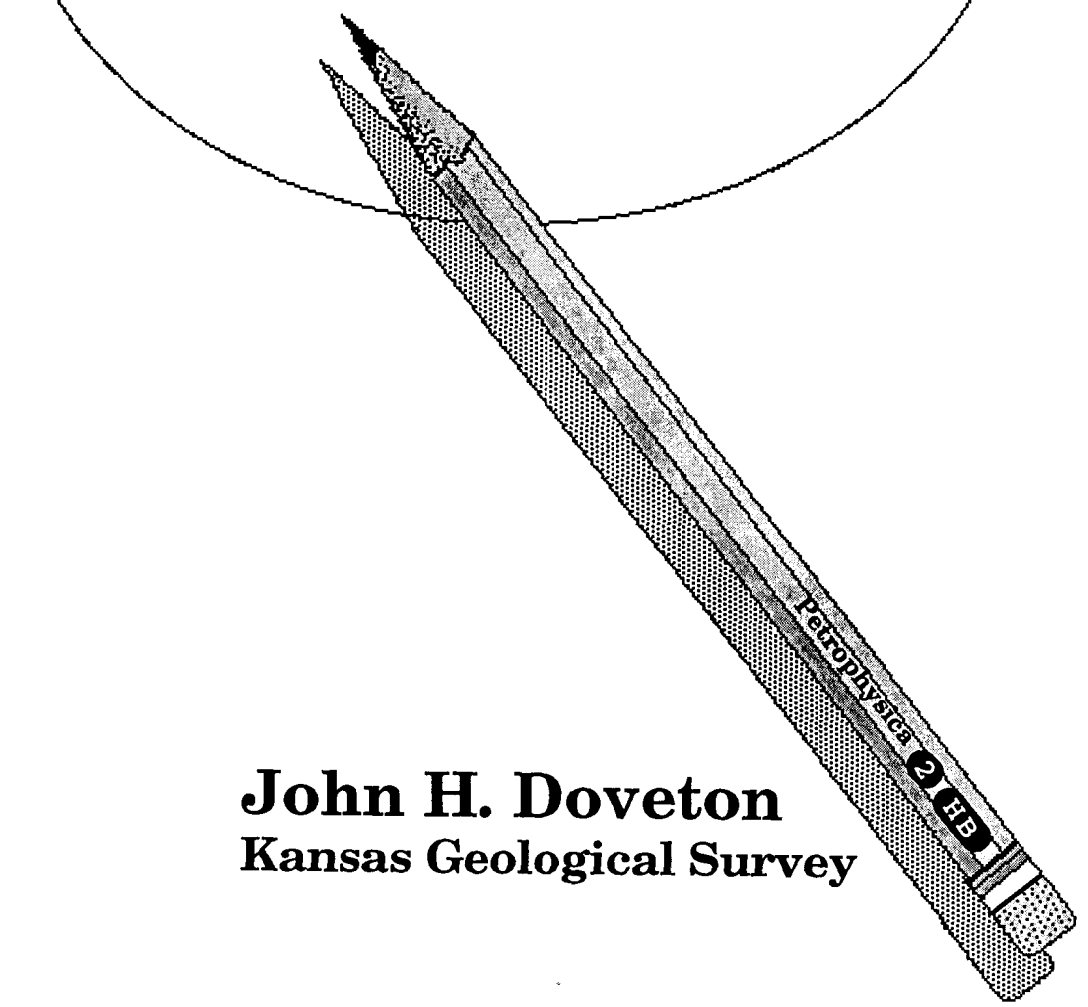
Basics of Oil & Gas Log Analysis



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RESISTIVITY LOGGING

In most runs of a resistivity tool, the major purpose is to obtain measurements of Rt, the true resistivity of the formation. However, there are a variety of complicating factors involved which may require corrections to be made to the recorded values in order to obtain good estimates of the true resistivities. All resistivity tools are to some extent "averaging" devices that record resistivities of zones rather than resistivities of discrete points. So, for example, the resistivity of a thin resistive horizon will generally be underestimated by most tools since its reading will be partly reduced by contributions of more conductive adjacent beds.

The process of drilling actually modifies the resistivities of formations in the vicinity of the borehole through the process of "invasion". In addition to its other functions, the drilling mud forms a mudcake seal on the borehole wall of permeable formations. In doing this, mud filtrate penetrates the formation, displacing formation water and oil or gas. In a zone immediately adjacent to the borehole the mud filtrate displaces all the formation water and any "moveable oil saturation" (the "flushed zone"). Beyond this, the mud filtrate displaces part of the formation water in a "transition zone" which ultimately peters out at a contact edge with the undisturbed formation. The relative depth of invasion is broadly a function of formation porosity/permeability properties, so that less porous formations (typical carbonates) are more highly invaded than moderately porous units (typical sandstones). Pore volume appears to be a major control on invasion depth, because this dictates the volume available to accomodate invading mud filtrate. Once the permeability of a formation exceeds a critical lower value (perhaps about 0.1 md), the formation will be invaded, but invasion depths appear to be insensitive to variations in permeability at higher values (Jorden and Campbell, 1984).

The replacement of formation water by mud filtrate involves a change of pore water resistivity from Rw to Rmf. In a typical logging operation, the mud is "fresh water" as contrasted with the formation waters encountered. The result of invasion is generally to create a more highly resistive annulus surrounding the borehole.

When the objective of most commercial logging is to evaluate the oil or gas potential of stratigraphic units, a resistivity tool is selected that will best estimate the true resistivity of the formation by taking into account borehole characteristics, drilling mud properties, formation lithologies, and degrees of invasion. There are two styles of resistivity tool for this purpose:

1) Induction

The focused induction tool was developed to measure conductivities deep within the formation with minimal disturbance by the invaded zone. The tool contains transmitter coils with a high frequency AC current which induce eddy currents in the adjacent section. Most of these eddy currents are focused beyond the diameter of the typical flushed zone and their magnitude is an approximation of the conductivity of the virgin formation. In turn, they induce voltages in the receiver coil

which are translated to estimates of formation conductivity and, as a reciprocal, resistivity.

Since the induction tool actually measures conductivity directly, rather than resistivity, more reliable readings tend to be made within lower resistivity sections. As a result, the induction tool is ideally suited for sandstone sections, which typically have high porosities, but may not be a satisfactory first choice in highly resistive sequences such as low-porosity carbonates. Unlike other resistivity tools, the induction tool can be run in holes drilled with air or with oil-base muds since it does not require electrical contact with the mud or formation. The tool operates well in "fresh muds" but readings become strongly degraded in "salt muds" due to the greatly increased contribution of the borehole to the total conductivity reading.

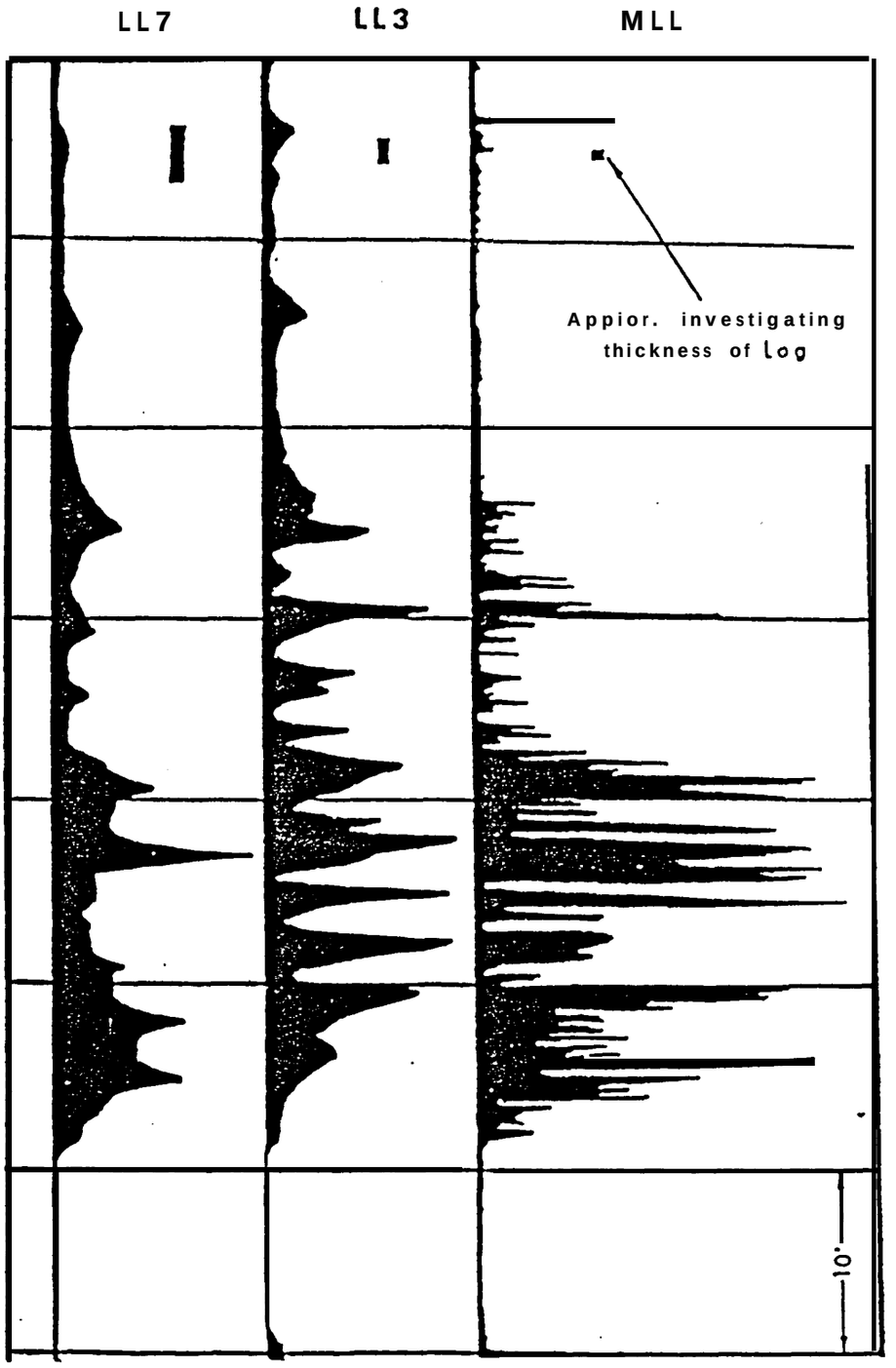
(2) Laterolog

The laterolog (or guard log) was developed to provide accurate readings of formation resistivity in holes drilled with salt water muds. There are various designs of laterolog tools but the central principle of operation is a three electrode arrangement in which a current supply of constant intensity is supplied to the central electrode. A variable current intensity is transmitted to the two surrounding ("guard") electrodes whose magnitude is adjusted so that there is a zero potential with the central electrode. As a result, current in the central electrode is constrained to flow radially outwards as a "current disc" into the surrounding formation. The thickness of the disc is determined by the spacing of the guard electrodes while the current density at any lateral distance from the central electrode is inversely proportional to this distance times the spacing. The drop in potential of the current disc radiating into the formation is monitored by a remote return electrode. As a result, an apparent resistivity is deduced which is the summation of resistivity contributions by the mud, invaded zone and virgin formation. In situations where the mud is relatively conductive, degree of invasion restricted and resistivity of the formation is fairly high, this apparent reading is a close approximation of the true formation resistivity.

