TPE 522

PETROPHYSICAL WELL LOGGING AND INTERPRETATION

COURSE CONTENT

- Introduction
- Invasion Process
- Resistivity Concept
- Lithology Logs (Spontaneous Potential and Gamma Ray Logs)
- Porosity Logs
- Shaly-Sand Analysis
- Cross-plots
- Modern Logging Tools

OBJECTIVE

The objective of the course is to introduce students to:

- Fundamental Principles and Technology used in Formation Evaluation.
- Invasion Process
- Cross-plots
- Traditional/Modern Well Logging Tools and their Interpretations.

EXPECTED LEARNING OUTCOMES

Students will be able to:

- Describe the classes of logs.
- Describe the principles of measurement of all logs.
- Do qualitative and quantitative analysis of the logs.
- Calculate Lithology from Cross-plots.

REFERENCES

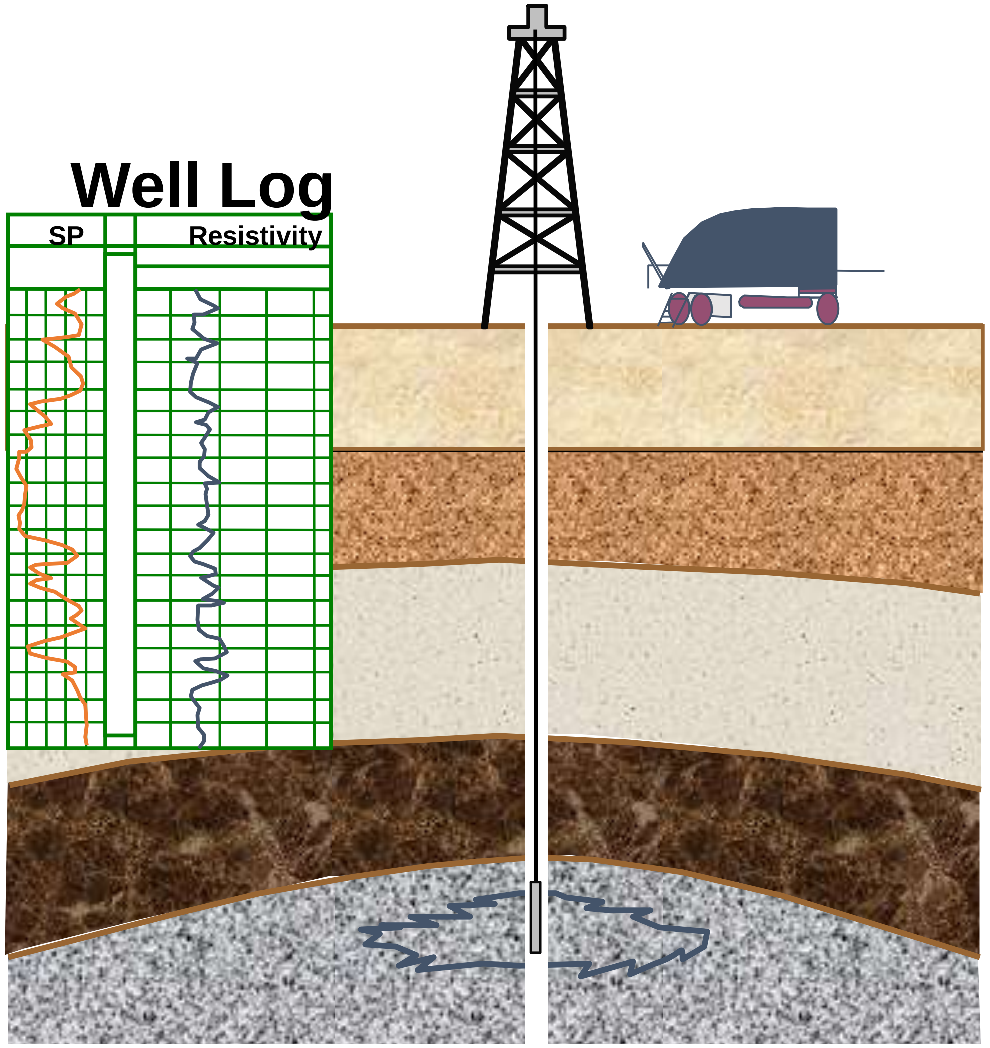
- ***General Petrophysics text books:***
- Schlumberger, Log Interpretation Principles/Applications, 1989
- Western Atlas, Introduction to Wireline Log Analysis, 1995
- Richard M. Bateman, Open-hole log analysis and formation evaluation,
- D. Reidel, John T. Dewan, Essentials of modern open-hole log interpretation, PennWellBooks, 1983
- Darwin V. Ellis, Well Logging for Earth Scientists, Elsevier, 1987
- ***Mudlogging***
- J.G. Bond, Mud logging, Manual GL304 of the IHRDC video library for E & P specialists, 1986

INTRODUCTION

Well Logging

- Is the continuous recording of the downhole measurement signals.
- Log Interpretation is the explanation of logs in terms of well and reservoir parameters, zones, porosity, oil saturation, etc.
- Log interpretation can provide answers to questions on:

1. How much hydrocarbon is in the well/reservoir.



Courtesy of Schlumberger

2. Where is the hydrocarbon?
3. Is there communication between these reservoirs?
4. What is the extent of these reservoirs?
5. How can it be produced?

- As the science of well logging advances, the art of interpreting the data also advanced.
- As logging tools and interpretation methods are developing in accuracy and sophistication they are playing great role in geological decision-making process.
- Today petrophysical log interpretation is one of the most useful, reliable and important tools available for to petroleum engineers and geologists for formation evaluation.
- Besides their traditional use in exploration to correlate zones and to assist with structure and isopach mapping.
- Logs help to define physical characteristics such as: lithology, porosity, pore geometry and permeability.

- Logging data is used to: identify productive zones, determine depth and thickness of zones, distinguish between gas, oil and water in a reservoir and to estimate hydrocarbon reserves.
- The basic concept that is needed as background knowledge in log analysis is the logging environment.
- This logging environments are:

1. Geological Environment
2. Borehole Environment

GEOLOGICAL ENVIRONMENT

- The logging tool encounters a variety of geological conditions during logging operation and respond accordingly to the particular rock characteristics – which are naturally highly variable and complex.
- When interpreting the logging tool response, minor details if not understood and accounted for could lead to an absolutely false conclusion.
- It is therefore necessary to have a good idea of the geological environment that the logging tools are exposed to, and, have a fairly good understanding of the rocks constituting the environment.

i. **Lithology** – These are rocks composed of minerals which are the basic building blocks.

ii. **Minerals** – These can be defined as a naturally occurring substance with chemical composition and physical properties that are either fixed or vary within a small range.

- Minerals are formed essentially by four processes: crystallization, precipitation, migration of ions in solid and sublimation.

- Minerals can be:

a) **Elements** (Gold, Copper, Diamond)

b) **Simple chemical compounds** such as quartz (SiO_2), calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and halite (NaCl)

c) **Complex chemical compounds** such as clay minerals like kaolinite ($Al_2Si_2O_5(OH)_4$ and Montmorillonite ($MgCaAl_2Si_4O_{10}(OH)_2nH_2O$)

iii. **Rocks** – These are collection of minerals or fragments of previously formed rocks that are cemented together and have physical strength.

- It may be made up of grains of only one type of material or mixture of two or more materials.
- Limestone a rock composed mainly of calcite ($CaCO_3$)
- Sandstone a rock composed mainly of quartz (SiO_2)
- Conglomerate a rock formed from a mixture of coarse fragments of a previous rock.

- **Classification of Rocks**

1) Igneous Rock

- Comprise 95% of the Earth's crust.
- Originated from the solidification of molten material from deep inside the Earth.
- There are two types:
- Volcanic - glassy in texture due to fast cooling.
- Plutonic - slow-cooling, crystalline rocks (e.g. granite)
- Igneous rocks (e.g. fractured granites) form reservoirs in some parts of the world.

2) Metamorphic Rocks

- Formed by the action of temperature and/or pressure on sedimentary or igneous rocks.
- The effect of heat and pressure transform the rock into a new form. In doing this it destroys all porosity and any hydrocarbon.
- E.g. Marble - formed from limestone
- Hornfels – formed from shale
- Gneiss - similar to granite but formed by metamorphosis.
- They do not exist in reservoirs.

3) Sedimentary Rocks

- This is the third category of rocks. They are the most important for the oil industry as it contains most of the source rocks and cap rocks and virtually all reservoirs.
- Sedimentary rocks come from the debris of older rocks and are split into two categories: Clastic and Non-clastic.

i. **Clastic rocks** – formed from the materials of older rocks by the actions of erosion, transportation and deposition e.g. shale, sandstone, silt, clay.

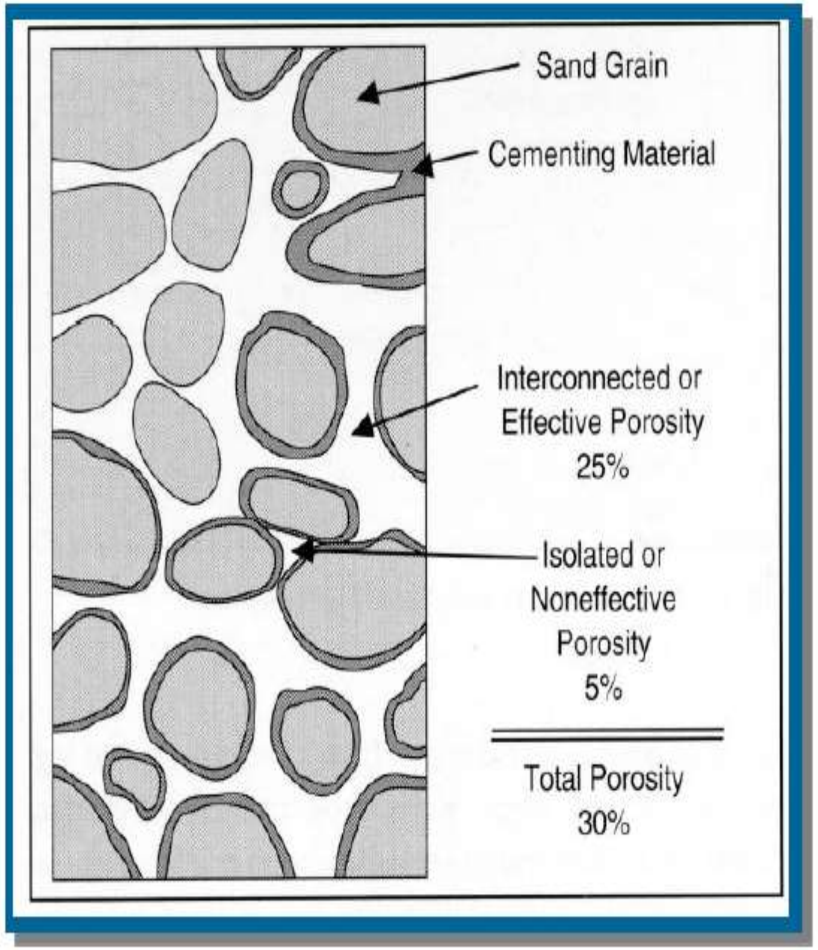
ii. **Non-clastic rocks** – formed from chemical or biological origin and then deposition. They are also known as **carbonate rocks** e.g. calcite, dolomite, limestone.

- **Reservoir Rocks**
- Reservoirs are usually named after the geological formation in which they occur.
- Reservoir rocks must be porous, permeable and needs a cap rock.
- **Rock Properties**
- Rock are described by three properties:
- **Porosity** – quantity of pore space. **Permeability** – ability of formation to transmit fluid.
- **Matrix** – major constituent of rock

- **Cap Rock**
- A seal is a fine-grained rock that prevents the oil migrating to the surface
- Impermeable cap rock keeps the fluids trapped in the reservoir.
- It must have zero permeability.
- Some examples are:
- Shales.
- Evaporites such as salt or anhydrite.
- Zero-porosity carbonates.

BOREHOLE ENVIRONMENT

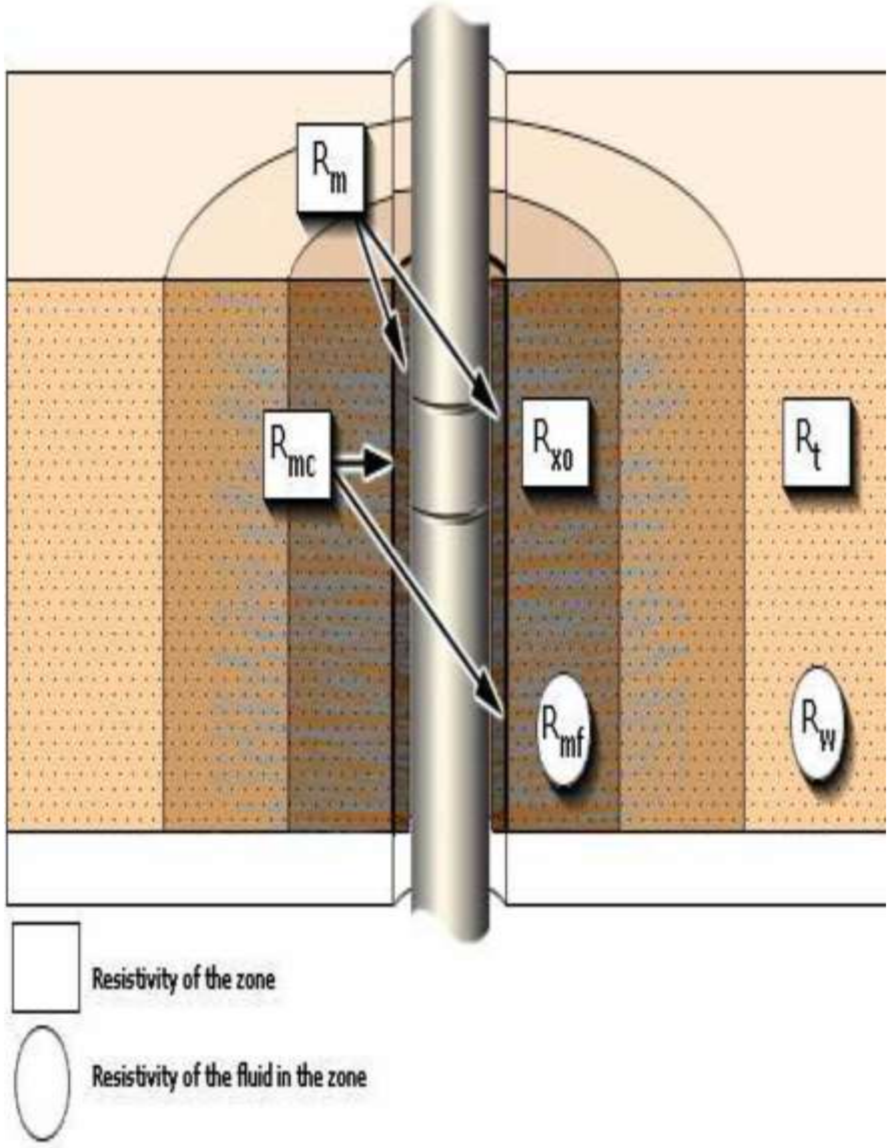
- The reservoir is composed of porous hydrocarbon bearing rock.
- The rock matrix is made up of grains of sandstone, limestone, dolomite or mixture of these.
- Between the grains are pore spaces filled with water, oil or gas.
- Where a hole is drilled into the formation, the rock and the fluids in it are altered in the vicinity of the borehole.



- All logging measurements are then affected by the borehole and the altered rock around it by drilling mud.

Borehole Conditions

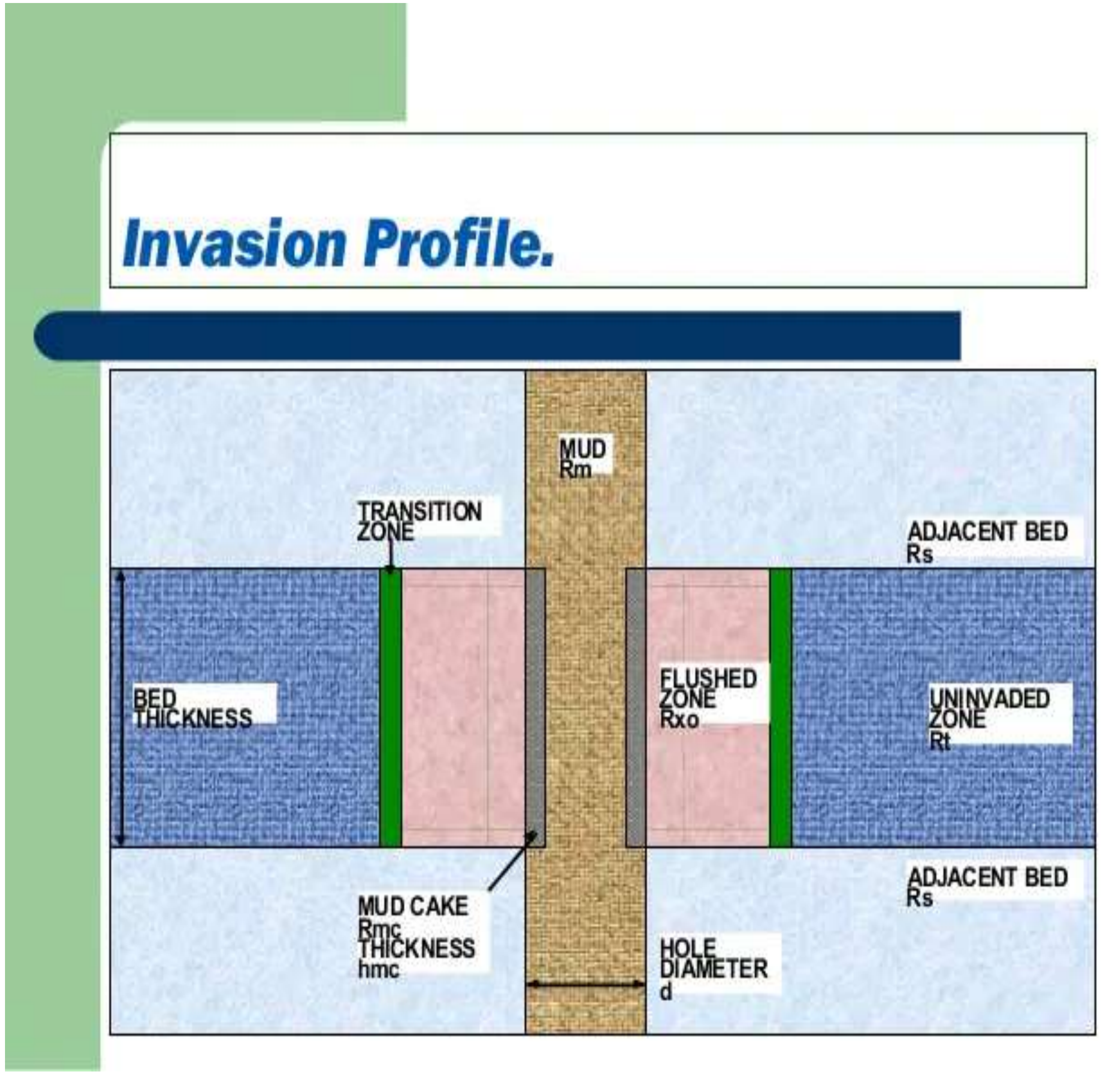
- Interpretation of logs without a working knowledge of borehole conditions is one of the chief causes of interpretation errors.
- Borehole conditions affecting the log measurement are:
- Hole size and shapes
- Drilling mud
- Mud cake
- Mud filtrate
- Temperature and Pressure



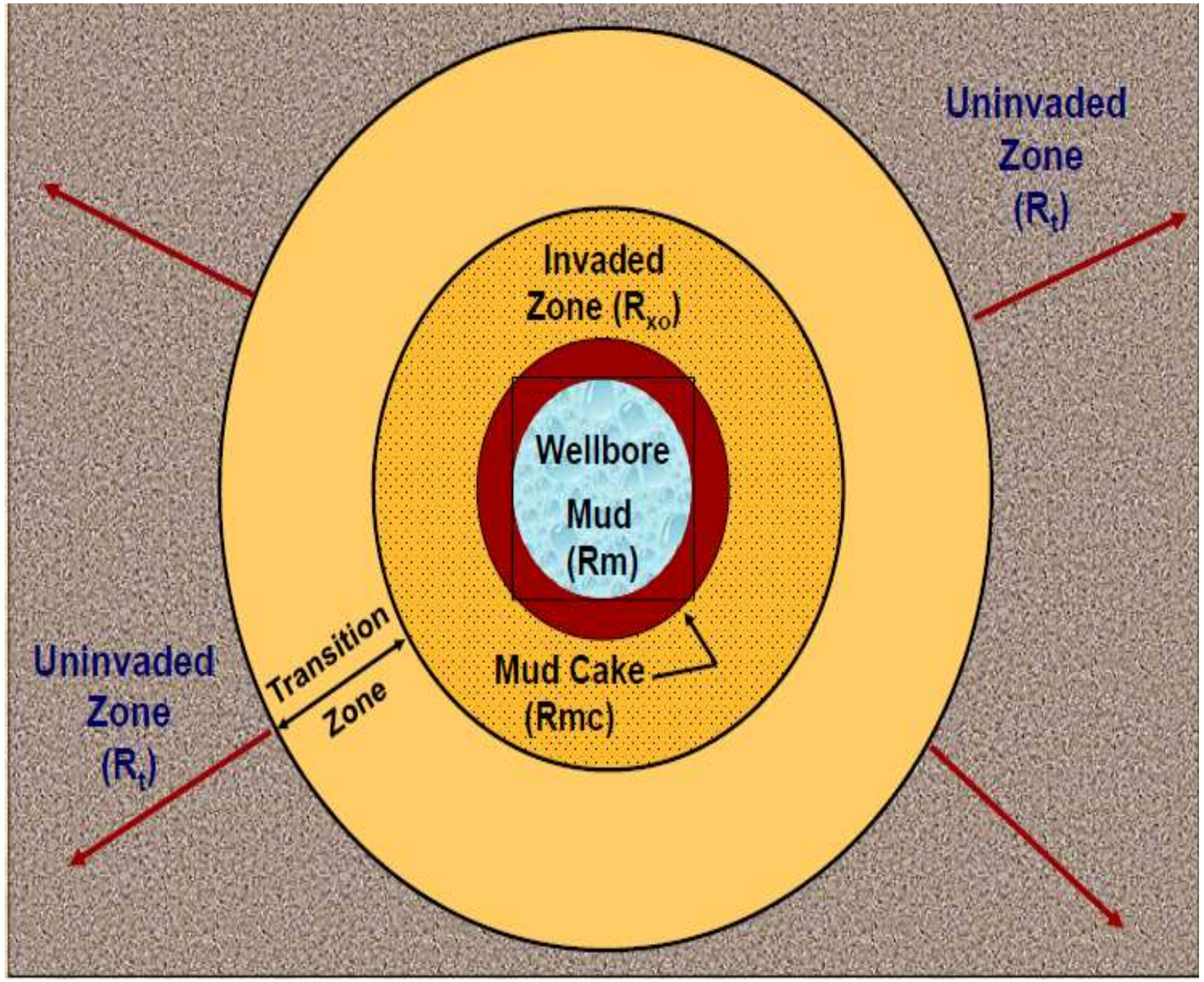
INVASION PROCESS

Invasion Profile

- The process of invasion creates an invasion profile (Fig 1) extending from the wellbore into the formation.
- Invasion is the process by which mud filtrate, and sometimes whole mud, enters a permeable formation.
- The mud filtrate displaces some or all of the moveable fluids in the formation, leaving an invaded zone.
- Three zones are recognized in the invasion process.



