Formation Evaluation
"Name of the Game"

From measurements in the borehole, extract information needed for making decisions

Pickett, 1980

Formation Evaluation

- Definition: the application of any and all available borehole measurements to determine properties of interest of the in-situ material surrounding the borehole (Pickett, 1980)

Formation Evaluation

- Applications:
  - Hydrocarbons in place
  - Recoverable hydrocarbon estimates
  - Rock typing
  - Geological and environment identification
  - Waterflood feasibility in early wells
  - Reservoir fluid contact location
  - Reservoir quality mapping
  - Water salinity determination
  - Reservoir fluid pressure determination during drilling of well
  - Fracture detection
  - Reservoir engineering parameter determination
  - Interzone fluid communication probability in casing-formation annulus
  - Porosity and pore size distribution determination
  - Reservoir fluid movement monitoring

Basic Objective:

- **Determine the volume of recoverable hydrocarbons (RH)**
- **RH= [c X RF X Sh X ϕ X h X DA]/Boi**

Where: **c = 7758 barrels/acre ft**

(43560 cu ft in 1 acre ft X 7.481 gallon in 1 cu ft / 42 gallons in 1 barrel)

DA = drainage area
h = thickness of pay zone
ϕ = porosity
Sh = hydrocarbon saturation
RF = recovery factor
Boi = Formation volume factor

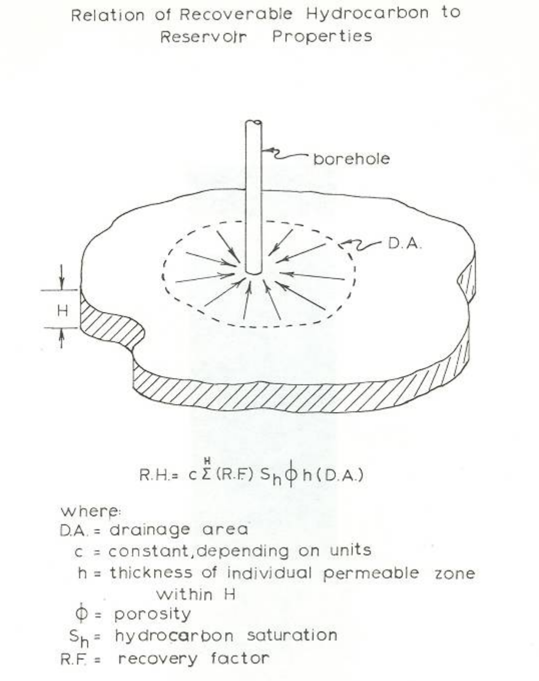
From borehole logs we obtain:
ϕ, Sh, h

Sh is the most important single quantity. Sh is not only a volumetric factor but is also intimately related to the ability of the rock to transmit fluid (permeability)

Basic Objective:

- **Determine the volume of recoverable gas hydrocarbons (Rg)**
- **Rg = [c X RF X Sg X ϕ X h X DA]* Bg**

Where: **c = 43560 cu ft in 1 acre ft**
DA = drainage area
h = thickness of pay zone
ϕ = porosity
Sh = hydrocarbon saturation
RF = recovery factor
Bg = Formation volume factor



Reserves – Data Required

Formation

- Depth
- Thickness
- Net Reservoir
- Permeability
- Formation dip

Fluid

- Type
- Saturation
- Distribution
- Properties
- Pressures
- Contacts

Data Gathering Techniques

Direct

- Mudlogging
- Formation Sampling
  - whole cores
  - sidewall cores
- Fluid Sampling
  - production tests
  - wireline tests
- Pressure Surveys

Indirect

- Wireline Logging
  - **Open Hole**
  - **Cased Hole**
- Logging While Drilling (LWD, MWD)
- Offset Well Analysis
  - **VSP's (vertical seismic profiling)**
  - **X-well seismic**

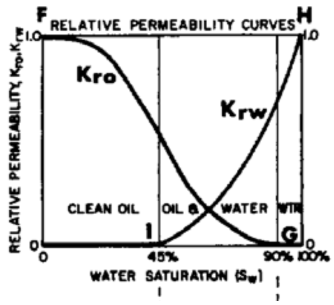
Wildcat Evaluation Objectives

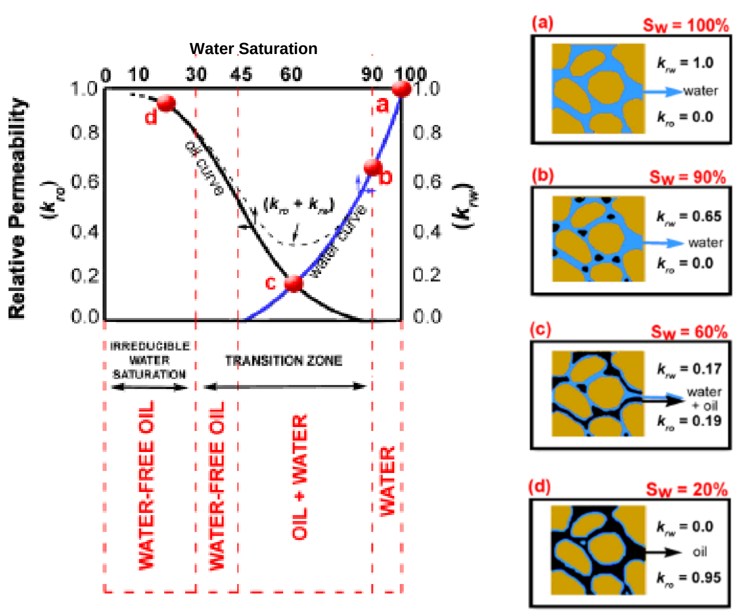
- Are there intervals where Sw < Sc (50%)
- What is the ϕ?
- What is h?
- What is RH?
- Is there productivity?
- Is it oil or gas?
- Is there vertical Sw gradient suggesting better locations elsewhere?

Relative Permeability

- Defined as the ratio of the effective permeability to a fluid at a given saturation to its permeability at 100% saturation

•Ability of oil to flow ceases when 90% or more of the pore space is occupied by water
•Below 45% Sw no flow of water; only oil can move
•Above 90% Sw, there is no permeability to oil; only water can move
•Between 45% and 90% Sw both phases will produce





Bend, 2007

Available Borehole Measurements for Formation Evaluation

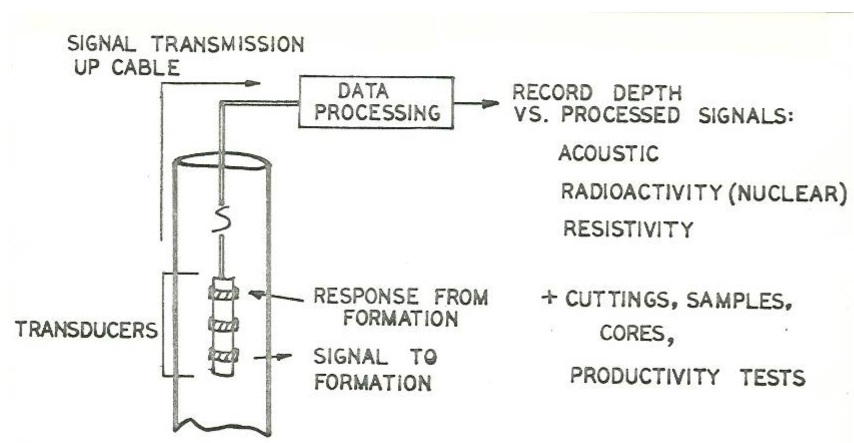
- Cutting Samples: lithology, shows, rock types
- Cores: lithology, porosity, permeability, grain density, formation factor, saturation exponent, capillary pressure curves, initial residual oil saturation curves, acoustic velocity

Available Borehole Measurements for Formation Evaluation

- Acoustic logs: transit time, amplitude, waveform displays, variable intensity cement bond logs, borehole televiewer, shear wave velocity
- Radioactivity logs: gamma-ray emission, neutron lifetime, spectral
- SP-Resistivity logs: self potential, electrical, focused resistivity, induction, flushed zone resistivity
- Borehole fluid logs: total mud gas, hydrocarbon component concentrations
- Productivity and fluid testing: transient pressure in borehole, fluid flow rates, reservoir fluid composition

Why Run Logs?

- To identify and delineate formations and to correlate from well to well
- To evaluate the hydrocarbon content of porous formations



BOREHOLE MEASUREMENTS

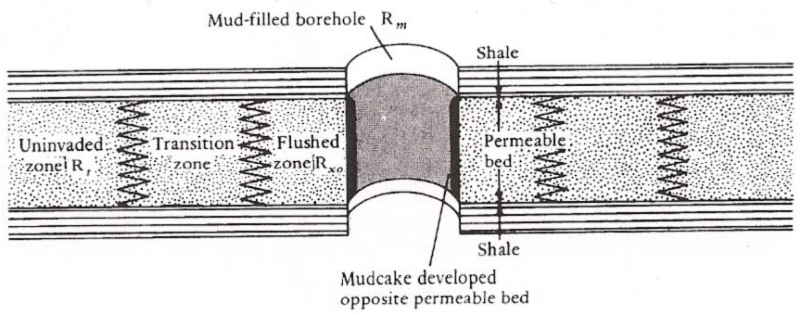


FIGURE 3.23 The situation around a borehole adjacent to a permeable bed. Resistivity of flushed zone, R_{xo}; resistivity of uninvaded zone, R_t; resistivity of mud filtrate, R_{mf}; and resistivity of formation water, R_w.

Selley, 1998

Drilling Mud

- Prevents formation fluids from flowing into well bore
- Mud cake builds up around borehole wall; mud filtrate is squeezed into formation
  - Original pore fluid displaced
  - Flushed zone created around well bore
  - Resistivity of flushed zone (Rxo) usually different than the uninvaded zone (Rt)

Problems:

- Sh, ϕ, h, DA, and RF are measured indirectly.

- Example: Sh = 1 – Sw
  - Sw depends on five variables
    - Bulk resistivity (Rt)
    - Water resistivity (Rw)
    - Porosity (ϕ)
    - Cementation exponent (m)
    - Saturation exponent (n)

Well Logs

Graph of Depth Versus some Property of Interest

- Major categories:
  - Logs from cuttings samples
  - Drilling time logs
  - Borehole fluid logs (“mud logs”)
  - Acoustic logs
  - Radioactivity logs
  - Resistivity logs
  - Productivity logs

MUD
LOGS
&
CORES

Logs from Cutting Samples

- Lithology
- Hydrocarbon shows

CUTTINGS AND CORES

→ cuttings: lithology - "rock type"

"shows"

→ cores: lithology, ϕ, permeability, ρ_s, F(m), n, cap. press., relative perm., ROS, Δt

Pickett, 1980

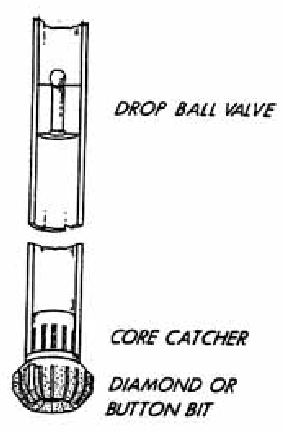


Figure 14-3 A rotary coring bit used to take a core.

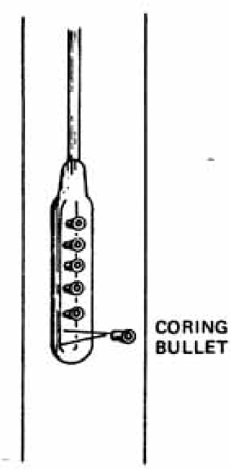
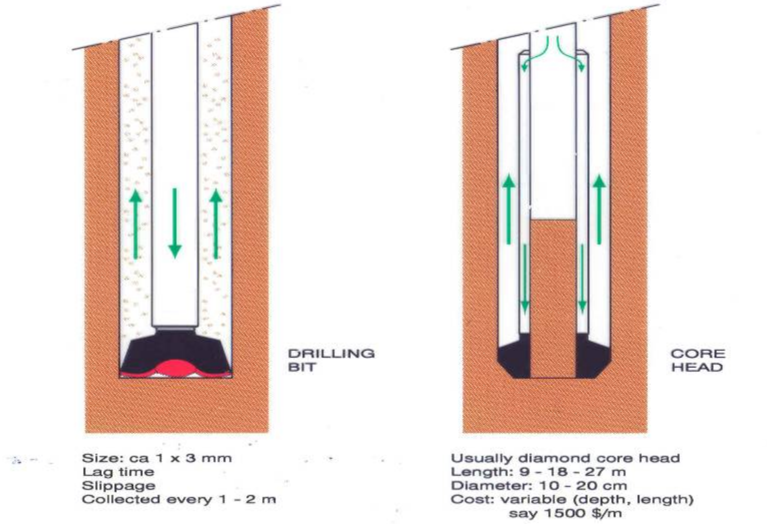


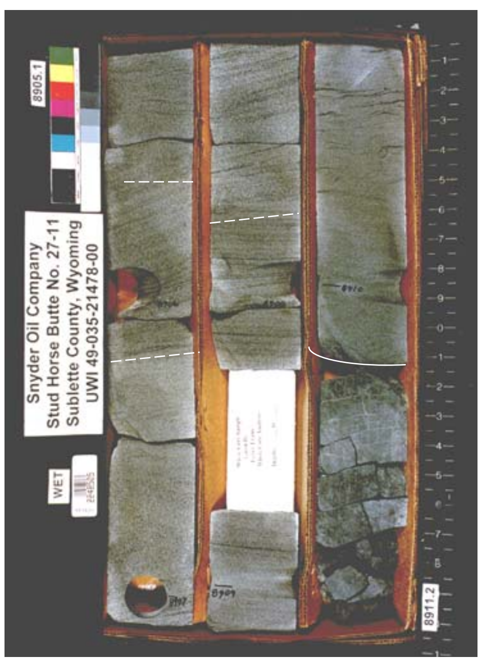
Figure 14-4 A sidewall coring device.

SAMPLING I

CUTTINGS | CORES

CHEAP NO EXTRA TIME | **EXPENSIVE EXTRA RIG TIME**





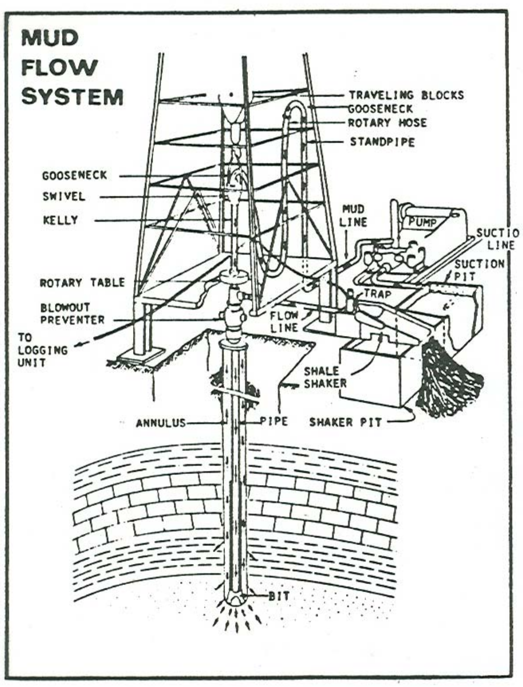
Coring

Use core report for :

matrix density ρ_{matrix}
Porosities Φ
Permeabilities k
Oil / Water saturations
Water salinities
Archie's "m" , "n"

Borehole Fluid Logs "Mud Logs"

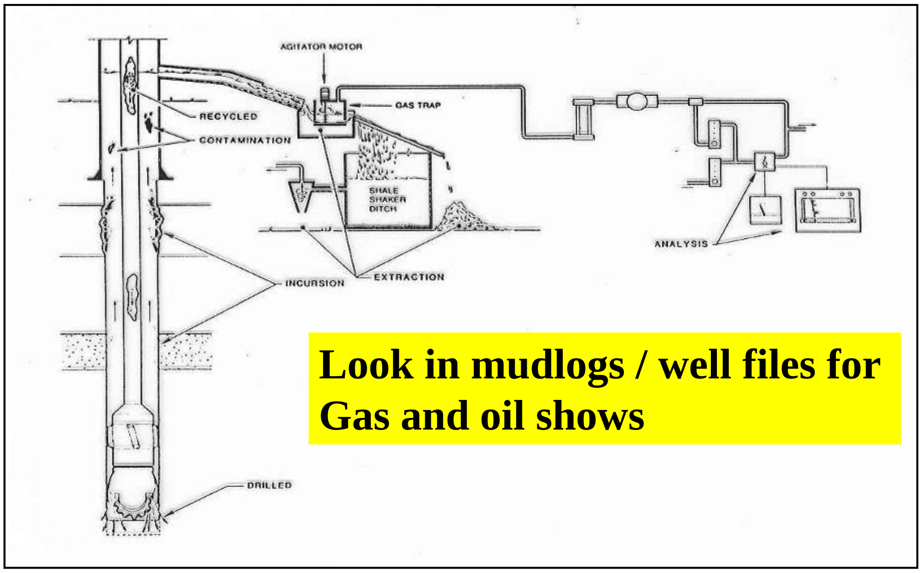
- Rate of penetration
  - Can be used as lithology indicator
  - Will parallel GR and SP
  - Often reflects varying % of porosity
- Lithologic description of well cuttings
- Type and quantity of hydrocarbons encountered
  - UV light
  - Hot-wire detector
  - Gas chromatograph



