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# QUALITY OF GROUNDWATER ESTIMATED FROM ELECTRIC RESISTIVITY LOGS

by  
Wayne A. Pryor

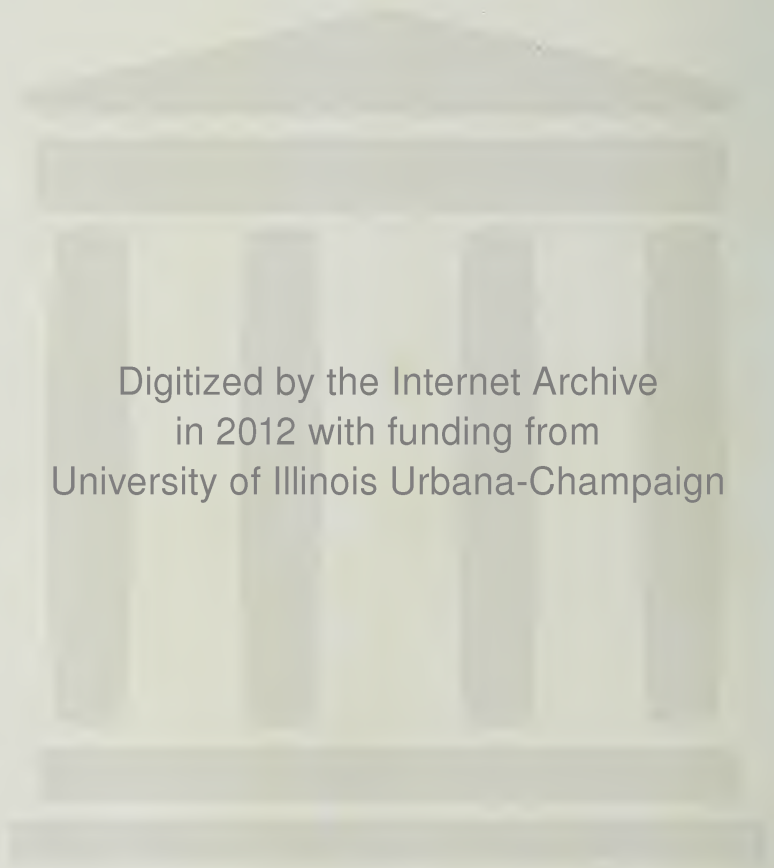
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## ABSTRACT

The resistivity of groundwater from 94 wells in Pennsylvanian sandstone is estimated from electric well logs by using the formula:

$$R_w = \frac{Ra_{64''} \times R_m}{Ra_{16''}}$$

where:  $R_w$  = resistivity of water in the bedrock (called "formation water")

$Ra_{64''}$  = apparent resistivity of "long normal" resistivity curve (64" or 71")

$Ra_{16''}$  = apparent resistivity of "short normal" resistivity curve (16" or 18")

$R_m$  = resistivity of drilling fluid

and converting the resistivity of the formation water to a sodium-chloride (NaCl) solution equivalent in parts per million. Content of chloride and total solids, determined from chemical analyses of water from nearby sandstone wells, are compared to NaCl equivalent concentrations computed from electric well logs. Graphs show the relationship between: 1) NaCl-solution equivalent and measured chloride content, and 2) NaCl-solution equivalent and measured total solids in water from Pennsylvanian sandstone strata in the Illinois Basin. The deflection of the spontaneous potential curve is plotted against the chloride content of formation water. Results indicate that any effort to determine the quality of formation water from spontaneous potential curves must also take into consideration the resistivity of the drilling fluid and the temperature of the formation, or the conclusions may be erroneous.

## INTRODUCTION

Within areas of the Illinois Basin where glacial deposits are thin and do not yield water, sandstone beds in the upper part of the Pennsylvanian bedrock are a common source of groundwater. Many wells drilled into the sandstone beds obtain water of high salinity, although others obtain relatively fresh water. Unfortunately not enough water analyses are available to indicate the distribution and extent of areas underlain by sandstones that carry fresh water.

For a number of years, groundwater geologists have used spontaneous potential (SP) logs to evaluate the quality of water in sandstones. The qualitative method of determining the resistivity of interstitial water by measuring the deflection of the SP curve from the "shale base line," as reported by Wyllie (1949), has been used successfully. However, the indefinite position of the shale base line in SP curves representing shallow Pennsylvanian sandstones in the Illinois

