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INFERRING RELATIVE PERMEABILITY FROM RESISTIVITY WELL LOGGING

Kewen Li and Roland N. Horne

Stanford Geothermal Program, Stanford University
Green Earth Science Building, 367 Panama St.
Stanford, CA 94305-2220, USA
e-mail: kewenli@stanford.edu

ABSTRACT

Steam-water relative permeability can be calculated from capillary pressure. However this technique still requires measurement of capillary pressure. In this study, a semianalytical model was developed to infer relative permeability from resistivity data. Although it would still be necessary to conduct experimental measurements of resistivity, these are easier than measuring capillary pressure. On the other hand, resistivity data are commonly available from routine well logging. The semianalytical model was tested against experimental data. The results demonstrated that the relative permeabilities calculated from resistivity data using the new model were close to those calculated from capillary pressure data. The model developed in this study may also provide an approach to estimate permeability using both the resistivity well logging and well testing.

INTRODUCTION

One important parameter in geothermal reservoir engineering is steam-water relative permeability. Yet it is difficult to measure steam-water relative permeability because of mass transfer and phase transformation as pressure changes. Previously, Li and Horne (2002, 2004) reported that steam-water relative permeability could be calculated from capillary pressure data. These models provide an easier and more economical approach to obtain steam-water relative permeability, compared to the experimental technique. The disadvantage is the need to measure steam-water capillary pressure, which can also be difficult and time consuming in many cases. It would be helpful for engineers and scientists to have a method to infer steam-water relative permeability from resistivity data because it is easier to measure and resistivity data may be available from well logging. In this study, a semianalytical model was developed to infer relative permeability from resistivity data.

MATHEMATICAL MODELS

The relationship between relative permeability and resistivity index is derived in this section. The main theory behind this is the similarity between fluid flow in a porous medium and electricity flow in a conductive body.

Calculation of the Wetting-Phase Relative Permeability

The conductance of a porous medium at a water saturation of 100% is:

$$G_a = 1/R_o \tag{1}$$

where R_o is the resistivity at a water saturation of 100%, G_a is the conductance of a porous medium at a water saturation of 100%.

The conductance of a porous medium at a specific water saturation of S_w is:

$$G_w = 1/R_t \tag{2}$$

where R_t is the resistivity and G_w is the conductance at a specific water saturation of S_w.

According to the similarity theory between fluid flow and electric flow, the relative permeability of the wetting phase can be calculated using the following equation:

$$k_{rw} = \frac{G_w}{G_a} = \frac{R_o}{R_t} = \frac{1}{I} \tag{3}$$

where I is the resistivity index, k_{rw} is the relative permeability of the wetting phase.

According to the Archie's equation (1942), the following equation applies:

$$I = \frac{R_t}{R_o} = (S_w)^{-n} \quad (4)$$

Where n is the Archie's saturation exponent.

At a water saturation of 100%, it is known that I=1, so the value of k_{rw} calculated using Eq. 3 would be equal to 1, which is true. At the residual water saturation, it is known that k_{rw} =0, which implies that I approaches infinity according to Eq. 3. But it is known that the value of I does not approach infinity at the residual water saturation. So the value of k_{rw} calculated using Eq. 3 is greater than zero, which is not consistent with physical observation.

One can also expect that the relative permeability of the wetting phase calculated using Eq. 3 will be greater than the true value. The reason is that the resistivity counts the average volumetric properties of the pore bodies in a porous medium while permeability counts the properties of pore throats. This is also why resistivity well logging can obtain porosity but not permeability.

Considering these problems, Eq. 3 is modified as follows:

$$k_{rw} = \frac{S_w - S_{wr}}{1 - S_{wr}} \frac{1}{I} \quad (5)$$

where S_{wr} is the residual saturation of the wetting phase. According to Eq. 5, k_{rw} =1 at S_w =100% and k_{rw} =0 at $S_w = S_{wr}$, which is reasonable.

Eq. 5 can also be expressed as follows:

$$k_{rw} = S_w^* \frac{1}{I} \quad (6)$$

S_w^* is the normalized saturation of the wetting phase and is expressed as follows:

$$S_w^* = \frac{S_w - S_{wr}}{1 - S_{wr}} \quad (7)$$

Relative permeability of the wetting phase can be calculated using Eq. 6 from resistivity index data once the residual saturation of the wetting phase is available. Note that the residual saturation of the wetting phase can be obtained from the experimental measurement of resistivity.