Vertical resolution and radius of investigation

The ideal resistivity tool would obviously be one that had extremely good vertical resolution (thereby defining very thin beds) and a large radius of investigation (giving reliable readings deep in the formation). These two criteria are almost impossible to meet in the design of a practical resistivity device, since it requires the vertical component to be extremely small (effects of adjacent beds) and the lateral component to be very large. As a result, different resistivity tools are run for different purposes and several types may be run in the same hole.

A comparison of three different laterologs run the same section (Mississippian carbonate, Saskatchewan) is shown overleaf. Moving from left to right (across log types) there is a progressive increase in vertical resolution, but, at the same time, a reduction in the radius of investigation, with increasing resistivity contributions from



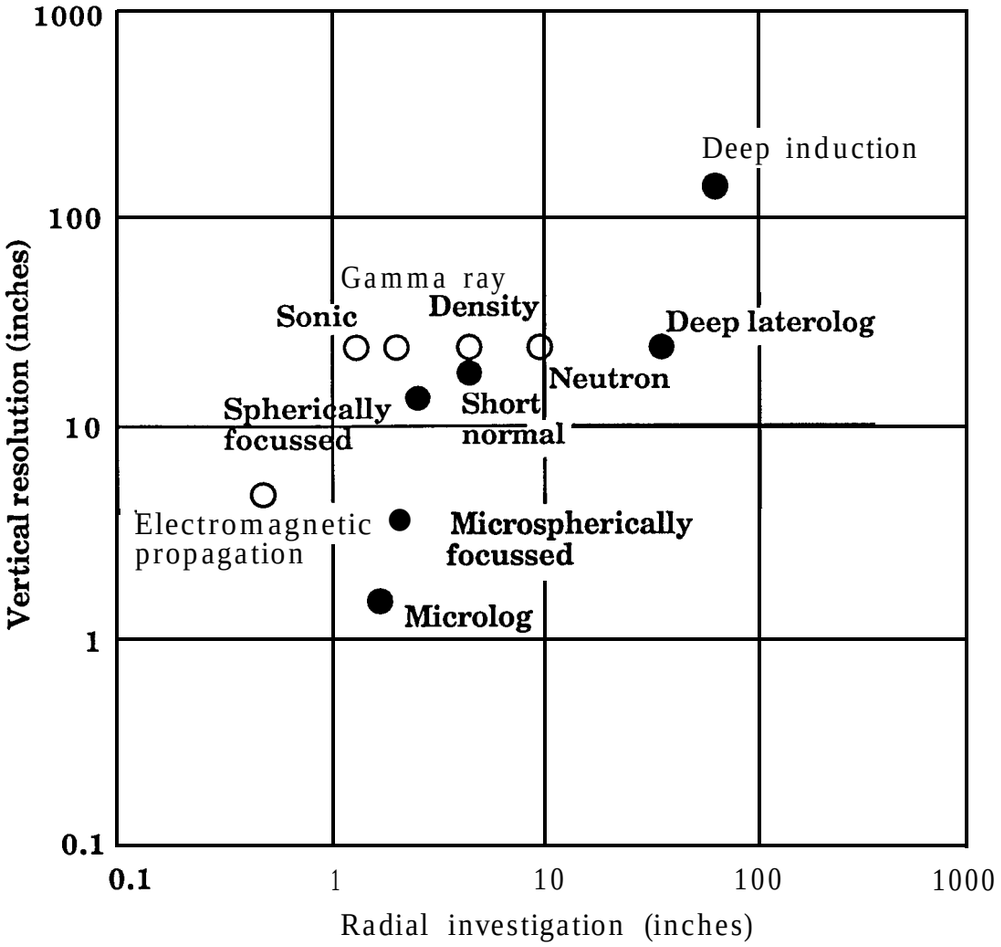
Laterolog-7, Laterolog-3, Microlaterolog resistivity profiles of a Mississippian carbonate section in Saskatchewan (after Jeffries, 1965)

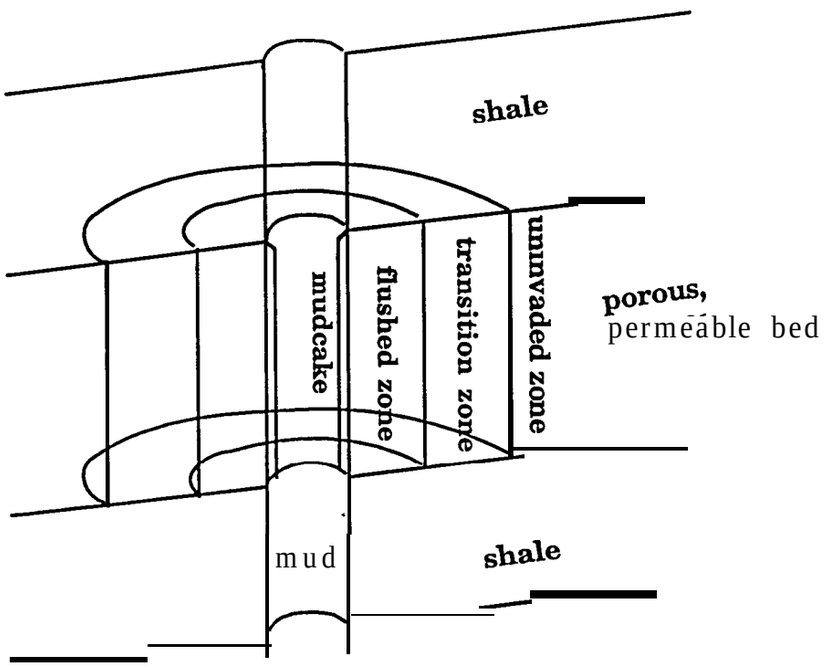
the flushed zone. If a stratigrapher wished to use one of these logs for bed correlation purposes, the microlaterolog (MLL) would be his choice. If a petroleum geologist required a reservoir analysis of the formation, he would use the laterolog LL7, since the readings are the best estimate of the virgin formation resistivity.

The preceding remarks on vertical resolution apply to all logging tools so that analysis by hand is most rationally done after zoning the logs as an initial step. As a general rule of thumb, the vertical resolution of the induction and larger laterologs runs at about 3-5 feet; the vertical resolution of the porosity tools is in the order of l-2 feet. Variations of these figures are introduced by different design features in any tool series and the magnitude of contrast between adjacent beds.

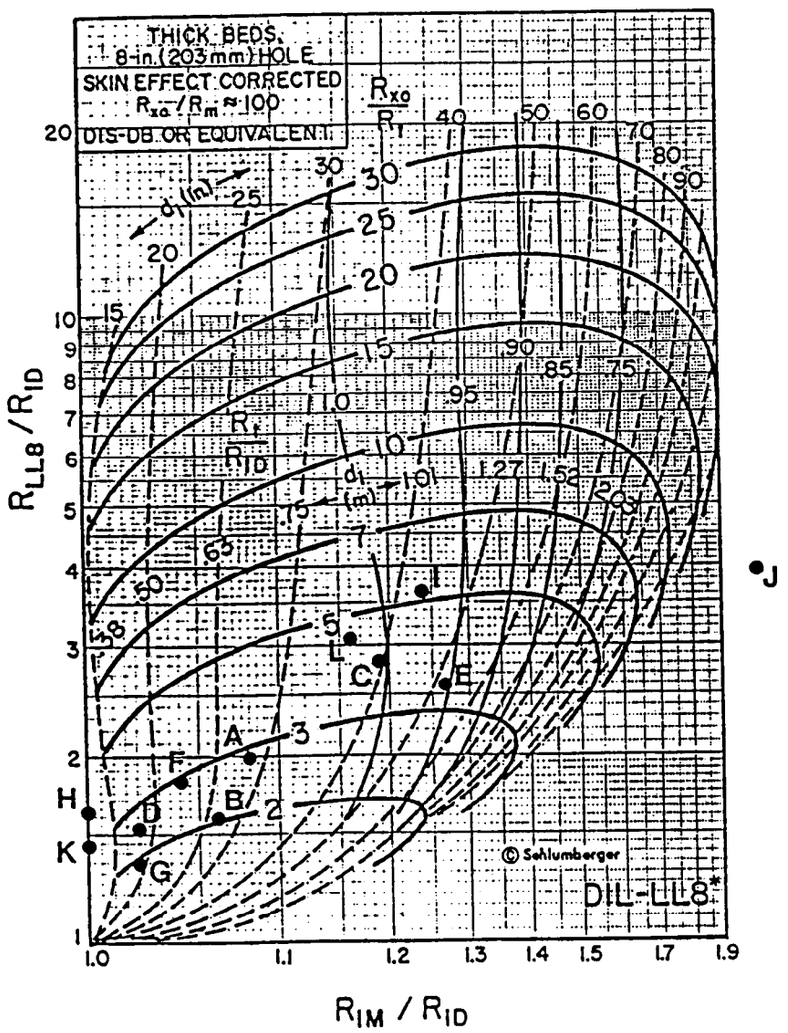
In carbonates, situations frequently occur when the depth of invasion is great enough to adversely affect all conventional resistivity tools to a marked degree so that good direct estimations of Rt are precluded. Deep invasion is generally associated with low porosity or underpressured zones. It would be possible to develop a tool with sufficiently high radius of investigation to register a major resistivity contribution beyond deeply invaded perimeters. However, the price would be an exceedingly gross vertical resolution and consequent large-scale averaging of zones of interest. There are some cases, where invasion exceeds the reach of standard commercial resistivity tools, such as the Chase Group in the giant Hugoton gas field, where holes are sometimes drilled with air or foam to minimize invasion and so allow resistivity tools to obtain good readings for saturation calculations (Olson and others, 1997).

