

# Effect of Wettability on the Electrical Properties of Reservoir Rocks

Dengen Zhou, Sepehr Arbabi, and Erling H. Stenby \*  
 Petroleum Engineering Department  
 Stanford University, Stanford, CA 94305-2220, U.S.A.

## Abstract

Measurements of the electrical resistivity of oil reservoirs are commonly used to estimate other properties of reservoirs, such as porosity and hydrocarbon reserves. However, the interpretation of the measurements is based on empirical correlations, because the underlying mechanisms that control the electrical properties of oil bearing rocks have not been well understood. In this paper, we employ percolation concepts to investigate the effect of wettability on the electrical conductivity of a reservoir formation. A three dimensional simple cubic network is used to represent an ideal reservoir formation, for which the effect of the wettability can be isolated from the others. The phase distribution in the network is analyzed for different flow processes, and the conductivity is then estimated using a power law approximation of the percolation quantities.

The proposed conceptual model predicts the generic behavior of reservoir resistivities of different wettabilities. It demonstrates that the resistivity index depends on saturation history and wettability as well. For strongly oil-wet systems, significant hysteresis is expected, while there is little hysteresis for strongly water-wet systems, and small hysteresis is also expected for intermediate wet systems. The most interesting result from this study is that for intermediate wet systems, the Archie's saturation exponent is between 1.9 and 3.0.

## Introduction

The amount of hydrocarbon reserves is one of the most important parameters in the decision-making process in developing a reservoir. Accurate estimation of the reservoir's reserves can reduce the uncertainty of financial forecasting. The estimation of hydrocarbon reserves is commonly obtained from electrical logging. The interpretation of the logging data is based on Archie's law [1], which is an empirical correlation of the electrical resistivity index and its brine saturation. Archie's law indicates that the resistivity index is only a function of the conducting phase saturation for a given formation, as expressed by the following equations:

$$F_f = \frac{R_s}{R_b} = \frac{a}{\phi^m}, \quad (1)$$

which is called the Archie's first law, and

$$RI = \frac{R_s}{R_w} = \frac{1}{S_w^n}, \quad (2)$$

where  $F_f$  is the formation factor,  $R_s$  and  $R_b$  are respectively the resistivities of the 100 percent brine-saturated formation and the brine phase,  $R_w$  is the resistivity of the formation at saturation  $S_w$ ,  $\phi$  is

---

\*Chemical Engineering Department, Technical University of Denmark, DK-2800 Lyngby, Denmark

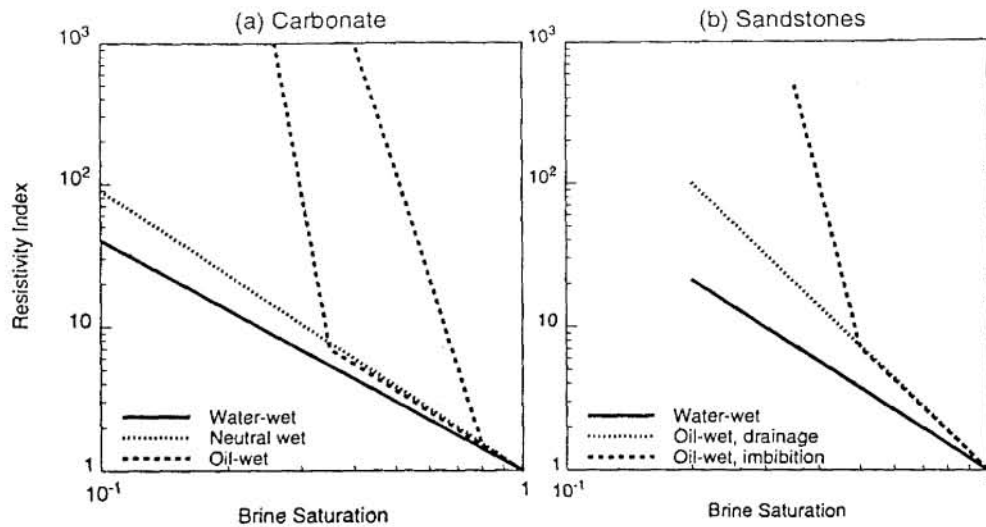


Figure 1: Typical wettability effect on resistivity index. (a) Sweeney and Jennings results on carbonate samples [11], and (b) Wei and Lile's results on sandstone samples [8].

the porosity,  $RI$  is the resistivity index,  $a$  is the empirical constant,  $m$  is the cementation exponent, and  $n$  is the Archie's saturation exponent.