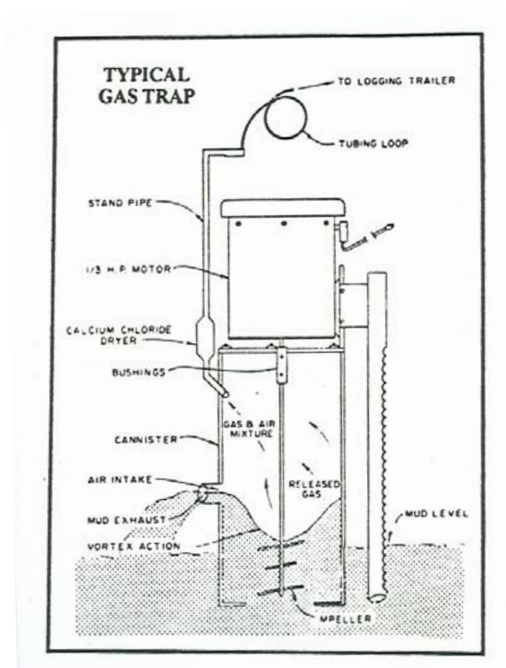
•Lag time-circulation time from the bit to shale shaker
•Gas trap at shale shaker
•Presence, absence, quantity, and type of HC's determined by 3 instruments:
•UV or fluoroscope
•Hot-wire gas detector
•Gas chromatograph

PSI = 0.052 X MW X depth

Drilling – Cuttings – Gas

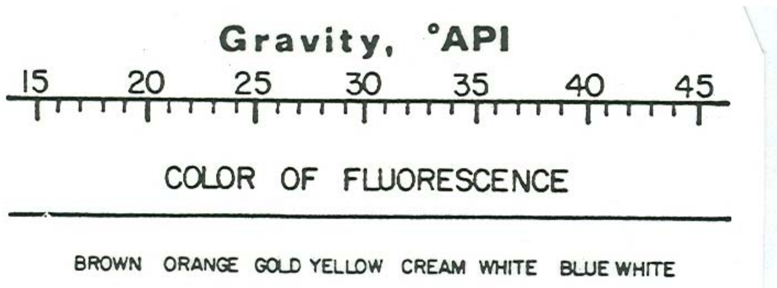


Look in mudlogs / well files for Gas and oil shows



UV light box or Fluoroscope

•Requires that drill cuttings be promptly and properly prepared and examined
•Care taken to distinguish mineral fluorescence from HC fluorescence
•Color and intensity important



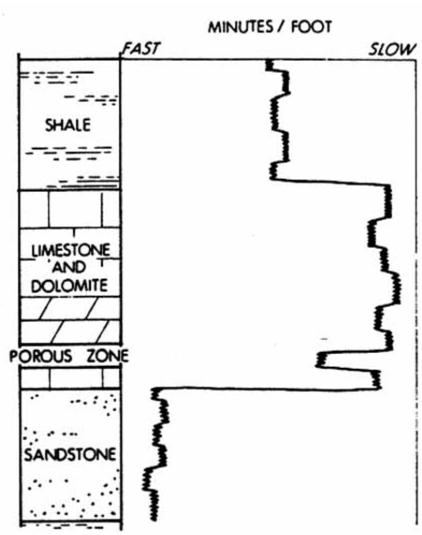
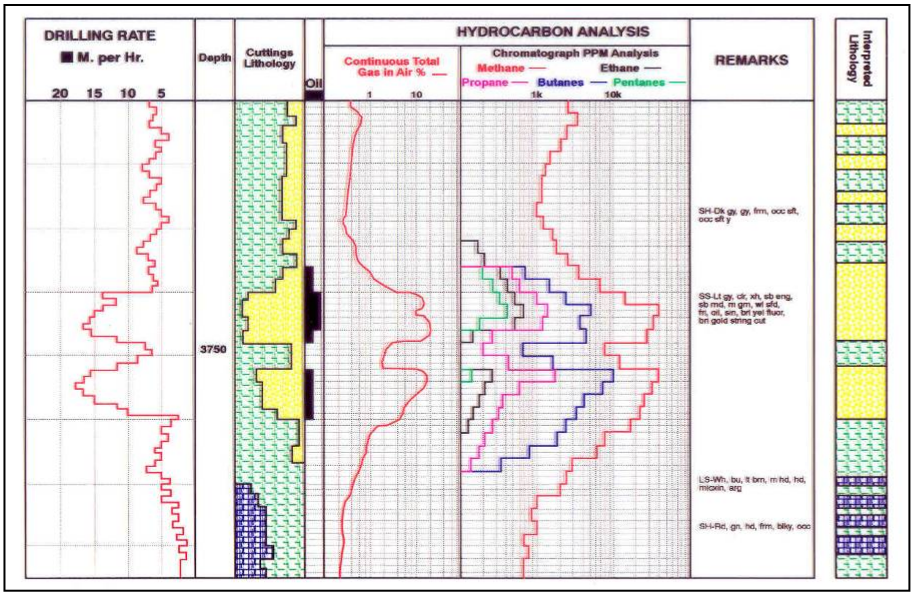
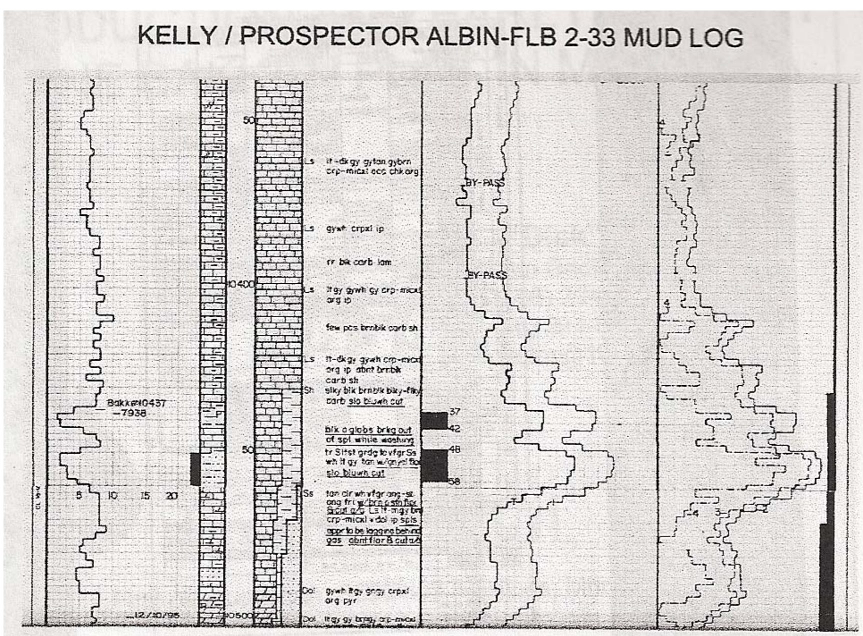


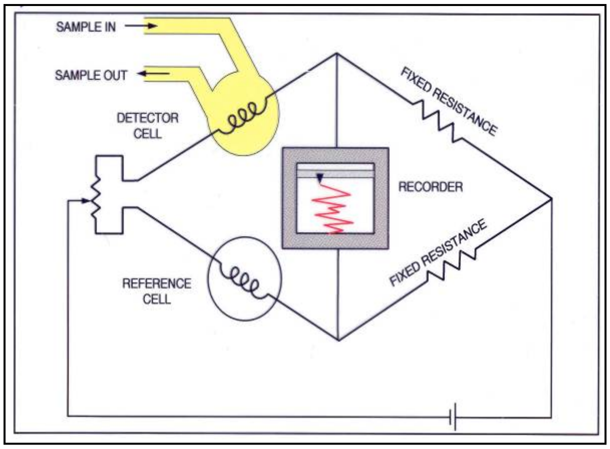
Figure 14-1 A drilling-time log showing drilling breaks where different rock layers are penetrated.

Mud Log Example

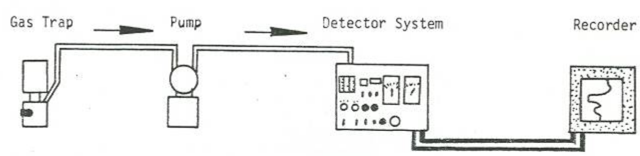




The Hotwire – Total Gas

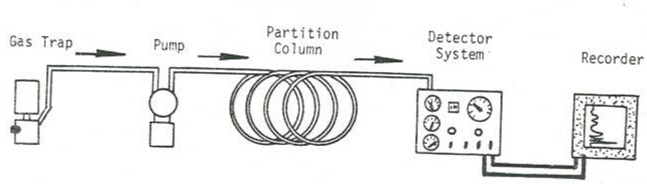


- **Common hot wire detector responds to all combustible gases: hydrocarbons, hydrogen, etc.**
- **Pair of filaments as measuring cells**
- **Reference cell measures only resistance in air while sample cell measures gas-air mixture**
- **Gas combustion in sample raises temperature of the filament, causing resistance of the filament to increase**
- **Resistance increase unbalances bridge circuit causing a recorder deflection**

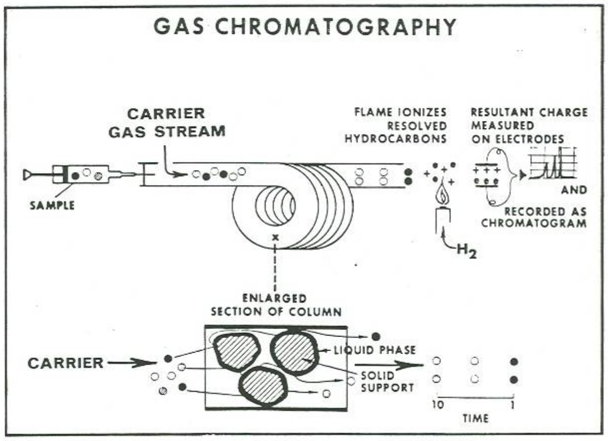


TOTAL GAS

Principle difference between a total gas detector and a gas chromatograph is the partition column.



GAS CHROMATOGRAPH



Most gas chromatograph columns have several characteristics in common:
•Start with long, small diameter metal tube which is filled with a particulate material (referred to as the solid support phase); provides large surface area in the column, liquid material often laid down on grains to increase its surface activity (want strong attraction between various gas molecules and surface of support material
•Typically oil field chromatographs are designed to separate the paraffin series of hydrocarbons at room temperature and using air as carrier
•Transit time for a given gas to flow through is called retention time

Types of Measuring Cells

- Catalytic Combustion Detector
  - Heated energy liberated by gas oxidation is recorded as voltage change
  - Similar to hot wire detector
- Thermal Conductivity Cell
  - Operates by varying its internal temperature and resistivity as a function of thermal conductivity of the gas present
- Hydrogen Flame Ionization
  - Hydrocarbon gases eluted from chromatographic column are ionized in presence of small hydrogen flame.
  - Electrically charged ions are collected at an electrode for measurement
  - Non hydrocarbon gases do not ionize

WIRELINE LOGGING

Wireline logging tools

<u>Measure</u>	<u>to get</u>
• Resistivity (DLL dual laterolog)	S_w
• Natural gamma radiation (GR)	V_{sh}
• Electron density (LDT litho-density)	
• Neutron absorption (CNL compensated neutron log)	ϕ

Formation Properties Needed From Logs

Rt – Resistivity of undisturbed formation

ϕ – Porosity

Rw – Resistivity of formation water

Ro – Resistivity of undisturbed formation, if 100% water saturated

Well Log Response

LOG	VARIABLE	RESPONSE
Gamma Ray	Rock Type	Detects shale from in situ radioactivity. •High GR—shales •Low GR—clean sands and carbonates
Resistivity	Fluid type	Measures resistivity of formation fluid. •High resistivity—hydrocarbons •Low resistivity--brine
Density	Porosity	Measures electron density by detecting Compton scattered gamma rays. Electron density is related to formation density. Good for detecting hydrocarbon gas with low density compared to rock or liquid. •Low response—low HC gas content •Large response—high HC gas content
Acoustic (sonic)	Porosity	Measures speed of sound in medium. Speed of sound is faster in rock than in fluid. •Long travel time—slow speed—large pore space •Short travel time—high speed—small pore space
Neutron	Hydrogen Content	Fast neutrons are slowed by collisions to thermal energies. Thermal neutrons are captured by nuclei, which then emit detectable gamma rays. Note: hydrogen has a large capture cross-section for thermal neutrons. Good for detecting gas. •Large response—high H content •Small response—low H content
Spontaneous Potential	Permeable Beds	Measures electrical potential (voltage) associated with movement of ions. •Low response—impermeable shales •Large response—permeable beds

SP

LOGS

SP

- **Spontaneous Potential** or self-potential
- Oldest geophysical log is use (first one run in 1927)
- Measures the electrical potential set up between an electrode in a sonde drawn up the borehole and a fixed electrode at earth's surface
- Used in open holes filled with conductive mud
- SP response is dependent on the difference in salinity between drilling mud and formation water

SP Logs

- Electrochemical potential between mud and formation fluid
- Uses:
  - Rw, correlation, bed boundaries
- Measures electrical potential (voltage) associated with movement of ions.
  - Low response—impermeable shales
  - Large response—permeable beds

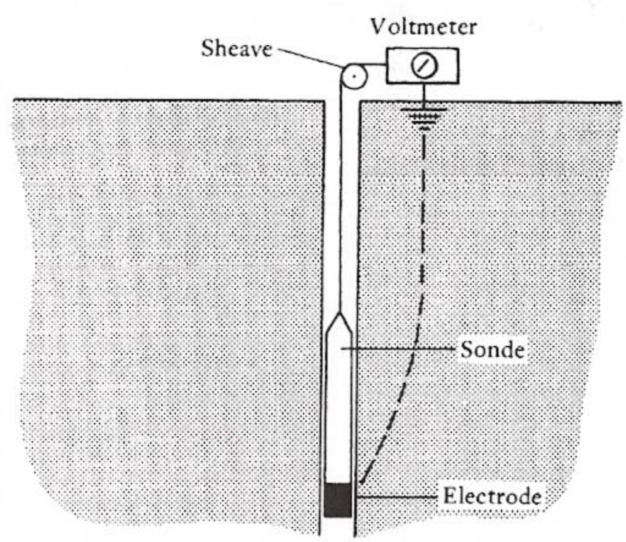


FIGURE 3.18 Basic arrangement for the S.P. log.

Selley, 1998

SP

- Electrical charge is caused by flow of ions (largely Na^+ and Cl^-) from concentrated to more dilute solutions
  - Generally from salty formation water to fresher drilling mud
- Basically related to the permeability of the formation
- Normal or negative SP deflection is to the left of a shale base line
- Impermeable formations yield poorly defined or absent SP deflection

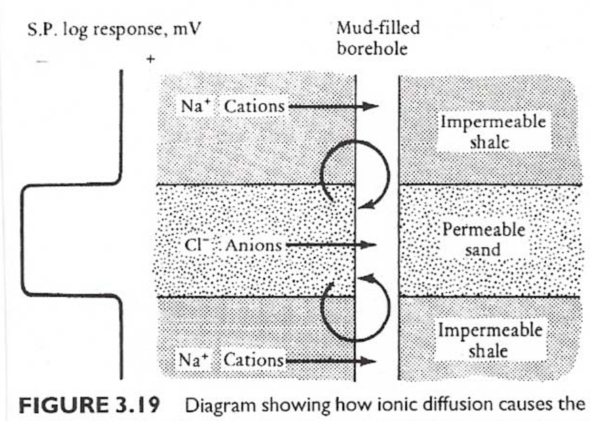


FIGURE 3.19 Diagram showing how ionic diffusion causes the spontaneous potential effect. Looped arrows show the direction of positive current flow. Log response is for the situation in which the salinity of the formation water is greater than that of the drilling mud.

Selley, 1998

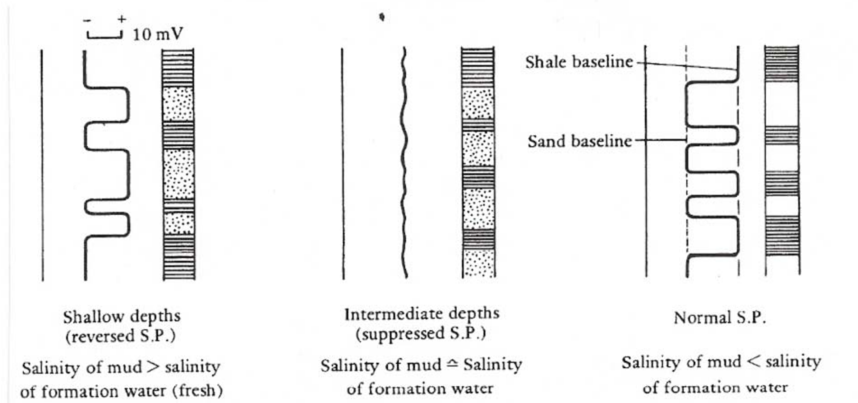


FIGURE 3.20 Schematic S.P. logs for different salinity contrasts of mud and formation water. Reversed S.P. logs are very rare. Suppressed S.P. logs occur where salt muds are used. The usual response, in which the salinity of the drilling mud is less than the salinity of the formation water, is shown in the right-hand log.

