DETERMINATION OF TDS IN GEOTHERMAL SYSTEMS BY WELL-LOG ANALYSIS

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ABSTRACT

An estimate of the chemistry of the fluid within a geothermal reservoir is required to establish the geological source and the possible environmental impact of the fluid as well as scaling and corrosion problems which might develop during production. While a detailed analysis of the chemical composition of a geothermal fluid can only be obtained from a water sample, an estimate of the total dissolved solids (TDS) in equivalent sodium chloride (NaCl) concentration can be obtained from well logs. TDS can also be useful in geological correlation between wells. TDS can be determined directly from a pulsed neutron log and a porosity log, (if the type of formation is known), or from the water resistivity, R_w, and the temperature, T. Three approaches are used to find R_w and thus TDS. The first method uses a dual induction focused log and information from the log heading. Next, R_w is found by employing an electrical log and a porosity log. The last approach utilizes the spontaneous potential log and header data. Examples are provided to illustrate the techniques described which utilize calculated values of R_w to determine TDS.

INTRODUCTION

The total dissolved solids found in geothermal fluids provide important information. From this information proper production equipment can be chosen and possible problems may be anticipated. TDS can be calculated from various combinations of well logs: (1) pulsed neutron log and a porosity log; (2) dual induction focused log; (3) an electric log and a porosity log; or (4) spontaneous potential log. The accuracy of each method depends on the estimated constants needed in each analysis and how well the assumptions underlying each method are valid.

THEORY

Using the Thermal Decay Time Log, the following equation can be written:

$$\Sigma_w = \frac{\Sigma_{log} - \Sigma_{ma}\,(1 - \phi)}{\phi} \qquad (1)$$

Porosity can be determined from a porosity log or from knowledge of the field. If the lithology is known, Σ_{ma} can be assumed (eg. Σ_{ma} is between 8 and 12 for a sandstone dominated reservoir). Using this approach Σ_w can be calculated at a particular depth.

If ϕ and Σ_{log} vary considerably over the zone of interest, a more accurate estimate of Σ_{ma} can be determined by plotting Σ_{log} versus ϕ. By rearranging equation 1, the following equation is obtained:

$$\Sigma_{log} = (\Sigma_w - \Sigma_{ma})\phi + \Sigma_{ma} \qquad (2)$$

This is the equation of a straight line with a slope of $(\Sigma_w - \Sigma_{ma})$ and intercept of Σ_{ma} (at $\phi = 0$). Thus, a least squares linear fit of the (ϕ, Σ_{log}) data can be used to obtain Σ_w from the intercept and slope.

Once Σ_w is determined, TDS is found from the correlation chart shown in Figure 1 (Schlumberger, 1979). This chart shows TDS as a function of Σ_w at 75°F and 200°F. The following equation describes this chart:

$$\mathrm{TDS} = a(\Sigma_w)^2 + b(\Sigma_w) + c \qquad (3)$$

where

$$a = -0.000007(T) - 0.003$$

$$b = 0.0016(T) + 2.881$$

$$c = -0.0247(T) - 63.172$$

and T is given in degrees Fahrenheit.

The next section describes the methods which calculate R_w and then TDS. The first method employs the resistivity of the flushed zone, R_{xo}, and the resistivity of the zone of interest, R_t, obtained from a dual induction focused log. The log heading provides information necessary to this analysis; the bit size used to drill each section of the well, the type of mud being circulated, the resistivity and temperature of the mud and mud filtrate (R_{mf} at T_{mf} and R_m at T_m), the depth and temperature at bottom hole (T_{BH}), and the stand off. Using Arp's equation (Arps, 1953), R_{mf} can be calculated at any depth given the temperature at that depth:

$$R_{mf2} = R_{mf1}\left(\frac{T_1 + 6.77}{T_2 + 6.77}\right) \qquad (4)$$

Temperature logs are generally run in geothermal wells. If a temperature log is available it can be used to find the temperature at the depth of interest. Otherwise, knowledge of the temperature gradients with depth in a field can be utilized by working up from the bottomhole temperature. It is known that these temperatures are time-dependent, but the small changes over time should not significantly affect these results. If the depth of interest is in the constant temperature zone, it can be used. The formation resistivity factor, F, is given by:

$$F = \frac{R_t}{R_w} \qquad (5)$$

or

$$F = \frac{R_{xo}}{R_{mf}} (S_{xo})^2 \qquad (6)$$

Assuming a geothermal reservoir is 100% water saturated, $S_{xo} = 1$, equation 6 becomes:

$$F = \frac{R_{xo}}{R_{mf}} \qquad (7)$$

Solving equations 5 and 7 an equation describing R_w is obtained:

$$R_w = \frac{R_t}{R_{xo}} R_{mf} \qquad (8)$$

Using this equation, R_w can be calculated for any depth. The actual values obtained from a Dual Induction Laterolog log are a deep, medium, and shallow resistivity (R_{ID}, R_{IM}, R_S) for each depth. After reading the values from the log and calculating the ratios R_s/R_{ID} and R_{IM}/R_{ID} a chart similar to the one shown in Figure 2 (Schlumberger, 1979) can be used to obtain R_{xo}/R_t and R_t/R_{ID}. From these ratios, R_{xo} and R_t can be calculated. However, before using the correlation chart, corrections of the log data may be necessary. These corrections compensate for borehole effects and bed size.

If an analysis is desired over a zone, a plot is made of R_t versus R_{xo} for all depths in that zone. The equation which describes this plot is obtained by rearranging equation 8:

$$R_t = \frac{R_w}{R_{mf}} R_{xo} \qquad (9)$$

A line can be drawn through the points which goes through the origin and has a slope of R_w/R_{mf}. R_{mf} is assumed to be constant, so R_w can be directly obtained.

The next method used to find R_w uses an electric log and a porosity log. For a given lithology, F can be calculated by:

$$F = a/\phi^m \qquad (10)$$

where the constants a, and m, are lithology dependent parameters. If ϕ can be obtained from a porosity log and R_t from an electrical log, R_w can be calculated from the following equation, derived from equations 10 and 6.

$$R_w = \frac{R_t \phi^m}{a} \qquad (11)$$

In many cases, the lithology is known and the appropriate values can be substituted for m and a. For a compacted formation $a = 1$ and $m = 2$, which reduces equation 11 to:

$$R_w = R_t \phi^2 \qquad (12)$$

If the lithology is not well defined, the following analysis yields another procedure. R_w and F are also related by (Archie's equation):

$$S_w{}^n = \frac{FR_w}{R_t} \qquad (13)$$

Substituting equation 10 and 13 and taking the logarithm of both sides gives:

$$n \log S_w = \log (aR_w) - m \log \phi - \log R_t \qquad (14)$$

Since S_w is assumed to be 1, $n \log S_w$ will be zero. This gives:

$$\log R_t = - m \log \phi + \log (aR_w) \qquad (15)$$

Assuming the lithology and salinity are constant over a zone, an indication of the constants, a and m, can be found by plotting $\log R_t$ versus $\log \phi$. The line obtained will have a slope of $-m$ and, at $\phi = 1$, the intercept will be $\log (aR_w)$. Although this does not obtain the constant, a, directly, it can be found from an independent value of R_w. For example, equation 12 could be used with average values of R_t and ϕ. This value of the constant, a, can then be used for further calculations.

The last method used to calculate R_w needs only the Spontaneous Potential Log. The static spontaneous potential value, SSP, is related to R_w by:

$$SSP = -K \log \frac{R_{mf}}{R_w} \qquad (16)$$

where $K = 61 + 0.133T$ (Schlumberger, 1979). R_{mf} can be found from the log heading and T can be obtained by a temperature log or known temperature gradient. So, at any depth,

$$R_w = R_{mf} 10^{(SSP/K)} \qquad (17)$$

After R_w is obtained from any of the three methods described above, TDS can be found from a nomograph for NaCl solutions such as the one shown in Figure 3 (Schlumberger, 1979). Knowing the resistivity and temperature, TDS in ppm of NaCl equivalents at 75°F can be found. This nomograph can be fitted by the following equation (Dresser, 1980):