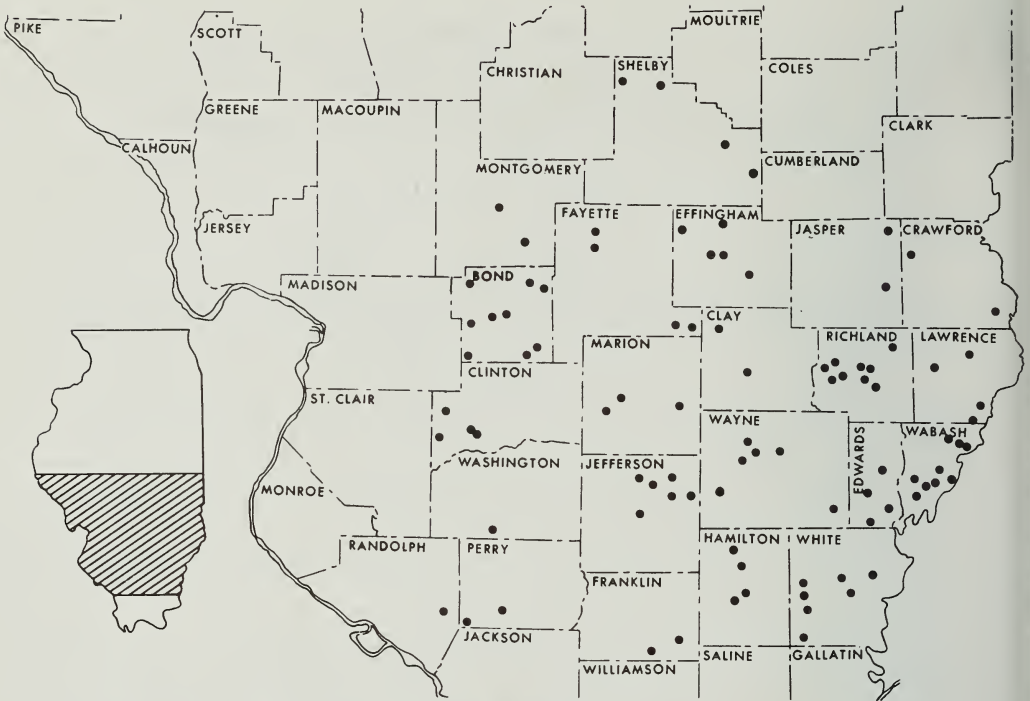


Fig. 1. - Index map showing location of pairs of sandstone wells and electric logs used in study.

Basin seriously limits the use of Wyllie's method in Illinois. The position of the shale base line is indefinite because the sandstone aquifers are near the surface.

Because the resistivity-log method of estimating water quality is not affected by shallow depth, this investigation was undertaken to evaluate the usefulness of electric resistivity logs to estimate water quality and to supplement data from water analyses. Analyses of water from wells in Pennsylvanian sandstones are compared with estimates based on resistivity logs from nearby wells that penetrated the same aquifer. Figure 1 shows the geographic location of the pairs of wells used in the study.

The Illinois State Water Survey supplied most of the water analyses used in the study. J. T. Lewis and J. P. Cheevers assisted in collection of data.

The manuscript and data were critically read and checked by George B. Maxey, Robert E. Bergstrom, and James E. Hackett of the Division of Groundwater Geology and Geophysical Exploration of the Illinois State Geological Survey. David Swann gave many helpful suggestions in regard to interpretations of electric logs.

#### METHODS

Chemical analyses of groundwater were obtained chiefly from the Illinois State Water Survey. Only those analyses were selected for water that was known to come from sandstone aquifers. Furthermore, to facilitate correlation of the aquifers and to assure similarity of water quality, the selections were limited to analyses of water from sandstone wells that were within one mile of

an electrically logged well. The method requires that the electric logs include a "short normal" resistivity curve, a "long normal" resistivity curve, and a resistivity measurement of the drilling fluid at a given temperature.

### Electric Well Logs

Electric well logs consist of two types of curves: 1) an SP curve, and 2) one or more resistivity curves.

The SP curve (Doll, 1949), shown on the left side of the electric log and expressed in millivolts, is influenced by the electrochemical effect, which varies with the ratio of the salinity of the drilling fluid to the salinity of the formation water, and the electrokinetic effect, produced by the motion of the drilling fluid into and through the sediments. The magnitude of the electrokinetic forces depends chiefly upon pressure difference between the drilling fluid and formation fluids, the volume and nature of the filtrate, the filter medium, and, to some extent, upon the depth of filtration. The electromotive forces set up by the electrochemical phenomena act at the contacts of media of different natures.

Most earth materials, particularly porous and permeable formations such as sandstone, conduct electricity only by means of the mineralized fluids they contain (Guyod, 1944). Sandstone formations adjacent to well bores may contain two types of fluids: 1) the water contained in the formation, and 2) the drilling fluid that may invade the sandstone. The average depth of invasion is less than one or two feet, but it varies with the porosity of the sandstone and the condition of the drilling fluid.

The resistivity curves, shown on the right side of the electric log and expressed in ohms per meter per square meter, record differences in the apparent electrical resistivity of the strata penetrated. The apparent resistivity of the strata is recorded by one or more curves which represent different electrode spacings that produce different amounts of penetration of the same beds and hence yield slightly different resistivities for the same bed.

The short normal resistivity curve is recorded at a measuring electrode generally located 16 or 18 inches from the current electrode. The apparent resistivity given by this spacing is largely affected by the true resistivity of materials within 18 inches of the midpoint between the electrodes. Because the strata adjacent to the bore have been more or less invaded by the drilling fluid, the short normal curve is essentially a measurement of the resistivity of the rock that is saturated with drilling fluid.

The long normal resistivity curve, with an electrode spacing usually of five or six feet, is largely influenced by the resistivity of the rocks within five or six feet from the center of the well bore (Guyod, 1944). Because much of the zone is relatively uncontaminated by drilling fluid, the long normal curve is essentially a measurement of the resistivity of the rock where it is filled with formation water.

