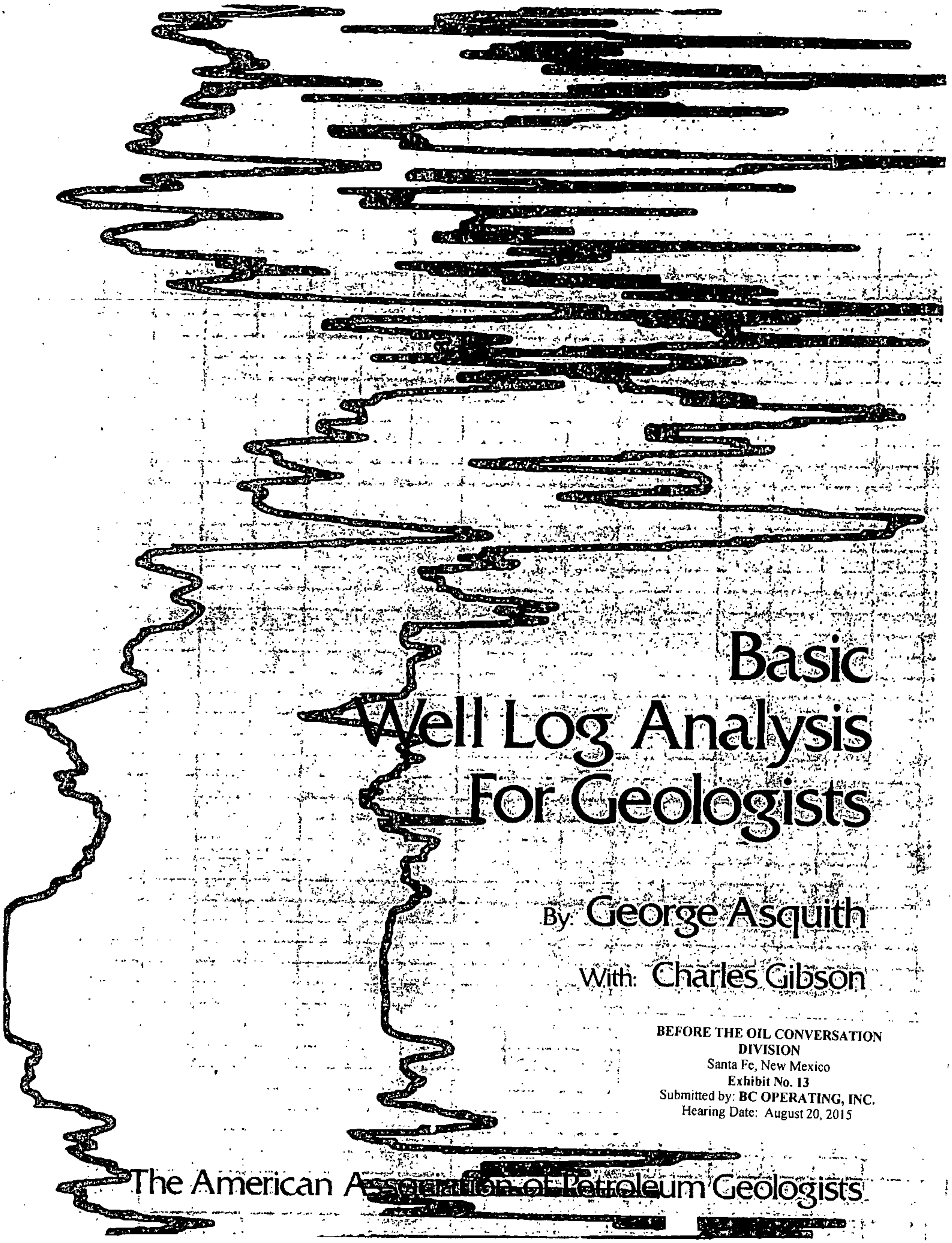

Basic Well Log Analysis For Geologists

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(i.e. sandstone, limestone, or dolomite). Porosity logs require a lithology or a matrix constant before a zone's porosity (ϕ) can be calculated. And the formation factor (F), a variable used in the Archie water saturation equation ($S_w = \sqrt{F \times R_w/R_t}$), varies with lithology. As a consequence, water saturations change as F changes. Table 1 is a list of the different methods for calculating formation factor and illustrates how lithology affects the formation factor.