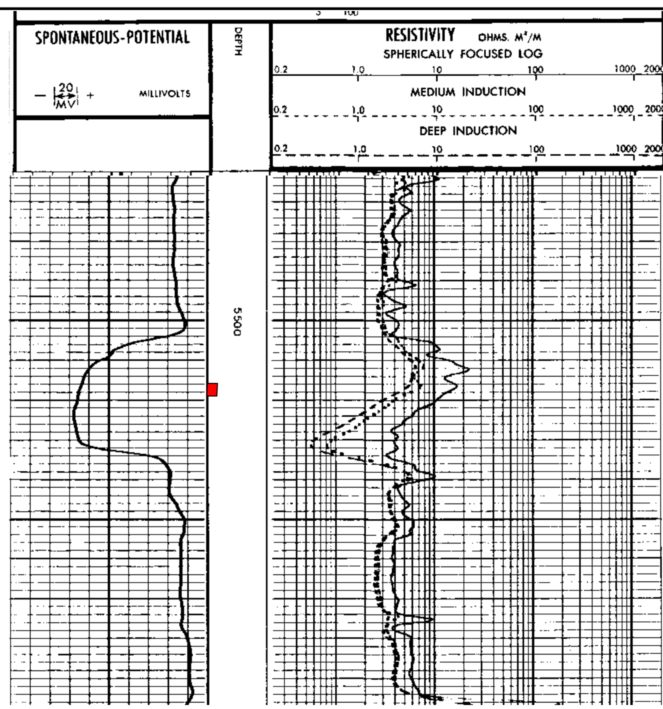
Selley, 1998

SP

- Amplitude of deflection related to permeability and contrast between the salinity of the drilling mud and formation water
- Empirically:
  - $E = - K \log (Rmf \backslash Rw)$
  - Where: E = SP charge (mV); K=a constant, which is generally $61+0.133T(^{o}F)$; Rmf = resistivity of mud filtrate (Ωm); Rw = resistivity of formation water (Ωm)

SP Log

- Used to delineate permeable zones
- Aid lithologic identification and well-to-well correlation
- Used to calculate Rw



Pfs: 5516-19
95 BOPD,
227 MCFD,
31 BWPD

RESISTIVITY

LOGGING

Resistivity Logs

- Three main ways to measure electrical resistivity of a formation: normal log, laterolog, induction log

Logs Run for Rt

- Induction log
- Focused-current electric log
- Conventional Electric log

Electric Logs

- Conventional electric log – Rt
- Lateral log – Rt
- Induction log – Rt
- Uses:
  - Estimation of Rt
  - Estimation of Rw
  - Correlation
  - Bed boundary definition
- Measures resistivity of formation water.
  - High resistivity—hydrocarbons
  - Low resistivity--brine

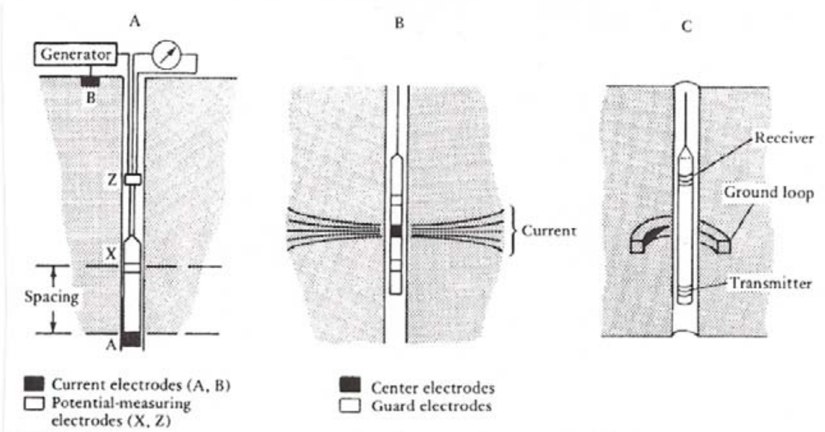


FIGURE 3.21 Illustrations of the three types of resistivity logging devices. (A) The normal resistivity logging device. Variation of the spacing between A and X determines the distance away from the borehole at which the resistivity is measured. (B) Diagram of the laterolog method. (C) Diagram of the induction principle. For explanations see text.

Selley, 1998

Normal Logs

- An electric potential and flow of current is set up between an electrode on the sonde and an electrode at the surface
- Pair of electrodes on sonde used to measure variation in formation resistivity as sonde raised to surface
- Run simultaneously with SP log
- Largely superseded by more sophisticated types

Laterologs

- Laterologs used for low-resistivity salty muds
- Single electrode cause focused current to flow horizontally into formation
  - Horizontal flow achieved by placing two guard electrodes above and below current electrode
  - Potential of the guard and central electrodes is measured

Induction Log

- For fresh water or oil-based muds
- Transmitter and receiver coils at two ends of a sonde
  - Transmit frequently alternating current
  - Current creates magnetic field which generates currents in formation
  - Currents measured at receiver coil

Formation Resistivity

- Solid rock or porous rock saturated with fresh water, oil, or gas is highly resistive
- Shale or porous formations saturated with salty water have very log resistivities

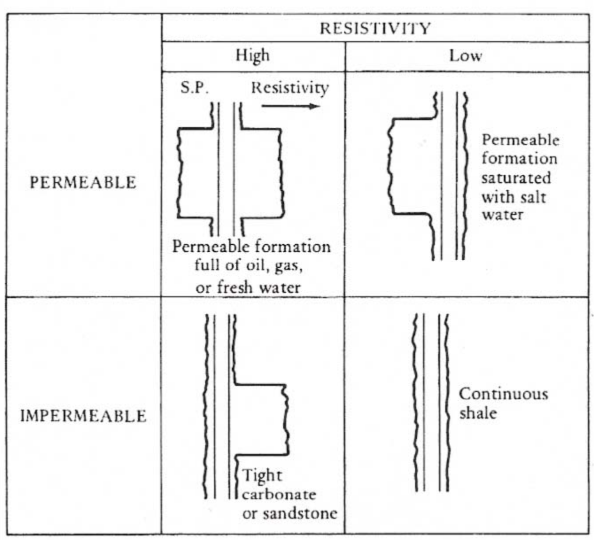


FIGURE 3.22 The four basic responses for S.P. and resistivity logs for a bed between impermeable formations.

Selley, 1998

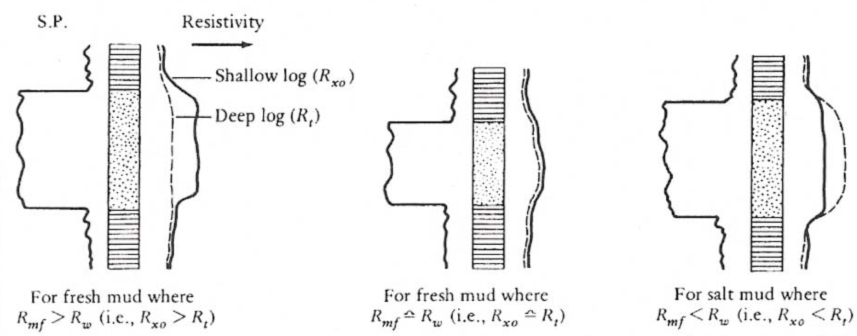


FIGURE 3.24 S.P. and resistivity logs showing the responses for a water-bearing reservoir for cases of various differences between the resistivity of the drilling mud (R_m) and that of the formation water (R_w).

Selley, 1998

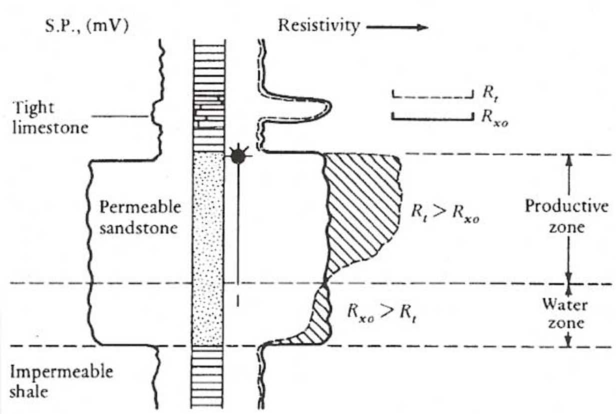


FIGURE 3.25 S.P. and resistivity logs through a hydrocarbon reservoir showing typical responses for the situation where $R_{mf} > R_w$.

Selley, 1998

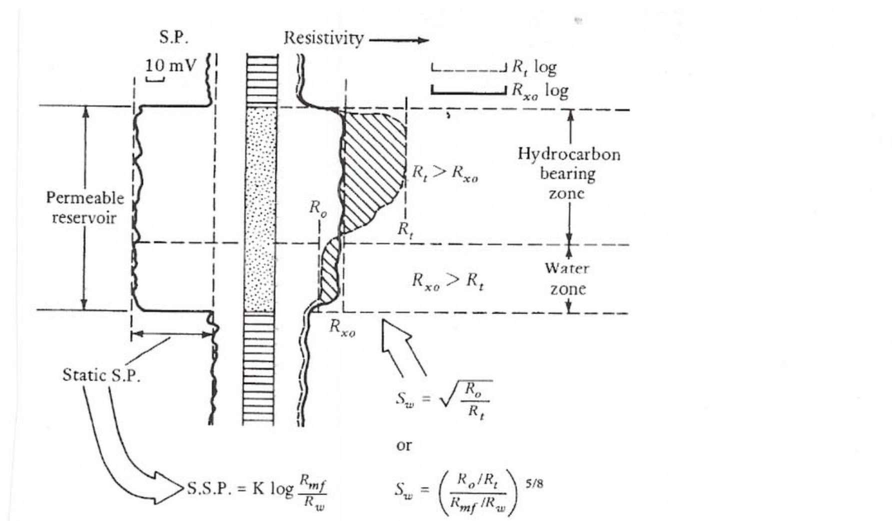
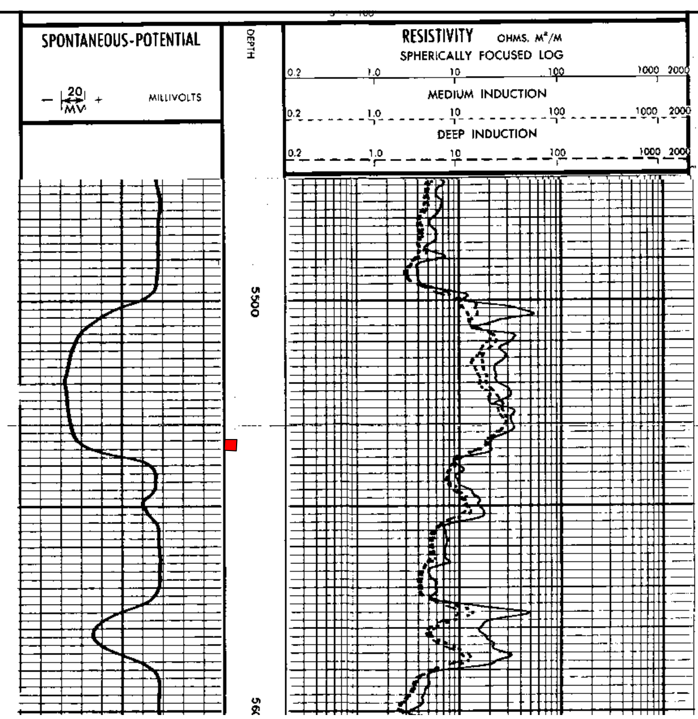


FIGURE 3.27 S.P. and resistivity logs for a hydrocarbon zone showing where readings are taken to solve the R_w and S_w calculations. For explanation see text.

Selley, 1998



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5534-37
203 BOPD

Dipmeter

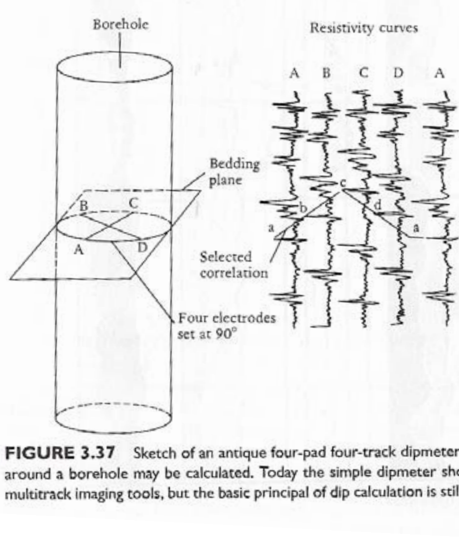


FIGURE 3.37 Sketch of an antique four-pad four-track dipmeter showing how the direction of dip around a borehole may be calculated. Today the simple dipmeter shown here has been superseded by multitrack imaging tools, but the basic principal of dip calculation is still as shown here.

Selley, 1998

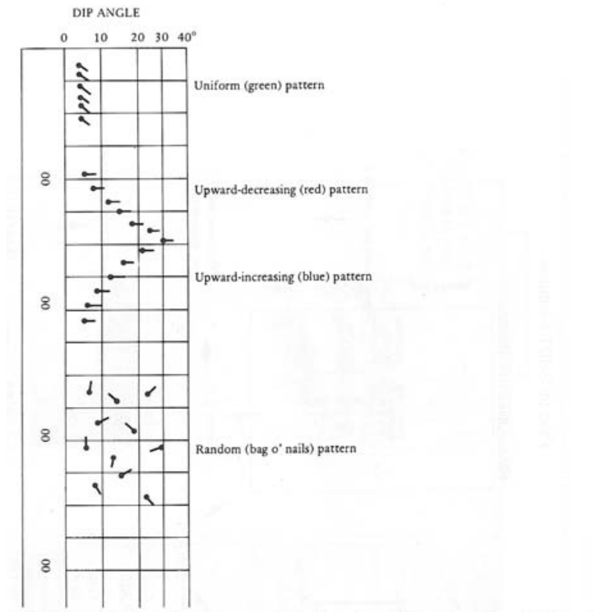
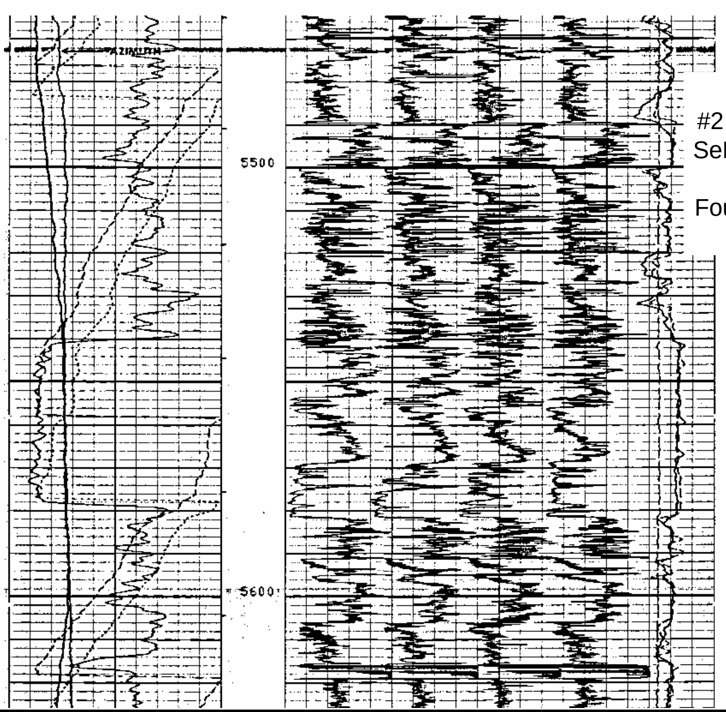


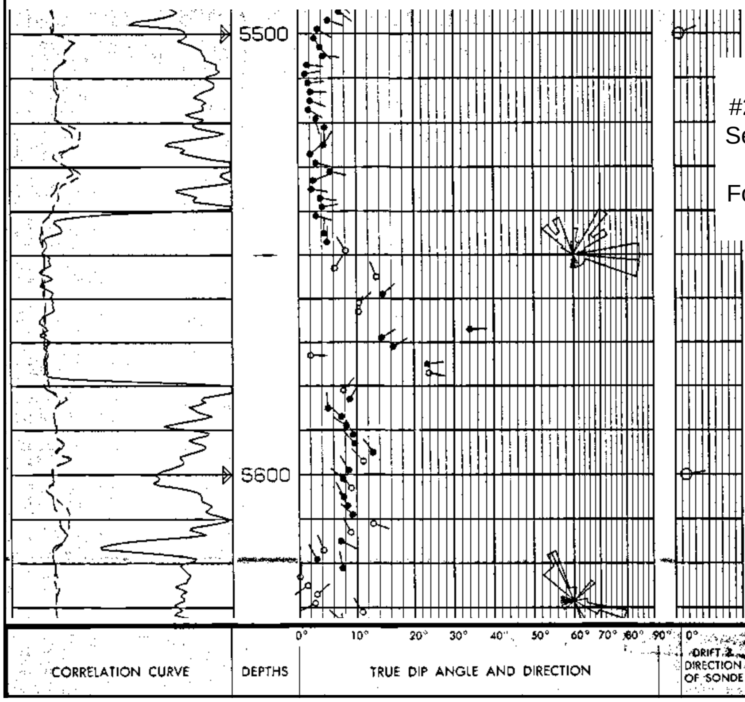
FIGURE 3.38 Conventional dipmeter tadpole plot showing the four common dip motifs. Each motif can be produced by several quite different geological phenomena. The head of the tadpole shows the amount of dip. The tail of the tadpole points in the direction of dip.