The resistivity of the drilling fluid and the temperatures at which the measurements were made are given on log headings. Drilling-fluid resistivities vary with temperature, and the well-bore temperatures at depth are usually different from surface temperatures. In Illinois the temperature of the earth and of the fluids contained therein is variable and fluctuates seasonally from just below frost level to a depth of about 55 feet below land surface (Ben-



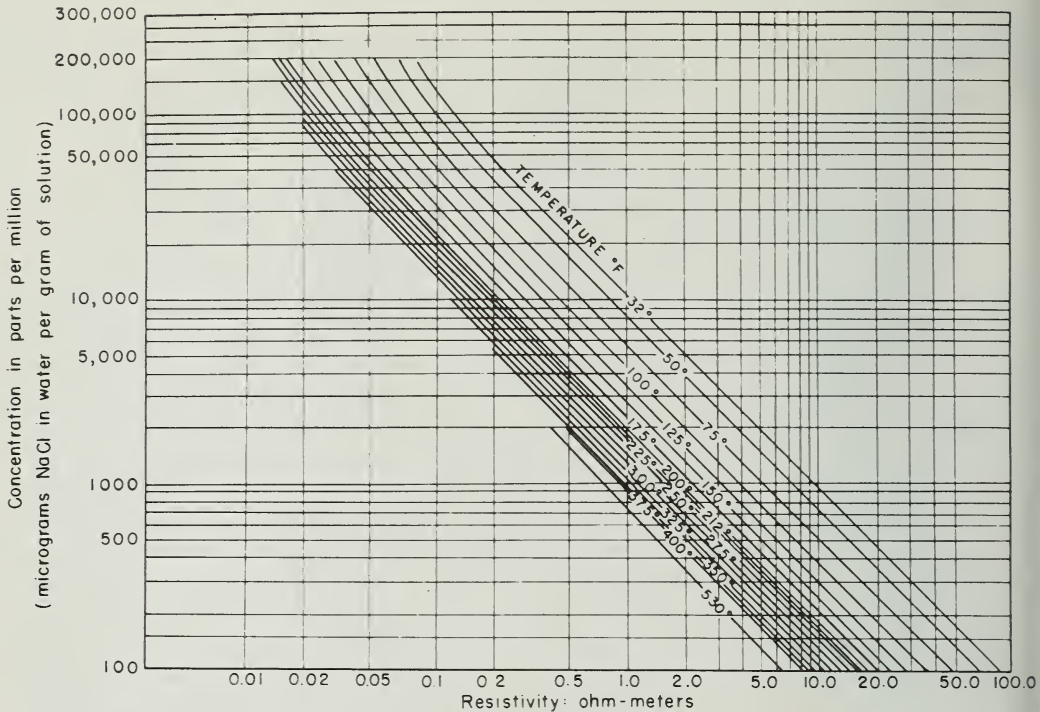


Fig. 2. - Resistivity graph for salinity and temperature of sodium chloride solution.

field, 1950), where the temperature is about 55°F. Below 55 feet the temperature is believed to increase at a rate of about 1°F. for each 100 feet of depth. Temperature corrections must be applied to drilling-fluid resistivities measured at the surface in order to determine their resistivities at depth.

Drilling fluids usually contain several soluble chemicals which vary in their capacity to conduct electric current. Formation waters in Pennsylvanian sandstone aquifers generally contain several ions, other than chloride, in solution. Some of them are ammonium, calcium, fluoride, iron, magnesium, manganese, nitrate, silica, and sulfate.

The quantitative influence that mixtures of the ions have on the resistivities of formation waters are not well known. The amounts of the various electrolytes are converted to an equivalent concentration of sodium chloride (NaCl) solution expressed in parts per million (ppm). The NaCl-solution equivalent is defined as the concentration, in ppm, of pure sodium chloride in water that has the same resistivity as that of a solution of salts. Figure 2 shows the variation of resistivity at various temperatures in such a solution of sodium chloride.

#### Methods of Calculation

The NaCl-solution equivalent concentration in the formation water is determined from the resistivity curves by: 1) determining the ratio of the apparent resistivity of the long normal curve to the resistivity of the short normal curve 2) converting the resistivity of the drilling fluid at the temperature given on the log heading to its resistivity at the temperature of the formation by the use of the graph shown in figure 2, 3) calculating the resistivity of the formation water



YINGLING OIL & MINING and ASHLAND OIL & REFINING CO.

Wallace No. 8-B

Wabash Co.

Sec. 20, T. 2 S., R. 13 W.

Mud Resistivity 2.8 at 66°F.

