Potential Uses for Borehole Logs in Mineral Exploration

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Abstract

The oil industry uses borehole measurements of electrical characteristics, radioactivity, density and other physical properties to determine quantitatively rock and fluid properties of significance. These same borehole measurements are available to the mining industry for quantitative calculations. Standard measuring devices which are lowered into the borehole on electrical cables are available to measure resistivity, natural gamma radiation, density, velocity of sound and hydrogen index (neutron porosity).

The range of values covered by the measuring instruments has been plotted so that, when measurements of the properties of the various rocks and fluids encountered in a borehole are superimposed on this plot, one can determine which of these measurements provides the resolution necessary to make quantitative calculations.

To demonstrate the use of the technique, typical rock and fluid mixtures encountered in petroleum and potash exploration are shown. Some rock mixtures encountered in coal and metallic mineral exploration are next examined to determine the resolution available and an attempt is made to predict the performance of the logs in the various rock mixtures.

Introduction

DURING THE PAST 30 YEARS, the art or science of well-log interpretation has evolved into a standard technique employed by the petroleum industry. The use of logs for geological correlation and subsurface mapping was first developed and still represents a large proportion of the usage. This application is well known in both the mining and petroleum industries, and will not be a part of this discussion.

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The use of wireline well logs for quantitative analysis has been the object of most of the research and technical development during the past 30 years, and has been the subject of the majority of publications during that same period. Technical development has resulted in a bewildering variety of logging devices with different trade names. We will examine the physical properties of the materials encountered by the boreholes, compare them with the range of values which available measuring devices can detect, and try to reach some conclusion regarding the requirements for successful quantitative measurements in various rock and mineral combinations.

In order to avoid involvement with the individual devices and their various features, we will assume that, most of the time, measurements of the following parameters can be made in fluid-filled boreholes:

(1) Electrical Resistivity
(2) Sound Velocity (sonic)
(3) Density
(4) Natural Gamma Radiation
(5) Hydrogen Index (often called neutron porosity)

Range of Available Measurements

Figure 1 shows the approximate range of response of the available measuring devices to the five parameters. The range of values on the chart corresponds roughly to one full track width on a recorded log. Figure 2 shows the properties of two frequently encountered materials in a borehole, sandstone and formation water, superimposed on Figure 1. The distance between the bars represents the total resolution available for us to distinguish between sandstone and water. The log readings will be somewhere between the bars. If the log reading is plotted on the chart, the distance from the log reading to the bar representing water will be inversely proportional to the percentage of water. The same applies to the log reading and the bar representing sandstone. In this example, all measurements display substantial resolution between sandstone and water, except the gamma ray.

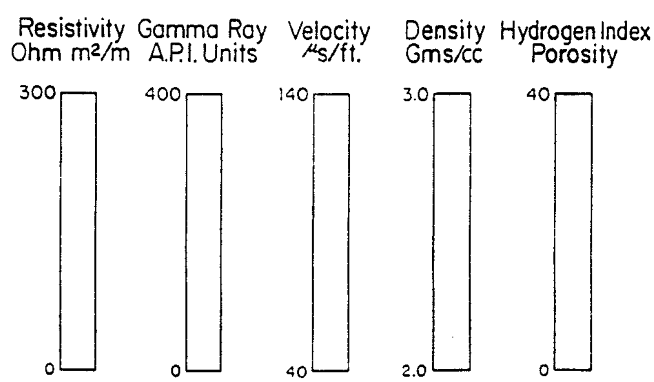

FIGURE 1 — Well Logging Parameters — range of available measurements.

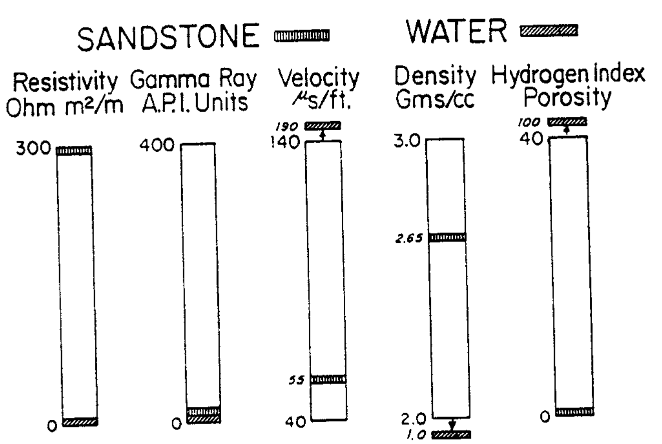

FIGURE 2 — Well Logging Parameters — sandstone and water.