Selley, 1998



Champlin
#2 Rhoades 22-35
SeNw 35-13S-49W

Four arm High Res
Dipmeter



Champlin
#2 Rhoades 22-35
SeNw 35-13S-49W

Four arm High Res
Dipmeter

Natural Gamma-Ray

LOGGING

Gamma Ray Log

- Uses scintillation counter to measure natural radioactivity of formations
- Measure of natural gamma radiation in sediments from:
  - Potassium found in illitic clays, mica, glauconite
  - Organic matter scavenges uranium and thorium
    - Oil source rocks, oil shales, algal coals are radioactive (humic coals not radioactive)
- Application
  - Correlation
  - Differences between sediments
  - Depth control for completion
- Detects shale from in situ radioactivity.
  - High GR—shales
  - Low GR—clean sands and carbonates

GR Uses

- Stratigraphic Correlation
- Shale content V_{sh}
  - **effective porosity** $\Phi_{effective} = \Phi_{total} - V_{sh} \cdot \Phi_{shale}$
  - shaly sandstone evaluation
- Net to Gross Estimation (NET PAY)
- Clay mineral identification*
- Depth control through casing (collar locator)

Typical GR API Readings

Lithology:		GR reading (API)
– Limestone		5-10
– Dolomite		10-20
– Sandstone		10-60
– Shale		80-140
Evaporites		
– Halite	NaCl	0
– Anhydrite	$CaSO_4$	0
– Polyhalite	K_2SO_4	180

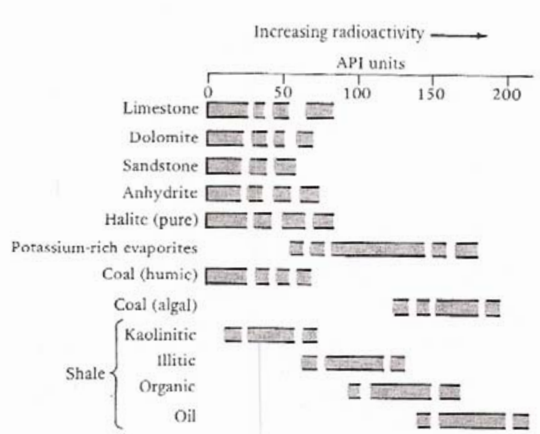
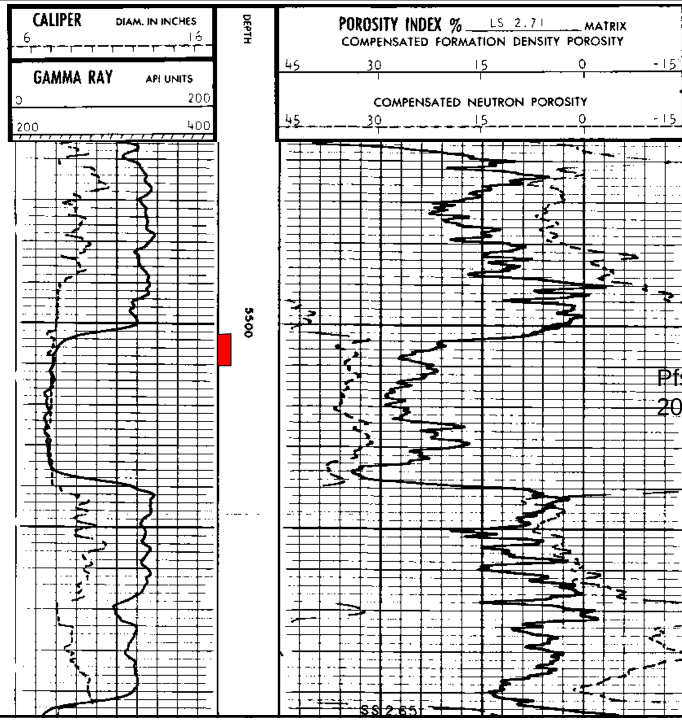


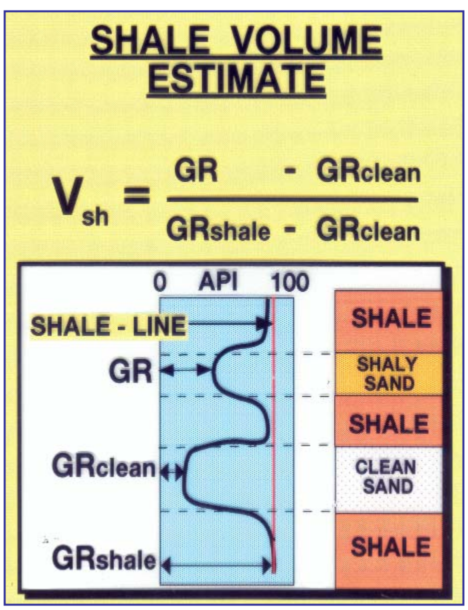
FIGURE 3.28 The approximate gamma log ranges for various rocks. Note that small quantities of radioactive clay, for example, can increase the reading of any lithology.

Selley, 1998



Pfs: 5503-10
200 BOPD

V_{sh} Estimation



- Must have clean and shale endpoints
- Net Pay =

total interval thickness minus cumulative shale thickness

Density
&
Neutron

LOGGING

Logs Run for Porosity

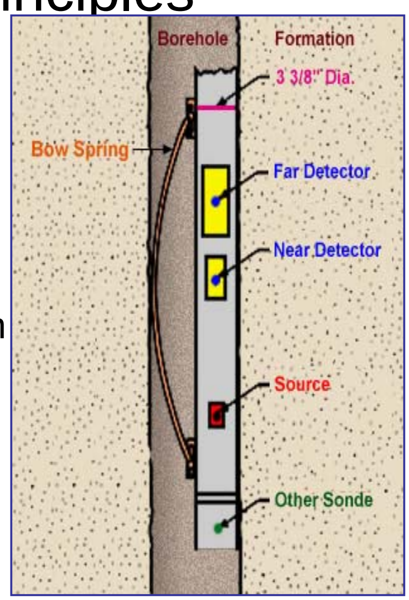
- Acoustic log
- Density log
- Neutron log

Neutron Log

- Measures hydrogen concentration in a formation
- Device that bombards the formation with neutrons from radioactive source
- Emitted neutrons collide with nuclei of the formation and lose some energy, maximum energy loss where they collide with hydrogen (neutron and hydrogen about the same mass)
- Causes rocks to emit gamma rays in proportion to their hydrogen content
- Energy loss related to porosity and presence of hydrogen
- Gamma radiation recorded by the sonde
  - Hydrogen occurs in all formation fluids (oil, gas, water) but not in the minerals
  - Response is correlative to porosity
  - Shales have bonded water so have higher apparent porosity (same with shaley reservoirs
  - Hydrogen content of oil and water about equal but lower in gas (thus gives low reading in gas zones)

Neutron - Principles

- Neutron logging tool has source that emits fast neutrons & two detectors (near and far).
- As neutrons collide with formation nuclei, they lose energy. After a number of collisions, the neutrons reach thermal energy state where they can be captured by the formation nuclei
- **When the neutrons are captured they emit Gamma rays**



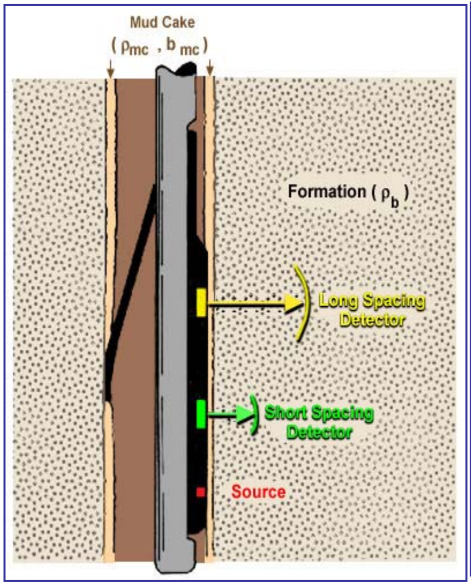
Neutron Log

- Measure of hydrocarbon density in sediments
- Uses:
  - Porosity determination
  - Correlation
  - Depth control for completion
  - Gas recognition
  - Large response—high H content
  - Small response—low H content

Density Log

- Measures electron density of a formation
- Measures formation density by emitting gamma radiation from the tool and recording amount of gamma radiation returning from the formation
  - Emitted gamma rays collide with formation electrons and scatter
  - A detector counts the number of returning gamma rays (indicator of formation density)
- Uses:
  - Porosity determination
  - Correlation
  - Gas recognition
- Gamma radiation reading can be related to the electron density of atoms in the formation which is directly related to bulk density of the formation
- Bulk density is a function of lithology and porosity
  - Low response—low HC gas content
  - Large response—high HC gas content
- Litho-density tool (LDT) also provides a photoelectron (Pe) cross section curve, an independent indicator of lithology

Density Tool – General LDT



- Chemical Gamma source, and two Gamma Ray detectors:
  - short spaced detector
  - long-spaced detector
- Gamma Rays scattered back are read by a scintillation detector (like the natural γ ray tool)

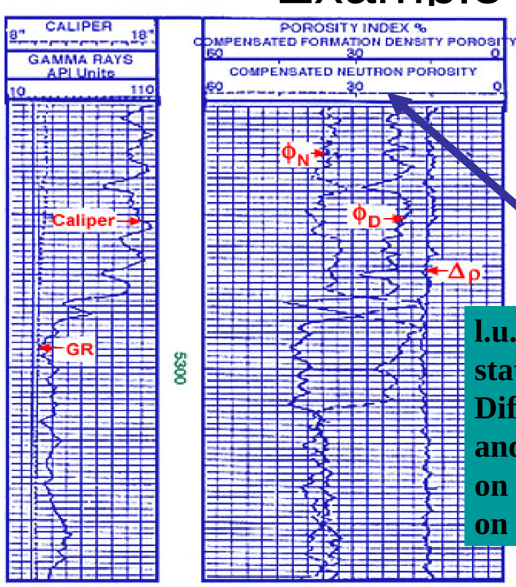
Density Log

- Porosity (Φ) = $(\rho_{ma} – \rho_b)/(\rho_{ma} – \rho_f)$
- Where ρ_{ma} = density of the dry rock (g/cm3); ρ_b = bulk density recorded by the log, and ρ_f = density of the fluid
- Gas lowers the density of the rock thus causes the log to give too high a porosity
- Typical Matrix Densities:
  - Clean Sandstone – 2.65 g/cc
  - Limestone – 2.71 g/cc
  - Dolomite – 2.87 g/cc

Lithology Matrix Densities to Determine Porosity and Average Pe to Determine Lithology

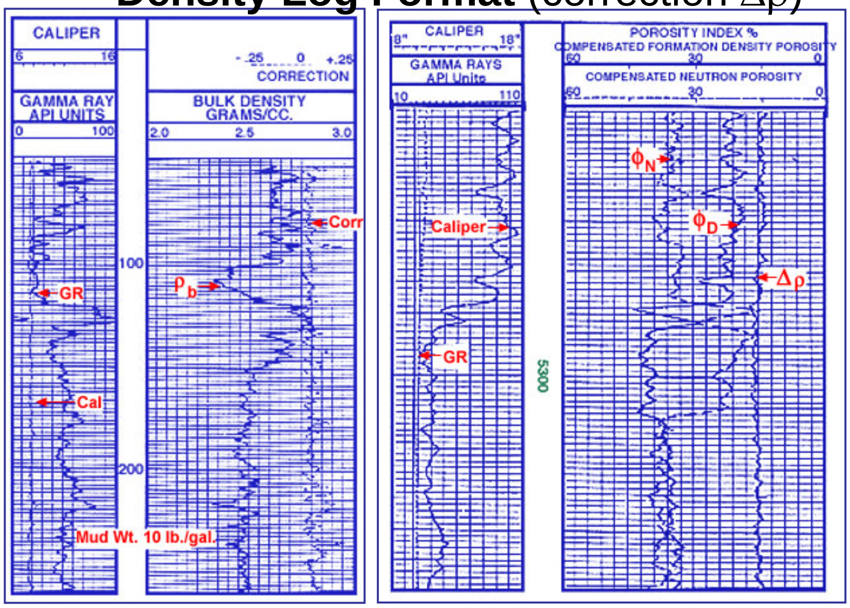
Lithology	Density, g/cc	Average P_e
Sandstone	2.65	1.8
Limestone	2.71	4.8
Dolomite	2.876	3.0
Anhydrite	2.977	5.05
Salt	2.032	4.6

Example Log



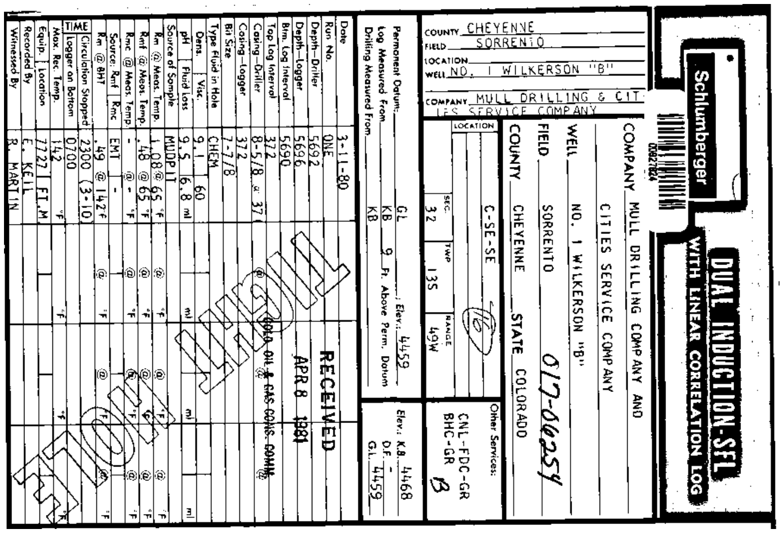
l.u. = "limestone units" unless stated otherwise.
Difference between sandstone and limestone scale is 3%. e.g on a limestone scale Φ= 10% on a sandstone scale Φ= 13%

Density Log Format (correction $\Delta\rho$)



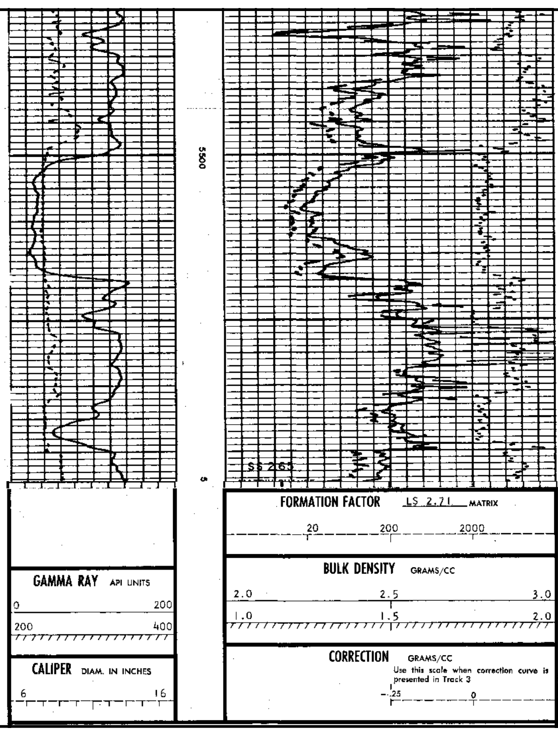
Density / Neutron Applications

- **Porosity determination**, individually but in gas / shale interval we need a combination of the two tools.
- **Gas detection**, neutron / density or with sonic tools.
- **Shale volume determination**.
- **Lithology indication**



LOGGING DATA

DEPTH		CNP			FDC				GR			
Top	Bottom	Porosity Scale	Matrix	Auto Corr. or Hole Size Setting	Porosity Scale	Grain Density	Liquid Density	Hole Fluid	Sens. Logged	T. C.	Zero Div. Left	Scale Per 100 Div.
372	5400	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200
5400	5600	20/TK	SS	AUTO	20/TK	2.65	1.00	LIQ.	0-200	2	0	200
5600	TD	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200

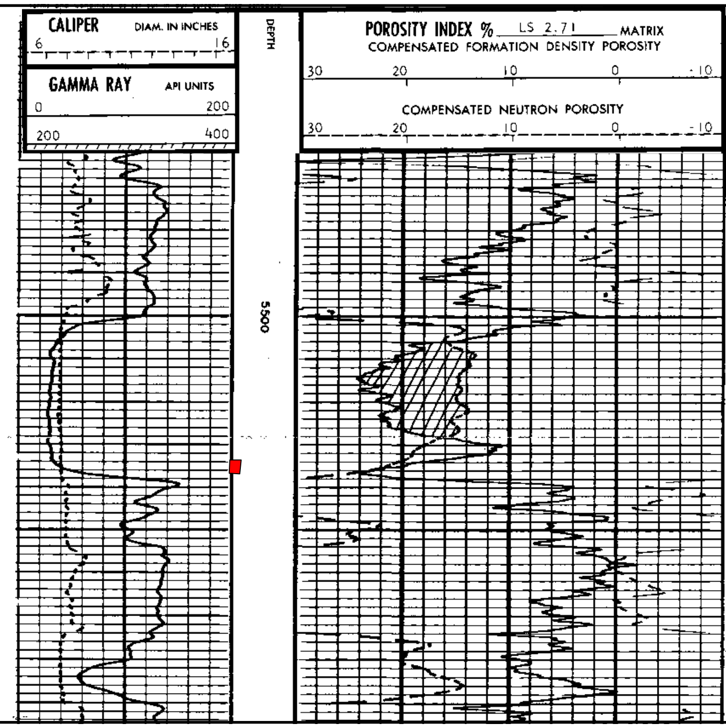


Mull Drilling
Wilkerson 1 B
C-Se-Se Sec. 32-13S-49W

$(\Phi) = (\rho ma - \rho b)/(\rho ma - \rho f)$

ρma = 2.65 ss, 2.71 ls
ρf = 1.0

For ρb = 2.25,
ϕ = 24.2% ss, 26.9% ls



Pfs:
5534-37
203 BOPD

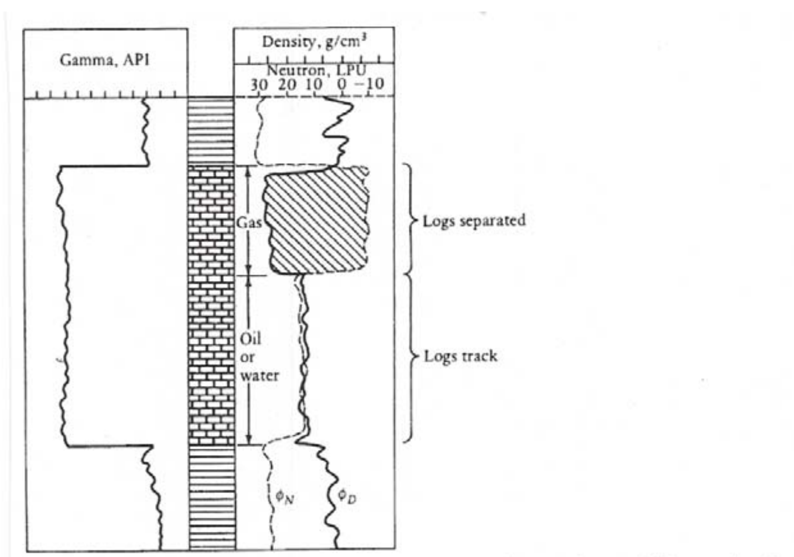


FIGURE 3.32 Log showing how separation of the density and neutron logs may indicate gas-bearing intervals.