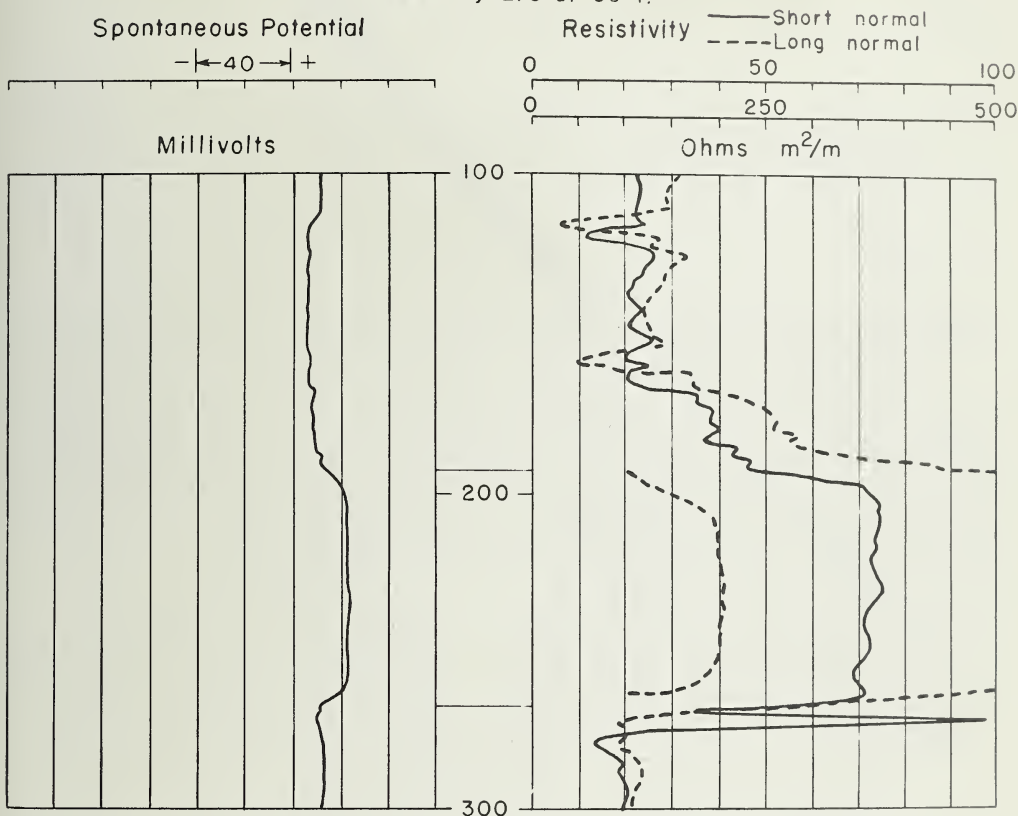


Fig. 3. - Resistivity and SP log of the Mt. Carmel sandstone in Wabash County.

from the equation:  $\frac{R_w}{R_m} = \frac{Ra_{64''}}{Ra_{16''}}$        $R_w = \frac{R_m \times Ra_{64''}}{Ra_{16''}}$

where:  $Ra_{16''}$  = apparent resistivity, in ohms  $m^2/m$ , of short normal curve (16" or 18")

$Ra_{64''}$  = apparent resistivity, in ohms  $m^2/m$ , of long normal curve (64" or 71")

$R_m$  = resistivity, in ohms  $m^2/m$ , of drilling fluid at formation temperature

$R_w$  = resistivity, in ohms  $m^2/m$ , of formation water, at formation temperature

and 4) converting the resistivity of the formation water at the determined temperature to ppm of NaCl-solution equivalent concentration, using the graph in figure 2.

Resistivity departure curves were not used to estimate the true resistivity of the formation fluids because the differences between the apparent resistivities

