DIGITAL CORE APPROACH TO THE EFFECTS OF CLAY ON THE ELECTRICAL PROPERTIES OF SATURATED ROCKS USING LATTICE GAS AUTOMATA

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ABSTRACT

Clay has a significant influence on the relationship between resistivity index I and water saturation Sw of reservoir rocks as it complicates the current paths of these rocks. In this paper, we present a digital rock approach to effectively study these clay effects on the electrical transport properties of reservoir rocks at pore scale using lattice gas automata (LGA) method. The digital rock samples are constructed with the information from rocks. The LGA is then applied on these digital rocks fully saturated with fluids to simulate the electrical transport properties for revealing the effects of volume and distribution patterns of clay on the non-Archie behaviors of the I-Sw relationship. The very good agreement between the simulated results and the laboratory measurements clearly demonstrates the validity of the LGA in numerical research of rock physics. Based on these studies, a new model has been developed for quantitatively describing the relationship between the saturation exponent and the volume of clay (Vsh). This development may improve the evaluation for the fluid saturations in reservoir rocks.

INTRODUCTION

One of the main objectives in reservoir evaluation is to obtain the fluid information from the well logs. Archie's equations[1] have been used to calculate the water saturation with resistivity log for identifying the fluid types of a reservoir. The Archie's equation formulated the I-Sw relation as

$$I = b / S_w^n, \tag{1}$$

where n is the saturation exponent and b is a parameter. Equation (1) indicates the relationship of the resistivity index and water saturation (I-Sw) shall be a straight line in log-log scale.

Archie's equation, as an empirical formula based on the experiments of clean sandstone samples, has limitations when used to calculate water saturation for the reservoirs bearing clay contents. More and more cases indicate the I-Sw relationship may be nonlinear in log-log scale, which is called non-Archie behavior of I-Sw. Much research has proven that the non-Archie behavior of I-Sw can be caused by a lot of factors including clay.

Experiments have proven that the clay has significant effects on the I-Sw relationship due to it providing additional current paths. However, it is difficult to reveal the effects of various distribution of clay by only rock experiments because the pore structure, micro distribution and content of clay inside rock can not be adjusted at micro scale during experiments in the laboratory. Therefore, many researchers turn to numerical methods to investigate the effect of micro-factors on electrical transport properties of saturated porous media[2-3]. However, only limited success has been achieved, for the model used in their researches is too simple to reflect the very complex pore structure of real rocks.

LATTICE GAS AUTOMATA

The LGA method is the evolution of Cellular Automata in updating rules in discrete space[4]. In the LGA, the fluid, space and time are all discrete. For the LGA, the collision and streaming of particles can be described by the evolution of the distribution function of particle density as following

$$f_i(x + e_i \cdot \Delta t, t + \Delta t) = f_i(x,t) + \Omega(f_i(x,t)), \tag{2}$$

where, the $f_i(x, t)$ is the distribution function of particle density at lattice node x, time t, moving along the direction i with the velocity of e_i. The Δt is time step. The Ω is the collision rules to control the redistribution of particles.

The Darcy's law can be retrieved at the macro scale based on the micro evolution of distribution function of particle density in the model developed by Frisch, Hasslacher and Pomeau (FHP)[4]. By comparing Darcy's law with Ohm's law, the similarity between them is evident if electrical charges replace fluid particles, the electric field replaces the pressure gradient and the resistivity corresponds to the viscosity of the fluid[5]. It is clear that LGA can also be used to simulate the current flow in fluid-saturated porous media.

The LGA method used to simulate the electrical transport of current has been improved by introducing the reflective (R) and transmissive (T) coefficient on the border between phases to control the moving direction of particles, instead of going freely from one phase to another as in the conventional LGA method. With the improved LGA method, the choice of current path can be realized automatically by adjusting the reflective coefficient, and the relation of R and T meets T+R=1.

CONSTRUCTION OF DIGITAL ROCK

The digital rock plays an attractive role due to its flexibility in handling complex pore geometry. One of the key problems is how to construct a digital rock with similar pore structure to the real rock [6, 7].

