

THE EFFECT OF CLAYS ON THE PERMEABILITY OF RESERVOIR SANDS TO WATERS OF DIFFERENT SALINE CONTENTS

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ABSTRACT

The average results of air- and water-permeability determinations are given for petroleum-reservoir sands in three Wyoming fields. The average amounts of materials of clay size in the sands and the types of clays present, as identified by X-ray diffraction methods, are also presented and discussed.

The sands are shown to be more permeable to air than to brines and more permeable to brines than to fresh water. Each of the sands exhibited different behavior when wetted by waters, and the percentage loss of permeability to waters, as compared to air, varied from sand to sand. The sand containing kaolins, illites, and mixed-layer clay (illite-montmorillonite) was found to be the most sensitive to water, and the sand containing only small amounts of kaolins and illites was the least sensitive. The sand that contained the most kaolins and illites was intermediate in water sensitivity. The water-permeability behavior of the sands and the dependence of this behavior on the clays present and the salinity of the water are discussed.

INTRODUCTION

General

The productivity of oil and gas wells depends, among other things, upon the effective permeability of reservoir sands to those fluids, and anything that decreases the permeability of sands will decrease the rate of oil and gas production. Most reservoir sands contain both interstitial waters and clay minerals. The clays are hydrated to a certain degree and are in swelling equilibrium with the water at the time of discovery of the oil fields. When wells are drilled for the production of oil, some water will infiltrate into the sand from the drilling mud; the introduced water probably will not be of the same chemical composition as the original interstitial water and will upset the equilibrium existing in the clay-water system. Usually the introduced water will have less salinity than the original water, and the fresher water will cause swelling of the clay particles, thereby partly blocking the capillary openings in the sand and reducing the rate of flow of oil to the well bore. The problem becomes even more serious when water is injected into the sands to obtain additional oil from nearly depleted fields.

Reservoir sands that are susceptible to damage by exposure to waters are termed water sensitive. The water sensitivity of oil-producing sands cannot be predicted at present but must be determined for each sand by a study of production performance (Wade, 1947, pp. 186-214) or by testing sam-

ples of the sand in the laboratory. One laboratory method widely used as a qualitative indication of the water sensitivity of a sand is determination of the difference in permeability of rock samples when dry and when saturated with waters of various chemical composition (Johnston and Beeson, 1945, pp. 43-55).

The permeability of a porous medium is a measure of the ease with which fluids may pass through the medium under the influence of driving pressure. The unit of permeability used in the petroleum industry is the darcy or, more commonly, the millidarcy, which is a one-thousandth of a darcy. The equation by which permeability to liquids may be calculated by laboratory measurements is: $k = \frac{uQL}{A(P_1 - P_2)}$. This equation gives permeability, k , in darcys if viscosity, u , is expressed in centipoises; rate of flow, Q , in cubic centimeters per second; length, L , in centimeters; area, A , in square centimeters; and pressure differential, $P_1 - P_2$, in atmospheres. This equation, known as Darcy's law, is also used to calculate gaseous permeability if the volumetric rate of flow is measured at mean pressure (Muskat, 1949, p. 136). The permeability value of a porous sample is a constant when the flowing fluid is either liquid or gas, provided however, that certain conditions are fulfilled (Muskat, 1949, p. 138). One of the limiting conditions for constancy of permeability is that there be no reactions between the flowing fluids and materials in the samples. Samples of most reservoir sands contain clays that are subject to swelling when wetted with waters; therefore, it is not to be expected that the permeability of samples of reservoir sands will be the same to water as to air. The difference in permeability of samples when tested with air and water indicates the magnitude of reactions taking place between the water and the clays in the samples.

Different clays exhibit varying capacity to change volume when wetted with water; and the change of volume depends, to some extent, upon the chemical composition of the water (Nowak and Krueger, 1951, p. 165).

In consideration of the physical phenomena just outlined, it seems reasonable to expect the existence of interrelationships among such factors as the type of clay present, the salinity of the introduced water, and the water sensitivity of the sand. This paper presents the results of a study undertaken to establish such possible interrelationships in petroleum reservoir sands in Wyoming.