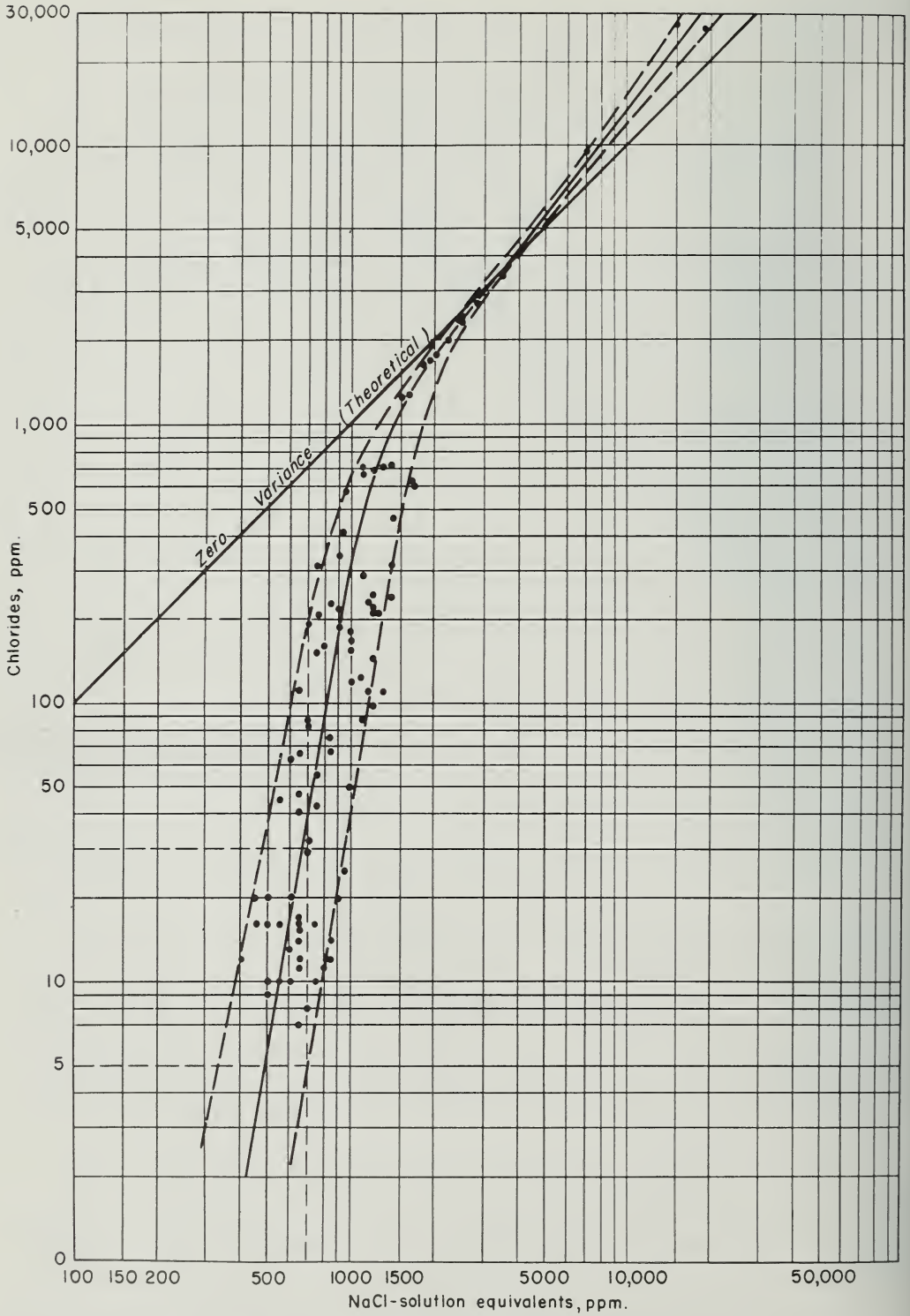


Fig. 4. - Measured chlorides vs. NaCl-solution equivalent concentration.

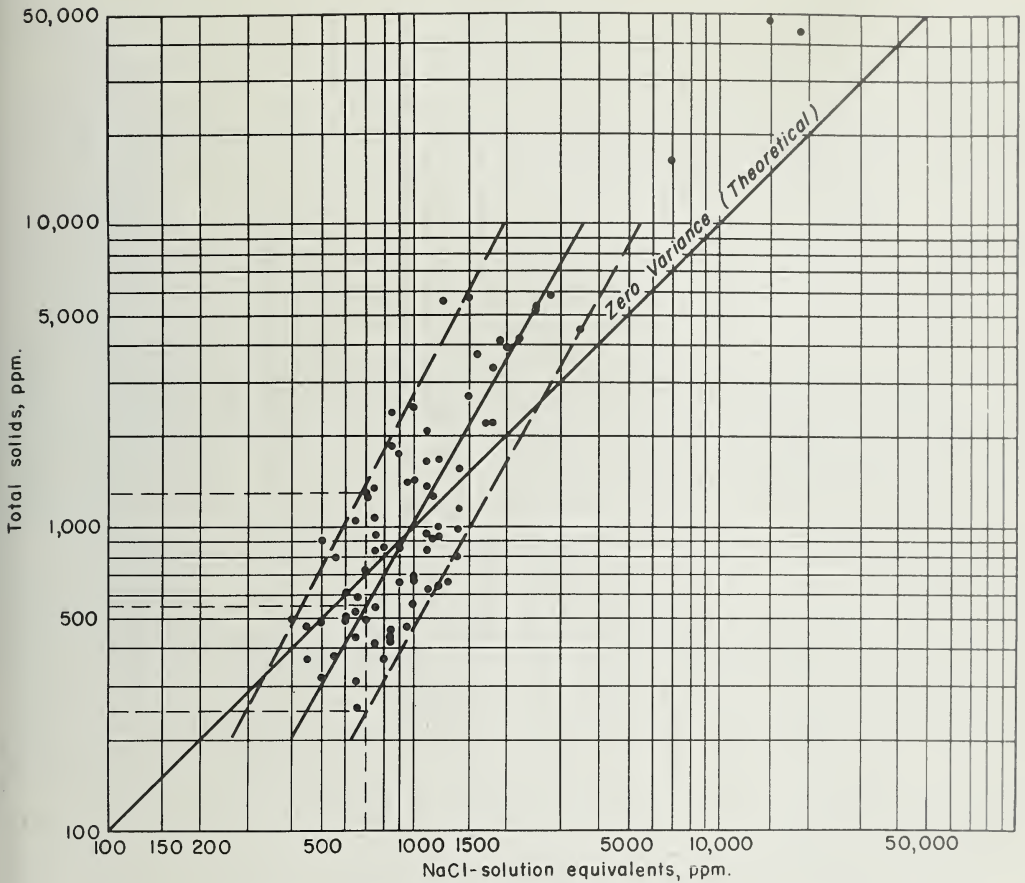


Fig. 5. - Measured total solids vs. NaCl-solution equivalent concentration.

and true resistivities were not appreciable. The use of micrologs to determine the true resistivities of the invaded zones is not possible in this study because such logs are generally not run at the shallow depths involved.

#### Example of Method

Figure 3 shows the electric log of the Yingling Oil and Mining and Ashland Oil and Refining Co. Wallace No. 8-B oil-test well. The boring is about half a mile from the W. H. Schafer water well, which is in the SW 1/4 sec. 17, T. 2 S., R. 13 W., Wabash County.