$$\text{NaCl}_{eq}\ (@\ 75^{o}F) = 10^{x} \qquad (18)$$

where

$$x = \frac{3.562 - \log\ (R_{75} - 0.0123)}{0.955}$$

and

$$R_{75} = R_{T}\left(\frac{T + 6.77}{75 + 6.77}\right)$$

EXAMPLES

Because of the difficulty in obtaining data, examples are presented from one well, US Geothermal A-1, in the Geysers, California field. It was chosen because it provided the best suite of logs. However, reasonable zones were still difficult to identify and these examples are primarily for illustrative purposes. Unfortunately, no pulsed neutron log was run in this well. The first example uses a Dual Induction Laterolog, a Spontaneous Potential log, and a Temperature log. The logs were run in the fall of 1974. Twenty feet of a zone were examined, beginning at a depth of 2602 ft. From the log heading the bit size was 12¼ in. with a 1.5 in. standoff. The temperature gradient was found from the temperature log (25°F/100 ft)around the depth of interest and at 2500 ft, T = 225°F. Therefore, at 2600 ft, T = 250°F. R_m is 11.9 Ω-m at 54°F or 2.82 Ω-m at 250°F. R_{mf} is 6.79 Ω-m at 65°F or 1.90 Ω-m at 250°F. For the given bit size and R_m no borehole correction was necessary. Values for R_{LL8}, R_{IM}, and R_{ID} were taken from the log and Figure 2 (R_{xo}/R_m = 20) was used to find the ratios from which R_t and R_{xo} are calculated. Table 1 presents this data and Figure 4 shows the plot of R_{xo} versus R_t. The slope of the line is R_w/R_{mf} = 0.475. Multiplying by R_{mf} gives R_w = .9025. Using Figure 3, TDS = 1840 ppm.

An independent calculation of R_w for this zone can be done using the Spontaneous Potential curve. Looking at the Spontaneous Potential log, the SSP value corresponding to this zone is -23 mV. K is found to be 94.25 and R_w is calculated to be 1.082. From Figure 3 TDS is found to be 1860 ppm.

The next example uses an Induction-Electrical log and a Compensated Neutron log run in January, 1975. Forty feet of a zone were examined beginning at a depth of 5200 ft. Table 2 lists the data and computed R_w for each depth. Figure 5 shows the plot of log ϕ versus R_t. From this figure, it can be seen that most points lie together with several others being widely scattered. To help draw a reasonable line through these points, Humble's formula can be used since it obtains reliable results for most sedimentary formations. Using Humble's formula, $F = 0.62/\phi^{2.15}$ and average values of $\phi = 19\%$, and $R_t = 31\ \Omega$-m, and average R_w of 1.41 Ω-m is obtained. The constant, a, can then be calculated to be 0.39. By iterating on the constant, a, and R_w, a value of 0.497 for the constant, a, gives a close approximation to the average R_w calculated from Humble's formula. R_w is then calculated for each depth and an arithmetic average is determined. For this zone R_w was found to be 1.53 Ω-m. No temperature logs were available at this depth, so $T = 280^{o}F$ was assumed (bottomhole temperature was $285^{o}F$ at 6280 ft). Using Figure 3, TDS is 980 ppm.

CONCLUSIONS

Four methods to find TDS from well logs have been presented. If a complete suite of logs is available for a given zone, several methods can be employed to obtain TDS. By using more than one method an indication of the accuracy may be determined. However, each method can be used independently so even with a minimum amount of data an estimate of TDS can be determined. However, the methods should be done statistically to successfully account for lithological differences and bad data points within a zone. These methods are dependent upon the accuracy of the constants needed, such as the resistivity of the mud filtrate and the temperature. Also, too large a borehole (greater than 14 in.) can cause the resistivity measurements to be inaccurate because of the increased borehole effects. In all methods, the lithology must be taken into account because it can significantly alter the log readings, especially from the porosity tools.

REFERENCES

1. Schlumberger: "Log Interpretation, Volume I-Principles," 1972.

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3. Arps, J.J.: "The Effect of Temperature on the Density and Electrical Resistivity of Sodium Chloride Solutions," Petroleum Transactions, AIME, 1953.