Experimental studies [2]-[10] have shown that although widely used, the Archie's law is not always valid. Saturation history, wettability, content of clay minerals and salinity of the brine phase affect the resistivity index correlations. Significant research effort [9] has been made to understand the effect of clay content and salinity of the brine phase for shaly sand formations. In this paper, we consider clean reservoir formations, in which the conductivity of the formation is due only to bulk brine phase in the pore space, and focus our attention on the effect of wettability and saturation hysteresis.

Anderson [2] reviewed the wettability effect on electrical properties of porous media. He carefully examined the measurements by Mungan and Moor [4] on artificial teflon cores and those by Sweeney and Jennings [11] on carbonate cores. Fig. 1a summarizes the measurements by Sweeney and Jennings on carbonate samples. Both studies showed that for oil-wet systems the saturation exponent increases dramatically when the brine saturation is below a certain value. For water-wet systems, the saturation exponents were about 2 for Mungan and Moor's results and about 1.6 for Sweeney and Jennings' measurements. Sweeney and Jennings measured the resistivity index on neutrally-wet systems and found the saturation exponents to be about 1.9. It is important to point out that in all their experiments brine was the displaced phase.

The effect of saturation hysteresis on resistivity index was studied by Goddard et al. [3] on sandstone samples. They observed significant differences in resistivities between the processes of mercury injection and withdraw when the mercury saturations were low. Wei and Lile [8] studied the saturation hysteresis on both water-wet and oil-wet sandstone samples (see Fig. 1b). They found the saturation exponents to be about 2 for both imbibition and drainage in water-wet media. However, for oil-wet samples, they found that Archie's law was valid for high brine saturations ( $>0.58$ ). In addition, they observed a significant difference in saturation exponents between drainage and imbibition processes (hysteresis) when the brine saturation was less than 0.58 in oil-wet media.

Theoretical consideration of electrical conductivity of a porous medium has been focused on the derivation of Archie's first law [12, 13]. Percolation and Effective Medium Approximation (EMA) have generally been used, showing that exponent,  $m$ , depends on the structure of the medium. These models can predict the saturation exponent for water-wet systems. However, they fail in explaining the conductivity behavior of oil-wet systems.

In summary, experimental observations indicate that wettability and saturation history can signifi-

cantly alter the correlation of the resistivity index with the brine saturation. There is no general theory that can explain the observations. The objective of this paper is to introduce a conceptual model to explain the reported observations. We, however, do not intend to match any specific measurements. In the following section, we introduce percolation concepts that relate the electrical conductivity of a reservoir formation to a percolation network.

## Percolation and Porous Media

Physical models for a porous medium have evolved from simple capillary-tube models to complicated network models [14]-[18]. Network models are much more satisfactory than the simple capillary-tube model in representing the multiphase flow properties of porous media. However, using network models to simulate physical properties of a porous medium requires a significant amount of computer time [19]. The development of percolation theory made it possible to obtain approximate solutions for some of the multiphase flow properties of a porous medium. Percolation theory was first introduced as a formal branch of mathematical physics by Broadbent and Hammersley [20] to describe the morphology and conductivity of random structures. Many transport processes may be successfully idealized as the transport of an ideal "fluid" through an abstract "medium" [20].

Classical percolation theory centers around two classes of problems: bond percolation and site percolation processes. There are a number of important properties for a percolation network [12]. In this paper, the following properties: accessibility, conductivity, and percolation threshold are involved in the discussion of the fluid distribution and resistivity index. As a simple example to illustrate the features of a percolation network, let us consider a large network of conducting bonds as shown in Fig. 2, in which the lines between joints are called bonds and the joints are the sites. The number of bonds connecting to a site is the coordination number,  $Z$ . For a bond percolation process, the bonds are randomly cut (zero conductivity). Two sites are called connected if there exists at least one path between them consisting solely of uncut bonds. After a number of bonds are randomly cut, a fraction of the total number of bonds,  $p_b$ , remains. The conductivity of the network,  $C_b(p_b)$ , decreases depending on the number of bonds left,  $p_b$ . The fraction of pores that can be accessible by a continuous path from one side of the network to the other is defined as the accessibility,  $X_b^a(p)$ , of the network, which decreases with deduction of  $p_b$ . When  $p_b$  is less than a certain value,  $p_{cb}$ , the network loses its conductivity and its accessibility is close to zero (neglecting the fraction of bonds which adjoin with the boundary).  $p_{cb}$  is the bond percolation threshold of the system. The percolation threshold,  $p_{cb}$ , is a function of the coordination number,  $Z$ , of the system. In a site percolation process, the sites are randomly removed with a probability of  $1 - p_s$ . Two nearest-neighbor sites are considered to be connected if they survive the removal process. Accessibility and conductivity are functions of total fraction of sites removed. There is also a site percolation threshold,  $p_{cs}$ , below which the network has zero conductivity. For a given network, the site percolation threshold,  $p_{cs}$ , is always greater than or equal to the bond percolation threshold,  $p_{cb}$ . There are many variants of bond or site percolation networks developed [12]. For the purpose of this paper, we consider the simple cubic networks. Fig. 3 shows the accessibility and conductivity functions for site percolation processes on a simple cubic network, which has  $Z = 6$ .