Previous Work

The difference between air and water permeability was first pointed out by Fancher, Lewis, and Barnes in 1933 (p. 141). Johnston and Beeson in 1945 reported the results of hundreds of water and brine permeability tests on numerous reservoir sands, mostly in California. Their data showed the wide difference between air and water permeability and showed that, as concentration of the brine was decreased, permeability values likewise decreased. They postulated that salt-water permeability is probably closer to

true reservoir permeability than is the measurement with air. Hughes and Pfister (1947) pointed out that brines would keep the clay content of producing sands in a permanently flocculated condition, and, therefore, brines were recommended for use in secondary recovery of petroleum by water flooding. The effect of drilling fluids on the productive capacity of sands was outlined by Sherborne and Fischer (1949), and they suggested improved drilling fluids to protect water-sensitive zones. Later, Nowak and Krueger (1951) reported the effect of mud filtrates upon the permeability of cores. They investigated the effect of chemical composition of interstitial waters on the effective permeability to oil and concluded that fresh water significantly reduces the effective oil permeability and that polyvalent salts (*e.g.*, calcium chloride) in aqueous solutions are more effective than solutions of monovalent salts (*e.g.*, sodium chloride) in preventing permeability impairment of cores. Bertness (1953) concluded that permeability of cores to reservoir water might not be indicative of effective oil permeability in the reservoir and that the oil productivity of some consolidated, water-sensitive oil sands, after being invaded by filtrates from drilling mud, could be partly restored by the flow of oil into the well.

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LABORATORY METHODS AND PROCEDURES

Permeability Measurements

Samples for permeability determinations were cut with a diamond drill from oil-well cores, as received from the field, and trimmed to a standard length. The samples were extracted with toluene or benzene and dried at 105° C, and the air permeability was determined. They were then evacuated, pressurized with helium, again evacuated, and then saturated with the first test solution of deaerated water containing 16,500 p.p.m. sodium chloride, after which pressure was applied to the saturant with compressed helium. After the samples had soaked for 24 hours in the first test solution, liquid permeability was determined in an apparatus in which nothing but glass or plastic contacted the flowing liquid. The strong brine solution was then displaced with a solution containing 8,250 p.p.m. sodium chloride, and the samples were again allowed to soak for a day, after which the permeability to the weaker brine was determined. The same procedure was repeated, using distilled water, after which the samples were dried and the final air permeability was determined.

For ease of reference, the following abbreviations will be used to indicate the permeability of the samples to the various fluids:

K_{a1} — air, initial

K_{b1} — water containing 16,500 p.p.m. sodium chloride

K_{b2} — water containing 8,250 p.p.m. sodium chloride

K_w — distilled water, also called fresh water

K_{af} — air, final.

Salinity of the interstitial waters found in most reservoirs in Wyoming is within the range of salinity used in this series of liquid permeability determinations.

Amount of Clay

Samples for clay analyses and liquid permeability determinations were taken from adjacent parts of a core in the same horizontal plane. The samples for clay analyses were reduced to grain size by crushing, care being taken to minimize reduction in particle size of any of the components. The disaggregated samples were cleaned with toluene, dried, weighed, and then mixed and shaken with water containing Aerosol as a wetting agent and ammonium hydroxide as a deflocculent. The mixture was allowed to settle for 10 minutes, and the turbid liquid, down to a depth of 7.3 centimeters from the surface, was removed by siphoning. In accordance with Stokes' law, the liquid so removed contained particles of 12-micron and smaller size and was, therefore, of clay size on Wentworth's scale of classification of sediments. By repeating this procedure of mixing with water, allowing the mixture to settle for a given time, and then siphoning off a given portion of the upper part of the liquid, all the materials of 12-micron and smaller size were separated from the disaggregated rock. The siphoned liquid was dried to a residue in evaporation dishes, and care was taken not to heat the residue above the boiling point of water. The dried material was passed through a 325-mesh sieve and was then ready for X-ray diffraction analyses. The material of 12-micron and smaller size separated from the samples is referred to as the 12- μ fraction. The material remaining after the removal of the 12- μ fraction was dried and weighed. The difference in weight between the original sample and the coarse residue remaining after the sedimentation process was taken as the weight of the 12- μ fraction.