Temperature of Formation—Formation temperature (T_f) is also important in log analysis because the resistivities of the drilling mud (R_m), the mud filtrate (R_{mf}), and the formation water (R_w) vary with temperature. The temperature of a formation is determined by knowing: (1) formation depth; (2) bottom hole temperature (BHT); (3) total depth of the well (TD); and (4) surface temperature. You can determine a reasonable value for the formation temperature by using these data and by assuming a linear geothermal gradient (Fig. 8).

Table 1. Different Coefficients and Exponents Used to Calculate Formation Factor (F). (Modified after Asquith, 1980).

$F = a/\phi^m$	general relationship Where: a = tortuosity factor* m = cementation exponent ϕ = porosity
†$F = 1/\phi^2$	for carbonates
†$F = 0.81/\phi^2$	for consolidated sandstones
†$F = 0.62/\phi^{2.15}$	Humble formula for unconsolidated sands
$F = 1.45/\phi^{1.54}$	for average sands (after Carothers, 1958)
$F = 1.65/\phi^{1.33}$	for shaly sands (after Carothers, 1958)
$F = 1.45/\phi^{1.70}$	for calcareous sands (after Carothers, 1958)
$F = 0.85/\phi^{2.14}$	for carbonates (after Carothers, 1958)
$F = 2.45/\phi^{1.08}$	for Pliocene sands, Southern California (after Carothers and Porter, 1970)
$F = 1.97/\phi^{1.29}$	for Miocene sands, Texas-Louisiana Gulf Coast (after Carothers and Porter, 1970)
$F = 1.0/\phi^{(2.05 - \phi)}$	for clean granular formations (after Sethi, 1979)

*Tortuosity is a function of the complexity of the path the fluid must travel through the rock.
†Most commonly used.

The formation temperature is also calculated (Asquith, 1980) by using the linear regression equation:

$$y = mx + c$$

Where:
- x = depth
- y = temperature
- m = slope—in this example it is the geothermal gradient
- c = a constant—in this example it is the surface temperature

An example of how to calculate formation temperature is illustrated here:

Temperature Gradient Calculation

Assume:
- y = bottom hole temperature (BHT) = 250°F
- x = total depth (TD) = 15,000 ft
- c = surface temperature = 70°F

Solve for m (i.e. slope or temperature gradient)

$$m = \frac{y - c}{x}$$

Therefore:

$$m = \frac{250° - 70°}{15{,}000 \text{ ft}}$$

$$m = 0.012°/\text{ft or } 1.2°/100 \text{ ft}$$

Formation Temperature Calculation

Assume:
- m = temperature gradient = 0.012°/ft
- x = formation depth = 8,000 ft
- c = surface temperature = 70°

Remember:

$y = mx + c$

Therefore:

$y = (0.012) \times (8{,}000) + 70°$
$y = 166°$ formation temperature at 8,000 ft

After a formation's temperature is determined either by chart (Fig. 8) or by calculation, the resistivities of the different fluids (R_m, R_{mf}, or R_w) can be corrected to formation temperature. Figure 9 is a chart that is used for correcting fluid resistivities to formation temperature. This chart is closely approximated by the Arp's formula:

$$R_{Tf} = R_{temp} \times (Temp + 6.77)/(T_f + 6.77)$$

Where:
- R_{Tf} = resistivity at formation temperature
- R_{temp} = resistivity at a temperature other than formation temperature