For a given network, the accessibility and conductivity only depend on the fraction of intact bonds,  $p$ . However, there are no general expressions correlating them in the literature. The simulated accessibility and conductivity functions consist of two parts: a straight line part for high values of  $p$  and a curved part when  $p$  is small. Investigations of percolation processes have been largely focused on the near-threshold region, in which, the accessibility and conductivity are found to scale as [12]:

$$X^a \propto (p - p_c)^\beta, \quad (3)$$

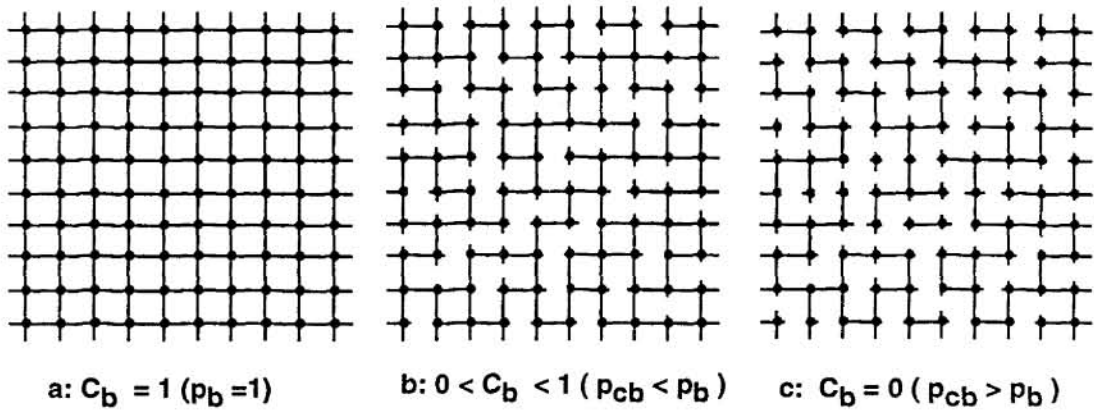


Figure 2: A simple two-dimensional bond percolation network.