Type of Clay by X-ray Diffraction Analyses

X-ray diffraction charts of the oil-well core samples were obtained with a spectrogoniometer unit having a copper target tube, a one-degree divergence slit system, and a nickel filter attachment. A setting of 40 peak kilovolts and 20 milliamperes was used, along with a chart speed of one degree per minute. The samples were of 12-micron particle size and were mounted in flat aluminum holders in such a manner that a smooth, flat surface was exposed to the X-radiation.

Known percentage mixtures of various clay minerals and quartz were prepared. These standard samples were of 12-micron particle size to agree with the particle size of the oil-well core samples. The clay minerals used were illite (Ohio), montmorillonite (Belle Fourche, S. Dak.), kaolin (Macon, Ga.), and a mixed-layer clay (Cameron, Ariz.).

A portion of the core sample to be analyzed was ashed for one hour at 600° C to destroy the kaolin structure (Brindley, 1951, p. 49). Ashing also increased the chlorite peak at 14.2 Å (Angstroms) and caused a slight shift in the montmorillonite peak from 10.3 Å to 9.7 Å. Another portion of the sample was thoroughly mixed with glycerol to expand the montmorillonite lattice (Brindley, 1951, p. 115). This treatment shifted the montmorillonite peak from 10.3 Å to about 18.0 Å. This characteristic peak is so intense that concentrations as low as 1 to 2 percent of montmorillonite could be detected. Since Wyoming montmorillonite and illite both have a strong peak at 10.0 Å to 10.3 Å, the glycerol treatment served to determine whether illite, montmorillonite, or a mixture of both was present.

The montmorillonite peak at 10.3 Å is smaller than that usually observed in other laboratories. This spacing has been found to depend upon the state of hydration of the mineral (Grim, 1953, p. 91). The relative humidity in the X-ray laboratory at Laramie is usually within the range of 5 to 10 percent. Due to this low humidity the dried clay does not rehydrate to an appreciable degree, thereby producing the small spacing observed.

Identifications were made by comparing the peak positions on the X-ray charts with those on standard charts of known clay mixtures. Semiquantitative estimates of amounts of clays were made by comparing the peak heights with the respective peak heights on the standard charts. The results of such estimates are shown in Tables I and II. The values do not indicate the order of accuracy because the absolute accuracy is not determinable and these values should be considered as representing only approximations of the amounts of clays in the samples.

TABLE I. — PERMEABILITY AND CLAY ANALYSES OF FOUR SAMPLES OF FRONTIER SANDS

Sample	Sand	Initial air permeability, md, K_{a1}	Ratio of other permeability to initial air permeability, %				Amt. of 12- μ fraction, % of sample	Clay minerals, % of 12- μ fraction		
			$\frac{K_{b1}}{K_{a1}}$	$\frac{K_{b2}}{K_{a1}}$	$\frac{K_w}{K_{a1}}$	$\frac{K_{af}}{K_{a1}}$		Kaolins	Illites	Mixed layer ¹
A	Second	27	15	1	0	89	9.6	4	7	26
B	Third	76	22	18	8	68	4.0	16	5	15
C	Third	52	64	64	19	115	4.7	14	14	0
D	Fourth	46	99	98	72	100	4.7	3	5	0

¹ Montmorillonite-illite type.

TABLE II. — TYPES AND AVERAGE AMOUNTS OF CLAYS IN THE 12-MICRON AND SMALLER FRACTIONS, TENSLEEP, NEWCASTLE, AND SECOND FRONTIER SANDS

Sand	Amt. of 12- μ fraction, % of sample	Clay minerals, % of 12- μ fraction		
		Kaolins	Illites	Mixed layers ¹
Tensleep	2.6	Trace	6	0
Newcastle	10.7	27	10	0
Second Frontier	8.1	5	7	53

¹ Montmorillonite-illite type.

DISCUSSION OF RESULTS

The properties of clays have been discussed by numerous authors (Grim, 1951 and 1953, A.P.I., 1951, Griffiths, 1946, Cox, 1950). The three properties of most importance in petroleum production and to the present study are: (1) adsorption and retention of water, (2) base exchange capacity, and (3) flocculation and deflocculation. Hughes (1950, p. 154) pointed out that these properties are exhibited by montmorillonites to a marked degree, by illites to a much less degree, and by kaolins to a relatively unimportant degree. Most of the reduction in permeability that occurs when a dry sample is wetted with an aqueous solution is probably due to one or more of these three properties of clays. Mechanical plugging, caused by dislodgement and transportation of particles within the sand, also is probably a significant factor in permeability reduction in some samples, but this process would be accentuated if hydrating clays were present to loosen the cementation binding the clays and inert particles.