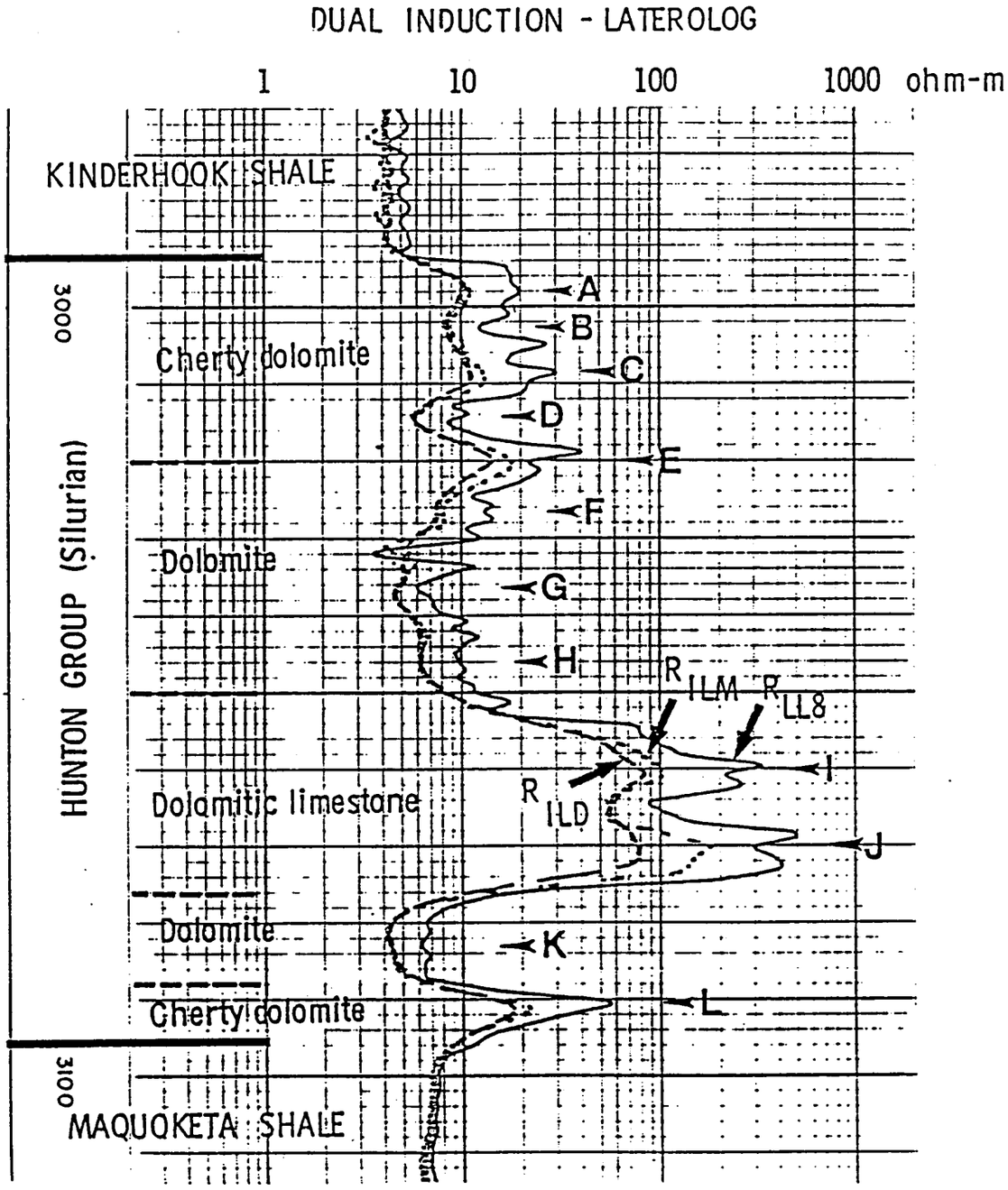
Cases of moderate invasion are resolved by running three different resistivity tools simultaneously (for a small slam) or four (for a grand slam). By utilizing the differing response characteristics of the tools, which are defined by the hardware design, the unknowns of the invasion profile may be deduced, namely the resistivities of the flushed zone and virgin formation, and the diameter or diameters of invasion. The small slam is usually made with a “dual induction-laterolog” (older) or “dual induction-spherically-focused log” (newer) combination which are common logging runs in Midcontinent boreholes, which penetrate thick platform carbonate sections. The three resistivity traces are recorded simultaneously on a logarithmic scale. The relative disposition of the traces gives an immediate impression of the degree of invasion in any zone. When the traces are almost coincident and the resistivity reading is low to moderate, invasion is virtually negligible and the resistivity is approximately Rt. With increasing invasion, the LL8 trace peels away to a higher value and is followed sluggishly by the ILm trace and, to a lesser degree, the IL_d trace. Ultirnately, if the depth of invasion is extraordinarily deep, the three traces will again roughly coincide in a common estimate of R_{xo}. Since the resistivities are recorded on a logarithmic scale, the resistivity reading ratios used in the tornado chart correspond directly with horizontal displacements on the log. As a result, a logarithmic rule to the same scale may be used to read the ratio values directly from the log.


1000
100
10
1
0.1
Vertical resolution (inches)
Deep induction
Gamma ray
Sonic
Density
Deep laterolog
Neutron
Spherically focussed
Short normal
Electromagnetic propagation
Microspherically focussed
Microlog
0.1
1
10
100
1000
Radial investigation (inches)


shale
mudcake
flushed zone
transition zone
uninvaded zone
porous, permeable bed
mud
shale

A dual induction - laterolog resistivity combination is shown of a water- - saturated Hunton Group section in central Kansas. The resistivity variability is therefore regulated by the pore network brine content, with the primary control being the volume of pore space. High resistivity zones have relatively low porosities; low resistivity zones have high porosities. Notice the greater separations between the curves in the lower porosity zones, indicating greater invasion. By crossplotting the three resistivity readings as two ratios on a tornado chart, the true formation resistivity, Rt, the resistivity of the flushed zone, Rxo, and the diameter of invasion, di, can be estimated. Inspection of the plotted points shows that many of these do not need a correction to be applied to the deep induction resistivity - it appears to be reading the formation resistivity, Rt. However, the crossplotted point of one zone falls outside and to the right of the tornado, suggesting that in this case, invasion is so deep that the deep induction tool does not read beyond the flushed zone.





Dual induction - laterolog resistivity combination in the Hunton Group (Silurian) in the borehole USGS-KGS Geis #1, 32-13S-2W, Saline County, Kansas.

POROSITY LOGGING

The porosity of a zone can be estimated either from a single "porosity log" (sonic, density, neutron, or magnetic resonance log) or a combination of porosity logs, in order to correct for variable lithology effects in complex reservoirs. In the carbonates, mineral mixtures are primarily drawn from calcite, dolomite, and quartz (either as sand grains or as chert); anhydrite and gypsum may also occur.

When using a single porosity log, the true porosity is calculated from interpolation between the values for the matrix mineral and the pore fluid (usually equated with mud filtrate, because of the shallow investigation of the porosity tools).

Density log:
Porosity is calculated from the mass-balance relationship:

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

where ρ_b is the bulk density, ϕ is the porosity, ρ_{ma} is the matrix density, and ρ_f is the pore fluid density. If a sandstone, then the matrix density is 2.65 gm/cc (quartz), if a limestone, the matrix density is 2.71 gm/cc (calcite); if a dolomite, then the matrix density is about 2.87 gm/cc. The density log is scaled as bulk density in grams per cubic centimeter. If a "density porosity log" is displayed, then it will be an apparent porosity keyed to a specific mineral, usually calcite, in which case the curve will be indexed as "limestone equivalent porosity". This porosity will be in error in all lithologies whose matrix density differs from that of calcite.

Neutron log:
Older neutron logs were scaled in counts, but modern neutron logs are recorded in apparent porosity units with respect to a given mineralogy. Calcite is commonly chosen as a default mineral, in which case the porosity values will be true porosities in limestone zones. Where zones are not limestone, the limestone-equivalent neutron log should be rescaled to the zone matrix mineral or combined with a density limestone-equivalent porosity in an estimate of the true porosity.

Neutron-density log combination:
The combination of density and neutron logs is now used commonly as a means to determine porosity that is largely free of lithology effects. Each individual log records an apparent porosity that is only true when the zone lithology matches that used by the logging engineer to scale the log. A limestone-equivalent porosity is a good choice for both neutron and density logs, because calcite has properties that are intermediate between dolomite and quartz. By averaging the apparent neutron and density porosities of a zone, effects of dolomite and quartz tend to cancel out. The true porosity may be

estimated either by taking an average of the two log readings or by applying the equation:

$$\phi = \sqrt{\frac{\phi_n^2 + \phi_d^2}{2}}$$

where ϕn and ϕd are neutron and density porosities. It has been suggested that the square-root equation is preferable as a means of suppressing the effects of any residual gas in the flushed zone.

Sonic log:

If a sonic log is used for porosity estimation, the equivalent relationship is:

$$\Delta t = \phi \cdot \Delta t_f + (1 - \phi)\Delta t_{ma}$$

where Δt is the zone transit time, ϕ is the porosity, Δt_{ma} is the matrix transit time, and Δt_f is the pore fluid transit time. The computation of porosity requires the stipulation of a matrix mineral transit time, which is about 55.5 microseconds per foot for quartz, 47.5 for calcite, and 43.5 for dolomite. So, transformation of the sonic log to a porosity log generates an apparent porosity trace keyed to one or other matrix mineral, in a similar fashion to the neutron and density logs.

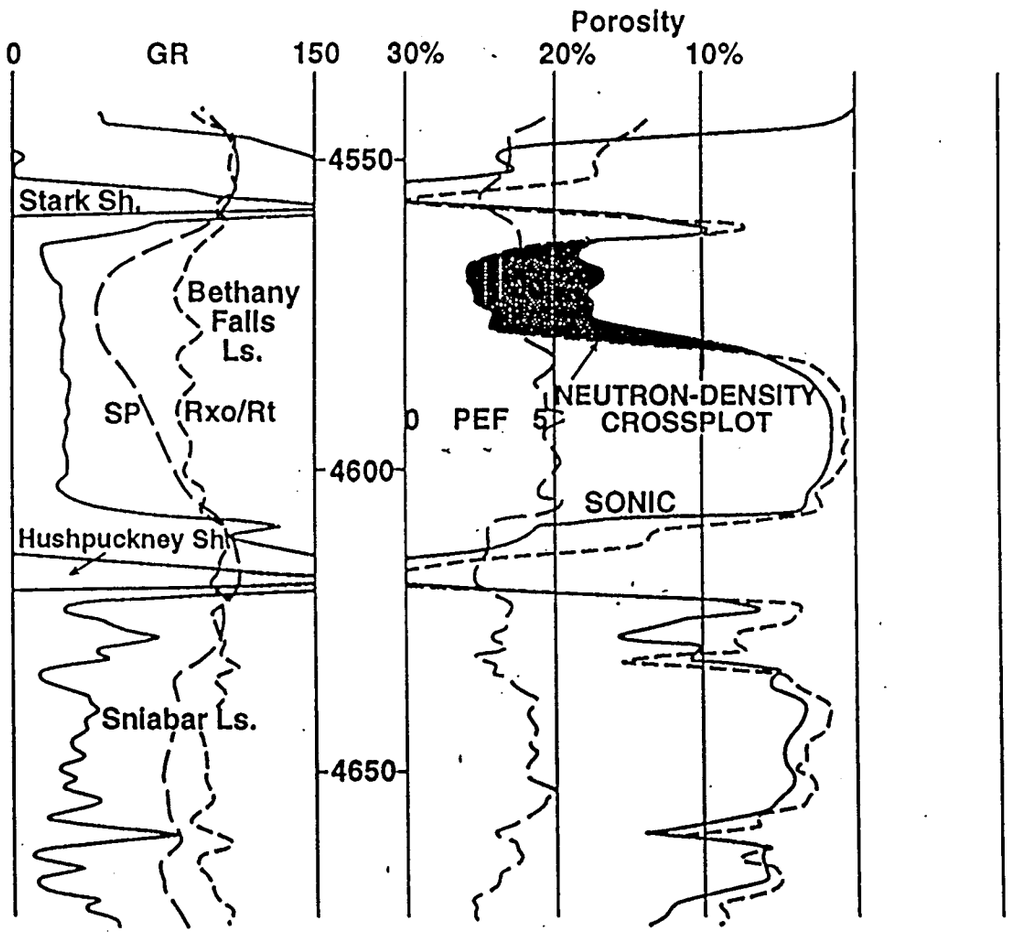
Primary and secondary porosity

The neutron and density logs are responses to pores of all sizes. However, field observation over many years has shown that the sonic log is a measure of interparticle (intergranular and intercrystalline) porosity but is largely insensitivity to either fractures or vugs. This discrimination can be explained largely by the way that the sonic tool measures transit time by recording the first arrival waveform which often corresponds to a route in the borehole wall free of fractures or vugs.

When sonic porosities are compared with neutron and density porosities, the total porosity can be subdivided between "primary porosity" (interparticle porosity) recorded by the sonic log and "secondary porosity" (vugs and/or fractures) computed as the difference between the sonic porosity and the neutron and/or density porosity. Typically, moderate values in secondary porosity are caused by vugs, because fracture porosity does not usually exceed 1 to 2% by volume.

