A Fortran Programme for Computing Formation (Connate) Water Resistivity from Spontaneous Potential Logs

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Abstract: A computer programme in Fortran language for computing formation water resistivity, $R_w$, from Spontaneous Potential (SP) log has been designed, coded and tested. The aim was to develop a fast alternative approach of measuring $R_w$ devoid of the use charts. The input data - bed thickness, flushed zone and mud resistivities, mud-filtrate resistivity, surface and formation temperatures and the static self potential (SSP) - were derived from digitized wireline logs from widely located sedimentary basins. The output was tested using borehole and laboratory data from pre-existing wells and the results were compared. The maximum percentage deviation was less than 5%. The programme has therefore provided a fast technique of estimating $R_w$, correcting for formation (bed) thickness/cleanliness and thus reducing the subjectivity inherent in the use of charts.

Key words: Fortran • Formation-Water-Resistivity • Spontaneous Potential • Log • Mud Filtrate

INTRODUCTION

The earth, especially in sedimentary areas, is highly stratified. The constituents of the various strata (rock and fluid contents) often have diverse physical and geologic properties. These properties include porosity, permeability, density, velocity etc. The porous and permeable layers often form the reservoir or aquifer unit and hydrocarbon reservoir rocks in which water, oil and gas could accumulate in commercial quantity.

Formation water resistivity, Ushie [1], represents the resistivity value of the water (uncontaminated by drilling mud) that saturates the porous formation. It is also referred to as connate water or interstitial water. It constitutes the free water which supplies the energy for the water drive in reservoirs and its resistivity is variable depending on the salinity, temperature and whether or not the formation contains hydrocarbons.

In the quantitative evaluation of such reservoirs/aquifers, the value of $R_w$ needs to be determined with reasonable accuracy. The $R_w$ value is a necessary input to the evaluation of water saturation for this purpose. Even in aquifers, the value of $R_w$ (inverse of salinity) serves as a veritable safety guide in the categorization of potable water for human consumption. Apart from lithologic indication, the SP log is one of the techniques of determining $R_w$. The Spontaneous or Self Potential (SP) log is a self-induced, natural potential that occurs spontaneously between reservoir rocks and a fluid-filled borehole. This natural voltage originates from electrochemical and electrokinetic actions, Tenchov [2] and causes an electrical current to flow in conductive borehole fluids. A record of this potential versus depth in a borehole is known as the SP log. The log is highly invaluable in geoenvironmental studies, Radhakrisna. and Gangadhara Rao [3,4]. The SP log is often subject to corrections for bed thickness and shaliness, [5, 6] after which it becomes highly valuable to the log analyst in the segregation of permeable strata from impermeable horizons, determination of formation water resistivity, estimation of lithofacies description of stratigraphic formations, Coudert et al. [5] etc.

Formation water resistivity, $R_w$, is one of the most important parameters in open hole log analysis. It is required to calculate fluid or gas saturation in the pore spaces of reservoir rocks. Its value can range from 0.01 ohm-m to several ohm-metres at reservoir temperature. Sodium Chloride (NaCl) is usually the dominant salt in solution and the resistivity of the electrolyte normally decreases with increasing salt concentration. $R_w$ can be determined, Bigelow [7], by the following methods: catalogued water resistivity
information, measured resistivity and temperature of a produced water sample from the reservoir horizon, chemical analysis of a water sample produced from the reservoir, calculation from the SP trace and Bassiouni [8], calculation from a reliable \( R_m \) and porosity values in a known water-bearing horizon etc. A most simplistic procedure of determining \( R_m \) from SP log, using charts, is undertaken by Asquith and Krygowski [9].

Several factors do influence the SP process and therefore the \( R_m \) calculated from it. Such factors include thin beds, adjacent beds, shaliness within the reservoir body (cleanliness), hydrocarbons, adequate permeability, drilling mud density etc. McConnell [6, 10] have carried out extensive studies on corrections for groundwater salinity calculations and SP logs in groundwater respectively. However, under favourable conditions (clean water-bearing horizons, moderate mud resistivity, saline formation water, appreciable formation permeability, hole size (less than 25cm) etc., the SP method can be used to compute acceptable \( R_m \) values.