Mud Filtrate Invasion



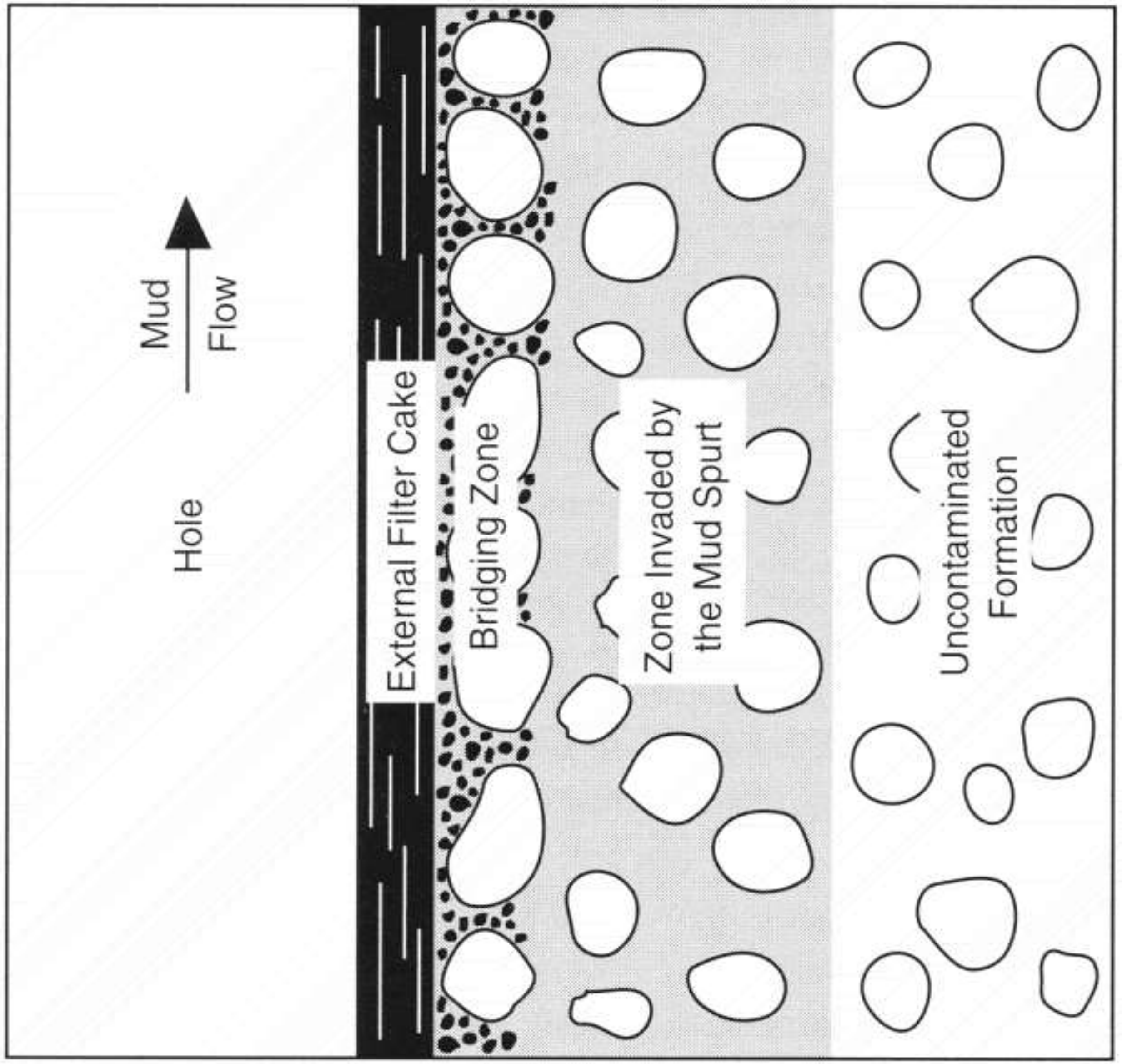


FIG. 1

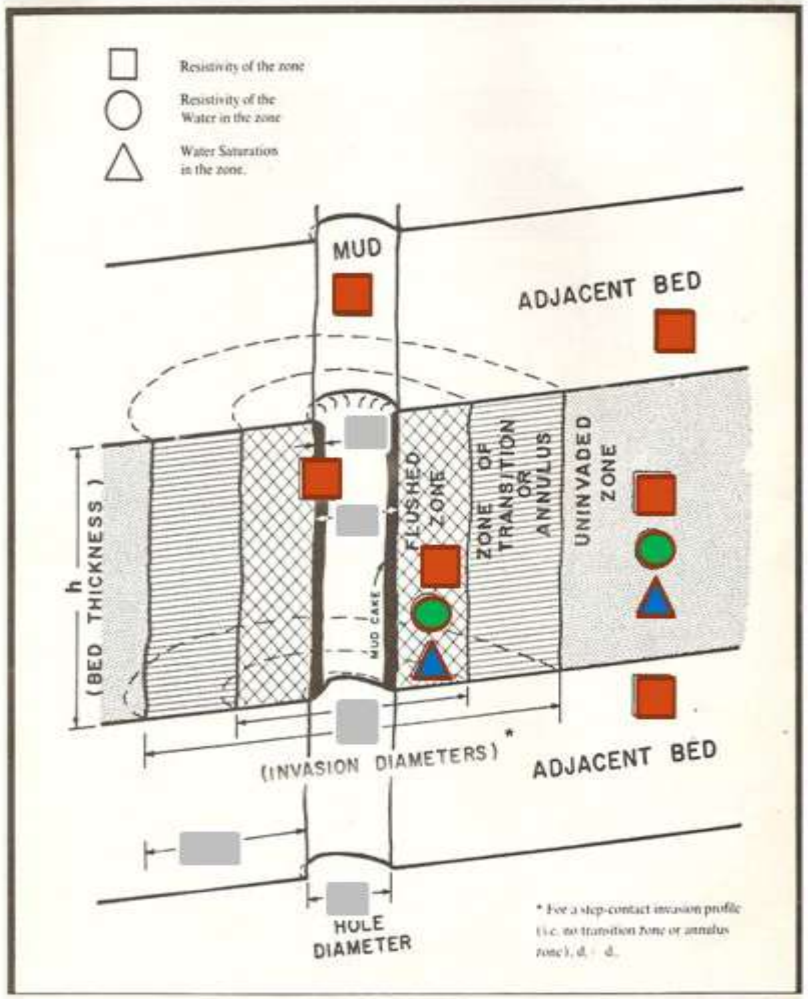


Figure 1. The borehole environment and symbols used in log interpretation. This schematic diagram illustrates an idealized version of what happens when fluids from the borehole invade the surrounding rock. Dotted lines indicate the cylindrical nature of the invasion.

Courtesy, Schlumberger Well Services.
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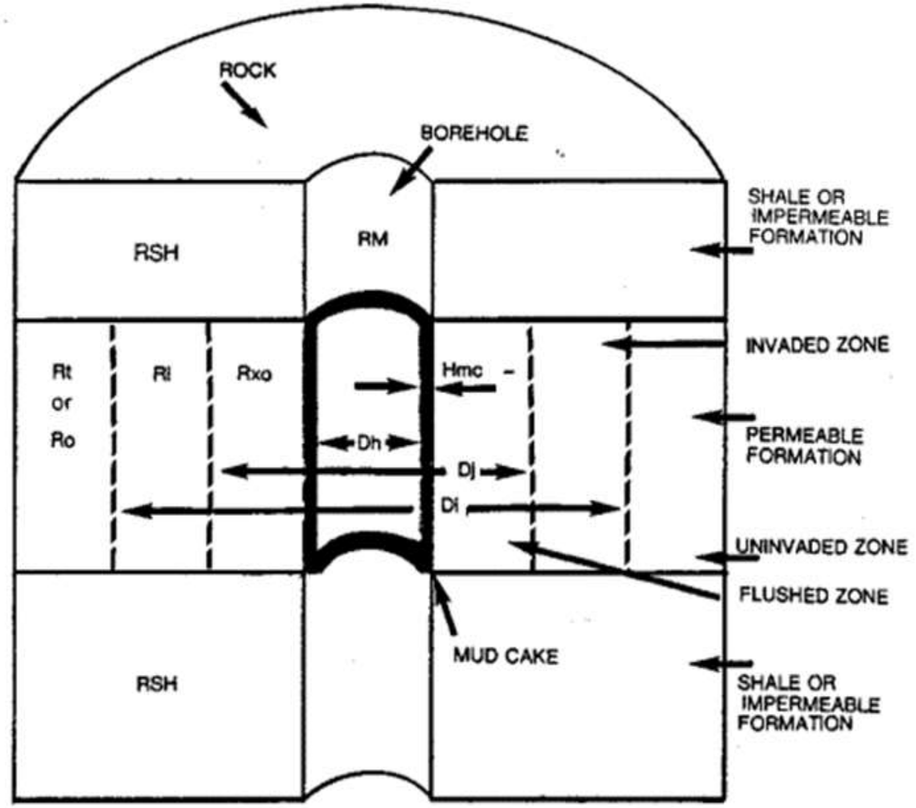
Exercise:
You have 15 min. to fill in your answer



LEGEND:

BITZ	=	bit size
Dh	=	hole diameter (CAL)
Di	=	invaded zone diameter
Dj	=	flushed zone diameter
Hmc	=	mud cake thickness
Hmc	=	1/2 (BITZ - CAL)
Ri	=	invaded zone resistivity
RM	=	mud resistivity
RMC	=	mud cake resistivity
RMF	=	mud filtrate resistivity
Ro	=	uninvaded zone resistivity when 100% water saturated
RSH	=	shale resistivity
Rt	=	uninvaded zone resistivity
RW	=	formation water resistivity
Rxo	=	flushed zone resistivity
RZ	=	invaded zone water resistivity

Permanent Datum: GROUND LEVEL	; Elev.: 3731	Elev.:	K.B. 3742
Log Measured From KB	11 Ft. Above Perm. Datum		D.F. ----
Drilling Measured From KB			G.L. 3731

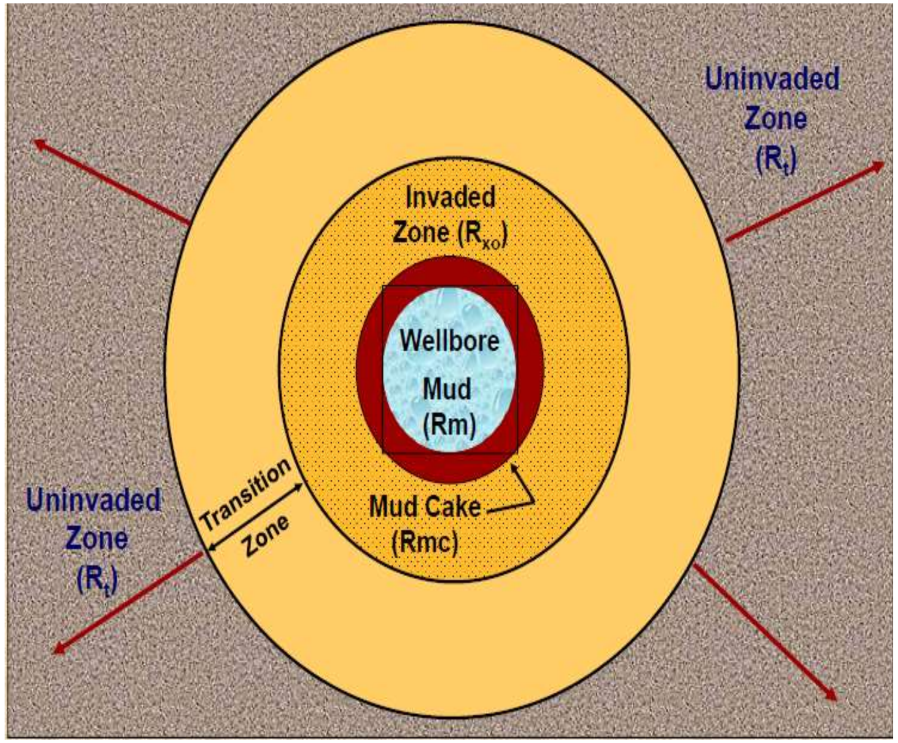
Date	6-11-79			
Run No.	ONE			
Depth—Driller	5000			
Depth—Logger	4990			
Btm. Log Interval	4984			
Top Log Interval	1601			
Casing—Driller	8 5/8 @ 1601	@	@	@
Casing—Logger	1601			
Bit Size	7 7/8			
Type Fluid in Hole	DRISPAC			
Dens. | Visc.	9.2 | 44			
pH | Fluid Loss	9.0 | 6.8 ml	ml	ml	ml
Source of Sample	FLOWLINE			
Rm @ Meas. Temp.	2.44 @ 81 °F	1.72 @ 115 °F	@ °F	@ °F
Rmf @ Meas. Temp.	2.04 @ 63 °F	1.12 @ 115 °F	@ °F	@ °F
Rmc @ Meas. Temp.	---- @ -- °F	@ °F	@ °F	@ °F
Source: Rmf | Rmc	M | --			
Rm @ BHT	1.72 @ 115 °F	@ °F	@ °F	@ °F
TIME Circulation Stopped	2000/6-10			
TIME Logger on Bottom	0000/6-11			
Max. Rec. Temp.	115 °F	°F	°F	°F
Equip. | Location	7688 | LIBERAL			
Recorded By				
Witnessed By MR.				

TIGHT HOLE

- The **Invaded** (Flush and Transition) **zone** is the portion of the formation that has been penetrated by drilling fluids.

- The **Flushed zone**, next to the wellbore, the hydrocarbon is at a minimum, and all the virgin formation water and some of the hydrocarbon, if present, are displaced by the mud filtrate.

- The **Transition zone** is located between the flushed and virgin zones. Within this zone water saturation can vary depending on the fluid type in the zone.

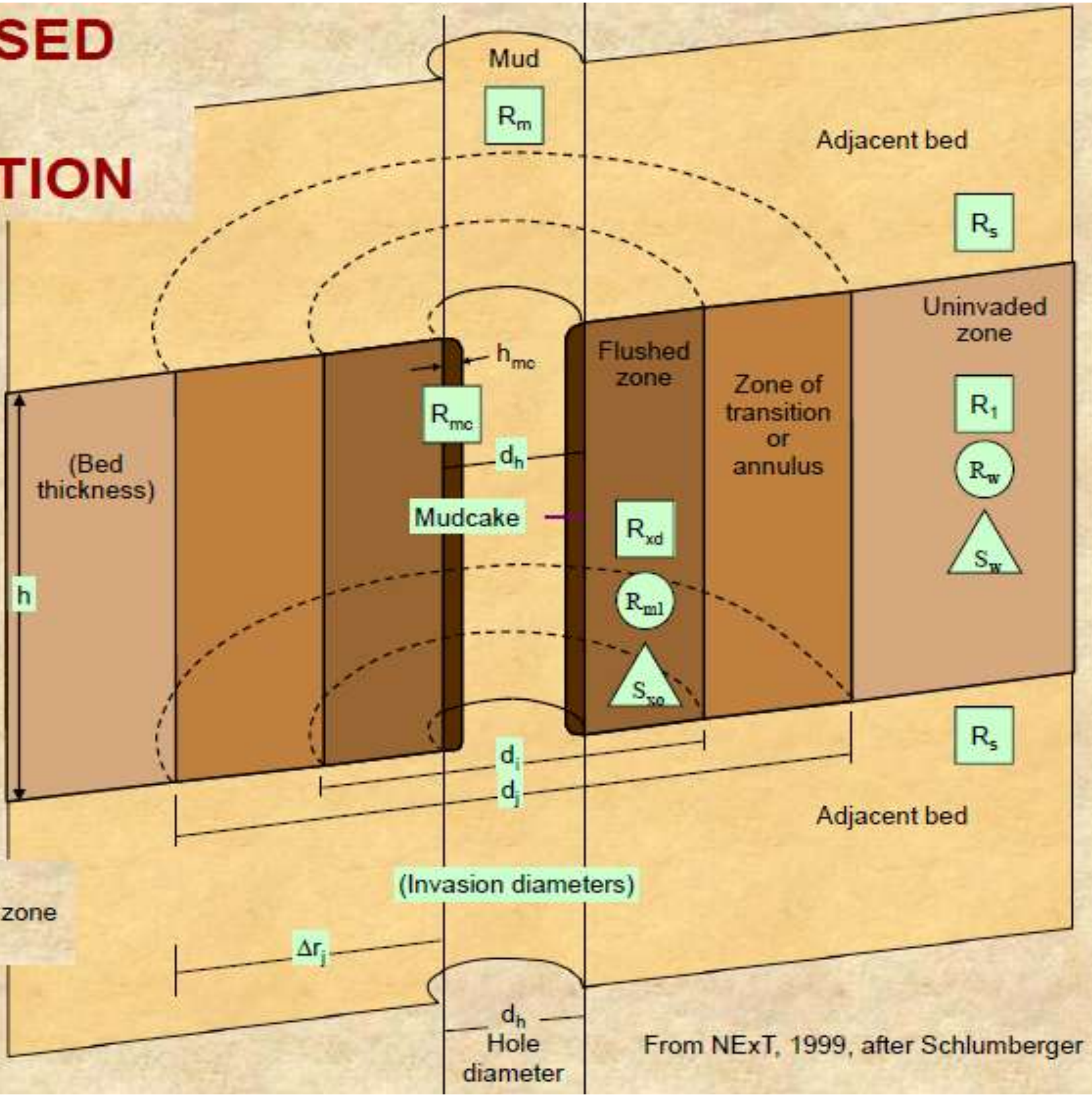


- ✓ In a water zone, there is no change in water saturation, only a change in water salinity or resistivity.

- ✓ In hydrocarbon zone, the hydrocarbon saturation is reduced. Usually about 70 to 95% of the oil is flushed out, the remaining oil is called the ***residual oil***.

- The **uninvaded (or Virgin)** zone is located beyond the invaded zone. Pores in this zone are uncontaminated by mud filtrate, rather they are saturated with formation water, oil or gas.

SYMBOLS USED IN LOG INTERPRETATION



From NExT, 1999, after Schlumberger

- □ Resistivity of zone
- ○ Resistivity of the water in the zone
- △ Water saturation in the zone

COMMON TERMINOLOGY

Borehole

Rm : Borehole mud resistivity

Rmc : Mudcake resistivity

Invaded zone

Rmf : Mud filtrate resistivity

Rxo : Invaded zone resistivity

Sxo : Invaded zone water saturation

Uninvaded zone

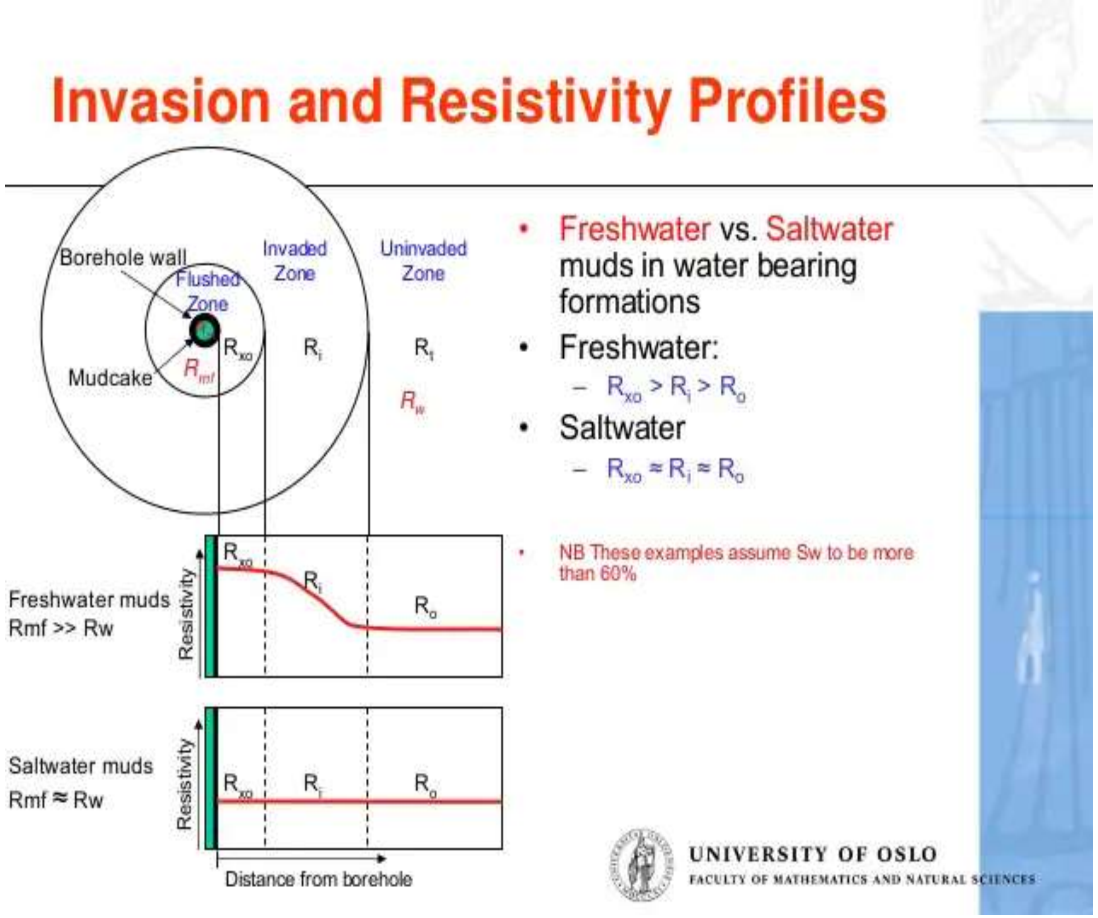
Rw : Interstitial water resistivity

Rt : Uninvaded zone resistivity

Sw : Uninvaded zone water saturation

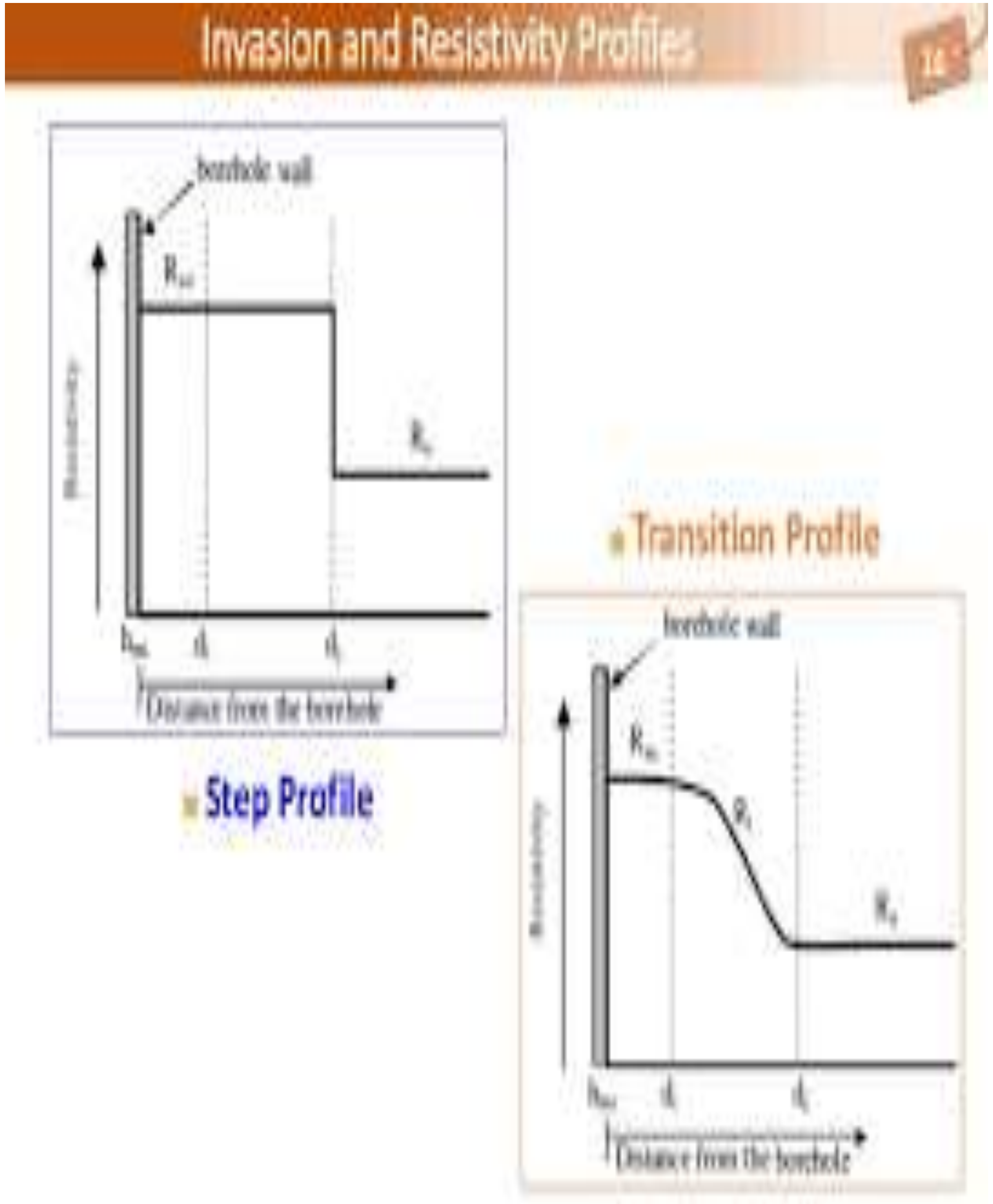
INVASION AND RESISTIVITY PROFILES (IRP)

- IRP are diagrammatic, theoretical cross-sectional views when moving away from the borehole into the formation.
- They illustrate the horizontal distributions of the invaded and uninvaded zones and their corresponding relative resistivity.
- There are three recognized invasion profiles.



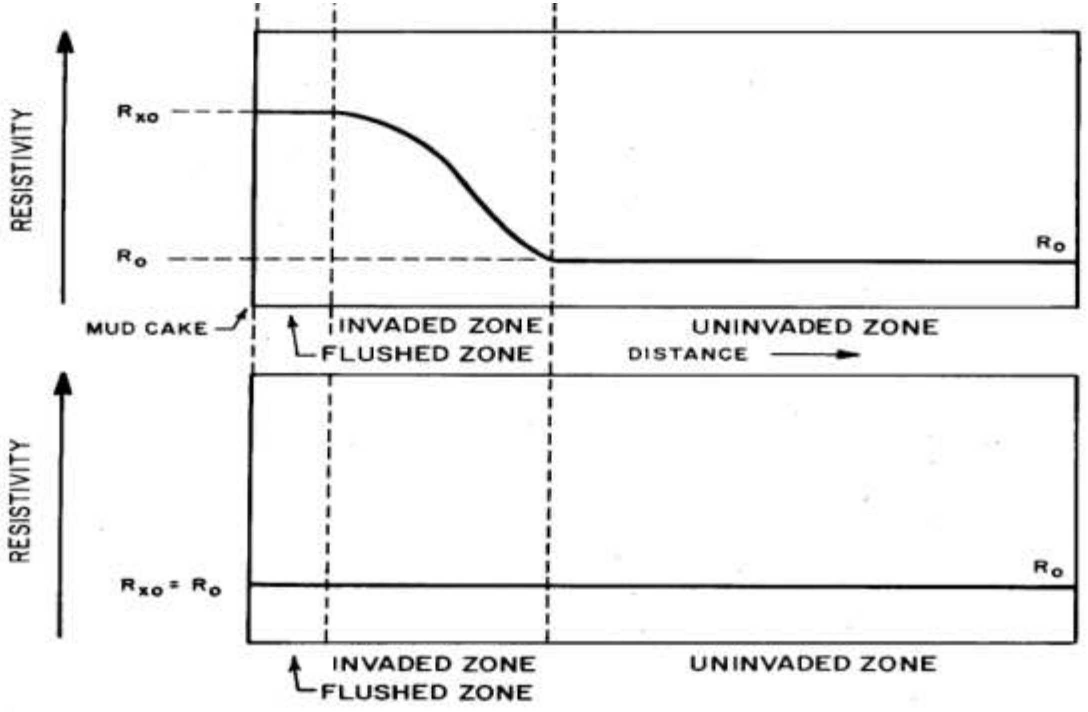
1. Step Profile

- Mud filtrate is distributed with a cylindrical shape around the borehole and creates an invaded zone.
- The cylindrically shaped invaded zone is characterized by its **abrupt contact** with the uninvaded zone.
- In the invaded zone (R_{xo}) pores are filled with mud filtrate (R_{mf}).
- Pores in the uninvaded zone are filled with water (R_w) or hydrocarbons.
- The resistivity of the uninvaded zone is either $\mathbf{R_o}$ if the formation is **wet** (i.e. 100% water bearing or $\mathbf{R_t}$ if formation is hydrocarbon bearing.



