GAS-LIQUID CONTACT DETERMINATION BY LOG ANALYSIS IN DEEPLY FLUSHED FORMATIONS

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ABSTRACT

A major objective of open-hole log analysis is the determination of the fluid content of the porous formations surrounding the wellbore. However, engineers frequently encounter severe difficulty when attempting this determination in low porosity pay zones because of deep, thorough flushing of the near wellbore formation by drilling mud filtrate. This problem is compounded if low pressure gas overlies oil or water, especially when resistivity logs are not available. This difficulty arises because virtually total replacement of the gas by mud filtrate will suppress the gas effect which porosity logs experience in gas-saturated zones. The technique described in this paper will help to identify gas accumulations and gas-liquid contacts in the reservoir in situations in which mud filtrate flushing has hindered such identification. Using only the dual porosity log, the compensated neutron-density log, and the definition of density-derived porosity, the log analyst can easily and accurately locate gas zones and gas-liquid contacts, thus saving the costs of additional well logging, formation testing, and/or coring.

INTRODUCTION

The primary objective of well log analysis is the identification of reservoir-quality rock which may contain accumulations of oil or gas. To accomplish this, the log analyst will use a porosity log and a resistivity log combining knowledge of formation lithology, formation water resistivity, log porosity, and electric log response to identify zones containing potentially commercial quantities of hydrocarbons. Frequently, the log analyst is asked to develop his conclusion further and identify whether the hydrocarbon is oil or gas. Using additional data such as prior knowledge of this reservoir or, in the case of an exploratory well, mud logging data, sample data, drill-stem tests, etc., such a judgment is possible. The use of multiple-porosity logs frequently aids in the identification because porosity devices will respond differently to liquid and gas-filled porosity.

Recent experience in a West Texas San Andres reservoir, however, revealed that drilling low porosity formations with a native salt mud can cause sufficient flushing of low-pressure gas to partially mask the gas effect on the porosity logs. Thus, in an area of a suspected gas column, there was little or no indication of gas effect on the sonic, neutron, or density logs and production tests were required to verify the presence of gas. Re-analysis of the neutron and density log responses using the technique herein discussed clearly showed that gas was present in the formation and subsequent drilling, logging, and production testing has verified the existence of a gas-oil contact and verified the analysis technique.

If a gas accumulation is suspected but not clearly indicated by the well logs, additional analysis of the neutron log and density log response using this method should be attempted prior to production testing. The technique is a simple extension of the neutron-density cross-plot and can be applied by anyone who is familiar with log analysis.

DEFINING THE PROBLEM

Utilization of the responses of both the neutron log and the density logs has provided the log analyst with a method for identifying gas accumulations in reservoir rock. This capability is the result of the basic functioning of each tool. The neutron tool is affected primarily by the concentration of hydrogen atoms in the surrounding formation, whereas the density tool responds to the electron density of the surrounding formation. In each case, accurate neutron-porosity or formation-density determinations are dependent upon the type of matrix around the wellbore, the porosity of the formation, and the fluid in the pore spaces. Both tools will provide good data in a consistent formation of known lithology in which the porosity is filled with a fluid of known composition. In reality such conditions seldom, if ever, exist so the log analyst should have some concept of lithology and of the fluid in the pore spaces. But, since each tool requires that liquid fill the pore space to give accurate data, it follows that low pressure gas which has a much lower electron density and lower hydrogen content than water or oil will affect the tool response. The neutron tool will record the low hydrogen content of the gas in the adjacent formation, and this will be interpreted as low porosity. The density device will register low electron density in the formation and in the conversion to porosity interpret this as an interval of high porosity.

In dolomite reservoirs, when the tools are referenced to a limestone matrix and the formation is liquid filled, the density log porosity values are lower than actual formation porosity while the neutron log values are higher than actual. The presence of residual, unflushed gas in the porosity causes the two log responses to approach each other and may even cause reversal; i.e., the neutron reads low porosity (few hydrogens), the density reads high porosity (low electron density) see Figure 1.

