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# INTRODUCTION TO PETROPHYSICS OF RESERVOIR ROCKS[1]

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## ABSTRACT

There is need for a term to express the physics of rocks. It should be related to petrology much as geophysics is related to geology. "Petrophysics" is suggested as the term pertaining to the physics of particular rock types, whereas geophysics pertains to the physics of larger rock systems composing the earth.

The petrophysics of reservoir rocks is discussed here. This subject is a study of the physical properties of rock which are related to the pore and fluid distrubution. Over the past few years considerable study has been made of rock properties, such as porosity, permeability, capillary pressure, hydrocarbon saturation, fluid properties, electrical resistivity, self- or natural-potential, and radioactivity of different types of rocks. These properties have been investigated separately and in relation, one to another, particularly as they pertain to the detection and evaluation of hydrocarbon-bearing layers.

## GENERAL

This paper is concerned with rocks and their fluids *in situ*, particularly for the detection and evaluation of hydrocarbon deposits penetrated by a bore hole. Fundamentally, therefore, the study is one of pore size distribution and fluid distribution of each phase (oil, gas, water) within the pores of the rock.

The subject must not be limited to permeable rocks containing hydrocarbons, but should include the impermeable layers and permeable layers containing water as well. This must be done in order to distinguish between them.

## DISCUSSION

Rocks are heterogeneous. Therefore, the pore-size distribution as well as the fluid distribution within the pores may be complicated, particularly from the microscopic point of view. We are dealing with a heterogeneous material, together with a great many varying conditions within this heterogeneous material. This, no doubt, is the reason for early belief that a quantitative approach to the problem might never be attained.

When rocks are studied from a macroscopic viewpoint, however, a definite continuity is found. A correlation of rock properties has resulted in the discovery that definite relations or trends exist between rock characteristics. If pieces of rock representing each transition phase of a formation are studied, definite trends are noted. No matter how thoroughly a single piece of rock is studied, even on a microscopic scale, it is not possible to predict the properties of a formation as a whole. This should not be taken to mean that fundamental research on a microscopic scale is not of great importance in the study of rock porosity.

Though permeable rocks are, by nature, heterogeneous, their characteristics

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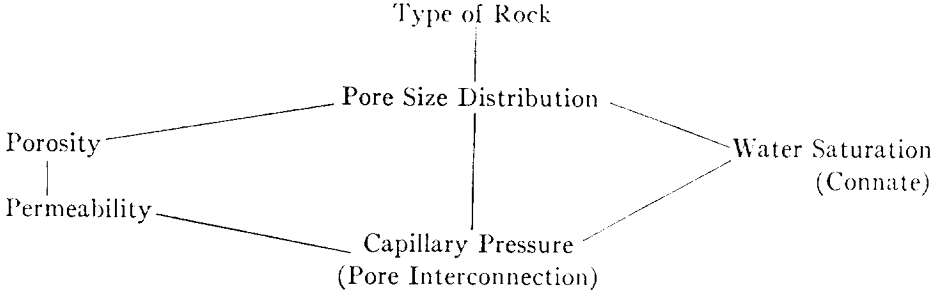
[1] Presented before Houston Geological Society, September 12, 1949. Manuscript received, October 15, 1949.

[2] Shell Oil Company. The writer expresses his appreciation to the Shell Oil Company for permission to publish this paper and to the many authors having published information on the subjects covered here. An extensive bibliography would be needed to refer the reader to all pertinent articles.

follow definite trends when considering a formation as a whole. Relations between the basic rock pore properties may be indicated somewhat as follows.



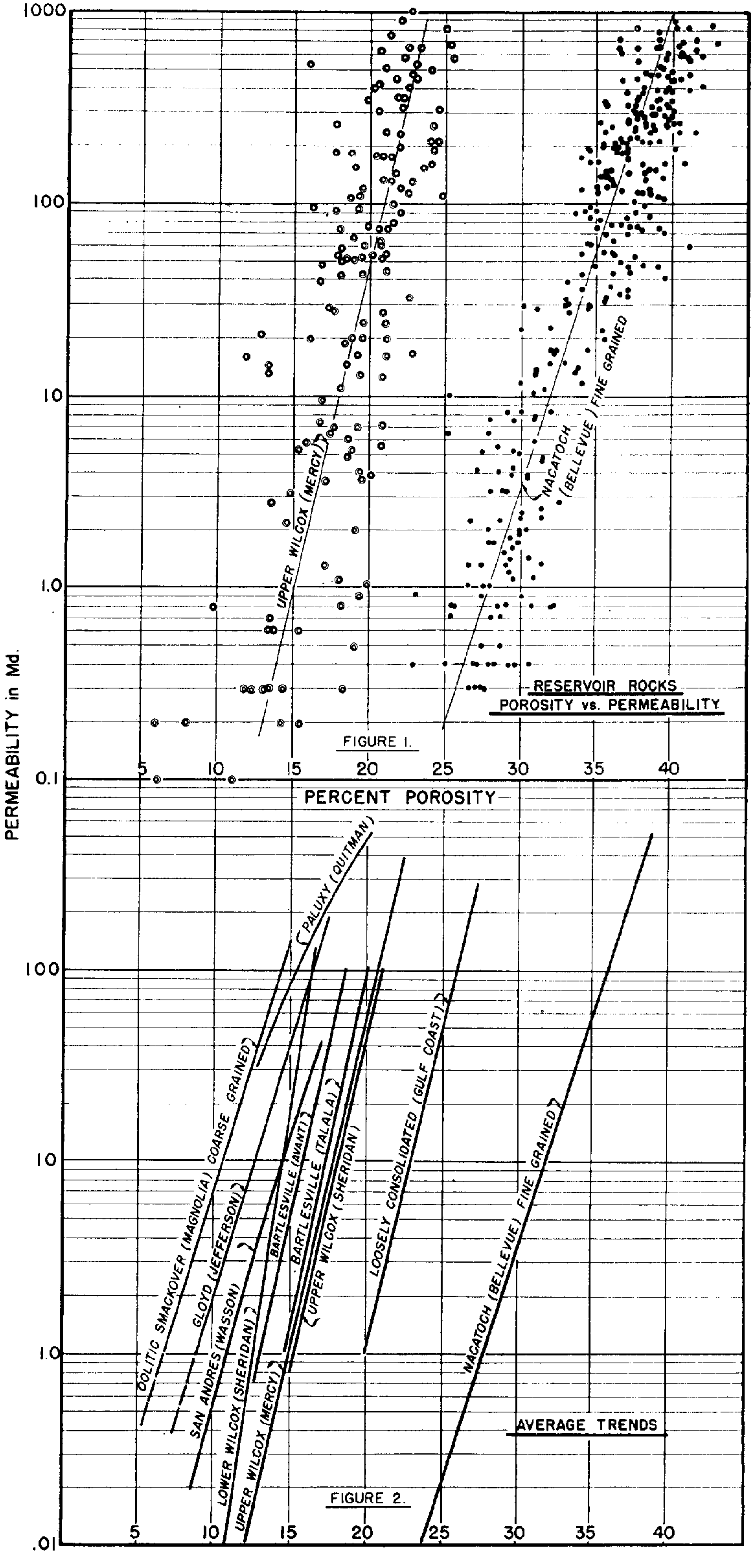
Type of rock, as here referred to, is a formation whose parts have been deposited under similar conditions and have undergone similar processes of later weathering, cementation or re-solution, as, for example, the upper Eocene Wilcox, lower Frio, Woodbine, or Bartlesville in a particular area.