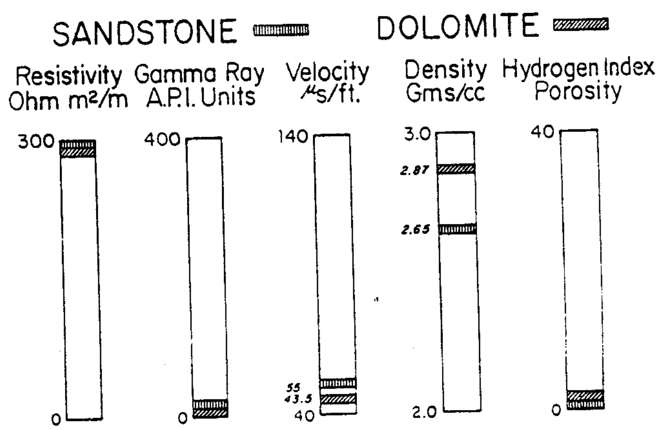

FIGURE 3 — Well Logging Parameters — sandstone and dolomite.

Figure 3 shows the values for sandstone and dolomite. It is apparent that the resolution for all logging tools is substantially less between sandstone and dolomite than it is between either of those rocks and water. This is one of the reasons why it is easier to establish porosity, which is a measure of water content, than it is to establish lithology.

Shale is a special case, because it is a mixture of chemical compounds, and we must use a range of values for the shale parameters. Figure 4 shows the values plotted on the chart. Considerable effort is normally devoted to the determination of shale properties.

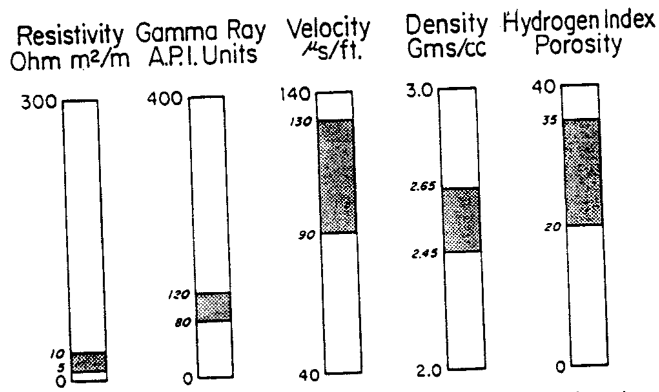

FIGURE 4 — Well Logging Parameters — range of values for shale.

Quantitative Analysis

The usual method of calculating percentages is by linear interpolation of the log reading between the end points to solve for the percentage of the material present. As an example, from Figure 1, consider the density log. The end point in this case is 1.0 for water and 2.65 for sandstone, and the log will read somewhere between these two points, depending on the proportions of the two materials present in the mixture. This relationship can be expressed algebraically as follows:

$$(DS)X + (DW)Y = DENS \quad \text{(1)}$$

DS = grain density of the sandstone
DW = density of the water
X = percentage of sandstone present in the mixture (as a fraction)
Y = percentage of water present in the mixture (as a fraction)
DENS = reading from density log

Assuming for this example that only the two materials, sandstone and water, are present, then:

$$X + Y = 100 \text{ per cent, or } 1.0 \quad \text{(2)}$$

Equations (1) and (2) can now be solved for X and Y to give the percentages of the two materials present:

$$X = (1 - Y)$$

Substitute in equation (1)

$$DS(1 - Y) + DW(Y) = DENS$$
$$DS - DS(Y) + DW(Y) = DENS$$
$$Y(DW - DS) = DENS - DS$$
$$Y = \frac{DENS - DS}{DW - DS}$$

We have now calculated the percentage of water (which is the porosity in a water-saturated sandstone) in terms of the log reading and the characteristics of the two materials as seen by the density log.

