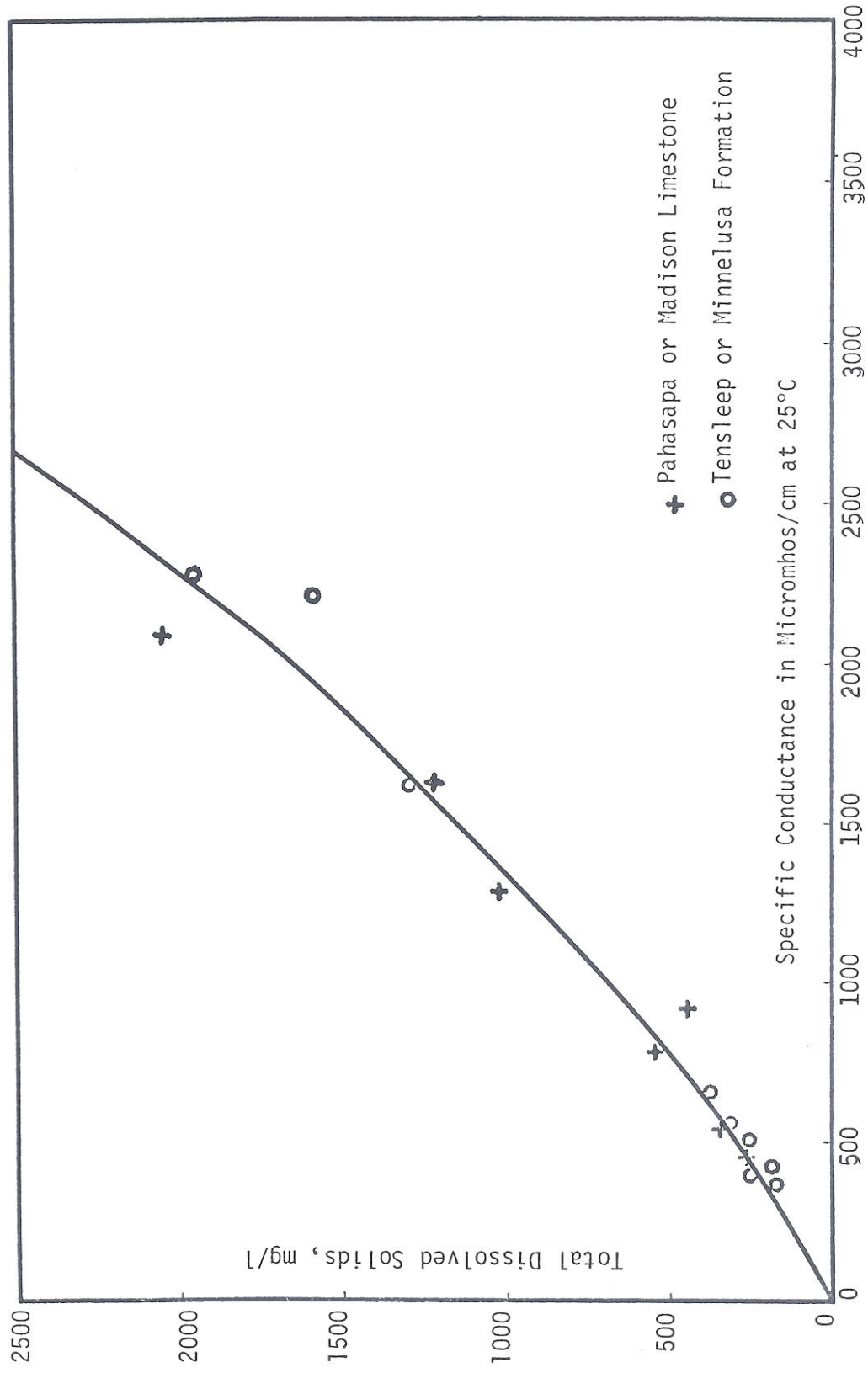
Figure 5 . Relationship of TDS and Specific Conductance for Carboniferous Formations
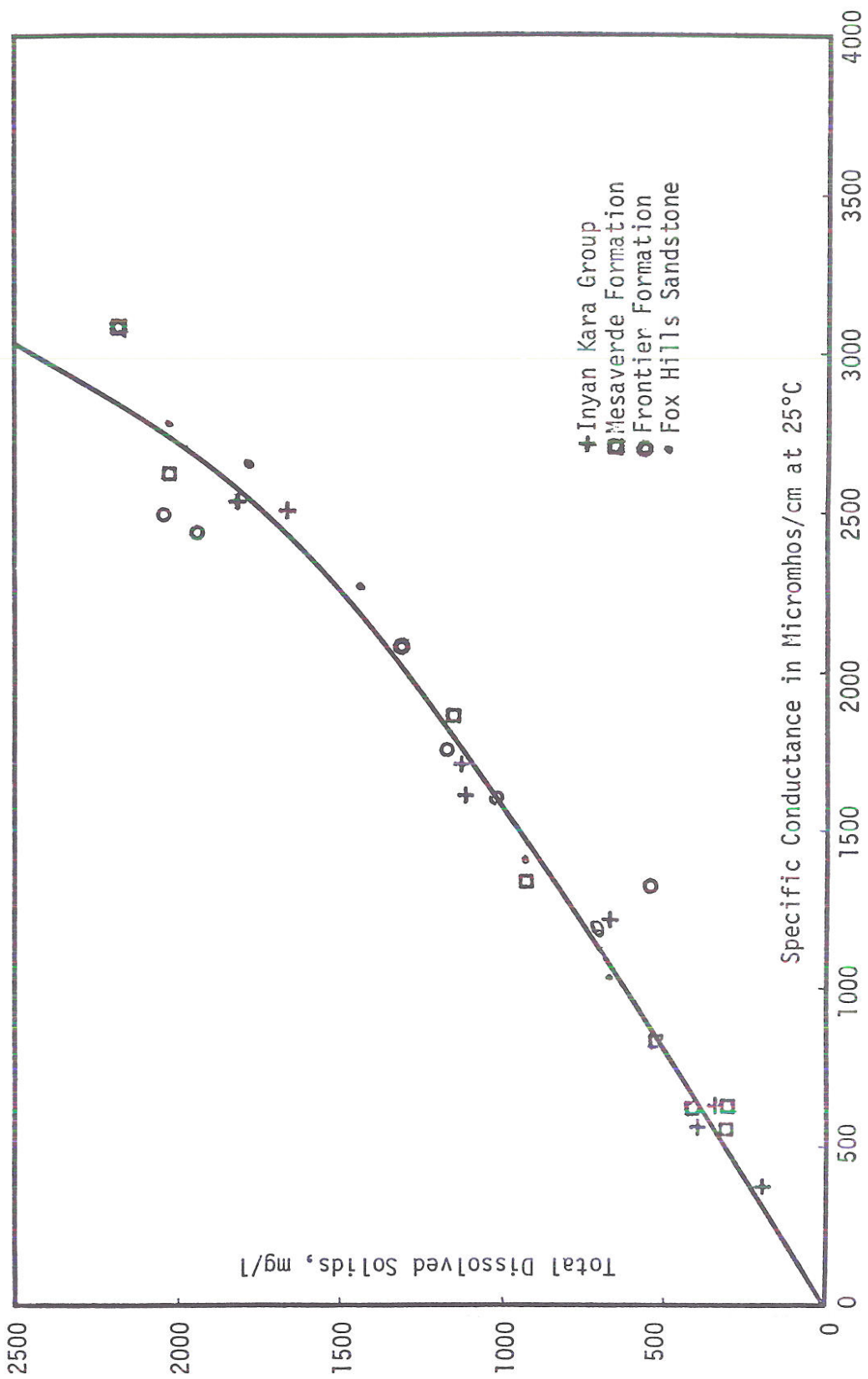
Figure 6. Relationship of TDS and Specific Conductance for Cretaceous Rock Formations
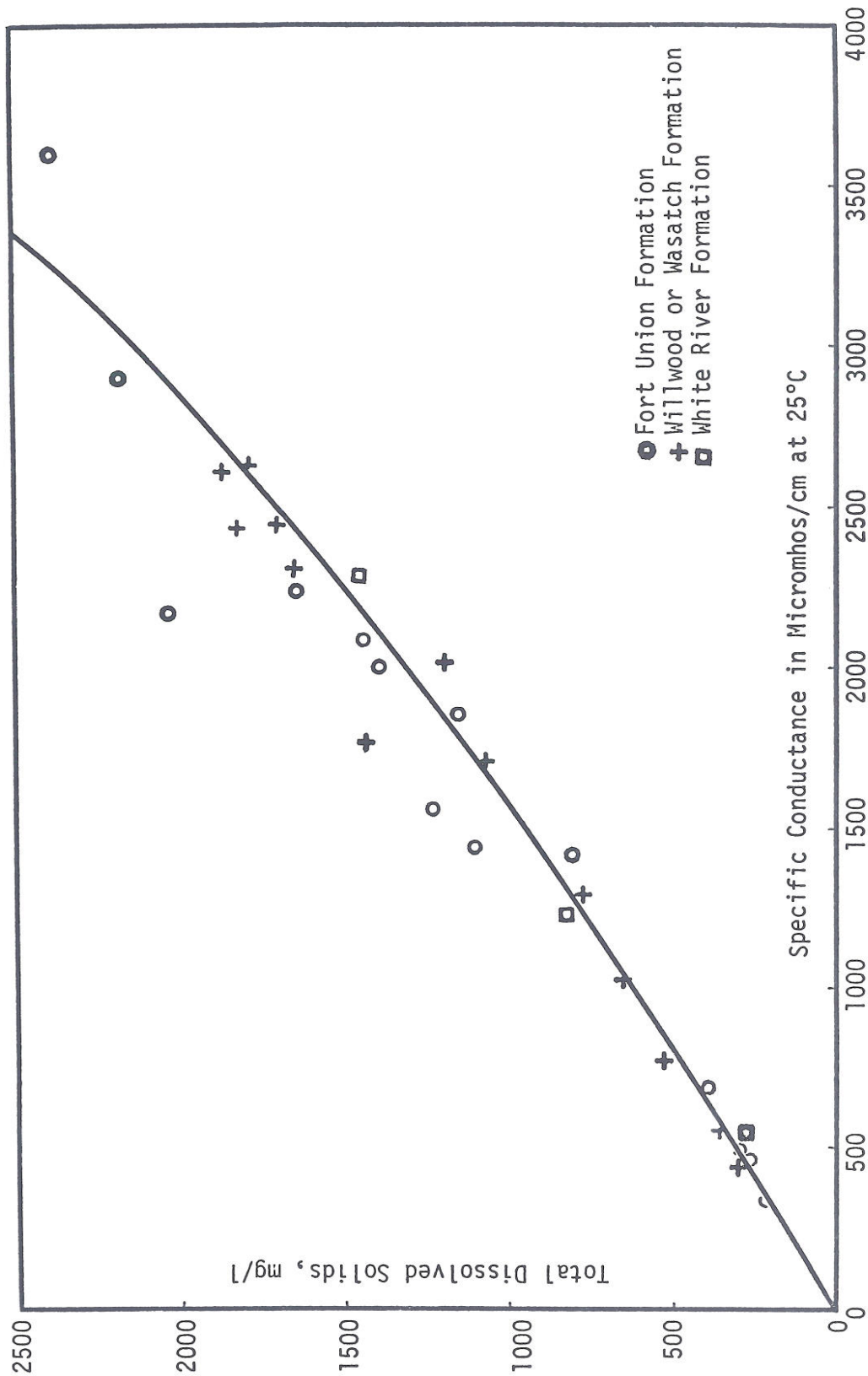
Figure 7. Relationship of TDS vs. Specific Conductance for Tertiary Rock Formations

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TABLE I

RESULTS FROM WATER ANALYSES AND ELECTRIC LOG INTERPRETATIONS

County and Well Location	Formation and Depth	$R_{w(e)}$ Calculated from SP (Ω-m) at 25°C	R_w Calculated from SP (Ω-m) at 25°C	R_w Measured	TDS Calculated	TDS Mg/1 Measured
Natrona 39N 79W Sec 11	Frontier 2100 ft	.7	2.1	2.8	2850	2360
Washakie 47N 89W Sec 6	Madison 2835 ft	2.1	19.9	25.3	250	210
Campbell 55N 75W Sec 9	Fort Union 1095 ft	2.3	4.9	5.1	1410	1240
Campbell 54N 70W Sec 10	Fort Union 900 ft	3.3	6.6	8.5	920	740
Campbell 53N 70W Sec 27	Fort Union 720 ft	3.6	7.1	8.0	880	790
Sheridan 58N 84W Sec 29	Wasatch 1260 ft	2.5	8.5	8.0	750	742