The Schafer well obtains water from the Mt. Carmel sandstone at a depth of 200 to 300 feet. A chemical analysis of the water gives a chloride concentration of 88 ppm and a total solids concentration of 737 ppm. The Mt. Carmel sandstone is represented on the electric log at a depth of 192 to 268 feet and the temperature at this depth is approximately 58°F. The drilling-fluid resistivity is given as 2.8 ohms m<sup>2</sup>/m at 66°F. on the log heading.

By referring to figure 2 we note that a solution of sodium chloride at the

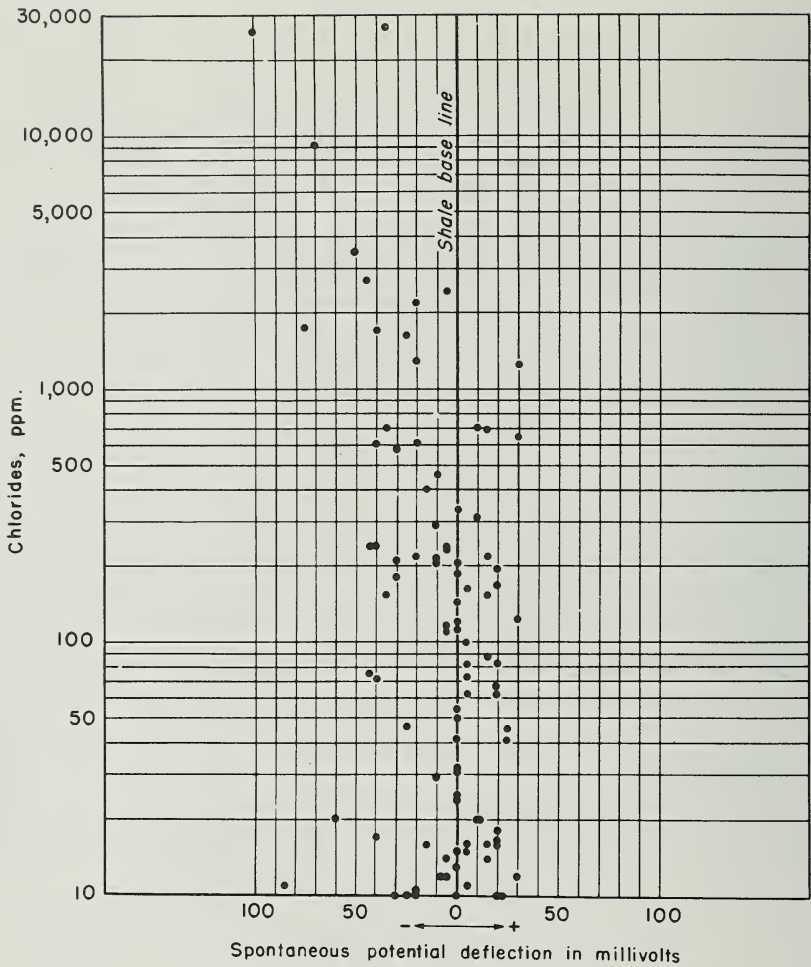


Fig. 6. - Measured chloride content vs. SP data.

resistivity and temperature given has a resistivity of about 3.5 ohms  $m^2/m$ . The resistivity of the short normal curve is approximately 75 ohms  $m^2/m$  and that of the long normal curve approximately 200 ohms  $m^2/m$ .

$$\begin{aligned} \text{Where: } R_{16''} &= 75 \text{ ohms } m^2/m \\ R_{64''} &= 200 \text{ ohms } m^2/m \\ R_m &= 3.5 \text{ ohms } m^2/m \\ R_w &= \frac{200 \times 3.5}{75} \\ R_w &= 9.4 \text{ ohms } m^2/m \end{aligned}$$

Figure 2 shows that water at a temperature of 58°F., with a resistivity of 9.4 ohms  $m^2/m$ , has an NaCl-solution equivalent concentration of approximately 700 ppm. Comparison of results from the electric log with the analysis shows that the total solids closely correspond but that the chlorides do not in this particular example.



## RESULTS

The results of the investigation are summarized in figures 4, 5, and 6.

In figure 4, data from 94 chemical analyses are plotted against estimates of water quality based on resistivity curves. Chlorides in ppm (taken from chemical analyses) are plotted along the vertical axis, and NaCl-solution equivalents (determined from resistivity-curve calculations) are plotted along the horizontal axis.

The distribution of the plotted data, with respect to a theoretical line drawn through points where the vertical and horizontal coordinates are the same, called the "zero variance line," indicates the degree of accuracy of the method. The computed values for NaCl-solution equivalent and the analyzed values for chloride coincide at about 4,000 ppm and diverge from the zero variance line. The computed values of NaCl-solution equivalent below 4,000 ppm are generally higher than the chloride values and become increasingly higher as the chloride content decreases. Conversely the computed values of NaCl-solution equivalent above 4,000 ppm are lower than the chloride values and become increasingly lower as the chloride content increases.

Figure 4 may be used to estimate the chloride content of formation water from calculations based on resistivity logs. The electric-log calculations from the resistivity curves in figure 3 give an NaCl-solution equivalent of 700 ppm. Applying this equivalent solution concentration to the curve in figure 4, one arrives at an estimated concentration of 30 ppm or, by referring to the outer dashed range curves, a concentration of chlorides ranging from 5 ppm to 200 ppm. A chemical analysis of the water from this formation indicates a chloride content of about 88 ppm.