An arbitrary assumption will be made that 10 per cent of the track width of a log recording is the minimum deflection of the instrument in which we can have confidence. The percentage is different for each measuring instrument and depends to some extent on recording techniques. A full discussion of this point is not in order here and the assumed 10 per cent is adequate for illustrative purposes.

$$Y_1 - Y = \frac{DENS_1 - DS}{DW - DS} - \frac{DENS - DS}{DW - DS} \quad \text{(3)}$$

$$Y_1 - Y = \frac{DENS_1 - DENS}{DW - DS}$$

where: $DENS_1$ = the density log reading after the 10 per cent change
$DENS_1 - DENS$ = 10 per cent of full-track deflection
$Y_1 - Y$ = the porosity change corresponding to 10 per cent of full-track deflection

Inasmuch as these relationships are assumed to be linear, the term $Y_1 - Y$ can be interpreted as the minimum percentage of water that can be detected with a 10 per cent change in log reading.

If the numerical values of the sandstone and water densities are put in equation (3), we can solve for the minimum water percentage or porosity that we can detect with a density log:

$DENS_1 - DENS = 0.1$ = 10 per cent of full-scale deflection
$DW = 1.0$
$DS = 2.65$

$$Y_1 - Y = \frac{0.1}{1.0 - 2.65} = -0.06, \text{ or 6 per cent}$$

The negative sign only indicates that the porosity varies inversely as the density.

We can interpret this to mean that a porosity lower than 6 per cent cannot be reliably detected with a density log. If we make the equation more general, it can be used for any combination of two materials and any logging device.

$$\text{Minimum detectable occurrence} = \frac{10\% \text{ of full-scale deflection}}{M_1 - M_2} \quad \ldots\ldots (4)$$

where M_1 = the response of the device to material No. 1
M_2 = the response of the device to material No. 2

A knowledge of the measurable physical properties of the mineral that we are looking for, and of the host rock, can give us an estimate of the resolution available from the logging devices. A simple calculation involving the response of the measuring devices and the resolution will give the minimum percentage of the mineral that it will be feasible to detect.

Our previous example of sandstone and water represented a mixture in which good resolution exists A sandy dolomite would represent a condition of poor resolution from the density log. If we consider dolomite to be the host rock, then from equation (4) the minimum detectable percentage of sand will be:

$$\frac{0.1}{2.65 - 2.87} = \frac{0.1}{-.22} = -.45, \text{ or } 45 \text{ per cent}$$

Computer Solution of Equations

The simultaneous equations developed at the beginning of the paper, equations (1) and (2), are often expanded to include several logs and take the following form:

$$L_1(X) + L_2(Y) + L_3(Z) = \text{Log } 1$$
$$M_1(X) + M_2(Y) + M_3(Z) = \text{Log } 2$$
$$N_1(X) + N_2(Y) + N_3(Z) = \text{Log } 3$$
$$X + Y + Z = 1$$

where: L_1, M_1 and N_1 are the responses of mineral No. 1 to the measuring devices Log 1, Log 2, and Log 3, which are logging different physical characteristics.
L_2, M_2 and N_2 are the responses of mineral No. 2 to the measuring devices, and L_3, M_3 and N_3 represent the response to mineral No. 3. X, Y and Z are the percentages of minerals No. 1, 2 and 3, respectively.
The assumption is made that the sum of the minerals present equals 100 per cent.

It is then possible to solve for one more rock or mineral type than there are measurements. Computer programs exist that generate results for as many as six different measurements. The validity of the answers, however, still depends on the resolution available. Most programs do not acknowledge that answers have been calculated from varying degrees of resolution available from the measurements of physical properties.