The overwhelming majority of reservoir rocks contain enough NaCl that standard charts and equations can be used to determine \( R_m \). In most cases, usage of these charts is often slow, prone to human error of judgment and as such leads to varied and subjective results. This paper, an adaptation of Bateman and Konen [11], is therefore intended to develop a computer programme capable of computing \( R_m \) with precision and improved speed and reduced subjectivity. The algorithms are based on standard empirical equations from which the charts are coded. The programme has been tested and the results found reasonably comparable to those from even laboratory techniques.

**Theory:** In order to perform quantitative analysis of the SP, the relationship between it and the resistivities of the mud filtrate and the formation water is necessary. Analysis based on various laws of physical chemistry has led to the equation:

\[
SP = -k \log \left( \frac{R_m}{R_w} \right)
\]

(1)

where \( SP \) is measured in millivolts and \( k \) is a temperature-dependent constant. The SP value can be read in a water-bearing clean and thick sandy formation. The \( k \) value can be estimated from the equation:

\[
k = T + \frac{505}{8}
\]

(2)

where \( T \) is the formation temperature in °F.

The mud filtrate resistivity, \( R_{mf} \), can be estimated from direct measurement on a drilling mud sample usually prepared by placing a circulated sample in a mud press. \( R_{mf} \) is the least well-defined parameter in SP log analysis. These data are usually entered on the log heading. In the absence of any reported value of \( R_{mf} \), the following, Schlumberger [12], can reasonably suffice:

\[
R_{mf} = (R_m)^{1.065} \times 10^{(9 - W)^3}
\]

(3)

where \( W \) = mud weight in lb/gal; \( R_m \) = mud resistivity.

The actual development of SP is controlled by the relative chemical activity of the formation water and mud filtrate solutions. Thus equation (1) can be written as:

\[
SP = - k \log \left( \frac{A_w}{A_{mf}} \right)
\]

(4)

Where \( A_w \) and \( A_{mf} \) are the activities of the connate water and the mud filtrate respectively. The solution resistivity is roughly inversely proportional to the activity at low salt concentrations. At high concentrations, there is marked departure. To compensate for this, we define the effective or equivalent resistivities \( R_{we} \) for salt solutions, which are inversely proportional to the activities:

\[
R_{we} = 0.075 / A_w \text{ (at 77 °F)}
\]

(5)

A conversion chart is normally used to convert \( R_{we} \) to the actual formation water resistivity, \( R_w \). The SP equation can then be rewritten to the strictly accurate formula:

\[
SP = - k \log \left( \frac{R_{mf}}{R_{we}} \right)
\]

(6)

The subjectivity attached to the usage of standard charts for the above has inspired the development of this programme.

**MATERIALS AND METHODS**

The basic material needed for the running of the programme is the Spontaneous Potential (SP) log from which the various input parameters, see Figure 1, can be extracted.
Information on these parameters such as reservoir depth \((z)\), reservoir thickness \((h)\), flushed zone resistivity \((R_i)\), mud resistivity \((R_m)\), mud filtrate resistivity at surface temperature \((R_mfs)\) are either provided on the log header or easily readable on the log proper.

According to Bateman [13], the procedure for using the SP equation (equation 6) is as follows:

1. Establish the formation temperature; find the value of \(R_{mf} \) at formation temperature; convert \(R_{mf} \) at formation temperature to an \(R_{mfe} \) value; compute the \(R_{mf}/R_{we} \) ratio from the SP; Compute \(R_{we} \); and convert \(R_{we} \) at formation temperature to an \(R_w \) value.

