Clay Content and Capillary Behavior of Wyoming Reservoir Sands

OREN C. BAPTIST
ELIOT J. WHITE
MEMBERS AIME

U. S. BUREAU OF MINES
LARAMIE, WYO.

T. N. 460

ABSTRACT

Samples of four reservoir sands having different degrees of water sensitivity were subjected to several laboratory tests to determine differences in capillary behavior attributable to clay-mineral effects. The degree of water sensitivity was estimated by the difference between gas and water permeability. Unsaturated pore volumes determined with mercury injection were comparable to irreducible water saturations determined with the semipermeable barrier method only for the non-sensitive sands that contained small amounts of non-swelling clay minerals. Irreducible saturations were independent of salinity of the water, which suggests that most residual water is adsorbed as a film over solid surfaces and that internal retention by clay minerals is relatively insignificant. The water-sensitive sands imbibed water to higher saturations than did non-sensitive sands, and this result is believed to be a combination of the effects of clay minerals and preferential wettability; however, the relative importance of each of these effects is not determinable. Thus it is concluded that the semipermeable barrier method is the best of the laboratory methods used for estimating formation water saturations in the sands studied.

INTRODUCTION

This investigation is a continuation of studies of the role of clay minerals in petroleum production in the Rocky Mountain area. Previous work has shown large differences in gas and water permeability in numerous reservoir sands; these water-sensitivity effects observed in the laboratory have been correlated with well behavior in the field, and the degree of water sensitivity imparted to reservoirs by the various clay minerals has been determined.[1,2]

The effect of interstitial clay minerals on formation water[3] saturations is not so well known. It has been reported that formation water saturations probably are higher in clayey than clean sands,[4] but this effect has not been evaluated in the laboratory, and the relative effect of the various types of clay minerals on formation water saturation has not been determined.

The clay-mineral groups of most importance to this study and to petroleum production in general are kaolinite, illite, and montmorillonite. The minute layers of montmorillonite are loosely bound to one another so that water enters between them, causing great expansion of the particles. Kaolinite and illite do not exhibit interlayer hydration, but they do immobilize considerable amounts of water owing to their large surface areas, which are of the order of 15 to 97 m²/gm of clay.[5]

The four Wyoming sands used in this study were selected to represent a wide range of water sensitivities. These sands, with the number of wells and fields from which the samples were obtained, are: Second Frontier, five wells in two fields; Newcastle, six wells in one field; Tensleep, two wells in two fields; and Lower Muddy, five wells in one field.

EXPERIMENTAL METHODS AND PROCEDURES

Water-displacement data were obtained by the semipermeable barrier method,[6] using both fresh water and brines having either 16,500 ppm sodium chloride or calcium chloride. A displacement pressure of 35 psi was found to be sufficient to obtain the practical irreducible water or brine saturation (IWS, IBS) in most samples.

Mercury-injection data were obtained with equipment and procedures similar to those described by Purcell.[7] Exceedingly high pressures are required to attain complete mercury saturation by this method; however, since saturations in most samples change very little with large pressure increases above 1,000 psia, the maximum pressure used was 1,400 psia. To facilitate comparison of mercury-injection and water-displacement results, it is convenient to express mercury-injection data in terms of unsaturated pore volume. The abbreviation, $(100 - S_{Hg})_{min}$, is used to denote the pore volume unsaturated by mercury at 1,400 psia injection pressure.

Gas permeabilities, k_l, were determined by the method proposed by Klinkenberg.[8] Methods of determining types and amounts of clay minerals by X-ray diffraction analyses, as well as methods of determining water permeability, have been described previously.[1]

The imbibition characteristics of

Original manuscript received in Society of Petroleum Engineers office on May 15, 1957. Revised manuscript received Nov. 8, 1957. Paper presented at Third Annual Joint Meeting of Rocky Mountain Petroleum Sections in Billings, Mont., May 23-24, 1957.

[1]References given at end of paper.

the sands were tested by placing the dry plug samples upright in a dish containing ⅛ in. of water. The samples were removed and weighed at timed intervals and the saturations calculated until the maximum saturation had been reached. The samples were then dried and the experiment repeated, using kerosene as the saturant.

EXPERIMENTAL RESULTS AND CORRELATIONS

The relative amounts of clay minerals in the four sands, as estimated by X-ray diffraction analyses, are given in Table 1.

