HYSTERESIS OF THE RESISTIVITY INDEX IN UNCONSOLIDATED POROUS MEDIUM

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Abstract. Four-electrode resistivity measurements were conducted on water-wet, oil-wet, and intermediate wet beach sandpacks for 4–5 saturation directions with a steady state flooding procedure. The data from 4 runs indicated that there was a resistivity index hysteresis loop in the S_w-I_R plot during saturation cycles on each sandpack. The hysteresis behavior substantially depended on the sand surface wettability and saturation history which included saturation sequence and saturation directions. The more oil-wet, the more hysteresis in resistivity index. In the water-wet and middle-wet sandpacks, a moderate hysteresis of the resistivity index was found. In the oil-wet pack, a large hysteresis was demonstrated between saturation and desaturation. The data from the intermediate sandpacks showed that the saturation sequence only influenced the first drainage resistivity index behavior and not the style of the hysteresis loop. The recommendation from this study is that the saturation history influence should be taken into account in laboratory resistivity measurements.

INTRODUCTION

Resistivity measurements in special core analysis are crucial to electrical log interpretation. It is well known that core wettability has a profound effect on the Archie's saturation exponent(Anderson, 1986). Our previous work has shown that the core resistivity is not only a function of brine saturation and wettability but also depends on saturation history(Jun-Zhi and Lile, 1990, 1991).

The saturation history-dependent hysteresis phenomenon in resistivity measurements is called *resistivity index hysteresis*. This hysteresis, like capillary pressure and relative permeability hysteresis, results from the irreversibility of the distribution of two(or more) immiscible phases saturating the porous medium during drainage and imbibition. The hysteresis behavior depends on pore geometry, interfacial tensions, and experimental conditions.

To obtain an accurate oil saturation from well-logging interpretation, one should try to duplicate the reservoir conditions in laboratory resistivity measurements. Generally speaking, a virgin reservoir system lies in thermodynamic equilibrium. It is impossible to restore this equilibrium in tested samples at laboratory conditions. Core cleaning, flooding manner used in saturation and desaturation, electrode pattern, etc. can affect the resistivity precision directly or indirectly.

This paper reports the influence of saturation history on electrical conductivity behavior in an unconsolidated porous medium. The history includes saturation sequence, or saturation order, and saturation directions. To avoid confusion, the following terminology is used in this paper:

Saturation sequence: the order in which a dried core is initially saturated with 100% brine and then drainaged by oil, or conversely.

Saturation direction: brine or oil saturation is increasing or decreasing. It is referred to as drainage or imbibition by rule.

Saturation cycle: a complete saturation cycle consists of a drainage displacement followed by an imbibition flooding.

Saturation history: this history includes the saturation sequence and all the saturation cycles.

EXPERIMENT

The dimensions of the sandpacks and the electrode pattern used in diate wet, and strongly oil-wet. It is obvious that as the porous medium surface becomes more oleophilic, the resistivity index increases and the hysteresis phenomenon becomes more serious.

Figures 2 and 3 demonstrate the resistivity index hysteresis behavior during two complete saturation cycles in a water-wet sandpack initially saturated 100% with brine(W-W-Wi) and a middle-wet sandpack initially saturated 100% with brine(M-W-Wi). In these two cases the second saturation cycle closely follows the first saturation cycle resistivity index. This means that one can get a unique resistivity value for a special water saturation in a definite saturation direction, drainage or imbibition, during saturation cycles through the whole flooding history. For all saturation directions at these two wettability conditions an appreciable hysteresis can not be seen when the brine saturation is larger than about 0.5.

The characteristics of the hysteresis loops are shown more clearly in Figures 4 and 5 by curves in which the data points and the coordinate grid are omitted.

Figures 6 and 7 show the data obtained from an intermediate wet sandpack initially saturated 100% with oil(M-W-Oi) and an oil-wet sandpack initially saturated 100% with oil(O-W-Oi). In these two cases, the measurements are shown in Figure 1. Sieved beach sand, Tyler mesh -65 to +100, was used as unconsolidated porous medium. The porosity of the sandpacks was 0.38. Beach sand cleaned with distilled water was strongly water-wet. The water-wet sand was made to be strongly oil-wet by treating it with a solution of 1.5 volume per cent dimethyldichlorosilane in toluene. Water-wet and oil-wet sandpacks were made of the pure water-wet and the pure oil-wet sand respectively. The intermediate wet sandpacks were made from a mixture of water-wet and oil-wet sand, 50% of weight for each.

The total flow rate was 8 ml per minute in the steady state displacement.

The details about fluids, brine and oil, instruments, experiment conditions, test set-up and resistivity measurement procedure applied in the investigation can be found elsewhere(Jun-Zhi and Lile, 1991).