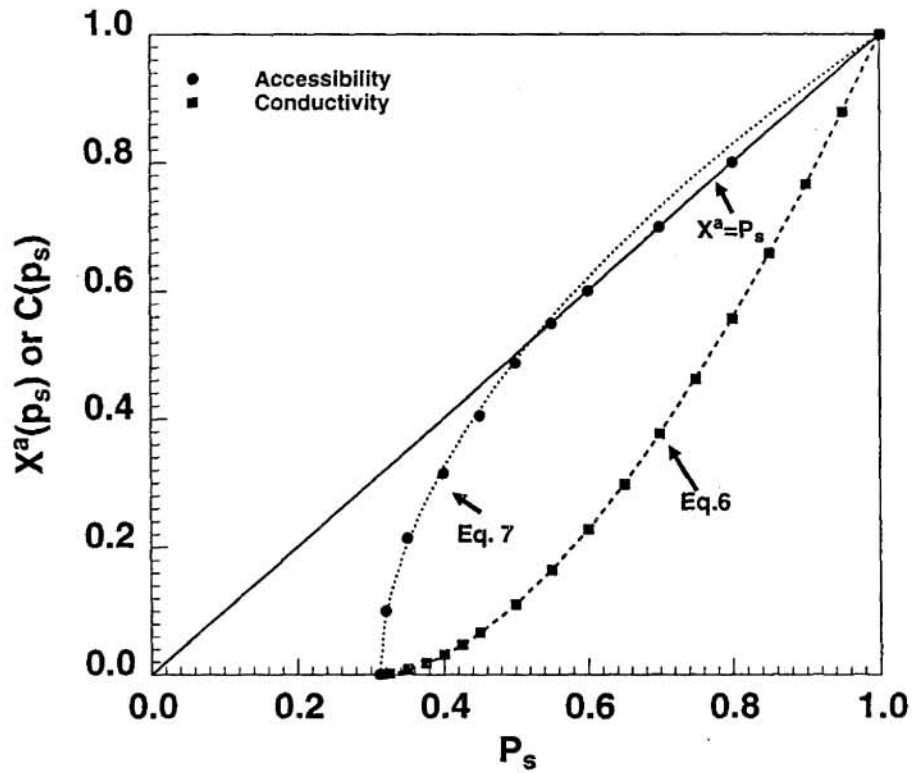


Figure 3: The accessibility,  $X_s^a$ , and conductivity,  $C(p_s)$ , of a site network. The dots are simulation results (averaged over five realizations) from cubic networks of size  $30 \times 30 \times 30$  and the curves are best fits of the simulation data. The solid line has a slope of unity, which represents the exact values of the accessibility at high values of  $p_s$ .

and

$$C(p) \propto (p - p_c)^\mu, \quad (4)$$

where  $\mu$  and  $\beta$  are universal scaling exponents. For a three-dimensional system [12, 19],  $\beta \simeq 0.41$  and  $\mu \simeq 2.0$  for infinitely large systems. Note that these values are valid only at or very near the percolation threshold. For values away from the percolation threshold, power laws may be used, but the exponents are significantly different from the threshold universal values. For example, Kirkpatrick [21] obtained 1.5 for  $\mu$  in his early work from a  $25 \times 25 \times 25$  bond network.

The development of EMA [12, 13] enables us to predict the conductivity when  $p$  is close to 1, which corresponds to the straight line part of the conductivity curve:

$$C(p) = \frac{p - p_{ce}}{1 - p_{ce}}, \quad (5)$$

where  $p_{ce} = 2/Z$ . At high values of  $p$ , the accessibility,  $X^a$ , equals the probability,  $p$ .

Combination of the results from EMA and percolation theory indicates that the exponent for conductivity varies from 1 to 2, and that the exponent for accessibility is between 0.41 to 1. For the purpose of this paper, we best-fit the entire conductivity curve with a power law, which is expressed as:

$$C(p) = \left( \frac{p - p_c}{1 - p_c} \right)^\alpha, \quad (6)$$

where  $1.0 < \alpha < 2$ . We found for site networks  $\alpha = \alpha_s = 1.70$  (see Fig. 3) and  $\alpha = \alpha_b = 1.21$  for bond systems. For accessibility, we have  $X_s^a = p_s$  when  $p$  is large and we best-fit a power law for low values of  $p$  ( $p_{cs} < p < 0.5$ ) as:

$$X^a = \left( \frac{p - p_c}{1 - p_c} \right)^t, \quad (7)$$

where  $0.41 < t < 1$  and  $t = 0.55$  is found for the site network (see Fig. 3). Note that Eqs. 6 and 7 are power-law approximations of the accessibility and conductivity for a given network.

A reservoir rock can be idealized as a three-dimensional pore network. The pores are randomly located in the reservoir rock and are connected through a complicated three-dimensional network. There are two important parameters in defining a pore in porous medium, the sizes of the pore throats and the pore bodies. The pore throat size determines the permeability of the medium and the pore body size is important in calculating the pore volume. Although large pore-body size tends to correlate with large pore-throat size, there is no well defined correlation between these two quantities. In order to use the correlations developed for percolation networks, we assume that each pore body had the same volume and the pore throats had the same conductivity, although they may have different sizes. This assumption may not be exact for an oil reservoir, but it isolates the effect of wettability from other influencing factors. Thus, the fraction of pores filled with brine phase is the same as the brine saturation, if the volume contribution from pore throats can be neglected. Therefore, if we know the fluid distribution for a given process, we can estimate the conductivity. In the following section, we discuss the fluid distributions in pore spaces and estimate the corresponding resistivity index.

## Fluid Distribution and Resistivity Index

In the previous section, we proposed to idealize the flow channels and pores in a porous medium as a percolation network. However, the geometries of the pores and the pore throat are highly irregular. What are the appropriate geometries for the bonds and sites in order for the network to represent the flow mechanisms in a rock? It has been recognized that the existence of corners and crevices in the pores plays a subtle role in determining the flow behavior of the wetting phase in a porous media [15, 22, 23]. Advanced network models [14]-[18] use noncircular cross-sectional pores and pore throats

to account for corner flows. Because of the corner flow, the wetting phase cannot be trapped during the displacement, consequently, there is little saturation configuration difference between imbibition and drainage. Therefore, saturation hysteresis on the wetting phase conductivity is small, as observed in the wetting phase relative permeability measurements. We should also expect little saturation hysteresis on the electrical conductivity in a water-wet medium.