The interdependence between the type of clay and the water permeability for 4 samples from a well is illustrated by the data presented in Table I. Sample "A" from the Second Frontier sand contained 9.6 percent of 12- μ fraction, of which 4 percent was kaolins, 7 percent illites, and 26 percent a mixed-layer type. The mixed-layer clay was a montmorillonite-illite type similar to "bentonite" from Cameron, Ariz. (A.P.I. Reference Clay Mineral No. 31). A small amount of free montmorillonite may also be present. With these clays present, the permeability of the sample to the strong brine was only 15 percent of the initial air permeability, and when fresh water was used the sample was completely plugged. In contrast to this, sample "D" from the Fourth Frontier sand had kaolins and illites in quantities comparable to those in sample "A," but no mixed-layer clay was found. This sample had almost as high a permeability to the brines as to air, and the fresh water permeability was 72 percent of the air permeability. For the two samples which contained no mixed-layer clays, the permeability determined with the two brines was almost identical.

Although the data presented in Table I are fairly typical of many such observations made in the laboratory, it is not always possible to show such a clear relationship between the type of clay present and the behavior of a

sand to waters of different salinity on the basis of a few sample determinations. However, if the results of several air-permeability tests are plotted on logarithmic graph paper against the corresponding water-permeability values, a general trend can be easily seen. Where the individual sand bodies are well developed and without shale partings, each sand tends to have a constant water sensitivity from top to bottom; only a few instances have been found where certain types of clays have had a limited vertical distribution within a massive sand body and abrupt changes in liquid-permeability characteristics occur.

Table II gives the average clay analyses from three oil reservoirs in Wyoming. These three sandstones are massive, are well indurated, and range from about 10 to over 100 feet thick.

In Table II the sums of the amounts of clays identified in the 12- μ fractions total much less than 100 percent. No attempt was made to identify all of the materials, other than clays, present in the samples, since it was assumed that these other materials would be relatively inert to waters. cursory examination of the spectrogoniometer charts showed that quartz, feldspar, and amorphous materials were present in most of the samples.

The tendency of these reservoir sands to contain similar clays and exhibit similar liquid permeability characteristics from top to bottom makes it possible to draw generalized curves relating air permeability to the various liquid permeabilities. Figure 1 shows such a set of curves for the Second

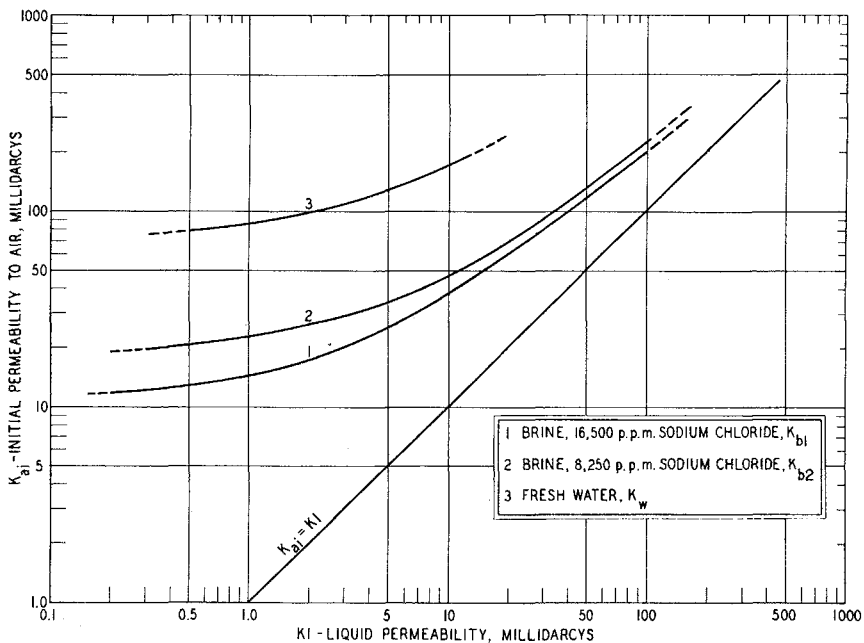


FIGURE 1. — Relation of air permeability to liquid permeability, Second Frontier sand.