Calculation of the Nonwetting-phase Relative Permeability

According to Li and Horne (2002), the wetting-phase relative permeability can be calculated using the Purcell approach (1949):

$$k_{rw} = (S_w^*)^{\frac{2+\lambda}{\lambda}} \quad (8)$$

where λ is the pore size distribution index and can be calculated from capillary pressure data.

After the relative permeability curve of the wetting phase is obtained using Eq.6, the value of λ can be inferred using Eq. 8.

According to the Brooks-Corey model (1964) and the study by Li and Horne (2002), the relative permeability of the nonwetting phase can be calculated once the value of λ is available. The equation is expressed as follows:

$$k_{rnw} = (1 - S_w^*)^2 [1 - (S_w^*)^{\frac{2+\lambda}{\lambda}}] \quad (9)$$

One can see that the entire relative permeability set (both wetting and nonwetting phases) can be inferred from resistivity index data using Eqs. 6 and 9.

RESULTS

The experimental data of resistivity and capillary pressure measured by Sanyal (1972) in rocks with different permeability were used to test the models (Eqs. 6 and 9) developed in this study. Firstly the values of relative permeability were calculated using Eqs. 6 and 9. Secondly relative permeability data were calculated using capillary pressure data (Li and Horne, 2002). According to the study by Li and Horne (2002), relative permeability could be calculated accurately using the capillary pressure technique. Finally the results of relative permeability inferred from resistivity index and capillary pressure data were compared.

Berea Sandstone

The Berea sandstone sample used by Sanyal (1972) had a porosity of 20.4% and a permeability of 300 md. Fig. 1 shows the relationship between resistivity index and water saturation in Berea sandstone at a temperature of 175°F.

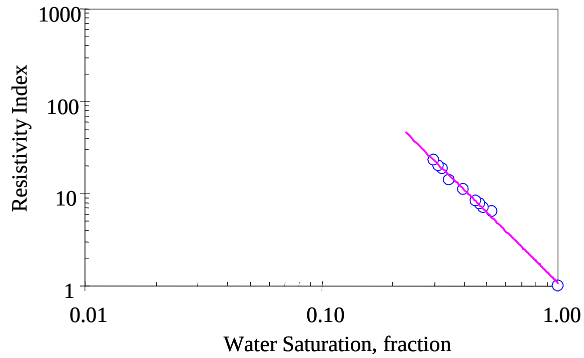

Figure 1. Relationship between resistivity index and water saturation in Berea sandstone at a temperature of 175^{o}F (Sanyal, 1972).

The values of the resistivity index at different water saturation shown in Fig. 1 were measured in oil-water (water displaced by oil) systems. Fig. 1 also shows that the relationship between resistivity index and water saturation in Berea sandstone at a temperature of 175^{o}F is linear on a log-log plot, which is consistent with Eq. 4.

Oil/water capillary pressure data were measured simultaneously with resistivity in the same core sample. The results are plotted in Fig. 2.

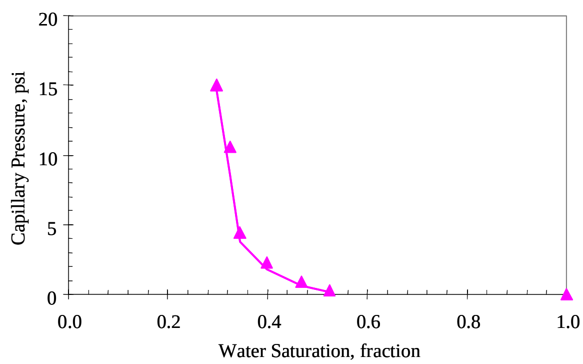

Figure 2. Capillary pressure data measured in Berea sandstone at a temperature of 175^{o}F (Sanyal, 1972).

Oil/water relative permeability data were calculated from resistivity index (using Eqs. 6 and 9) and capillary pressure data (See Li and Horne, 2002) respectively. The results are compared and shown in Fig. 3.

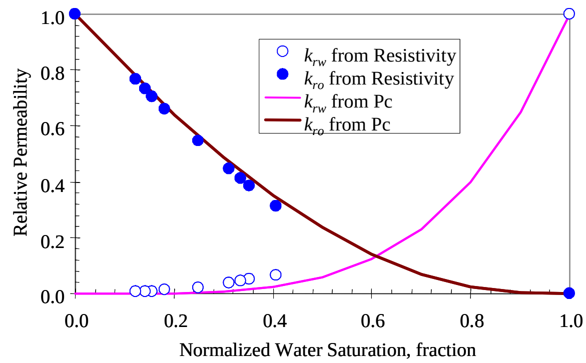

Figure 3. Relative permeability calculated from resistivity and capillary pressure data in Berea sandstone at a temperature of 175^{o}F.