Selley, 1998

Obtaining Porosity from Density-Neutron Logs

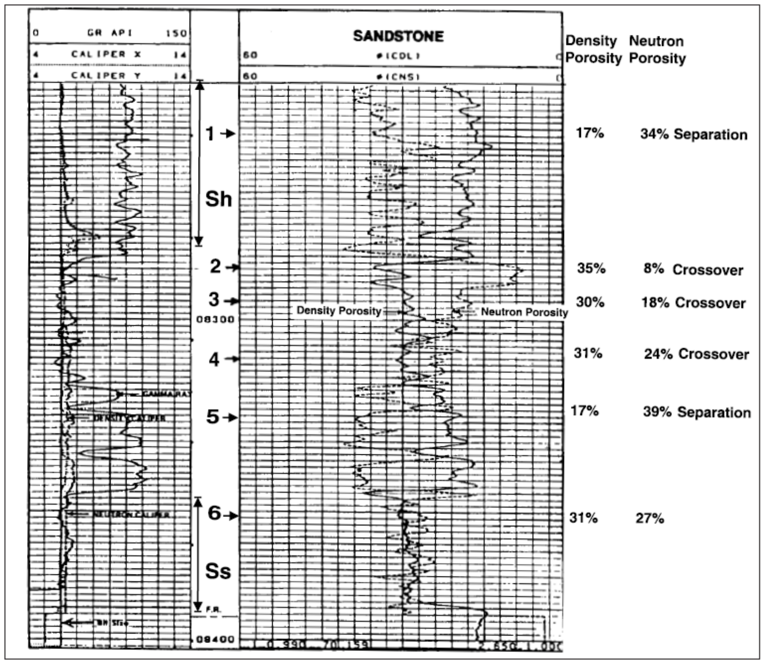
Condition	Method
Log matrix lithology is known and the two log curves separate (density porosity is less than neutron porosity)	If density porosity is less than neutron porosity, such as in a sandstone with shale/clay content, the density log provides a reasonable approximation of formation porosity.
Log matrix lithology is known and there is crossover (density porosity is greater than neutron porosity)	Crossover (density porosity is greater than neutron porosity) is due to the presence of gas in the formation. Recompute density porosity using $\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$ Use gas density instead of water density.
Chartbook is available	Plot the porosities on a density–neutron crossplot from a log interpretation chartbook. Use the appropriate crossplot for the log type (i.e., SNP, CNL) and mud type (fresh or salt).
Chartbook is not available	Calculate porosity using the equation $\Phi = \left(\frac{\Phi_N^2 + \Phi_D^2}{2} \right)^{1/2}$ where Φ is percent porosity, Φ_N is neutron percent porosity, and Φ_D is density percent porosity.

Hartman and Beaumont, 1999

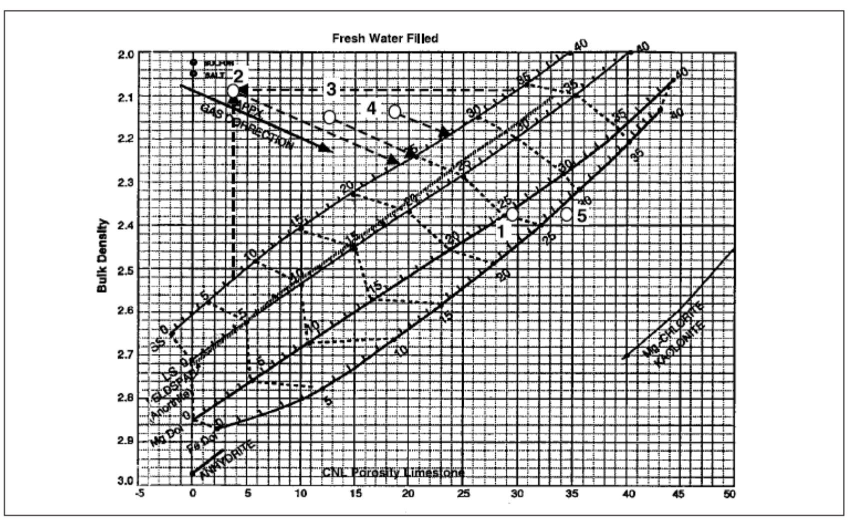
Using Density-Neutron Cross-plot

Step	Action	
1	Use the table below to determine how to enter a neutron porosity value.	
	If...	**Then...**
	Neutron porosity is in limestone units	Enter the chart along the x-axis with neutron porosity. Project up to density porosity.
	Neutron porosity is in sandstone or dolomite units	Enter the chart on the sandstone or dolomite line. Project up or down to a density value.
2	Use the table below to determine how to enter a density porosity value	
	If...	**Then...**
	Density log porosity is in sandstone, limestone or dolomite units	Find the density log percent porosity value on the diagonal line that matches the lithologic units recorded on the log (i.e., use the sandstone line if the log was recorded in sandstone units). Move left or right to intercept the neutron projection.
	Density log scale is bulk density	Enter the y-axis with the log bulk density value and intercept the neutron projection.
3	Use the table below to determine formation lithology and porosity.	
	If...	**Then...**
	Point falls on a diagonal line	The point defines the lithology of the formation by which line it falls on and the porosity is the value marked on the line at that point.
	Point falls away from appropriate diagonal line	Move down and to the right parallel to the nearest dashed line until a diagonal line is intersected. Read the value for porosity at that point. The lithology is a combination of the lithologies of the lines on either side of the point of intersection. Gas is present if the original point is northwest of the appropriate diagonal lithology line.

Hartman and Beaumont, 1999



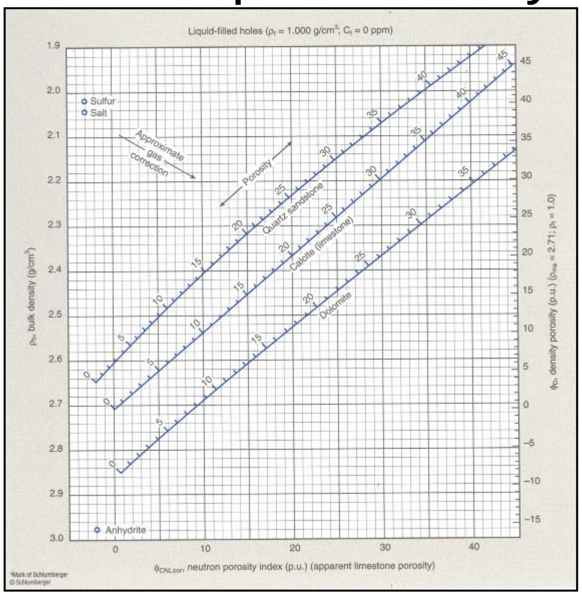
Hartman and Beaumont, 1999



Points 1-5 are from the log example, points 2, 3, 4 from a zone that shows crossover. Once completed point 2 was gas reservoir; point 3 was light oil reservoir; point 4 in a zone with residual oil

Hartman and Beaumont, 1999

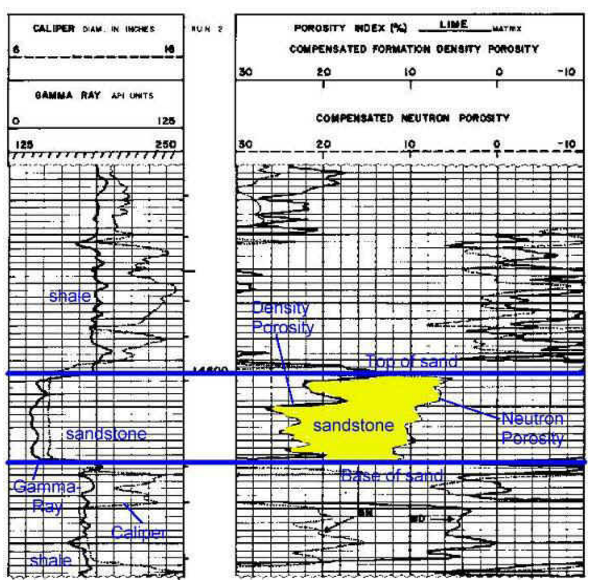
Cross-plot Porosity & Lithology



Cross-plot (X-plot) of neutron porosity and density gives :

1. Total porosity Φ_t
2. lithology

SLB Log Interpretation Charts, 1998



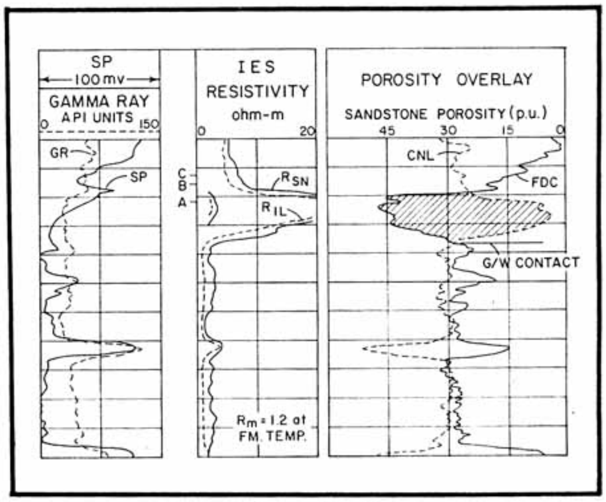


Fig. 3-4 — CNL-FDC overlay showing gas zone in cleaner part of sand. As shown by Gamma Ray the upper part of the interval is shaly. (From Ref. 1, courtesy of SPWLA.)

ACOUSTIC

LOGGING

Acoustic Logs

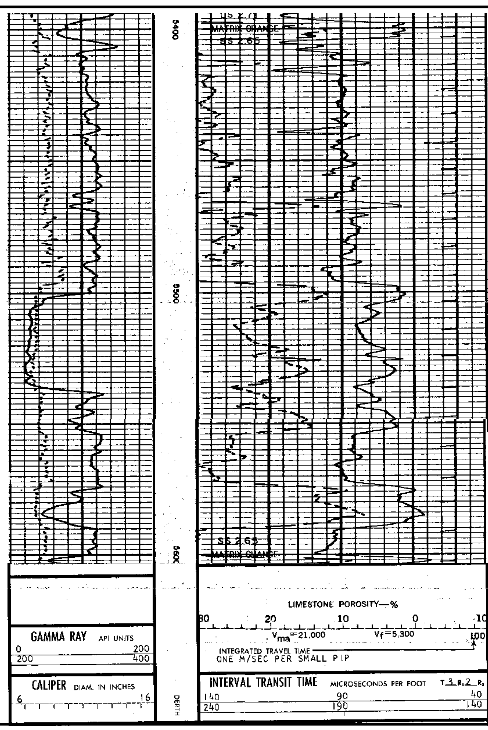
- Measuring acoustical velocity
- Transits times recorded of clicks emitted from one end of the sonde traveling to one or more receivers at the other end
- Sonic log - $\phi = (\Delta t_{log} - \Delta t_{ma}) / (\Delta t_f - \Delta t_{ma})$
- Measures speed of sound in medium. Speed of sound is faster in rock than in fluid.
  - Long travel time—slow speed—large pore space
  - Short travel time—high speed—small pore space

TABLE 3.1 Some Commonly Used Velocities

Lithology (i.e., pure mineral, $\phi = 0$)	Velocity ft/s	Velocity μs/ft
Sandstone (quartz)	18,000–21,000	55.5–51.3
Limestone (calcite)	21,000–23,000	47.5
Dolomite (dolomite)	23,000	43.5
Anhydrite (calcium sulfate)	20,000	50.0
Halite (sodium chloride)	15,000	67.0
Fluid (fresh water or oil)	5300	189.0

Acoustic Logs

- Least accurate of the three porosity logs because it is one most affected by lithology
- Widely used, however, for lithology identification
- Used to determine interval velocities



Mull Drilling
Wilkerson 1 B
C-Se-Se Sec. 32-13S-49W
KB 4468

LOGGING DATA

Porosity Selectors				Depth	
Δt_m	Δt_f	Cp	ϕ Scale	From	To
47.6	189	1.0	20/TK	300	5400
52.6	189	1.0	20/TK	5400	5600
47.6	189	1.0	20/TK	5600	TD

$\phi = (\Delta tlog - \Delta tma) / (\Delta tf - \Delta tma)$

APPLICATION OF LOGS

Major Applications of Common Log Types

(After Selley, 1998)

Log Type	Lithology	Hydrocarbons	Porosity	Dip
ELECTRIC				
SP	X			
Resistivity	X	X		
RADIOACTIVE				
Gamma Ray	X			
Neutron		X	X	
Density		X	X	
SONIC	X	X	X	
DIPMETER				X

COMPUTATION EQUATIONS

Apparent Porosity Computation:

Density: $\varnothing D = \dfrac{\rho ma - \rho b}{\rho ma - \rho f}$

Sonic: $\varnothing S = \dfrac{\Delta t - \Delta tma}{\Delta tf - \Delta tma}$

Neutron: $\varnothing N$ = as recorded on log

Formation Factor Computations:

$F = a/\varnothing^m = Ro/Rw$

Water Saturation Equations:

$Sw = \sqrt{\dfrac{F\,Rw}{Rt}} = \sqrt{\dfrac{Ro}{Rt}}$

Archie's Basic Saturation Equation

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

R_w resistivity of formation water

R_t resistivity of rock filled with hydrocarbons

Φ porosity (from density / neutron or combination)

m cementation exponent

n saturation exponent

m=n~2

RELATION OF WATER SATURATION AND RESISTIVITY INDEX

$Sw^{-n} = Rt/Ro = I$

n = saturation exponent

$$Sw = \sqrt[n]{\frac{Ro}{Rt}} = \sqrt[n]{\frac{F\,Rw}{Rt}}$$

Hydrocarbon saturation can be determined if n, Rt, and Ro are known

FORMATION FACTOR POROSITY RELATIONSHIP

ARCHIE $F = 1/\phi^{m}$

m = cementation exponent

HUMBLE $F = 0.62/\phi^{2.15}$

Formation Evaluation Summary

Parameter :	**Derived from :**
Net Pay	**gamma-ray log (GR)**
Lithology	**density / neutron (DEN /NEU X-plot)** **spectral GR, photo electric effect**
Shale content	**gamma-ray, DEN / NEU X-plot**
Porosity	**DEN, NEU, or (DEN /NEU X-plot)**
HC / Water	**deep resistivity logs**
Gas or Oil	**separation density & neutron**
water saturation	**deep and shallow resistivity logs**

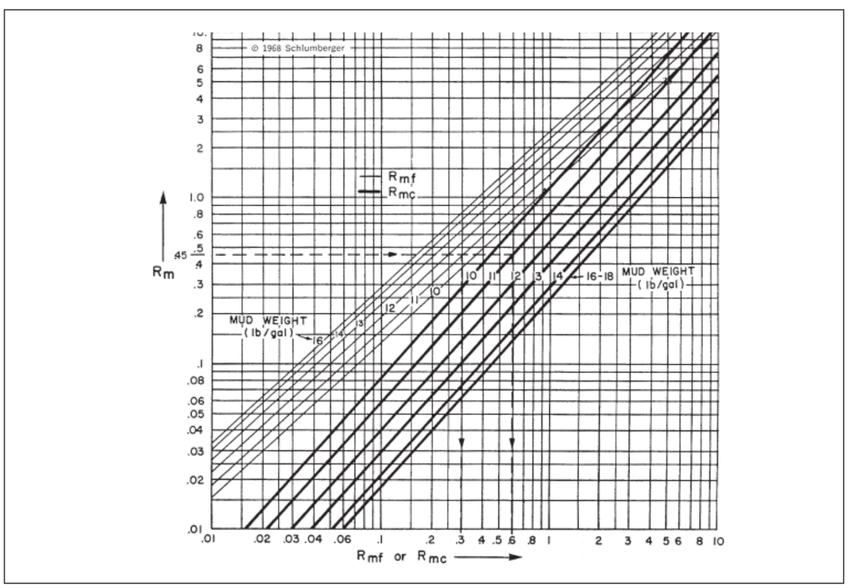
Table 14-2 Wire-Line Well Logs

Name	Measures	Primary Uses	Comments
Electrical log Spontaneous potential (self-potential), SP		Correlation Location of reservoir rocks	Older type of log Reservoir rocks kick to left
Resistivity, R	Electrical resistivity		Salt water drilling mud only
Short normal	Adjacent to well bore	Tops and bottoms	
Long normal	Away from well bore	Identification of reservoir fluids	Oil and gas gives kick to far right Higher oil saturations kick further to right
Induction log Dual induction log	Measures SP, R, and conductivity	Same as electrical log; shallow induction same as short normal and deep induction same as long normal	Used in well filled with any type of drilling mud or air No SP measurement in air or oil drilling mud Modern type of log
Gamma ray log	Natural radioactivity of rocks	Correlation Tops and bottoms Location of reservoir rocks Shale content	Shale kicks to right; used in cased and uncased wells
Neutron porosity log Neutron log	Hydrogen atom density	Porosity	Reads low on gas reservoirs; used in cased and uncased wells
Formation density log Density log	Density of rock	Porosity	Must know lithology (matrix)
Acoustic velocity log Sonic log Velocity log	Sound velocity through rock layer; measures interval transit time, Δt	Porosity Correlation	Must know lithology (matrix)
Caliper log	Size of well bore	Engineering calculations Calibration of other logs	Thick filter cake (small hole) indicates permeable zone
Dipmeter Dip log	Orientation of subsurface rocks	Interpretation of structure and depositional environment	Uncased well

Calculating Rw from SP Logs

- Rw critical component of log analysis
- Can be calculated from SP or measured from a sample of formation water taken in the zone of interest
- To calculate from SP we need:
  - Resistivity of mud filtrate (Rmf) at measured temperature, found on log header
  - If only Rm is given, convert to Rmf using chart
  - Bottom hole temperature and TD
  - SP reading from porous zone at least 20 ft thick

Enter Rm and move across to appropriate mud weight
Project to bottom of chart to estimate Rmf



Hartman and Beaumont, 1999

Calculating Rw from SP Logs

Step	Action
1	Estimate formation temperature.
2	Convert R_{mf} to formation temperature.
3	Convert R_{mf} to $R_{mf\ eq}$.
4	Read SP response and estimate R_{we}.
5	Convert R_{we} to R_w and NaCl at formation temperature.