Frontier sand in a Wyoming field. The curves were constructed by averaging the results obtained from 32 series of air- and liquid-permeability tests and are confirmed by the similar behavior shown by the same sand in two other fields in the same area which contain the same groups of clays. As shown in Table II, the analyses of the 12- μ fractions of the samples averaged 5 percent kaolins, 7 percent illites, and 53 percent mixed-layer clays. Due to the presence of a swelling type of mixed-layer clay, this sand would be expected to be sensitive to brines and highly affected by fresh water. The degree of sensitivity of the sand is indicated in Figure 1 by the displacement of the brine and fresh-water curves from the theoretical line equating air and liquid permeability. The greater displacement of the weaker-brine and fresh-water curves indicates increasing sensitivity with decreasing salinity. The increasing divergence of the brine- and water-permeability curves from the theoretical line with decreasing permeability indicates that water sensitivity is also a function of permeability. The trend of increasing water sensitivity with decreasing permeability shows that the sand becomes impermeable to water and brines at low air permeability, but the spread of the curves indicates that there is a range of air permeability where the sand will be permeable to brines but impermeable to water.

Figure 2 shows the relationship between K_{bl} and K_a for three sands in three widely separated fields in Wyoming. Curve 1 represents the average

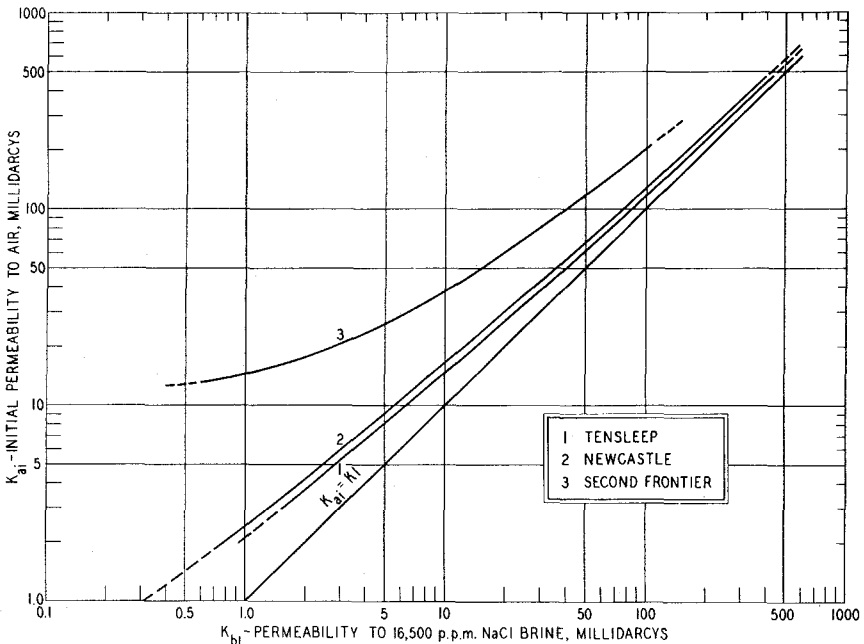


FIGURE 2.—Relation of air permeability to brine permeability (16,500 p.p.m. sodium chloride), Tensleep, Newcastle, and Second Frontier sands.

data for the Tensleep sand, which contains the least amount of clay minerals and exhibits little decrease in permeability between tests with air and the strong brine. The Newcastle sand, represented by curve 2, is high in clay content, but since the clays are of the less reactive type, the permeability to strong brine shows only a slightly greater decrease from the air permeability than does the Tensleep.

The Second Frontier sand is represented by curve 3, which is the same as curve 1 in Figure 1. By comparing curve 3 to curves 1 and 2 (Fig. 2), it can be seen that the Second Frontier exhibits greater decreases in permeability with the strong brine than does either the Newcastle or Tensleep sand at the same initial air permeability. In other words, the former is more water sensitive than either of the latter two sands.