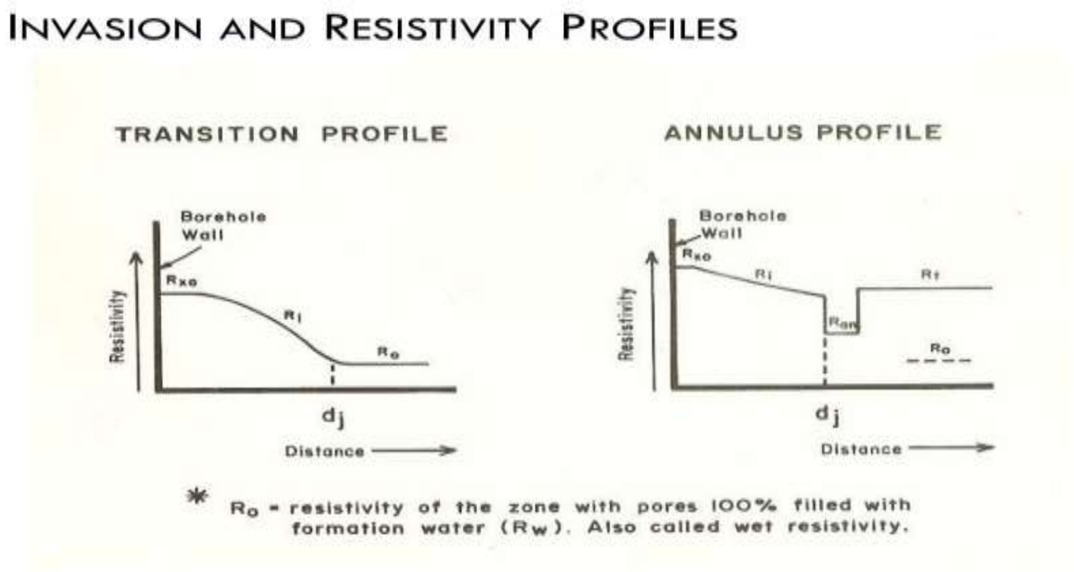
2. Transition Profile

- This is the most realistic model of true borehole conditions
- Here invasion is also cylindrical, but in this profile the invasion of the mud filtrate (R_{mf}) diminishes gradually, rather than abruptly, through a transition zone toward the outer boundary of the invaded zone.
- In the flushed part pores are filled with mud filtrate (R_{mf}), giving a high resistivity reading.
- In the transition part, pores are filled with mud filtrate (R_{mf}), formation water (R_w) and if present residual hydrocarbon.
- In the virgin zone, pores are filled with formation water (R_w) and if present hydrocarbon

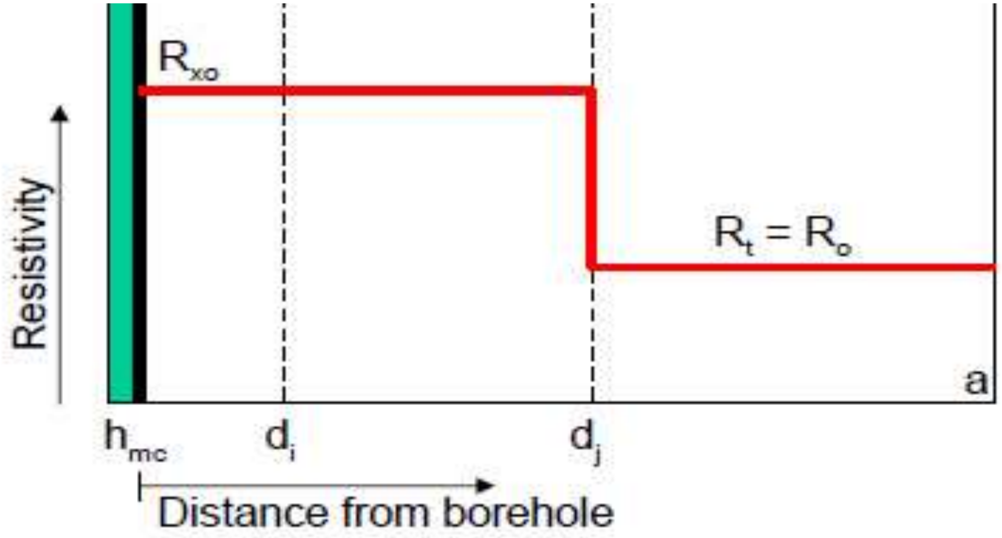


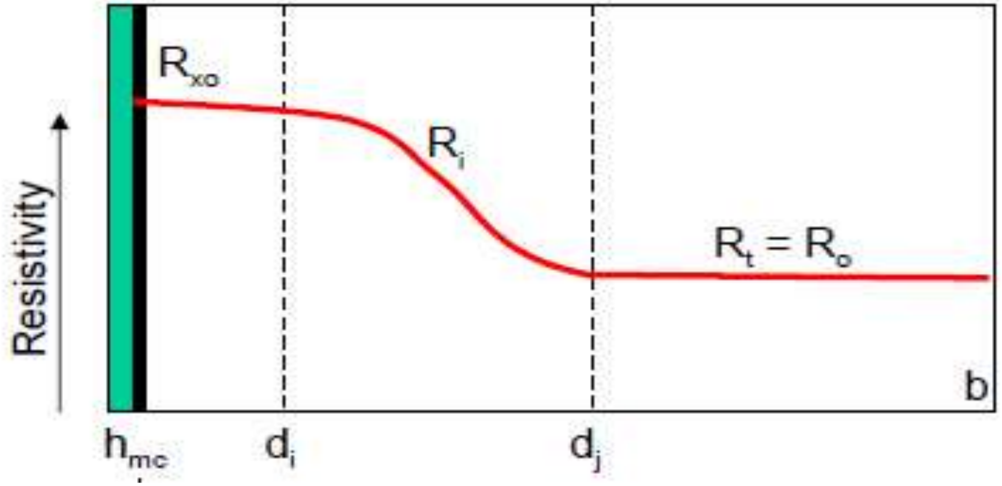
3. Annulus Profile

- This represents a fluid distribution which occurs between the invaded and uninvaded zones and denote the presence of hydrocarbon.
- This profile is very important because occurs in zones which bear hydrocarbons.
- When an annulus profile is present, there is an abrupt drop in measured resistivity due to high concentration of formation water in the annulus zone.
- As the mud filtrate invades the hydrocarbon-bearing zone, hydrocarbons move out first.
- Next, formation water is pushed out in front of the mud filtrate forming an annular (circular) ring at the edge of the invaded zone.

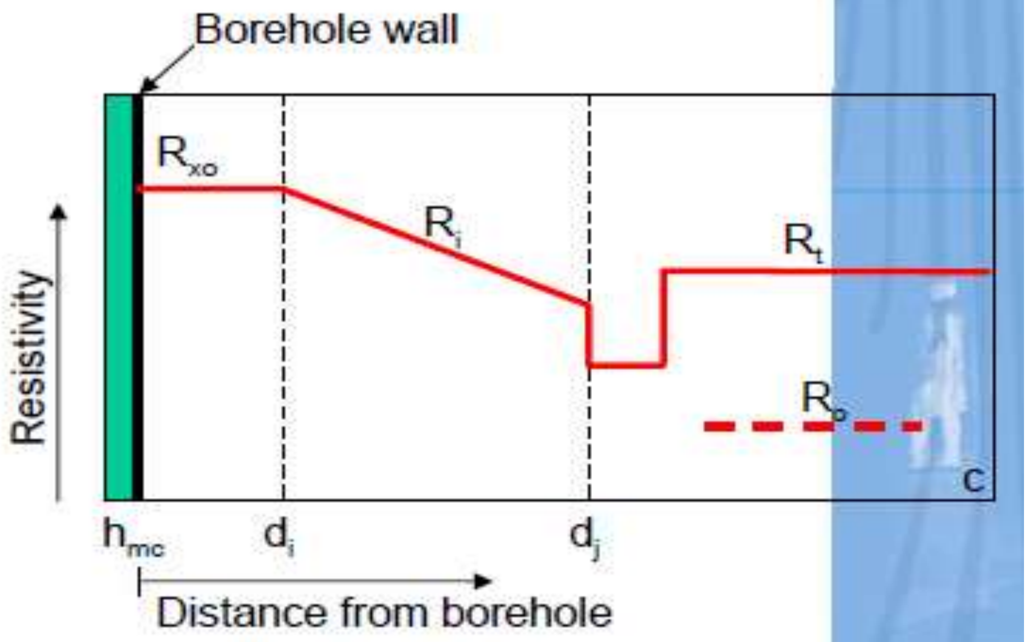


TYPES OF RESISTIVITY PROFILE

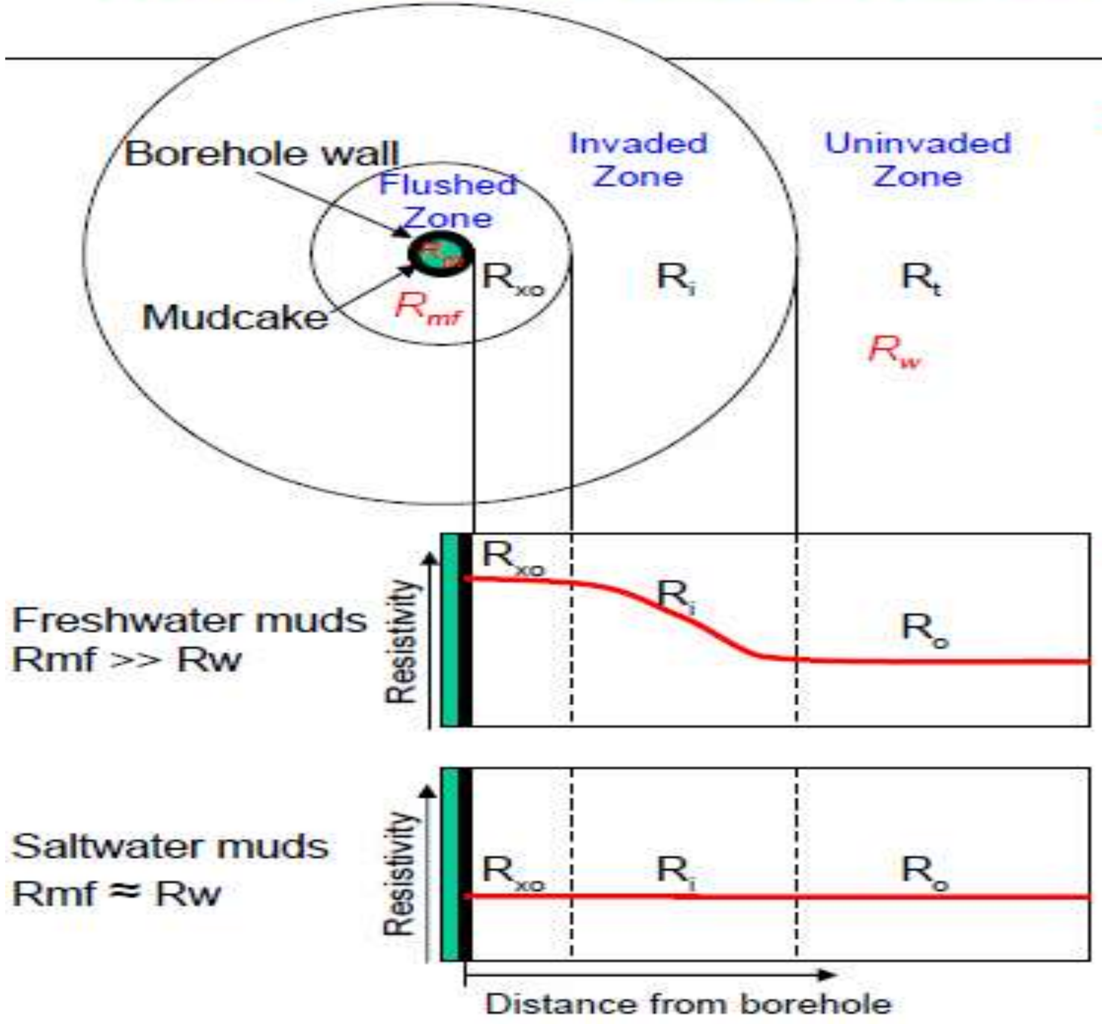




a) Step Profile
b) Transition Profile
c) Annulus Profile



RESISTIVITY PROFILE IN WATER BEARING FORMATION



- Freshwater vs. Saltwater muds in water bearing formations
- Freshwater:
  - $R_{xo} > R_i > R_o$
- Saltwater
  - $R_{xo} \approx R_i \approx R_o$

- NB These examples assume Sw to be more than 60%

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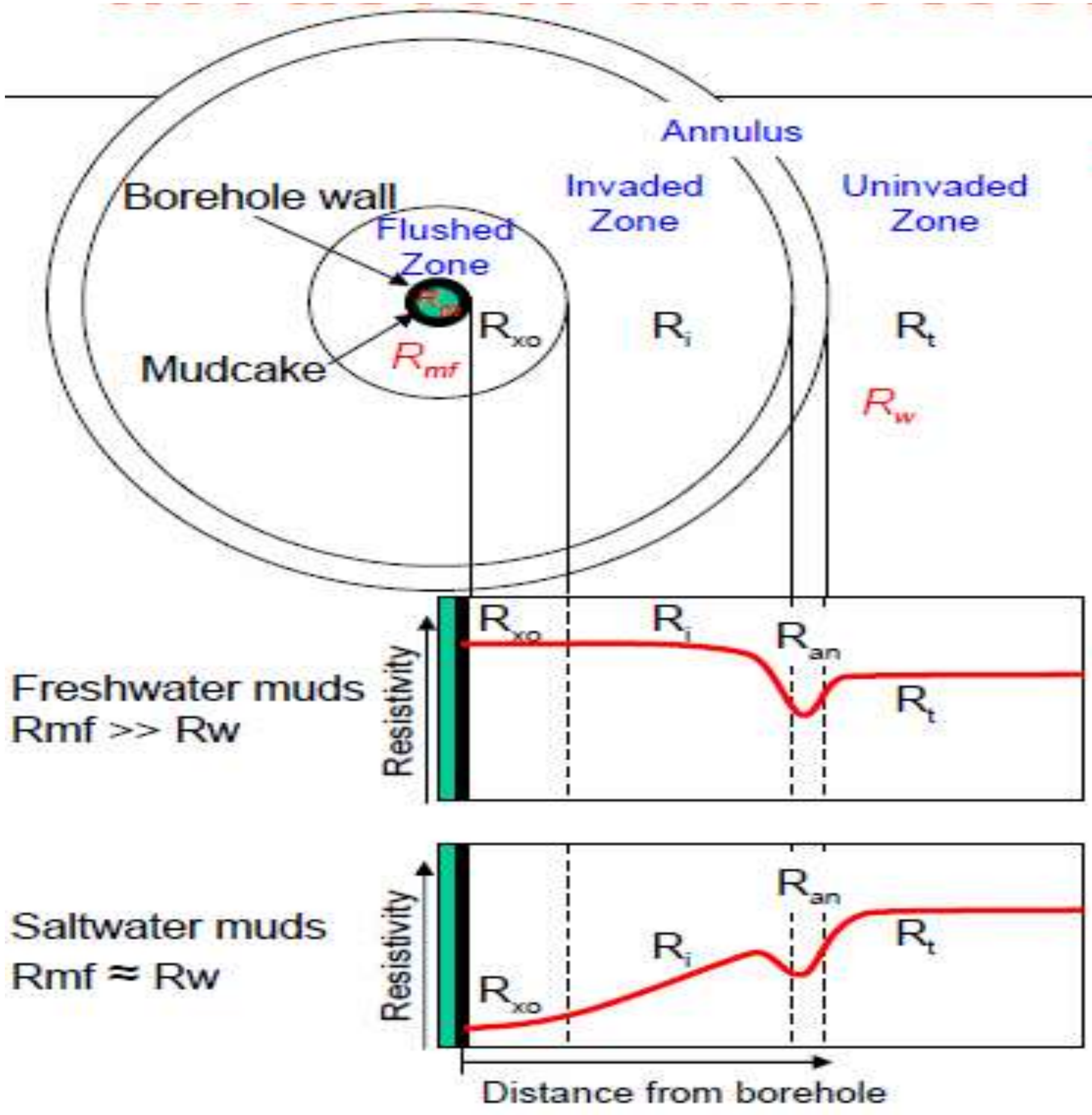
RESISTIVITY PROFILE IN HYDROCARBON BEARING FORMATION



- Freshwater vs. Saltwater muds in hydrocarbon bearing formations
- Freshwater:
  - $R_{xo} > R_i > R_t$ or
  - $Rxo > Ri < R_t$
- Saltwater
  - $R_t > R_i > R_{xo}$

- NB These examples assume Sw to be much less than 60%

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FORMATION TEMPERATURE

- Formation temperature (T_f) is important in log analysis because R_m, R_{mf}, and R_w vary with temperature.
- Formation temperature can be determined by assuming linear geothermal gradient together with knowing the following data: Formation depth, Bottom-hole temperature (BHT), Total depth of the well and surface temperature (T_s).

- BHT can be calculated by using

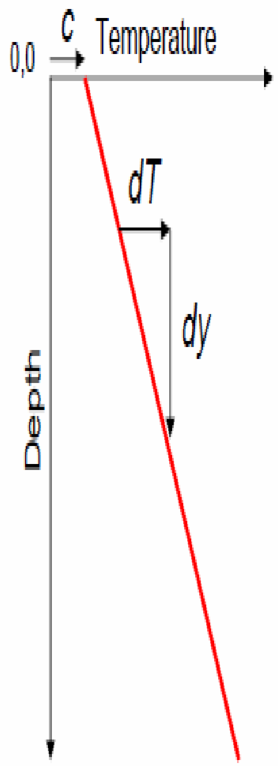
1. Linear regression equation

$$Y = mx + c$$

- Y = Temperature; x = depth
- Slope m = geothermal gradient
- c = surface temperature

2. Chart

- After determining T_f, the resistivity of different fluids (R_m, R_{mf}, and R_w) can then be corrected to T_f



- Example 1
- Using Chart and by calculation what is T_f given the following data
- Mean Surface temp = 80°F
- BHT = 200°F
- Total depth (TD) = 10,000 ft
- Formation depth = 7,000 ft
- From Chart: $\mathbf{T_f = 164°F}$
- By calculation: Y = mx + c
- m = (200 – 80)/10,000 = 0.012°F/ft

$$Y = 0.012(7000) + 80$$

$$= 84 + 80 = 164$$

$\mathbf{T_f = 164°F}$

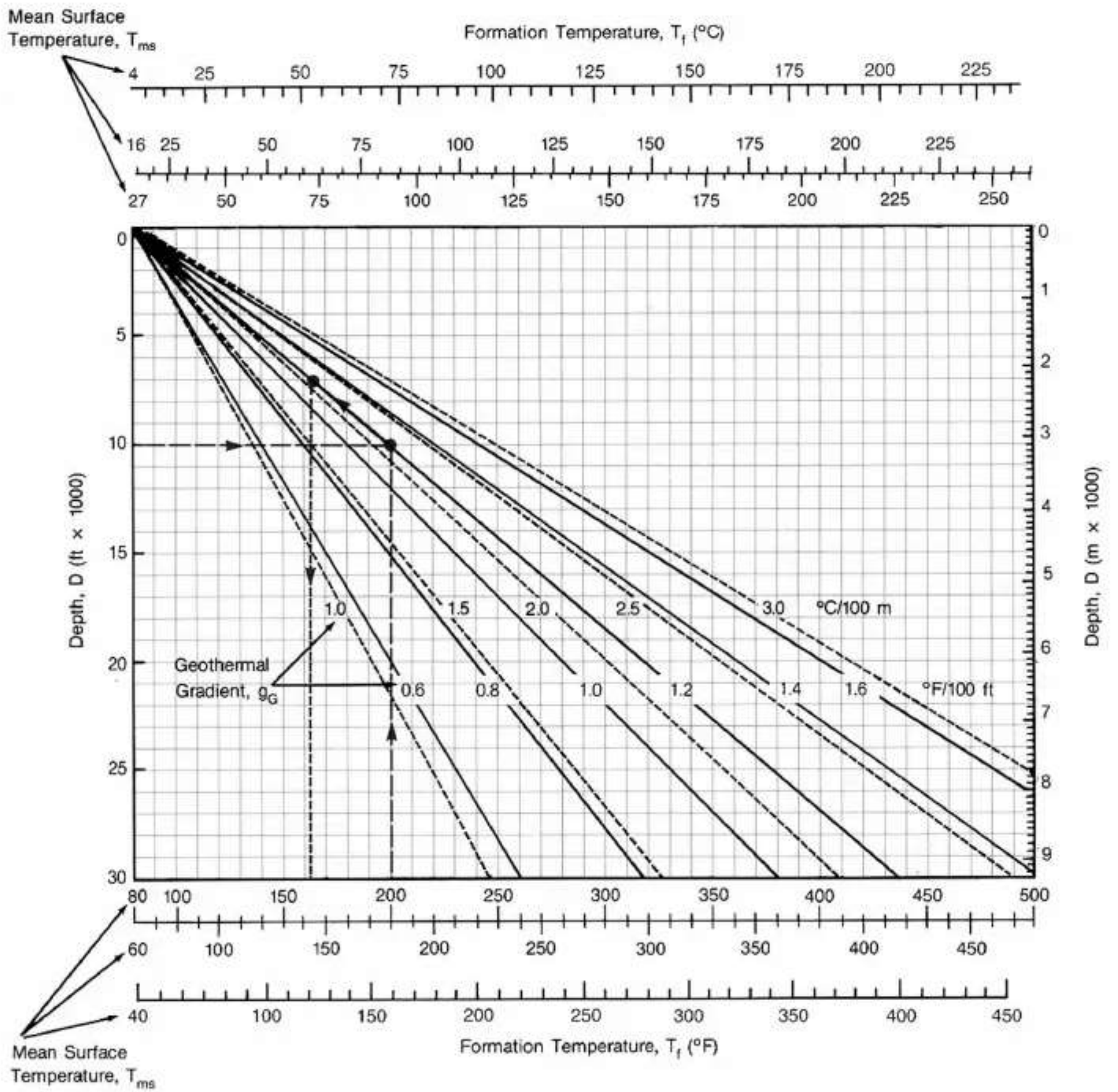
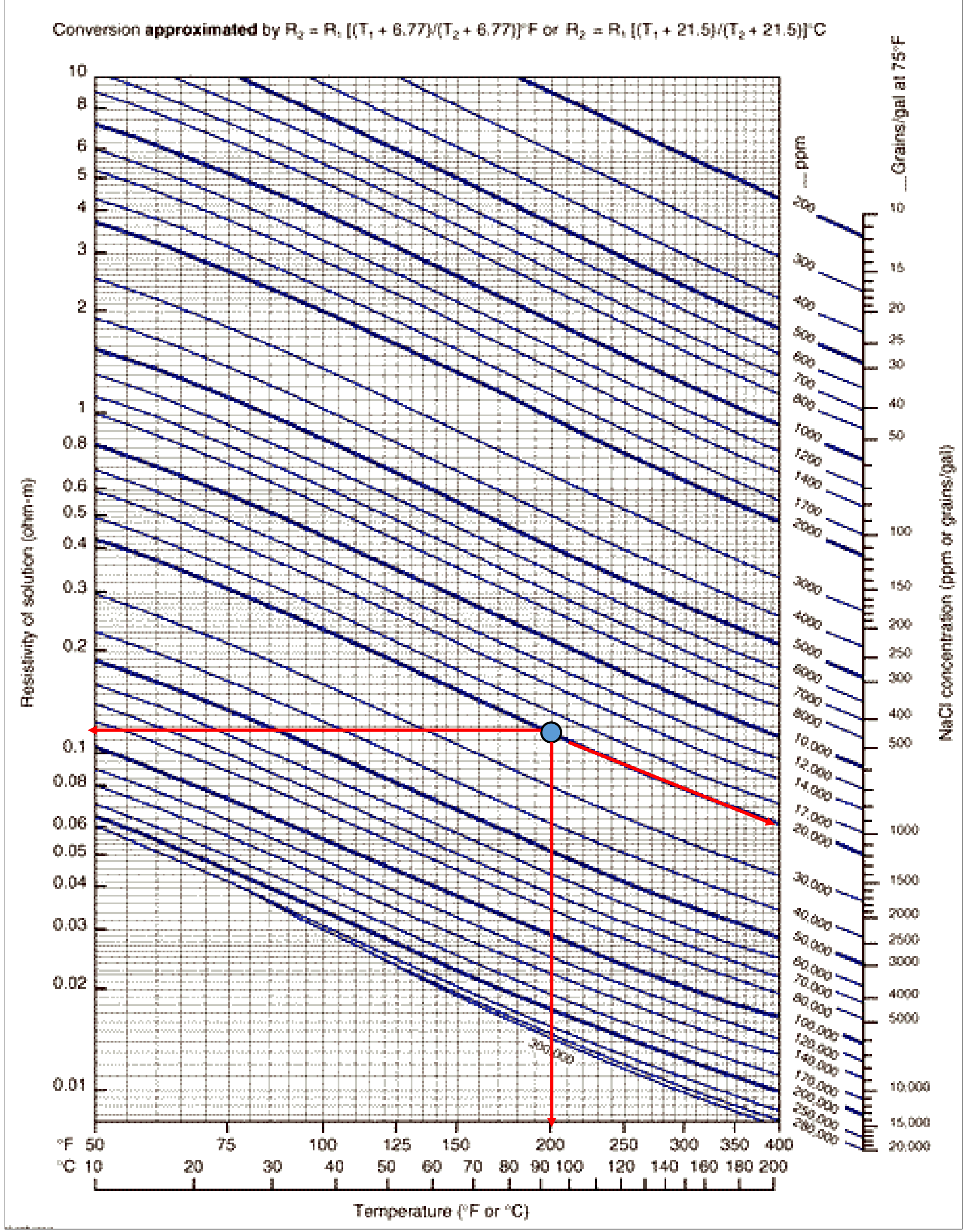