The log example shows the averaged neutron-density porosity log together with a sonic log in a Pennsylvanian limestone - shale sequence in a Kansas well. They are both scaled in limestone equivalent porosity units. Notice how the neutron-density and sonic porosity logs track fairly closely at about 3% porosity in the Sniabar limestone, but in the upper part of the Bethany Falls limestone, there is a marked increase in overall porosity and a distinctive separation of the sonic from the neutron-density porosity. These features are quite common in south-central Kansas and distinguish high-porosity oomoldic limestones from low-porosity wackestones. While the neutron and density logs are sensitive to all pore sizes, the sonic log porosity does not reflect all the

oomoldic pores. The distinction is commercially important because much of the oomolds are poorly connected vuggy pores that cause an increase in resistivity such that water-saturated oomoldic zones can look to be promising hydrocarbon shows and be confused with real oomoldic oil and gas producers. This has been enough of a problem to encourage the specific use of EPT (electromagnetic propagation tool) logging in some wells.



Comparison of neutron-density and sonic porosity logs in a Pennsylvanian section in Mesa Leathersland #1-14 NE-SE 14-30S-34W. Notice the oomoldic porosity zone in the upper part of the Bethany Falls Limestone.

"THE ARCHIE EQUATION"

In his classic paper, Archie (1942) proposed two equations that described the resistivity behavior of reservoir rocks, based on his measurements on core data. The first equation governs the resistivity of rocks that are completely saturated with formation water. He defined a "formation factor", F, as the ratio of the rock resistivity to that of its water content, Rw, and found that the ratio was closely predicted by the reciprocal of the fractional rock porosity (Φ) powered by an exponent, he denoted as "m". The value of m increased in more consolidated sandstones and so was named the "cementation exponent", but seemed to reflect increased tortuosity in the pore network. For generalized descriptors of a set of rocks with a range of m values, workers after Archie introduced another constant, "a". In a second equation, Archie described resistivity changes caused by hydrocarbon saturation. Archie defined a "resistivity index", I, as the ratio of the measured resistivity of the rock, Rt, to its expected resistivity if completely saturated with water, Ro. He proposed that I was controlled by the reciprocal of the fractional water saturation, Sw, to a power, "n", which he named the "saturation exponent.

The two equations may be combined into a single equation, which is generally known as "the Archie equation". Written in this form, the desired, but unknown, water saturation (Sw) may be solved.

$$F = \frac{R_o}{R_w} = \frac{a}{\Phi^m}$$

$$I = \frac{R_t}{R_o} = \frac{1}{S_w^n}$$

$$S_w = \left[\frac{a}{\Phi^m} * \frac{R_w}{R_t} \right]^{1/n}$$

Although "rule-of-thumb" numbers for the cementation exponent, m, and the saturation exponent, n, are often quite adequate for estimates of water saturation when making a decision whether to run a drill-stem test, they may be poor for reserve estimations, particularly for a major field. They can also be misleading when applied to a carbonate unit that has (for example) significant oomoldic porosity, or fractures. The errors can lead one into being either too pessimistic or too optimistic. Similar concerns apply to the value of the saturation exponent, n. For water-wet formations, n is approximately equal to two, but will be much higher in formations that are oil-wet. Some backgound to "m and "n" in sandstones and carbonates are given in the following sections.

FORMATION FACTOR - POROSITY RELATIONSHIPS FOR SANDSTONES

Archie (1942) measured the formation factor of a variety of sandstones (a simple laboratory procedure involving a Wheatstone bridge) and compared these with their porosities to deduce the variation of *m* with type of sandstone. He found that m was 1.3 for unconsolidated sands and ranged between 1.8 and 2.0 for consolidated sandstones. Guyod gave the name cementation exponent to *m*, but noted that the pore geometry controls on *m* were complex and went beyond simple cementation. However, a useful rule-of-thumb comparative scale is widely quoted as::

m	
1.3	unconsolidated sandstones
1.4 - 1.5	very slightly cemented
1.6 - 1.7	slightly cemented
1.8 - 1.9	moderately cemented
2.0 - 2.2	highly cemented

In 1952, Winsauer and other workers measured formation factors and porosities in 29 samples of a highly varied suite of North American sandstones. They generalized Archie's equation to:

$$F = \frac{a}{\Phi^m}$$

Since low porosity sandstones are more highly cemented than higher porosity sands, the constant 'a' functions as a slippage element which automatically incorporates the cementation exponent changes associated with sandstones of differing porosities. By taking logarithms of both sides, this can be transformed to a straight line relationship:

$$\log F = \log a - m \log \Phi$$

On fitting log F to log ϕ, they came up with a relationship for sandstones:

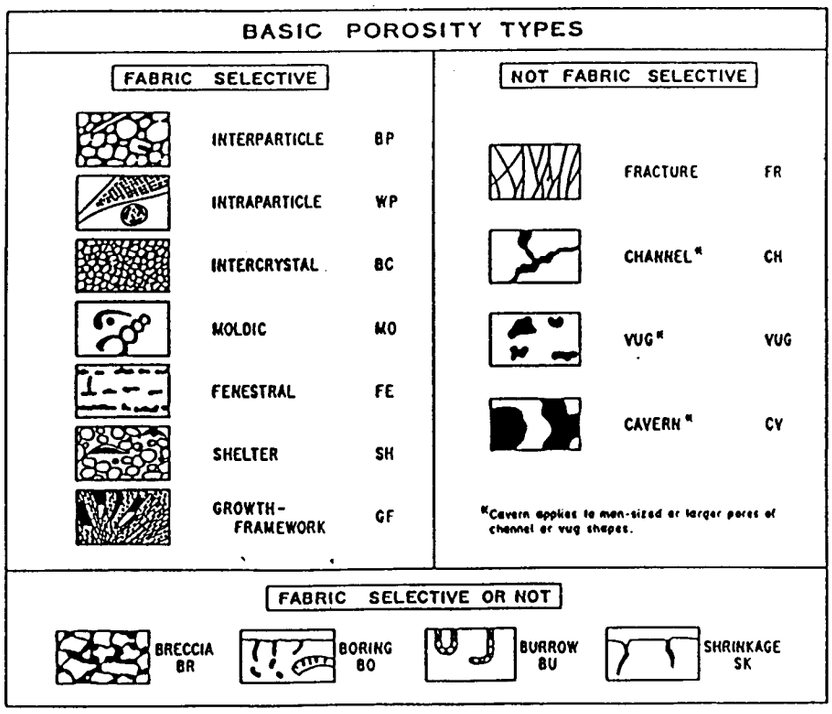
$$F = \frac{0.62}{\Phi^{2.15}}$$

which is known as the "Humble equation" (since they worked for the Humble Oil Company) and is the most widely used equation for sandstones in the world.

FORMATION FACTOR - POROSITY RELATIONSHIPS FOR CARBONATES

Porosity in sandstones generally takes the form of *intergranular* pores: the pore space between the grains of quartz and other detrital minerals. In some cases there may be *intercrystalline* porosity caused most commonly by calcite or quartz cement introduced by diagenesis in the lithification of the sandstone. Porosity in carbonate rocks (limestones and dolomites) can take a wide variety of forms as shown in the illustration from Choquette and Pray (1970). The geological classification of carbonate pore types is based on *genesis;* geologists are interested in the history of pore formation. The petrophysicist should pay attention to the geological description and interpretation of carbonate pore types in a reservoir. However, there will be times when such detailed information is limited or non-existent and the petrophysicist should focus on the *morphology* of the pores, because it is this aspect that affects the wireline log measurement.

Petrophysicists subdivide pore types between:
(1) **interparticle**: intergranular and intercrystalline porosity;
(2) **fracture**
(3) **vug**: either moldic porosity from the dissolution of grains or vugs that are larger than the grains.
Notice that all the genetic forms in the carbonate classification of Choquette and Pray can be assigned to these broad petrophysical categories.



from Choquette and Pray, 1970

The most widely used form of the Archie equation for both limestones and dolomites is the basic:

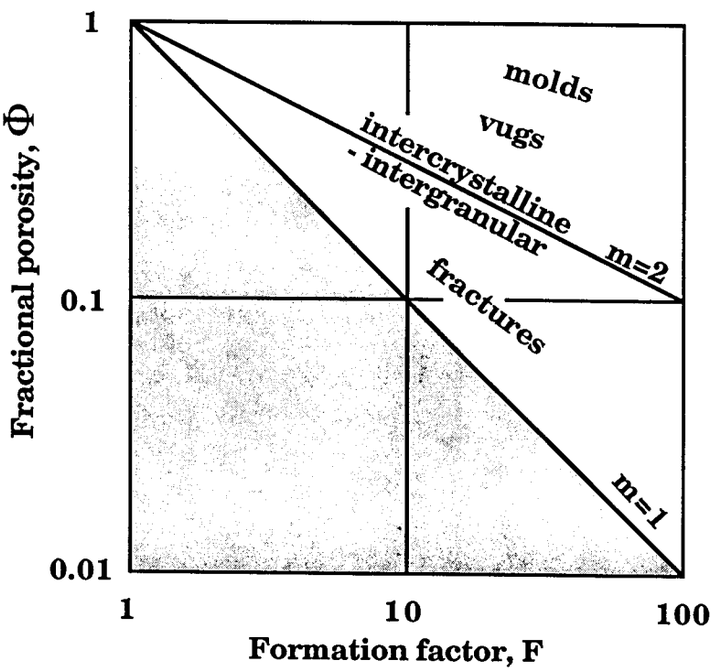
$$F = \frac{1}{\Phi^2}$$

This choice is not intuitively obvious when comparing the complex variability of carbonate pore types with the relatively simple pore structure of sandstones, given the variability of the sandstone cementation exponent, m. However, a cementation exponent value of two (m = 2) is a good choice for carbonate rocks whose porosity is dominantly intercrystalline as shown by numerous core measurements and log evaluations. Dullien (1992) showed that for a rock framework with uncorrelated pore and solid components, the expected value of m should be 2. The uncorrelated pore space will contain both electrically connected pore space and "dead end" pore space that is by-passed by electrical flow. If there is an increase in unconnected pore space (vugs), then there will be an increase in m; if there is an increase in connected pore space (fractures), then there will be a decrease in m.

Rule-of-thumb values of m quoted in the log analysis literature for various pore systems are:

	m
intergranular/intercrystalline	2.0
fractures	1.4
vugs	2.3
moldic	3+

Obviously, these numbers will be controlled by the degree of fracturing, vugginess, and proportion of moldic porosity and can lead to a wide variety of m values observed in the field.



RESISTIVITY INDEX - SATURATION RELATIONSHIPS

Archie's second equation is: $I = \frac{R_t}{R_o} = \frac{1}{S_w^n}$ which states that the resistivity index, I, is defined as the ratio between the measured resistivity, R_t and the expected resistivity of the zone, if it was completely saturated with formation water, R_O ; the resistivity index is a function of the reciprocal of the fractional water saturation, S_W, powered by a saturation exponent, *n*.

Laboratory measurements of the resistivity index in water-wet rocks show that an n value of 2 is not an unreasonable figure to use in most cases. However, lab measurements also show that an equivalent rule-of- thumb figure for oil-wet rocks would be about 9. The difference is matched by intuition: in partially-saturated water-wet rocks, the water phase would provide a continuous film on grain surfaces to conduct electrical current through the rock, albeit on a much more tortuous route than fully water-saturated rocks; in oil-wet rocks, the surfaces would be coated with oil and the water phase would be restricted to a partially connected system of conductive globules within the pore network.