Hartman and Beaumont, 1999

Estimating Formation Temperature

$$T_f = T_s + D_f \frac{BHT - T_s}{TD}$$

where:

T_s = average surface temperature
D_f = depth to the formation
BHT = bottom-hole temperature (found on log header)
TD = total depth (make sure BHT and TD are from same log run)

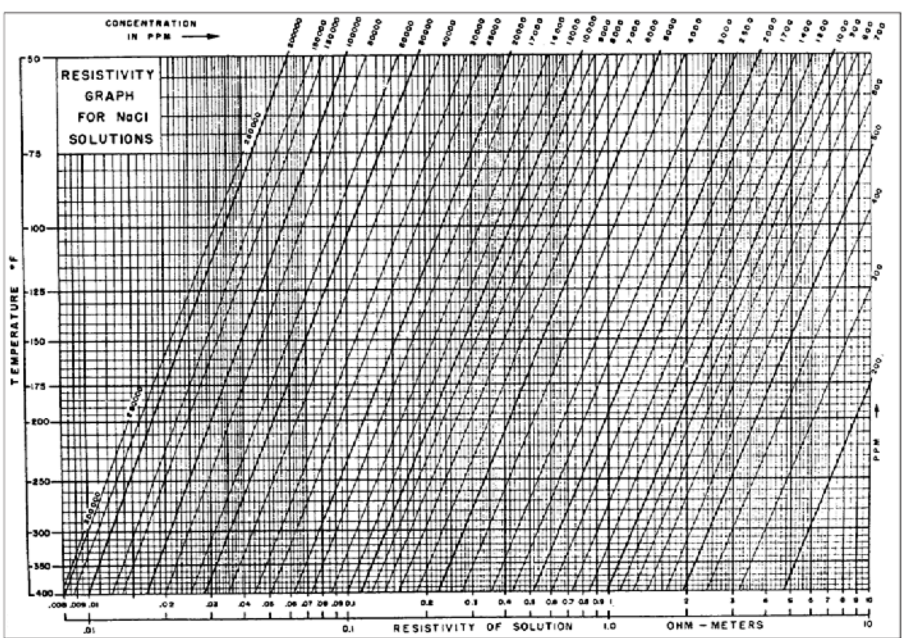
Hartman and Beaumont, 1999

Convert Rmf to Rmf at Formation Temperature

Follow this procedure to convert R_{mf} (measured at surface temperature) to R_{mf} at formation temperature.

Step	Action
1	Enter Figure 9–33 along the resistivity of solution axis and the temperature axis using the measured values for R_{mf} and surface temperature found on the log header.
2	Follow the appropriate salinity line intercepted at step 1 to the appropriate formation temperature and mark on the chart.
3	Project down the chart from this mark to the resistivity scale and read R_{mf} at formation temperature. Record the value of R_{mf} at a specific temperature.

Hartman and Beaumont, 1999



9-33

Hartman and Beaumont, 1999

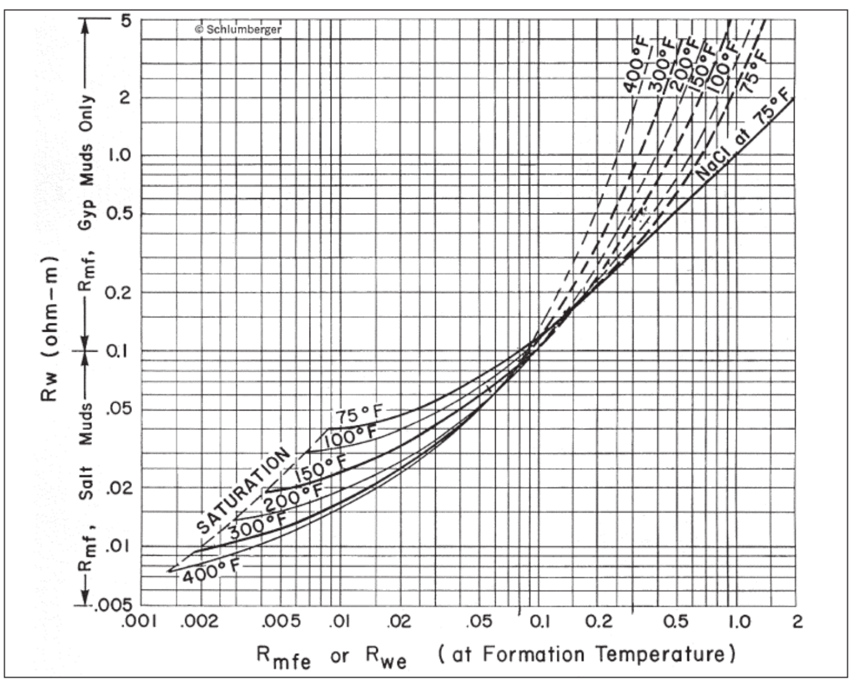
Convert Rmf to Rmf eq

Step	Action
1	Enter Figure 9–34 with R_{mf} at formation temperature on the vertical axis.
2	Move across the chart to the appropriate formation temperature contour, and mark this point on the figure.
3	Read down to $R_{mf\ eq}$. This value is used in the equation $R_{we} = R_{mf\ eq}\ (R_{mf\ eq}/R_{we}$ value).

Hartman and Beaumont, 1999

9-34

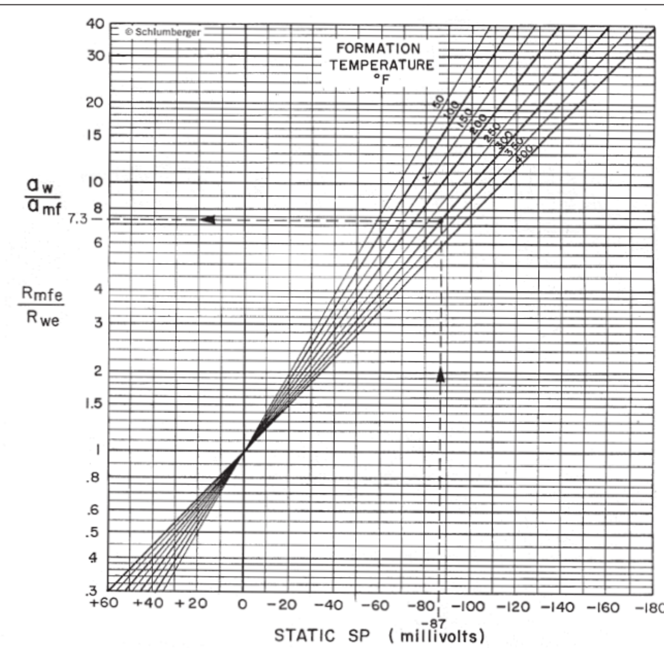
Hartman and Beaumont, 1999



Convert SP to Rwe

Step	Action
1	On the log, establish the shale base line for the SP curve.
2	Read the maximum SP response in a zone at least 20 ft thick.
3	Enter the base of Figure 9–35 with SP (SP is negative if it deflects to the left of the shale base line). Follow the SP grid line up the chart to the appropriate formation temperature. At this point, move across the chart and read the $R_{mf\ eq}/R_{we}$ value.
4	Solve for R_{we} using the equation $R_{we} = R_{mf\ eq}/(R_{mf\ eq}/R_{we}$ value).

Hartman and Beaumont, 1999



9-35

Hartman and Beaumont, 1999

Concert Rwe to Rw

Follow the procedure below to convert R_{we} to R_w.

Step	Action
1	Enter Figure 9–34 again with R_{we} (along the base). Move up the chart until R_{we} intersects the temperature slope.
2	Directly across from the intersection point, read R_w from the vertical axis.

Hartman and Beaumont, 1999

Determining Water Saturation

- Calculated from the Archie equation

$$S_w{}^n = \frac{R_w}{(\Phi^m \cdot R_t)}$$

where:

S_w = water saturation of the uninvaded zone
n = saturation exponent, which varies from 1.8 to 4.0 but normally is 2.0
R_w = formation water resistivity at formation temperature
Φ = porosity
m = cementation exponent, which varies from 1.7 to 3.0 but normally is 2.0
R_t = true resistivity of the formation, corrected for invasion, borehole, thin bed, and other effects

Hartman and Beaumont, 1999

Step	Find	Use...	If...	Then...
1	n	• 2.0 for Archie porosity • 1.8 (or less) for rocks with clayey matrix or fractures • 4.0 for very strongly oil-wet rocks	Not sure of rock type	Use 2.0
2	R_w	• Value calculated from SP log • Estimated from R_w catalogs • Estimated from wet zone R_o value • Measured from water sample	Thin beds, hydrocarbons in zone, or fresh formation waters make SP calculations uncertain	Use thin-bed correction or another method
3	Φ	Value derived from cores, density, density–neutron, or sonic logs	Density–neutron log matrix setting does not match formation matrix	Use density–neutron crossplot
4	m	• 2.0 for Archie porosity • 1.7–2.0 for shaly sandstones • 2.0–2.5 for porosity with connected vugs • 2.5–3.0 for nonconnected moldic porosity • ~1.0 for fractured rocks	Not sure of rock type or pore geometry	Use 2.0
5	R_t	Value derived from deep resistivity log such as RILD or RLLD	Beds are thin, invasion occurred or borehole has washouts	Use chartbook corrections

Hartman and Beaumont, 1999

Obtaining a Valid Rt Value

Step	Action
1	Read the resistivity of the log with deepest investigation (ILD, LLD, etc.).
2	Use the table below to determine how to make corrections.

If...	Then...
Bed is < 20 ft thick for an induction log or < 4 ft thick for a laterolog	Correct for this bed using appropriate service company chart
Shallow, medium, and deep investigating tools measure, different resistivities (i.e., log has step profile)	Correct for invasion using appropriate service company tornado chart

Hartman and Beaumont, 1999

Determining Porosity from Density-Neutron Logs

- Combination provides a good source of porosity data

Constructing a Pickett Plot

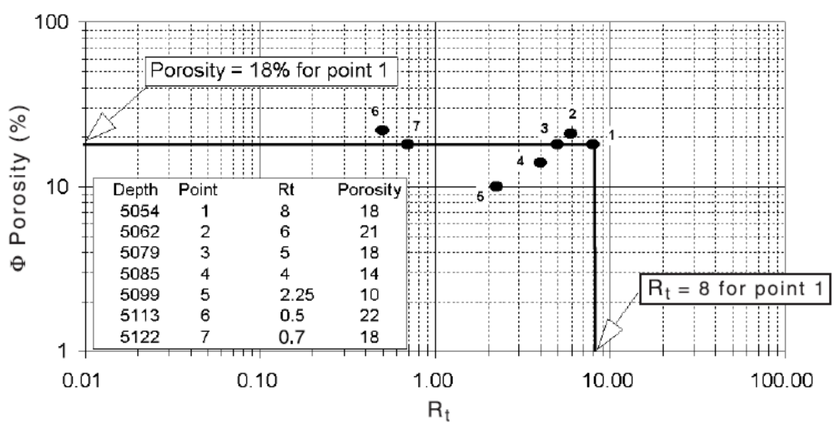
- Visual representation of the Archie equation
- All that is needed is a set of porosities and corresponding resistivities taken from well logs and 2X4 cycle log-log paper

Procedure

Step	Action
1	Plot points of matching porosity and true resistivity (R_t) on log-log paper.
2	Plot R_w point on the R_t scale.
3	Determine m using the table of values.
4	Plot the 100% S_w line.
5	Plot the lines representing lower values of S_w.

Pickett Plot Step 1

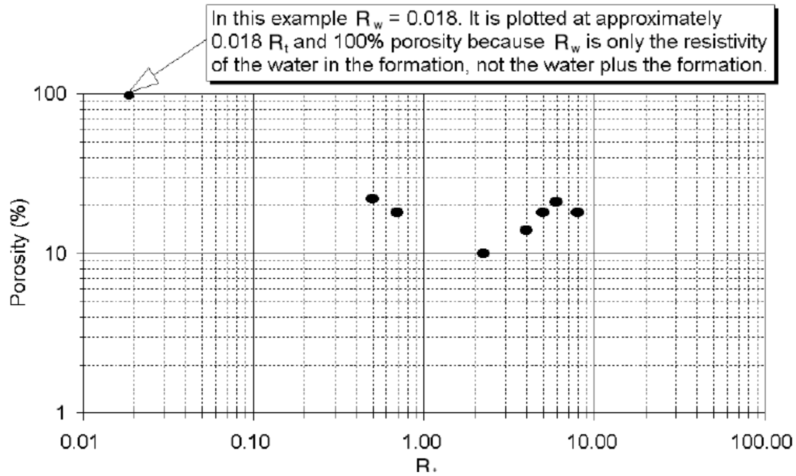
- Plot points of matching porosity and true resistivity (Rt) on 2X4 cycle log-log paper



Depth	Point	Rt	Porosity
5054	1	8	18
5062	2	6	21
5079	3	5	18
5085	4	4	14
5099	5	2.25	10
5113	6	0.5	22
5122	7	0.7	18

Plot Rw point

- Plot the Rw value by plotting Rw point along the Rt scale on the x-axis at the top of the graph grid where porosity is 100%

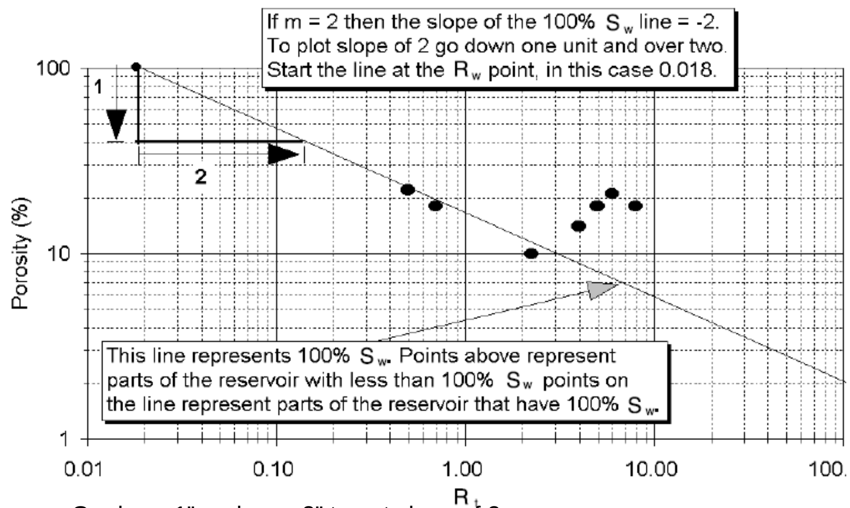


Estimate m (cementation factor)

Porosity Type	Value for *m*
Sandstones with diagenetic or detrital clay in pores	1.7–1.8
Formations with clean, macro- to micro-sized pore throats (Archie rocks)	2
Formations with vuggy porosity (touching to nontouching)	2.2–3.0

Step 4: Plot the 100% Sw line

The example below shows how to plot an m of 2.



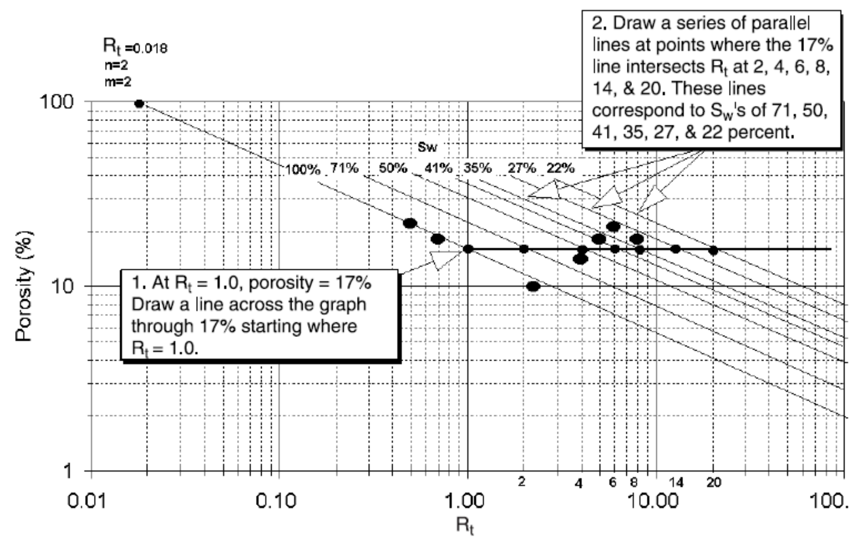
Go down 1” and over 2” to get slope of 2

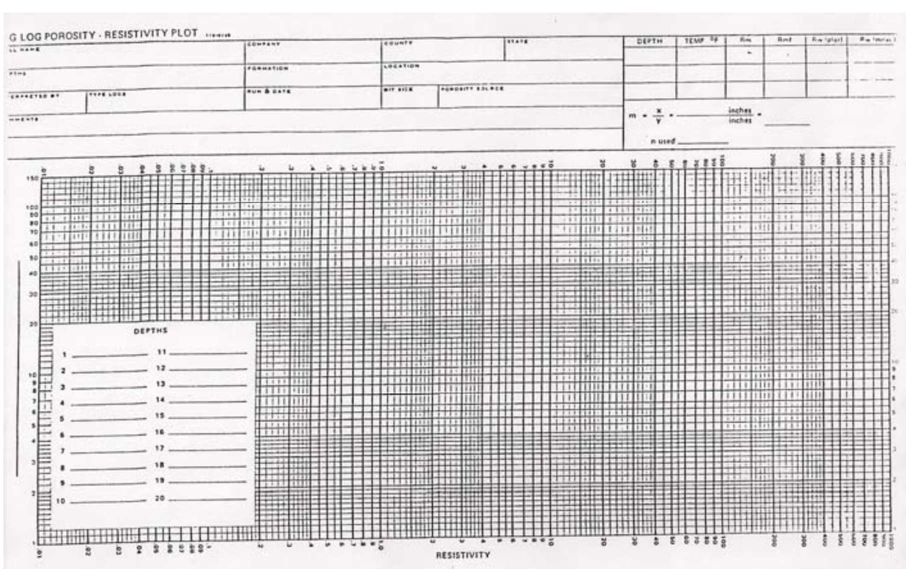
Plot Sw lines

After plotting the 100% S_w line, plot the lines representing lower percentages of S_w using this procedure.