POTASH

Figure 5 is an example of a computer solution in a potash deposit. The example is from Reference 1 and shows a comparison between log and core analysis through the Prairie Evaporite Formation in Saskatchewan. It was the first application of the simultaneous equation technique in Canada. The host rock in this deposit is halite and the mineral of economic interest is sylvite. Figure 6 shows the resolution between sylvite and halite. In this case, measurements of natural radioactivity provided the resolution to detect the sylvite. The minimum detectable percentage will be, from equation (4):

$$\frac{40}{400 - 0} = 0.1, \text{ or } 10 \text{ per cent}$$

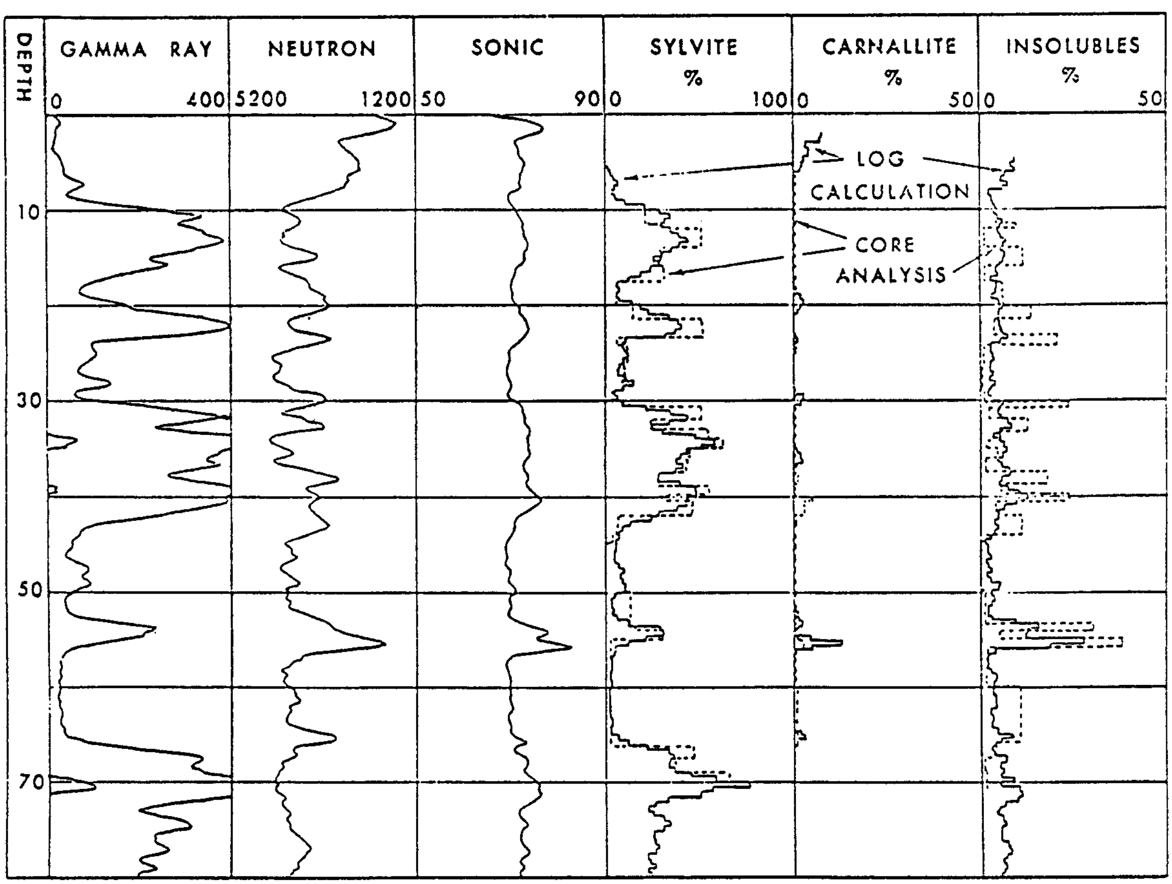

FIGURE 5 — Comparison of well log analysis and core analysis through a potash deposit in Saskatchewan.

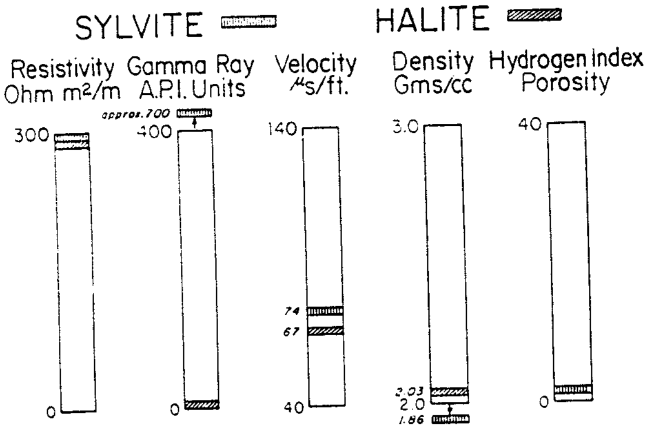

FIGURE 6 — Well Logging Parameters — sylvite and halite.