In figure 5, chemical analyses and resistivity curve computations are plotted for 78 pairs of data. Total solids in ppm (taken from chemical analyses) are plotted along the vertical axis, and NaCl-solution equivalents (determined from resistivity-curve calculations) are plotted along the horizontal axis.

A curve drawn through the plotted points, when compared to the zero variance line, generally indicates a low degree of accuracy of estimating total solids by this method, although a number of the points lie upon or are very near the zero variance line. The computed values of NaCl-solution equivalent and the analyzed values of total solids concentration coincide at about 1000 ppm. Unlike the chloride curve (fig. 4), this series of points is distributed on both sides of the zero variance line below and above the point of coincidence, but it generally can be said that below 1000 ppm the computed values of NaCl-solution equivalent are higher than total solids values and become higher as the content of total solids decreases. Inversely the computed values of NaCl-solution equivalent above 1000 ppm are lower than total solids values and become increasingly lower as the content of total solids increases.

The curve in figure 5 may be used to estimate from electric-log calculations the content of total solids in formation water. The electric-log calculations from the resistivity curves in figure 3 give an NaCl-solution equivalent concentration of about 700 ppm. Applying the solution-equivalent concentration to the curve in figure 5, one arrives at an estimated concentration of 550 ppm or, by referring to the dashed range lines, a concentration of total solids rang-

ing from 250 ppm to 1300 ppm. A chemical analysis of the water from this formation indicates a total solids content of 737 ppm.

Figure 6 is a point-distribution diagram, based on 94 electric logs, that shows the relationship of the SP deflection from a shale base line to chloride content of formation water without regard to drilling-fluid resistivities and formation temperatures.

At concentrations of less than 1000 ppm of chlorides, an equal distribution of both positive and negative SP deflections appears, with the deflections ranging from minus 85 millivolts to plus 30 millivolts. The deflections are general negative at concentrations higher than 1000 ppm of chlorides.

### SUMMARY AND CONCLUSIONS

Comparison of chemical analyses of formation water to calculated values of NaCl-solution equivalent for 94 resistivity logs shows that the chloride content and total solids content of water in Pennsylvanian sandstones of the Illinois Basin can be determined within a limited range by the use of resistivity logs. The curves in figures 4 and 5 show that with extremely low or high content of chloride and total solids, the concentration computed from resistivity logs varies greatly. Within certain limits, the curves can be used to estimate concentrations.

Comparison of the chloride content of formation waters to deflections of the 94 SP curves shows that the commonly used method of determining the relative quality of formation waters, as reported by Priddy (1955), by the position of the SP curve relative to the shale base line is likely to lead to erroneous conclusions. Figure 6 shows that unless the resistivity of the drilling fluid and the formation temperatures are considered in SP determinations, deflections of the SP curve may be either positive or negative for formation water that has a low chloride content.

We need further study of the part played by electrolytes other than sodium chloride in influencing resistivity of drilling fluids and formation fluids. For formation waters in which sodium chloride is the predominant electrolyte, the relations shown in figure 2 permit reliable calculations.

Table 1. - Chemical Analyses and Electric Log Data for 94 Wells in Pennsylvanian Sandstones

Water well	Location			Analyses (ppm)		Electric logs	
	sec.	T.	R.	Chlorides	Total solids	NaCl-equivalent (ppm)	SP Millivolts
BOND							
J. D. Biggs	24	4N	2W	230	430	850	-5
B. Boits	26	4N	2W	25	468	950	0
E. Seidler	37	4N	4W	310	980	1,400	0
L. Rich	28	5N	4W	9,595	16,590	7,000	-70
Pet Milk	10	5N	3W	1,770	3,920	2,000	-75
Pet Milk	9	5N	3W	181	671	1,000	-30
A. K. Moon	22	6N	2W	590	1,400	950	-30
Unit School 1	35	6N	2W	3,400	4,410	3,500	-50
N. Shidler	8	6N	4W	72	476	400	+5
CHRISTIAN							
Bilyeau 1	10	13N	1E	26,157	44,322	19,000	-100
CLAY							
F. Haymes	14	3N	6E	10	760	550	+20
V. Lewis	33	5N	5E	210	926	1,200	-10
CLINTON							
Star Milling	3	1N	4W	220	857	900	-20
J. Schweir	4	1N	4W	162	876	800	+5
New Baden	18	1N	5W	315	1,091	750	+10
Trenton	20	2N	5W	215	-	750	-10
CRAWFORD							
J. H. Ford	1	5N	12W	1,654	3,379	1,800	-25
L. M. Baker	1	7N	14W	154	565	1,000	+15
EDWARDS							
Federal Bank	20	1S	14W	153	-	750	-35
A. O. Bunting	3	2S	10E	29	-	700	-10
.. Siegert	29	2S	14W	47	-	650	-25
lover	4	3S	10E	32	-	700	0
EFFINGHAM							
ffingham School	30	7N	6E	720	1,536	1,400	-40
. Tophorn	7	8N	4E	2,700	5,800	2,800	-45