Essentially, the algorithm involves:

- Reading-in the above listed input parameters;
- Calculating the mud filtrate resistivity at formation temperature, \(R_{mf} \);
- Conversion of the observed SP value to SSP depending on the reservoir thickness \((h<3 \text{ metres})\);
- Conversion of the pseudostatic potential (PSP) to Static self Potential (SSP), Tabanou et al. [14],

\[ R_{mf} = R_{mf} \left( \frac{T_{mf} + 6.77}{T_i + 6.77} \right) \]

\[ R_{we} = R_{mf} \left( 10^{SSP/(60-0.133T_f)} \right) \]

\[ R_{w} = \frac{R_{we} + 0.131 \times 10^{(T_{mf}/T_f)^{0.95}}}{-0.5R_{we} + 10^{(0.426+0.1xT_f)}} \]

\[ SP_{cor} = \frac{4 \left( \frac{R_i}{R_m} + 2 \right)^{1/3.65}}{h - \left( \frac{R_i}{R_m} + 11 \right)^{1/6.05}} - 1.5 + 0.95 \]

\[ SSP = PSP \times S \]

**Definition of Terms**

- \(Z\) = Depth (ft), \(h\) = Thickness (ft)
- \(R_i, R_m, R_{mfs}, R_{mf}, R_{we}\), and \(R_w\) = Resistivities of invaded zone, mud, surface mud filtrate, formation mud filtrate, water equivalent, and formation water respectively.
- \(T_{ms}\), and \(T_f\) = mean surface and formation temperature (°F) respectively.
- \(SP, PSP,\) and \(SSP\) = Self potential, pseudostatic potential and static self potential values respectively.
Table 1: Input parameters and computed Rw (Rwform) for twelve wells

<table>
<thead>
<tr>
<th>S/N</th>
<th>Z(ft)</th>
<th>h(ft)</th>
<th>R/Rm</th>
<th>Rmfsurf(Ω-m)</th>
<th>Tmfs(°F)</th>
<th>SSP(mV)</th>
<th>Rmfform(Ω-m)</th>
<th>Rwe(Ω-m)</th>
<th>Rwform(Ω-m)</th>
</tr>
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<tr>
<td>1</td>
<td>3590</td>
<td>10</td>
<td>0.50</td>
<td>10.200</td>
<td>60</td>
<td>-71</td>
<td>0.54592</td>
<td>0.06824</td>
<td>0.07247</td>
</tr>
<tr>
<td>2</td>
<td>3780</td>
<td>12</td>
<td>0.50</td>
<td>0.700</td>
<td>100</td>
<td>140</td>
<td>0.29107</td>
<td>0.02464</td>
<td>0.03095</td>
</tr>
<tr>
<td>3</td>
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<td>8</td>
<td>0.50</td>
<td>0.510</td>
<td>60</td>
<td>130</td>
<td>0.37446</td>
<td>0.05025</td>
<td>0.05761</td>
</tr>
<tr>
<td>4</td>
<td>3960</td>
<td>20</td>
<td>0.50</td>
<td>0.510</td>
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<td>135</td>
<td>0.24898</td>
<td>0.07562</td>
<td>0.07918</td>
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<td>5</td>
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<td>140</td>
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<td>0.11971</td>
<td>0.11730</td>
</tr>
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<td>0.26759</td>
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<td>60</td>
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<td>148</td>
<td>0.00663</td>
<td>0.13774</td>
<td>0.13387</td>
</tr>
</tbody>
</table>

depending on the thickness and cleanliness (degree of shaliness) of the formation;

- Calculation of equivalent (effective) formation water resistivity (Rw);
- Conversion of the computed Rw to formation water resistivity, Rw.

Figure 1 is a flowchart depicting the ‘road map’ for the coding process.

RESULTS AND DISCUSSION

The programme has been successfully run and tested with input data from twelve wells obtained from both field and laboratory measuring techniques in basins across continents. The computed results were compared with those earlier determined using other standard field and laboratory techniques, Bigelow [7] and Bateman [13].

Table 1 shows the various input parameters as well as the computed output, (Rwform).