RESULTS AND DISCUSSION

Resistivity Index Hysteresis

Figures 2 through 9 show that a hysteresis of resistivity index exists in all sandpacks with various wettabilities: strongly water-wet, intermeresistivity measurements were started from the lowest brine saturation because of the initial saturation with oil. The two figures show that the electrical behavior during the first drainage has its own special behavior which differs from the following imbibition and subsequent drainage. After the first drainage, the imbibition and the second drainage resistivity index follow a fixed loop track, as shown in the diagrams.

The resistivity index hysteresis loops in M-W-Oi and O-W-Oi sandpacks are drawn in Figures 8 and 9 which are matched with data in Figures 6 and 7. The loops started from the first imbibition because the first drainage resistivity index curve does not follow the loops. Note that the difference in resistivity exists between all saturation direction pairs over the whole saturation range.

To examine the hysteresis phenomenon microscopically, the *channel flow* concept(Craig, 1971) in porous media is helpful. When the brine saturation changes from decreasing to increasing, more brine is pumped into the oil-filled pores and new water channels are created. A new channel does not become a continuous electrically conductive path until it becomes a part of the interconnected network which offers a path for electricity to pass. The isolated brine makes the resistivity being higher than normal in this manner and disobeying Archie's law, and the largest gap can be found in the hysteresis loop at the lowest brine saturation end. As the brine saturation increases, the proportion of isolated brine decreases, which results in the hysteresis decrease at higher brine saturations.

First Drainage Resistivity Behavior

The most important resistivity data are the drainage resistivities which are useful for the petrophysicists for evaluating hydrocarbon migration in the reservoir occurrence and its exploitation.

Figure 10 shows the first drainage resistivity data obtained from water-wet and middle-wet sandpacks initially saturated with brine. The resistivity behavior in the first drainage may correspond to hydrocarbon migrating into a water-filled trap structure to form an oil reservoir. The two curves show that the data points break away from a straight line after a brine saturation of 0.3 in the diagram. A possible explanation for this deviation is that the tortuosity of the electrically conductive network increases during the first dranaige to an extent sufficient to affect the resistivity measurements for brine saturations lower than 0.3.

Figure 11 shows the behavior of the first drainage resistivity index on intermediate wet and oil-wet sandpacks initially saturated with oil. It is significant for logging engineers to analyse these data to guide their log interpretation because the electrical behavior in this case is analogous to that in the flushed zone of an open hole. The flushed zone is subjected to the same drainage as the first drainage in these measurements. Generally, the flushed zone resistivity is obtained after the oil formation has been drilled through. Once the formation is entered, drilling mud filtrate pushes away crude oil to some distance, i.e., the virgin oil formation undergoes a first drainage in its development history. It is interesting that the first drainage resistivity index curve has its own special behavior, see figures 6 and 7, which is different from both the drainage and the imbibition ones in the hysteresis loop. Some uncertainty may be introduced into reserve estimation of an oil formation if one uses a saturation exponent which has been derived from an unrealistic saturation direction resistivity measurement in the laboratory.

Obviously, the resistivity index curves in Figure 11 demonstrate that as brine saturation increases, more brine becomes isolated so that the slope of the curves becomes larger, i.e., the Archie's saturation exponent increases during the process.

Saturation Sequence Effect

Saturation sequence, or saturation order, is an important factor which affects the resistivity measurements in the laboratory. An unsteady desaturation will happen when the wetting phase displaces a non-wetting phase which initially saturated the core. The degree of instability is mostly affected by the core wettability. For the normal interfacial tension of laboratory fluids, the instability will increase as the preferable wetting becomes stronger, being either oil- or water-wetting. Jun-Zhi and Lile(1991) have reported this phenomenon in a water-wet Berea sandstone plug. This instability made the resistivity measurements impossible in an oil-wet Berea sample which was initially saturated 100% with brine.

Nobody can ensure that this instability can be avoided in core desaturation because it is not all cores which are 100% water-wet. Generally, special core analysis begins with test samples being saturated 100% with brine. The potential influence of the saturation order on resistivity measurements was examined on two intermediate wet sandpacks in this study.

Figures 12 and 13 show that, except for the first drainage in M-W-Oi, all data for increasing or decreasing brine saturations from M-W-Oi tests match well with the data from the M-W-Wi. Figure 14 demonstrates a rather similar style of resistivity index hysteresis loop for a different saturation order. It would be expected that there will be a unique resistivity hysteresis loop in any porous medium saturated with a mixture of brine and oil when displacing cycles are applied.