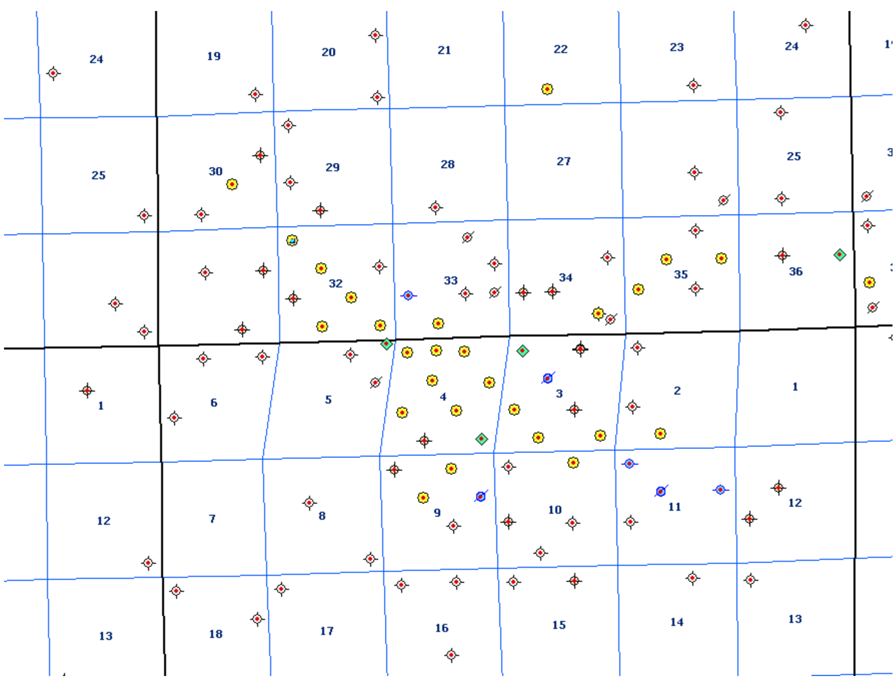
Step	Action
1	Find the intercept of R_t = 1 and the 100% S_w line (made in the last procedure).
2	From this intercept, draw a line parallel to the x-axis across the plot. Any point on this line has the same porosity.
3	Where this line passes through R_t of 2, 4, 6, 8, 14, and 20, draw a series of lines parallel to the 100% S_w line.
4	Points on these lines correspond to S_w of 71, 50, 41, 35, 27, and 22%. These percentages are calculated from the Archie equation using m = 2 and n = 2 at R_t of 2, 4, 6, 8, 14, and 20.

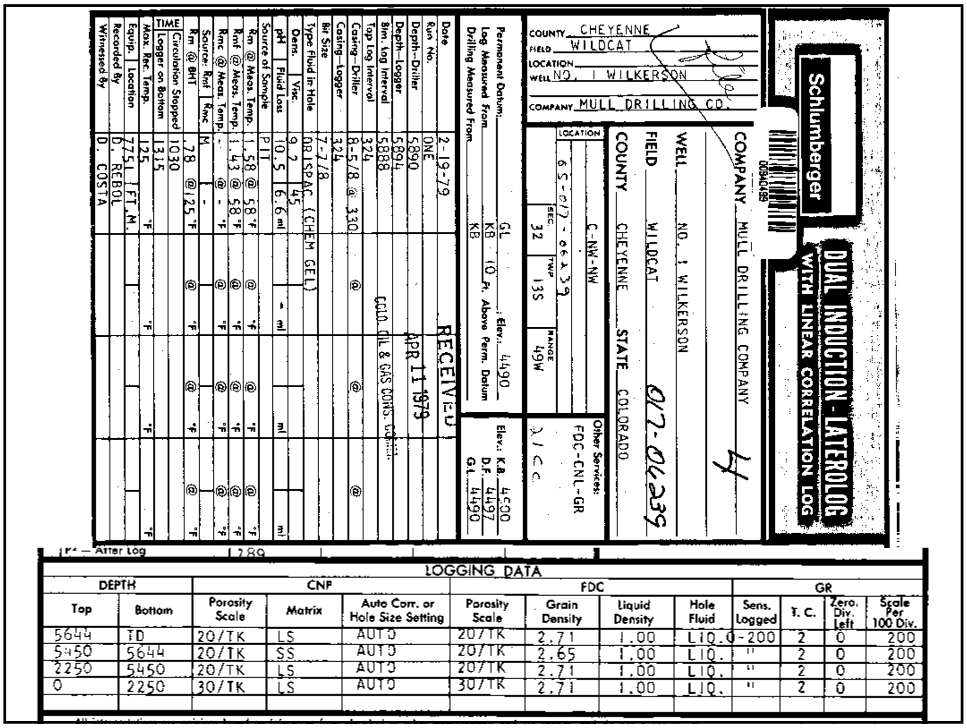
The figure below is an example of following this procedure.





Sorrento Field





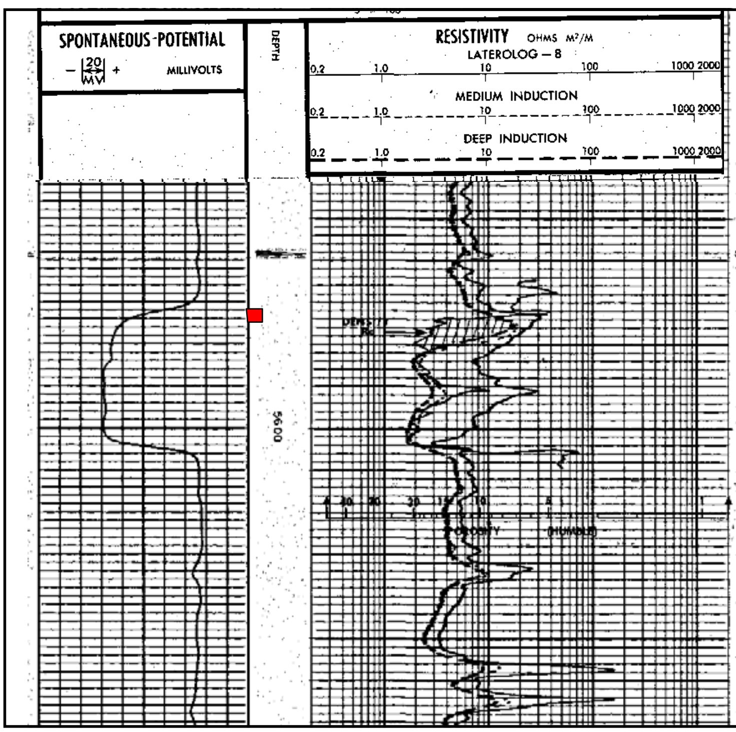
Schlumberger

DUAL INDUCTION-LATEROLOG WITH LINEAR CORRELATION LOG

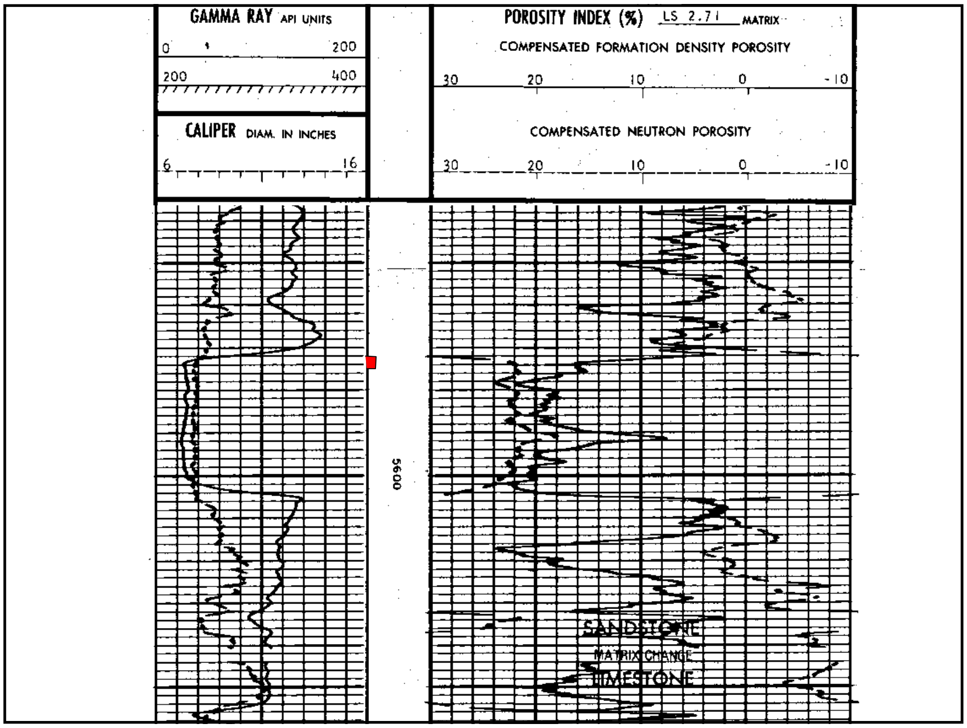
COMPANY MULL DRILLING COMPANY
WELL NO. 1 WILKERSON
FIELD WILDCAT
COUNTY CHEYENNE STATE COLORADO
LOCATION C-NW-NW
SEC. 32 TWP. 13S RANGE 49W
Other Services: FDC-CNL-GR
Permanent Datum: GL Elev.: 4490
Log Measured From KB 10 Ft. Above Perm. Datum
Drilling Measured From KB
Elev.: K.B. 4500 D.F. 4497 G.L. 4490
Date 2-19-79
Run No. ONE
Depth-Driller 5890
Depth-Logger 5894
Btm. Log Interval 5888
Top Log Interval 324
Casing-Driller 8-5/8 @ 330
Casing-Logger 324
Bit Size 7-7/8
Type Fluid in Hole DRISPAC (CHEM GEL)
Dens. 9.2 Visc. 45
pH 10.5 Fluid Loss 6.6 ml
Source of Sample PIT
Rm @ Meas. Temp. 1.58 @ 58 °F
Rmf @ Meas. Temp. 1.43 @ 58 °F
Source: Rmf M
Rm @ BHT .78 @ 125 °F
Circulation Stopped 1030
Logger on Bottom 1315
Max. Rec. Temp. 125 °F
Equip. Location 7751 FT.M.
Recorded By D. REBOL
Witnessed By D. COSTA

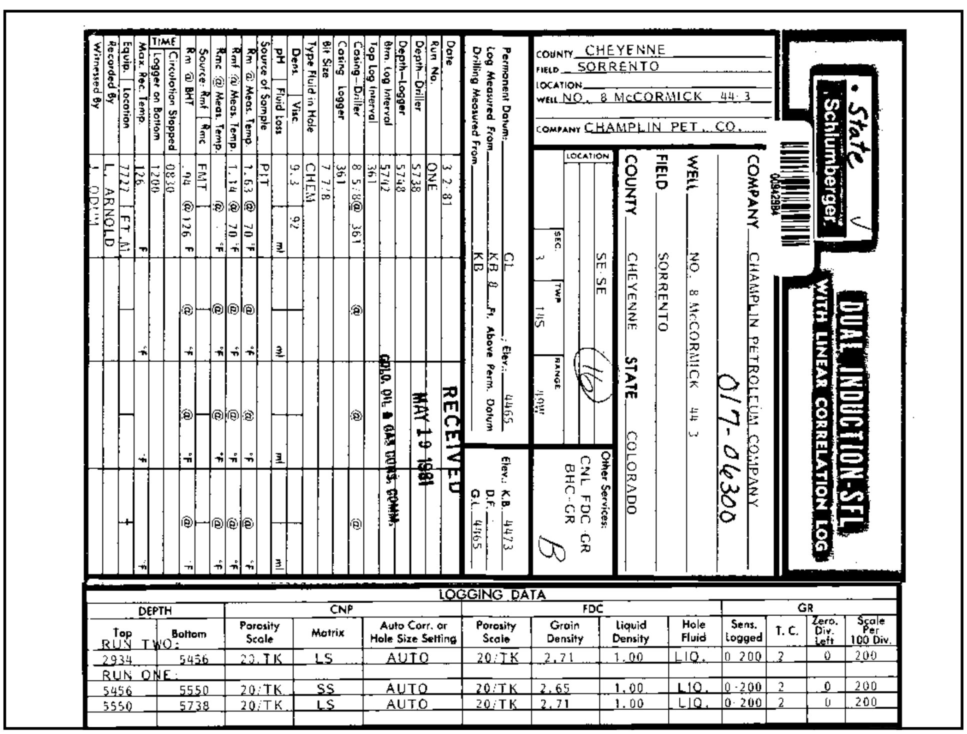
RECEIVED APR 11 1979 COLO. OIL & GAS CONS. COMM.

LOGGING DATA												
DEPTH		CNP			FDC				GR			
Top	Bottom	Porosity Scale	Matrix	Auto Corr. or Hole Size Setting	Porosity Scale	Grain Density	Liquid Density	Hole Fluid	Sens. Logged	T. C.	Zero. Div. Left	Scale Per 100 Div.
5644	TD	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200
5450	5644	20/TK	SS	AUTO	20/TK	2.65	1.00	LIQ.	"	2	0	200
2250	5450	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	"	2	0	200
0	2250	30/TK	LS	AUTO	30/TK	2.71	1.00	LIQ.	"	2	0	200