The maximum percentage deviation between field and computed Rw is less than 5%. It could be observed that the computed values of Rw - ranging from a few hundredths of an ohm-metre (brines) to several ohm-metre for fresh water, Bateman [13] - are reasonably in the range of values normally observed in the field. This result is sufficiently reasonable and reliable for any scientific purpose. This lends credence to the suitability of the programme as a faster and highly viable option to the use of charts for determining formation water resistivity from SP logs.

CONCLUSION

In this study, we have developed a Fortran programme for computing formation water resistivity from SP logs. It can be run in both the Disk Operating System (DOS) or Windows environments. The input parameters are often read from log headers or measured from the SP log proper. It is capable of automatically correcting for bed thickness (where thickness is less than 3 meters) as well as converting pseudostatic potential to static self potential (for dirty sands). Data from twelve wells, scattered over four sedimentary basins, have been employed in test-running the programme. The computed Rw values were compared with standard previously determined field and laboratory measurements. In all the wells, the maximum deviation between computed and other methods of measurement was less than 5%. This closeness suggests that the programme is accurate, sufficiently reliable and could serve as a quicker option to the method of determining Rw from SP logs, using charts.

ACKNOWLEDGEMENTS

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REFERENCES


PROGRAM GeoResist
C DIMENSION
COMMON h, SP, INVAMUD, Tf, Tms
CHARACTER WELLNAME*60
INTEGER Tms, Tmf, SP, SSP, Tf, Z, h, ENT
REAL INVAMUD, KEM, NUME, NUMETERM1, NUMEINDEX
EQUIVALENCE (Tmf, Tms)
REM(L) = 0.131 * 10***(1/(LOG10(L/19.9)) - 2))
KEM(M) = 10***(0.0426/(LOG10(M/50.8)))
RK(N) = 60 + 0.133 * N
WRITE(*,60) WRITE(*,10)
10 FORMAT(2X,*GeoResist 1.0*) WRITE(*,55)
WRITE(*,*) ' COPYRIGHT @ 2007 BY P.A.
C45 FORMAT ///,15,2X,F5.2 = 375.56  
C RK = 60 + 0.133 * Tf  
C IF(Ri .EQ. 99.5 .OR. Rm .EQ. 99.5) GOTO 62  
FINVAMUD = Ri/Rm  
IF(INVAMUD.GT.5 .AND. (h.GT.3 .AND. h.LT.50)) THEN  
C CALL CORFACTOR  
C IF(INVAMUD .GT. 5) THEN  
C CALL CONDIT  
NO.1  
C TRATIO(J,K)  
PSP = SP  
SSP = PSP  
WRITE(2,65) COMMON INVAMUD, h, SP  
65 FORMAT(1X,’_________ PSP = SP  
 ELSE  
 SSP = SP  
ENDIF  
GOTO 63  
62 SSP = SP  
63 Rwe = Rmfform*(10**(SSP/RK(Tf))))  
C Rwe = Rmfform*(10**(SSP/RK))  
Rwform = (Rwe + REM(Tf))/((-0.5*Rwe) + KEM(Tf))  
WRITE(2,65)  
65 FORMAT(1X,’_________ WRITE(2,70)ENT,Z,h,INVAMUD,Rmfsurf,Tms,Tf,S  
SP,Rmfform,Rwe,Rwform  
70 FORMAT(1X,’_________ 1,7X,I3,3X,I5,1X,I5,6X,F5.2,4X,F5.3,9X,I  
3.7X,I3,7X,I4,15 X,F7.5,6X,F7.5,4X,F7.5,3X,’"’)  
40 CONTINUE  
WRITE(2,75)  
75 FORMAT(1X,’_________ 1,7X,I3,3X,I5,1X,I5,6X,F5.2,4X,F5.3,9X,I  
3.7X,I3,7X,I4,15 X,F7.5,6X,F7.5,4X,F7.5,3X,’"’)  
50 FORMAT(/”/)  
55 FORMAT(/”/)