Resistivity Behavior in Middle-Wet Sandpack

In practice, few oil formations demonstrate a strong oil wetting or water wetting property. Most oil reservoir formations have moderate oil- or water-wet surfaces. Comparing resistivity behavior in a middle-wet sandpack with that in a water-wet sandpack is helpful for log analysts to apply laboratory data in log interpretation.

Figure 15 shows the difference in resistivity between the two sandpacks during drainage. In Figure 16, no difference in resistivity is observed between the two wettability cases during imbibition.

CONCLUSIONS

The following conclusions are made from this study:

1. There are resistivity index hysteresis loops in the S_w-I_R diagrams for sandpacks of varying wettability: water-wet, oil-wet, and intermediate wet, during saturation cycles under steady state flooding.

2. The stronger the oil wetting is in the porous medium, the larger hysteresis in the resistivity index is found.

3. For water-wet and middle-wet sandpacks initially saturated 100% with brine, the hysteresis loop starts from the first drainage. For middle-wet and oil-wet sandpacks initially saturated 100% with oil, the hysteresis loop starts from the first imbibition.

4. The first drainage resistivity behavior in M-W-Oi and O-W-Oi sandpacks demonstrates a special behavior that is very different from the following hysteresis loops in the same sandpack.

5. Influence of the saturation sequence on the resistivity index hysteresis loop style is not noticeable in intermediate wet sandpacks.

6. For middle-wet sandpack initially saturated 100% with brine, the drainage resistivity is larger than that in water-wet sandpack for the same saturation direction. However, their imbibition resistivity behavior is the same for the two sandpacks.

ACKNOWLEDGMENTS

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Fig. 1—Scheme of sandpack for resistivity measurements.

Fig. 2—Resistivity index hysteresis in water-wet sandpack initially saturated 100% with brine(W-W-Wi) (DRN.1=drainage 1, IMB.1 =imbibition 1, DRN.2=drainage 2, and IMB.2=imbibition 2.).

Fig. 3—Resistivity index hysteresis in middle-wet sandpack initially saturated 100% with brine(M-W-Wi).

Fig. 4—Resistivity index hysteresis loop in W-W-Wi sandpack.

Fig. 5—Resistivity index hysteresis loop in M-W-Wi sandpack.

Fig. 6—Resistivity index hysteresis in middle-wet sandpack initially saturated 100% with oil(M-W-Oi).

Fig. 7—Resistivity index hysteresis in oil-wet sandpack initially saturated 100% with oil(O-W-Oi) (DRN.3=drainage 3).

Fig. 8—Resistivity index hysteresis loop in M-W-Oi sandpack.

Fig. 9—Resistivity index hysteresis loop in O-W-Oi sandpack.

Fig. 10—First drainage resistivity index in W-W-Wi and M-W–Wi sandpacks.

Fig. 11—First drainage resistivity index in M-W-Oi and O-W–Oi sandpacks.

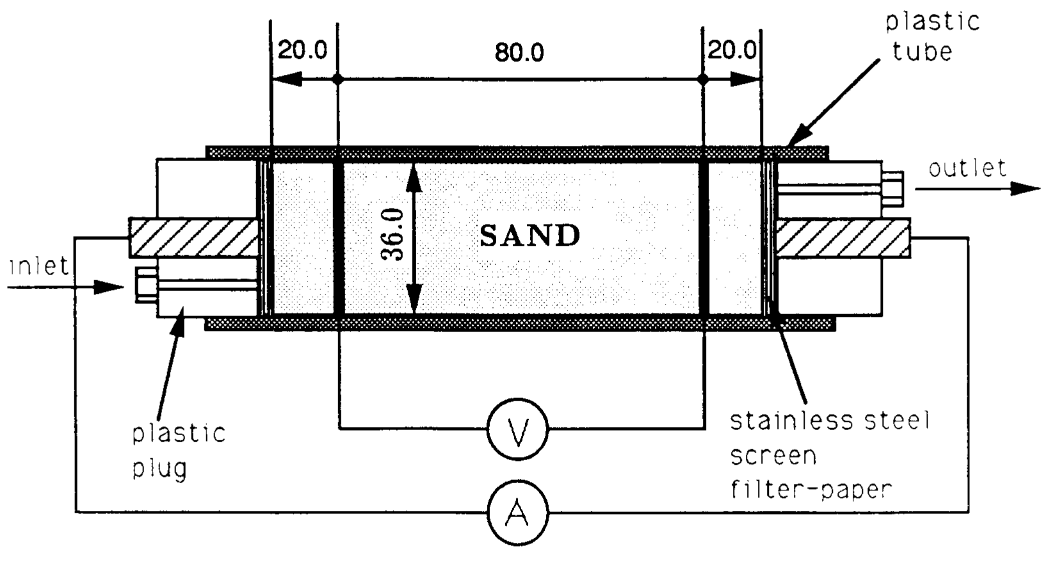
Fig. 12—Resistivity index matching for different saturation sequence on middle-wet sandpacks when brine saturation decreasing.