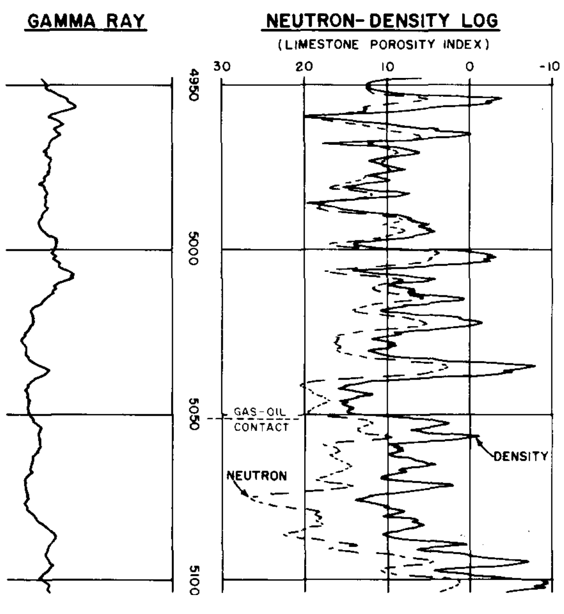

FIGURE 1—EXAMPLE WELL NO. 1

A problem arises, however, if formation flushing by drilling mud filtrate is excessive such that nearly all the gas in the formation is swept out of the pore spaces within the radius of investigation of the neutron and density tools. This radius is usually less than 12 in. and mud filtrate invasion may often exceed 30 in. in low porosity formations when drilled with a high water-loss mud such as a native salt mud. This flushing action causes most of the gas to be replaced with filtrate and the logging devices respond with reduced gas effect (Figure 2). This reduction of gas effect may result in mistaking a gas zone for oil or completing a well above the gas-oil contact.

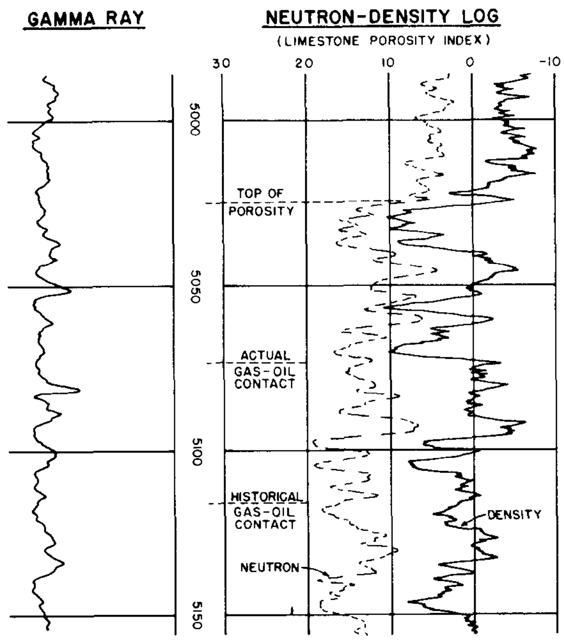

FIGURE 2—EXAMPLE WELL NO. 2

THE THEORY

The technique presented here requires both the neutron and density tools. Combining the sonic device with either of these tools is also suited to this procedure in the absence of secondary porosity (see Appendix). The technique uses the mathematical definition of density log porosity and enables the log analyst to locate what little residual gas may remain in the pore spaces. As stated above, the density tool relates electron density in the formation to an apparent density, ρ_a. This apparent density is roughly the same as the bulk formation density, ρ_b, if the porosity is liquid filled. Both apparent density and bulk-formation density are related to porosity as follows:

$$\rho_a \cong \rho_b = \phi\,\rho_f + (1 - \phi)\,\rho_{ma} \qquad (1)$$

in which,

ρ_a = apparent density, gm/cc.

ρ_b = bulk-formation density, gm/cc.

ρ_f = fluid density, gm/cc. Fluid in the pore spaces. Usually assumed as 1.0 gm/cc for fresh mud filtrate, or 1.1 gm/cc for for salt mud filtrate.

ρ_{ma} = matrix density, gm/cc. Usually assumed 2.65 gm/cc for sandstone, 2.71 gm/cc for limestone, 2.87 gm/cc for dolomite.

ϕ = porosity, fraction.

Thus, the density tool will give valid porosity values if the assigned matrix density is the same as that of the formation of interest and the rock pore spaces are completely filled with a mud filtrate of a known density.

Relationship (1), above, can be rearranged as follows:

$$\rho_b = \rho_{+a} + \phi(\rho_f - \rho_{ma}) \qquad (2)$$

$$\text{and, } \rho_b = \rho_{ma} + C_1\,\phi \qquad (3)$$

where, $C_1 = (\rho_f - \rho_{ma})$ and is always negative.