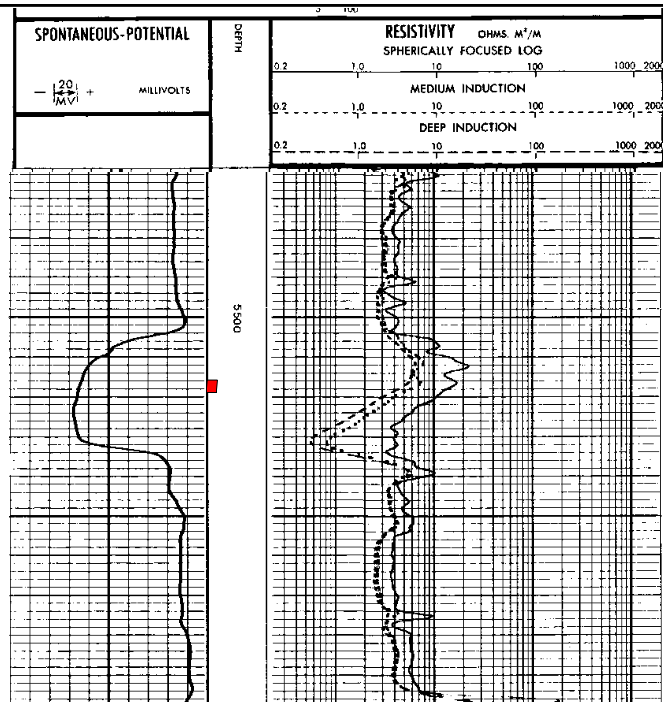


Pfs: 5572-75
57 BOPD

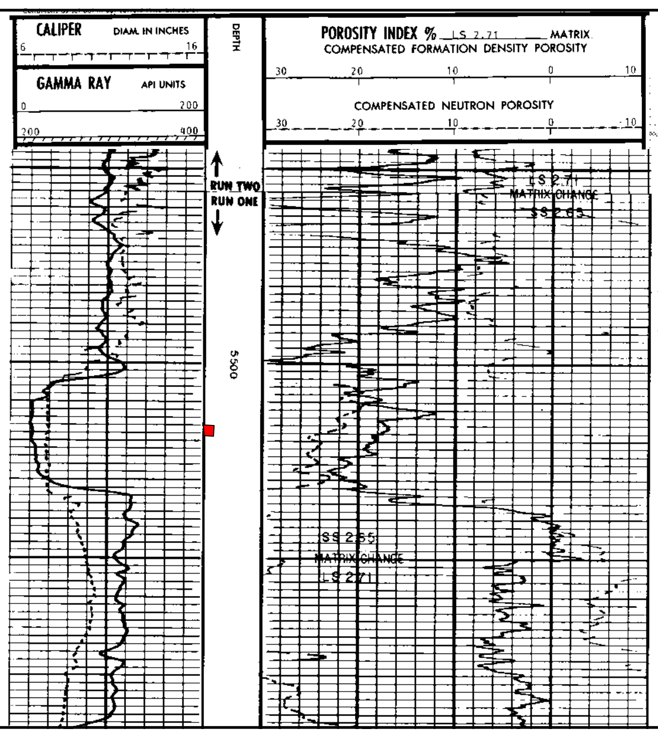


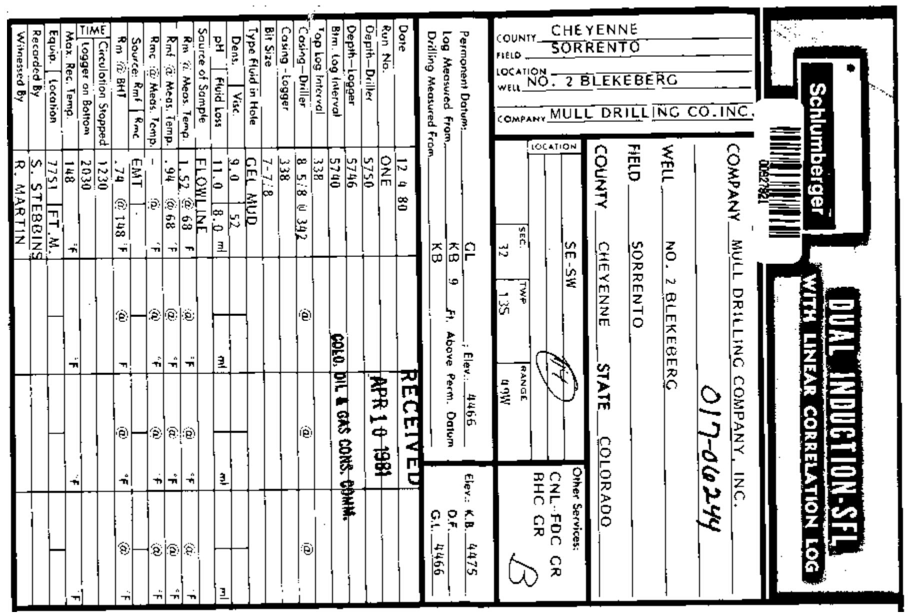


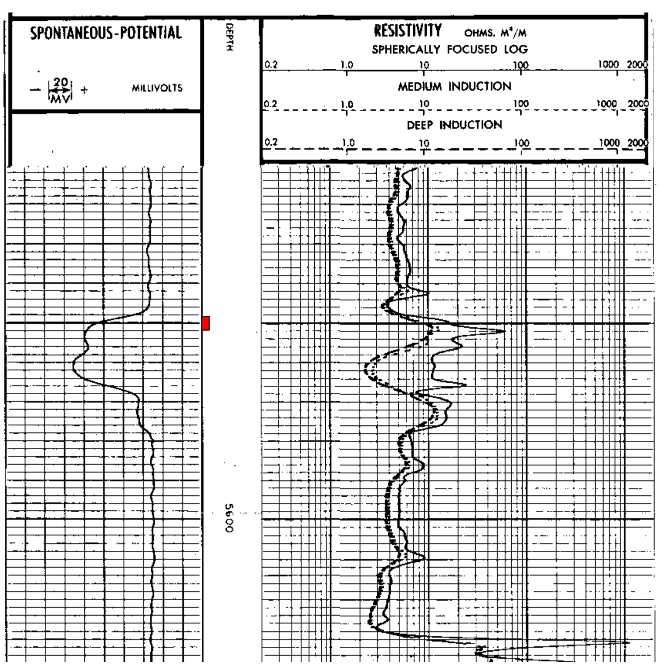
DEPTH		CNP			FDC				GR			
Top	Bottom	Porosity Scale	Matrix	Auto Corr. or Hole Size Setting	Porosity Scale	Grain Density	Liquid Density	Hole Fluid	Sens. Logged	T. C.	Zero. Div. Left	Scale Per 100 Div.
RUN TWO:												
2934	5456	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200
RUN ONE:												
5456	5550	20/TK	SS	AUTO	20/TK	2.65	1.00	LIQ.	0-200	2	0	200
5550	5738	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200



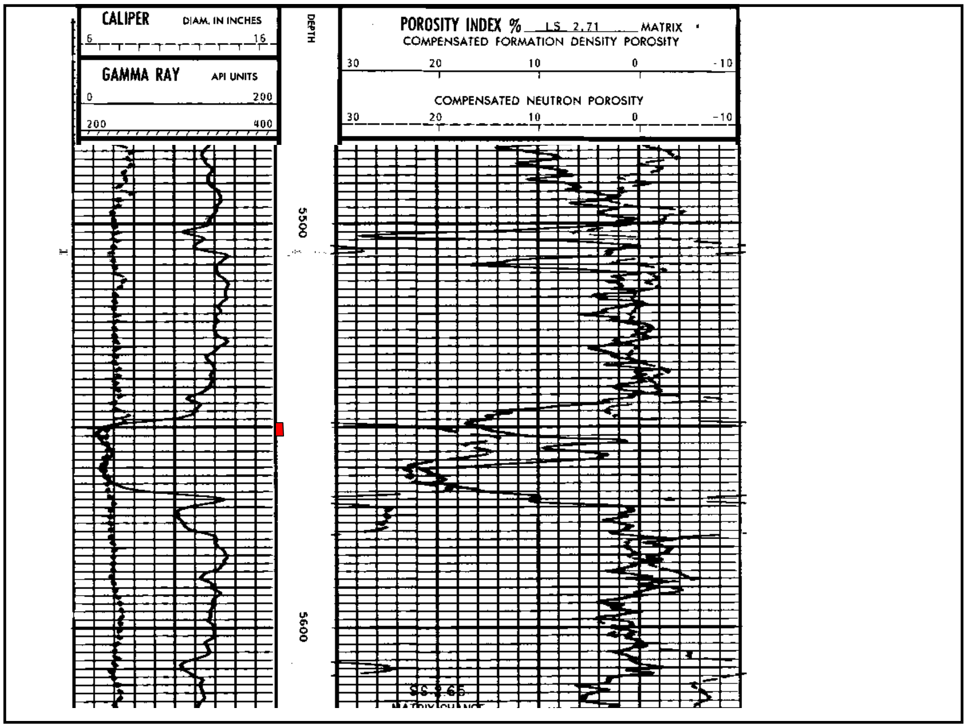
Pfs: 5516-19
95 BOPD,
227 MCFD,
31 BWPD

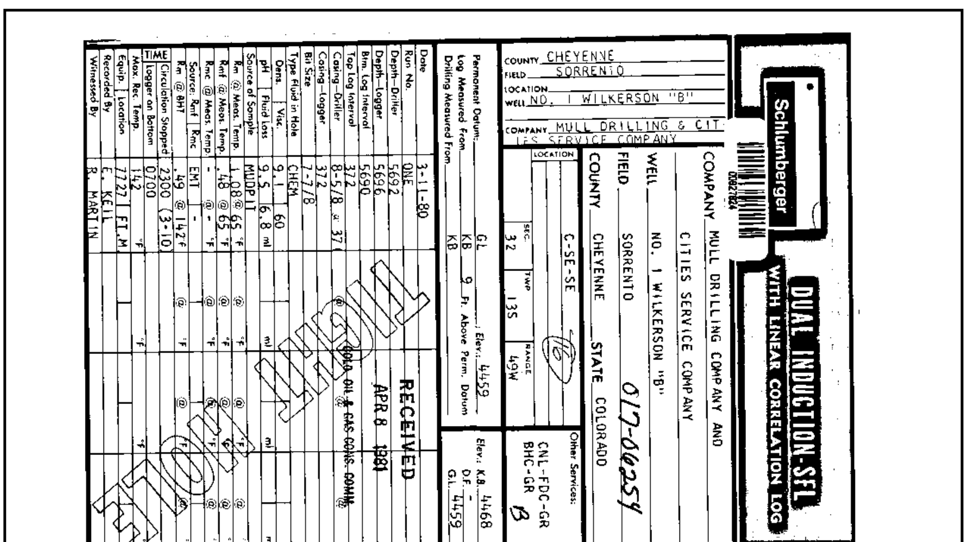






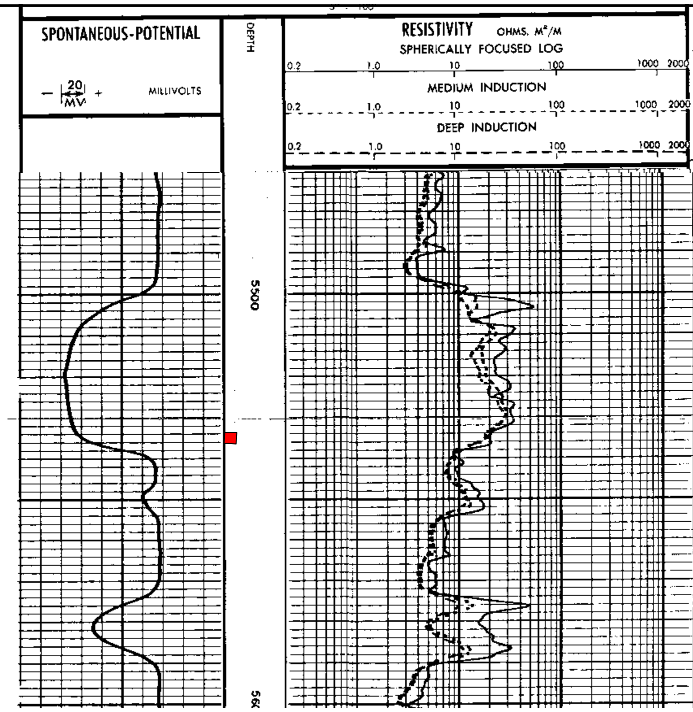
Pfs: 5549-52
130 BOPD,
870 BWPD



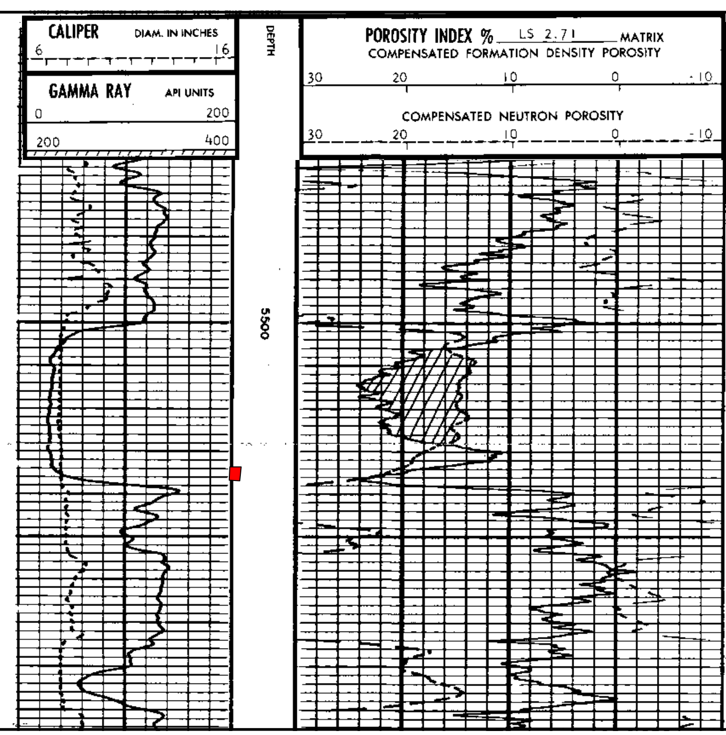


LOGGING DATA

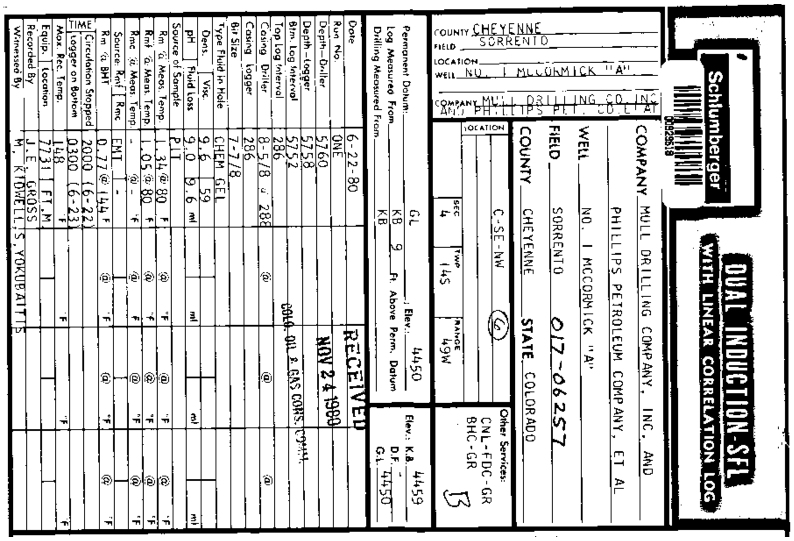
DEPTH Top	DEPTH Bottom	CNP Porosity Scale	CNP Matrix	CNP Auto Corr. or Hole Size Setting	FDC Porosity Scale	FDC Grain Density	FDC Liquid Density	FDC Hole Fluid	GR Sens. Logged	GR T. C.	GR Zero, Div. Left	GR Scale Per 100 Div.
372	5400	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200
5400	5600	20/TK	SS	AUTO	20/TK	2.65	1.00	LIQ.	0-200	2	0	200
5600	TD	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200



Pfs:
5534-37
203 BOPD



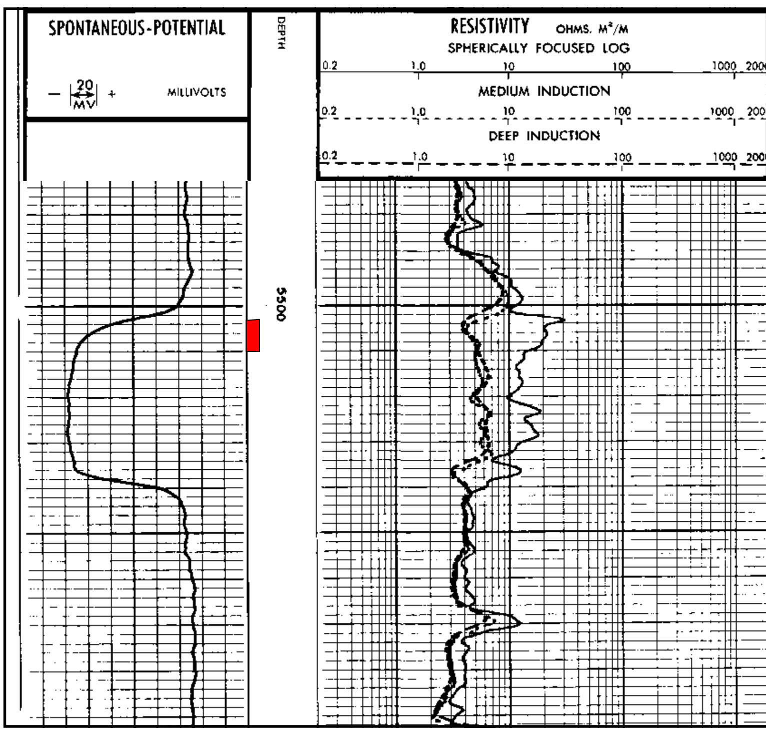
Pfs:
5534-37
203 BOPD



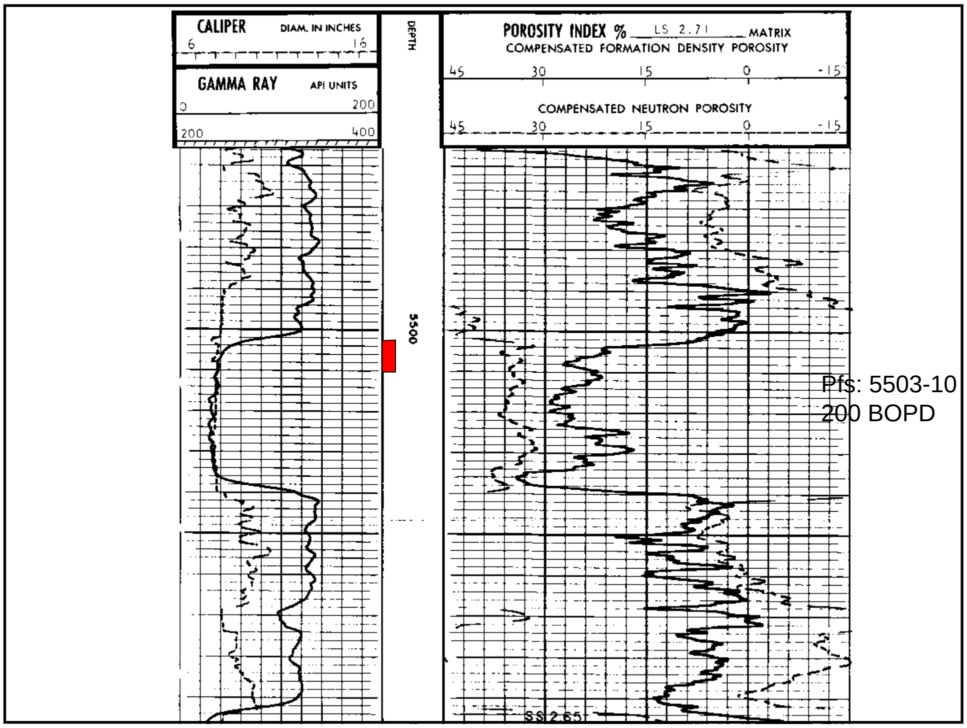
LOGGING DATA

DEPTH		CNP			FDC				GR			
Top	Bottom	Porosity Scale	Matrix	Auto Corr. or Hole Size Setting	Porosity Scale	Grain Density	Liquid Density	Hole Fluid	Sens. Logged	T. C.	Zero. Div. Left	Scale Per 100 Div.
CSG	2100	30/TK	LS	AUTO	30/TK	2.71	1.00	LIQ.	0-200	2	0	200
2100	5380	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200
5380	5600	20/TK	SS	AUTO	20/TK	2.65	1.00	LIQ.	0-200	2	0	200
5600	TD	20/TK	LS	AUTO	20/TK	2.71	1.00	LIQ.	0-200	2	0	200

All interpretations are opinions based on inferences from electrical or other measurements and we cannot, and do not guarantee the accuracy or correctness of any inter-



Pfs: 5503-10
200 BOPD


CALIPER
DIAM. IN INCHES
6
16
GAMMA RAY
API UNITS
0
200
200
400
DEPTH
5500
POROSITY INDEX % LS 2.71 MATRIX
COMPENSATED FORMATION DENSITY POROSITY
45
30
15
0
-15
COMPENSATED NEUTRON POROSITY
45
30
15
0
-15
SS 2.65
Pfs: 5503-10
200 BOPD