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Ever see a water flood?

A capillary micromodel has been used to study fluid distributions under various wettability conditions, and to find the effects of wettability on water-oil displacement. This article gives the results of these studies, with detailed photographs of the events occurring within the model.

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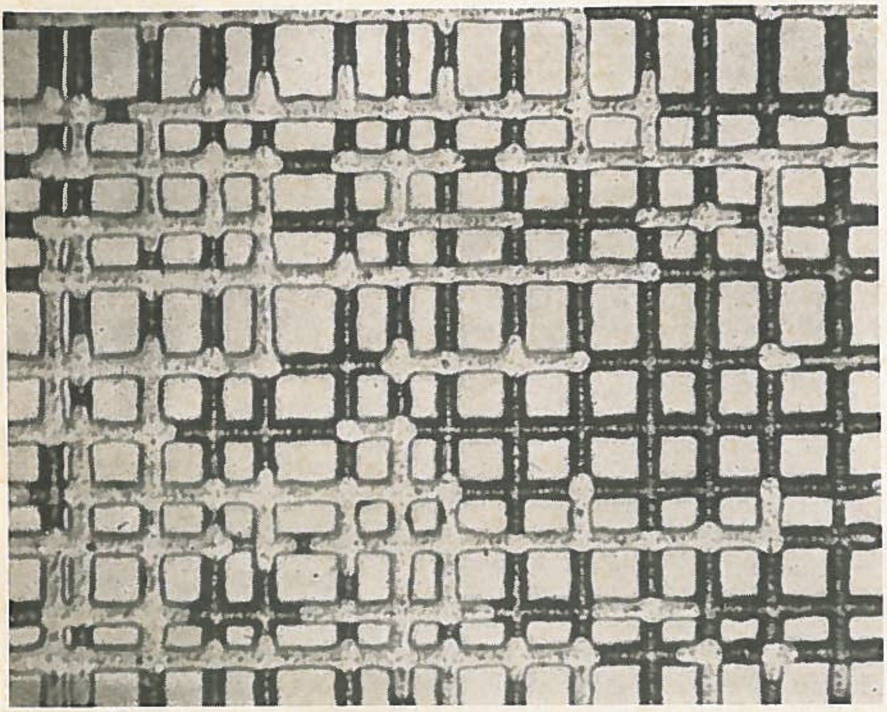


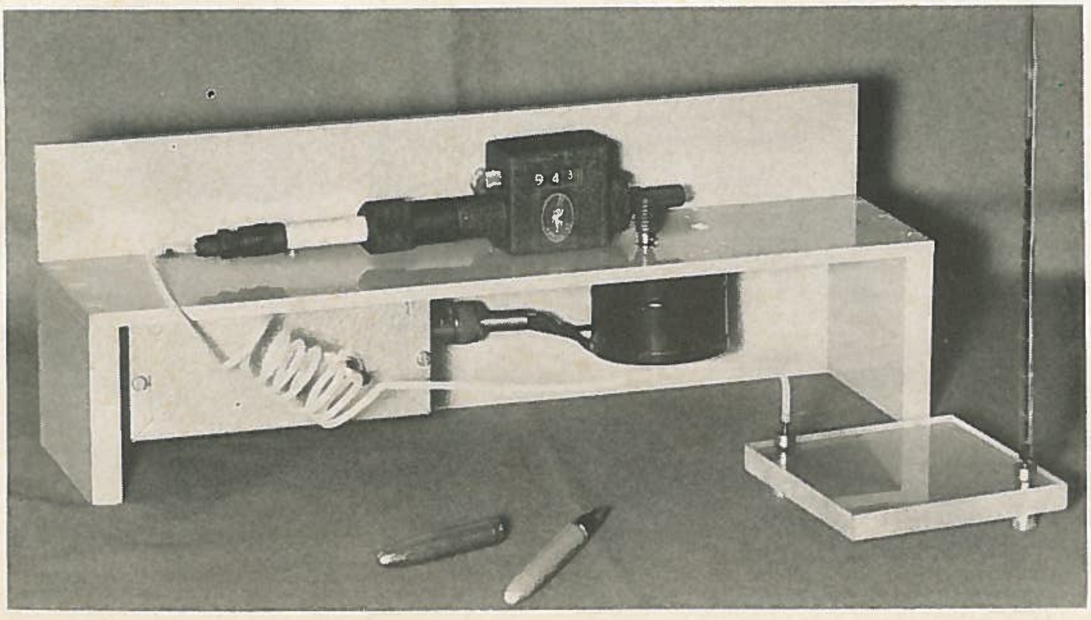
CAPILLARY network in a portion of a micromodel. Fig. 1.