This linear relationship is shown in Figures 3 and 4. Thus, for any given matrix density, the bulk density log will record matrix density if porosity is zero,

$$\rho_b = \rho_{ma} + C_1\,(0) = \rho_{ma}$$

And, if porosity goes to 100% and, therefore, no matrix exists, then the bulk-density log reading becomes fluid density,

$$\begin{aligned}\rho_b &= \rho_{ma} + C_1\,\phi \\ &= \rho_{ma} + (\rho_f - \rho_{ma})\,\phi \\ &= 0 + (\rho_f - 0)\,1.0 = \rho_f\end{aligned}$$

Figure 5 is a family of curves for matrix densities ranging from sandstone, 2.65 gm/cc, to dolomite,

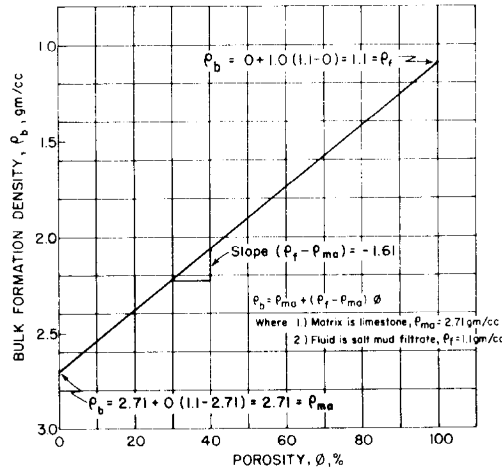

FIGURE 3—BULK FORMATION DENSITY VS. POROSITY

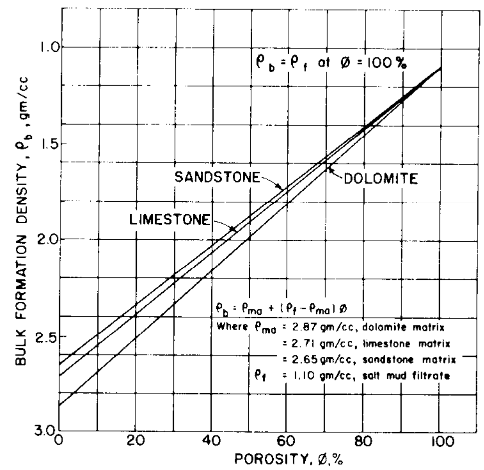

FIGURE 4—BULK FORMATION DENSITY VS. POROSITY COMPARING VARIOUS MATRIX DENSITIES

2.87 gm/cc, and for a salt mud filtrate of density 1.1 gm/cc. Figure 6 is a similar family of curves for a fresh mud filtrate of density 1.0 gm/cc. These families of curves are matrix-density cross-plots which can be used to determine porosity from the density log response for a known filtrate density and any assumed matrix density. However, the primary use of the matrix-density cross-plots is not to determine porosity, but to help locate gas or a gas-liquid contact in the reservoir. This can be accomplished by using log-derived values of porosity and bulk-formation density and solving the cross-plot for an apparent matrix density; variations in this apparent matrix density will indicate the presence of gas.

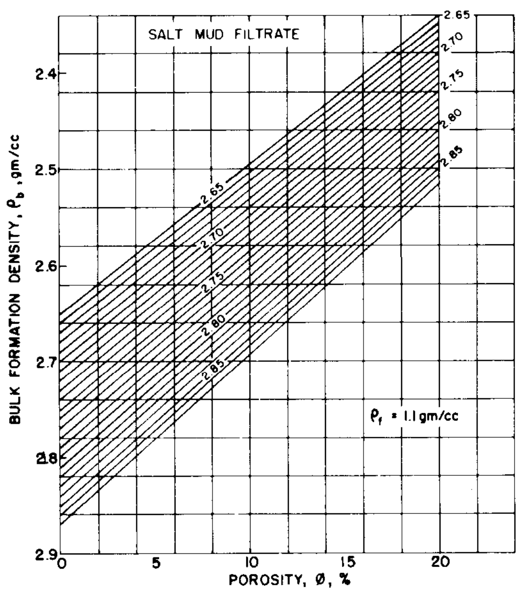

FIGURE 5—MATRIX DENSITY CROSS-PLOT FOR A FAMILY OF MATRIX DENSITIES (ρ_f = 1.1 gm cc).