The connecting lines are meant to portray the fact that a specific formation or rock type will have certain effective pore-size distributions which will produce a particular family of capillary pressure curves. The pore-size distribution controls the porosity and is related to the permeability and water saturation. Further, a certain rock will exhibit a relation between porosity and permeability.

### ROCK TYPE-POROSITY-PERMEABILITY RELATION

A broad relationship exists between porosity and permeability of a formation. Figure 1 shows a plot of the measured values of these properties of cores from the upper Eocene Wilcox sandstone at Mercy, Texas, and the Nacatoch sandstone at Bellevue, Louisiana. The scattering is great, but it must be remembered that the only reason a trend exists at all is that the formation as a whole was deposited under a similar environment; individual parts (local environment) may differ from the whole. The trends shown in Figure 1 may be represented by a line. The average trend for different formations is shown in Figure 2. Note the paralleling of trends of different formations. (Only limited data are available in the high permeability range; therefore the lines have not been extended beyond the values shown.) Rocks indicated on the left, those having low porosity for a certain permeability, have relatively large pores, for example, the oölitic limestone. Those on the right have a high porosity for the permeability, indicating a smaller pore size, for example, the poorly sorted shaly sands of the Gulf Coast and the poorly sorted, shaly, calcareous Nacatoch sandstone.

It is interesting to find that the increase in permeability with increase in porosity is of the same general order for many of the formations. An increase in porosity of about 3 per cent produces a ten-fold increase in permeability. This is striking in view of the fact that the formations are widely different. For example,



Figs. 1 and 2.—Average relation between porosity and permeability for different formations.

the Smackover limestone, on the average, has a permeability of 1 millidarcy when the total porosity is only 7 per cent; the Nacatoch sandstone for the same permeability has an average total porosity of about 28 per cent.

It will be noted that some of the trends are not essentially parallel with the others: (1) Paluxy sandstone is believed to be of dune origin and has grains of uniform size; as a result, the average pore size is larger than for water-deposited sandstones and the permeabilities are higher, particularly in the lower range of porosity; (2) lower Wilcox has probably undergone considerable change since deposition (cementation of the fine pores and solution causing larger pores) and has a steeper trend than the other formations.

It appears that as diagenesis continues, the porosity-permeability trend moves toward the left. Compare the loose Gulf Coast sand trend with the harder sandstones where the smaller pores are absent and the larger pores are possibly enlarged.

Figure 2 indicates that an approximation of the probable permeability can be made when the porosity of a formation is known. It must be remembered, however, that the relation is an average of a large number of data from a formation and, when applying the relation to the same formation at a different locality, the assumption is made that the rock structure is similar.

If the type of void structure throughout the formation is similar, the relation is, of course, more significant. However, even at the same location, certain parts of a formation may deviate considerably from the average trend because the pore structure or type of rock changes appreciably. An example of this is shown in Table I. This small interval is purposely chosen from several hundred feet of Eocene Wilcox formation.

TABLE I

| *Depth* | *Permeability* | *Porosity* |
|---|---|---|
| 10,450–51 | 1.0 | 14.1 |
| 10,451–52 | 1.0 | 17.1 |
| 10,452–53 | 0.5 | 15.1 |
| 10,453–54 | 0.8 | 15.0 |
| 10,454–55 | 2.3 | 16.3 |
| 10,455–56 | 1.1 | 16.1 |
| 10,456–57 | 3.4 | 16.0 |
| 10,457–58 | 0.1 | 11.2 |
| 10.458–60 | 72.6 | 14.6 |
| 10,460–61 | 82.0 | 14.9 |
| 10,461–62 | 45.2 | 12.9 |
| 10,462–64 | 140.0 | 14.6 |
| 10,464–67 | 11.4 | 10.4 |

The interval 10,458–64 feet has a porosity of about 14.5 per cent and a permeability of about 100 millidarcys, whereas the interval immediately above, from 10,450–58 feet, has a porosity of about 16 per cent and only 1 millidarcy permeability. The former interval is clean and well sorted and therefore not typical of the lower Wilcox. Therefore, this relation of porosity versus permeability is only valid in a general way for a formation as a whole, and may not apply to a small integral part. The average data shown in Figure 2 does, however, help one visualize relative pore size of different types of formations.

### ROCK TYPE-CAPILLARY PRESSURE-CONNATE WATER-PERMEABILITY RELATION

Air permeability of a dry rock sample is a measure of the average contributing effect of pores of all sizes. This average is not sufficient for complete analysis because the pore size must be considered in order to obtain permeability *"in situ"* (relative permeability) and fluid distribution. Capillary pressures of rocks help to analyze this average figure by obtaining what may be called effective pore-size distribution.

Capillary pressures of rocks have been discussed in the literature regarding connate water, and recently the relation between permeability and capillary pressure has been presented.[3] In order to tie the captioned relation more closely to rock type, capillary-pressure curves of different types of permeable formations are presented; the pore structures are due to a wide variety of geologic processes, that is, (a) sedimentation with little alteration, (b) alteration by solution, (c) redeposition or cementation. A comparison of capillary-pressure curves for different rock types and for the same type with varying permeabilities may then be made.

The following types of permeable formations are presented.

1. Friable sandstone, having high permeability and well sorted grains (Pennsylvanian sand, Healdton, Oklahoma)
2. Friable sandstone, poorly sorted grains, grading to shaly sandstone in the low-permeability range; partly cemented (upper Eocene Wilcox formation, Mercy, Texas)
3. Friable sandstone, poorly sorted grains, shaly and calcareous; comparatively high porosity for permeability (Nacatoch formation, Bellevue, Louisiana)
4. Hard sandstone, heavily cemented and considerable resolution; comparatively low porosity for permeability (lower Eocene Wilcox formation, Sheridan, Texas)
5. Limestone, crystalline texture, rock material of original deposition, porosity being of secondary nature, consisting of small interconnected vugs due to solution (San Andres limestone, West Texas)
6. Limestone, finely granular to earthy texture, siliceous; comparatively high porosity for permeabilities (Devonian cherty limestone, West Texas)

In types 1, 2, and 3, the pore size, shape of pore, and interconnection of the pores are controlled mainly by the original deposition, altered little by later cementation or solution. Therefore, pore structure is due mainly to the manner in which the fragments were deposited, that is, the sorting action and packing of the grains due to wave action and later compaction. The pore structure in type 4 is due mainly to later cementation and solution; in other words, the pore structure originally due to sedimentation has been altered considerably. The effective pore structure in type 5 is due almost entirely to solution with some redeposition. The origin of 6 is controversial.