WHAT WE KNOW about multiphase flow through a porous medium is based in part on what we have seen in simple systems such as single capillaries and capilliary doublets.[1,2,3,4]

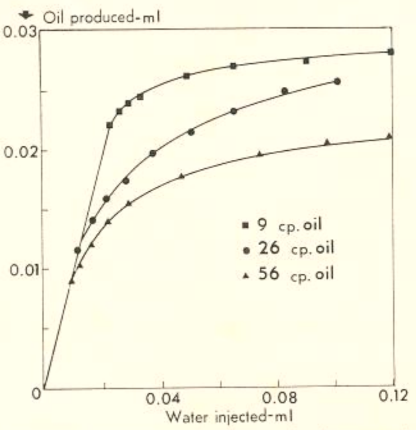
Visual studies in systems of more complex geometry have been made by Chatenever and coworkers.[5,6] They used synthetic flow models consisting of single layers of glass beads between two transparent plates. But it is hard to make detailed observations of interface movements.

To improve on these observations, a capillary micromodel was developed in which fluid movement can be seen in detail. The model possesses many of the over-all characteristics of a reservoir rock, and permits observation of fluid movement from pore to pore.

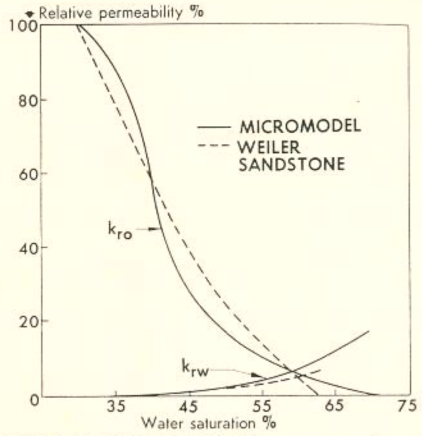
The capillary micromodel is a



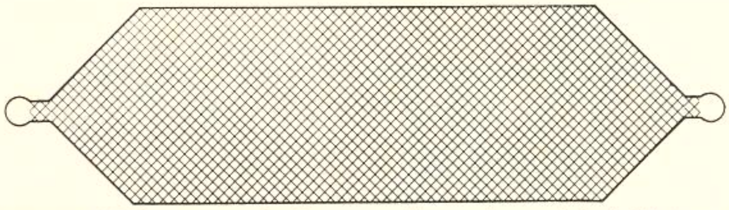
MICROMODEL and auxiliary equipment, including a microburet. Fig. 2.



WATER-FLOOD behavior of the capillary micromodel. Fig. 3.



RELATIVE-PERMEABILITY curves from studies of a capillary micromodel and a natural sandstone. Fig. 5.



LINEAR FLOW is approached in a capillary micromodel of this type. Fig. 4.

network of interconnecting capillary grooves etched into a flat glass plate. A low-magnification view of part of a micromodel showing oil (transparent) and water (dark) is shown in Fig. 1. A typical model contains about 350 horizontal and 350 vertical capillary grooves intersecting at right angles. If each intersection is considered to represent the end of a pore, a model of this size contains the equivalent of about 250,000 individual pores. In cross-section, each capillary is shaped like a shallow V, from 0.0025 to 0.005 in. wide and from 0.008 to 0.0015 in. in depth. The V-shaped capillary grooves taper off to thin wedges on either side, simulating the grain-to-grain contacts of many natural rocks.

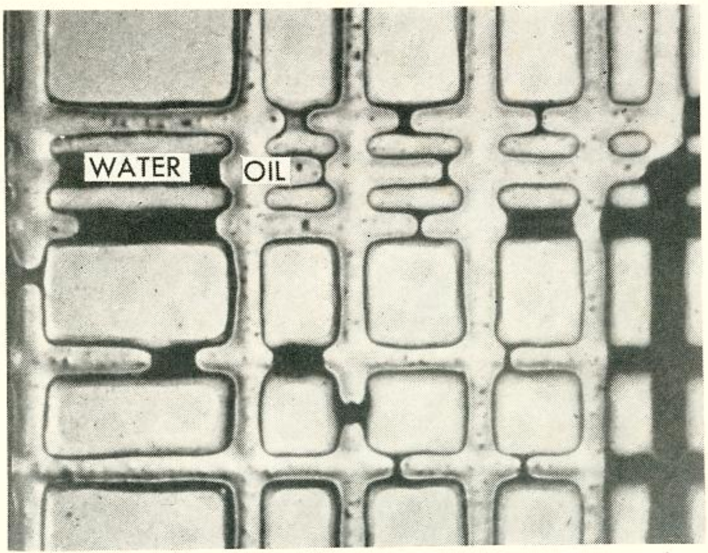
The capillary network is made by coating a glass plate with a thin layer of wax, scribing lines through the wax with a stylus, and then contacting the exposed glass surface with hydrofluoric acid for 1 to 3 minutes. After the wax is removed from the glass plate, a second plate is fused to the first in an annealing oven. Holes which penetrate the capillary network are then drilled through the fused glass plate in any desired pattern. The pore volume of a representative model is about 0.1 ml. The models will hold up to 300 psi. internal pressure without fracturing.