To investigate the influence of pore structure, various matrix geometries such as diamond, triangle, point and rectangle shapes are employed to construct the digital rock. The complexity of pore structure is different for the digital rock constructed with different matrix grain shapes. In order to produce digital rock, the porosity and the distribution of grain size should be measured first. Therefore, based on the distribution, we can construct the digital rock models through piling up the grains and compacting into the limited space to obtain the required porosity, for investigation of electrical properties with LGA simulation. During the compacting process, the grains may be moved from the original positions to the new sites for reaching the balance of contacted grains under pressure. Therefore, the digital rock samples can be constructed with different porosity and pore structure, and saturated with different fluids.

The distribution of clay in rock can be divided into three types, dispersed clay, structured clay and laminar clay. Thus, different amount of clay particles, according the volume of clay content(Vsh) will deposit into the digital rock in different distribution types to reveal the effects of clay on the conductivity of rock. We assigned all clay minerals identical electric properties in the modelling. However, the distribution types of clay contents in the rocks will lead to different macro electric properties.

RESULTS AND DISCUSSIONS

The LGA is used to simulate the electrical transport properties of current in digital rock saturated with fluids under the effects of clay. In Figure 1, it is clear that the relation of I-Sw is linear in log-log scale as described by Archie's equation for the digital rock of Vsh=0. Increasing the structured clay, the linear I-Sw relationship holds for all the Vsh with the saturation exponent n decreasing. In fact, all the digital rocks used in Figure 1 have the same pore structure, saturation and fluids distribution. As mentioned above, the structured clay cannot change the pore structure of rock, therefore, the only reason for the results is the additional conductivity of clay. The resistivity of clay is far lower than that of the matrix, thus, the clay in the rock can change the path of current to reduce the changing rate of conductive path with the decrease of water saturation. Larger Vsh corresponds to a simpler conductive path.

Researchers pointed out the saturation exponent n is a function of fluid distribution[8], the exponent n of heterogeneous distribution of fluids is bigger than that of uniform distribution. However, it is indicated in Figure 1 that the exponent *n* is variable even under the condition of same uniform distribution of fluids. The reason is that the changing rate of conductive path with saturation due to the pure rock is bigger than that for the clay rock. The structured clay in rock can reduce the changing rate of conductive path with saturation for its extra conductivity, simplifying the conductive path of current. Therefore, the exponent *n* decreases with the increase of Vsh. The results demonstrate the exponent *n* reflects the changing rate of conductive path with saturation instead of the fluid distribution. This means that larger saturation exponent *n* corresponds to greater changing rate of conductive path with saturation, and vice versa.

The simulated results of digital rock with dispersed clay have been plotted in Figure 2 to indicate the change of I-Sw relationship with the Vsh. Comparing Figure 2 and Figure 1, it is clear that the change of the I-Sw relationship with Vsh is different even for the same digital rocks with different distribution style of clay. For the digital rock with dispersed clay, at beginning, the saturation exponent *n* decreases with increase of Vsh up to no more than 0.12. As shown in Figure 2, the relation of I-Sw in log-log scale will no longer be linear when the Vsh is more than 0.12 and gradually turns towards the horizontal axis (i.e. the axis of saturation) with decreasing water saturation. The non-linear relationship of I-Sw is obvious for the Vsh=0.12 and 0.18 in Figure 2.

The simulated results of the effects of laminar clay on the I-Sw relationship have been plotted in Figure 3. The laminar clay content can both reduce the effective porosity of rock as dispersed clay and change the conductive path of current as structured clay. Figure 3 demonstrates that the laminar clay content can produce an obvious non-Archie I-Sw relationship. Moreover, the non-Archie I-Sw relationship caused by the dispersed clay is obvious only for the Vsh greater than 0.12, while it is obvious even for the Vsh greater than 0.04 with the effects of laminar clay. The results demonstrate that the effects of laminar clay on the I-Sw are stronger than that of dispersed clay.