Families of capillary pressure curves for each of these types are shown in

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[3] W. R. Purcell, "Capillary Pressures: Their Measurement Using Mercury and the Calculation of Permeability Therefrom," *Petrol. Tech.*, 1, 39 (1949). *T. P. 2544*.

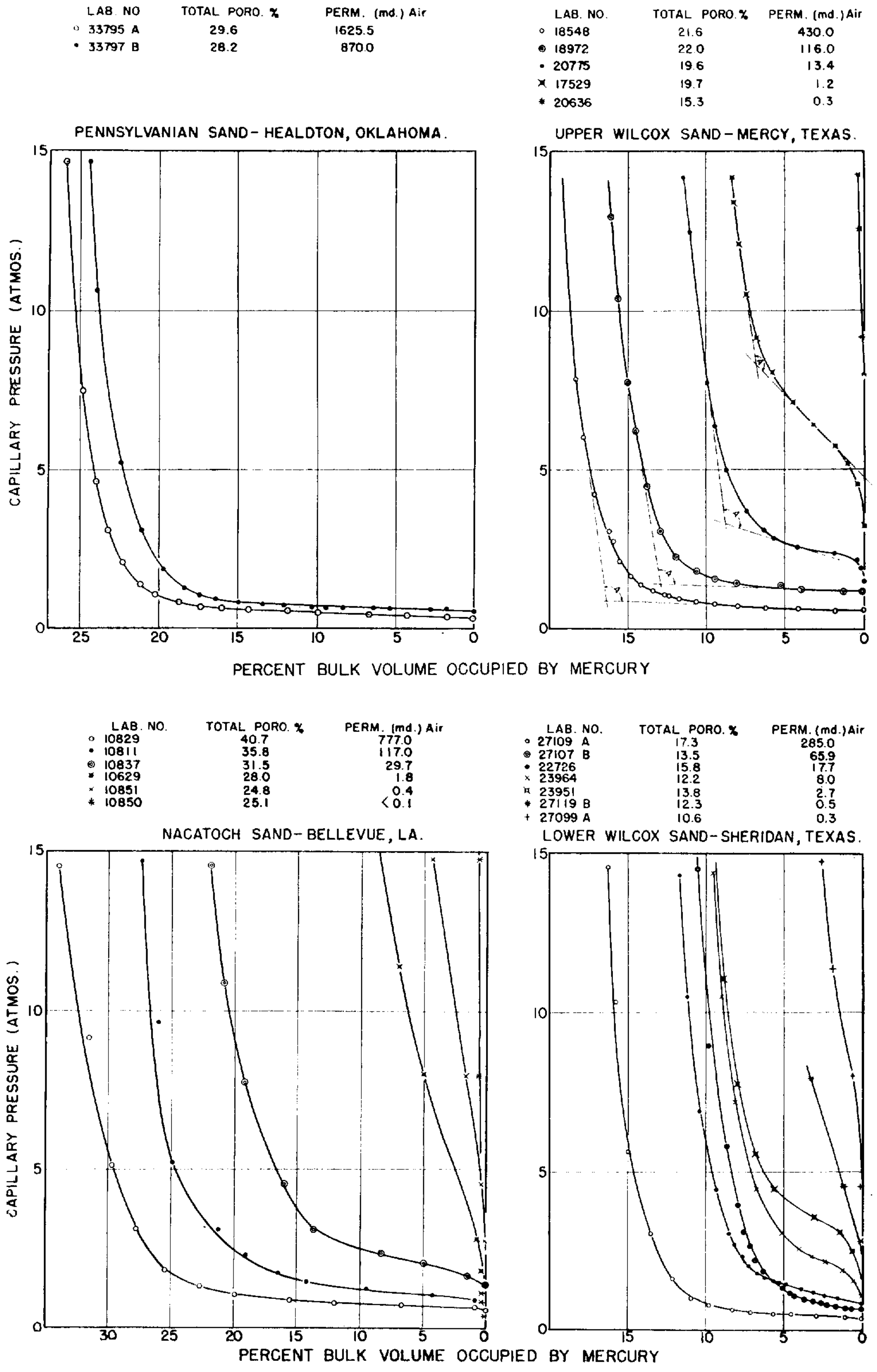


FIG. 3.—Families of capillary pressure curves for some sandstones.