Fig. 13—Resistivity index matching for different saturation sequence on middle-wet sandpacks when brine saturation increasing.

Fig. 14—Resistivity index loop matching for different saturation sequence on middle-wet sandpacks when saturation cycling.

Fig. 15—Resistivity index behavior in W-W-Wi and M-W-Wi sandpacks during drainaging.

Fig. 16—Resistivity index behavior in W-W-Wi and M-W-Wi sandpacks during imbibing.



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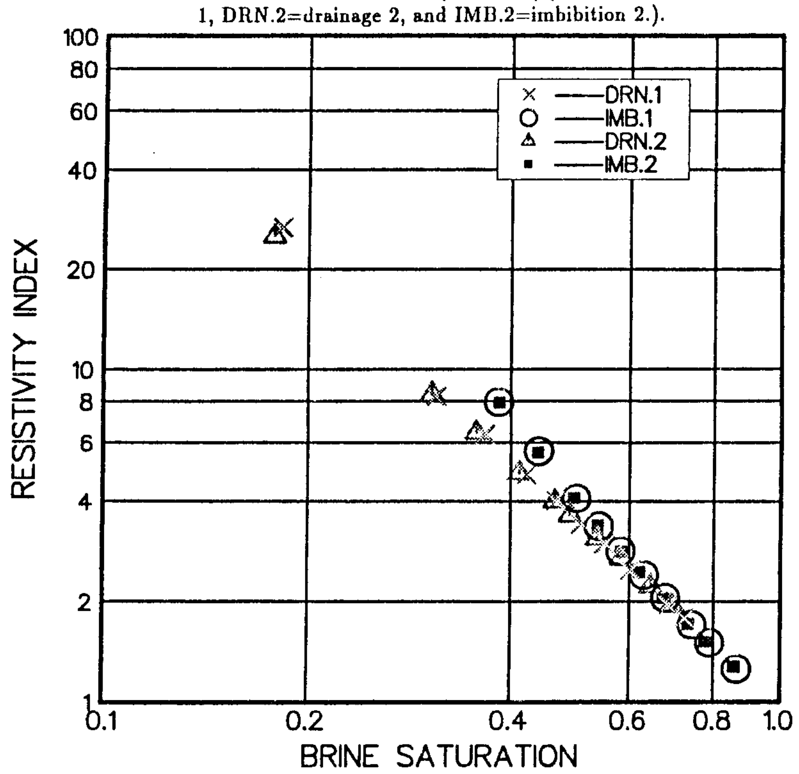

Fig. 3—Resistivity index hysteresis in middle-wet sandpack initially saturated 100% with brine(M-W-Wi).