Chart Gen 9, Rw of NaCl solutions



Example Point
- 200 degrees F
- 20000 ppm NaCl
- 1.1 ohmm

RESISTIVITY CONCEPT

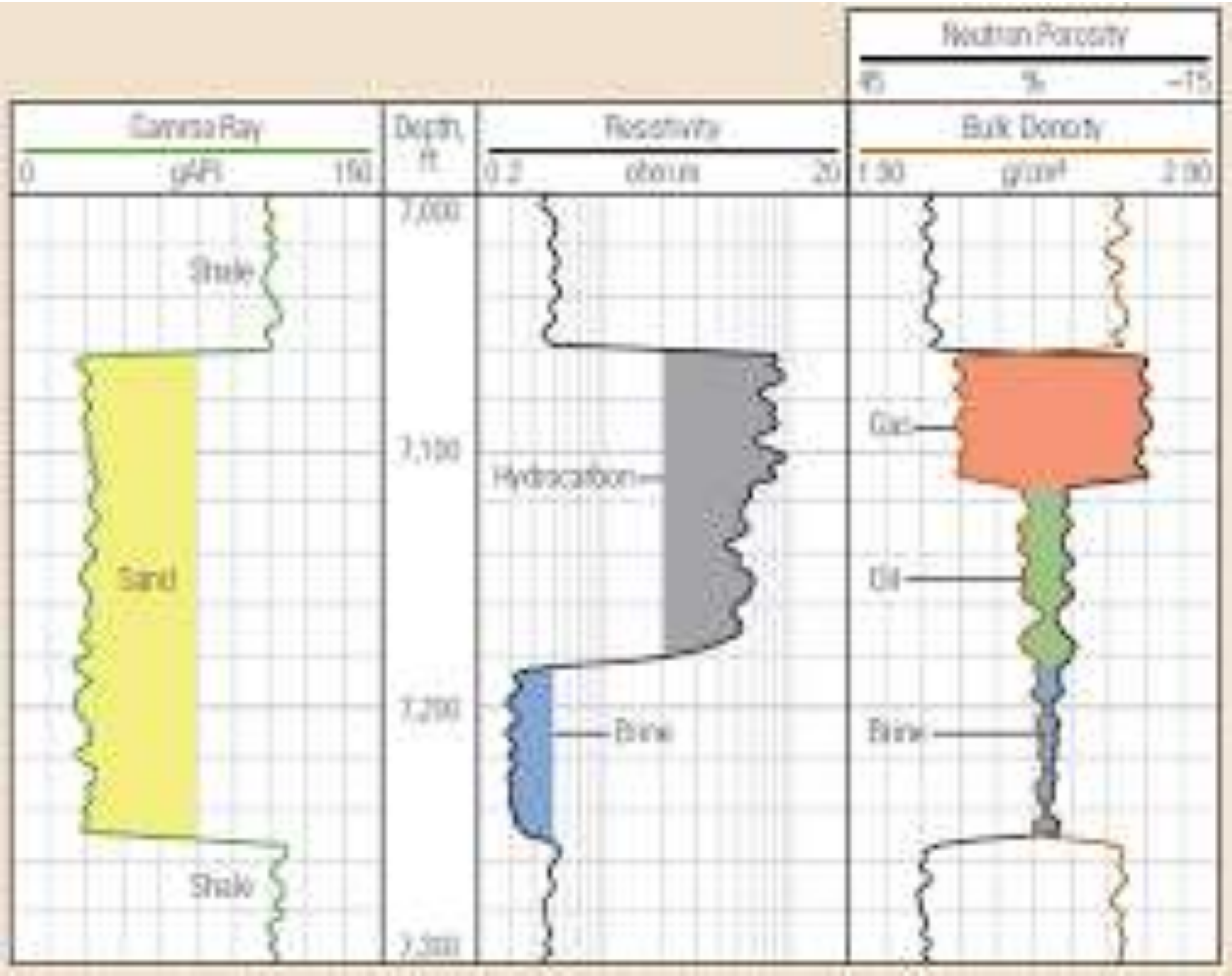
- Formation resistivity is a key parameter in determining hydrocarbon saturation.
- Dry rock is a good electrical insulator
- An electric current can pass through a formation only if it contains water with dissolved ions to be conductive.
- The resistivity of a formation therefore depends on:

i. Formation water Resistivity.

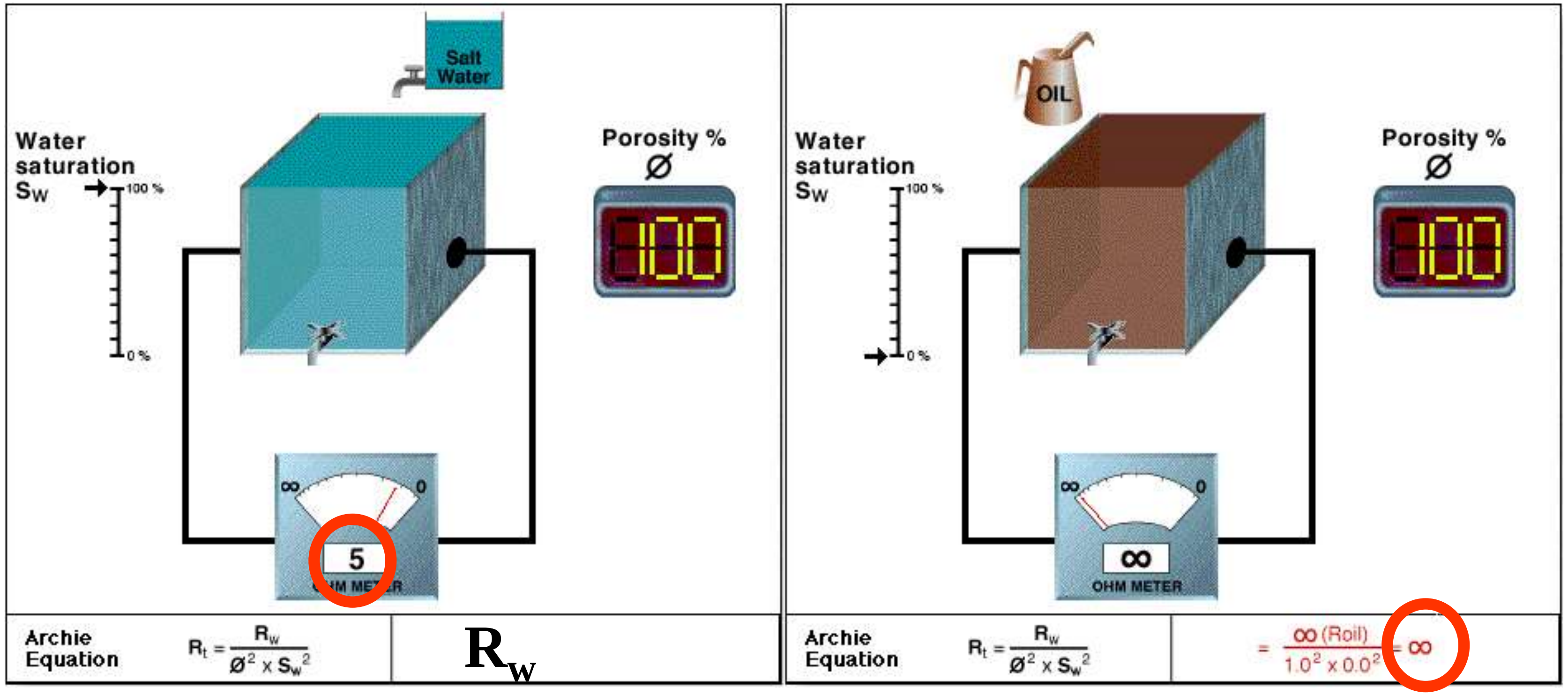
ii. Amount of water present.

iii. Geometry of Pore structure

- Resistivity is a measure of the formation's resistance to the flow of electric current.
- The response from the formation will depend on the fluid content (**note that hydrocarbon act as insulator**).
- Electrical Conductivity is the reciprocal of resistivity.
- Unit of resistivity used in logging is *ohm-m* (Ωm) while that of conductivity is millimhos per meter (mmho/m).


Gamma Ray
0
gAPI
150
Depth, ft
Resistivity
0.2
ohm.m
20
Neutron Porosity
45
%
–15
Bulk Density
1.90
g/cm³
2.90
7,000
7,100
7,200
7,300
Shale
Sand
Shale
Hydrocarbon
Brine
Gas
Oil
Brine

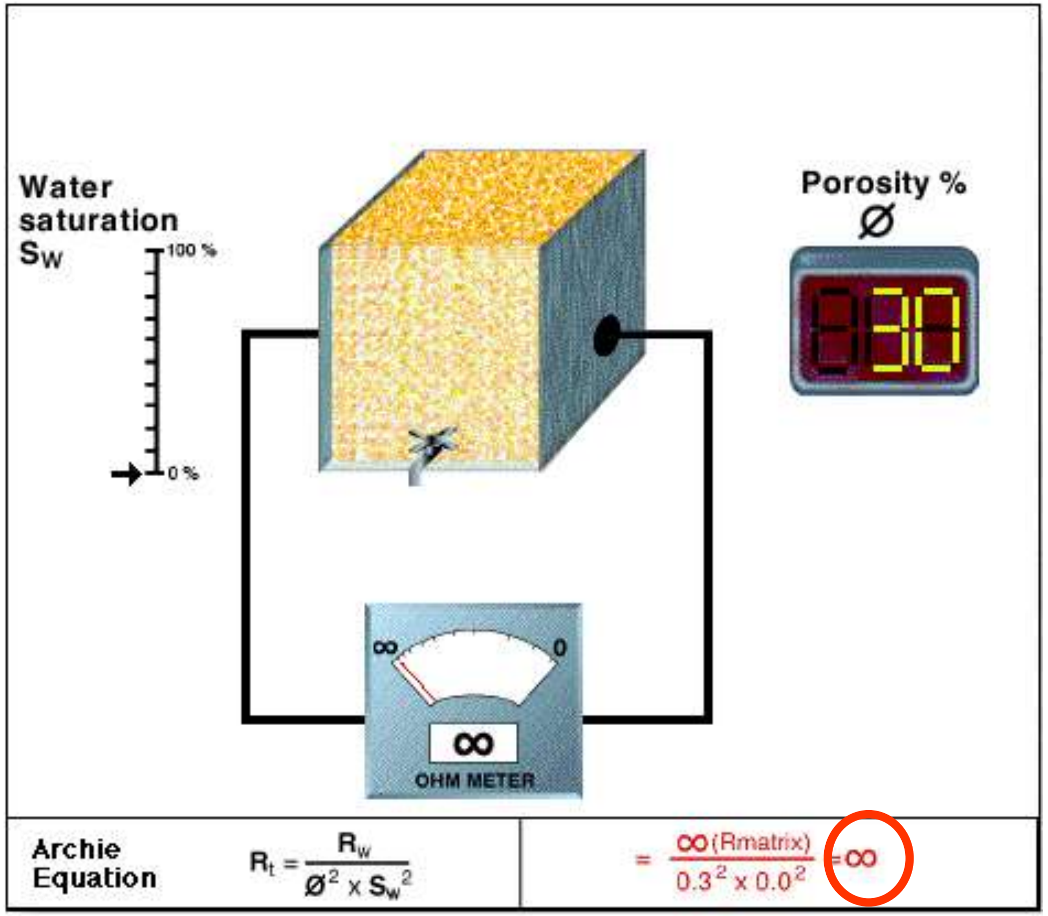
Resistivity



- **Resistivity of the salt water is low (Good conductor)**

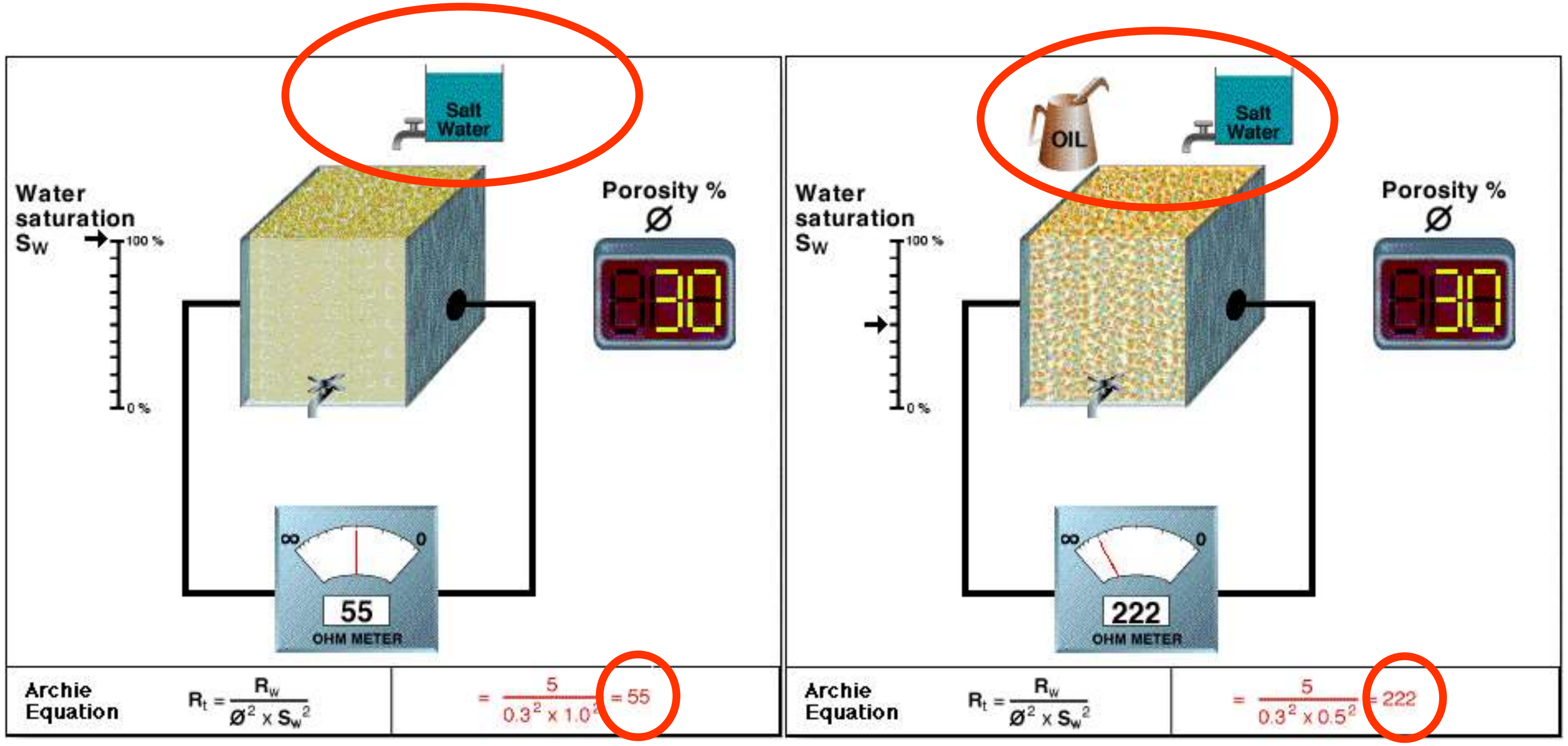
➢ **Resistivity of the oil is high (Poor conductor)**

Resistivity



- **Dry, nonmetallic minerals (rock matrix) have a very high resistivity**

Resistivity



- **The resistivity of a rock will depend on the conductivity of the fluids saturating the porous volume**

- Mathematically

$$R = r\frac{A}{L}$$

(1)

$$R = \frac{V}{I}\frac{A}{L}$$

R – Resistivity (Ωm)

r – Resistance (Ω)

A – Area (m^2)

L – Length (m)

V – Voltage (volts)

I – Current (Ampere)

- Mathematically

$$C = 1000\frac{1}{R} \qquad (2)$$

C – Conductivity (mmho/m)

1000 mmho/m = 1 mho/m

Archie's Equation for Water Saturation

Experiments (Archie, 1942) show:

$$R_0 = F \times R_w$$

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

- S_w = Water saturation
- F = Formation Resistivity Factor (a/ϕ^m):
  - Porosity (ϕ)
  - Tortuosity factor (a), 0.62-2.45
  - Cementation factor (m), 1.0-2.15
- R_w = Resistivity of the formation water
- R_t = Resistivity of a rock with HC, i.e. true resistivity
- R_o = Resistivity of the 100% water-saturated rock
- Where there is no knowledge of local parameters the following values can be used: n = m = 2.0; a = 1.0

$$S_w = \left(\frac{R_0}{R_t}\right)^{\frac{1}{n}} = \left(\frac{F \times R_w}{R_t}\right)^{\frac{1}{n}} = \left(\frac{a \times R_w}{R_t \times \phi^m}\right)^{\frac{1}{n}}$$

Formation Water Resistivity (Archie's Equation)

Empirical constant (usually near unity)

$$S_w = \sqrt[n]{\frac{a\,R_w}{\phi^m\,R_t}}$$

Resistivity of formation water, Ω-m

Water saturation, fraction

Cementation exponent (usually near 2)

Saturation exponent (also usually near 2)

Porosity, fraction

Resistivity of uninvaded formation, Ω-m

$$OIIP = \frac{7758 A h \phi \left(1 - S_w\right) {}^{N}\!/_{G}}{B_{oi}}$$

$$GIIP = \frac{43560 A h \phi \left(1 - S_w\right) {}^{N}\!/_{G}}{B_{gi}}$$

- The mud filtrate saturation of the flushed zone is also expressed by Archie's equation as:

$$S_{xo} = \sqrt{\frac{FR_{mf}}{R_{xo}}}$$

$$S_{xo} = 1 - S_{hr}$$

$$S_w = 1 - S_h$$

- S_{hr} = residual hydrocarbon saturation in the flushed zone

- Bulk-volume fraction of oil displaced by invasion process is given as:

$$\phi\left(S_h - S_{hr}\right) = \phi\left[\left(1 - S_w\right) - \left(1 - S_{xo}\right)\right] = \phi\left(S_{xo} - S_w\right)$$

- The equation implies that oil production is be expected when the reservoir is put on production.

- Also if S_w is divided by S_{xo}

- Gives:

$$\frac{S_w}{S_{xo}} = \left(\frac{FR_w}{R_t} \div \frac{FR_{mf}}{R_{xo}} \right)^{\frac{1}{2}} = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w} \right)^{\frac{1}{2}}$$

- Empirical study showed that
- $S_{xo} \sim S_w^{1/5}$

$$\frac{S_w}{S_w^{\frac{1}{5}}} = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w} \right)^{\frac{1}{2}}$$

- Simplifying

$$S_w^{\frac{4}{5}} = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w} \right)^{\frac{1}{2}}$$

$$S_w = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w} \right)^{\frac{5}{8}}$$

- This is **ratio method** of determining S_w
- It does not require the knowledge of porosity or formation resistivity factor.

- The values of formation R_w and mud filtrate R_{mf} are needed for the S_w calculations.
- Mud R_m , mudcake R_{mc} and R_{mf} are generally measured at the time time of the survey of a mud sample from the mud pit.
- These values are recorded on the log heading.
- Actual (or direct) resistivity measurements are always preferred, but if the values are not available, they may be estimated from one of the following methods.

- Lowe and Dunlap Method ($0.1<R_m \leq 2.0$ @ 75°F)

$$\log\left(\frac{R_{mf}}{R_m}\right) = 0.396 - 0.0475\rho_m$$

- Overton and Lipson Method ($0.1<R_m \leq 10.0$ @ 75°F)

$$R_{mf} = K_m\left(R_m\right)^{1.07}$$

$$R_{mc} = 0.69R_{mf}\left(\frac{R_m}{R_{mf}}\right)^{2.65}$$

- Statistical Approximation (for predominantly NaCl muds)

$$R_{mc} = 1.5R_m$$

$$R_{mf} = 0.75R_m$$

FORMATION WATER RESISTIVITY

- Formation water sometimes called connate water, is the water, uncontaminated by drilling mud, that saturates the porous formation rock.
- The R_w is an important interpretation parameter since it is required for the calculation of water and/or hydrocarbon saturations from basic resistivity logs

Sources of formation R_w information

1. R_w from water catalog
2. R_w from chemical analysis
3. R_w from the Spontaneous Potential

Classes of Log

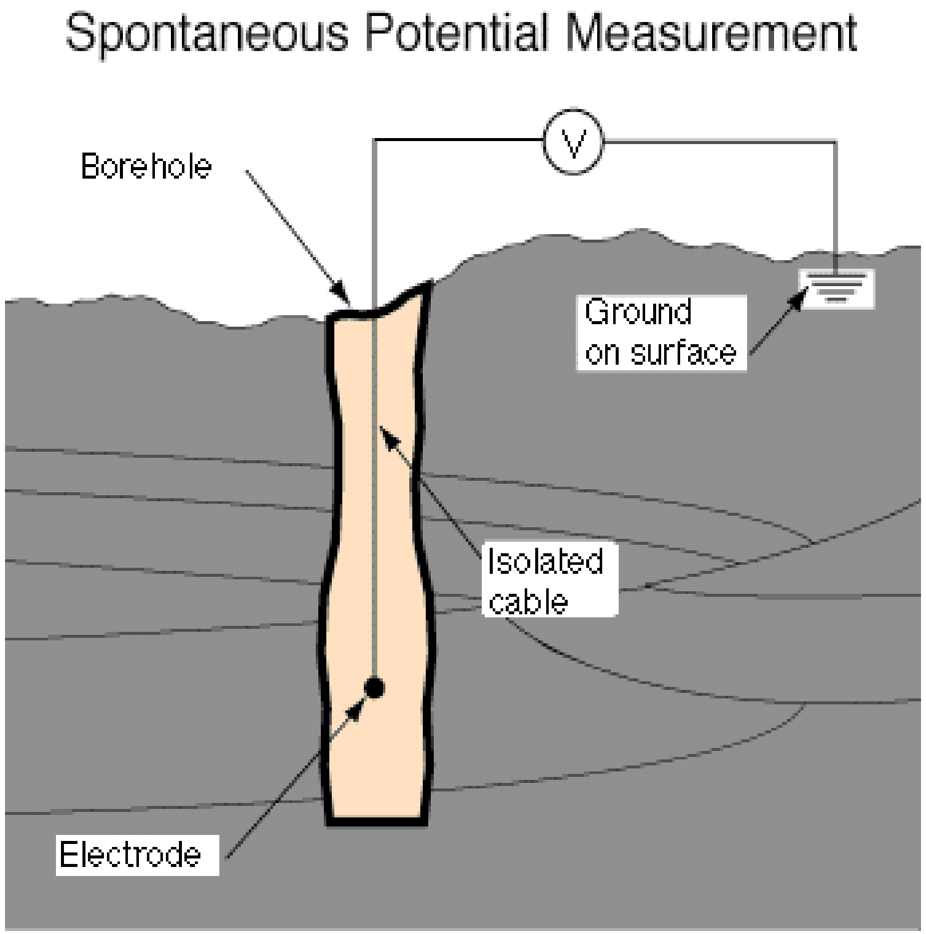
- Reservoir Thickness Logs (e.g. Spontaneous (SP) and Gamma Ray).
  - *Discriminate Reservoir from Non-Reservoir*

- Resistivity Logs (Laterolog, Induction and Microresistivity).
  - Together with porosity logs are used to compute hydrocarbon saturations.

- Porosity Logs (Sonic, Density and Neutron).
  - Used to calculate porosity, identify lithologies and differentiate oil from gas.