A micromodel and the experimental setup used in tests are shown in Fig. 2. A motor-driven microburet is used as a positive-displacement pump for injecting controlled volumes of fluids. Produced fluid is measured in a capillary pipet attached to producing wells in the model. With this arrangement it is possible to get recovery data during a test with an error of less than 3% of pore volume.

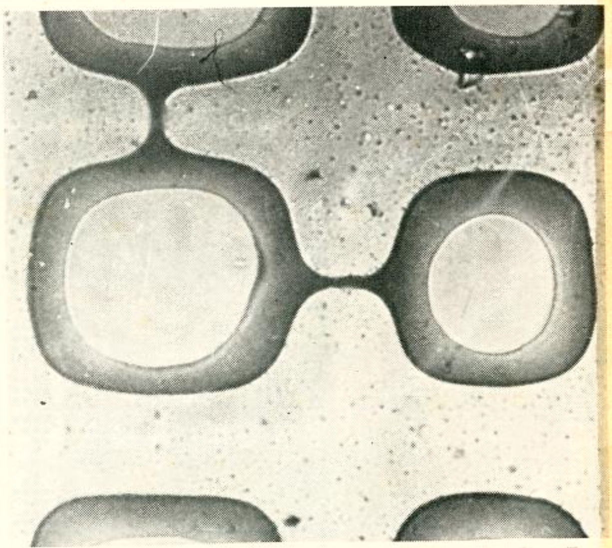
Water-flood behavior curves of the micromodel, Fig. 3, were obtained in floods where flow was essentially linear, Fig. 4. From data such as these the water-oil relative-permeability characteristics of the micromodel can be calculated.[7] The calculated relative-permeability curves are shown in Fig. 5 along with the relative permeability curves obtained on a sample of Weiler sandstone. The relative-permeability functions of the micromodel are quite similar to those of the sandstone core, although the residual-oil saturation in the micromodel is about 5% of pore volume less than that of the Weiler core. Since the behavior of the micromodel is similar to that of the rock, it is probable that the capillary micromodel is a reasonable representation of a natural porous medium.

Static Fluid Distributions Strongly Water-Wet Systems

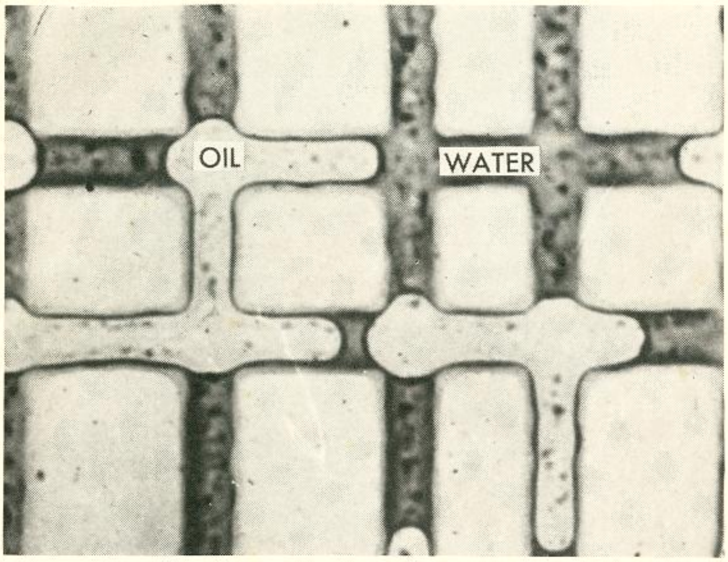
Distribution of connate water in the capillary micromodel is shown in Fig. 6. Connate-water saturation