If the displacement is quasi-static, the fluid distribution in a porous medium is determined by the capillary pressure, the pressure difference between the nonwetting ( $P_n$ ) and the wetting phases ( $P_w$ ), which is given by the Young-Laplace equation:

$$P_n - P_w = \gamma \left( \frac{1}{r_1} + \frac{1}{r_2} \right), \quad (8)$$

where  $\gamma$  is the interfacial tension and  $r_1$  and  $r_2$  are the principal radii of curvature of the fluid interface. For a drainage process, in which the nonwetting phase displaces the wetting phase, the capillary pressure increases and the nonwetting phase enters the large pore throats first. Whereas when the wetting phase displaces the nonwetting phase in an imbibition process, the capillary pressure decreases and the wetting phase would first enter the corners and crevices before entering the pores and pore throats, because the small dimensions of the corners and crevices create large capillary pressures. In addition to corner flow, it is also possible for the wetting phase to flow in pores and pore throats in a piston-like manner governed by the Young-Laplace equation. The nonwetting phase flow is controlled by the piston-like displacement only.

Although the bonds and sites are interconnected in networks, the conductivity of a network is dominated by either the bond connectivity or the site connectivity. If the wetting phase is the conducting phase, the corners and crevices in the pore space enable to connect the two neighboring pore throats, even though the pore is occupied by the nonwetting phase. The conductivity of the system depends on the connectivity of the pore throats (bonds) and therefore is a bond percolation problem. We have

$$C_w = \left( \frac{p_b - p_{cb}}{1 - p_{cb}} \right)^{\alpha_b}. \quad (9)$$

When the nonwetting phase is the conductor, both the sites and the bonds should be connected in order to have the electrical current flow through them. If we assign the same probability for the nonwetting phase to occupy a pore and a pore throat, the pore throats (bonds) reach their threshold and become connected earlier than the pores do, because the site percolation threshold,  $p_{cs}$ , is greater than the bond percolation threshold,  $p_{cb}$ . The conductivity of the system is then controlled by the site connectivity, and is a site percolation problem.

$$C_n = \left( \frac{p_s - p_{cs}}{1 - p_{cs}} \right)^{\alpha_s}. \quad (10)$$

If we assume the pore volume of the medium is controlled by the pore sizes, the saturation is controlled by the site percolation process. Because the corners do not allow the wetting phase to be trapped in the displacement processes, all pores filled with the wetting phase are accessible, that is:

$$S_w = X_s^a. \quad (11)$$

It is important to note that we used the site percolation properties. This subtle difference ensures that there is a finite conductivity when the wetting phase saturations are low (i.e.  $p_{cb} < p < p_{cs}$ ).

The configuration of the nonwetting phase in the pore space is determined by the displacement processes. Let us consider a drainage process (the nonwetting phase is injected from one end of the system). At the beginning, the nonwetting phase enters the large pore throats and the pore directly connected to them. A continuous flow path is formed as more nonwetting phase is injected. In this

case, all the pores filled with the nonwetting phase are accessible through the continuous nonwetting phase cluster, and the saturation is determined by the accessibility of the system, or

$$S_n = X_s^a. \quad (12)$$

However, for an imbibition process, the wetting phase enters the medium initially through the corners and crevices. As the wetting phase spreads through the corners, some of the nonwetting phase originally in the medium can be trapped by snap-off [23]. The portion of the nonwetting phase trapped by snap-off forms a part of the saturation but contributes little to the conductivity of the nonwetting phase. In this case, the nonwetting phase saturation consists of two parts: one is the portion that is accessible through the nonwetting phase cluster and the other is the trapped part. In the percolation theory, this is represented by the probability of the nonwetting phase occupying a pore space, that is,

$$S_n = p_s. \quad (13)$$

As imbibition proceeds, the trapped portion of the nonwetting phase increases and the accessible portion decreases, resulting in a dramatically decreasing conductivity.