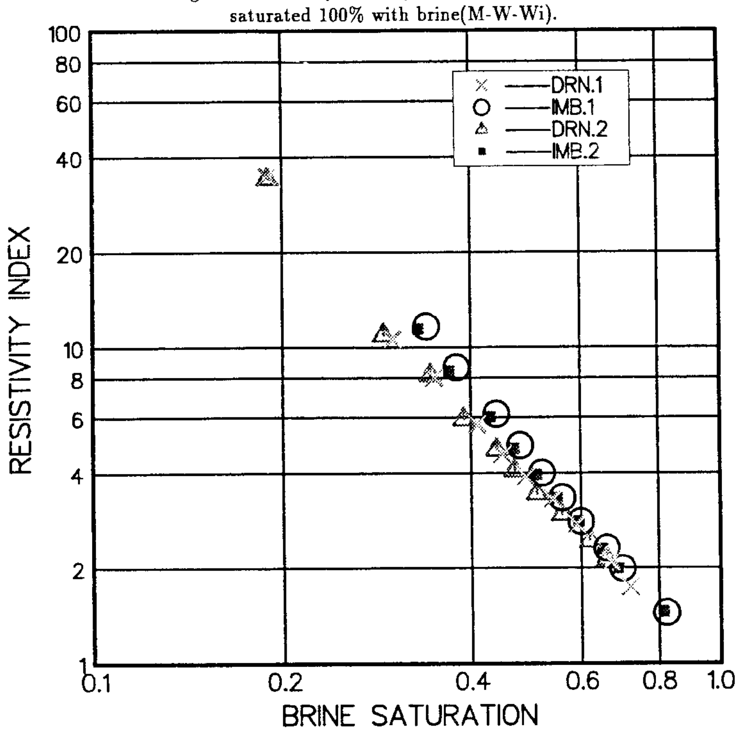

Fig. 4—Resistivity index hysteresis loop in W-W-Wi sandpack

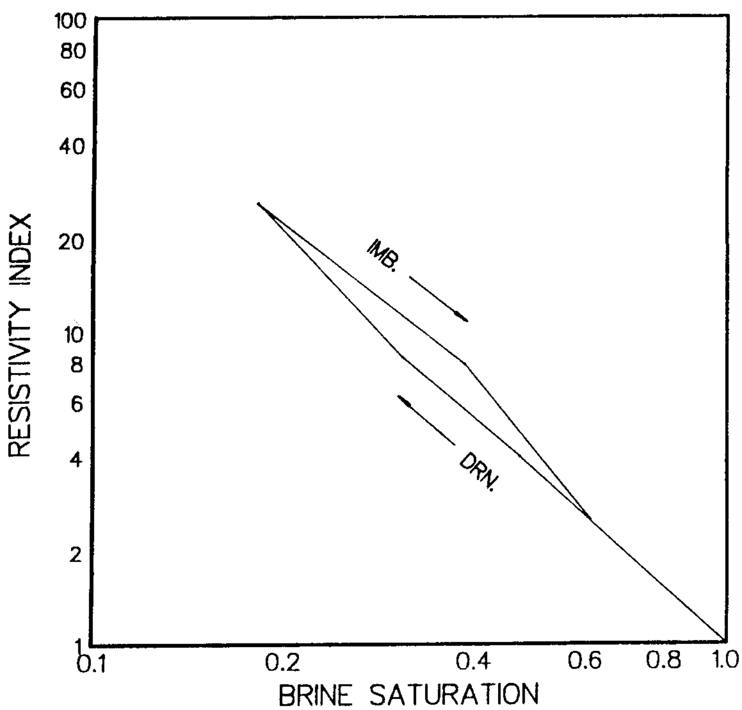

Fig. 5—Resistivity index hysteresis loop in M-W-Wi sandpack

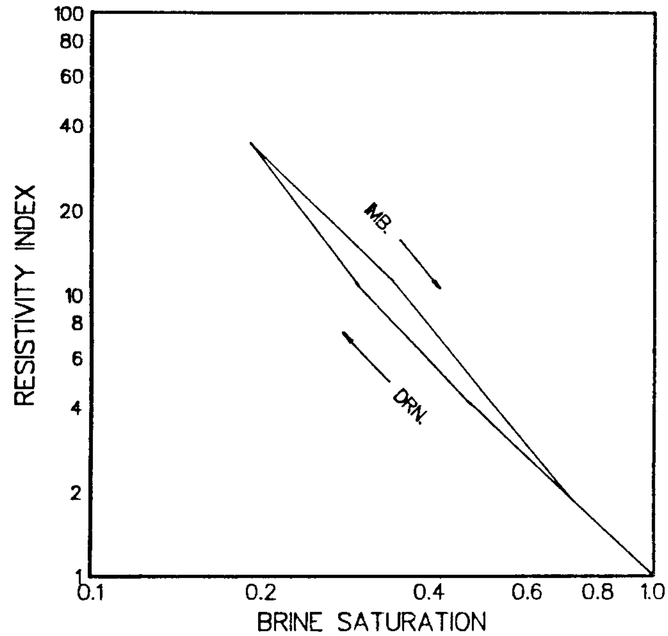

Fig. 6—Resistivity index hysteresis in middle-wet sandpack initially saturated 100% with oil(M-W-Oi).

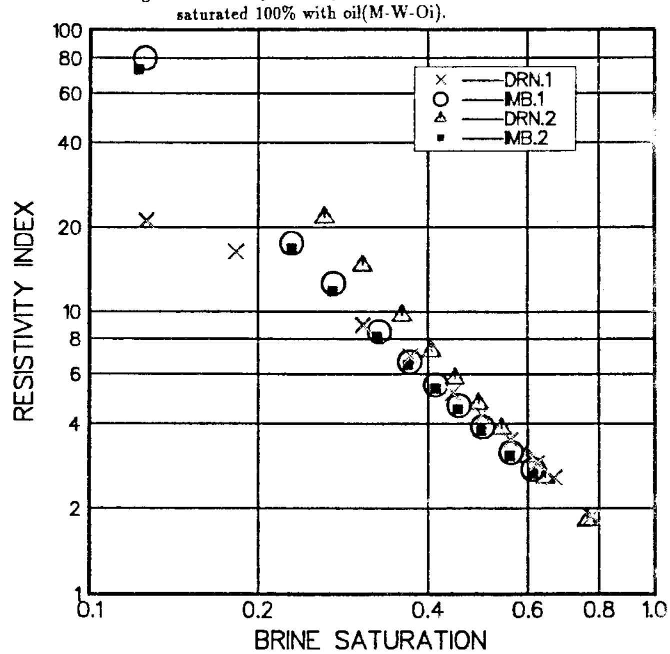

Fig. 7—Resistivity index hysteresis in oil-wet sandpack initially saturated 100% with oil(O-W-Oi) (DRN.3=drainage 3).