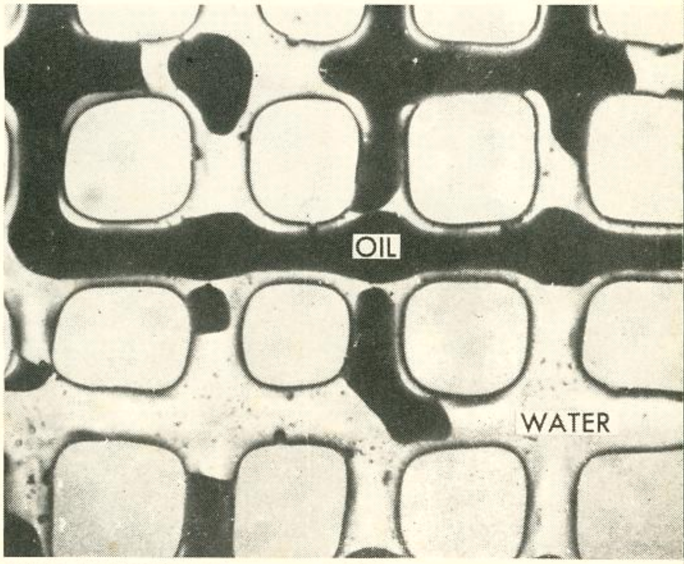
CONNATE-WATER distribution in a strongly water-wet micromodel. Fig. 6.



PENDULAR RINGS and slugs of connate water. Fig. 7.



RESIDUAL OIL in a strongly water-wet micromodel. Fig. 8.



FLUID DISTRIBUTION in a slightly water-wet micromodel. Fig. 9.

was established by first saturating the model with water, then flushing with several pore volumes of oil. The water is dark (an inorganic dye had been added) and the oil, which is a refined white oil, is transparent.

Much of the connate water is located at the edges of the V-shaped capillary grooves. This configuration is analogous to the pendular rings observed by Chatenever.[5] Connate water is also found as "slugs" or thin "membranes" which stretch across the pores but do not completely fill them. Fig. 7 is an enlarged photograph showing pendular rings and two of the water slugs. The capillary grooves in this case are wide but shallow and, as a consequence, the pendular rings of water extend for a considerable distance away from the walls of the pores.

Distribution of water and oil at residual-oil saturations in a linear micromodel is shown in Fig. 8. Although this view covers an area of only about 0.004 sq. in., it is representative of the fluid distributions over the entire model. Continuous residual-oil pockets usually extend over very short distances. In most cases the pockets occupy only three or four pores, although infrequently the residual-oil pockets extend over 20 to 30 pores. Very little of the residual oil is in the form of free spherical droplets. These observations are similar to those of Chatenever.[5]

Slightly Water-Wet Systems

There has been considerable speculation during the past few years about the true nature of a slightly water-wet surface. By analogy with work on single crystal faces and in capillary tubes, a slightly water-wet porous medium is often visualized as a medium whose surface has been uniformly altered to increase the angle of contact of the water-oil interface at the rock surface. The model is visualized as having a surface of essentially uniform wettability.

The second explanation of wettability variation considers that the rock surface is heterogeneous. As a consequence of surface heterogeneities, the "wettability" of the rock is a localized characteristic varying from point to point. This explanation forms the basis for the work of Fatt[8] and Holbrook.[9] It is often termed the "Dalmation" or "spotted" wettability concept. Visual evidence of the validity of the concept is shown in Fig. 9. The model was made slightly water-wet by first saturating it with brine and then flushing to connate water with a selected crude oil, after which the fluids were allowed to remain in contact with the model for several hours.

Examination of individual contact angles shows that some areas in the model are strongly water-wet, whereas other areas are strongly oil-wet. In this condition the waterflood behavior and imbibition behavior of the model are similar to those of a natural, slightly water-wet rock sample.[10] Thus, rock surfaces of intermediate wettability are probably mixtures of strongly water-wet and strongly oil-wet surfaces.