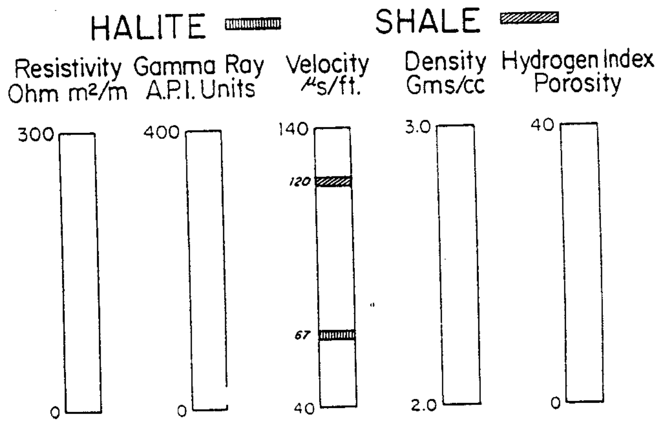

FIGURE 7 — Well Logging Parameters — halite and shale.

For the sylvite determination, the two necessary requirements exist — good resolution and a percentage occurrence well above the minimum detectable.

Of special interest in this example is the insoluble (mostly shale) content of the orebody, which is determined from sonic log measurements. Figure 7 shows the degree of resolution available and the minimum detectable percentage is 10/(120-67) = 0.18, or 18 per cent. The shale content of the formations, as determined from the core analysis, is approximately 5 per cent, with four or five thin streaks of up to 20 per cent over the 60-foot section. The percentage occurrence is well below the minimum of 18 per cent and we can see from the plot of Figure 5 that the log-calculated values of insolubles agree much less closely with the core analyses than those for the sylvite determination.

COAL

Coal must be treated differently because, in a coal deposit, the host rock is coal and we are concerned with impurities

The physical properties of coal vary with grade, moisture and ash content. The range of physical properties result in sonic, density and neutron porosity values that are noticeably different than the values for other sedimentary rocks in which the coal may be deposited. The coal appears as a rock with an unusually high water content. As a result, the identification of coal deposits is relatively straightforward. Figure 8 shows a 12-foot coal bed (from 158 to 170 ft) encountered by a well in central Alberta.

The range of physical properties of coal is too wide for adequate quantitative analysis, although it is satisfactory for identification. The range of coal properties is included in Table 1.

Reports of successful quantitative log analyses are available where coal is treated as the host rock and ash and moisture percentages are determined. The values used for the constants in the simultaneous equations were not listed. They would, in any case, be usable for only the one coal deposit.

OTHER

Figure 9 is a portion of a density log run in a well drilled through the iron ore deposit north of Prince Albert, Saskatchewan. The density reading is mostly on the second scale of 3.0 to 4.0 and the readings go as high as 3.25 gms/cc.

This deposit is magnetite and the host rock is quartz. By substituting the density values for magnetite (4.5 gms/cc) and quartz (2.65 gms/cc) in equations (1) and (2), magnetite percentage values of 19 and 33 can be established for log readings of 3.0 and 3.25 respectively. Available information on the ore deposit suggests that the average magnetite content is 45 per cent. The log-calculated values appear to be too low, even though the conditions are favourable for quanti-