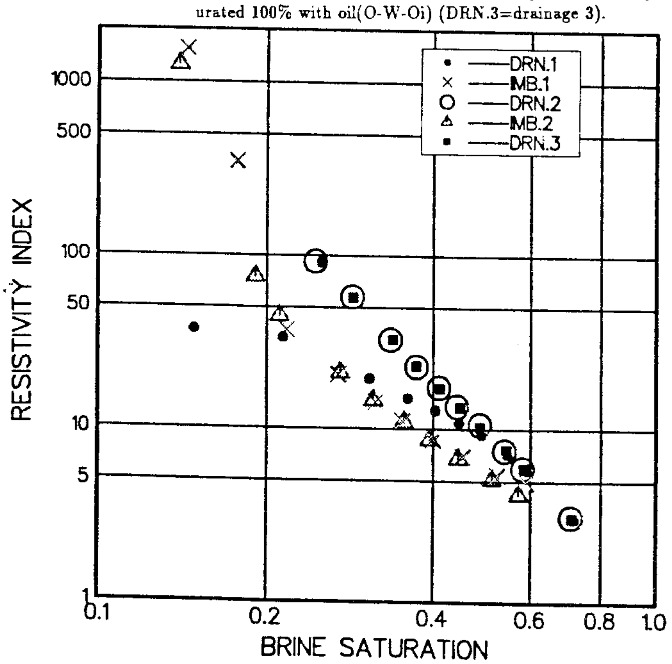

Fig. 8—Resistivity index hysteresis loop in M-W-Oi sandpack

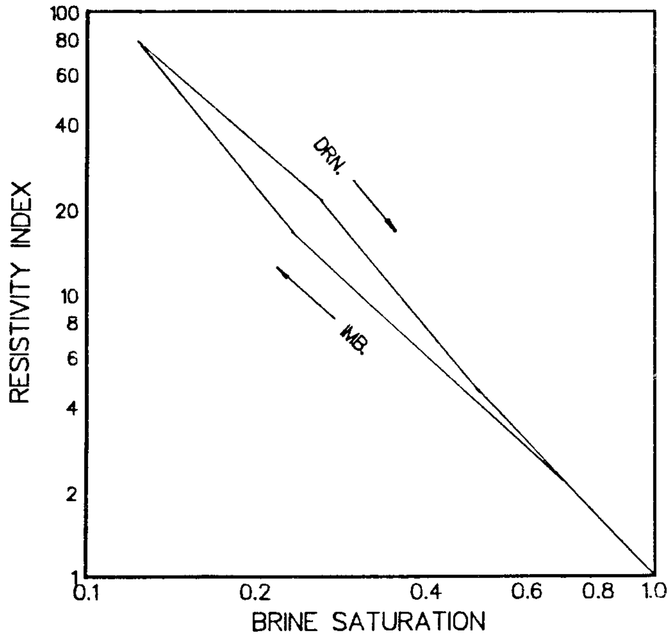

Fig. 9—Resistivity index hysteresis loop in O-W-Oi sandpack

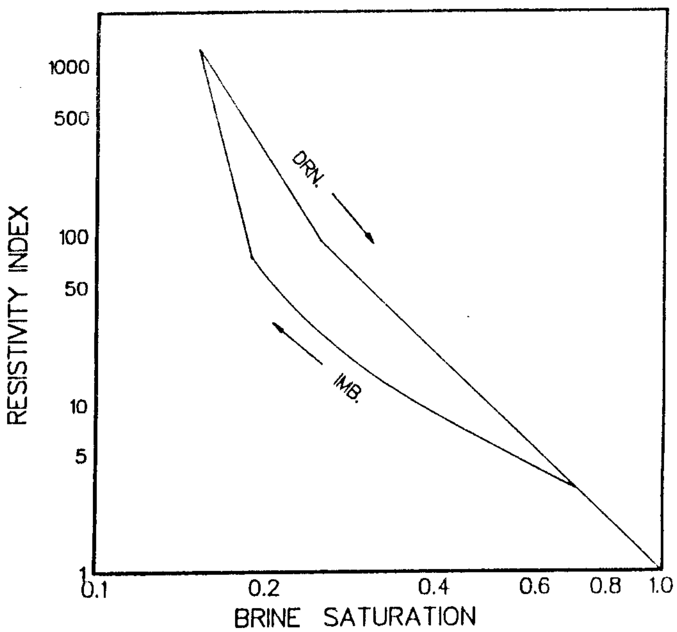

Fig. 10—First drainage resistivity index in W-W-Wi and M-W-Wi sandpacks.

