Common Openhole Petrophysics Interpretation Equations

Comments

The equations on the following pages convert the measurements commonly made in open (uncased) boreholes into the formation properties of scientific and economic interest to us; those being porosity, fluid saturation, and lithology. There are also equations which take us from some of the measurements to calculation parameters that are needed in some of the equations, such as formation water resistivity, Rw.

The listing of the equations follows a generic workflow. In this workflow, the order of the steps may sometimes change, and all the workflow steps may not be used. The steps in the workflow and the measurements used are as follows:

Workflow	***Measurement group*:** Measurements
• Is the data valid? • Where is the reservoir?	*Correlation/Reservoir:* Gamma ray, SP, Caliper, Tension
• Is there sufficient porosity? • Is the lithology different than expected, or varying in some way?	*Porosity and Lithology:* Acoustic slowness, bulk density, neutron porosity. Combinations of acoustic slowness, bulk density, photoelectric effect, neutron porosity.
• What are the fluids in place? • What fluids will be produced?	*Resistivity/Fluid saturation:* Induction and laterologs, both close to and away from the borehole, with porosity.

The Measurement Groups, above, are how the measurements are grouped in two courses that have been taught (with revisions) for decades: *Basic Well Log Analysis* and *Basic Openhole Log Interpretation*. The groupings are based on the targets or goals of the measurements, and not the physics of the measurements, as the measurement targets are more in line with the general workflow.

The references are listed on the last page of this document.

This document is intended to be updated periodically as necessary to include new and corrected information.

Questions and comments about this document are welcomed and encouraged. Please contact Dan Krygowski at The Discovery Group; DanKrygowski@Discovery-Group.com.

Common Openhole Petrophysics Interpretation Equations

Determination of formation temperature

$$FmTemp = \left(\frac{BHT - AMST}{TD} * FD \right) + AMST$$

Where: BHT = Bottom Hole Temperature
TD = Total Depth; FD = Formation Depth
AMST = Annual Mean Surface Temperature

Temperature conversion of resistivity

$$R_{FmTemp} = \frac{R_{MeasTemp} * (MeasTemp + C)}{FmTemp + C}$$

Where: MeasTemp = Measured Temperature
FmTemp = Formation Temperature
For °F, C = 6.77; for °C, C = 21.3

Arps, 1953

Formation water resistivity, Rw

From the SP

First order: *Wyllie, 1949*

$$Rw = 10^{(K \cdot \log(Rmf) + SP)/K}$$

Where K = 61 + 0.133*FmTemp

Rweq method (preferred): *Gondouin et al, 1957*

$$Rweq = Rmf * 10^{\left(\frac{SSP}{61 + 0.133 * Fm.Temp} \right)}$$

$$Rw = \frac{Rweq + 0.131 * 10^{[1/\log(Fm.Temp/19.9)] - 2}}{-0.5 * Rweq + 10^{[0.0426/\log(Fm.Temp/50.8)]}}$$

Shale/Clay Volume

Spontaneous Potential

(no reference found)

$$Vsh = \frac{SPclean - SP\log}{SPclean - SPshale}$$

Neutron Porosity and Density Porosity

(no reference found)

$$Vsh = \frac{PhiN - PhiD}{PhiN_{shale} - PhiD_{shale}}$$

Gamma Ray

Linear: (no reference found)

$$I_{GR} = Vsh = \frac{GR\log - GRclean}{GRshale - GRclean}$$

Clavier (Clavier et al, 1971):

$$Vsh = 1.7 - \left[3.38 - (I_{GR} + 0.7)^2 \right]^{\frac{1}{2}}$$

Steiber (1970):

$$Vsh = \frac{I_{GR}}{(3.0 - 2.0 \cdot I_{GR})}$$

Larionov (Tertiary) (1969):

$$Vsh = 0.083 \cdot (2^{(3.7 \cdot I_{GR})} - 1.0)$$

Larionov (older rocks) (1969):

$$Vsh = 0.33 \cdot (2^{(2.1 \cdot I_{GR})} - 1.0)$$

Because logging measurements measure a volume in space, rather than a point in space, the SP and gamma ray usually measure “shale” rather than a specific clay. Given enough core information about the clays that are present, one can make that transition from working in shale-space to working in clay-space. Working in either “space” is adequate if one is consistent in the approach used.