Figure 3 presents relationships between K_a and K_{b_2} . There was no decrease in permeability of the Tensleep samples between tests with the strong and weak brines, consequently curve 1 (Fig. 3) is identical to curve 1 (Fig. 2). The differences in permeability values determined with the strong and weak brines for the other two sands are of the same magnitude as those between the air and strong brine tests; that is, the changes were greatest in the Second Frontier and intermediate in the Newcastle.

The even lower permeability values obtained with fresh water are shown in Figure 4, where K_a to K_w relationships are shown. The Second Fron-

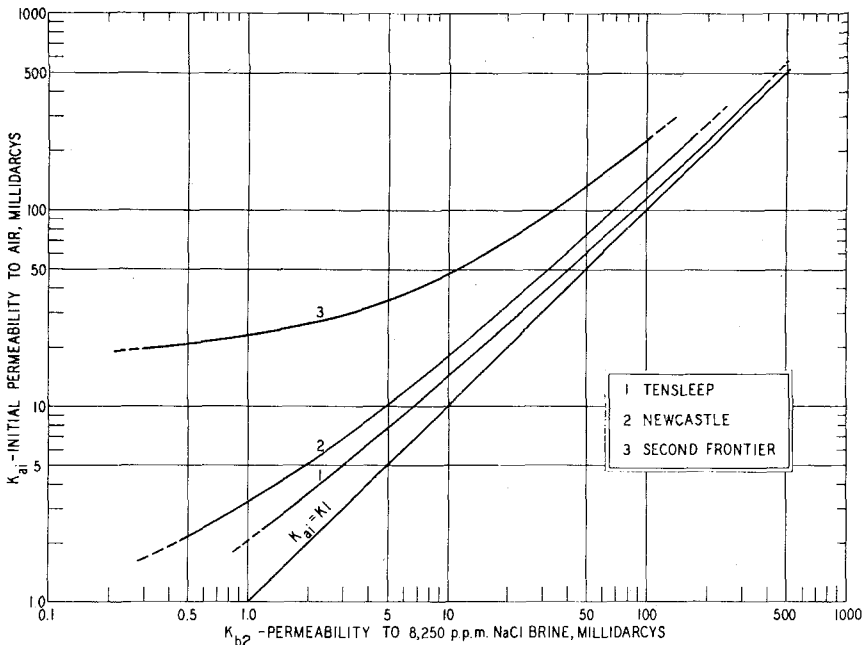


FIGURE 3.—Relation of air permeability to brine permeability (8,250 p.p.m. sodium chloride), Tensleep, Newcastle, and Second Frontier sands.

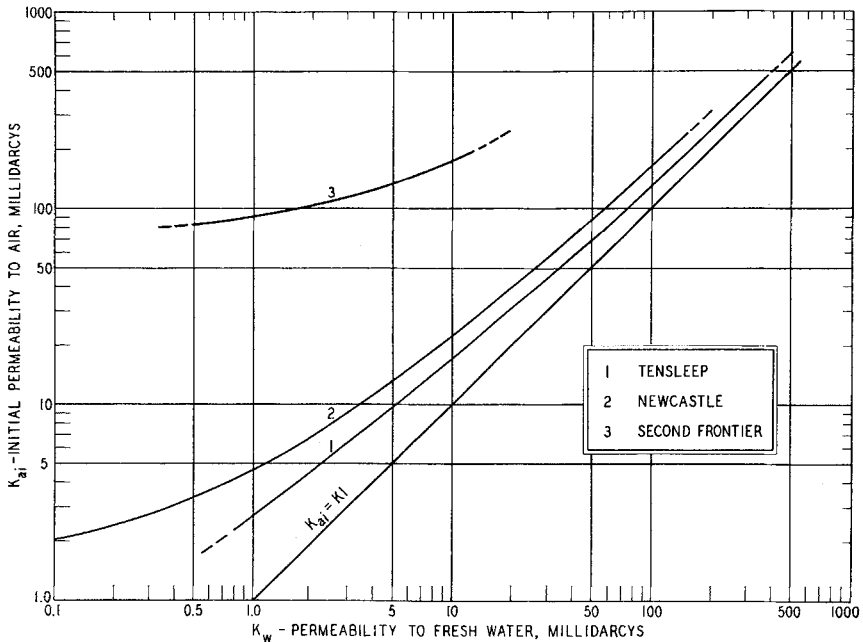


FIGURE 4. — Relation of air permeability to fresh water permeability, Tensleep, Newcastle, and Second Frontier sands.