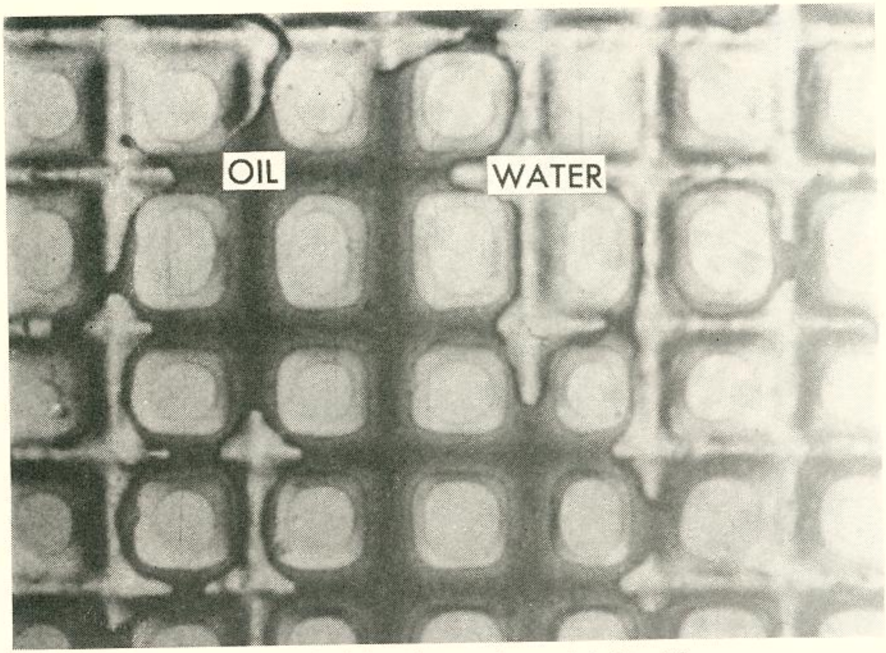
Effect of oil-wet surfaces on the size of residual-oil formations is shown in Fig. 10. Residual-oil pockets are usually larger when the micromodel is slightly water-wet than when it is strongly water-wet. However, in either case residual-oil pockets usually extend over only a few pore diameters.

Mechanisms of Water-Oil Displacement

With the capillary micromodel three principal mechanisms of flow have been observed in water-oil displacements. These are:

- Channel flow of oil and water.
- Flow of water through pendular rings into water slugs.
- Flow of oil through oil filaments which connect two or more oil-filled pores.

Channel flow. Oil is displaced primarily by channel flow, both in strongly water-wet and in intermediate wettability systems. In channel flow the water-oil interface moves essentially as a piston. Each fluid moves through its own network of interconnected pores and both flowing phases remain continuous throughout the entire period of oil production. Whenever the oil phase becomes discontinuous, it will remain trapped as residual oil. No migration of the trapped oil pockets can be induced until the water-injection rate is drastically increased. At very high flow rates, however, the oil can be made to break up into isolated slugs or globules, and in this state part or all of the residual oil can be produced. These observa-



RESIDUAL-OIL POCKET in a slightly oil-wet micromodel. Fig. 10.

tions are consistent with the findings of Chatenever and Calhoun.[5]

Flow of water through pendular rings. As mentioned earlier, some of the connate water in a strongly water-wet system is found as slugs which stretch across pores but do not fill them completely. The water slugs connect two pendular rings of water. It has been observed that water can flow through the pendular rings, causing the water slugs to grow. This is another mechanism for the transport of water in a strongly water-wet system. The mechanism is illustrated in Fig. 11. Fig. 11a shows the advancing water front just before the oil-water interface touches the wall of a pore at point A.

Fig. 11b shows the advancing water after it has contacted the opposite wall of the pore and has imbibed a short distance into pore 1. It can be seen that the water slugs B, C, and D have become slightly enlarged at this stage. It is apparent that the pendular ring of water, E, has served as a flow line between the main water front and the water slugs.

Fig. 11c shows that the size of the water slugs has greatly increased before the water advances into pores 2 and 3. The rate of growth of the water slugs is indicated by the fact than only 2 seconds elapsed between the time photographs a and c were taken. This is conclusive evidence of the mobility of the water in the pendular rings. This mechanism for water movement tends to smooth the water front during a flood, thereby increasing the efficiency of the process.