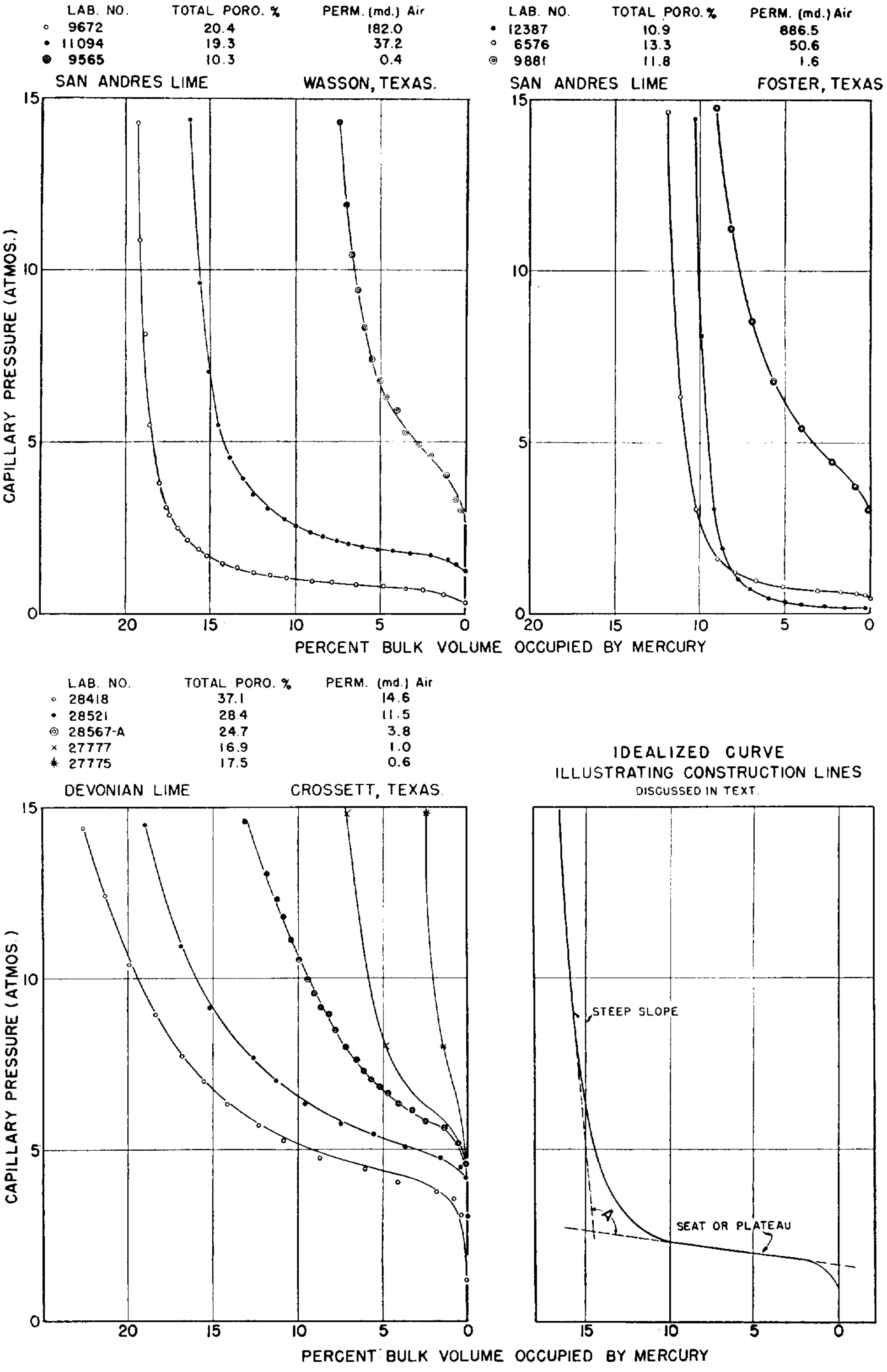


FIG. 4.—Families of capillary pressure curves for some limestones; also idealized curve.

Figures 3 and 4. These curves depict results obtained by injecting mercury into the cores. In order to show porosity in the graphs, the abscissae are "per cent bulk volume occupied by mercury." For example, it may be noted in Figure 3 that for sample No. 33795A, permeability 1625 millidarcys, the curve, with increasing pressure, approaches the abscissa 27.7, its effective porosity. These charts representing data from suites of cores show how the capillary-pressure curve, permeability, and porosity are related.

Certain general conclusions can be drawn by comparing the graphs. It can be seen that all of the samples having appreciable permeability exhibit a plateau, or seat, and a steep slope (idealized curve, Fig. 4). Examination of the capillary pressure curves will reveal that two straight lines (representing plateau and steep slope) can be drawn in and define the curves fairly well. The angle formed by extending these characteristic lines is useful. This angle "A" increases as the permeability of each type of rock decreases until one line appears and the plateau disappears.

The families of curves exhibit a striking similarity for the same permeabilities, regardless of type of formation or origin of porosity. Of course there are differences; for example, the rocks with high permeability for porosity exhibit much steeper steep slope (for example, San Andres limestone) because of a less amount of small pore space. Formations with comparatively low permeability for porosity, however, exhibit a more gentle steep slope because of the many small pores (Nacatoch and Devonian limestone). The curves of the Devonian limestone, which approaches chalk in texture, differ most from the others. It has a proportionally large amount of fine to very fine pores.

Photomicrographs of specimens of each type of rock investigated are presented in Plates I and II in order to show the visible difference in rock texture and pore structure. Notice the large pores in one of the San Andres limestone specimens, the medium pores in the sandstones and the very fine pores in the Devonian limestone and shaly sandstones. The rock textures include crystalline limestone, medium to very fine granular sandstones and very fine granular, almost chalky, Devonian limestone.

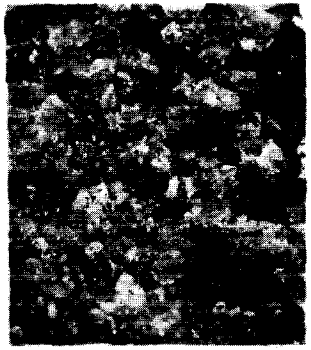
## OTHER ROCK PROPERTIES RELATED TO PORE-SIZE DISTRIBUTION

If it were possible to measure the fundamental properties (exact pore size and fluid distribution) *in situ* of formations penetrated by the bore hole, the volume of the hydrocarbon in place and the productivity of the layer could be calculated. However, it is practically impossible as yet to get a direct measurement of the factors, porosity, permeability, hydrocarbon saturation, and thickness of the layer, in place, by coring or other physical measurements.

Complete recovery of cores can not be assured and all permeable cores recovered are invariably contaminated with the drilling fluid, or fluid conditions have changed because of pressure and temperature changes on bringing the core to the surface. Therefore, we must resort to indirect measurements, such as elec-

UPPER EOCENE WILCOX, MERCY TEXAS

FRIABLE SANDSTONE, POORLY SORTED GRAINS GRADING TO SHALY SANDSTONE 15X



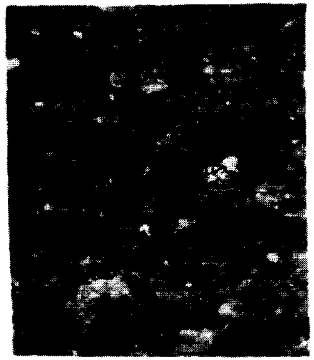
1240 MD. 23.1% POR.

101 MD. 20.9% POR.

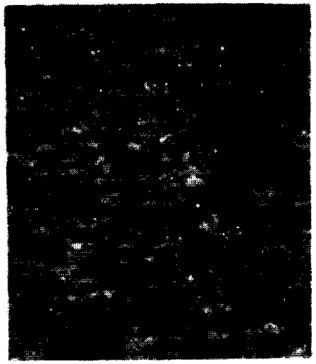
0.3 MD. 15.3% POR

LOWER EOCENE WILCOX, SHERIDAN TEXAS

HARD SANDSTONE, HEAVILY CEMENTED AND CONSIDERABLE RE-SOLUTION 15X



285 MD. 17.3% POR.



8 MD. 10.9%

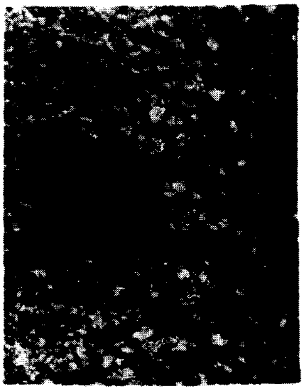
0.5 MD. 12.3% POR.