Having related the conductivity to saturations in a network, we can discuss the resistivity behavior of different systems. For a strongly water-wet system, Eqs. 9 and 11 are valid, in which both the brine saturation ( $S_w$ ) and the conductivity are related to the probabilities  $p_b$  and  $p_s$ . Assuming that for  $p > p_{cs}$ ,  $p_b = p_s = p$ , one can eliminate  $p$  from Eqs. 9 and 11 to obtain

$$RI_w = \frac{1}{C_w} = \left(1 - \frac{1 - p_{cs}}{1 - p_{cb}}(1 - S_w^{1/t})\right)^{-\alpha_b}, \quad (14)$$

for low brine saturations ( $S_w < 0.5$ ). When brine saturation is large ( $S_w > 0.5$ ),  $X_s^a = p_s$ , and the resistivity index is

$$RI_w = \left(\frac{1 - p_{cb}}{S_w - p_{cb}}\right)^{\alpha_b}. \quad (15)$$

For strongly oil-wet systems, the resistivity depends on the saturation history. In a drainage process in which brine saturation increases, Eqs. 10 and 12 are applicable. By eliminating  $p_s$ , we have

$$RI_n = \frac{1}{S_w^{\alpha_s/t}}, \quad (16)$$

at low brine saturation and

$$RI_n = \left(\frac{1 - p_{cs}}{S_w - p_{cs}}\right)^{\alpha_s}, \quad (17)$$

at high brine saturations. For imbibition processes, we have

$$RI_n = \left(\frac{1 - p_{cs}}{S_w - p_{cs}}\right)^{\alpha_s}, \quad (18)$$

for saturations that are larger than  $p_{cs}$  by combining Eqs. 10 and 13.

In an intermediate wet system, the brine phase can be either the wetting phase or the nonwetting phase depending on the displacement process. Morrow [24] has shown that there is a significant contact angle hysteresis for intermediate wet systems. For example, for systems with intrinsic contact angles from about  $60^\circ$  to  $110^\circ$ , the advancing contact angles are larger than  $90^\circ$  and the receding contact angles are less than  $90^\circ$ . Thus, in an intermediate wet system, the injected phase becomes less wetting. Strictly speaking, all displacements are drainage processes in an intermediate system (the nonwetting phase displaces the wetting phase). For a process in which brine saturation increases, the system behaves as oil-wet and Eqs. 16 and 17 should be used. While for processes in which oil saturation increases, Eqs. 14 and 15 are applicable.

In summary, in this section, we have examined the fluid configurations in porous media for different displacement processes and related resistivity index to brine saturations.

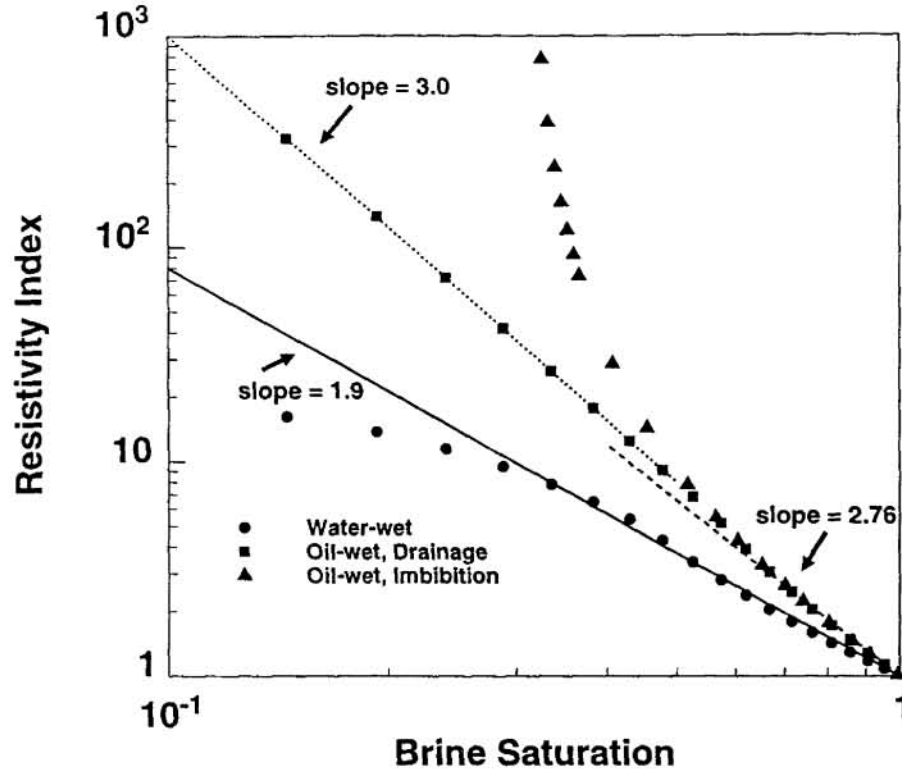


Figure 4: The predicted resistivity index for water-wet and oil-wet systems. The straight lines are best linear fits to the prediction.