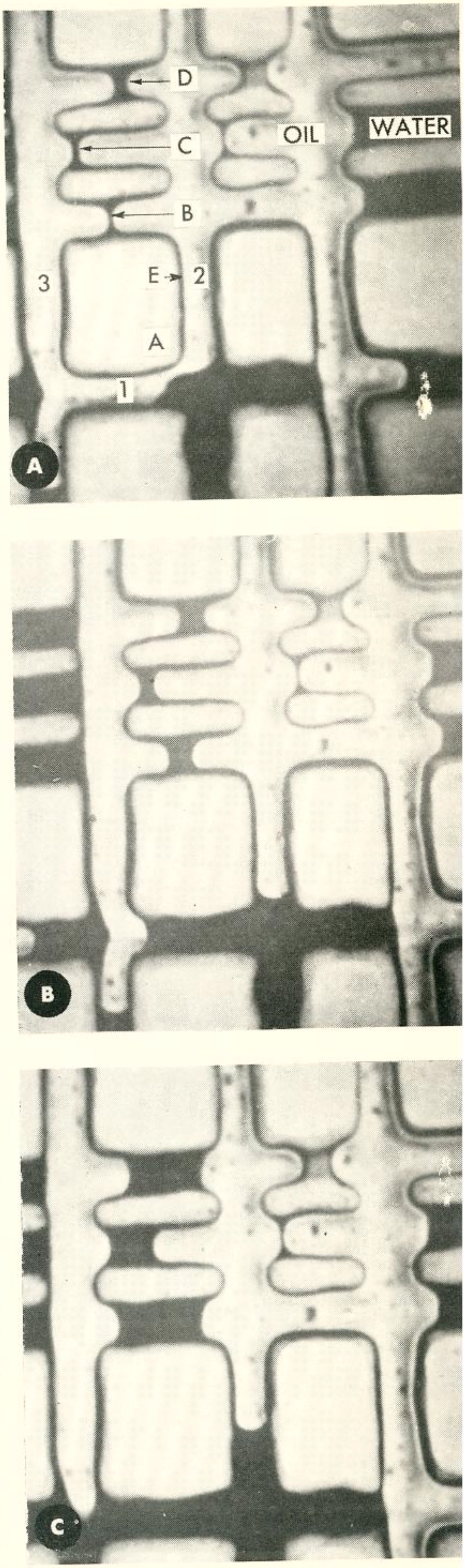
Filament flow of oil. Frequently, in systems of intermediate wettability, oil in pores behind the water front is connected to oil in pores ahead of the water front by thin filaments of oil, Fig. 12. It is probable that the filaments form because parts of the model are oil-wet and, thus, a continuous film of oil "sticks" to one pore wall. Studies using various oils, including refined white oils, indicate that viscous interfacial films are not necessary for filament formation.

As the water flood progresses, oil will flow through the filament and "drain" from the partially trapped oil pocket. Eventually, the filament will rupture and a droplet of residual oil will form. Photographs illustrating this sequence of events are shown in Figs. 12a, b, and c.

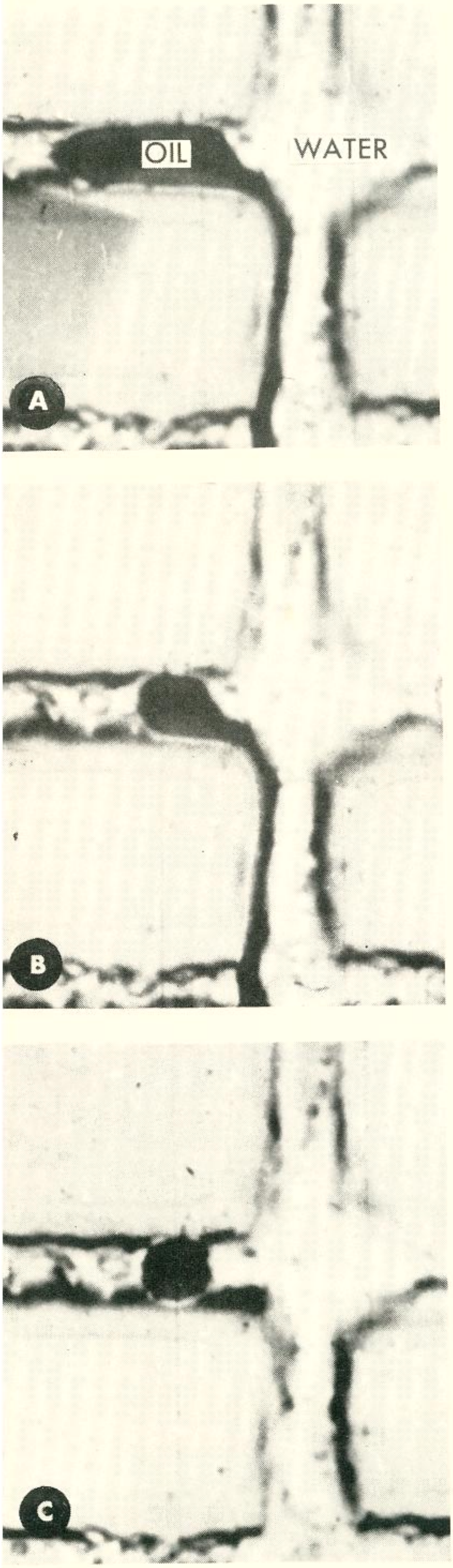
Oil cannot move over long distances by filament flow. However, observations indicate that in slightly water-wet models, moderate volumes of oil move in this way. Filament flow does not occur in strongly water-wet micromodels.