PLATE 1

# NACATOCH SANDSTONE, BELLEVUE LA. 15X

HIGH POROSITY FOR GIVEN PERMEABILITY

1180 MD. 38.4% POR.



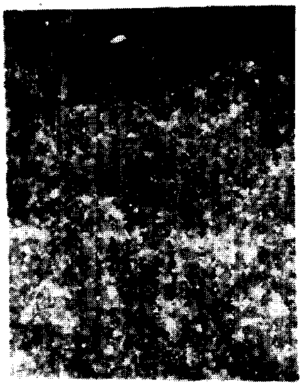
126 MD. 39.3% POR.

1.4 MD. 29.7% POR.

# SAN ANDRES LIMESTONE, WEST TEXAS 10X

887 MD. 10.9% POR.

182 MD. 20.1% POR.



1.6 MD. 11.5% POR.

# DEVONIAN CHERTY LIMESTONE, CROSSETT TEXAS 10X

COMPARATIVELY HIGH POROSITY FOR GIVEN PERMEABILITY

16.4 MD 35.9% POR.

<0.1 MD. 14.6% POR.

PLATE 2

trical resistivity, self-potential, and neutron reaction, which can be recorded in a bore hole filled with mud. In order for these indirect measurements to be useful they must be directly related to the physical properties desired (porosity, permeability, and fluid saturation). Correlation of the indirect with the actual physical properties from a macroscopic point of view by actually testing numerous cores has led to the discovery that definite relationships or trends do exist.

### ROCK TYPE-SELF POTENTIAL-GROUND WATER SALINITY-PERMEABILITY RELATION

Discussions in the literature have pointed out that the self potential is composed chiefly of two components:[4] (1) the flow potential, and (2) the chemical potential.[5] The flow potential is thought to be a smaller part of the total where the ground waters are very saline. Actually, the flow potential in a well can be measured by recording the S.P. with pressure on the well head.

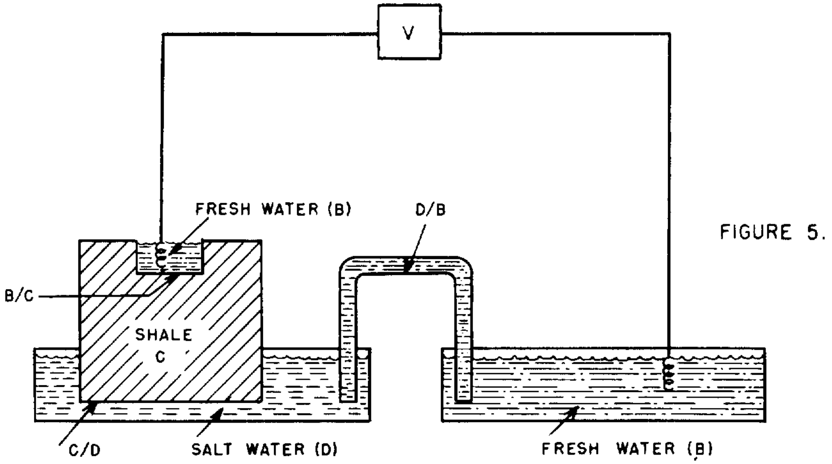


FIG. 5. Measurement of shale potential.

The chemical potential has been expressed by the equation

$$S.P. = -K \log \frac{R_1}{R_2}$$

where $K$ depends mainly on the type of impermeable rock, and the resistivity ratio is that of the mud filtrate $R_1$ and formation water $R_2$. The difference between the S.P. recorded opposite an impermeable shale, for instance, and that recorded opposite an infinitely permeable clean sandstone may be expressed by

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[4] Schlumberger and Leonardon, "A New Contribuiton to Subsurface Studies by Means of Electrical Measurements in Drill Holes," *Trans. A.I.M.E.*, Vol. 110, Geophysical Prospecting (1934), p. 273.

[5] M. R. J. Wyllie, "A Quantitative Analysis of the Electrochemical Component of the S.P. Curve," *Jour. Petrol. Tech.*, Vol. 1, No. 1 (January, 1949), p. 17.

this equation. This difference can be measured in the laboratory by placing salt water at one end of a piece of shale and fresh water at the other end. Actually, in the laboratory it is difficult to measure the voltage thus generated by placing the electrodes in the salt and fresh water because of electrode potentials; therefore, the set-up shown in Figure 5 is used. It will be seen that each of the electrodes is now in the same solution, thus cancelling the electrode potential so bothersome in laboratory measurements. Note further that the potential recording at *V* is the "shale potential" plus the liquid contact potential (*D/B*). The recorded potential is the result of:

*B/C* fresh water-shale contact
*C/D* shale-salt water contact
*D/B* salt water-fresh water liquid junction contact.

Shale cores obtained from different formations have been tested by using different amounts of dissolved salts in the salt water. It appears that *K* in the foregoing equation takes on different values for different shales. For example, shales of the Eocene Wilcox have a *K* value of the order of 60, while that of some shallow Pennsylvanian shales may be as low as 25.

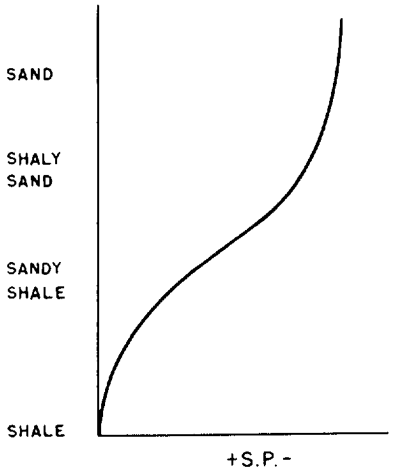

FIG. 6.—Qualitative relation between self potential and sand-shale section.

When the permeability of the formation is not high, however, the S.P. recorded opposite it in a bore hole is somewhat less. In the case of a sand and shale section, the relation between type of formation and self potential may be expressed by Figure 6. Actually, in some cases, the ordinate in Figure 6 may be replaced qualitatively, at least, with a permeability scale. For example, Figure 7-A shows the S.P. curve recorded opposite a section of the Eocene Wilcox formation. The interval 10,800 to 11,800 feet is a sandstone and shale section. The