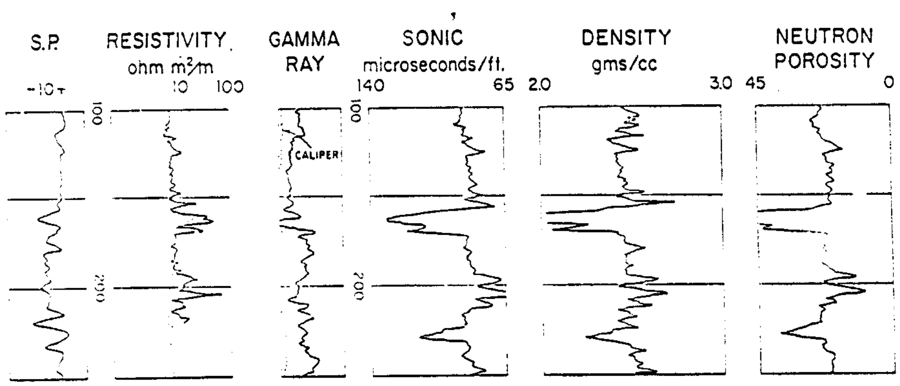

FIGURE 8 — Well logs run in a well drilled through a coal deposit.

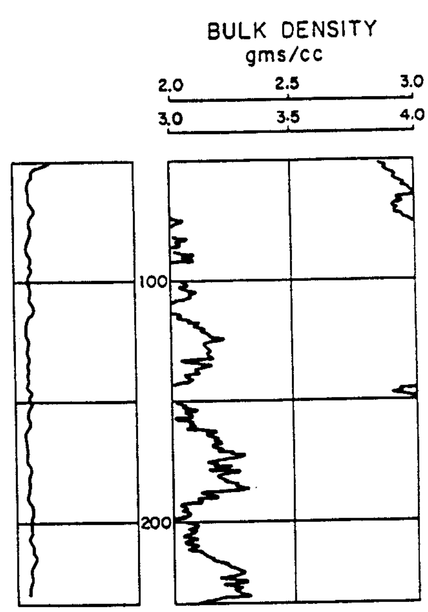

FIGURE 9 — (right) — Density log run in a well drilled through an iron ore deposit showing high densities.

tative determinations. A possible explanation for this discrepancy lies in the calibration of the density log. It is customary to calibrate the devices up to a maximum density of 3.0 gms/cc; the response of the tools is not known above this. Calibration for the higher density range is feasible and could be provided with advance notice.

Conclusions

It has been shown that two requirements are necessary to achieve successful quantitative log analysis. The first is that a sufficient degree of resolution must exist for one or more of the measuring devices to detect the mineral of interest. The second requirement is that the mineral of interest must be present in sufficient quantity to be detected. The minimum detectable percentage is easily calculated and depends on the degree of resolution.

The widespread usage of quantitative log analysis in the petroleum industry is based mainly on the ability of the resistivity, sonic, density and neutron devices to discriminate between the common sedimentary rocks and water.

The available devices can provide a similar degree of discrimination between many combinations of rocks and minerals of interest to the mining industry. The methods presented here will be useful in predicting when quantitative determinations can be made with currently available tools, and hopefully will encourage the research necessary to provide the additional information on the physical properties of rocks and minerals necessary for quantitative log analysis.

Table 1 shows some of the commonly accepted values of physical properties for rocks and minerals. Available information on most minerals excludes data on resistivity, sound velocity and neutron log response.

TABLE 1 — Values for Physical Properties of Rocks and Minerals

Mineral	Composition	*Apparent Log Density gms/cc	Sonic Delta T micro-second/ft	Hydrogen Index % Porosity
Limestone	$CaCO_3$	2.71	47.5	0
Dolomite	$CaMg(CO_3)_2$	2.876	43.5	4
Quartz	SiO_2	2.65	51.5	0
Anhydrite	$CaSO_4$	2.977	50	0
Halite	NaCl	2.032	67	0
Sylvite	KCl	1.86	74	0
Carnalite	$KCl.MgCl_2.6H_2O$	1.57	78	65
Lignite		0.7-1.5	140-170	High 50%
Bituminous Coal		1.3-1.5	110-140	High 50%
Anthracite Coal		1.4-1.8	—	High 50%
Magnetite	Fe_3O_4	4.45	55.6	—
Hematite	Fe_2O_3	3.89	—	—
Galena	Pbs	6.17	—	—
Sphalerite	ZnS	3.85	—	—

$$\text{*Apparent log density} = \text{true density} \times \frac{2Z}{A}$$

Z = atomic number
A = atomic weight

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