SPONTANEOUS POTENTIAL (SP) LOG

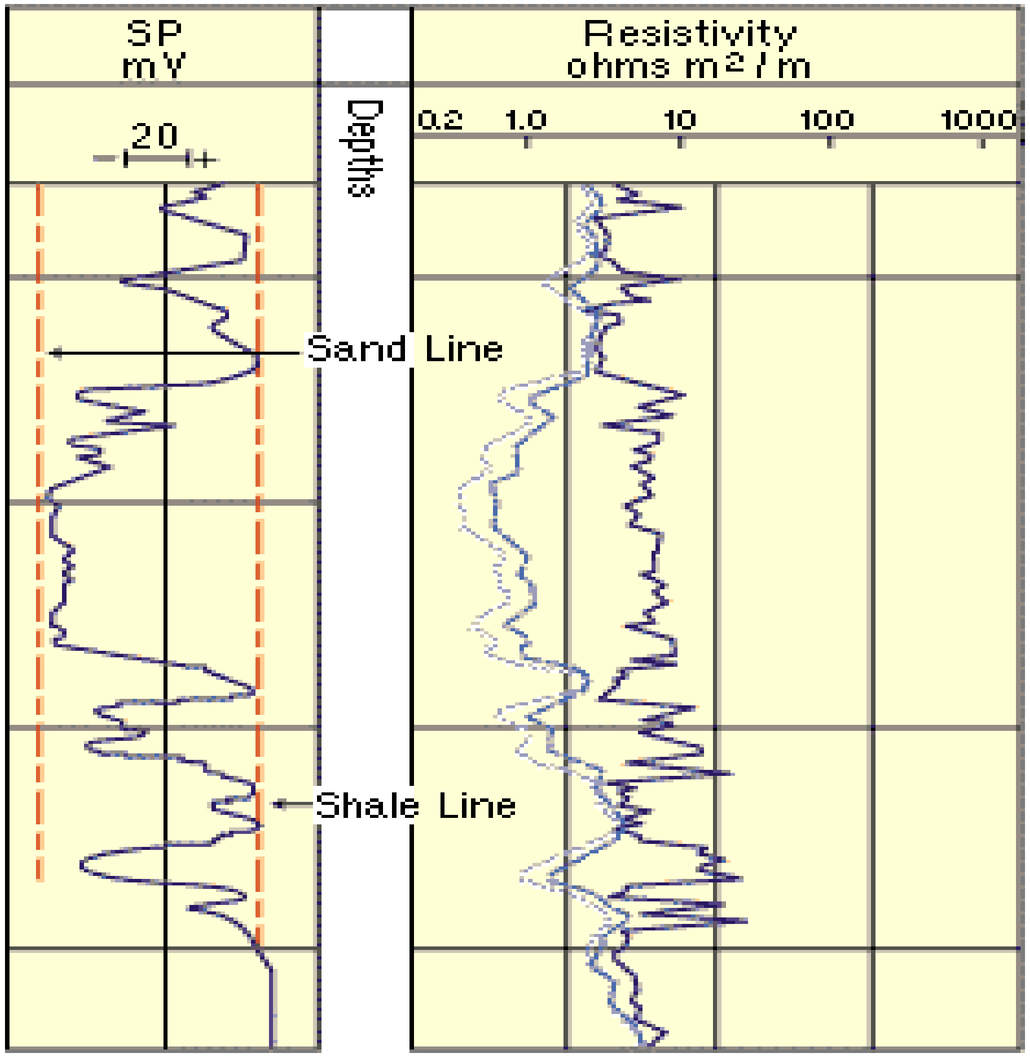
- The SP curve is a continuous recording vs. depth of the natural potential difference between a movable electrode in the borehole and a surface electrode.
- Adjacent to shales, SP readings usually define a straight line known as the **shale baseline**.
- Next to permeable formations, the curve departs from the shale baseline; in thick permeable beds, these excursions reach a constant departure from the shale baseline, defining the **"sand line."**



The spontaneous potential is a measurement against depth of the potential difference between the voltage in the wellbore and an electrode on the surface.

- The deflection may be either to the left (negative) or to the right (positive), depending on the **relative salinities** of the **formation water** and the **mud filtrate**.
- If the formation-water salinity is greater than the mud-filtrate salinity (the more common case), the deflection is to the left.
- The relevant features of the SP curve are its **shape** and the **size** of its departure from the shale baseline.

SP Log Example



This example illustrates how the SP curve responds to shales and sands.

In this example $R_{mf} > R_w$.

NOTE:

Shale must be present next to a permeable zone like a sandstone in order to have an SP.

- If the resistivity of the mud filtrate and formation water are similar, the SP deflections are small and the curve is rather featureless.
- An SP curve cannot be recorded in holes filled with nonconductive muds, such as oil-based muds (OBMs).

Principle of SP Log

- Deflections of the SP curve are the result of **ELECTROCHEMICAL** and **ELECTROKINETIC** potentials in the formations that cause electric currents to flow in the mud in the borehole.

Electrochemical Component

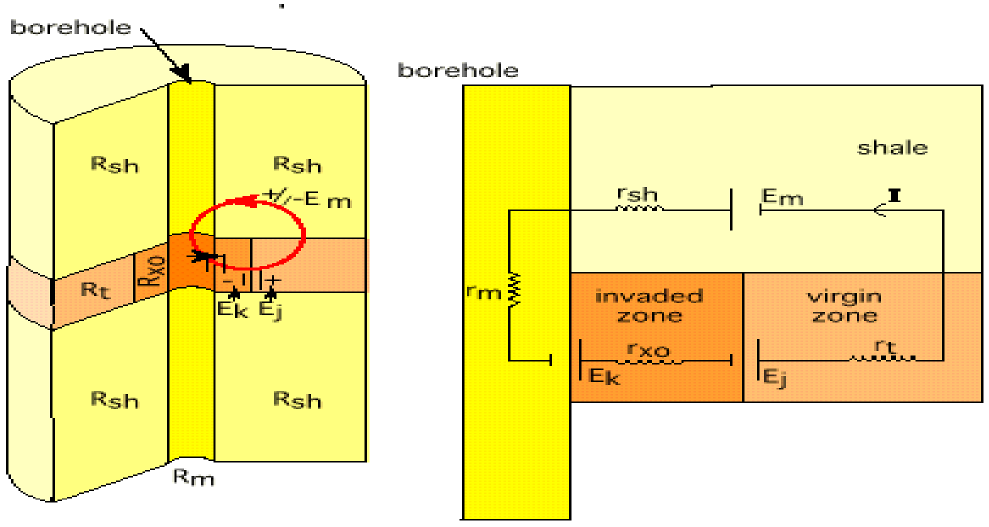
- This is the largest component of the SP and is due to the chemical interaction caused by a difference in salinity between the mud filtrate and the formation water.
- The electrochemical component is broken into two smaller components;

i. the *membrane potential and*

ii. the *liquid junction potential.*

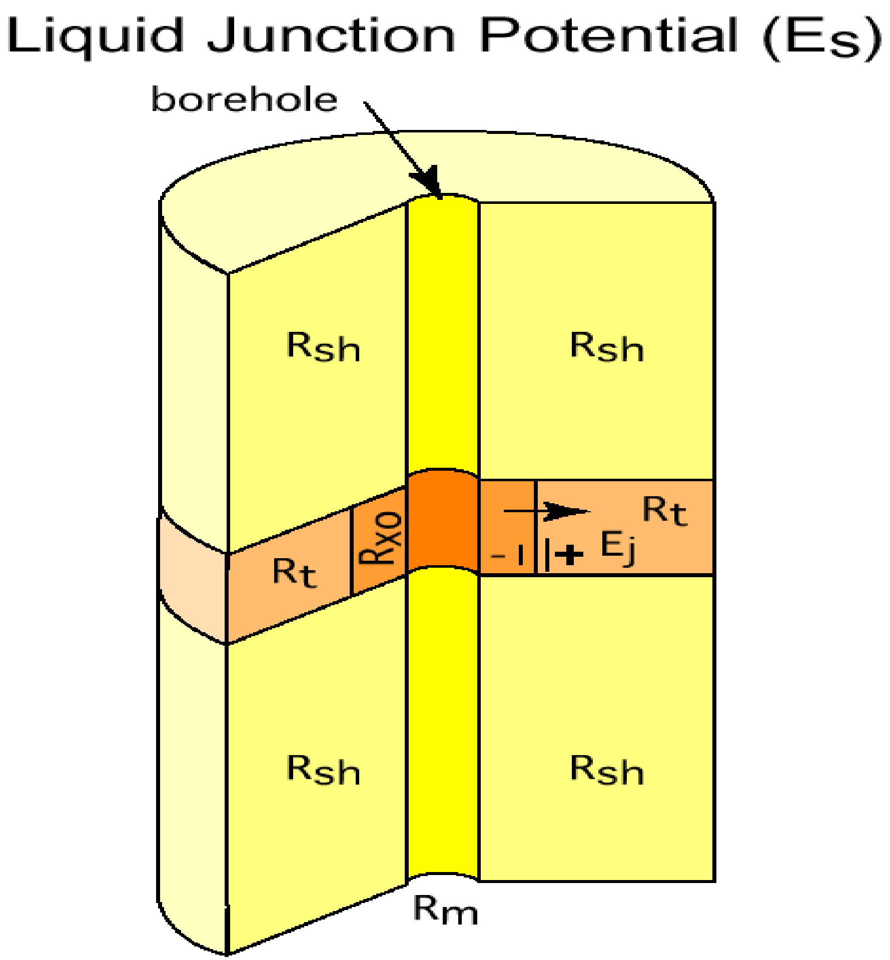
(a) Membrane Potential (Em)

- Ion selective membranes allow ions with certain electrical charges (positive or negative) to pass through them. Shales act like ion selective membranes as they allow only cations (positively charged ions) to pass through. This flow of charged particles is an electric current.
- The Membrane Potential graphic illustrates the current flow for the case where Rmf > Rw (fresh mud). The flow would be reversed if Rmf < Rw (salt mud).
- The membrane potential exist because shales (Rsh) are known as ion selective membranes. That is, they are permeable only to certain ions. In this case the shale is permeable to the Na+ ions.
- The Na+ ions move through the shale from the higher salinity (Rt) to the lower salinity (Rm). This results in a current flow through the shale as indicated.



(b) Liquid Junction Potential (Ej)

- Liquid junction potential (Ej) exists due to a difference in salinity between two fluids that are in contact with each other.
- Ions will move between liquids of differing salinities. The ions will normally move from higher salinity to lower. The most abundant ions in a wellbore are sodium (Na^+) and chlorine (Cl^-). Because chlorine is a smaller atom it moves easier and faster through the formation.



Electrokinetic Potential (E_k)

- It is also known as streaming potential or electrofiltration potential.
- It is produced when an electrolyte flows through a porous nonmetallic medium.
- In the well or hole the E_k is being produced by the flow of mud filtrate during the formation of the mudcake across from a permeable zone.
- The Elecrokinetic potential (E_k) exists due to the flow of an electrolyte (R_m) through a nonconductive medium (mudcake).
- This flow exists because of the differential pressure between the mud column and the formation.
- Electrokinetic potential is normally very small and will stop as soon as the mudcake becomes impermeable.

Oilfield applications of SP log includes:

i. Differentiate potentially porous and permeable reservoir rocks (sandstone, limestone and dolomite) from non-permeable formations (clay and shale).

ii. Define bed boundaries and permit correlation of beds.

iii. Identify the fresh / salt water interface

iv. Give qualitative indication of bed Shaliness.

v. Formation water resistivity (R_w) determination.

vi. Aid in Lithology identification.

vii. Volume of Shale in Permeable bed.

Shale Baseline and Static Spontaneous Potential (SSP)

- The definition of the Spontaneous Potential (SP) Zero is called the **Shale Baseline**.
- This is made on thick shale interval intervals where the SP curve does not move.
- The theoretical maximum deflection of the SP opposite permeable beds is called the **Static Spontaneous Potential (SSP)**.
- SSP is the maximum possible SP opposite a permeable, water-bearing formation with no shale.

- The SSP is used to calculate formation-water resistivity.
- SSP is determined by **formula** or **chart**
- **Pseudo-Static Spontaneous Potential (PSP)** Is the ideal SP opposite shaly bed.

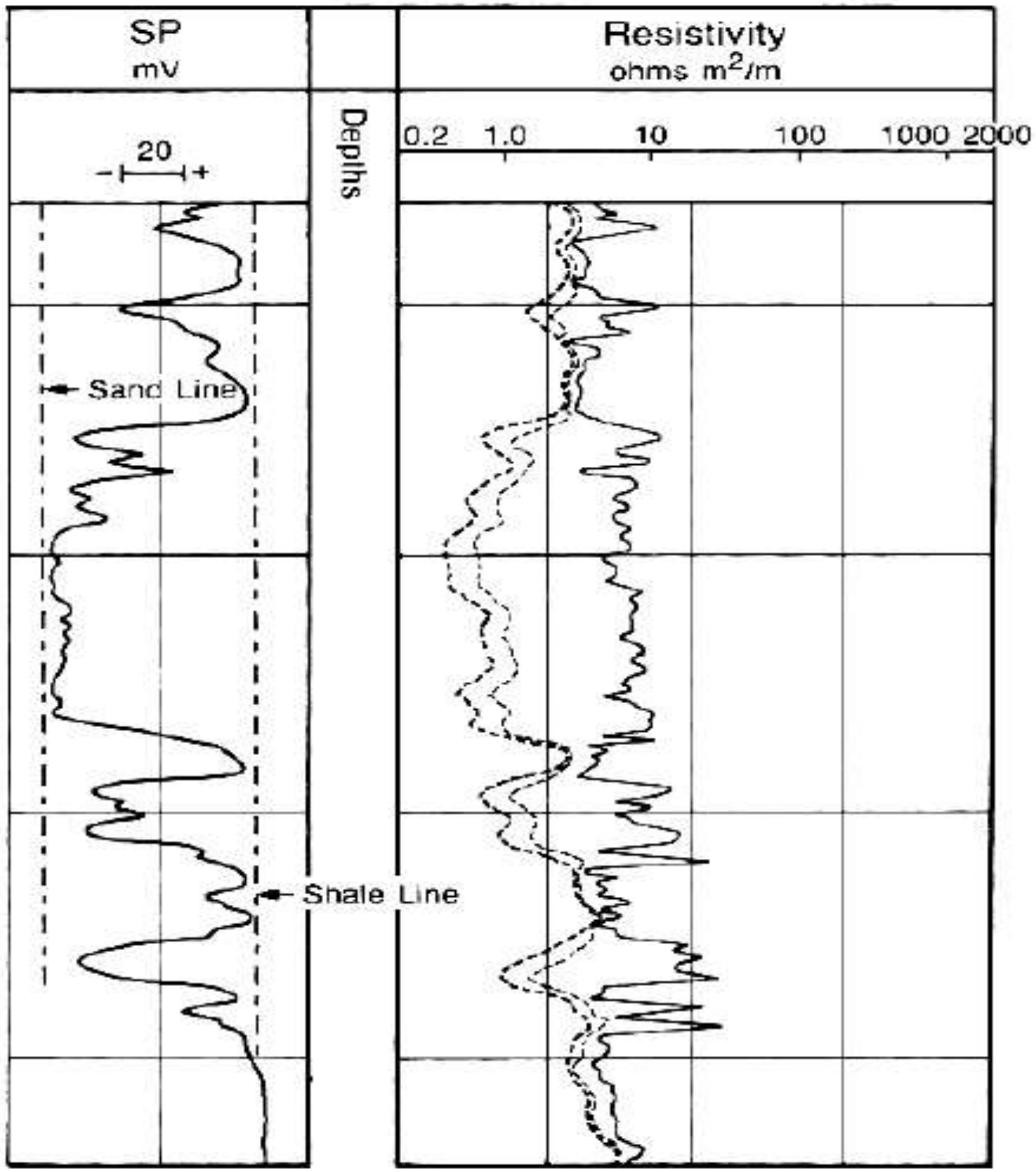
$$SSP = -K \log \frac{R_{mfe}}{R_{we}}$$

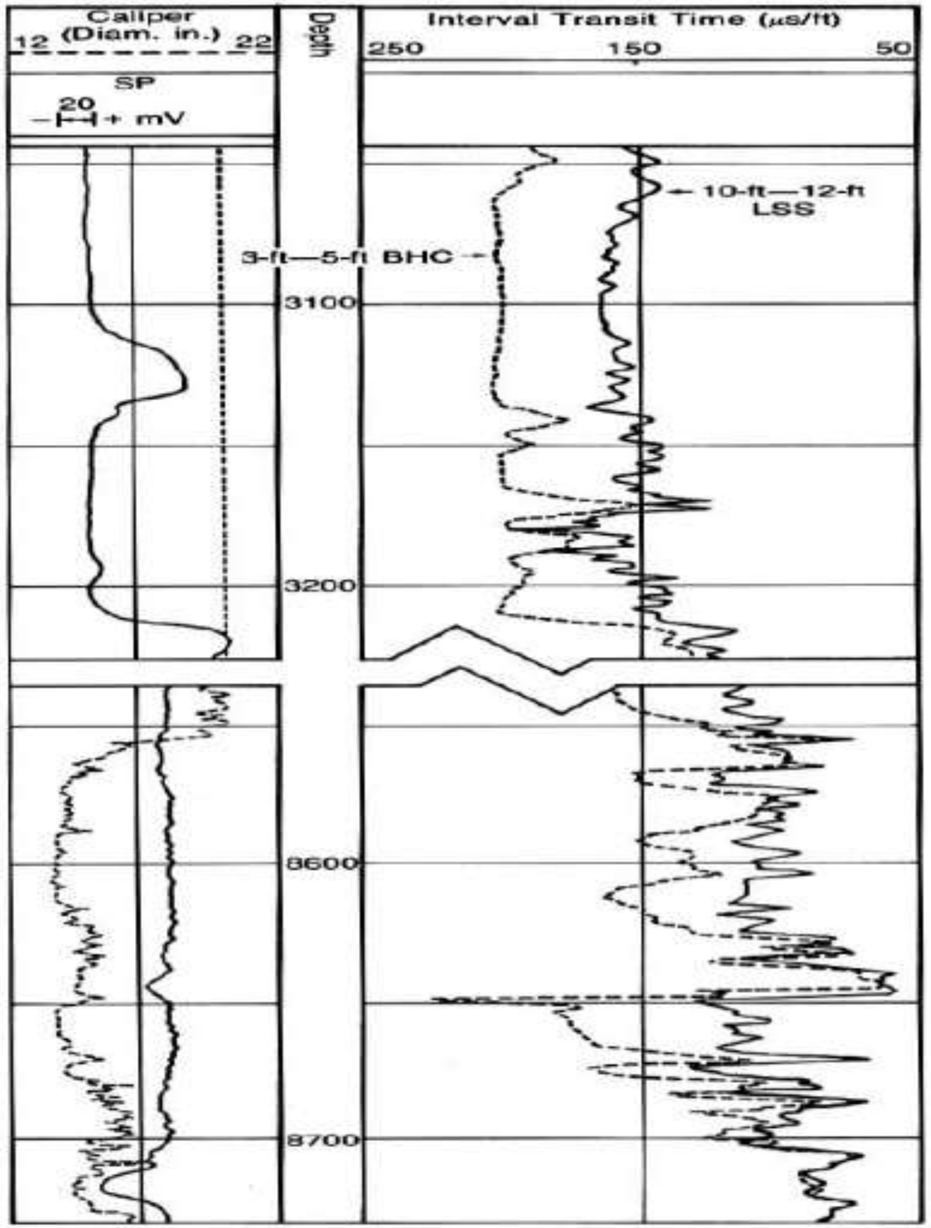
OR

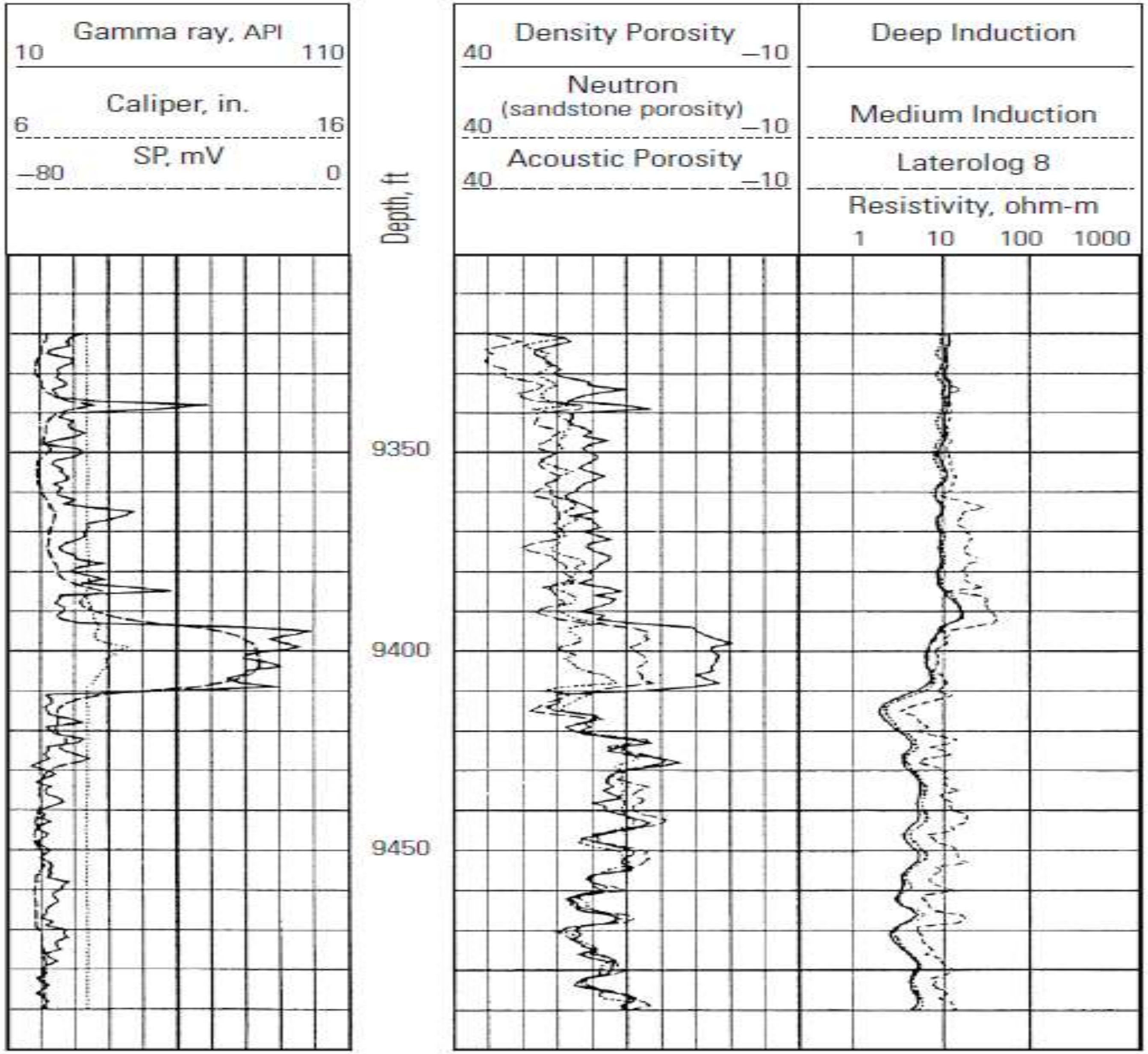
$$SSP = -K \log \frac{R_{mf}}{R_w}$$

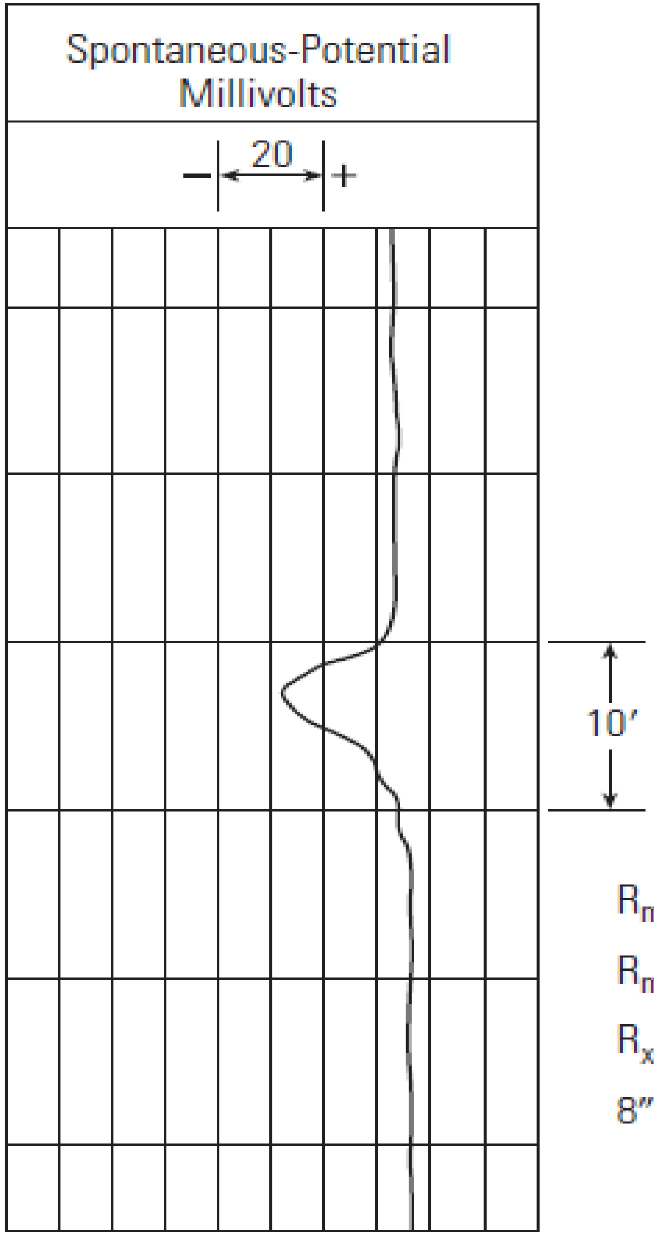
- K = 60 + (0.133T_f)
- **Shale Volume**

$$V_{sh} = \left(1.0 - \frac{PSP}{SSP}\right) \times 100$$


SP
mV
20
- +
Depths
Resistivity
ohms m²/m
0.2 1.0 10 100 1000 2000
Sand Line
Shale Line


Caliper
(Diam. in.)
12 22
SP
20
- + mV
Depth
Interval Transit Time (μs/ft)
250 150 50
10-ft—12-ft LSS
3-ft—5-ft BHC
3100
3200
8600
8700