The results shown in Fig. 3 demonstrate that the relative permeability data inferred from the resistivity index data are close to those calculated using capillary pressure data. The oil relative permeabilities inferred from resistivity index data are almost equal to those calculated from capillary pressure data.

Sanyal (1972) also conducted the experimental measurements of resistivity index and capillary pressure at different temperatures in the same core sample. The resistivity index data at a temperature of 300^{o}F are plotted in Fig. 4. One can see from Fig. 4 that the resistivity index data also follows the Archie's law (Eq. 4).

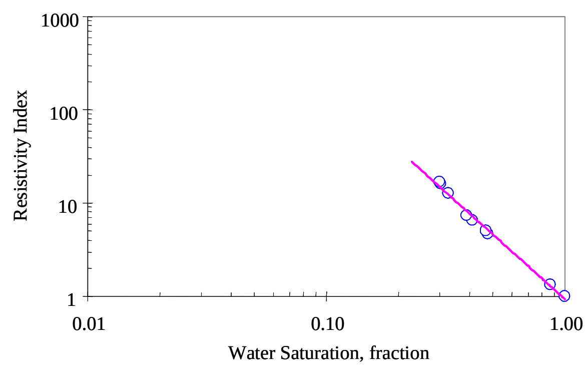

Figure. 4. Relationship between resistivity index and water saturation in Berea sandstone at a temperature of 300^{o}F (Sanyal, 1972).

Fig. 5 shows the oil/water capillary pressure data measured simultaneously with resistivity in the same Berea sandstone core sample at a temperature of 300^{o}F.

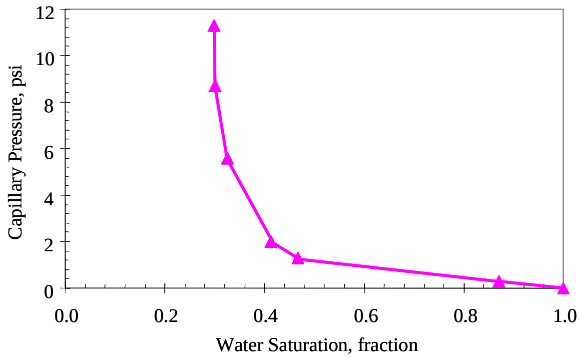

Figure 5. Capillary pressure data measured in Berea sandstone at a temperature of 300°F (Sanyal, 1972).

Fig. 6 demonstrates the relative permeability data calculated from both the resistivity index data shown in Fig. 4 (using Eqs. 6 and 9) and the capillary pressure data in Fig. 5 (see Li and Horne, 2002).

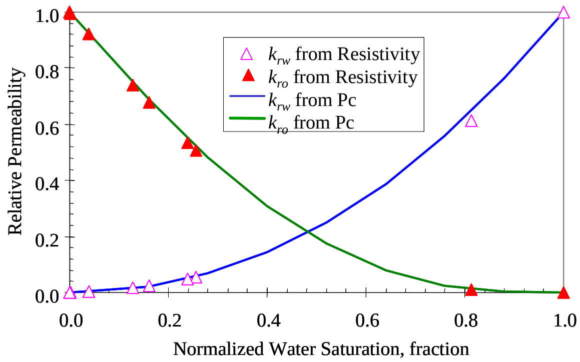

Figure 6. Relative permeability calculated from resistivity and capillary pressure data in Berea sandstone at a temperature of 300°F.

One can see in Fig. 6 that both the oil and water relative permeabilities inferred from the resistivity index data are almost equal to those calculated from the capillary pressure data.

Boise Sandstone

The Boise sandstone core sample had a porosity of 32% and a permeability of 960 md. The values of porosity and permeability are greater than those of Berea sandstone used by Sanyal (1972).

Figs. 7 and 8 show the resistivity index data and capillary pressure vs. water saturation in Boise sandstone at a temperature of 175°F.