Although the physical model may be straightforward, the consequences of the choice of an oil-wet or water-wet saturation exponent will result in drastically different water saturation estimates. Traditionally, log analysts have assumed the formation to be water wet and used a saturation exponent value of two (n = 2) unless laboratory measured values are available. Combining the two original Archie equations together and rearranging to solve for water saturation, S_W gives:

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

TEMPERATURE AND WATER RESISTIVITY

For shale-free formations, the conduction of electrical current is almost entirely carried by ions in the formation water. Quantitative calculations of oil or gas saturation are therefore predicated on a knowledge of the formation water resistivity. For any given brine, this value is not constant, but decreases with increasing temperature. A common source of formation water resistivity data is a catalog of laboratory measurements made of samples from drill-stem tests, etc.

For example, if you had drilled a well in Stafford County, Kansas and one of your target formations was the Viola Limestone, this is the information that you would see in the KGS Brine Catalog (along with chemical composition of the dissolved solids). Water resistivity catalogs are available in a number of areas that have oil and gas development. Data for samples that are obviously contaminated by acid treatment, excessive mud invasion, etc. are screened out of the catalog, but there is usually some variability left, and the catalog reader should look for a "typical" value. Some of the log analysis techniques described later (the Rwa method, the Pickett plot, and estimation from the SP log) provide additional checks on these values. Once a representative value of Rw has been chosen, its value must be corrected from that of its laboratory measurement to that at the temperature of the formation in the well.

FORMATION WATER RESISTIVITIES
laboratory measurements of produced samples
Stafford County, Kansas
VIOLA

Location	Rw	RwT
Sec-T-R	ohm-m	deg F
27-21-13W	0.127	100
9-21-14W	0.210	70
10-24-11W	0.048	100
12-24-11W	0.082	100
22-24-11W	0.055	100
2-24-12W	0.077	100
10-24-12W	0.062	100
11-24-12W	0.072	100
15-25-11W	0.088	100
2-25-14W	0.075	60
2-25-14W	0.070	60

kgs

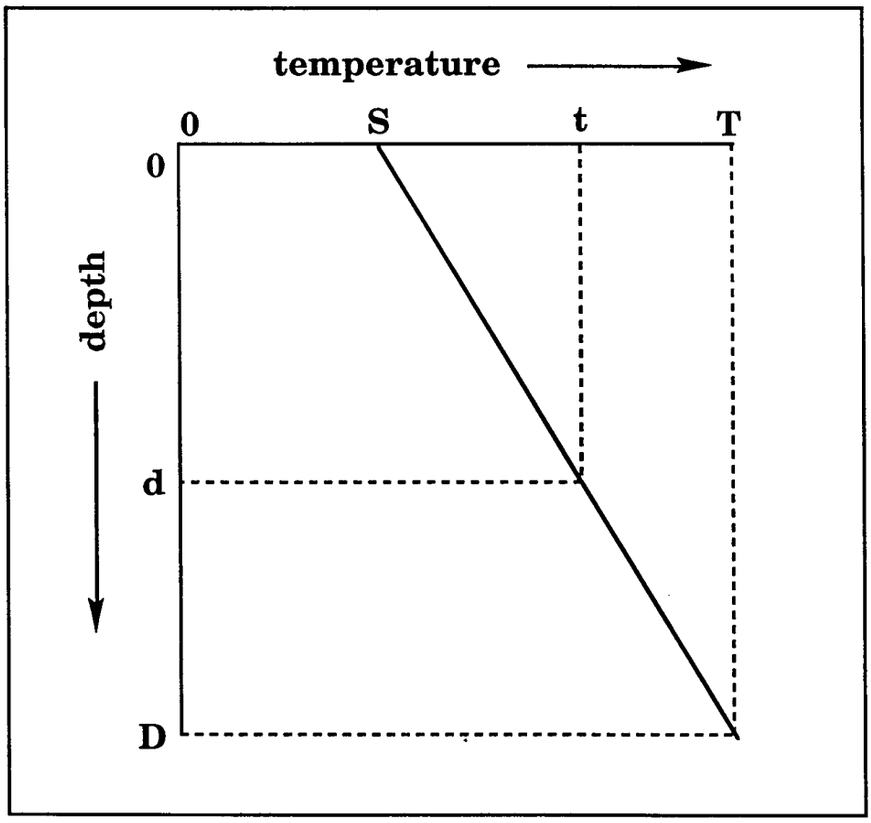
Estimation of formation temperature

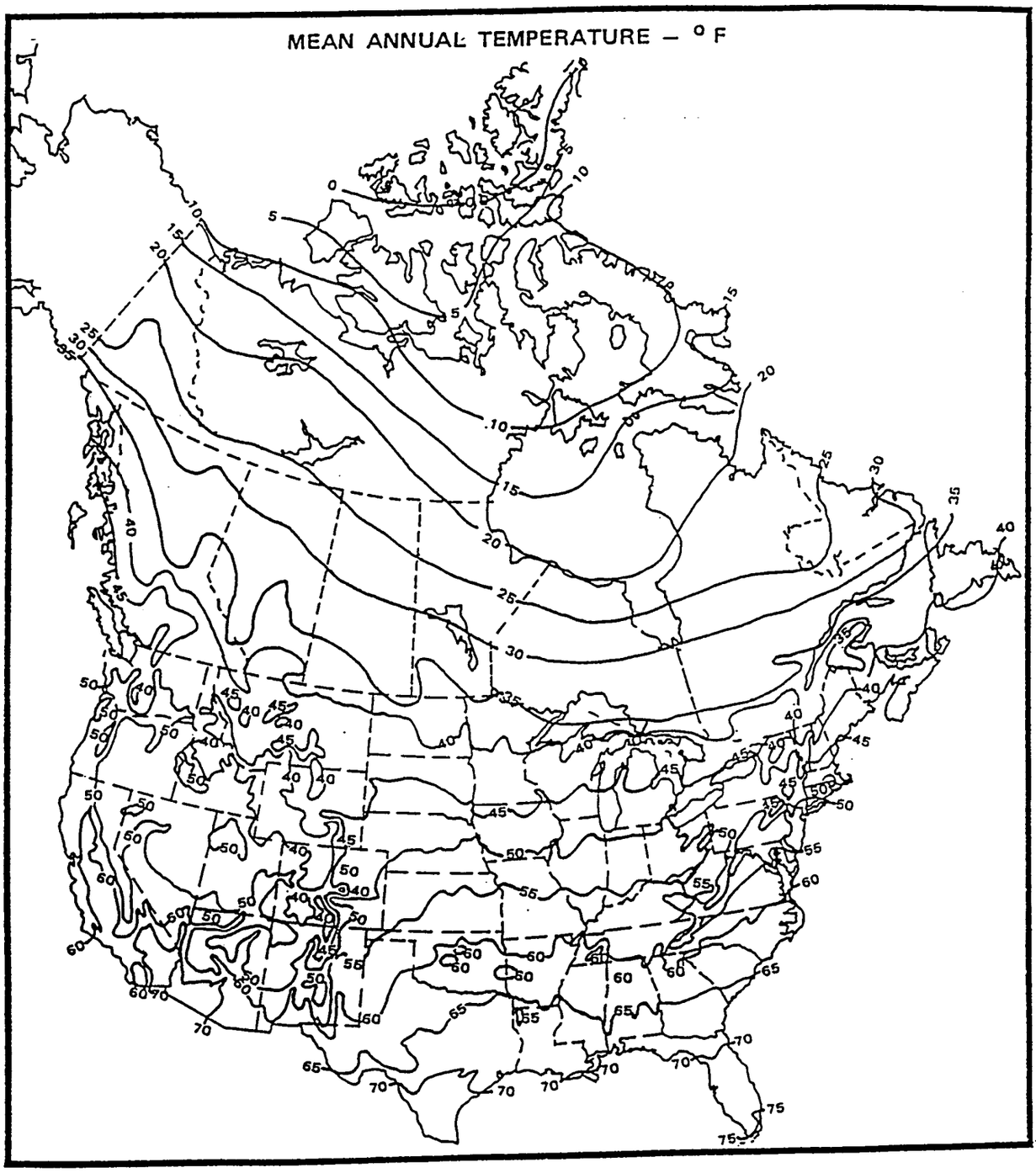
All conventional logging runs carry a maximum temperature recording device whose value, T, is recorded on the log heading and corresponds to the temperature at the deepest point of the log run, D (generally bottom hole). A linear temperature gradient is assumed as a first approximation between the bottom of the hole and the topographic surface.

The mean annual surface temperature, S, is used to establish the temperature at approximately zero depth. Then the temperature of the formation:

$$t = S + d\left(\frac{T-S}{D}\right)$$

The procedure is a simple linear interpolation where the quantity in parentheses represents an estimate of the temperature gradient. A map of mean surface temperature enables the selection of an appropriate value for any well location.





Mean annual surface temperatures in North America
(after Connolly and U.S. Dept. of Agiculture)

Conversion of formation water resistivity to that at formation temperature

The formation water resistivity may be corrected from its value at laboratory temperature to formation temperature either by use of a chart found in most logging manuals or by Arp's empirical formula,
for Fahrenheit:

$$R_{w2} = R_{w1} \frac{(T_1 + 6.77)}{(T_2 + 6.77)}$$

and for Centigrade:

$$R_{w2} = R_{w1} \frac{(T_1 + 21.5)}{(T_2 + 21.5)}$$

where R_{w1} and R_{w2} are formation water resistivities at temperatures T_1 and T_2

Example of formation temperature calculation and correction of a laboratory measured water resistivity to its value at formation temperature

A Mississippi "chat" well is located in Kiowa County, south Kansas.
The log header reports a BHT (bottom-hole temperature) of 118°F at a TD (total depth) of 5398 feet.
The "Chat" zone to be evaluated is at a depth of 4838 feet. What is the zone's formation temperature?

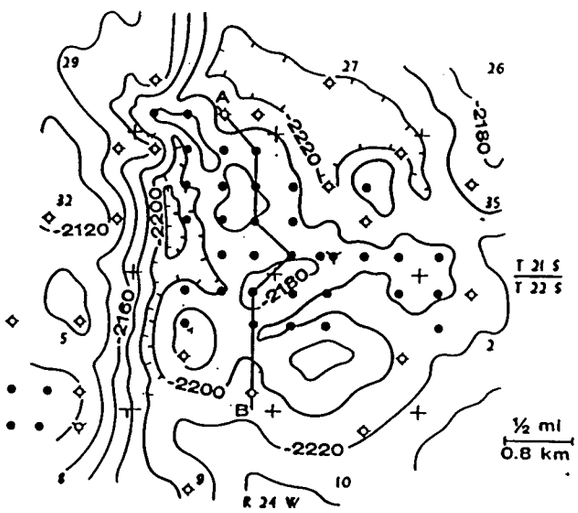
Answer:
Mean annual surface temperature in south Kansas = 57 degrees Fahrenheit
"Chat" zone formation temperature = 57 + 4838 * ((118 - 57) /5398)
= 112 degrees F

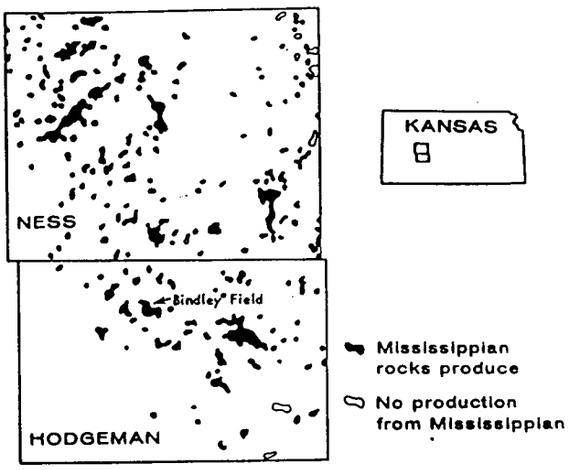
The resistivity of a Mississippi "Chat" water sample was measured to be 0.05 ohm-m at a laboratory temperature of 75°F.
What would be its resistivity in the subsurface zone at the well?