Temp = temperature at which resistivity was measured
T_f = formation temperature

Using a formation temperature of 166° and assuming an R_w of 0.04 measured at 70°, the R_w at 166° will be:

$$R_{w166} = 0.04 \times (70 + 6.77)/(166 + 6.77)$$
$$R_{w166} = 0.018$$

Resistivity values of the drilling mud (R_m), mud filtrate (R_{mf}), mudcake (R_{mc}), and the temperatures at which they are measured, are recorded on a log's header (Fig. 2). The resistivity of a formation's water (R_w) is obtained by analysis of water samples from a drill stem test, a water producing well, or from a catalog of water resistivity values. Formation water resistivity (R_w) is also determined from the spontaneous potential log (discussed in Chapter II) or can be calculated in water zones (i.e., S_w = 100%) by the apparent water resistivity (R_{wa}) method (see Chapter VI).

Fundamental Equations

Table 2 is a list of fundamental equations that are used for the log evaluation of potential hydrocarbon reservoirs. These formulas are discussed in detail in subsequent chapters.

Table 2. Fundamental Equations of Well Log Interpretation.

Porosity:

Sonic Log $$\phi_{SONIC} = \frac{\Delta t - \Delta t_{ma}}{\Delta tf - \Delta t_{ma}}$$

Density Log $$\phi_{DEN} = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Neutron-Density Log $$\phi_{N\text{-}D} = \sqrt{\frac{\phi_N^2 + \phi_D^2}{2}}$$

Formation Factor:

$F = a/\phi^m$	General
$F = 1.0/\phi^2$	Carbonates
$F = 0.81/\phi^2$	Consolidated Sandstones
$F = 0.62/\phi^{2.15}$	Unconsolidated Sands

Formation Water Resistivity:

$$SSP = -K \times \log(R_{mf}/R_w)$$
$$R_{we} \rightarrow R_w$$
$$R_w = \frac{R_o}{F}$$

Water Saturations:

$S_w^{n\dagger} = F \times (R_w/R_t)$	water saturation uninvaded zone
$S_{xo}^n = F \times (R_{mf}/R_{xo})$	water saturation flushed zone
$S_w = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w}\right)^{0.625}$	water saturation ratio method

Bulk Volume Water:

$$BVW = \phi \times S_w$$

Permeability

$K_e = [250 \times (\phi^3/S_{w\,irr})]^2$ oil
K_e = permeability in millidarcies
$K_e = [79 \times (\phi^3/S_{w\,irr})]^2$ gas
$S_{w\,irr}$ = irreducible water saturation

†n = saturation exponent which varies from 1.8 to 2.5 but most often equals 2.0

Review - Chapter I

1. The four most fundamental rock properties used in petrophysical logging are (1) porosity; (2) permeability; (3) water saturation; and (4) resistivity.

2. The Archie equation for water saturation is:

$$S_w = \left(\frac{F \times R_w}{R_t}\right)^{1/n}$$

Where:

S_w = water saturation of uninvaded zone
F = formation factor
R_w = formation water resistivity
R_t = formation resistivity (uninvaded zone)

3. Where a porous and permeable formation is penetrated by the drill bit, the drilling mud invades the formation as mud filtrate (R_{mf}).

4. The invasion of the porous and permeable formation by mud filtrate creates invasion zones (R_{xo} and R_i) and an uninvaded zone (R_t). Shallow, medium, and deep reading resistivity logging tools provide information about the invaded and uninvaded zones and about the depth of invasion.

5. The lithology of a formation must be known because: (1) porosity logs require a matrix value—sandstone, limestone, or dolomite—in order to determine porosity; (2) the formation factor varies with lithology; (3) the variation in formation factor causes changes in water saturation values.

6. The four fluids that affect logging measurements are: (1) drilling mud, R_m; (2) mud filtrate, R_{mf}; (3) formation water, R_w; and (4) hydrocarbons.

7. The resistivities of the drilling mud (R_m), mudcake (R_{mc}), mud filtrate (R_{mf}) and formation water (R_w) all vary with changes in temperature. Consequently, a formation's temperature (T_f) must be determined and all resistivities corrected to T_f.