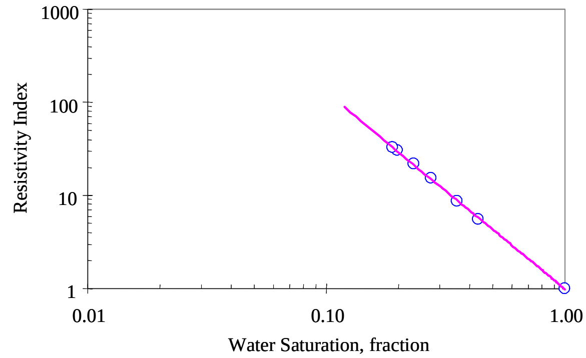

Figure 7. Relationship between resistivity index and water saturation in Boise sandstone at a temperature of 175°F (Sanyal, 1972).

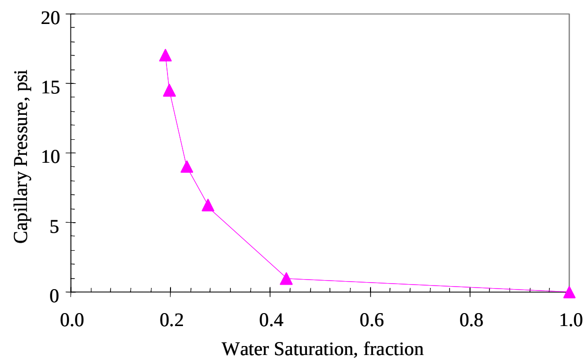

Figure 8. Capillary pressure data measured in Boise sandstone at a temperature of 175°F (Sanyal, 1972).

The relative permeability data calculated from both the resistivity index data shown in Fig. 7 (using Eqs. 6 and 9) and the capillary pressure data in Fig. 8 are plotted in Fig. 9.

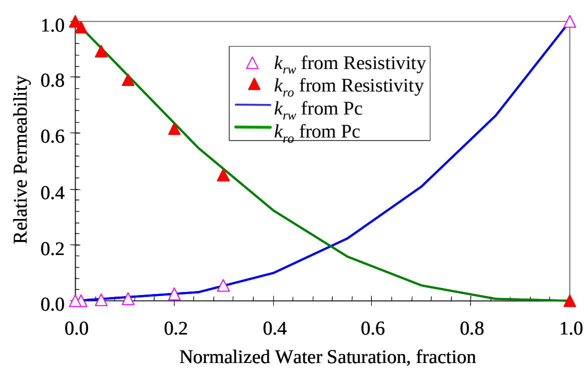

Figure 9. Relative permeability calculated in Boise sandstone at a temperature of 175°F.

Fig. 9 shows that the oil and water relative permeabilities calculated from the resistivity index data are close to those calculated from the capillary pressure data.

The results at a temperature of 300°F are demonstrated in Figs. 10-12. Fig. 10 shows the resistivity data and Fig. 11 shows the capillary pressure data. Fig. 12 plots the relative permeability calculated from the resistivity index shown in Fig. 10 (using Eqs. 6 and 9) and the capillary pressure in Fig. 11 respectively.

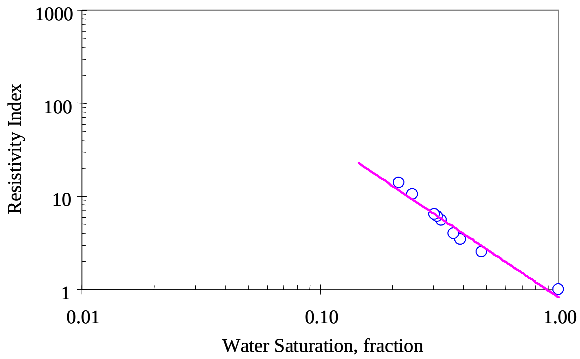

Figure 10. Resistivity index in Boise sandstone at a temperature of 300°F (Sanyal, 1972).

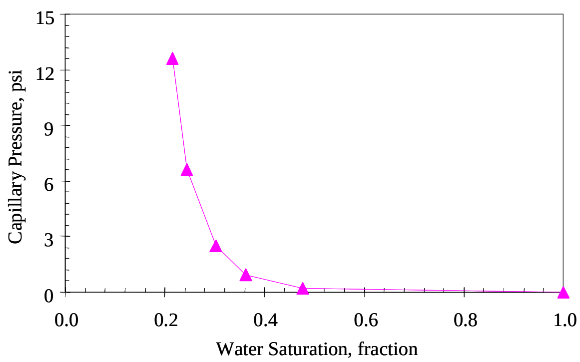

Figure 11. Capillary pressure data measured in Boise sandstone at a temperature of 300°F (Sanyal, 1972).