Answer: Rw = 0.05 * (75 +7) / (112 + 7)
= 0.0345 ohm-m

AN EXAMPLE OF ESTIMATION OF WATER SATURATION FROM LOG ANALYSIS OF RESISTIVITY AND NEUTRON POROSITY LOGS

Bindley oil field is located in Hodgeman County in south Kansas, and was interpreted by Ebanks and others (1977) to be a combination paleogeomorphic and facies trap formed by the exhumation of a lower Mississippian bryozoan mound. Deutsch #1 is a well in the Bindley field that produces from the Mississippian "Warsaw" Formation section of (from top to bottom) dolomite breccia, bryozoan dolomite, spicule dolomite, and cherty dolomite. The well was perforated in the depth interval of 4616 - 36 feet and had an initial production of 205 BOPD with no water.





Bindley Field

Lib

Welex

SEP 18 19

RADIATION-GUARD LOG

COMPANY OASIS PETROLEUM INCORPORATED
WELL DEUTSCH # 1
FIELD HODGEMAN County
State KANS

COMPANY OASIS PETROLEUM, INCORPORATED

WELL DEUTSCH # 1

BEST COPY AVAILABLE

FIELD

COUNTY HODGEMAN STATE KANSAS

Location C-NE-SE

Sec. 33 Twp 21S Rge 24W

Other Services:
COMP. A.V.

Permanent Datum GROUND LEVEL Elev. 2418'
Log Measured From KELLY BUSHING Ft. Above Perm. Datum
Drilling Measured From KELLY BUSHING

Elev.: K.B. 2423'
D.F. 2421'
G.L. 2418'

Date	8-16-72	8-16-72	8-16-72	
Run No. ONE	GAMMA	NEUTRON	GUARD	REVISED COPY
Depth—Driller	4724'	4724'	4724'	Date 8-28-72
Depth—Welex	4723'	4723'	4723'	Revisions
Btm. Log Inter.	4715'	4723'	4715'	
Top Log Inter.	0'	0'	3510'	
Casing—Driller	@	@	8-5/8" @ 561'	@
Casing—Welex			8-5/8" 561'	
Bit Size			7-7/8"	
Type Fluid in Hole			WATER BASE SALT MUD	
Dens. | Visc.	|	|	9.2 | 57	|
pH | Fluid Loss	| ml	| ml	6.6 | 10.4 ml	| ml
Source of Sample			FLO LINE	
R_m @ Meas.Temp.	@ °F	@ °F	.15 @ 80 °F	@ °F
R_{mf} @ Meas.Temp.	@ °F	@ °F	.105 @ 80 °F	@ °F
R_{mc} @ Meas.Temp.	@ °F	@ °F	.225 @ 80 °F	@ °F
Source R_{mf} R_{mc}	|	|	MEAS. |	|
R_m @ BHT	@ °F	@ °F	.10 @ 117°F	@ °F
Time Since Circ.			2 HOURS	
Max. Rec. Temp.	°F @	°F @	117F @ TD	°F @
Equip. | Location	8766 | GT. BEND |		|	|
Recorded By	C. PEBLEY & K. STUEVE			
Witnessed By	MR. EUWER			

FORMATION WATER RESISTIVITIES
laboratory measurements of produced samples
MISSISSIPPIAN
Hodgeman County, Kansas

Location	Rw	RwT
Sec-T-R	ohm-m	deg F
24-22-24W	0.136	100
24-22-24W	0.180	77
25-22-24W	0.170	77
25-22-24W	0.168	77
25-22-24W	0.170	77
25-22-24W	0.166	77
3-24-24W	0.094	100

kgs

A KGS Water Resistivity Catalog of laboratory measurements of Hodgeman County Mississippian formation brines.

Rw = 0.17 ohm-m @ 77°F.

Well location:

Mean annual surface temperature (ST) of Hodgeman County (south-central Kansas) from the North American temperature map:
ST = 57 degrees Fahrenheit

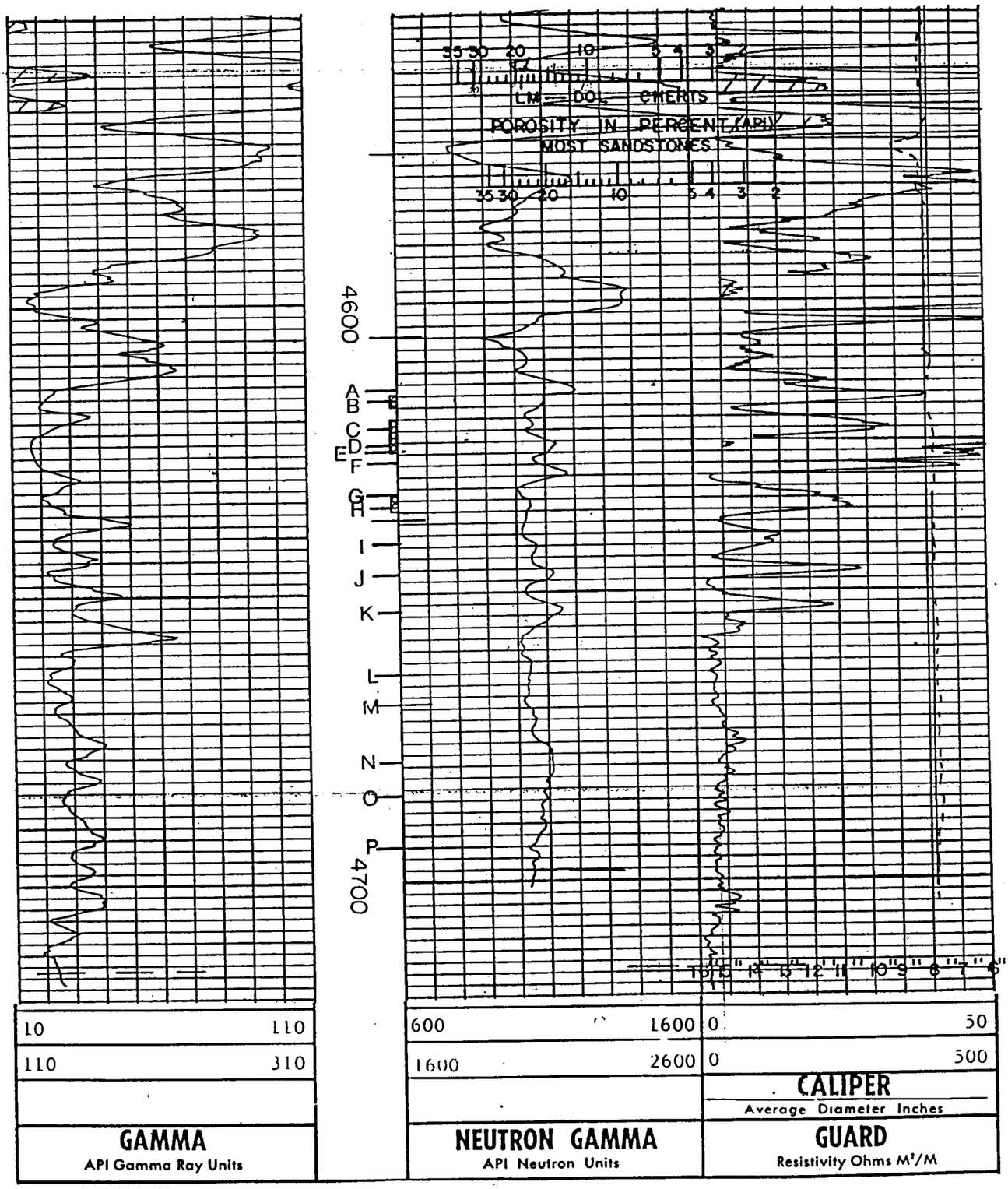
From Header:

Total depth (TD) = 4723 feet
Bottom-Hole Temperature (BHT) = 117 degrees F

Formation :

Formation depth (FormD) = 4650 feet
Formation temperature of the Mississippian section (FormT) = 116 degrees F
Expected value of Rw in the Mississippian, using Arps' Formula: Rw = 0.116

Oasis Deutsch #1 C-NE-SE 33-21S-24W Hodgeman County, Kansas



GAMMA API Gamma Ray Units	NEUTRON GAMMA API Neutron Units	CALIPER Average Diameter Inches GUARD Resistivity Ohms M²/M
10 — 110	600 — 1600	0 — 50
110 — 310	1600 — 2600	0 — 500

EXCEL procedure for log analysis of the Warsaw Formation (Mississippian) in Oasis Deutsch #1

(1) Create a worksheet template similar to that shown for the Oasis Deutsch #1 well.

(2) Set up the **PARAMETERS** box:

ST = Mean annual surface temperature (from map)
TD = Total depth (from log header)
BHT = Bottom-hole temperature (from log header)
FormD = Formation depth from log)
FormT = Formation temperature (calculated from **ST, TD, BHT,** and **FormD**)
RwCAT = Formation water resistivity from catalog
RwT = Temperature of RwCAT measurement
A = Archie equation a (=1)
M = Cementation exponent (=2)
N = Saturation exponent (=2)
RW = Formation water resistivity at formation temperature (calculated using Arps' formula with **FormT, RwCAT,** and **RwT**)

(3) Complete the log data table by inserting readings of porosity (**PHI**) and formation resistivity (**Rt**) for zones A to P.

(5) Compute an estimate of the water saturation for each zone in the column headed **SW** using the Archie equation **PARAMETERS** applied to **PHI** and **Rt**.