4. Dresser Atlas: "Log Interpretation Charts," 1980.

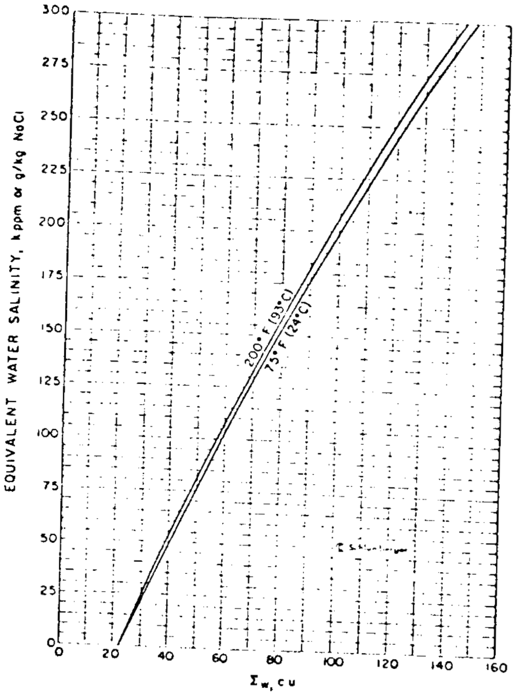

Figure 1. TDS versus Σ_w for TDT Log.

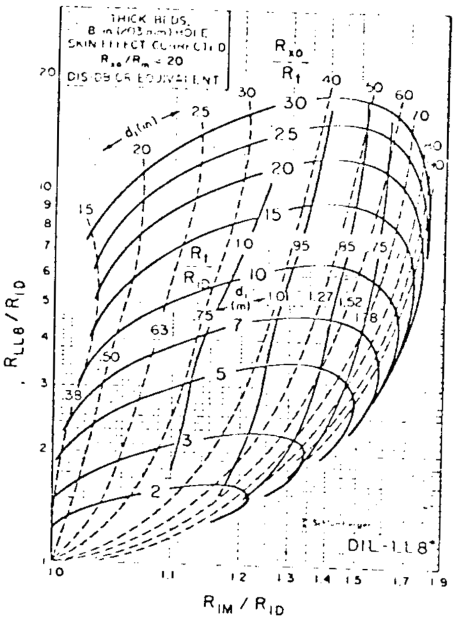

Figure 2. Solution chart for Dual Induction-Laterolog.

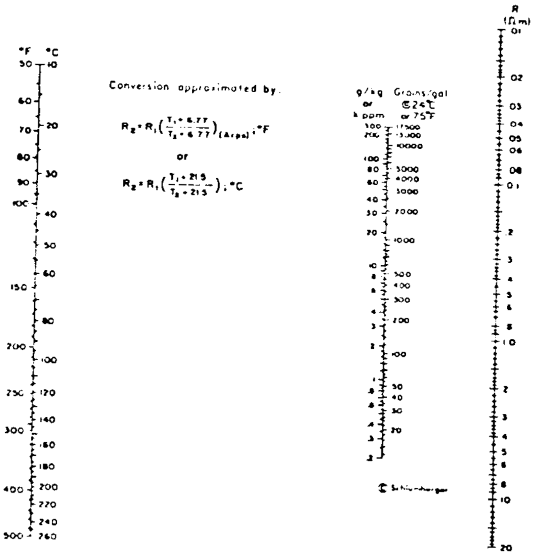

Figure 3. Resistivity Nomograph for NaCl Solutions.

TABLE 1

Data for Example 1 - Dual Induction Laterolog.

depth (ft)	R_{LL8}	R_{IM}	R_{ID}	$\frac{R_{LL8}}{R_{ID}}$	$\frac{R_{IM}}{R_{ID}}$	$\frac{R_{xo}}{R_t}$	$\frac{R_t}{R_{ID}}$	R_{xo}	R_t
		(Ω-m)						(Ω-m)	
2602	40	28	23	1.74	1.22	2.25	0.90	46.58	20.70
2603	36	28	23	1.56	1.22	2.05	0.85	40.08	19.55
2604	34	28	23	1.47	1.22	2.00	0.84	38.64	19.32
2605	45	32	27	1.67	1.19	2.05	0.94	52.03	25.38
2606	40	31	26	1.54	1.19	1.95	0.91	46.14	23.66
2607	37	25	30	1.48	1.20	1.95	0.865	42.17	21.625
2608	44	32	27	1.62	1.185	2.00	0.93	50.22	25.11
2610	55	34	29	1.89	1.17	2.50	0.96	69.60	27.84
2611	50	32	28	1.785	1.14	2.40	0.98	65.86	27.44
2612	40	32	27	1.48	1.185	1.90	0.90	46.17	24.30
2613	35	31	26	1.35	1.19	2.00	0.84	43.68	21.84
2614	38	33	28	1.36	1.17	2.00	0.90	50.40	25.20
2615	37	32	27	1.37	1.185	2.00	0.85	45.90	22.95
2616	37	31	25	1.48	1.24	2.15	0.75	40.31	18.75
2617	35	28	23	1.59	1.22	2.05	0.85	40.07	19.55
2618	32	26	21	1.52	1.23	2.05	0.82	35.30	17.22
2619	26	21	17	1.53	1.24	2.10	0.75	26.78	12.75