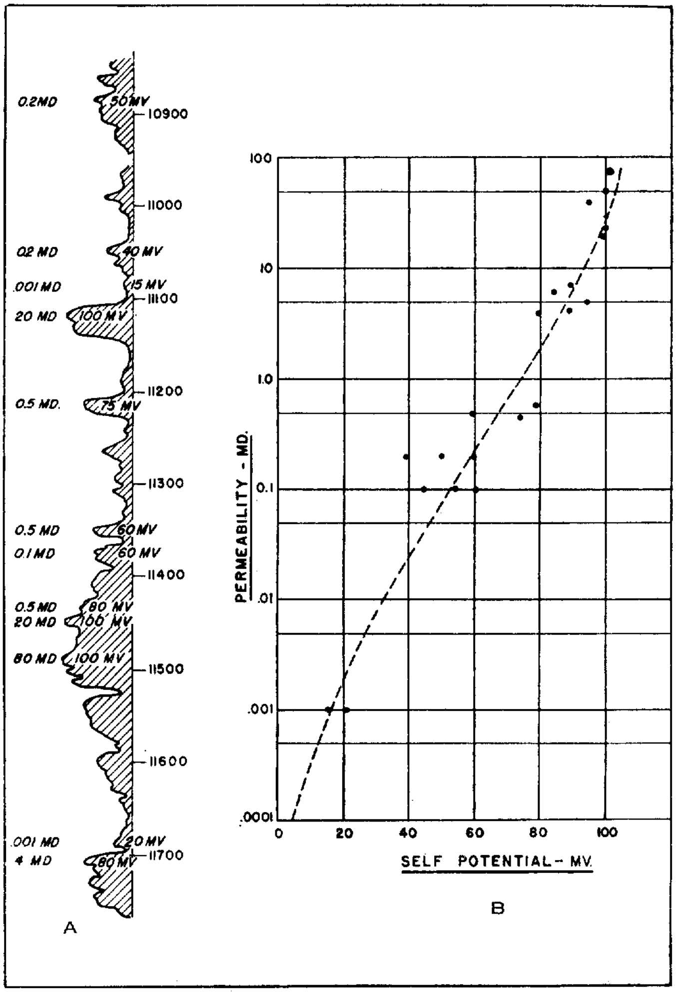

FIG. 7.—Relation between self potential and permeability of Eocene-Wilcox sandstone, Mercy, Texas.

sandstone is more or less the same type throughout, being poorly sorted, well cemented, and hard. Increasing amounts of argillaceous material are noted with decreasing permeabilities. The formation water is the same throughout this section, the mud in the bore hole at the time of the survey was uniform, and all the formations are water-bearing. The formation was extensively cored and the average permeability is indicated opposite the layers from which sufficient cores were recovered and analyzed.

The magnitude of the self-potential for the various layers is plotted *versus* the permeability in Figure 7-B. Note the apparent semi-logarithmic relation (similar to that shown in Figure 6).

It may be noted that there is considerable scattering of points and the relation between S.P. and permeability is qualitative in nature.

### ROCK TYPE-ELECTRICAL RESISTIVITY-POROSITY-WATER SATURATION RELATION

The electrical resistivity of rocks when the pores are saturated with brine may be expressed by:[6]

$$R_0 = FR_w$$

where $R_0$ is the resistivity of the rock when saturated with brine (over about 10 grams per liter dissolved salts): $F$ is the formation resistivity factor; and $R_w$ is the resistivity of the brine. $F$ is found to be related to the porosity and the type of rock.

$$F = f^{-m} \text{ or } R_0 = R_w f^{-m}$$

where $f$ is the porosity of the rock and $m$ is related to the type of rock.

Again it must be remembered that this equation represents a trend or an average line through a number of measured values (Fig. 8 and 9).

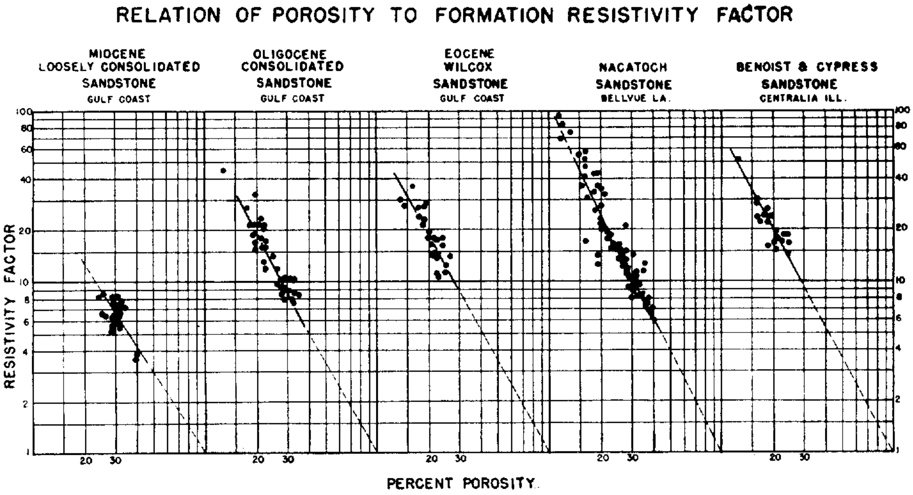

Fig. 8.—Resistivity factors of various sandstones *versus* porosity.

The electrical resistivity of a rock when hydrocarbon-bearing may be expressed by:

$$R = R_0 S^{-n}$$

where $S$ is the fraction of the voids filled with brine; $R$ is the resistivity of the hydrocarbon-bearing rock; and $n$ depends, apparently, on the type of rock.

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[6] G. E. Archie, "The Electrical Resistivity Log as an Aid in Determining some Reservoir Characteristics," *Trans. A.I.M.E.*, Vol. 146 (1942), p. 54.