Table 1. - Continued

Water well	Location			Analyses (ppm)		Electric logs	
	sec.	T.	R.	Chlorides	Total solids	NaCl-equiv- alent (ppm)	SP Millivol
M. P. Smith	31	8N	5E	112	921	1,150	-5
Unit School 40	34	8N	5E	460	1,122	1,400	-10
Shumway School	33	8N	5E	10	415	750	-20
FAYETTE							
Smith	36	5N	4E	205	846	1,100	0
Joy's Cafe	32	5N	4E	98	624	1,200	+5
S. Morrison	8	8N	1E	120	690	1,000	0
Ramsey	17	8N	1E	113	660	1,300	0
FRANKLIN							
L. Clayton	30	7S	3E	75	1,853	850	-45
4-H Club	17	7S	4E	11	366	800	+5
HAMILTON							
A. L. Eswine	32	3S	6E	50	1,406	1,000	0
A. N. Allen	24	4S	6E	2,470	5,760	1,500	-5
Webb	14	5S	6E	610	2,200	1,700	-40
Reeves Court	14	5S	6E	610	2,220	1,800	-20
JASPER							
O. Jones	6	6N	11E	20	609	600	+10
W. A. Cromer	4	8N	14W	188	669	900	0
JEFFERSON							
F. Frost	4	2S	3E	67	2,461	850	+20
J. E. Lisenby	10	2S	3E	16	839	750	+20
J. E. Atkinson	17	2S	4E	123	956	1,100	+30
Ill. Central	26	2S	4E	12	903	400	-5
R. C. Ashby	27	2S	4E	169	2,512	1,000	+20
Game Farm	28	3S	3E	211	5,810	1,250	-30
LAWRENCE							
St. Francisville	20	2N	11W	10	-	600	-25
E. L. Potts	20	2N	11W	16	373	550	+15
J. E. Whittaker	24	4N	12W	195	1,281	700	+20
E. H. Eichorn	35	4N	13W	46	-	550	+25



Table 1. - Continued

Water well	Location sec. T. R.			Analyses (ppm)		Electric logs	
				Chlorides	Total solids	NaCl-equivalent (ppm)	SP Millivolts
MONTGOMERY							
Comm. Unit 3	35	8N	3W	660	2,082	1,100	+30
Glen Heirs	31	9N	3W	340	1,754	900	0
MARION							
Centralia 1	1	2N	2E	14	430	850	-5
Salem	11	2N	2E	243	750	1,400	0
Iuka School	18	2N	4E	8	495	700	0
PERRY							
O. Bird	13	5S	3W	1,292	3,784	1,600	-20
Willisville	30	6S	4W	12	302	650	-5
RANDOLPH							
Percy	11	6S	5W	18	322	500	+20
RICHLAND							
Noble	4	3N	9E	11	591	650	-85
B. Lemon	9	3N	9E	16	474	450	+5
Pure Oil	10	3N	9E	20	373	450	-60
Noble	16	3N	9E	1,700	4,140	1,900	-40
Hazel Hotel	17	3N	9E	246	1,001	1,200	-40
International Shoe	3	3N	10E	715	1,612	1,100	-35
H. A. Keer	4	3N	10E	1,260	2,701	1,500	+30
Olney Sanatorium	34	3N	10E	697	1,680	1,200	+15
Claremont	4	4N	14W	16	493	500	+20
SHELBY							
Baumgarten	1	10N	6E	2,450	5,028	2,500	-40
E. Kribe	13	11N	5E	2,350	5,222	2,500	-5
D. Casey	16	13N	5E	83	628	1,100	+20
WABASH							
Andrews et al.	4	1N	12W	43	545	750	0
Allendale High School	11	1N	12W	12	460	850	+30
L. G. Stillwell	12	1N	12W	7	430	650	+20
P. P. Murray	34	1N	13W	9	912	500	0
E. Crow	9	1S	12W	63	510	600	+20
M. W. Willson	20	1S	12W	17	257	650	-40

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Table 1. - Continued

Water well	Location		Analyses (ppm)		Electric logs	
	sec.	T. R.	Chlorides	Total solids	NaCl-equivalent (ppm)	SP Millivolts
R. Wolf	14	1S 13W	13	500	600	0
Groff School	19	1S 13W	16	956	750	-15
R. C. Hardy	20	1S 13W	14	1,058	650	+15
C. P. Steckler	24	1S 13W	112	-	650	-5
W. H. Schafer	7	2S 13W	88	737	700	+15
WASHINGTON						
McKinley	29	3S 3W	2,250	-	2,500	-20
WAYNE						
D. Latch	16	1N 6E	20	-	900	0
Texas Co.	27	1N 6E	710	-	1,300	+10
Texas Co.	34	1N 6E	410	-	950	-15
Billington	27	1N 7E	41	-	650	+25
L. Finley	6	1S 6E	20	-	900	+10
M. Schaffer	12	2S 5E	82	-	700	+5
Vaught	33	2S 9E	27,500	47,650	15,000	-35
WHITE						
Geff	26	4S 9E	2,050	4,215	2,200	0
Crossville	23	4S 10E	63	520	650	+5
Enfield	8	5S 8E	144	-	1,200	0
Enfield	8	5S 8E	15	1,365	750	+5
J. C. Stokes	13	5S 9E	295	1,387	1,100	-10
Kingwood Oil Co.	10	7S 9E	230	1,265	1,150	+15

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