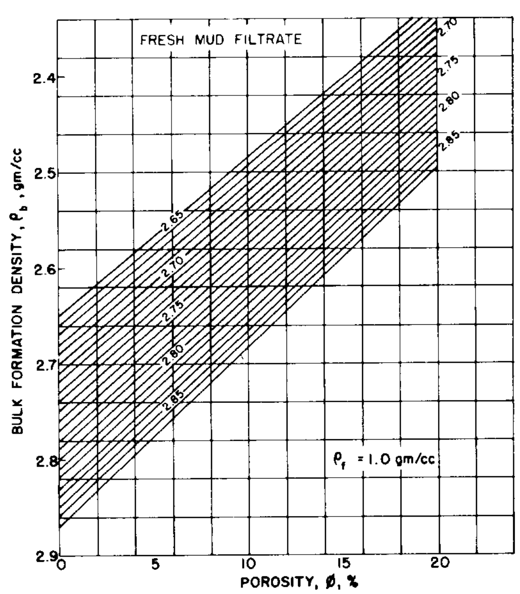

FIGURE 6—MATRIX-DENSITY CROSS-PLOT FOR A FAMILY OF MATRIX DENSITIES (ρ_f = 1.1 gm/cc).

THE APPLICATION

Since the log analyst seldom has knowledge of true formation density, true porosity, or true filtrate density, certain simplifying assumptions must be made. And, since the purpose of this analysis is to isolate and interpret variations in apparent matrix density, these assumptions will involve the porosity and density values available from the neutron and density logs. The purpose of the simplifications will be to minimize the effects of lithology on the tool response and maximize the effects of the fluid in the porosity.

First, it must be assumed that the density log is recording the true bulk-formation density of a filtrate saturated zone. By using the density values rather than immediately converting the log response to porosity values, the log analyst avoids biasing the data by the assignment of assumed matrix- and fluid-density values, i.e.,

$$\rho_b = \rho_{ma} + (\rho_f - \rho_{ma})\,\phi$$

$$\phi = \frac{\rho_b - \rho_{ma}}{\rho_f - \rho_{ma}} \qquad (4)$$

in which

ρ_{ma} and ρ_f must be assumed.

If residual gas is present in the pore spaces, the density log will be affected. However, if the formation has been highly flushed, the observed tool response may appear little different from the response in oil- or water-filled zones.

Second, it must be assumed the neutron device is recording the true hydrogen content of a liquid-filled formation. If residual gas is present, the neutron log will be affected but the gas-effect may be greatly reduced and not obvious to the log analyst. Having accepted both assumptions, the log analyst can now cross-plot the neutron-density log responses to determine an apparent formation porosity. When analyzing a zone with liquid-filled porosity, this conventional cross-plotting technique will help correct the tool responses for lithologic effects and result in reasonable porosity values. Also, when gas effect is apparent this technique results in porosity values which will fall along a low matrix-density line indicating that the formation contains something other than mud filtrate. Yet, formation matrix density is seldom known precisely for a specific two-foot interval of a reservoir and this cross-plot porosity may appear reasonable if the gas effect has been minimized by excessive flushing.

Based on these two assumptions, the analyst may select the appropriate matrix-density cross-plot (on the basis of fresh or salt mud filtrate) and use the intersection of bulk-formation density and cross-plot "true" porosity to indicate an apparent matrix density for each foot of log analyzed (Figure 7). Using the matrix-density cross-plot in this manner maximizes the fluid effects in the apparent matrix-density value as follows:

$$\rho_b = \phi \rho_f + (1 - \phi) \rho_{ma} \quad (5)$$

$$\rho_{ma} = \frac{\rho_b - \phi \rho_f}{1 - \phi} \quad (6)$$

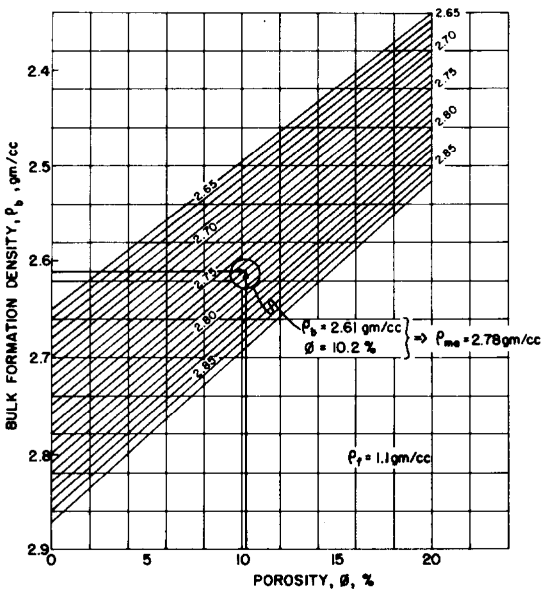

FIGURE 7—MATRIX-DENSITY CROSS-PLOT

Inspection of this relationship will show that bulk density, ρ_b, which was assumed correct, is gas affected. The density of the fluid in the pore spaces is low since it is a combination of gas and filtrate and the use of an assumed liquid density, ρ_f, enhances the gas effect on matrix density. The porosity term is very sensitive to fluid since the neutron-density cross-plotting normalized lithologic effects but did not correct for fluid effects. Thus, this exercise maximizes the effect of the fluid filling the pore spaces. If a residual gas saturation actually exists in the interval of interest, the apparent matrix density should be reduced. Across a gas-liquid contact, the apparent matrix density will be low through the gas column and increase in the oil or water column thus identifying the gas-liquid contact.