The analysis has been implemented for the results of a mixture of distribution types to find the dependence of the *n* on the Vsh, as shown in Figure 4. Generally, the quantitative model for the dependence of the *n* on the Vsh can be written as follows

$$n = 1.1353 - 0.0199 \cdot V_{sh} \qquad r=1 \tag{3}$$

Where, the *r* is correlation coefficient. Based on the simulated results, both the dispersed clay and the laminar clay can produce a non-Archie I-Sw relationship. The effect of laminar clay on the non-Archie I-Sw relationship is more significant than that of dispersed clay. Our numerical simulation shares the same conclusion with the rock experiments of other researchers[9].

CONCLUSION

The volume and the distribution style of clay have been proven by the LGA simulations to have significant effects on the relationship of I-Sw for its associated conductivity. The detailed effects of volume and distribution style of clay on the I-Sw relationship can be revealed by the LGA based on the digital rock because the pore structure, volume and distribution of clay inside digital rock can be adjusted in numerical experiments. The simulated results demonstrate that the saturation exponent n is a function of Vsh. Moreover, both the dispersed clay and the laminar clay can produce a non-Archie I-Sw relationship. The effect of laminar clay on the non-Archie I-Sw relationship is more significant than that of dispersed clay. The non-Archie I-Sw relationship is caused by the comprehensive mixture of matrix, pore-filling fluids and clay.

ACKNOWLEDEGEMENT

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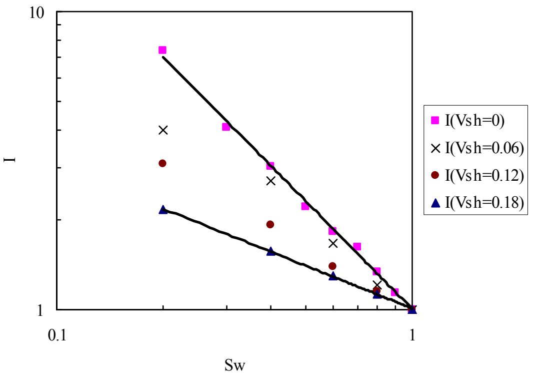

Figure 1 The relation of I-Sw for structured clay obtained from digital rock

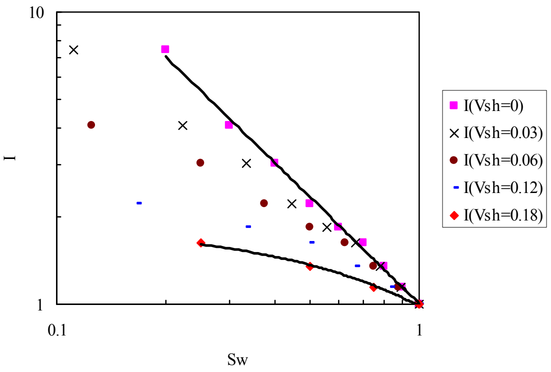

Figure 2 The relation of I-Sw for dispersed clay obtained from digital rock

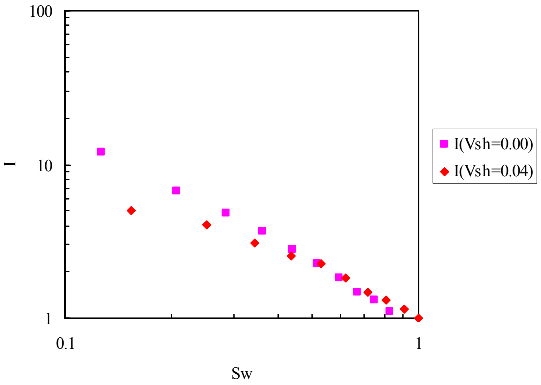

Figure 3 The relation of I-Sw for the digital rock with laminar clay

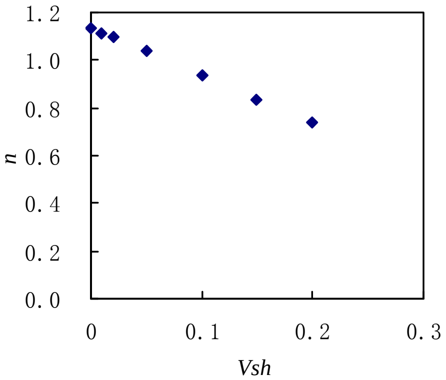

Figure 4 The relation of *n* and *Vsh* as formulated by Equation 3