The average difference between gas and water permeability is illustrated in Fig. 1. The data points were scattered on the individual plots used to make the smoothed curves; however, enough data were available for these curves, as well as for those shown on subsequent figures, so that the general correlations were clearly defined.

Typical curves of water displacement and mercury injection are given in Fig. 2. The scale of the pressure ordinate for mercury injection has been reduced by a factor to correct for the differences in surface tensions of the two liquids.

Values of $(100 - S_{Hg})_{min}$ were plotted against the corresponding k_i for all samples from the same formation, and average lines were fitted to these plots by the method of least squares. The resulting curves for the four sands are given in Fig. 3. Similar plots were made to show the relation of k_i to IWS, and the average results are given in Fig. 4.

The arithmetical averages of IWS and IBS (16,500 ppm NaCl) for samples that were tested with both brine and water are given in Table 2. The average gas permeability of the samples from each sand is also given, because irreducible saturations vary with permeability, as illustrated in Fig. 4. Sixteen samples of Frontier were also tested with a brine containing 16,500 ppm calcium chloride. The values of IBS from these tests did not differ significantly from those in Table 2 for the same samples.

A summary of the average results

TABLE 1—AVERAGE AMOUNTS OF CLAY MINERALS IN THE SANDS

Sand	Kaolinite	Illite	Montmorillonite*
Frontier	Small	Small	Moderate to abundant
Newcastle	Moderate to abundant	Small to moderate	Not detected
Tensleep	Trace	Small	Not detected
Muddy	Moderate	Small	Not detected

*Includes mixed-layered montmorillonite-illite, which exhibited swelling characteristics similar to montmorillonite.

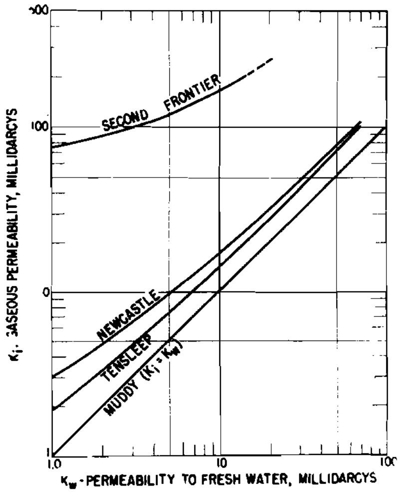

FIG. 1—AVERAGE RELATION, k_i TO k_w.

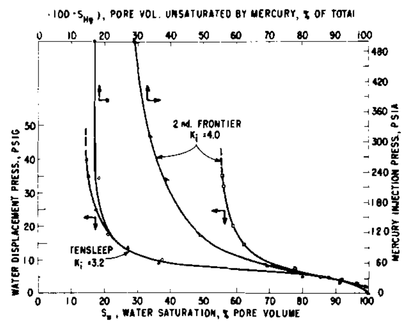

FIG. 2—COMPARISON OF CAPILLARY BEHAVIOR, SECOND FRONTIER AND TENSLEEP SANDS.

of the imbibition tests is given in Table 3. The samples chosen for the imbibition tests had a wide range of gas permeability, but the maximum oil or water saturation attained by imbibition was found to be independent of the permeability of the samples.

The values given in Table 4 correspond to a gas permeability of 30 md in Figs. 1, 3, and 4. This table together with Table 3 makes it easy to visualize the average capillary behavior of the four sands at a permeability which is probably close to the average gas permeability of the sands.

DISCUSSION OF RESULTS

Considering only the relative abundance of clay minerals in the sands and the swelling capacity of each, the order of increasing water sensitivity of the four sands would be expected to be: Tensleep, Muddy, Newcastle, and Frontier. The experimental degree of sensitivity is indicated by the relative position of the average lines correlating k_i with k_w in Fig. 1. The values of k_w are the same as k_i for the Muddy throughout the entire range of permeabilities, and, therefore, this sand

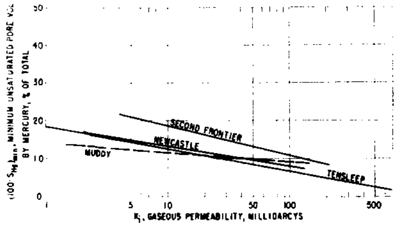

FIG. 3—AVERAGE RELATION OF k_i TO $(100 - S_{Hg})_{MIN}$.