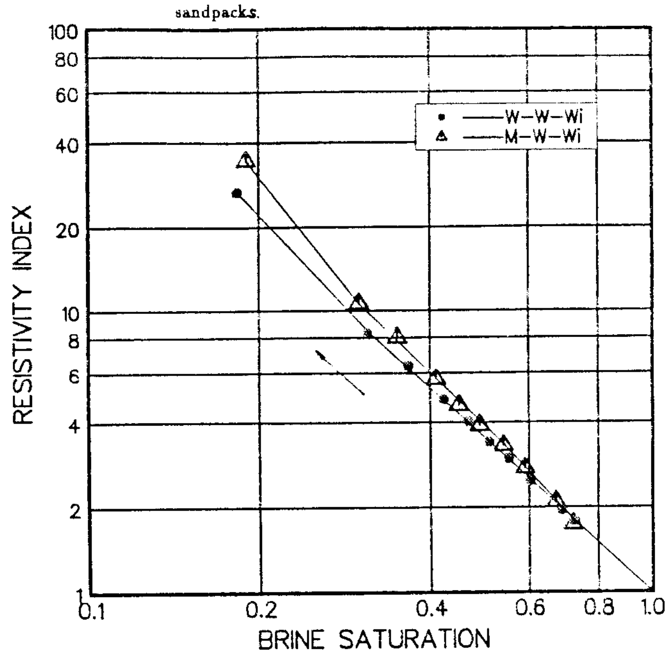

Fig. 11—First drainage resistivity index in M-W-Oi and O-W-Oi sandpacks.

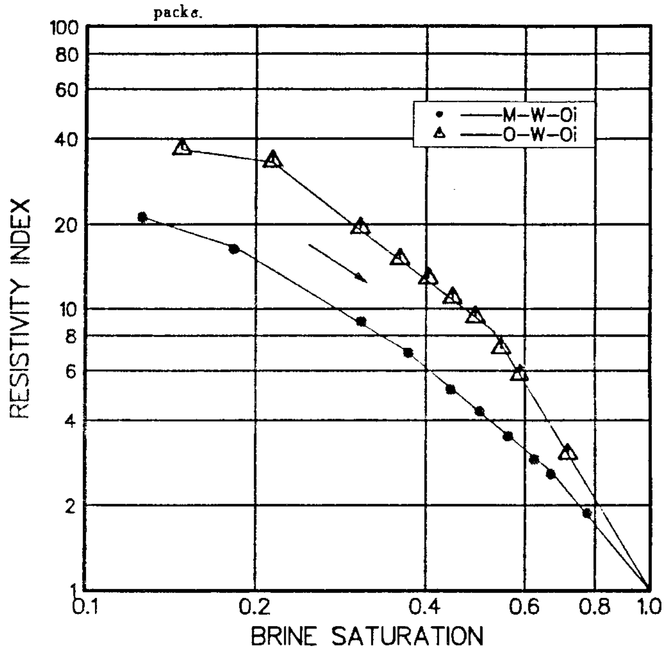

Fig. 12—Resistivity index matching for different saturation sequence on middle-wet sandpacks when brine saturation decreasing.

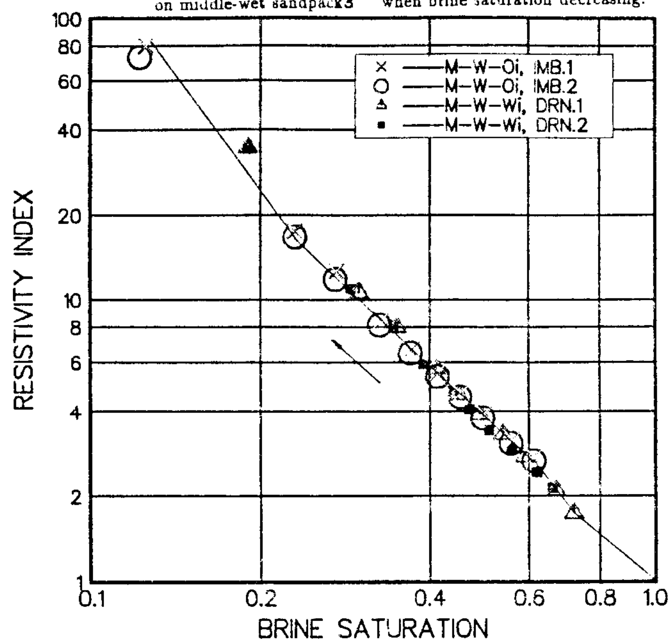

Fig. 13—Resistivity index matching for different saturation sequence on middle-wet sandpacks when brine saturation increasing.