Effect of Wettability on Sweep Efficiency

Sweep efficiency in a water flood of a slightly water-wet micromodel is much lower than that obtained in a strongly water-wet model. Decreased efficiency under slightly



GROWTH OF WATER SLUGS in a strongly water-wet system. Fig. 11.



FILAMENT FLOW of oil in a slightly water-wet micromodel. Fig. 12.

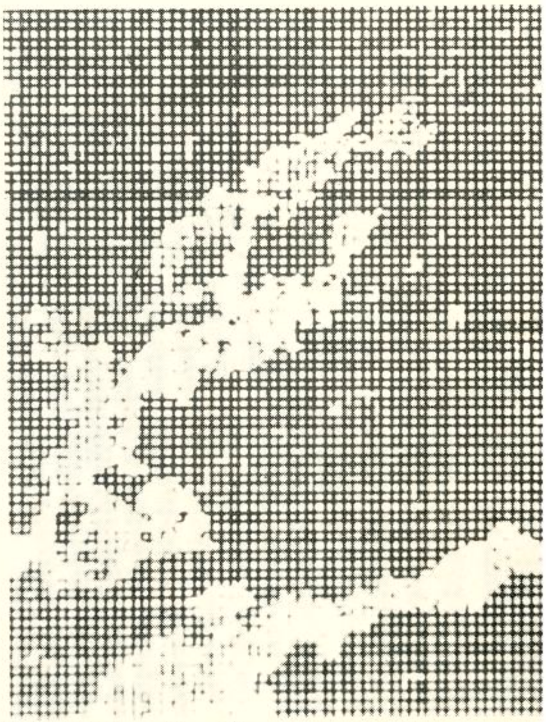
water-wet conditions results from the formation and growth of water "fingers." The initial phase of finger development is shown in Fig. 13. This photograph was taken after the injection of about 2% of pore volume of water in a micromodel containing a Middle East crude oil and connate water. The oil-water viscosity ratio is about 8 to 1. The model in this case represents one-quarter of a five-spot flood pattern. The injection well is at the lower left; the producing well is at the upper right. The length of a finger increases much more rapidly than does its width. This is because water imbibition forces are weak and viscous forces, which favor finger development at this viscosity ratio, are dominant. This effect is further illustrated in Fig. 14, which is an enlarged view of two of the fingers.

Development and growth of water fingers result in an early water breakthrough. Fig. 15 shows that, at water breakthrough, large areas of the slightly water-wet model have not been swept. Thus, to produce the slightly water-wet model to residual oil requires the injection and production of several pore volumes of water.

Areal coverage in a flood of a strongly water-wet model is much more favorable than that shown above. This is because strong capillary forces pull water from the fingers into areas where oil has been bypassed. As a result, finger formation is inhibited and finger growth is retarded.

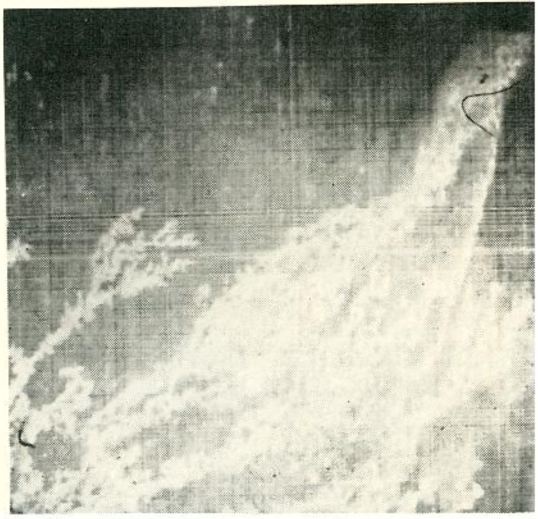
Figs. 16 and 17 illustrate this point. These photographs were taken during a water flood of a strongly water-wet model containing an 8-cp. white oil. The viscosity ratio was 8 to 1, the same as in the slightly water-wet flood. The model used in this test contained two areas of high permeability (the dotted areas in Fig. 16) which were not present in the model used in the slightly water-wet flood. The high-permeability areas were introduced to encourage finger formation and more clearly illustrate the benefits of strong imbibition forces on areal coverage. Fig. 16 shows the model after the injection of 6% of pore volume of water. (The water is the dark phase in the photographs.) At this stage a large water finger has formed in one of the high-permeability areas. Otherwise, however, the model is