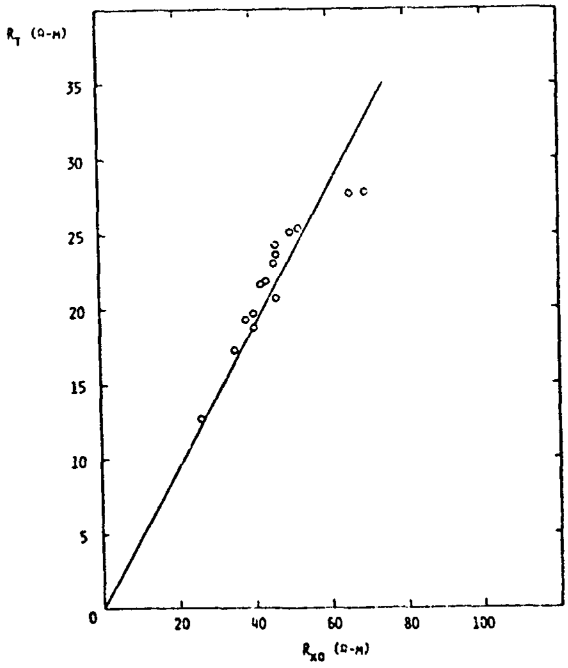

Figure 4. R_t versus R_{xo} for Example 1.

TABLE 2

Data for Example 2 - Induction-Electrical/Compensated Neutron.

depth (ft)	R_t (Ω-m)	ϕ_n (%)	$R_w = R_t^{2.28}/0.497$ (Ω-m)
5200	31.0	20.0	1.59
5202	35.0	19.5	1.69
5204	35.0	19.2	1.64
5206	35.0	19.0	1.60
5208	35.0	18.0	1.43
5210	40.0	20.0	2.05
5212	39.0	16.7	1.33
5214	36.0	18.0	1.45
5216	36.0	18.0	1.45
5218	36.0	18.0	1.45
5220	30.5	19.2	1.43
5222	39.5	19.8	1.98
5224	42.5	18.5	1.82
5226	40.0	18.0	1.72
5228	35.5	18.4	1.51
5230	31.0	18.2	1.28
5232	28.0	17.0	0.99
5234	25.5	17.8	1.00
5236	30.0	21.0	1.72
5238	30.5	19.0	1.39
5240	30.5	20.0	1.56

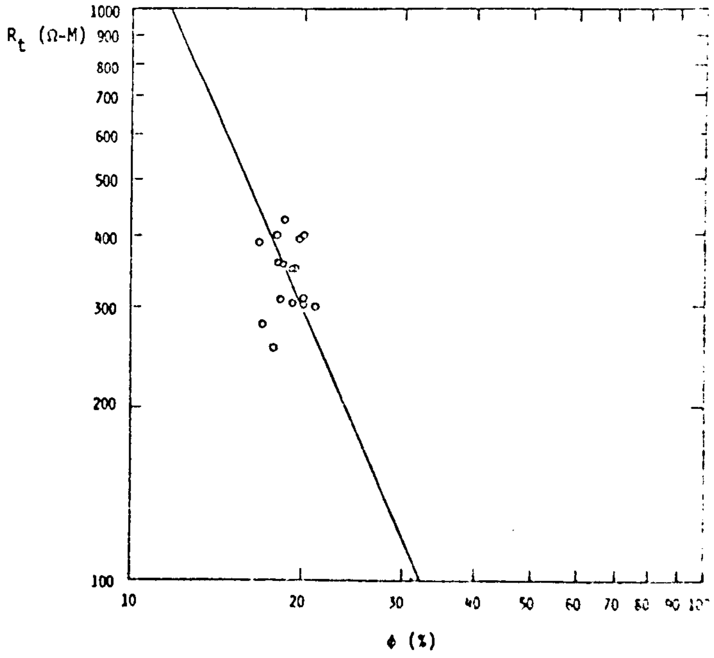

Figure 5. R_t versus ϕ for Example 2