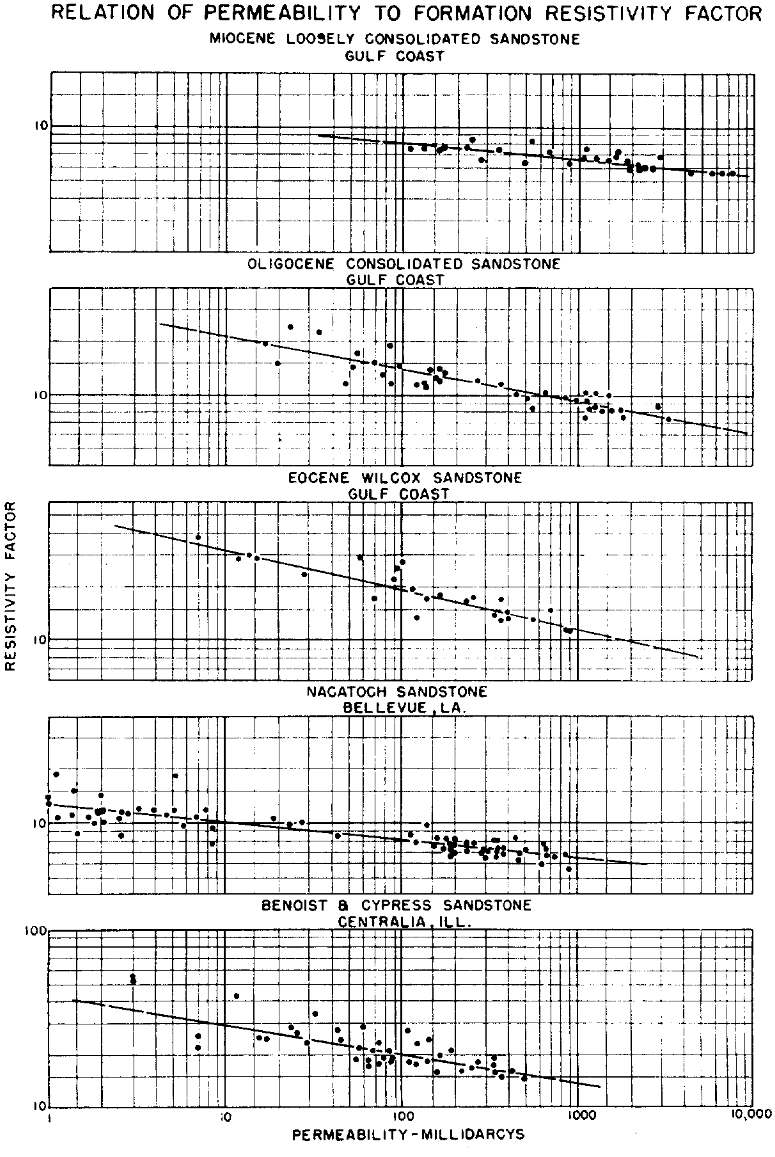

FIG. 9.—Resistivity factors *versus* permeability.

Laboratory results on artificially saturated loose sand packs indicate $n=2$, (Figure 10-a), whereas measurements on consolidated sandstones naturally saturated (as withdrawn from the well) indicate $n=1.9$ (Fig. 10-b). The foregoing equation holds for water saturations down to about 10 per cent. Below this value there is some indication that the interconnection between the water is no

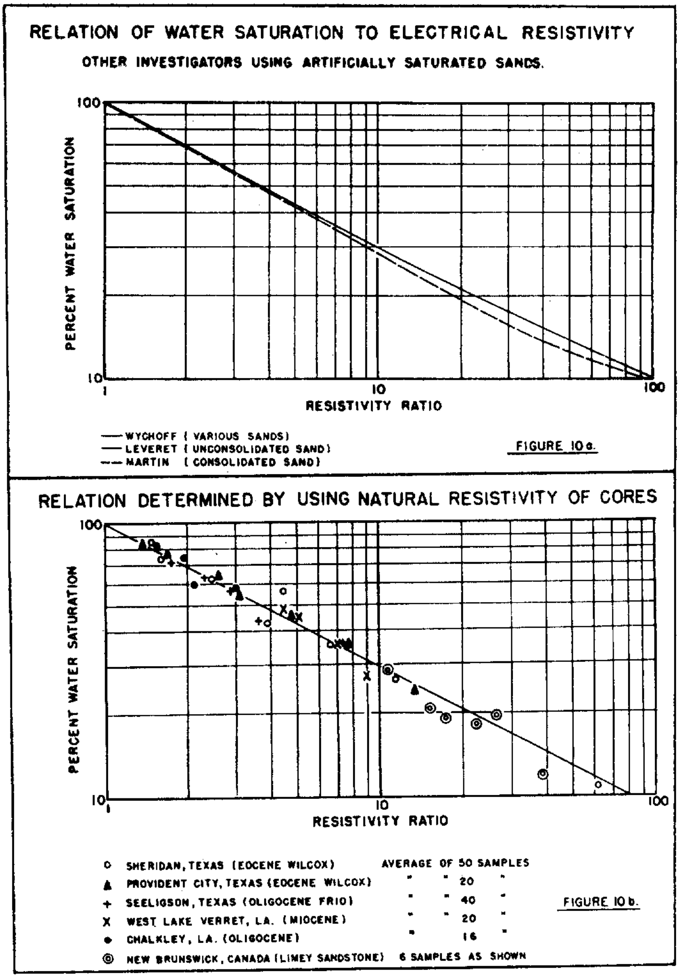

FIG. 10.—Relation of water saturation to electrical resistivity.

longer uniformly continuous and the resistivity increases more rapidly than indicated by the equation.

Actually, therefore, it may be said that the electrical resistivity of a hydrocarbon-bearing rock depends on the porosity, brine saturation, salinity of the brine, and type of rock.

## ROCK TYPE-NEUTRON REACTION-HYDROGEN CONTENT-POROSITY RELATION

Several papers have been written on this subject, and it appears that the reaction from neutron bombardment of formations depends to a large extent on their hydrogen content.[7] The effect of rock type is apparently not known. The porosity must be considered, for this determines the actual void space available to contain hydrogen-bearing fluids. The relative relation between total porosity and response to neutron bombardment, using present field methods, is illustrated in Figure 11. The limestone zones are oil-bearing. Each point represents an average of several feet where the porosity was relatively uniform. The relation would be different if these zones were dry gas-bearing, for the hydrogen density of dry gas in the pores is much lower.

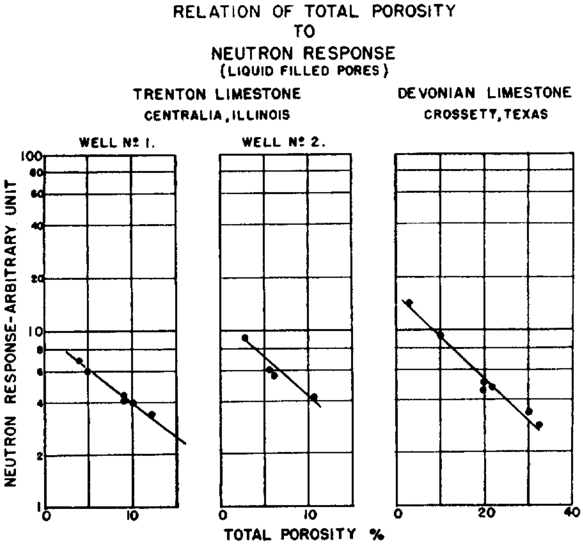

FIG. 11.—Response to neutron bombardment.

SUMMARY OF INDIRECT PROPERTIES

Figure 12 illustrates diagrammatically how the various indirect properties are related to the desired reservoir properties. Some relationships are rigid and quantitative, while others are not easily predicted and are considered only qualitative. After a qualitative relation is studied further, other factors may be discovered which, when incorporated in the equation, put the relationship on a more quantitative basis. For example, the qualitative relation between porosity and permeability is made more quantitative by introducing pore size or the capillary-pressure curve. The solid lines in the chart indicate what are now known to be quantitative relationships, while the broken lines indicate qualitative relationships.

Figure 12 shows how intricately the various properties are related; all relations

[7] R. E. Fearon, "Neutron Bombardment of Formations," *Oil Weekly*, Vol. 118, No. 2 (1945), p. 38; also "Nucleonics," Vol. 4, No. 6 (June, 1949), p. 30.