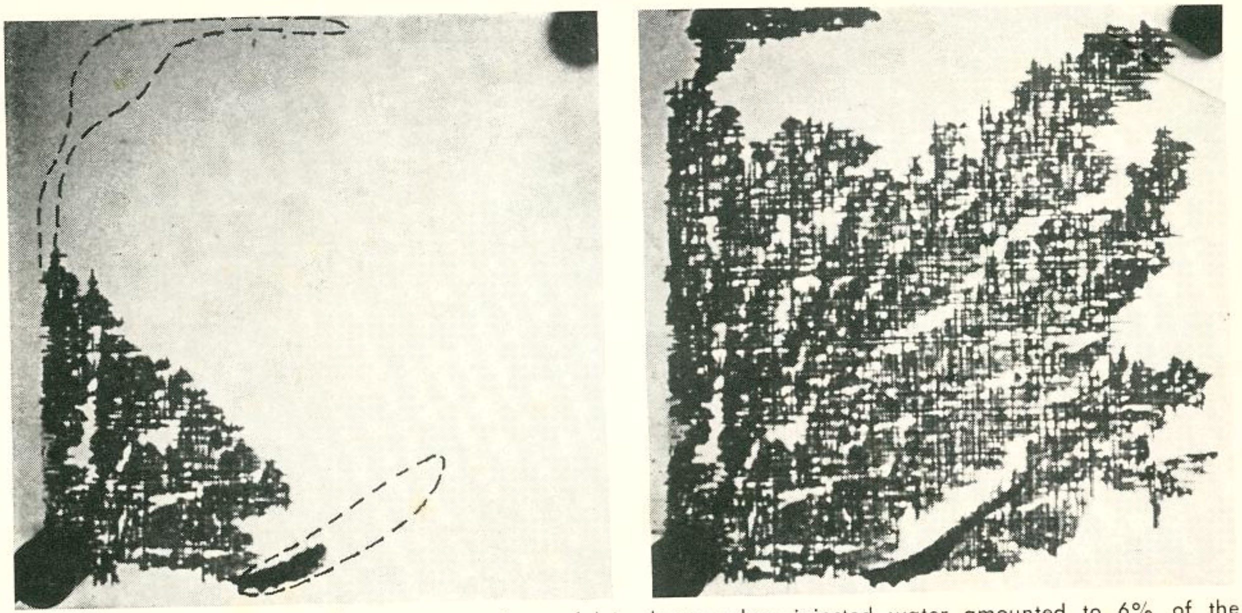
FINGER FORMATION in a water flood of a slightly water-wet micromodel. Fig. 13.



FINGERS from Fig. 13 are enlarged in this view. Fig. 14.

AREAL COVERAGE at water breakthrough in a slightly water-wet micromodel. Fig. 15.





AREAL COVERAGE in a strongly water-wet micromodel is shown when injected water amounted to 6% of the pore volume, Fig. 16, left, and at water breakthrough, Fig. 17, right. The dotted lines of Fig. 16 enclose two high-permeability areas.

being very efficiently swept by water.

Coverage at water breakthrough is shown in Fig. 17. Note that the finger shown in Fig. 16 has disappeared, although some oil near this finger has been trapped and cannot be recovered. Water has now fingered through the second high-permeability area and, also, through the center of the pattern. For the most part, however, efficient coverage of the model has been obtained at water breakthrough.

It is apparent that reduced water-wetness of the reservoir rock will result in decreased flooding efficiency, not only because of an unfavorable effect on relative permeabilities, but also because areal coverage is severely reduced.

Acknowledgment

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The authors conclude . . .

1. The similarity between the relative-permeability functions of the micromodel and those of natural rock indicates that the model is a reasonable representation of natural porous media. Comparison of the water-flood performance of the micromodel and rocks under various wettability conditions supports this general conclusion.

2. Reservoir rock surfaces of intermediate wettability are probably mixtures of strongly water-wet and strongly oil-wet surfaces. The oil-wet surfaces promote water fingering and reduce the efficiency of a water-oil displacement process:

3. Channel flow of oil and water is the principal flow mechanism in both strongly water-wet and intermediate wettability systems.

4. Flow of water through pendular rings is a second mechanism for water movement in strongly water-wet media. This type of water movement helps to smooth the flood front in a water flood, reducing the severity of water fingering.

5. Noticeable volumes of oil move through oil filaments in rocks of intermediate wettability.

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Film available

Some of the figures in this article are clipped from a motion picture that Jersey engineers have made of the micromodel in action. This film is available for loan by writing to Dr. R. N. Meinert, Jersey Production Research Co., 1133 North Lewis, Tulsa, Okla.