It must be emphasized at this point that the lithology of a zone must be somewhat consistent for this technique to work, or a knowledge of variations of lithology in a specific interval is needed to make a reasonable interpretation of the results. Assuming that the formation is dolomite with an approximate matrix density of 2.84 to 2.87 gm/cc and an apparent matrix density of 2.78 gm/cc, then a residual gas saturation should be suspected. To verify the presence of gas and locate an existing gas-liquid contact, this analysis should be performed foot by foot through the suspected interval. A plot of the developed apparent matrix-density data by depth will help locate the gas-liquid contact. Table 1 is a tabulation of this analysis and Figure 8 is an apparent matrix-density depth graph showing a gas-oil contact in Example Well No. 2. Visual interpretation is aided by drawing an average apparent matrix-density line through the points above and below the contact. The quantitative difference between the two average lines is not important since the analysis is greatly affected by the degree of flushing. The significance of this difference is the indication of gas in the formation which was not apparent on the well logs.

FIELD CASES

The technique was developed to enable reservoir engineers to properly evaluate a San Andres dolomite reservoir in West Texas. The modern sonic, neutron, and density logs which were run in freshly drilled bore holes had no obvious indication

Log Depth ft	Density Log Bulk Density ρ_b, gm/cc	Density Log Porosity $Ø_D$, %	Neutron Log Porosity $Ø_N$, %	Cross-Plot Porosity $Ø_x$, %	Apparent Matrix Density ρ'_{ma}, gm/cc	
5026	2.68	2.0	12.0	7.5	2.81	
7	2.60	7.0	14.0	10.7	2.79	
8	2.60	7.0	13.5	10.5	2.79	
9	2.56	9.0	12.0	10.7	2.74	
30	2.55	10.0	16.0	13.1	2.77	
⋮	⋮	⋮	⋮	⋮	⋮	
5065	2.63	5.0	14.0	9.8	2.80	
6	2.66	3.0	10.5	7.1	2.78	
7	2.65	4.0	12.0	8.4	2.79	Avg ρ'_{ma}=2.79 gm/cc
8	2.60	7.0	14.0	10.8	2.78	
9	2.56	9.0	15.0	12.3	2.76	
70	2.55	10.0	16.5	13.4	2.78	
1	2.58	8.0	16.0	12.2	2.79	
2	2.66	4.0	14.0	9.4	2.82	
3	2.71	0.0	12.0	5.6	2.81	
4	2.76	-3.0	13.0	6.0	2.86	
5	2.71	0.0	15.0	8.1	2.85	
6	2.73	-1.0	15.0	7.6	2.87	
7	2.73	-1.0	15.0	7.6	2.87	
8	2.73	-1.0	14.0	7.1	2.86	
9	2.71	0.0	13.0	7.0	2.83	
80	2.76	-3.0	12.0	5.5	2.86	
1	2.76	-3.0	12.0	5.5	2.86	
2	2.73	-1.0	14.0	7.1	2.86	Avg ρ'_{ma}=2.84 gm/cc
3	2.70	0.5	12.0	6.3	2.81	
4	2.73	-1.0	13.0	4.8	2.81	
5	2.71	0.0	15.0	6.6	2.83	
⋮	⋮	⋮	⋮	⋮	⋮	
5120	2.66	3.0	17.0	10.4	2.85	
1	2.67	2.5	15.0	9.2	2.83	
2	2.65	3.5	15.0	9.5	2.82	
3	2.65	3.5	14.5	9.4	2.81	
4	2.69	1.5	14.0	8.2	2.84	
5125	2.73	-1.0	12.5	6.5	2.85	

TABLE 1—LOG DATA

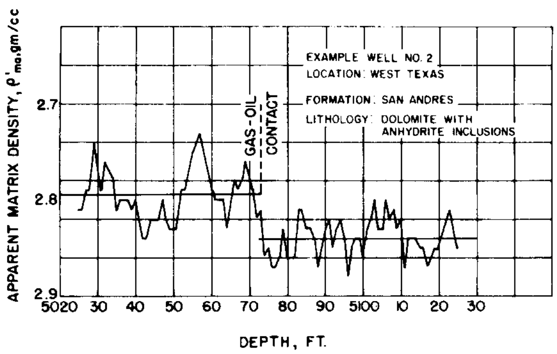

FIGURE 8—APPARENT MATRIX-DENSITY CROSS-PLOT

of the presence of the expected gas cap. Prior to using this technique, however, it was necessary to prove its validity by using logs which exhibited gas effect in a field with a proven gas-oil contact.