tier samples having an initial air permeability of less than 70 millidarcys were almost completely plugged by fresh water, whereas the fresh-water permeability of the Tensleep samples of the same initial air permeability was only 24 percent less than the initial air permeability. These relationships again emphasize that the presence of even small amounts of montmorillonites (in this case mixed-layer) will seriously affect the permeability of a reservoir sand to waters. However, the absence of montmorillonites does not guarantee that a sand will be insensitive to water, as is shown by the permeability behavior of the Newcastle sand.

CONCLUSIONS

Several conclusions can be made as a result of these studies of water permeability and clay content of Wyoming reservoir sands:

1. The water sensitivity of the reservoir sands is related to the salinity of the water and to the permeability of the sand. Water sensitivity increases with decreasing salinity and with decreasing permeability.
2. The water sensitivity of a sand is also related to the type and amount of clays present. The sand containing kaolins, illites, and mixed-layer montmorillonite-illite was found to be the most water sensitive, and that containing only small amounts of kaolins and illites was the least sensitive. The sand that contained the most kaolins and illites was intermediate.

3. The predominant clay mineral found in the three reservoir sands was kaolin. Illites were next in abundance, and a mixed-layer type was found in only one of the three sands.

4. Semiquantitative analyses by X-ray diffraction methods indicated only a small portion of the material of 12-micron and smaller size was clay minerals.

REFERENCES

- American Petroleum Institute (1951) *Reference clay minerals*: API Research Project 49, Columbia University, N.Y.
- Bertness, T. A. (1953) *Observations of water damage to oil productivity*: API Drilling and Production Practice, pp. 287-295.
- Brindley, G. W. (editor) (1951) *X-ray identification and structure of clay minerals*: The Mineralogical Society, London, pp. 49-115.
- Cox, B. B. (1950) *Influence of clay in oil production*: World Oil, vol. 131, No. 7, pp. 174-182.
- Fancher, G. H., Lewis, J. A., and Barnes, K. B. (1933) *Some physical characteristics of oil sands*: Pa. State College, Min. Ind. Exp. Sta. Bull. 12, p. 141.
- Griffiths, J. C. (1946) *Clay research in oil development problems*: Jour. Inst. Pet. Tech., vol. 32, No. 265, pp. 18-31.
- Grim, R. E. (1951) *Clay mineralogy and the petroleum industry*: World Oil, vol. 132, No. 4, pp. 61-68.
- Grim, R. E. (1953) *Clay mineralogy*: McGraw-Hill Book Company, N.Y.
- Hughes, R. V. (1950) *The application of modern clay concepts to oil field developments*: API Drilling and Production Practice, pp. 151-167.
- Hughes, R. V., and Pfister, R. J. (1947) *Advantages of brines in secondary recovery of petroleum by water flooding*: Petroleum development and technology: Trans. Am. Inst. Mining and Met. Engrs., vol. 170, pp. 187-201.
- Johnston, N., and Beeson, C. M. (1945) *Water permeability of reservoir sands*: Petroleum development and technology: Trans. Am. Inst. Mining and Met. Engrs., vol. 160, pp. 43-55.
- Muskat, M. (1949) *Physical principles of oil production*: McGraw-Hill Book Company, N.Y., pp. 123-142.
- Nahin, P. G., Merrill, W. C., Grenall, A., and Crog, R. S. (1951) *Mineralogical studies of California oil-bearing formations. I. Identification of clays*: Jour. of Petrol. Tech., vol. 192, pp. 151-158.
- Nowak, T. J., and Krueger, R. F. (1951) *The effect of mud filtrates and mud particles upon the permeability of cores*: API Drilling and Production Practice, pp. 164-181.
- Sherborne, J. E., and Fischer, P. W. (1949) *Use of improved drilling fluids in well completion*: World Oil, vol. 122, No. 7, pp. 112-126.
- Wade, F. R. (1947) *The evaluation of completion practice from productivity-index and permeability data*: API Drilling and Production Practice, pp. 186-214.