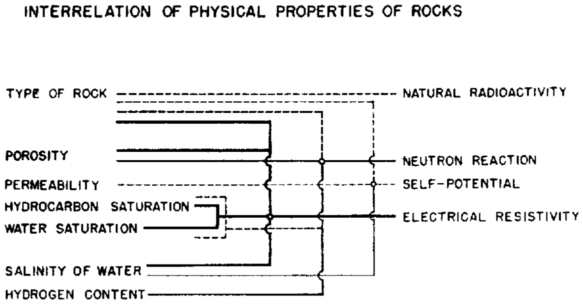
INTERRELATION OF PHYSICAL PROPERTIES OF ROCKS
TYPE OF ROCK
POROSITY
PERMEABILITY
HYDROCARBON SATURATION
WATER SATURATION
SALINITY OF WATER
HYDROGEN CONTENT
NATURAL RADIOACTIVITY
NEUTRON REACTION
SELF-POTENTIAL
ELECTRICAL RESISTIVITY

FIG. 12.

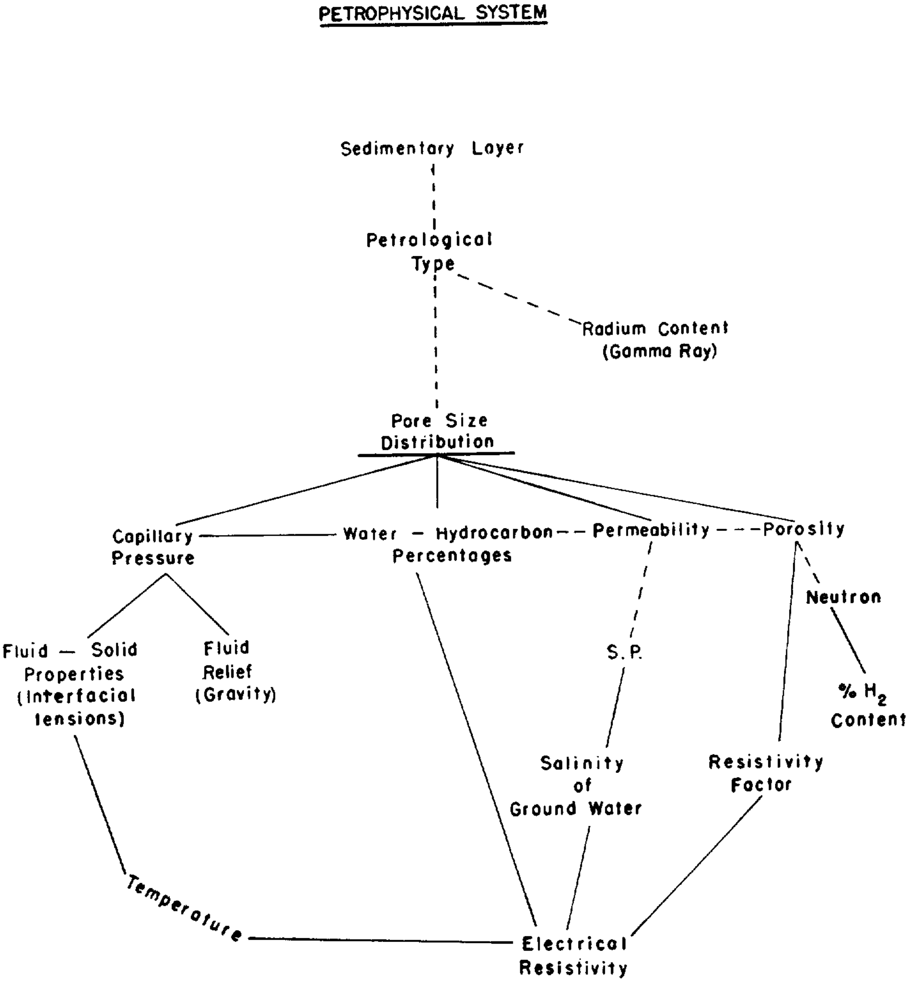
PETROPHYSICAL SYSTEM
Sedimentary Layer
Petrological Type
Radium Content (Gamma Ray)
Pore Size Distribution
Capillary Pressure
Water – Hydrocarbon Percentages
Permeability
Porosity
Neutron
Fluid – Solid Properties (Interfacial tensions)
Fluid Relief (Gravity)
S.P.
% H₂ Content
Salinity of Ground Water
Resistivity Factor
Temperature
Electrical Resistivity

FIG. 13.

are tied to the type of rock. The diagram shows the many possibilities that can arise in attempting to unravel the interrelationships in order to evaluate a hydrocarbon accumulation *in situ.* In actual practice, further complications arise due to practical difficulties, economic considerations, and the personal equation. For example, the presence of the bore hole itself, its geometry, and the fact that the bore hole must be filled with mud in order to drill the hole brings up many problems.[8] The layers penetrated are not infinitely thick; therefore, boundary effects (thin layer effect) must be calculated and applied to all indirect measurements.[9] Also, mud filtrate contaminates the permeable layers near the bore hole and it too must be considered.[10] In fact, these practical complications are commonly the most difficult to interpret in attempting to detect and evaluate deposits penetrated in a bore hole.

## CONCLUSIONS

In conclusion, a tentative petrophysical system, from the macroscopic viewpoint, is presented in Figure 13 for illustrative purposes. The system revolves mainly around pore-size distribution which defines the capillary-pressure curve, permeability, and porosity. The pore-size distribution does not necessarily define the type of rock, for actually several types of rock may have essentially the same pore-size distribution.

It is not meant that the mineral composition of the rock should be neglected in a study of these relationships. It must be recognized that the type of clay minerals present, for example, will no doubt play a greater role in future study.

It should also be mentioned that lithologic description of rocks is important. In fact, it should be broadened to express pore-size distribution as well as mineral distribution. It is felt that this is very important because drill-cuttings sample-logging (formation type) really is an integral part of this outline.

The relations between rock characteristics should be thought of as trends. Actually, these may be expressed by mathematical formulae; however, the formulae can not be applied in a rigid manner, as is done when considering the properties of homogeneous materials. It must be kept in mind that appreciable deviations from the average trend may occur. The less uniform the data, the less rigid will be the average relation, for some permeable rocks are more heterogeneous than others. The generally uniform types of permeable rocks are sandstones, oölitic limestones, and the so-called granular-appearing dolomites. The less uniform types are the so-called vesicular, vugular, or cavernous, or even fractured limestones and dolomites.

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[8] Schlumberger Company pamphlet, *Resistivity Departure Curves* (May, 1947).

[9] H. G. Doll, "The S.P. Log: Theoretical Analysis and Principles of Interpretation," *Trans. A.I.M.E.*, Petroleum Branch, Vol. 179, p. 146.

[10] Schlumberger Company pamphlet, *op. cit.*