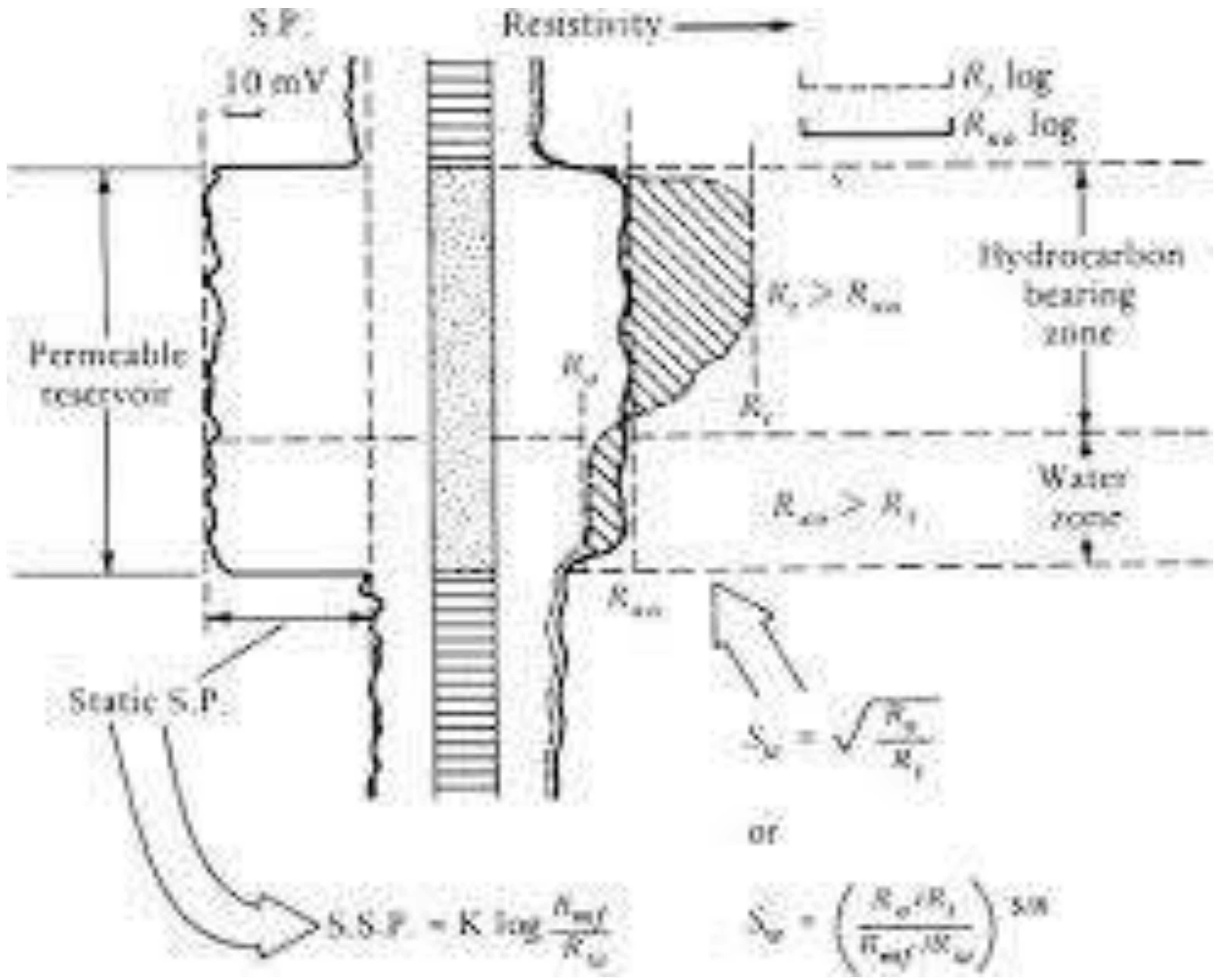


$R_m = 0.91\ \Omega_m$

$R_{mf} = 0.51\ \Omega_m$

$R_{xo} = 30\ \Omega_m$

8″ Borehole


S.P.
10 mV
Resistivity
R_t log
R_{xo} log
Permeable reservoir
Hydrocarbon bearing zone
$R_t > R_{xo}$
R_{xo}
R_t
Water zone
$R_{xo} > R_t$
R_{xo}
Static S.P.
$S_w = \sqrt{\frac{R_{xo}}{R_t}}$
or
S.S.P. $= K \log \frac{R_{mf}}{R_w}$
$S_w = \left(\frac{R_{xo}/R_t}{R_{mf}/R_w}\right)^{5/8}$

FORMATION WATER RESISTIVITY FROM SP

Using Chart

1. Find formation temperature T_f at the depth at which R_w is required using chart Gen 6 .
2. Convert R_m and R_{mf} obtained from log heading or measured at the surface to R_m and R_{mf} at T_f using chart Gen 9.
3. Determine SP from given log.
4. Correct SP to SSP using chart SP4

Data needed

- Bed thickness (from SP log)
- R_i from resistivity log
- R_m @ T_f
- Compute (R_i /R_m) and use to determine SP correction factor (CF) from chart.
- $SSP = SP \times SP_{CF}$

5. Determine (R_{mfe} /R_{we}) ratio using Chart SP1 with SSP value @ T_f
6. Convert R_{mf} to R_{mfe} using chart SP2
7. Determine R_{we} using

$$R_{we} = R_{mfe} \div \frac{R_{mfe}}{R_{we}}$$

8. Convert R_{we} to R_w using chart SP2

By Calculations

1. Find T_f at the depth at which R_w is required using chart Gen6.
2. Compute R_{mf} @ 75°F using:

$$R_{mf}\ @\,75°F = R_{mf_{temp}} \times \frac{(temp + 6.77)}{81.77}$$

3. Compute SSP as follows:

$$SSP = -K \log \frac{R_{mfe}}{R_{we}}$$

$$\frac{R_{mfe}}{R_{we}} = 10^{-\frac{SSP}{K}}$$

$$K = 60 + 0.133T_f$$

4. Compute R_{mfe}

$$R_{mfe} = \frac{146R_{mf} - 5}{337R_{mf} + 77} \qquad If\ R_{mf}\ @75°F < 0.1$$

$$R_{mfe} = 0.85R_{mf} \qquad If\ R_{mf}\ @75°F > 0.1$$

5. Compute R_{we} and R_w

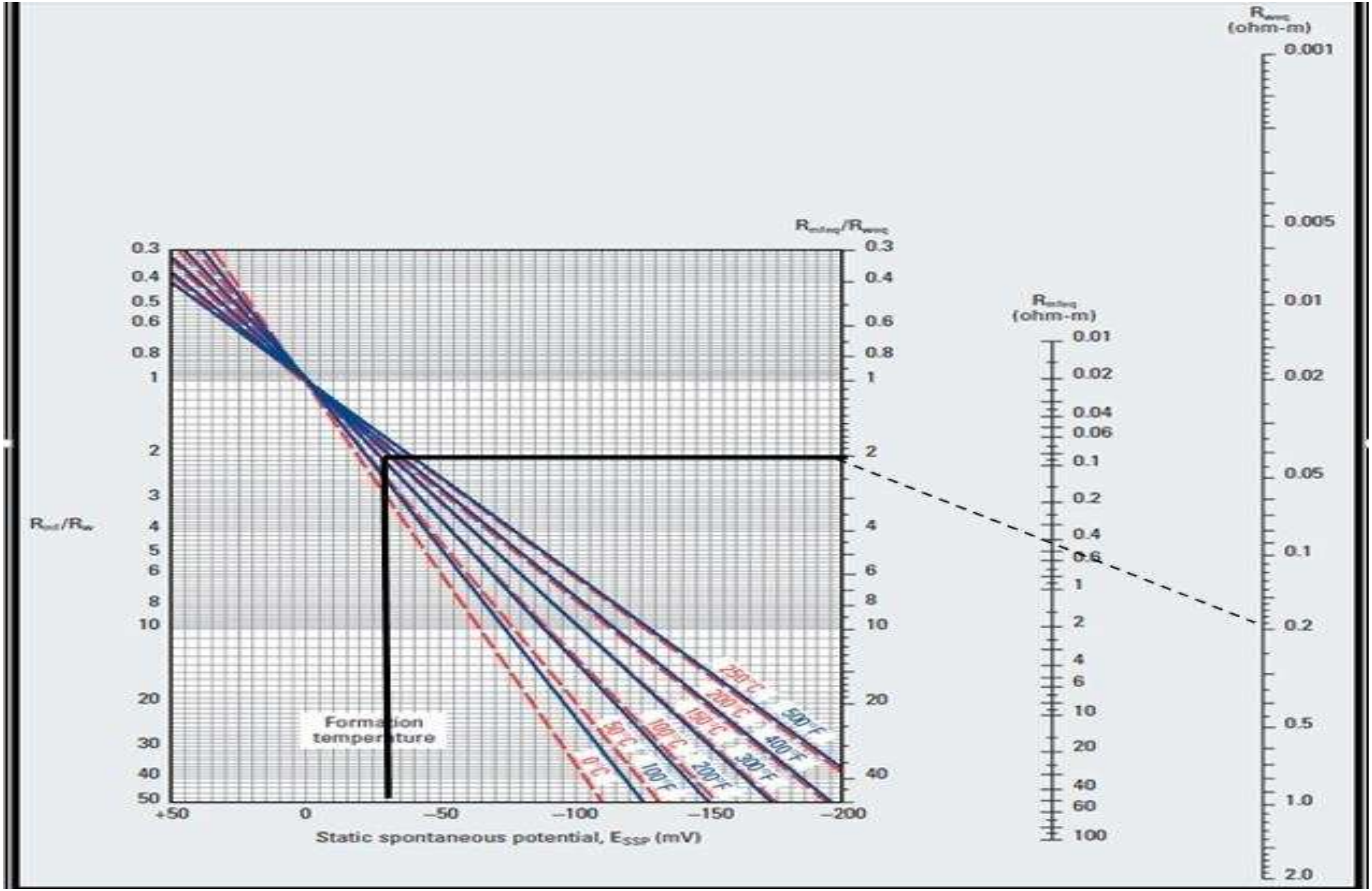
$$R_{we} = R_{mfe} \div \frac{R_{mfe}}{R_{we}}$$

$$R_w\ @75°F = \frac{77R_{we} + 5}{146 - 377R_{we}} \qquad If\ R_{we} < 0.12$$

$$R_w\ @75°F = -\left[0.58 - 10^{(0.69R_{we} - 0.24)}\right] \qquad If\ R_{we} > 0.12$$

- Compute R_w @ T_f

$$R_w\ @T_f = \frac{81.77 \times R_w\ @75°F}{6.77 + T_f}$$



R_{weq} (ohm-m)
R_{mfeq}/R_{weq}
R_{mfeq} (ohm-m)
R_{mf}/R_w
Formation temperature
Static spontaneous potential, E_{SSP} (mV)
+50
0
−50
−100
−150
−200
0.3
0.4
0.5
0.6
0.8
1
2
3
4
5
6
8
10
20
30
40
50
0.01
0.02
0.04
0.06
0.1
0.2
0.4
0.6
1
2
4
6
10
20
40
60
100
0.001
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
250°C
200°C
150°C
100°C
50°C
0°C
500°F
400°F
300°F
200°F
100°F

TYPES OF RESISTIVITY LOGS

- Resistivity logging is the recording in a borehole of the resistivities (or the conductivities) of the subsurface formations, generally along with the spontaneous potentials (SPs) generated in the borehole.
- These recordings are used for:

i. correlation of the strata

ii. qualitative detection of productive zones.

iii. quantitative evaluation of possibly productive horizons.

1. Conventional Electrical Survey (ES) Logs

- This is the only resistivity logs available during the first quarter century of well logging.
- The conventional ES usually consist of:

i. Spontaneous Potential (SP)

ii. 16-in normal device

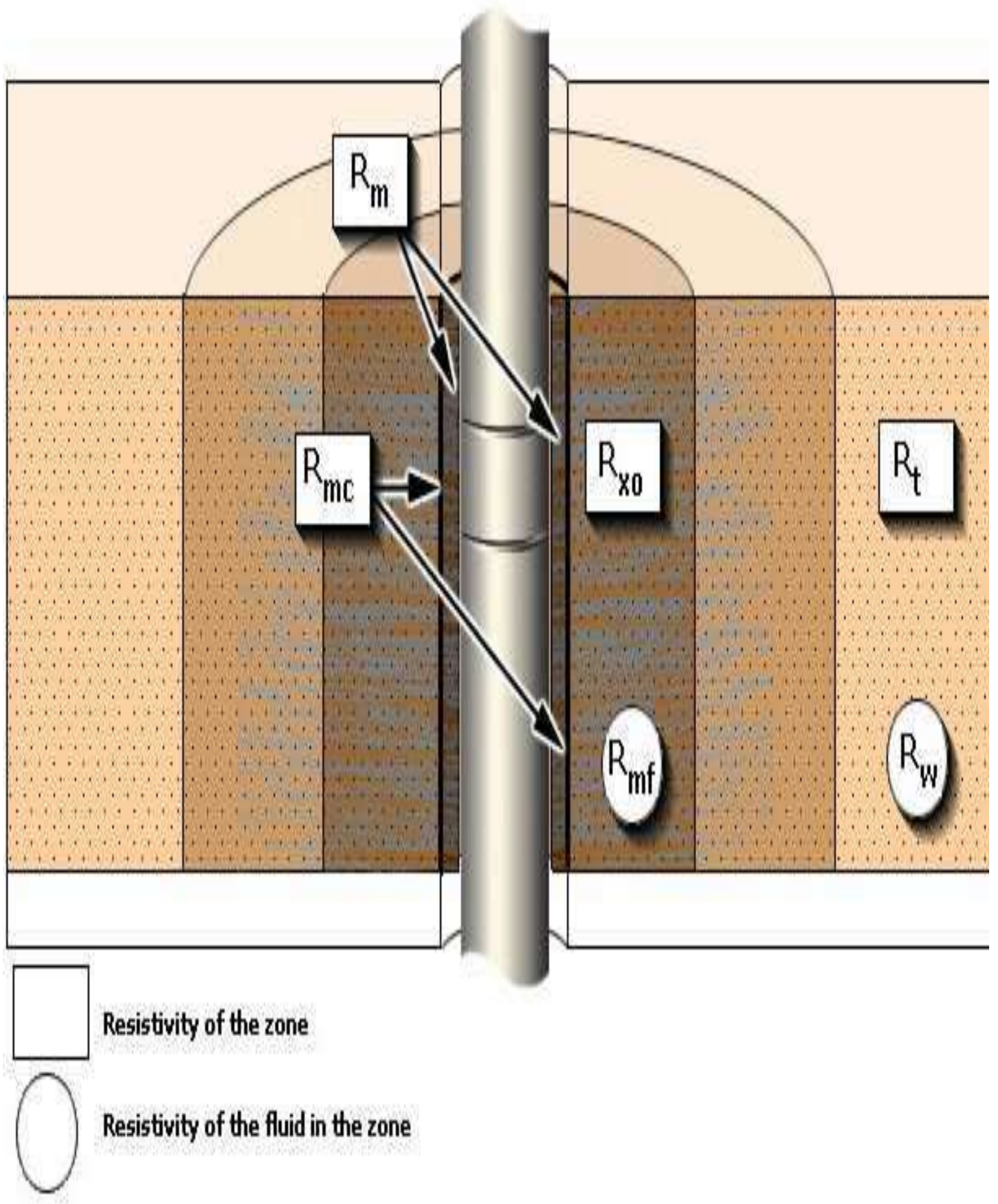
iii. 64-in normal device

iv. 18-ft 8-in lateral device

R_t from the ES Logs

- The general rule for obtaining R_t from ES logs are based on the relative resistivity of the bed compared to R_m and surrounding formation.
- Formation are divided into three classes depending on ratio

Class of Formation	Resistivity	Range of Resistivity	
1	Low	$\frac{R_{16''}}{R_m} \langle\, 10$	16-in and 64-in normal most useful in finding R_t
2	Medium	$10 \,\langle\, \frac{R_{16''}}{R_m} \langle\, 50$	64-in normal and 18-ft 8-in lateral very useful in finding R_t
3	High	$\frac{R_{16''}}{R_m} \rangle\, 50$	64-in normal is greatly affected by invasion, hence 18-ft 8-in lateral is the best choice for estimating R_t



2. Focusing Electrode Logs

- The responses of conventional ES logs are greatly affected by the borehole and adjacent formations.
- These influences are minimized by a family of resistivity tools that uses focusing currents to control the path taken by the measure current.
- These currents are emitted from special electrodes on the sondes.
- The Focusing Electrode Tools include: Laterologs (laterolog 7, laterolog 3, laterolog 8, dual laterolog) and Spherically Focused Log (SFL).
- Focusing Electrode Logs are available with Deep (LLD or DLL), Medium (LLM or MLL) and Shallow (LLS) depths of Investigation.
- The laterolog is generally recommended for holes drilled with very conductive drilling muds (i.e., salt muds).

3. Induction Logging

- This tool is generally recommended for holes drilled with only moderately conductive drilling muds or nonconductive muds (e.g., oil-based mud (OBM)) and for air-drilled holes.
- Induction tools are **conductivity-sensitive** devices, which are most accurate in low- to medium-resistivity formations.
- Induction tools see the more conductive zones while Laterolog devices see the more resistive zones.
- Laterolog tools are resistivity devices, which are most accurate in medium- to high-resistivity formations.
- When $R_{xo} > R_t$: An induction tool is preferred for R_t determination because laterolog tools are affected mostly by R_{xo}.
- Conversely, a laterolog tool is preferred when $R_{xo} < R_t$.

4. Micro-resistivity Devices

- A knowledge of the resistivity of the flushed zone (R_{xo}) is essential for applying corrections to deep resistivity readings to account for invasion effects.
- A "R_{xo} log" is obtained from recording of the micro-resistivity devices.

Uses of Micro-resistivity log

- Estimation of Porosity

$$F = \frac{R_o}{R_w} = \frac{R_{xo}}{R_{mf}} = \frac{1}{\phi^m}$$

- Determination of "residual" or "moveable" hydrocarbon.
- Measurement of mud-cake thickness
- Qualitative location of the porous and permeable zones i.e. for delineating permeable bed boundaries.

Types of micro-resistivity tools

- Micro log (MLC)
- Micro laterolog (MLLC)
- Proximity log (PLC)
- Microspherically Focus log (MSFL)
- Electromagnetic Propagation log (EPT)
- Dipmeter logs (HDT, SHDT)
- Formation MicroScanner (FMS) or MicroImager (FMI)

Micro log

- This is the first non-focused, pad type contact tool.
- The pad must be pressed tightly against the wall of the hole.
- It is the best micro-resistivity devices for delineating permeable bed boundaries.
- Two micro-resistivity curves are recorded on the log. They are

i. Micro Inverse 1”×1”

ii. Micro Normal 2”

Depth of Investigation

- The 2” micro normal has a greater depth of investigation than the 1”×1” micro inverse.
- It is therefore less influence by the mud cake and reads higher resistivity.
- The two micro curves give sufficient information to determine mud cake thickness (t_{mc}) and R_{xo}.

Qualitative Interpretation

- Separation between the two micro log curves known as **“positive”** or **“negative”**
- Is a diagnostic, qualitative indication of whether the adjacent formation is porous and permeable.

1. Positive Separation

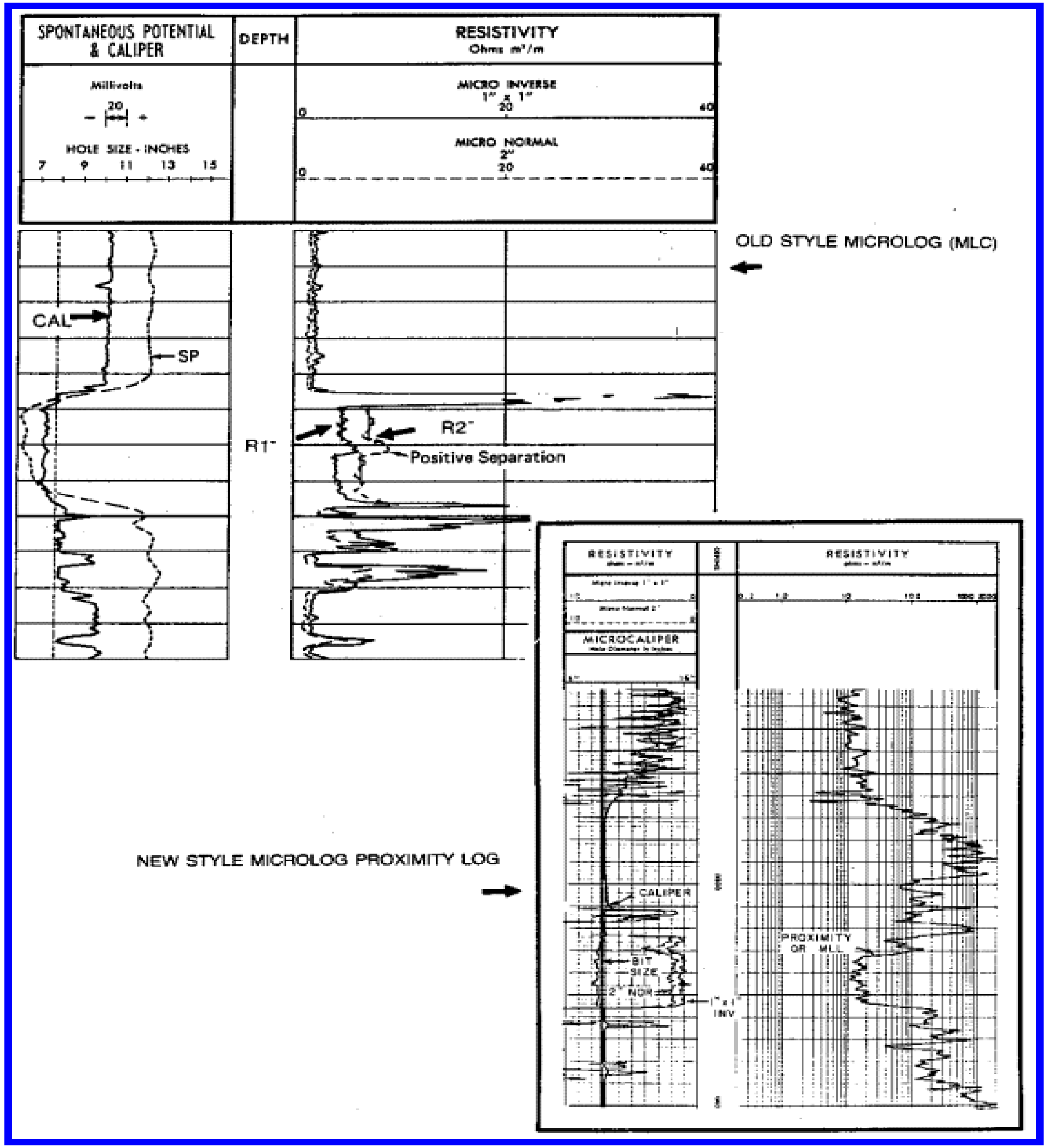
- $R_{2''} > R_{1''\times1''}$; bed is permeable; hydrocarbon is present.

2. Negative Separation

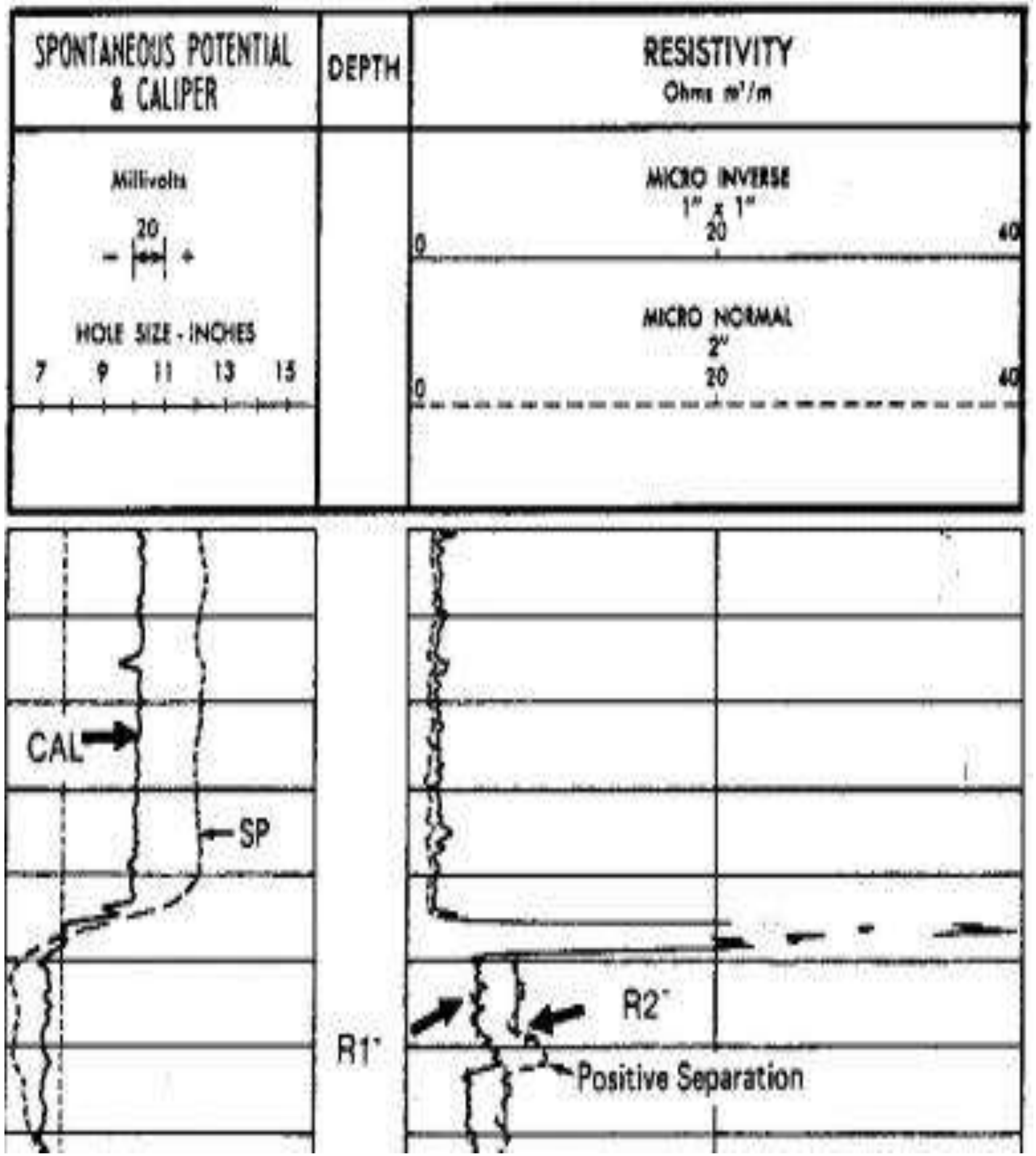
- $R_{1''\times1''} > R_{2''}$; observes opposite high porosity sand having good k_v ; zone of saline water bearing.