## Discussion

There are many variants of networks in the literature, however, we use simple cubic network to demonstrate the generic behavior of reservoir resistivities. Note that using other three dimensional networks would not change the generic behavior of the problem. For a simple cubic network, the site and bond percolation thresholds are nearly 0.3116 and 0.2488 respectively. Fig. 4 shows the estimated resistivity index for water-wet and oil-wet systems. In all the calculations, we used  $t = 0.55$ ,  $\alpha_s = 1.70$  and  $\alpha_b = 1.21$ . Fig. 4 agrees well with the experimental trends observed in Fig. 1. For strongly water-wet systems, the resistivity index can be approximated by a straight line with the slope of 1.9. When the brine saturation becomes small, the slope decreases. This type of behavior has been observed [25] in laboratories and was contributed to the existence of microporosity. It is interesting to relate the microporosity concept and the pore geometries (corners and crevices). One can consider the corners and crevices as parts of the microporosity in a medium.

For strongly oil-wet systems, the model correctly predicts the resistivity hysteresis. In an imbibition process (oil is injected), the brine phase can be trapped by the oil phase and the resistivity increases as more brine is trapped. As the brine phase reaches its percolation threshold, almost all the brine phase in the medium is trapped, resulting in a dramatically increased resistivity. Thus, in this situation, there is a minimum saturation below which the system has near-zero conductivity. In a drainage process (brine is injected), the brine phase invades the large pore throats and forms continuous flow paths. There is no brine phase being trapped. Therefore, for the same saturation, the resistivity in an imbibition process is greater than that in drainage. At high brine saturations ( $S_w > 0.5$ ), the accessibility and the probability,  $p_s$ , are equal, and there is little difference in fluid distribution between imbibition and drainage. Thus, the resistivity behavior at high brine saturation are very similar for both imbibition and drainage.



For intermediate wet systems, the conceptual model reveals that the saturation exponent is bounded between 1.9 and 3.0 and small hysteresis is expected. For a process in which the brine phase saturation is reduced, the brine phase is the wetting phase, and the resistivity of the system behaves like a water-wet system. The saturation exponent is about 1.9. While when brine saturation is increased, the brine phase becomes the nonwetting phase and the fluid distribution is the same as in a drainage process in an oil-wet medium. The corresponding saturation exponent is about 3.0. Thus, some hysteresis is expected. However, because the systems are neither strongly water wet nor strongly oil wet, the prediction overestimates the hysteresis. The measured resistivity index should be in between the two predicted cases. Longeron et al.[25] reported small hysteresis in their measurements of oil/brine systems on sandstones.

It is important to point out that the proposed model can only predict the generic behavior of the problem, because of the simplifications involved in deriving the model. Detailed features of the measured resistivity index for a given system depend on the pore structure and the network configuration of the medium. For a specific reservoir sample, the conceptual model proposed is still valid, however, the representative accessibility and conductivity functions need to be known, which can be determined by detailed network simulations.

## Conclusions

In this paper, we examined the fluid distributions during various displacement processes and related the conductivity of an oil-bearing reservoir rock to the percolation conductivity of a network. A combination of the site and bond percolation processes has been introduced to describe the fluid distributions and conductivities. The conceptual model correctly predicts the generic behavior of the electrical conductivities of reservoir rocks with different wettability.

## References

- [1] G.E. Archie, G.E.: "The Electrical Resistivity as an Aid in Determining Some Reservoir Characteristics," *Trans. Am. Inst.Min.metall.Engrs.* **146**, 54-62, 1942.
- [2] Anderson, W.G.: "Wettability Literature Survey- Part 3: The Effects of Wettability on the Electrical Properties of Porous Media," *JPT* 1371-1378, Dec., 1986.
- [3] Goddard, R.R., Gardner, G.H.F. and Wyllie, M.R.J.: "Some Aspects of Multiphase Distribution in Porous Bodies," *Proceedings of European Federation of Chemical Engineering, Third Congress* Inst. of Chemical Engineering, London (June 1962) 326-32.
- [4] Mungan, N. and Moore, E.J.: "Certain Wettability Effects on Electrical Resistivity in Porous Media," *J. Cdn. Pet. Tech.* (Jan. - March) **7**(1), 20-25, 1969.
- [5] Pallatt, N. and Palmar, T.: "The Role of Pore Geometry in the Interpretation of Shaly Sands," *Reviewed Proceedings of the Second Society of Core Analysis European Core Analysis Symposium* London, UK. 20-22 May 1991.
- [6] Pallatt, N. and Thornly, D.: "The Role of Bound Water and Capillary Water in the Evaluation of Porosity in Reservoir Rocks," *Proceedings of the First Society of Core Analysis European Core Analysis Symposium* London, UK. 21-23 May 1990.
- [7] Wang, Z., Hirsche, W.K. and Sedgwick, G.E.: "Electrical and Petrophysical Properties of Carbonate Rocks," SPE 22661, *Proceedings of the 66th SPE Annual Technical Conference and Exhibition* Dallas, TX Oct. 6-9, 1991.