Common Openhole Petrophysics Interpretation Equations

Porosity

Effective porosity (from any source) *(no reference found)*

$$PhiE = PhiT - Vsh * PhiXsh$$

where PhiT = Total porosity
PhiXsh = porosity in a nearby shale

Bulk Density *(no reference found)*

$$PhiD = \frac{RHOma - RHOB}{RHOma - RHOfl}$$

Neutron *(no reference found)*

Neutron porosity is referenced to a specific lithology. Conversion of porosity is dependent on the company that ran the log, the generation of the neutron tool, and often the specific curve name.

Sonic

Wyllie Time-Average:

Wyllie et al, 1958; Tixier et al, 1959

$$PhiS = \frac{DT - DTma}{DTfl - DTma} * \frac{1}{Bcp} \qquad Bcp = \frac{DTshale}{100} \geq 1.0$$

Empirical/Field Observation:

Raymer et al, 1980; Baker Hughes, 2003

$$PhiS = -\alpha - \left[\alpha^2 + \frac{DTma}{DT} + 1\right]^{\frac{1}{2}} \qquad \alpha = \frac{DTma}{2 * DTfl} - 1$$

Empirical/Field Observation (simplified form):

AERA, 2007

$$PhiS = \frac{2}{3} * \frac{DT - DTma}{DT}$$

Neutron and Density *(no reference found)*

With both porosity curves referenced to limestone porosity units:

Liquid-filled holes:

$$PhiND = \frac{PhiN_{LS} + PhiD_{LS}}{2}$$

Gas-filled holes:

$$PhiND = \left(\frac{PhiN_{LS}^2 + PhiD_{LS}^2}{2}\right)^{\frac{1}{2}} \cong \left(\frac{1}{3} * PhiN_{LS} + \frac{2}{3} * PhiD_{LS}\right)$$

See also the Characteristic Logging Tool Responses *table for additional matrix and fluid values.*

Lithology from porosity logs

M-N plots *Burke et al, 1969*

$$M = \left(\frac{DTfl - DT}{RHOB - RHOfl}\right) * C$$

$$N = \left(\frac{1 - PhiNls}{RHOB - RHOfl}\right) * D$$

*MID (**M**atrix **ID**entification) plots*

$$DTmaa = \frac{DT - (PhiNS * DTfl)}{1 - PhiNS}$$

$$RHOmaa = \frac{RHOB - (PhiND * RHOfl)}{1 - PhiND}$$

Clavier & Rust, 1976

Fluid values and constants		*Bulk density*		*Sonic slowness*		*Neutron porosity*	*C*	*D*
		g/cm³	*Kg/m³*	*µsec/ft*	*µsec/m*	*decimal*		
US Oilfield	*fresh*	*1.0*		*189*		*1*	*0.01*	*1*
	salt	*1.1*		*189*				
Metric	*fresh*	*1.0*			*620*	*1*	*0.003048*	*1*
	salt	*1.1*			*620*			
Canadian	*fresh*		*1000*		*620*	*1*	*3.048*	*1000*
	salt		*1100*		*620*			

$$Umaa = \frac{(Pe * RHOB) - (PhiND * Ufl)}{1 - PhiND}$$

Gardner & Dumanoir, 1980

Where…	*Fresh water*	*Salt water*
RHOfl (g/cm3)	1.0	1.2
DTfl(µsec/ft)	189	189
Ufl (b/cm3)	0.398	1.36

See also the Characteristic Logging Tool Responses *table for additional matrix and fluid values.*

Common Openhole Petrophysics Interpretation Equations

Water Saturation

Apparent water resistivity, Rwa *(no reference found)*

$$Rwa = \frac{Rt * Phi^{m}}{a} \qquad Sw = \left(\frac{Rwa_{minimum}}{Rwa_{zone}}\right)^{\frac{1}{n}}$$

Archie *(1942)*

$$Sw = \left[\frac{a * Rw}{Rt * Phi^{m}}\right]^{\frac{1}{n}}$$

Bulk Volume Water, BVW

Buckles, 1965; Morris & Biggs, 1967

$$BVW = Phi * Sw$$

$$BVWirr = Phi * Swirr$$

Permeability from logs

Timur (1968)

$$K = 62500 * \frac{Phi^{6}}{Sw_{irr}^{2}}$$

where Phi and Sw are in v/v decimal.