(6) Compute values of the bulk-volume water (**BVW**) from:

$$BVW = \Phi.Sw \text{ (both in fractional units)}$$

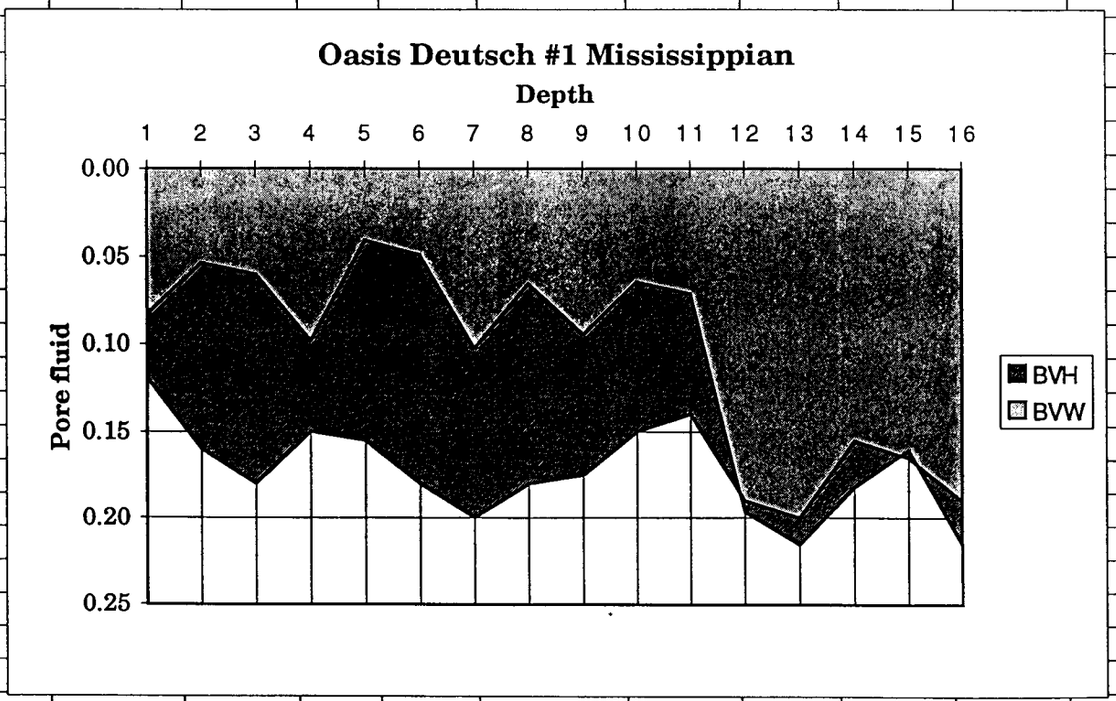
and bulk volume hydrocarbon (**BVH**) from: $BVH = \Phi - BVW$.

(7) Select the cells in the area of the **BVW,** and **BVH** columns and click on **ChartWizard**.
Choose a gridded cumulative plot form from **Area** for output.
Reverse the **Scale** of Y (this is the logging convention for porosity direction).
You now have a graphic log profile of the volume of porosity subdivided between oil and water content as an ordered (not scaled) function of depth.

Oasis Deutsch #1 C-NE-SE 33-21S-24W Hodgeman Co., Kansas

Warsaw Formation (Mississippian)

PARAMETERS		ZONE	DEPTH	PHI	RT	SW	Graphic: BVW	Graphic: BVH
		A	4615	0.12	17	0.688	0.083	0.037
A	1	B	4617	0.16	40	0.337	0.054	0.106
M	2	C	4621	0.18	32	0.335	0.060	0.120
N	2	D	4625	0.15	12	0.656	0.098	0.052
RW	0.116	E	4626	0.155	70	0.263	0.041	0.114
		F	4627	0.18	48	0.273	0.049	0.131
ST	57	G	4633	0.2	11	0.514	0.103	0.097
TD	4723	H	4635	0.18	27	0.364	0.066	0.114
BHT	117	I	4642	0.175	13	0.540	0.094	0.081
FormD	4650	J	4647	0.15	28	0.429	0.064	0.086
FormT	116	K	4653	0.14	23	0.507	0.071	0.069
RwCAT	0.17	L	4664	0.19	3	1.035	0.197	-0.007
RwT	77	M	4669	0.2	2.5	1.077	0.215	-0.015
		N	4679	0.155	3.5	1.175	0.182	-0.027
		O	4685	0.165	4.5	0.973	0.161	0.004
		P	4694	0.19	2.5	1.134	0.215	-0.025



72

10-4-25MB Rpt. No.
OPER OASIS PETROLEUM
800 SUTTON PLACE, WICHITA, KS
WELL #1 DEUTSCH
CONTR GABBERT-JONES
FIELD BINDLEY (MISS)
IP STATE IPP 205 BOPD, NO WTR, MISS 4616-36
API # 15-083-20234

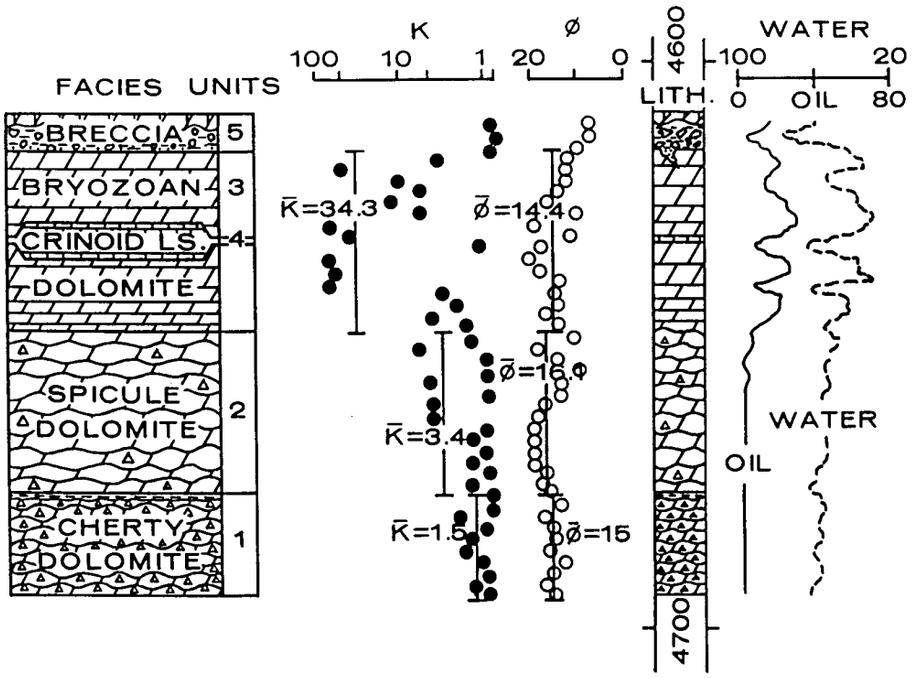
S-T-R 33-21S-24W
SPOT APP C NE SE
CO HODGEMAN, KS
ELEV 2423' KB

D
INIT ✓
DO
FIN

SPUD 8-4-72, 8-5/8"@561 w/300, Geol-Bob Euwer
CORE #1(FS-MISS)4609-41, rec 32' descrip not avail
DST #1(FS-MISS)4603-41, op 2 hr, 480' GIP, rec 3300' oil, no wtr, ISIP 1288/30min, IFP 102, FFP 1170, FSIP 1280/60min
CORE #2(MISS)4641-94, rec 53' descrip not avail
DST #2(MISS)4641- 94, rec 1½ hr, 60' GIP, rec 690' very heavily oil gas cut muddy wtr, 60' sli oil cut wtr, 60' wtr, ISIP 1382/30min, IFP 31, FFP 748, FSIP 1374/60min
Drlg Completed 8-17-72
RTD 4724, Welex Log, 5½"@4723 w/250, DV tool @1722 w/325 MICT, CO 4700, Perf(MISS)4/4616 -18, 12/4620-26, 6/4633-36, Fill up 3500' oil, no wtr, 12 hrs, swab 7½ BOPH, 6 hrs, 2000' off btm, POP
STATE IPP 205 BOPD, NO WTR, MISS 4616-36 COMPLETED 10-18-72

KB LOG TOPS

ANHYDRITE	1670 +753
HEEBNER	3920 -1497
LANSING	3970 -1547
FORT SCOTT	4500 -2077
MISS DOLOMITE	4612 -2189
LTD	4723 -2300
RTD	4724 -2301
TD IN MISS	



From Ebanks and others (1977)

DIGITAL LOG DATA

Log analysis calculations used to be done mostly with slide-rules and charts (pre-1972), then with calculators, and now increasingly with computers. The digital data for computations are recorded by the logging truck and are made available either directly or from the logging company computer processing center. The data are stored either in binary format (LIS) on tapes, or in ASCII format (LAS) usually on floppy discs. LAS (Log Ascii Standard) is the more recent standard and was introduced by the Canadian Well Logging Society in the late 1980's. LIS (Log Information Standard) tapes are often difficult to read, not only because of their binary code, but the variability in formatting styles. LAS files on floppy discs can be read by standard word-processing programs and LAS is ideal for PCs. Both forms conventionally list data at a rate of two readings per foot of hole for common log combinations which have vertical resolutions of 2 to 3 feet or greater. This frequency is fine enough to pick up the systematic features of the log curves without wasteful oversampling, but not so coarse as to cause "aliassing" problems.

Blue-line logs can also be digitized using relatively inexpensive hardware and software, or through the service of a digitizing company. Digitized logs for some areas are available for purchase over the Internet. In all cases, the most popular data format is LAS.

The header information and initial curve data are shown overleaf for a an extension well in the Hugoton North field of Scott County , Kansas. The data were read from an LAS file on the floppy disc pictured below, by a standard word processing program on a PC.

The file OCRK.LAS records logs from Lario Oil & Gas Whitebead #2-2 drilled in Garvin County, Oklahoma. The digitized interval on the file ranges from 5950 - 6150 feet. The well produces oil from the Oil Creek Sandstone (6010 - 6115), a Middle Ordovician formation. The Oil Creek Sandstone is a prolific oil producer in parts of Oklahoma, while at other localities it is mined in quarries as a source of sand for glass manufacture. The grains in this highly pure sandstone are both well-sorted and very well-rounded.

The logs on OCRK.LAS can be read using a word-processor (such as WORD) or a spreadsheet program (such as EXCEL).

A spreadsheet program can be used to plot the logs. See the gamma ray, neutron and density porosity, and resistivity logs plotted for the interval from 5950 - 6150 feet depth by EXCEL.

Log analysis of the Oil Creek Sandstone section between depths of 6010 and 6115 feet depth. can be made on a spreadsheet using the deep induction for the resistivity (Rt) and the porosity estimated by an average of the neutron and density limestone-equivalent porosity readings for each depth increment.

Water saturations were computed for the zones, using an Oil Creek Sandstone water resistivity at formation temperature of 0.03 ohm-m, in conjunction with the Archie equation, using equation constants of: a=1, m=1.8, n=2.