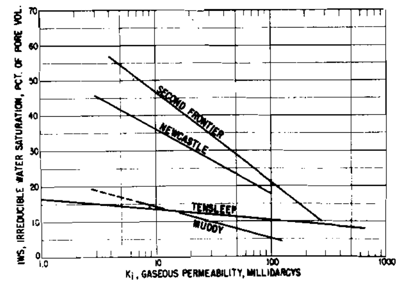

FIG. 4—AVERAGE RELATION, k_i TO IWS.

is considered non-sensitive to water. The Tensleep and Newcastle have moderate sensitivity, and only the Frontier shows a high sensitivity to water.

Dodd and others[2] investigated the clay content and permeability behavior of reservoir sands from widely scattered American oil fields and correlated these results with water-sensitivity history as inferred from field-production experience. They concluded that only sands containing high-swelling clay minerals exhibited economically serious water-sensitive behavior in the field. Extending these results to the present work leads to the conclusion that, of the four sands, only the Frontier would have an economically serious water sensitivity.

Comparison of Figs. 3 and 4 and the summary given in Table 4 shows that the IWS curve for the Frontier is considerably higher than the corresponding $(100 - S_{Hg})_{min}$ curve, whereas the IWS and $(100 - S_{Hg})_{min}$ curves for the Muddy and Tensleep practically superimpose. This suggests that there is a relationship between water-retention characteristics and the amount of clay minerals in the sand. The Newcastle, which contains the most non-expandable clay, exhibited a behavior between the water-sensi-

TABLE 2—IRREDUCIBLE BRINE AND WATER SATURATIONS

Sand	No. of Samples	IWS Per Cent Pore Vol.	IBS Per Cent Pore Vol.	k_i Avg., md
Frontier	24	27.3	27.5	76
Newcastle	15	25.5	28.4	52
Tensleep	37	12.2	12.6	90
Muddy	17	8.7	9.9	81

TABLE 3—MAXIMUM OIL AND WATER SATURATIONS BY IMBIBITION AND DIFFERENCES BETWEEN THESE VALUES, PER CENT OF PORE VOLUME

Sand	S_o	S_w	S_o-S_w
Frontier	66	60	6
Newcastle	76	58	18
Tensleep	47	23	24
Muddy	66	18	48

TABLE 4—WATER PERMEABILITIES AND SATURATIONS WHEN k_i = 30 md

Sand	k_w, md	IWS Per Cent Pore Vol.	$(100 - S_{Hg})_{min}$ Per Cent Pore Vol.	IWS − $(100 - S_{Hg})_{min}$ Per Cent Pore Vol.
Frontier	0	35	15	20
Newcastle	18	28	11	17
Tensleep	21	12	10	2
Muddy	30	10	10	0

tive Frontier and the non-sensitive Muddy and Tensleep.

The slopes of the average lines for the Frontier in Figs. 3 and 4 show that the difference between IWS and $(100 - S_{Hg})_{min}$ increases with decreasing permeability. This increasing water-sensitivity effect with decreasing permeability may also be due to the presence of clays which cause an increase in the proportion of fine capillaries and an increase in internal surface areas.

The interpretation just given of the significance of differences between values of $(100 - S_{Hg})_{min}$ and IWS stresses the importance of the volume of fine capillaries in the sands and suggests that these differences are at least partly due to clay minerals. This reasoning led to the expectation that IWS would be somewhat greater than IBS in most sands and considerably greater in sands containing expandable clay minerals. However, IBS was found to be slightly greater than IWS (Table 2), and there are no apparent differences in these values for the four sands that are attributable to the type or amount of clay minerals.

The maximum oil or water saturations attained in the samples by imbibition should be indicative of the preferential wettability of the sands to these liquids. Experiments by Jennings[9] showed that preferentially water-wet Alundum cores imbibe either oil or water, whereas preferentially oil-wet cores imbibe oil but not water. These conclusions were confirmed by experiments in connection with the work reported herein.

The value of the maximum saturation by imbibition imparts as much information as the entire curve of imbibition saturation with time, and therefore, only the values of maximum saturation are given in Table 3.