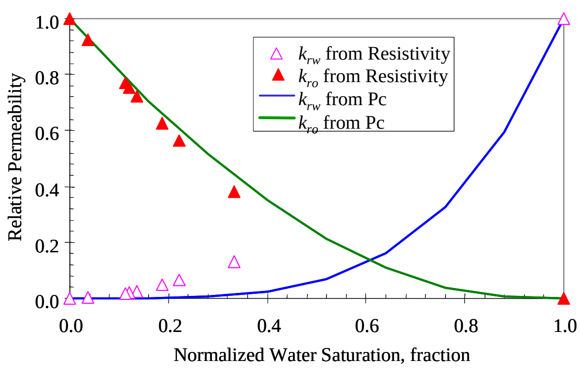

Figure 12. Relative permeability calculated from resistivity and capillary pressure data in Boise sandstone at a temperature of 300°F.

Fig. 12 shows that the oil relative permeability calculated from resistivity index is close to those inferred from capillary pressure. However the water relative permeability calculated from resistivity index data is smaller than those inferred from capillary pressure.

Limestone

The limestone core sample had a porosity of 19% and a permeability of 410 md.

The resistivity index and capillary pressure data at a temperature of 300°F are displayed in Figs. 13 and 14 respectively.

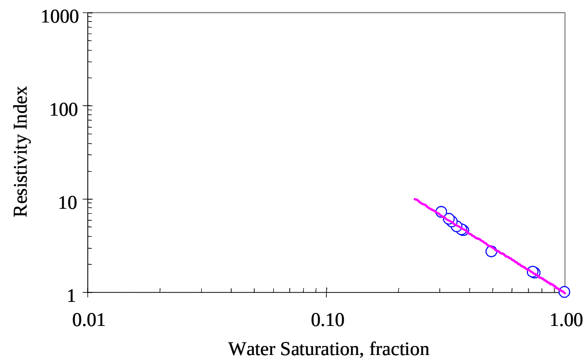

Figure 13. Resistivity index vs. water saturation in limestone at a temperature of 300°F (Sanyal, 1972).

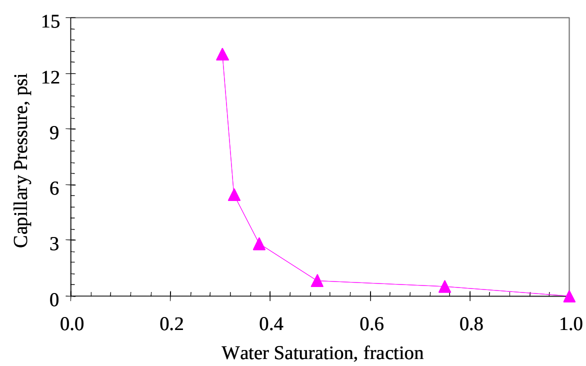

Figure 14. Capillary pressure data measured in limestone at a temperature of 300°F (Sanyal, 1972).

The results of relative permeability calculated from the resistivity index and the capillary pressure data are shown in Fig. 15.

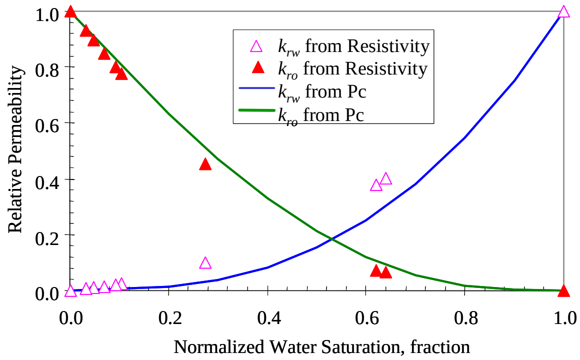

Figure 15. Relative permeability calculated from resistivity and capillary pressure data in limestone at a temperature of 300^{o}F.

One can see in Fig. 15 that the oil relative permeabilities inferred from the resistivity index data are almost equal to those calculated from the capillary pressure data in limestone core sample. The difference between the relative permeability inferred from the resistivity index and those calculated from capillary pressure is acceptable in terms of reservoir engineering applications.

CONCLUSION

Based on the present study, the following conclusions may be drawn in the cases studied:

1. A semianalytical model was developed to infer relative permeability from resistivity index data.
2. The values of the nonwetting phase relative permeability inferred from the resistivity index data are almost equal to those calculated from capillary pressure data.
3. For the wetting-phase relative permeability, the values inferred from the resistivity index are close to those calculated from capillary pressure in most of the cases studied.

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