3. NO Separation

- $R_{2''} = R_{1''\times1''}$; It is a transition zone; signifies an impermeable bed (shale formation)



SPONTANEOUS POTENTIAL & CALIPER
DEPTH
RESISTIVITY
Ohms m²/m
Millivolts
20
HOLE SIZE - INCHES
7 9 11 13 15
MICRO INVERSE
1" x 1"
0 20 40
MICRO NORMAL
2"
0 20 40
CAL
SP
R1"
R2"
Positive Separation
OLD STYLE MICROLOG (MLC)
NEW STYLE MICROLOG PROXIMITY LOG
RESISTIVITY
RESISTIVITY
MICROCALIPER
CALIPER
BIT SIZE
2" NOR
1" x 1" INV
PROXIMITY OR MLL



SPONTANEOUS POTENTIAL & CALIPER
DEPTH
RESISTIVITY
Ohms m²/m
Millivolts
20
HOLE SIZE - INCHES
7 9 11 13 15
MICRO INVERSE
1" x 1"
0 20 40
MICRO NORMAL
2"
0 20 40
CAL
SP
R1"
R2"
Positive Separation

GAMMA RAY LOG

- The Gamma Ray log is measurement of the formation's natural radioactivity.
- Gamma ray emission is produced by three radioactive series (uranium, thorium, potassium) found in the Earth's crust.
- Gamma rays passing through rocks are slowed and absorbed at a rate which depends on the formation density.
- The gamma ray tool was the first nuclear log to come into service around 1930.
- Gamma ray logs are used primarily to distinguish clean, potentially productive intervals from probable unproductive shale intervals.
- The measurement is used to locate shale beds and quantify shale volume; because radioactive elements tend to concentrate in clay and shales.

- Unlike all other nuclear tools ϒ-ray is completely passive in that it emits no radiation.
- Instead, it simply detects incoming ϒ-rays from the formation.

➢ *Geiger-Muller Detectors*

➢ *Scintillating Crystal Detectors*

- Gamma rays are burst of high energy electromagnetic waves that are emitted spontaneously by some radio active elements (K40, Th232, U238) as they decay or disintegrate.

Principle of Gamma Ray Log

- In passing through matter, gamma rays collide with, and are scattered by, the atoms of the formation material.
- During this scattering process, known as ***Compton scattering***, the gamma rays lose energy with each collision.
- After the gamma ray has lost enough energy, it is absorbed, by means of the ***photoelectric effect***, by an atom of the formation.
- Thus, natural gamma rays are gradually absorbed and their energy reduced as they pass through the formation.
- The rate of absorption varies with formation density.

Gamma ray interactions with formations

- Gamma rays interact with formations in three different ways:

i. Compton scattering

ii. Photoelectric absorption

iii. Pair production (to a limited extent)

- One of these will dominate depending on the energy of the gamma ray

i. Compton Scattering

- This is the most important interaction for logging measurements which dominates in the middle energy range.
- It controls the transport of natural ϒ-rays through a formation to the standard ϒ-ray tool.
- Compton scattering is scattering off an atomic electron.
- In the process, the ϒ-ray loses some of its energy to the electron.

- Compton scattering is the dominant form of ϒ-ray interaction with a formation, from several hundred keV all the way to 10 MeV.

ii. Photoelectric (PE) Absorption

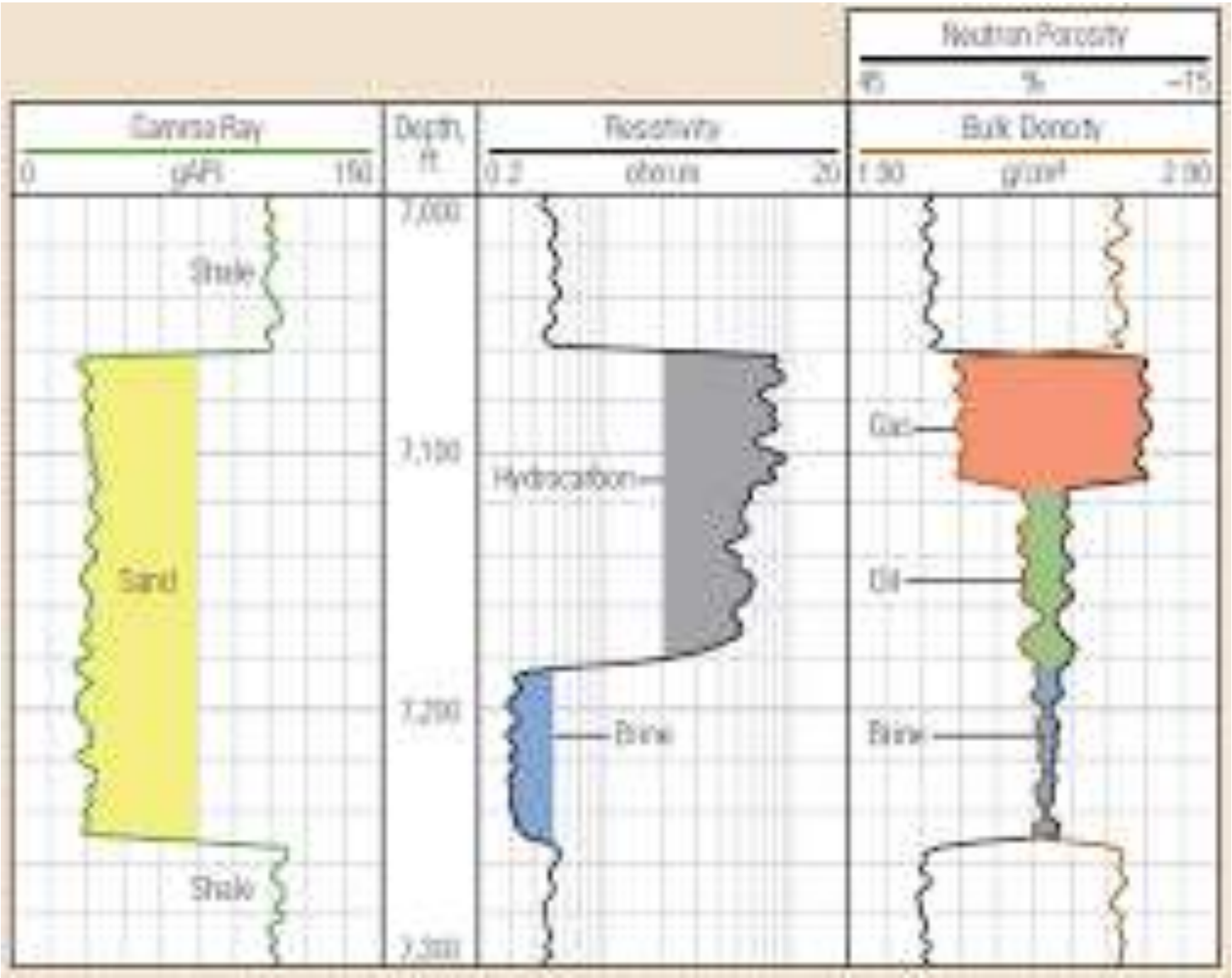
- Photoelectric absorption of ϒ-rays is the scattering process that dominates at low energy.
- In this process, the incoming ϒ-ray is absorbed by an atomic electron, giving up all its energy to the electron in the process.
- If the ϒ-ray is energetic enough, the added energy causes the electron to break free from its atom.
- PE Absorption is a significant factor in ϒ-ray scattering only for energies less than 100 keV.
- This means that it is easy to separate the effects of PE absorption from those of Compton scattering.
- The PE cross section falls off very strongly as the energy of the incoming gamma ray increases.

iii. Pair production

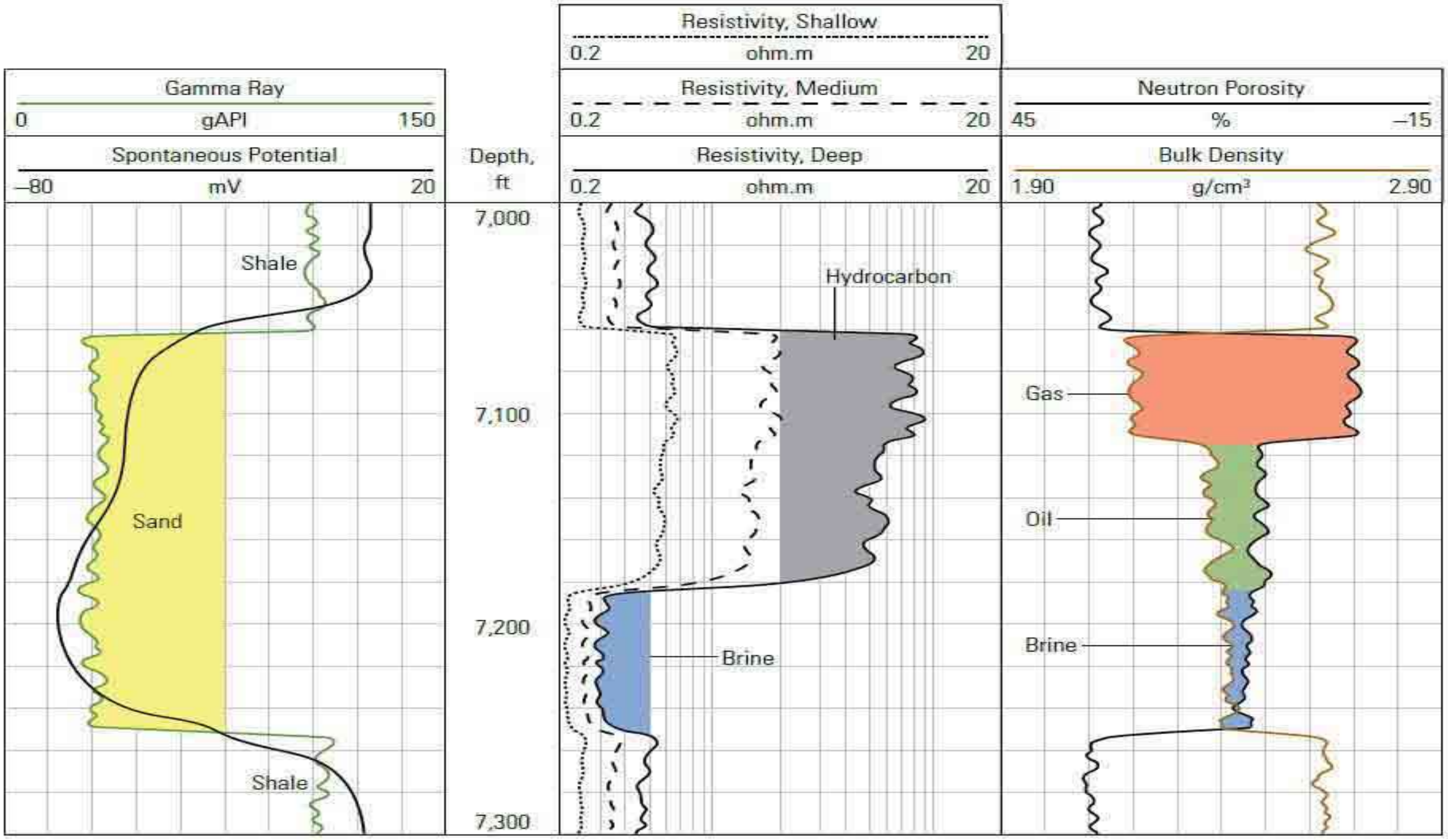
- This is the final process by which gamma rays interact with a formation, it has a minimal impact on logging measurements.
- This process, pair production, occurs only at very high gamma ray energies (threshold of 1.022 MeV).
- The incoming gamma ray interacts with the electric field of the nucleus and is absorbed if it has enough energy. This generates an electron-positron pair. The positron is quickly annihilated, yielding two 511-keV gamma rays.

Uses of Gamma Ray Logs

- General Lithology indicator
- Log Correlation – correlate core depths to log depth.
- Quantitative Shaliness evaluation
- Locate bed boundaries and thickness
- Gross and Net sand calculations



Neutron Porosity
45
%
−15
Gamma Ray
0
gAPI
150
Depth, ft
Resistivity
0.2
ohm·m
20
Bulk Density
1.90
g/cm³
2.90
7,000
7,100
7,200
7,300
Shale
Sand
Shale
Hydrocarbon
Brine
Gas
Oil
Brine



Gamma Ray
0
gAPI
150
Spontaneous Potential
–80
mV
20
Depth, ft
7,000
7,100
7,200
7,300
Resistivity, Shallow
0.2
ohm.m
20
Resistivity, Medium
0.2
ohm.m
20
Resistivity, Deep
0.2
ohm.m
20
Neutron Porosity
45
%
–15
Bulk Density
1.90
g/cm³
2.90
Shale
Sand
Shale
Hydrocarbon
Brine
Gas
Oil
Brine

GAMMA RAY INDEX CALCULATION

- Because shale is more radioactive than sand, gamma ray logs can be used to estimate volume of shale in porous reservoirs.
- The volume of shale can then be applied for the analysis of shaly sands.
- Calculation of gamma ray index is the first step needed to determine the volume of shale from gamma ray logs.

$$I_{GR} = \frac{GR_{\log} - GR_{\min}}{GR_{\max} - GR_{\min}}$$

- I_{GR} = Gamma ray Index
- GR_{min} = Gamma ray min (in clean sand)
- GR_{max} = Gamma ray max (in shale)
- GR_{log} = Gamma ray reading of formation

- **Larinov: older rocks, consolidated**

$$V_{sh} = 0.33\left[2^{(2\times I_{GR})} - 1.0\right]$$

- **Larinov: Tertiary rocks, unconsolidated**

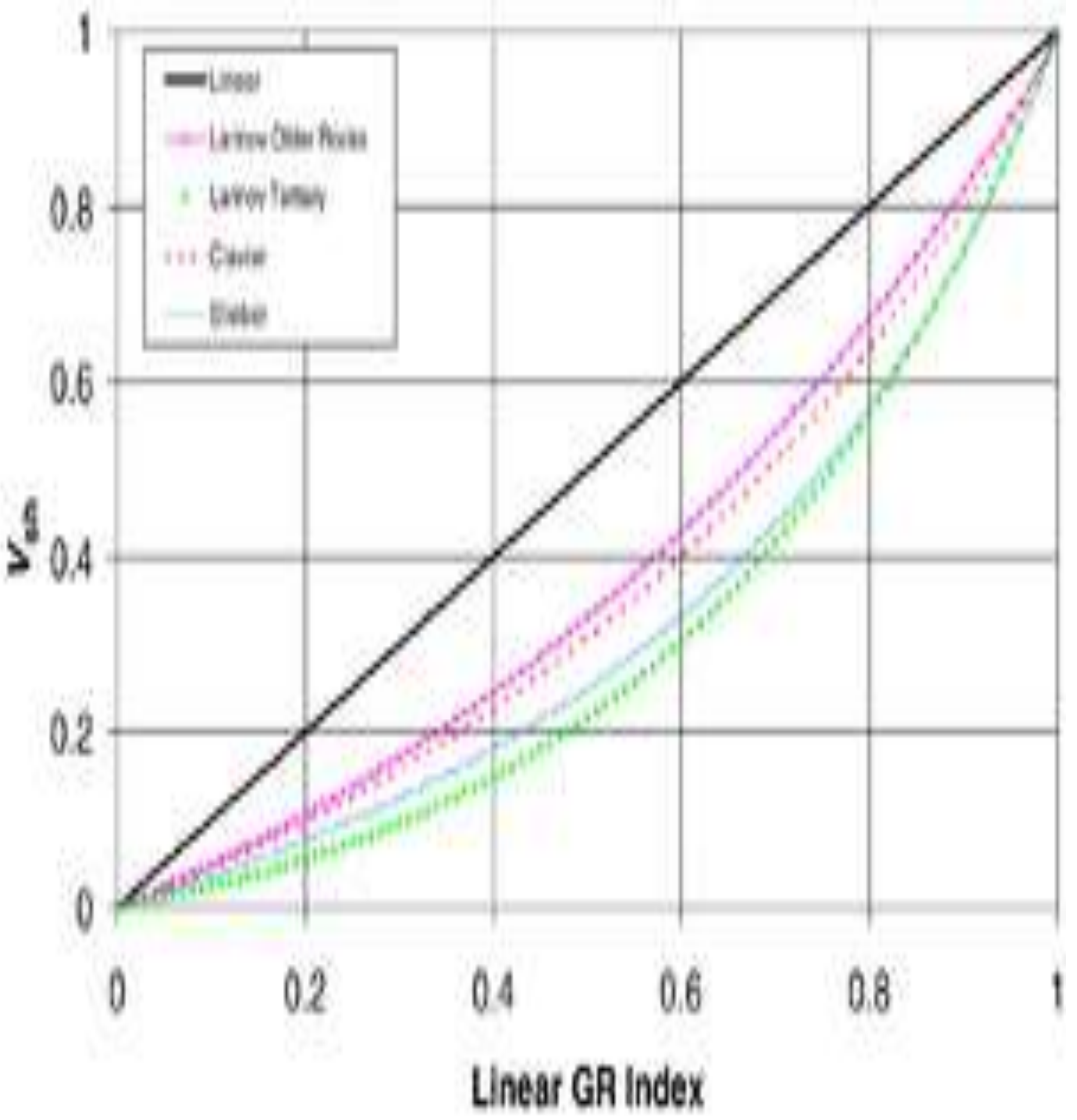
$$V_{sh} = 0.083\left[2^{(3.7\times I_{GR})} - 1.0\right]$$

- **Clavier**

$$V_{sh} = 1.7 - \left[3.38 - \left(I_{GR} + 0.7\right)^2\right]^{0.5}$$

- **Stiober**

$$V_{sh} = \frac{I_{GR}}{3 - 2I_{GR}}$$



POROSITY LOGS

- Porosity Logs measure the fraction of pore volume in a volume of rock.
- Most porosity logs use either **acoustic** or **nuclear** technology.
- Rock Porosity can be obtained from the **Sonic Log, Density Log** and/or **Neutron Log**.
- For all these devices, the tool response is affected by the formation porosity, fluid and matrix.
- If the fluid and matrix effects are known, the tool response can be related to porosity.

1. SONIC LOG

- To understand sonic log, we need to look at acoustics.
- Acoustics is defined as – a science that deals with the production, control, transmission, reception and effects of sound.
- Using acoustic to search for hydrocarbon is an offshoot of the science of earthquake seismology.

- **Acoustic Waves**
- These are pressure waves that propagate (move) through the earth at velocity that is dependent upon the characteristics and geometry of the formations
- These waves are recorded and analysed to estimate many properties of interest in the oil field.
- Acoustic waves propagate through a medium as wave fronts.
- There are three types of wave fronts:

i. Compressional Wave

- Also known as Primary or P-waves which move in the direction of particle displacement.

ii. Shear Wave

- Also known as Secondary or S-waves because they are a result of the P-wave propagation.
- They move in the direction perpendicular to the direction of particle displacement. They are slower than P-wave

iii. Stoneley Wave

- This is the slowest wave

- The **Sonic Log** is a porosity log that measures interval transit time or slowness (Δt) versus depth of a compressional sound wave travelling through one foot of formation.

- It is also called acoustic velocity log

- It is measured in µsec/ft

Sonic Equipment

- There are currently four sonic tools in use:

i. Borehole Compensated Tool (BHC)

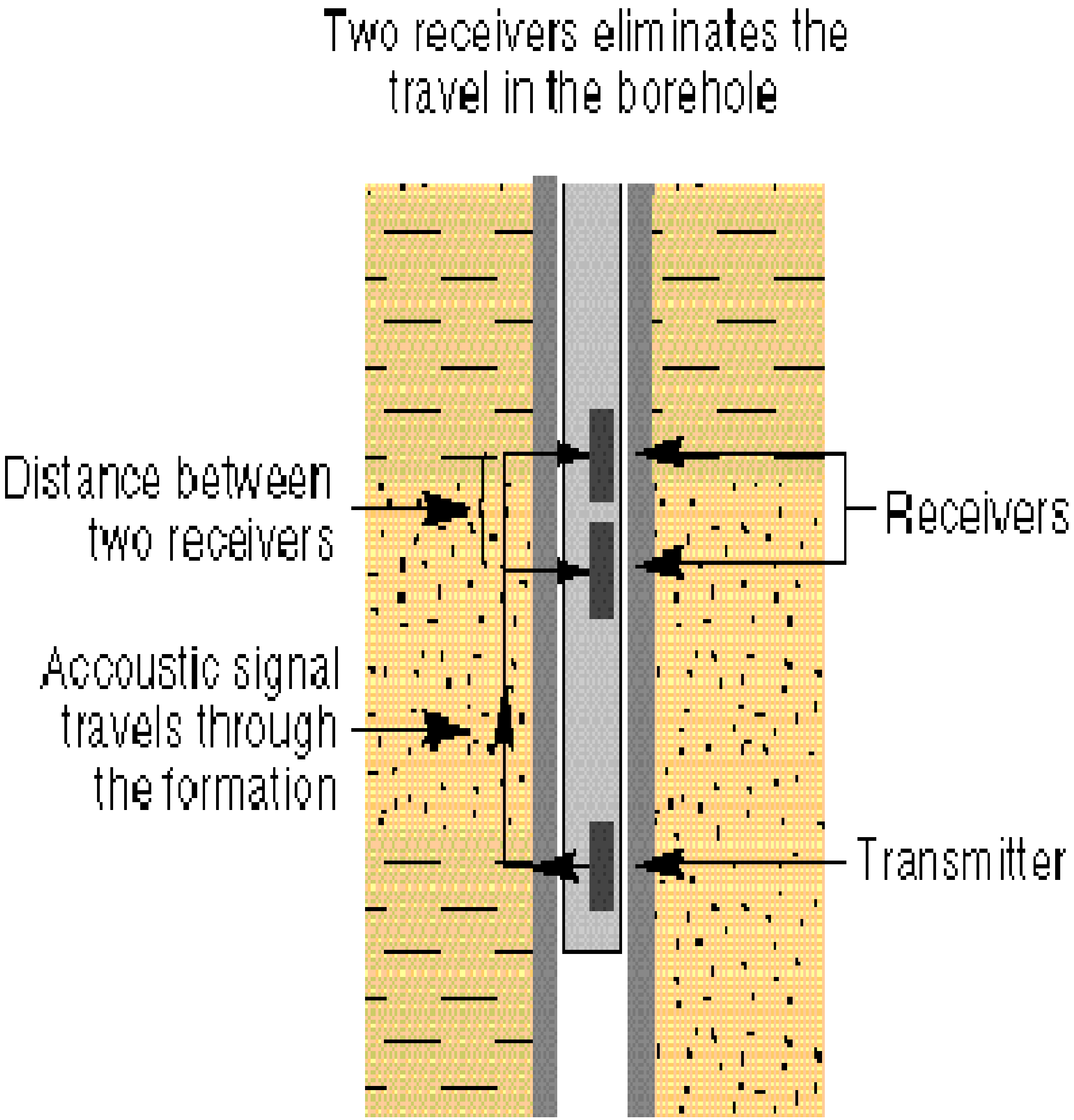
ii. Long-spaced Sonic Tool (LSS)

iii. Array-sonic Tool

iv. Diphole Shear Imager (DSI)

Principle

- A transmitter sends out sound pulse.
- The difference in arrival time of the pulse at two receivers which are 60cm apart is measured.
- A second transmitter and a pair of receivers measure the same physical parameter in the opposite direction.
- Averaging the two measurements eliminates the borehole effects on the travel time.
- P-wave is the first arrival at the receiver followed by S-wave and then Stoneley wave.