All sands imbibed oil freely, but the maximum water saturation graded from the lowest in the Muddy to the highest in the Frontier. The unusually low IWS in the Tensleep and Muddy suggests that these samples are preferentially oil-wet and the imbibition results tend to confirm this assumption. The high IWS and the high saturations by water imbibition in the Frontier is likely due to the combination of a preferentially water-wet sand and its comparatively high content of clay minerals. It is impossible with present knowledge to separate the behavior effects due to surface wettability from those due to clay minerals. Furthermore, it is not known to what extent behavior of the cores in the laboratory represent behavior in the reservoir.

The best comparison of laboratory and field results for water saturations is obtained when analyses are available from cores that were cut with oil in the drill hole from a reservoir at a location which is more than 50 ft above the oil-water contact. Unfortunately, of the four sands studied, these ideal conditions are available for only the Tensleep sand. Rogers[10] reported that the average permeability of the Tensleep sand at Steamboat Butte is 32 md and the formation water saturation is 11 per cent. At this permeability, the value of $(100 - S_{Hg})_{min}$ from Fig. 3 is 10 per cent and that of IWS from Fig. 4 is 12 per cent. In this one instance, both the mercury-injection and semipermeable barrier methods proved to give an accurate estimate of the formation water in preferentially oil-wet and non-sensitive cores.

CONCLUSIONS

The important conclusions resulting from this study are as follows:

1. Capillary behavior of reservoir sands is related to the types and amounts of interstitial clay minerals. Sands containing considerable amounts of a high-swelling clay mineral such as montmorillonite have the following characteristic behavior: (1) gas permeability is much higher than water permeability, (2) irreducible water saturations are unusually high, and (3) water is imbibed to high saturations. Sands containing relatively large amounts of kaolinite and illite exhibit these characteristics to a lesser degree than sands containing high-swelling clays but to a greater degree than clay-free sands.

2. Water-displacement and mercury-injection tests give comparable results for relatively clay-free sands, but these results differ greatly for clayey sands; therefore, the difference between the results of these two tests is a measure of the water sensitivity of the sand.

3. The observation that irreducible saturations are not affected by the salinity of the water suggests that most residual water is adsorbed on solid surfaces and held in fine capillaries, and that only a minor amount is retained as interlayer water within the clay mineral particles.

4. Capillary behavior is affected greatly by the clay-mineral content of the sands. It is also recognized, however, that preferential wettability is sometimes important in capillary behavior and that this effect may predominate in clean sands if they are preferentially oil-wet.

5. If it is assumed that irreducible water saturations as determined with the semipermeable barrier method are a measure of formation water saturations, then the following observations may be made: (1) formation water saturations may be estimated from results of mercury-injection tests without the use of correlation factors only in relatively clay-free sands, and (2) formation water saturations are independent of salinity of the water.

REFERENCES

1. Baptist, O. C., and Sweeney, S. A.: "Effect of Clays on the Permeability of Reservoir Sands to Various Saline Waters, Wyoming," RI 5180 USBM (Dec., 1955) 23.
2. Dodd, C. G., Conley, F. R., and Barnes, P. M.: *Clays and Clay Minerals*, NAS-NRC 395 (1955) 221.
3. Case, L. C.: "Origin and Current Usage of the Term 'Connate Water'," *Bull.* AAPG (1955) **25,** 1879; also, "The Contrast in Initial and Present Application of the Term 'Connate Water'," *Jour Pet. Tech.* (Jan. 1957) **IX,** No. 1, 12.
4. Muskat, M.: *Physical Principles of Oil Production*, McGraw-Hill Book Co., Inc., New York (1949).
5. Grim, R. E.: *Clay Mineralogy*, McGraw-Hill Book Co., Inc., New York (1953).
6. Bruce, W. A., and Welge, H. J.: "The Restored-State Method for Determination of Oil in Place of Connate Water," *Drill. and Prod. Prac.*, API (1947) 166.
7. Purcell, W. R.: "Capillary Pressures—Their Measurement Using Mercury and the Calculation of Permeability Therefrom," *Trans.* AIME (1949) **186,** 39.
8. Klinkenberg, L. J.: "The Permeability of Porous Media to Liquids and Gases," *Drill. and Prod. Prac.*, API (1941) 200.
9. Jennings, H. Y., Jr.: "Surface Properties of Natural and Synthetic Porous Media," *Preprints*, Symposium of Div. Petro. Chem., ACS, Dallas, Tex. (April, 1956) 69.
10. Rogers, E. W.: "Pressure Maintenance by Water Injection in Steamboat Butte Field," *Pet. Engr.* (Oct., 1953) **25,** B78. ★★★