The bulk volume water (BVW) of each zone is found by multiplying the (fractional) porosity by the (fractional) water saturation: $BVW = \Phi * Sw$
The BVW is the proportion of the rock that is estimated to be formation water. Bulk volume hydrocarbon (BVH) is computed from $BVH = \Phi*(1-Sw)$. Notice that $BVW + BVH = \Phi$, so that the bulk volumes subdivide the pore volume into water and hydrocarbon. A log profile of Φ- BVW - BVH is a graphic illustration of the reservoir structure created by the log analysis.

```
~Version Information Section
VERS.          2.0            : CWLS LOG ASCII Standard
WRAP.          YES            : Multiple lines per depth step
~Well Information Section
STRT.FT        5950.000       : Start Depth
STOP.FT        6150.000       : Stop Depth
STEP.FT        0.500          : Step
NULL.          -999.000       : NULL Value
COMP.   LARIO OIL AND GAS     : Company
WELL.   WEST WHITEBEAD 2-2    : Well
FLD.                          : Field
LOC.                          : Location
SRVC.                         : Service Company
DATE.                         : Date
CTRY.          USA            : Country
STAT.      OKLAHOMA           : State
CNTY.        GARVIN           : County
API.                          : API Number
~Curve Information Section
DEPTH.FT                      :   Depth
CALI.IN                       :   Caliper
GR.GAPI                       :   Gamma ray
SP.MV                         :   Spontaneous Potential
ILD.OHMM                      :   Deep induction resistivity
ILM.OHMM                      :   Medium induction resistivity
SFL.OHMM                      :   Spher-focussed resisistivity
RHOB.G/C3                     :   Bulk density
DRHO.G/C3                     :   Density correction
PDL.DECIMAL                   :   Density porosity (ls equiv.)
PEF.B/E                       :   Photo-electric factor
NPHI.DECIMAL                  :  Neutron porosity (ls equiv.)
~A Log Data Section
DEPTH  CALI  GR  SP  ILD  ILM  SFL  RHOB  DRHO  PDL  PEF  NPHI
5950 7.958 81.229 -29.436 6.719 6.569 9.786 2.587 0.032 0.072 3.292 0.106
5950.5 7.881 82.519 -30.689 6.401 5.782 7.672 2.566 0.061 0.084 2.997 0.119
5951 7.815 86.114 -32.691 5.924 5.346 6.151 2.536 0.089 0.102 2.844 0.144
5951.5 7.862 87.242 -34.944 5.561 5.074 5.525 2.506 0.101 0.119 2.835 0.158
5952 7.81 85.754 -36.446 5.194 5.081 5.397 2.49 0.103 0.128 2.946 0.179
5952.5 7.898 89.822 -37.449 4.962 5.144 5.912 2.502 0.124 0.122 2.91 0.176
5953 8.017 84.862 -36.951 4.947 5.009 5.639 2.5 0.123 0.123 3.096 0.192
5953.5 7.804 87.764 -36.204 5.098 5.141 5.684 2.507 0.114 0.119 3.087 0.183
5954 7.739 76.56 -35.956 5.313 5.471 6.384 2.511 0.091 0.116 3.01 0.168
5954.5 7.751 76.118 -35.959 5.488 6.016 7.451 2.512 0.065 0.116 2.919 0.116
5955 7.781 67.354 -35.961 5.599 6.355 8.995 2.561 0.065 0.087 3.015 0.081
5955.5 7.888 63.105 -34.964 5.704 6.235 10.451 2.61 0.071 0.059 3.016 0.072
5956 7.823 63.672 -33.716 6.036 6.145 11.099 2.623 0.057 0.051 3.164 0.082
5956.5 7.741 70.295 -32.469 6.502 6.119 9.565 2.627 0.053 0.048 3.262 0.1
5957 7.806 89.456 -31.221 6.896 6.39 8.283 2.615 0.05 0.056 3.365 0.12
5957.5 7.862 93.581 -30.224 7.27 7.078 7.395 2.618 0.05 0.054 3.719 0.137
5958 7.886 85.196 -28.976 7.675 7.875 7.315 2.613 0.041 0.057 3.921 0.129
5958.5 7.823 60.369 -28.979 7.841 8.741 8.822 2.63 0.05 0.047 3.669 0.081
5959 7.811 44.075 -29.481 7.931 9.427 15.912 2.64 0.065 0.041 3.476 0.056
5959.5 7.624 35.666 -30.484 8.145 8.7 19.204 2.635 0.069 0.044 3.435 0.059
5960 7.645 42.684 -31.736 8.423 8.697 16.336 2.605 0.053 0.061 3.255 0.088
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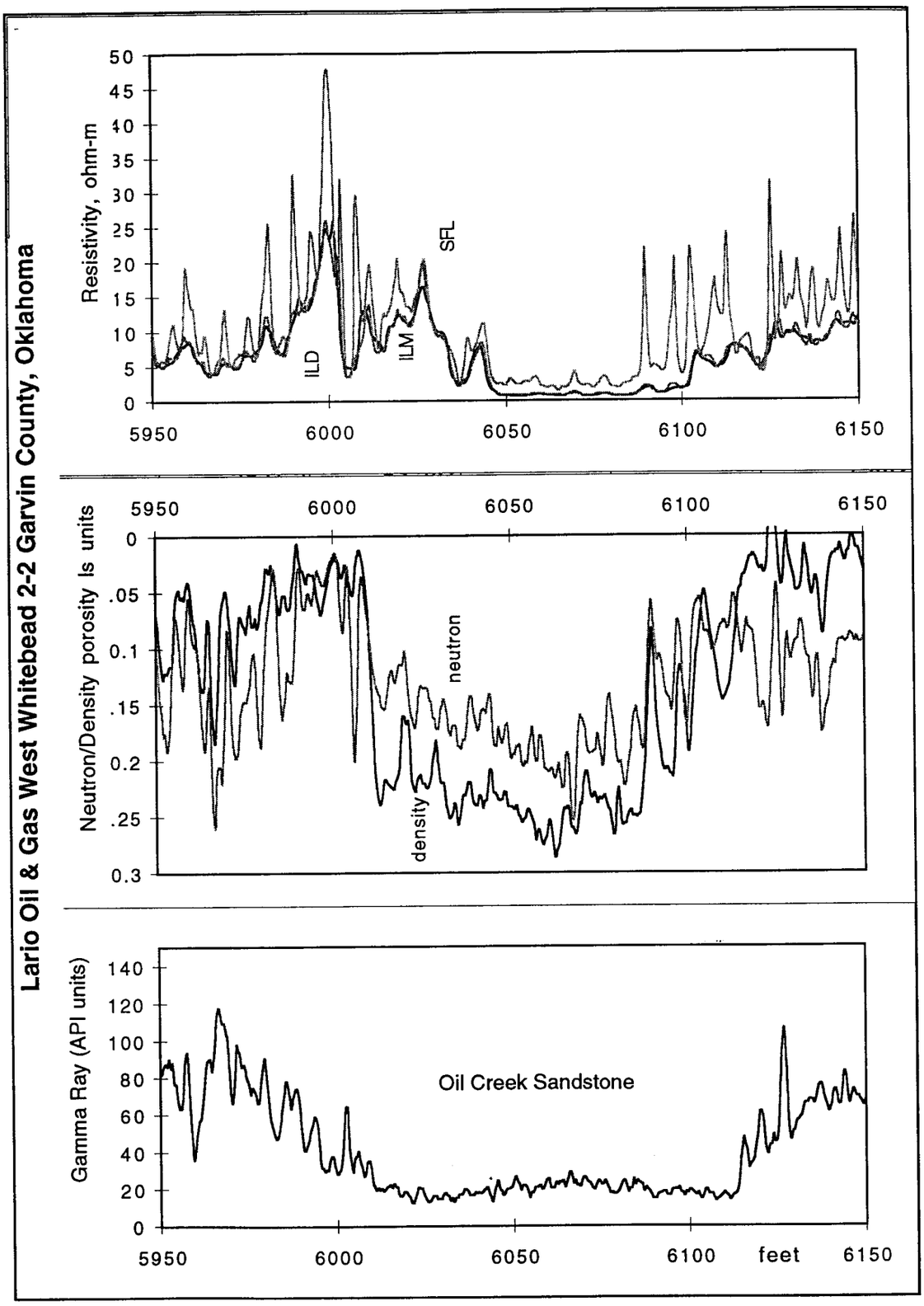
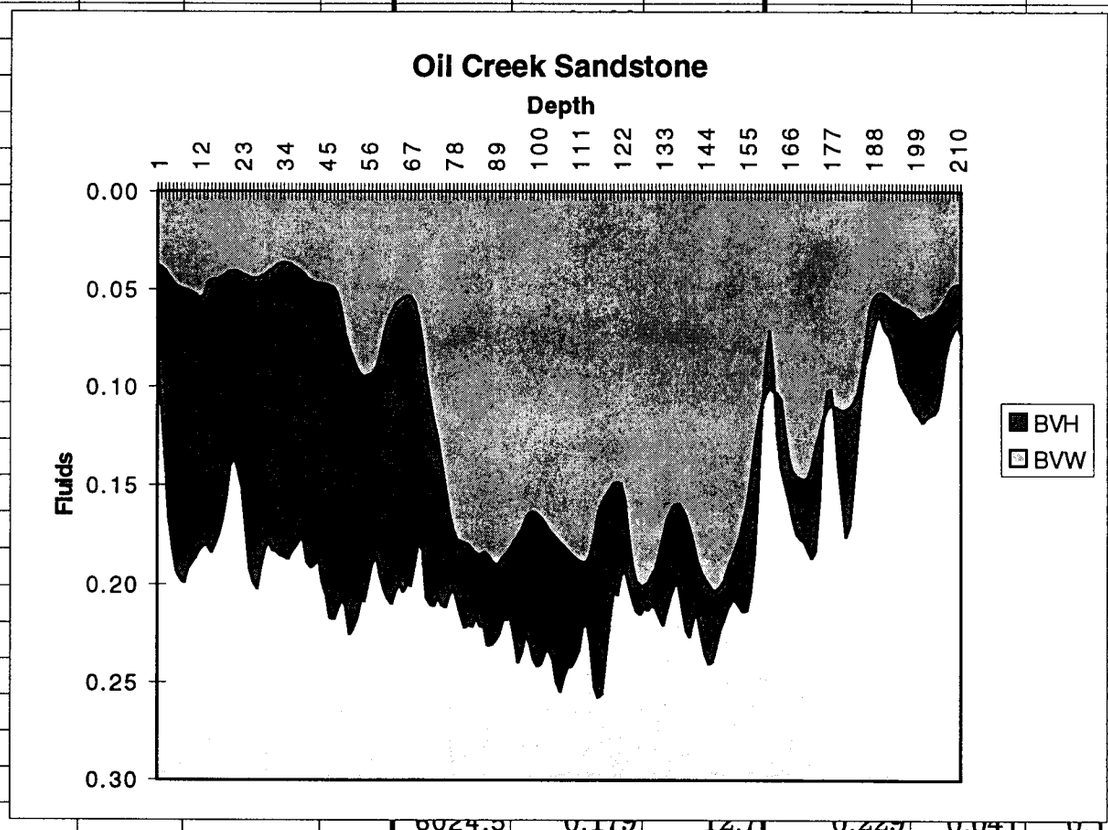

Lario Oil & Gas West Whitebead 2-2 Garvin County, Oklahoma
Resistivity, ohm-m
50
45
40
35
30
25
20
15
10
5
0
ILD
ILM
SFL
5950
6000
6050
6100
6150
Neutron/Density porosity ls units
0
.05
0.1
.15
0.2
.25
0.3
neutron
density
Gamma Ray (API units)
140
120
100
80
60
40
20
0
Oil Creek Sandstone
feet

Lario Oil & Gas West Whitebead #2-2, Garvin County, Oklahoma

Oil Creek Sandstone (Middle Ordovician)

PARAMETERS	
A	1
M	1.8
N	2
RW	0.030



DEPTH	PHI	RT	SW	Graphic: BVW	BVH
6010	0.087	12.9	0.434	0.038	0.049
6010.5	0.109	12.9	0.354	0.039	0.071
6011	0.138	12.2	0.294	0.041	0.098
6011.5	0.167	11.1	0.260	0.043	0.123
6012	0.183	9.9	0.254	0.046	0.136
6012.5	0.193	9.2	0.251	0.049	0.145
6013	0.198	8.9	0.249	0.049	0.148
6025	0.183	13.8	0.215	0.039	0.144
6025.5	0.183	15.0	0.206	0.038	0.146
6026	0.186	15.8	0.198	0.037	0.149
6026.5	0.186	16.3	0.195	0.036	0.150
6027	0.187	16.1	0.195	0.036	0.151
6027.5	0.184	15.1	0.205	0.038	0.146
6028	0.181	14.2	0.214	0.039	0.142
6028.5	0.178	13.3	0.225	0.040	0.138