A San Andres dolomite reservoir with a known gas-oil contact was located in which extensive logging and coring had been accomplished in recent years. Conventional analysis of log and core data for Example Well No. 1 clearly indicates the presence of a gas cap and a correlatable gas-oil contact. An example of a typical neutron-density log is shown in Figure 1. As stated above, the gas effect which causes the two log traces to converge or reverse through the gas zone is obvious. (Note that the tools were calibrated to a limestone reference and will trace separate porosity levels through a dolomite interval.) The gas-oil contact would be picked at 5051 ft. Conventional core analysis from this same well indicates a gas-oil contact at 5055 ft log depth (Figure 9). The apparent matrix-density technique also indicates the gas-oil contact at 5051 ft where there is a consistent change in apparent matrix density (Figure 10).

In the San Andres reservoir of interest, the historical gas-oil contact was 1718 ft subsea; and in early field studies this point was identified as the base of a gas zone which contained a high oil saturation. The 1718 subsea datum has been used as a gas-oil contact from the late 1930's when the field was discovered to the present. In late 1976, a five-well infill drilling and coring program was approved and all five wells were logged with three porosity and two resistivity tools. The porosity logs indicated little or no gas effect (Figure 2). The saturation profile from the core analysis did not show a definite

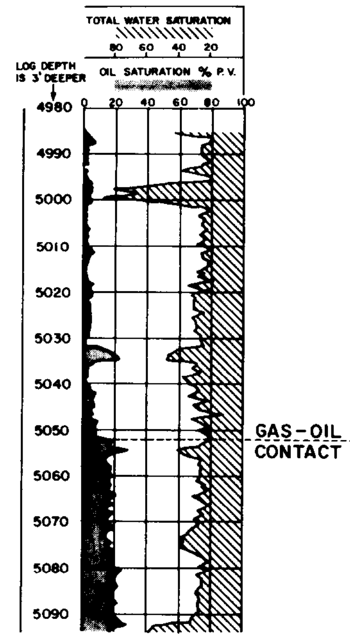

FIGURE 9—EXAMPLE WELL NO. 1, CONVENTIONAL CORE, SATURATION PROFILE

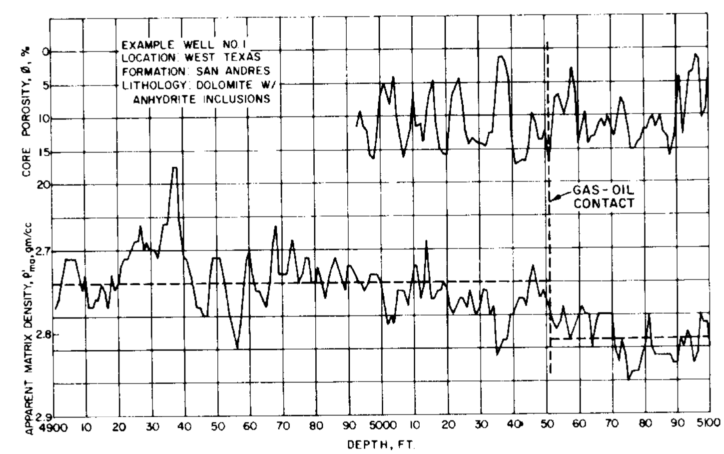

FIGURE 10—EXAMPLE WELL NO. 1, APPARENT MATRIX DENSITY VS. DEPTH

gas-oil contact either. Since part of the purpose of the drilling program was to test for the gas-oil contact, the wells were cased and zonal production testing was begun. These well tests produced gas from porosity stringers in the uppermost part of the reservoir and crude oil at the historical contact. A re-analysis of the neutron and density logs using the apparent matrix-density technique identified a gas-oil contact above the historical datum and a highly oil saturated interval at the former gas-oil contact, confirming the actual test results (Figure 11).