- [8] Wei, J.Z. and Lile, O.B.: "Influence of Wettability on Two- and Four-Electrode Resistivity Measurements on Bera Sandstone Plugs," *SPE Formation Evaluation* 470-476, Dec., 1991.
- [9] Worthington, P.E.: "The Evolution of Shaly Sand Concepts in Reservoir Evaluation," *The Log Analyst* **26**, 23-40, 1985.
- [10] Worthington, P.F., Pallatt, N. and Toussaint-Jackson, J.E.: "Influence of Miscoporosity on the Evaluation of Hydrocarbon Saturation," *SPE Formation Evaluation* **4**, 203-209, 1989.
- [11] Sweeney, S.A. and Jennings Jr., H.Y.: "Effect of Wettability on the Electrical Resistivity of Carbonate Rock from a Petroleum Reservoir," *J. Phys. Chem.* **64**, 551-553, 1960.
- [12] Sahimi, M.: *Applications of Percolation Theory*, Taylor & Francis, 1994.
- [13] Sheng, P.: "Effective-Medium Theory of Sedimentary Rocks," *Physical Review B* **41**, 4507-4515, 1990.
- [14] Blunt, M., King, M. and Scher, H.: "Simulation and Theory of Two-Phase Flow in Porous Media," *Physical Review A* **46**(12), 7680-7699, 1992.
- [15] Blunt, M. and Scher, H.: "Pore Level Modeling of Wetting," *Physical Review E* **52**, 6387-6403, 1995.
- [16] Fenwick, D.H. and Blunt, M.J.: "Pore Level Modeling of Three-Phase Flow in Porous Media," *Proceedings of the 8th European Symposium on Improved Oil Recovery* Vienna, Austria, May 15-17, 1995.
- [17] Larson, R.G., Scriven, L.E. and Davis, H.T.: "Percolation Theory of Two phase Flow in Porous Media," *Chemical Engineering Science* **36**, 57-74, 1981.
- [18] Oren, P.-E., Billiotte, J. and Pimczewki, W.V.: "Pore-Scale Network Modeling of Residual Oil Recovery by Immiscible Gas Flooding," SPE 27814, *Proceedings of the SPE/DOE Ninth Symposium on Improved Oil Recovery* Tulsa, OK 1994.
- [19] Yanuka, M.: "Percolation Theory Approach to Transport Phenomena in Porous Media," *Transport in Porous Media* **7**, 265-282, 1992.
- [20] Broadbent, S.R. and Hammersley, J.M.: "Percolation Processes I. Crystals and Mazes," *Proc. Camb. Phil. Soc.* **53**, 629, 1957.
- [21] Kirkpatrick, S.: "Percolation and Conduction," *Review of Modern Physics* **45**(4), 547-588, 1973.
- [22] Lenormand, R. and Zarcone, C.: "Role of Roughness and Edges During Imbibition in Square Capillaries," SPE 13264, *Proceedings of the 59th SPE Annual Technical Conference and Exhibition* Houston, TX Sept. 16-19, 1984.
- [23] Mohanty, K.K., Davies, H.T. and Scriven, L.E.: "Physics of Oil Entrapment in Water-wet Rock," *SPE Reservoir Engineering*, Feb. 1987.
- [24] Morrow, N.R.: "The Effect of the Roughness on Contact Angles," Preprint A-1, presented at the 48th National Colloid Symposium of American Chemical Society, Austin, Texas, 1974.
- [25] Longeron, D.G., Arqaud, M.J. and Feraud, J.-P.: "Effect of Overburden Pressure and the Nature and Microscopic distribution of Fluids on Electrical Properties of Rock Samples," *SPE Formation Evaluation* June 1989.