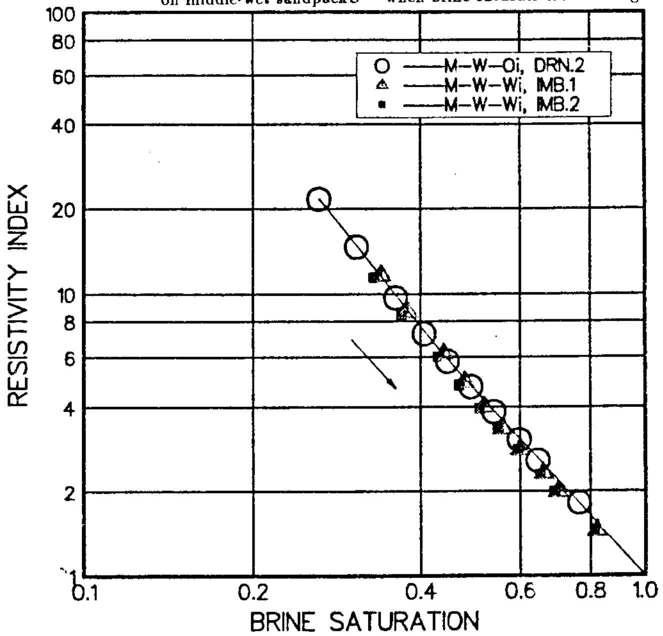

Fig. 14—Resistivity index loop matching for different saturation sequence on middle-wet sandpacks when saturation cycling.

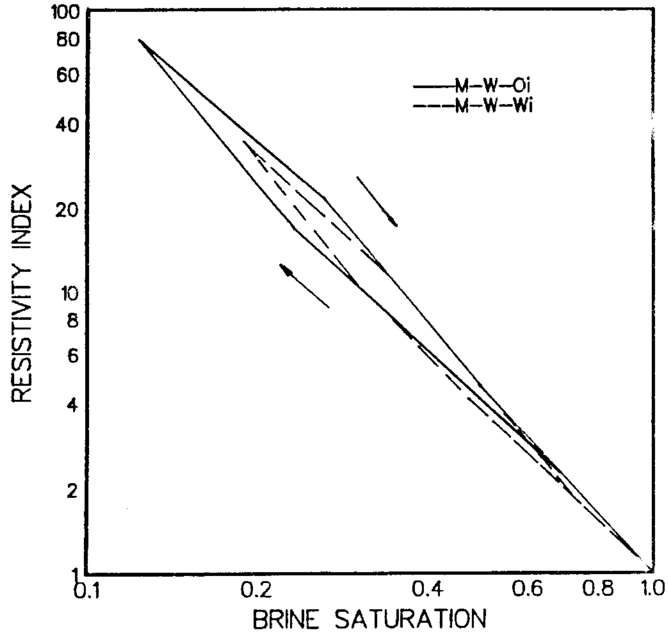

Fig. 15—Resistivity index behavior in W-W-Wi and M-W-Wi sandpacks during drainaging.

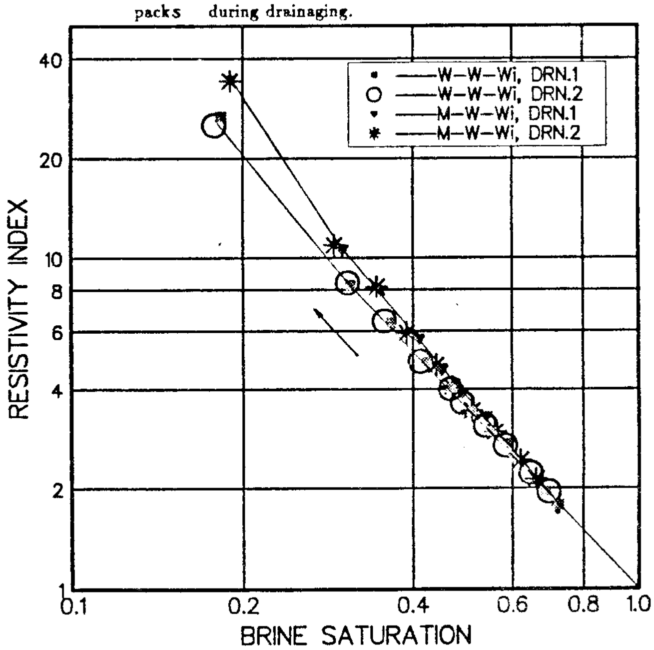

Fig. 16—Resistivity index behavior in W-W-Wi and M-W-Wi sandpacks during imbibing.