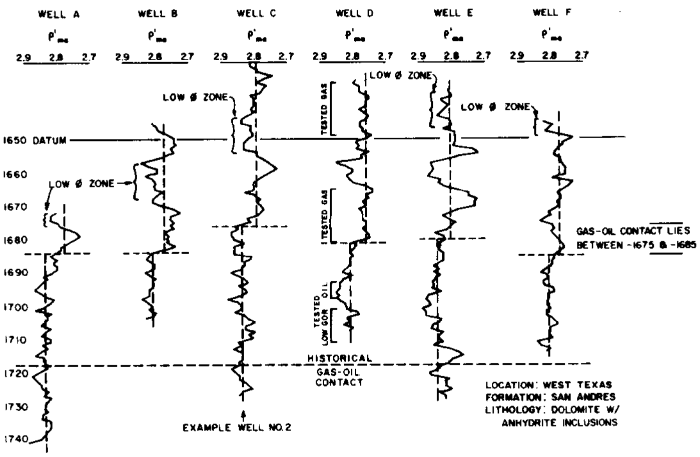

FIGURE 11—EAST-WEST CROSS SECTION SHOWING GAS-OIL CONTACT

SUMMARY AND CONCLUSIONS

This simple extension of conventional dual-porosity log analysis can be used to determine the presence of gas and the gas-liquid contact easily and accurately when excessive flushing of formation porosity causes the results of conventional analysis techniques to be minimized. The only requirements are a combination of any two porosity logs and a relatively consistent lithology. This procedure requires only the following steps:

1. Digitize the porosity logs through the zone of interval.
2. Determine the cross-plot porosity for the digitized interval.
3. Determine the apparent matrix density.
4. Determine the gas-liquid contact by visual inspection of an apparent matrix-density depth graph.

Although not developed in this paper, this technique can be applied for combinations of porosity devices other than the neutron and density log combination. The decentralized neutron- and sonic-porosity logs may be used together or in combination with the density or compensated neutron tool. However, the sonic or density device should be part of the combination for ease of analysis. The neutron-density combination was used for this paper since it is becoming a popular combination. The Appendix includes the development of a matrix transit-time cross-plot for the sonic log which can be used in the same manner as the matrix-density cross-plot.

NOMENCLATURE

SYMBOL	DEFINITION
ρ_a	Apparent Density, gm/cc
ρ_b	Bulk Formation Density, gm/cc
ρ_f	Fluid Density, gm/cc
ρ_{ma}	Matrix Density, gm/cc
ρ'_{ma}	Apparent Matrix Density, gm/cc
Δt_l	Formation Transit, Time, μ sec/ft
$\Delta t'_{ma}$	Fluid Transit Time, μ sec/ft
Δt_{ma}	Matrix Transit Time, μ sec/ft
Δt_f	Apparent Matrix Transit Time, μ sec/ft
ϕ	Porosity, fraction
ϕ_N	Neutron Porossity, fraction
ϕ_x	Cross-Plot Porosity, fraction

REFERENCES

1. "Log Interpretation, Volume 1 - Principles," Schlumberger Well Services, 1972.
2. "Log Interpretation, Volume II - Applications," Schlumberger Well Services, 1974.
3. "Log Interpretation Charts," Schlumberger Well Services, 1977.
4. "Log Review 1," Dresser Atlas Wireline Services, 1974.

APPENDIX

The sonic logging device measures the time required for sound waves to travel through the formation immediately adjacent to the bore hole. The sonic response, like the response of the radioactive porosity devices, is affected by the type of fluid in the pore spaces. However, since the induced sound wave travels primarily through the first in. or two of the formation around the bore hole, flushing excessive enough to mask the gas effects on the deeper-investigating neutron or density tools may cause the formation to be almost completely flushed within this shallow interval and result in minimal effect on the sonic response. Therefore, use of this tool with the neutron or density tools may not give as good an answer as the neutron-density combination. In addition, the sonic log can only be used in the absence of secondary porosity.

Figure 12 is a graph of the Wiley Equation solved in terms of matrix transit time and porosity. Notice that the density relationship is analogous to this transit time function. Figure 13 is a matrix transit time cross-plot which is simply a multiple solution of the Wiley Equation for a specific fluid and porosity interval. Using the sonic log response and the neutron log response to arrive at a lithologically normalized porosity and using the matrix transit time, Table 2 can be constructed. A graph of Apparent Matrix Transit Time and Depth, Figure 14, shows the location of the gas-oil contact in the example well.