Tixier (no reference found)

$$K = \left(\frac{250 * Phi^{3}}{Sw_{irr}}\right)^{2}$$

Coates-Timur (NMR)

(no reference found)

$$MPERM = \left[\left(\frac{MPHI}{C}\right)^{2}\left(\frac{FFI}{BVI}\right)\right]^{2}$$

C = constant

SDR (Schlumberger Doll Research) (NMR)

(no reference found)

$$PERM = aT_{2gm}^{2} \cdot \phi^{4}$$

a = constant; T_{2gm} = T2 geometric mean

Mechanical Properties

Young's Modulus

$$E = \left(\frac{RHOB}{DTS^{2}}\right) \bullet \left(\frac{3DTS^{2} - 4DTC^{2}}{DTS^{2} - DTC^{2}}\right) \bullet 1.34 \times 10^{10}$$

Shear Modulus

$$\mu = \left(\frac{RHOB}{DT_{S}^{2}}\right) \bullet 1.34 \times 10^{10}$$

RHOB in g/cm^3

DTS, DTC in μsec/ft

Bulk Modulus

$$K = RHOB \bullet \left(\frac{3DTS^{2} - 4DTC^{2}}{3DTS^{2} - DTC^{2}}\right) \bullet 1.34 \times 10^{10}$$

Poisson's Ratio

$$\sigma = \frac{1}{2} \bullet \left(\frac{DTS^{2} - 2DTC^{2}}{DTS^{2} - DTC^{2}}\right)$$

Kowalski, 1975

Equation References

AERA Oil and Gas, ca 2007, Personal communication from an unnamed employee with contacts in Schlumberger Well Services, during a logging course.

Archie, G.E., 1942, The electrical resistivity log as an aid to determining some reservoir characteristics, *Petroleum Technology*, January; SPE of AIME.

Arps, J.J., 1953, The effect of temperature on the density and electrical resistivity of sodium chloride solutions, *Petroleum Transactions*, AIME.

Baker Hughes, 2003, *Log Interpretation Charts* (digital document), Baker Hughes Incorporated, Houston, Texas.

Buckles, R.S., 1965, Correlating and averaging connate water saturation data, *Journal of Canadian Petroleum Technology*, **9** (1), pp.42-52.

Burke, J.A., R.L. Campbell, Jr., A.W. Schmidt, 1969, The Litho-Porosity Crossplot: A New Concept for Determining Porosity and Lithology from Logging Methods, *Transactions, SPWLA Annual Logging Symposium*, Paper Y, Society of Petrophysicists and Well Log Analysts, Houston, Texas.

Clavier, C., Hoyle, W.R., Meunier, D., 1971, Quantitative interpretation of Thermal Neutron Decay Time logs; Part 1 – Fundamentals and techniques, JPT (**251**) June, pp. 743-755.

Clavier, C., D.H. Rust, 1976, MID Plot: A New Lithology Technique, *The Log Analyst*, November-December, Society of Petrophysicists and Well Log Analysts, Houston, Texas.

Gardner. J.S., J.L. Dumanoir, 1980, Litho-Density Log Interpretation, *Transactions, SPWLA Annual Logging Symposium*, Paper N, Society of Petrophysicists and Well Log Analysts, Houston, Texas.

Gondouin, M., M.P. Tixier, G.L. Simard, 1957, An experimental study on the influence of the chemical composition of electrolytes on the SP curve, SPE Paper 657-G.

Kowalski, John, 1975, Formation strength parameters from well logs, SPWLA Symposium Transactions, Paper N: Society of Petrophysicists and Well Log Analysts, Houston, Texas.Larionov, V.V., 1969, Borehole radiometry, Nedra, Moskwa.

Morris, R.L, and W.P. Biggs, 1967, Using log-derived values of water saturation and porosity; Society of Professional Well Log Analysts, 8th Annual Symposium Transactions, Paper X.

Raymer, L.L., E.R. Hunt, J.S. Gardner, 1980, An improved sonic transit time to porosity transform, Society of Professional Well Log Analysts, 21st Annual Logging Symposium. Transactions, Paper P, 9p.

Steiber, S.J., 1970, Pulsed Neutron Capture log evaluation in the Louisiana Gulf Coast, SPE Paper 2961, SPE Annual Meeting, Houston.

Timur, A., 1968, An investigation of permeability, porosity, and residual water saturation relationships for sandstone reservoirs; Society of Professional Well Log Analysts, The Log Analyst, (**9**), pp. 8 to 17.

Wyllie, M.R.J, 1949, A quantitative analysis of the electrochemical component of the S.P. curve, Jour. Petrol. Tech. (**1**)1, January, p.17.

Wyllie, M.R.J., A.R. Gregory, G.H.F. Gardner, 1958, An experimental investigation of the factors affecting elastic wave velocities in porous media, Geophysics, (**23**)3, p.459-493.