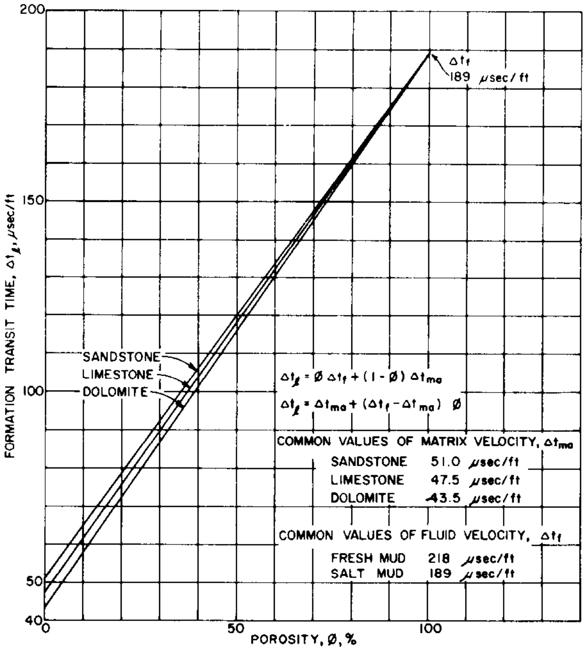

FIGURE 12—FORMATION TRANSIT TIME VS. POROSITY

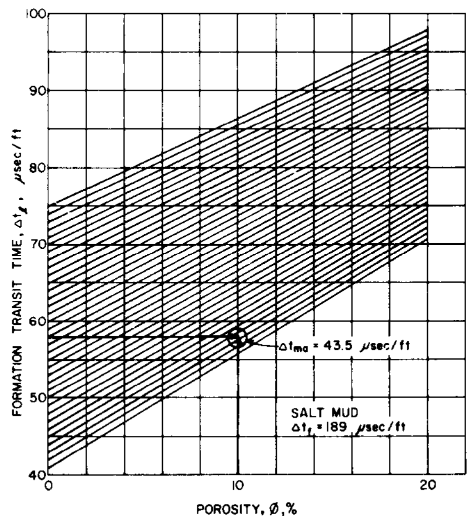

FIGURE 13—MATRIX TRANSIT-TIME CROSS-PLOT

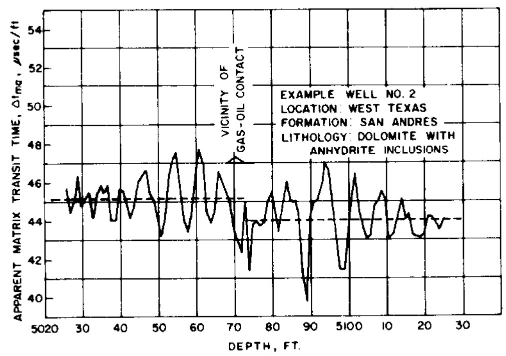

FIGURE 14—APPARENT MATRIX TRANSIT TIME VS. DEPTH

Log Depth Ft	Neutron Log Porosity $Ø_N$, %	Sonic Log Transit Time Δt_ℓ, μsec/ft	Cross-Plot Porosity %	Apparent Matrix Transit Time $\Delta t'_{ma}$, μ sec/ft
5026	12.0	58.0	8.5	45.8
7	14.0	56.6	8.4	44.4
8	13.5	57.4	8.7	45.0
9	12.0	60.4	9.8	46.3
30	16.0	59.2	10.1	44.8
⋮	⋮	⋮	⋮	⋮
5065	14.0	57.1	8.7	44.5
6	10.5	58.9	8.6	46.6
7	12.0	59.9	9.5	46.2
8	14.0	60.2	10.2	45.6
9	15.0	58.8	9.7	45.0
70	16.5	56.1	8.7	43.5
1	16.0	54.1	7.6	43.0
2	14.0	53.9	8.0	42.2
3	12.0	54.9	6.9	45.0
4	13.0	55.1	7.4	41.3
5	15.0	55.4	8.0	43.8
6	15.0	56.2	8.4	44.0
7	15.0	55.1	7.9	43.7
8	14.0	54.4	7.3	43.9
9	13.0	56.9	8.3	45.0
80	12.0	57.1	8.1	45.5
1	12.0	53.4	6.4	44.1
2	14.0	52.4	6.3	43.4
3	12.0	54.4	6.5	45.0
4	13.0	54.6	6.0	46.0
5	15.0	54.7	6.8	45.0
⋮	⋮	⋮	⋮	⋮
5120	17.0	56.2	8.9	43.2
1	15.0	56.9	8.7	44.2
2	15.0	56.6	8.6	44.2
3	14.5	53.9	7.0	43.8
4	14.0	52.6	6.3	43.4
5125	12.5	53.2	6.3	44.0

TABLE 2—LOG DATA