Working Equation

$$\Delta t_L = \phi S_{xo} \Delta t_{mf} + \phi (1 - S_{xo}) \Delta t_{hc} + V_{sh} \Delta t_{sh} + (1 - \phi - V_{sh}) \Delta t_{ma}$$

- If V_{sh} = 0 and if hydrocarbon is liquid (i.e. $\Delta t_{mf} \approx \Delta t_f$), then

$$t_{\log} = t_{ma} (1 - \phi) + t_f \phi$$

$$\boldsymbol{\phi_s = \frac{t_{log} - t_{ma}}{t_f - t_{ma}}}$$

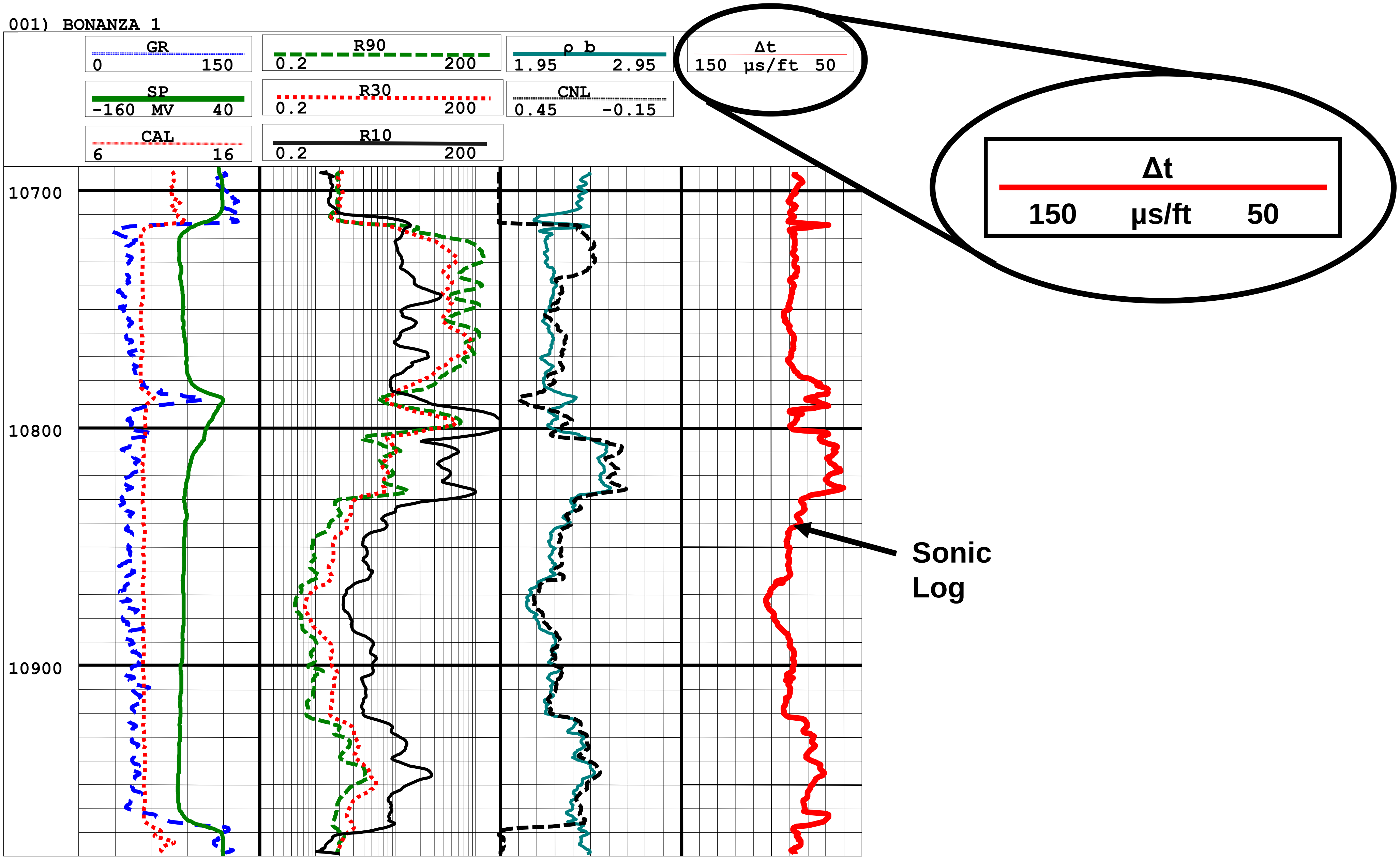
- The **interval transit time** of a formation is **increased due to the presence of hydrocarbons** (i.e. hydrocarbon effect) – causing ϕ_s to be too high.
- To correct for hydrocarbon effect, the following empirical relations are used:
- **ϕ_s x 0.9 = ϕ_t for oil**
- **ϕ_s x 0.8 = ϕ_t for gas**

Common Lithology Matrix Travel Time

Lithology	Typical Matrix Travel Time, Δt_{ma}, μsec/ft
Sandstone	55
Limestone	47
Dolomite	43
Anhydrite	50
Salt	67
Steel	57
Water	189

Factors affecting Sonic Log Interpretation

- Lithology
- Shale content
- Fluid type
- Compaction



001) BONANZA 1
GR
0 150
SP
-160 MV 40
CAL
6 16
R90
0.2 200
R30
0.2 200
R10
0.2 200
ρ b
1.95 2.95
CNL
0.45 -0.15
Δt
150 μs/ft 50
10700
10800
10900
Δt
150 μs/ft 50
Sonic Log

2. Density Log

- The formation density log is a porosity log that measures **electron density** and **photoelectric** captured cross section of a formation.
- Density logging tools uses gamma rays to measure bulk formation density in g/cc
- Each rock matrix (Lithology) has a characteristic density between 2-3 g/cc
- Fluids generally have a lower density between 0.2 - 1.0 g/cc

Principle

- The density logging device is a contact tool which consists of a medium energy gamma ray sources (Cobalt-60 or Celsium-137) that emits ϒ-ray into the formation.
- At each collision ϒ-ray losses some, but not all, of its energy to the electrons in the formation and continues with diminishing energy (Compton scattering interaction).
- The scattered ϒ-rays reached the detector at a fixed distance from the source are counted as an indication of formation density.

- The number of Compton scattering collisions is related directly to the number of electrons in the formation (i.e. electron density);
- Electron density is related to the true (formation) bulk density g/cc.
- True bulk density in turn depends on:

i. The density of the rock matrix material.

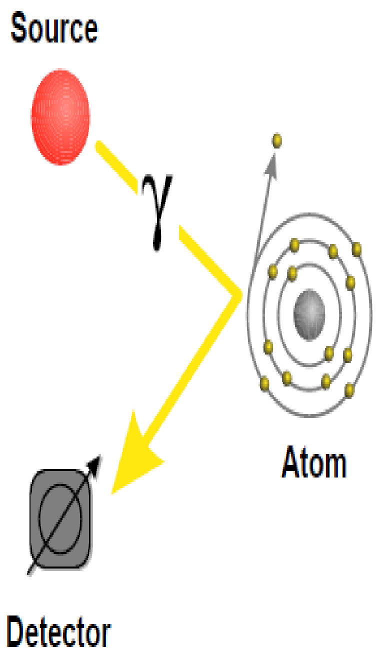
ii. Formation porosity

iii. The density of the fluids filling the pores (salt mud, fresh mud or hydrocarbons)

Bulk Density - Gamma Ray Interactions

How it works...

Compton Scattering



- Atomic Number "A" = number of Electrons/Protons
- Atomic weight depends on number of Protons + Neutrons = "Z"
- Probability of interaction depends on electron density only (A)
- Interaction most likely with high energy gamma rays
- High counts = low electron density
- Low electron density = low bulk density

Evaluation Technique

- Two inputs into the porosity equation are the matrix density and the fluid (mud filtrate) density.

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

$$\phi_d = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f}$$

Common Lithology Matrix Densities

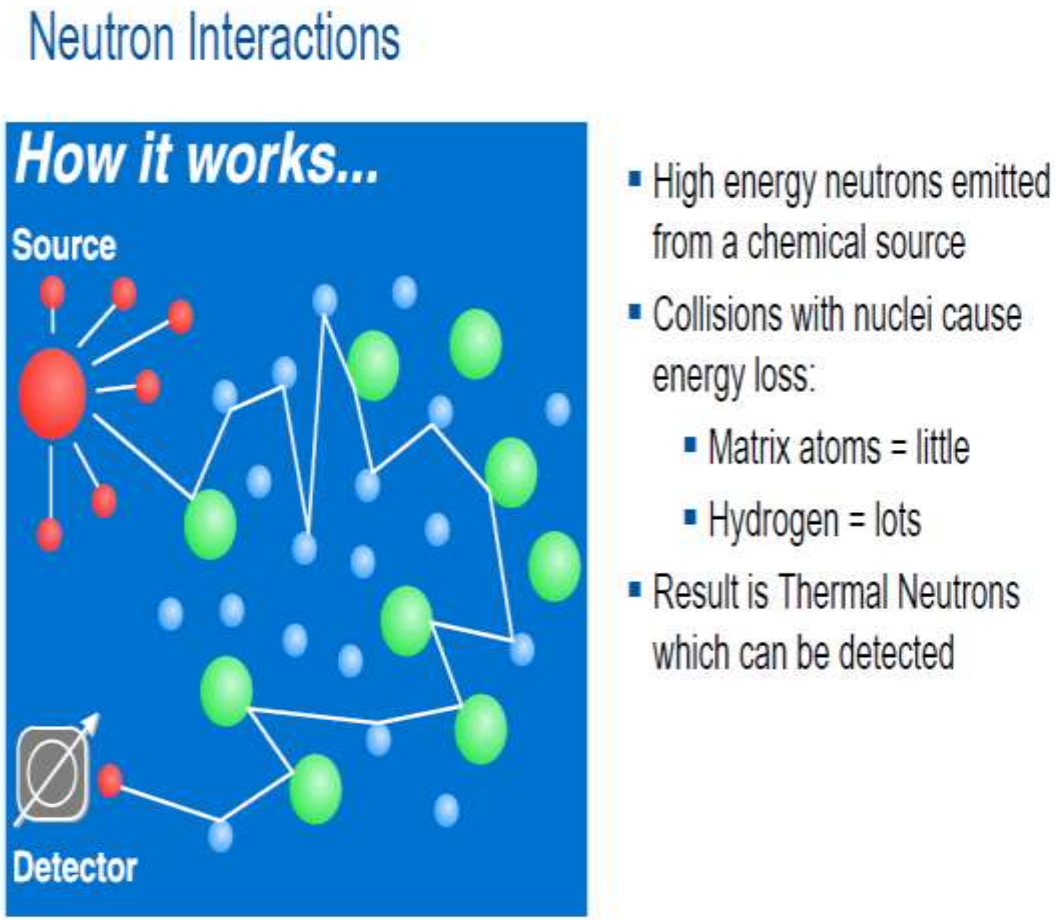
Lithology	Matrix Density (g/cc)
Sandstone	2.648
Limestone	2.710
Dolomite	2.876
Anhydrite	2.977
Salt	2.032

3. Neutron Log

- Neutrons are used to exite atoms by bombardment in well logging
- They have high penetrating power and are only significantly absorbed by hydrogen atoms
- This is an important property for well logging since the hydrogen atoms in formation fluids (hydrocarbons and water) are very effective in slowing neutrons.

NOTE

- Log calibrated and scaled in Limestone porosity units (In most areas)



Neutron Measurement Summary

How it works...

High energy neutrons emitted by source

↓

Collisions with hydrogen atoms in formation slow down the neutrons

↓

Slowed neutrons detected

The more hydrogen in the formation, the fewer the counts at the detectors.

The fewer the counts, the higher the porosity!

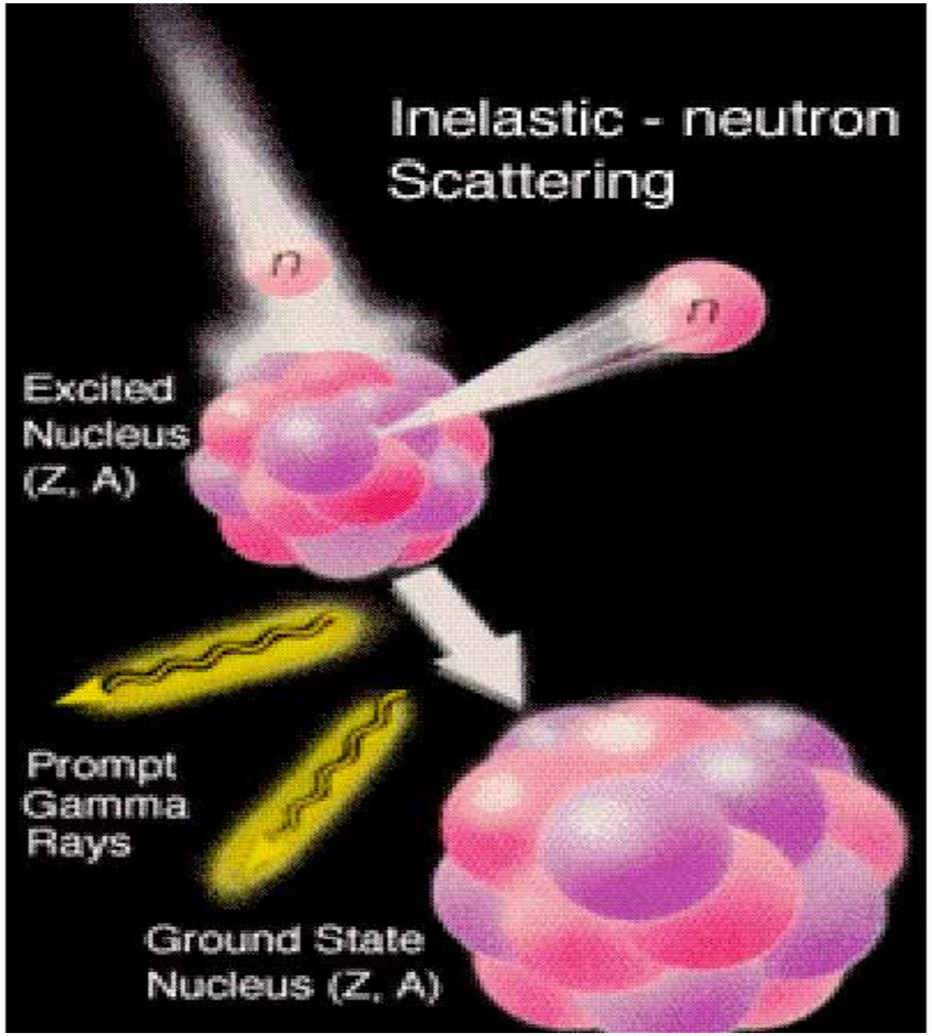
Applications

- Porosity Analysis
- Gas detection
- Borehole and formation salinity
- Specific element and mineral identification
- Reservoir monitoring

Neutron Interaction

1. Inelastic interactions

- These occur when a **neutron** is traveling fast (kinetic energy **above 1 MeV**) and
- Excites the nucleus to a higher internal energy state.
- Almost instantly, the nucleus falls back to its ground state, emitting **gamma rays at energies unique to the struck nucleus**.



- The energy spectrum of prompt gamma rays:

i. Is used to measure the relative concentration of Carbon (**C** due to hydrocarbons) & oxygen (**O** due to water) to determine **saturations** .

ii. It is also useful in identifying silicon (**Si**), calcium (**Ca**), iron (**Fe**), and sulfur (**S**) which can be used in determining **lithology.**

2. Elastic Interaction

- Neutrons can interact elastically regardless of their kinetic energy.
- With each interaction, sometimes referred as slowing down interaction, the neutron loses kinetic energy , imparting some to the bombarded nucleus , which, unlike during an inelastic interaction, remains in its ground state.
- This interaction can be thought of as a **billiard-ball collision** between a fast moving neutron and a stationary nucleus in the formation.
- The energy loss depends on the mass of the target nucleus relative to the neutron. Neutrons lose most energy when interacting with hydrogen (H) which has a mass equal to the neutron and is present primarily in formation fluids thus indicates porosity.
- **This principle is employed by all neutron porosity logging tools**

3. Thermal-Neutron Capture

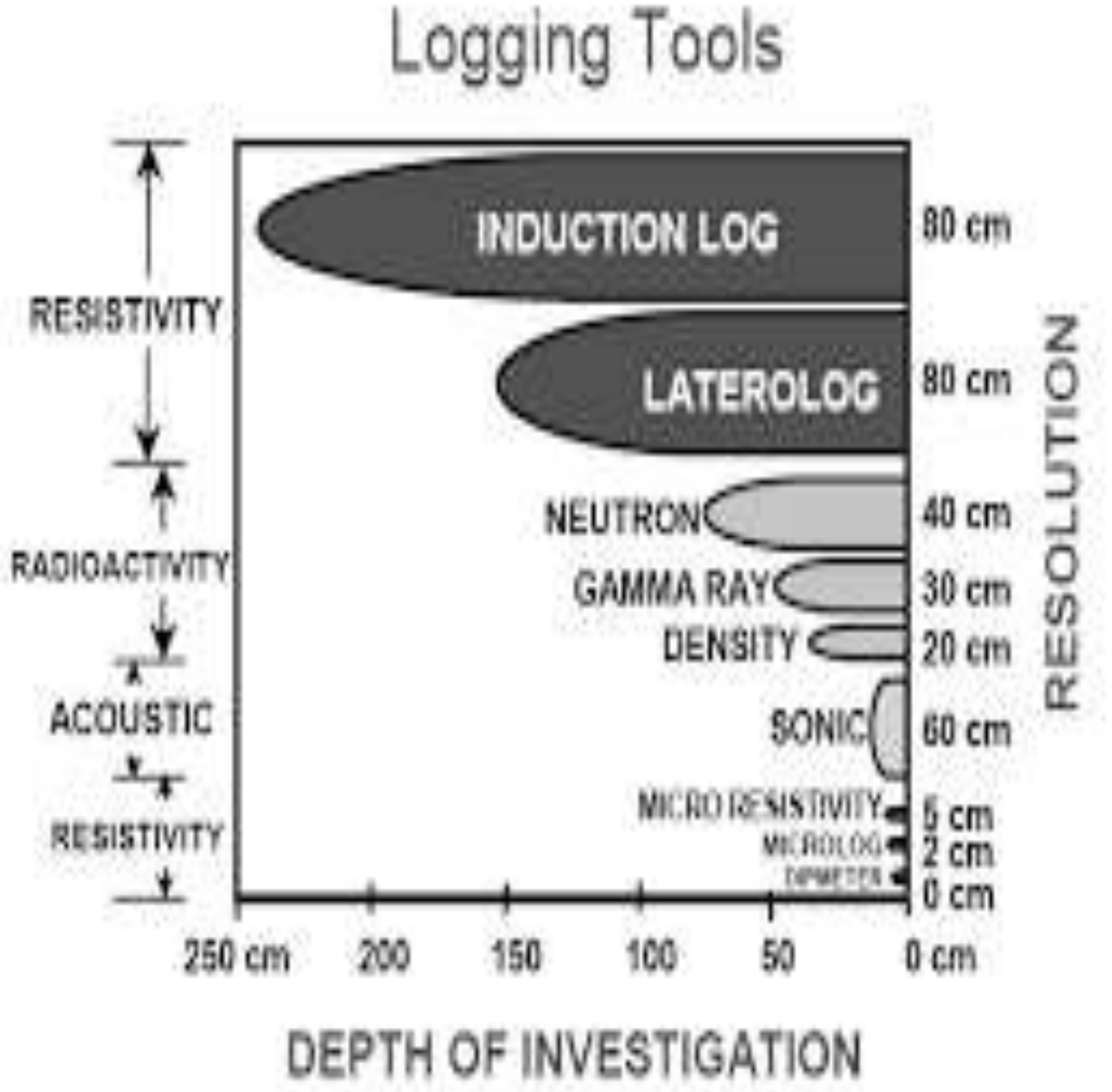
- Neutron absorption is most common after a neutron has been slowed, by inelastic & elastic scatterings, to thermal energies, about 0.025 eV at room temperature.
- This absorption called **thermal-neutron capture** may create a new isotope with exited nucleus which, immediately, emits capture gamma rays of unique energies.
- The rate of thermal-neutron absorption is used to indicate chlorine (**Cl**) which is the most efficient, abundant (**saline formation water**) thermal-neutron absorber

Neutron Sources

- **Chemical neutron logging sources** are still used in logging tools where relatively lower neutron energies are sufficient.
- The Americium Beryllium (AmBe) source used in these tools emit neutrons of energy from 1 to 10 MeV (peak around 4.5 MeV).
- All radioactive safety regulations must be followed (storage, transportation & handling).
- To follow the basic contamination rules ALARA (As Low As Reasonably Achievable) by minimising exposure time, maximising distance and maximising shields.

- A **minitron is an electronic neutron accelerator** which produces neutron pulses.
- A minitron typically emits eight times as many neutrons (108 neutrons per second) with three times as much energy (14 MeV) as a conventional source.
- minitrons are used for applications where inelastic prompt gamma rays as well as fast neutron activation delayed gamma rays are measured.
- On the safety point of view the advantage of the minitron is that it is only radioactive when minitron is switched on. Due to its high energy output the minitron should be switched off when tool is less than 150’ below rotary table.

LOGS RESOLUTION AND DEPTH OF INVESTIGATION



SHALY SAND ANALYSIS

Shaly Formations

- The responses of many well logs are affected by formation shaliness.
- As a result, the interpretation for shaly formations becomes somewhat more involved than for clean formations.
- This is because of the high frequency of occurrence of **shaly sands** in sand-shale sequences.
- Shales are one of the more important common constituents of rocks in log analysis.
- Aside from their effects on porosity and permeability, their importance stems from their electrical properties, which have a great influence on the determination of fluid saturations.
- **Shales** are loose, plastic, fine-grain mixtures of clay-sized particles or colloidal particles.

- They often contain a high proportion of clay minerals.
- Most clay minerals are structured in sheets of alumina-octahedron and silica-tetrahedron lattices.
- There is usually an excess of negative electrical charges (anions) within the clay sheets.
- This local electrical imbalance must be compensated for to maintain the electrical neutrality of the clay particle.
- The compensating agents are positive ion (cations) which clings to the surface of the clay sheets in a hypothetical dry state.
- When the particles are immersed in water, the coulomb forces holding the positive surface ions are reduced by the dielectric properties of water.
- The cations leave the clay surface and move relatively freely in a layer of water close to the surface and contribute to the conductivity of the rock.

- Since Archie's water saturation that relates rock resistivity to water saturation assumes that the formation water is the only electrically conductive material in the formation.
- The presence of another conductive material (i.e. shale) requires either that the Archie equation be modified to accommodate the existence of another conductive material, or,
- That a new model be developed to relate rock resistivity to water saturation in shaly formations.
- The layer of closely bound surface water on the clay particle can represent a significant amount of porosity.
- However, this porosity is not available as a potential reservoir for hydrocarbons.
- Thus, a shale or shaly formations may exhibit a high **total porosity** yet it has a **low effective porosity** as a potential hydrocarbon reservoir.
- The way shaliness affects log reading depends on:

- The proportion / amount of shale
- Shale physical properties
- The way shale is distributed in the formation.
- Note: Responses of the radioactivity tools (Gamma ray, density, neutron, Thermal neutron decay time) are not affected by the way the shale is distributed.
- Inspection of cores reveal that shaly material may be distributed in the formation in **three** possible ways.

1. Laminar Shale

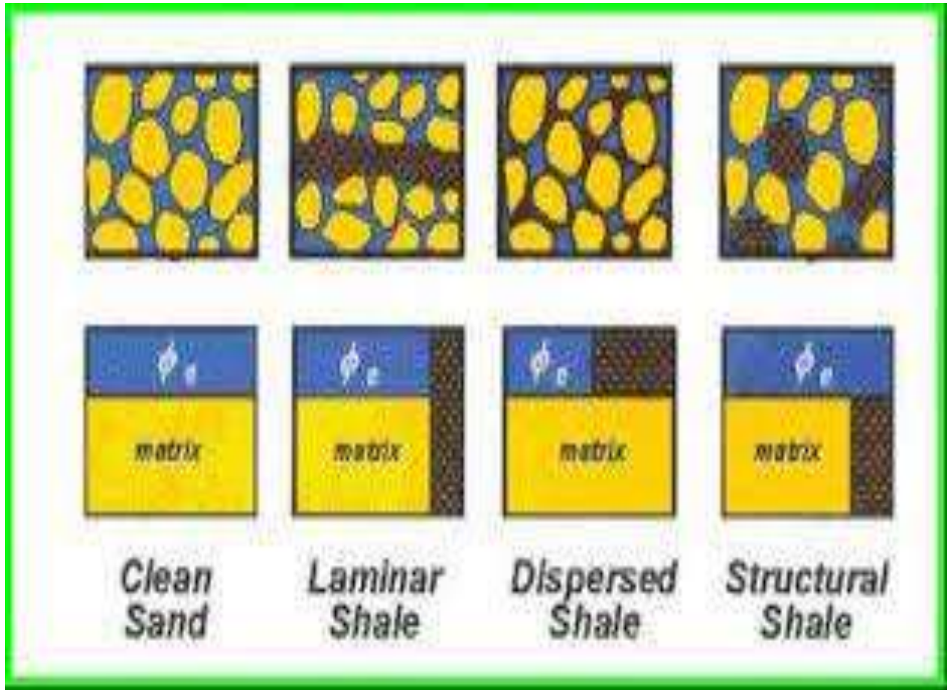
- Shale may exist in the form of laminae between which are layers of sand. The laminae shale does not affect the porosity or permeability of the sand streaks.
- But when the proportion of laminar shale is increased and decreasing the amount of porous medium, overall average effective porosity is reduced in proportion.
- It is subjected to overburden pressure.

2. Dispersed Shale

- The shaly material may be dispersed throughout the sand, partially filing the intergranular interstices.
- The dispersed shale may be in the form of accumulations adhering to or coating the sand grains or it may partially fill the smaller pore channels.
- It reduces the permeability of the formation
- It is subjected to only hydrostatic pressure, hence, contain more bound water.

3. Structural Shale

- This is when shale exist as grains or nodules in the formation matrix.
- It is has properties similar to those of laminar shale



Clay or Shaliness Indicators

- Clay or shaliness indicators have qualitative use to indicate whether the formation is clean or shaly.
- These indicators are more useful if they can provide quantitative estimate of the clay fraction in the formation.
- They then make it possible to estimate the shaliness effect on the log readings and to correct them to the clean formation readings.

- The clay or shaliness indicators are:

i. The SP log
ii. The Resistivity log
iii. Gamma ray log
iv. Q-log
v. Sonic-Density Crossplot
vi. Neutron-Density Crossplot

Shaly Sand Evaluation

- The presence of shale (i.e. clay minerals) in a reservoir can cause erroneous values for water saturation and porosity derived from logs.
- These erroneous values are not limited to sandstones, but also occur in limestones and dolomites.
- Whenever, shale is present in a formation, all the porosity tools (sonic, density and neutron) will record too high a porosity.
- The only exception to this is the density log which will not record too high porosity if the density of shale is equal to or greater than the reservoir's matrix density.
- Also, the presence of shale in a formation will cause the resistivity log to record too low a resistivity.
- Note that all shaly sandstone formulas reduce the water saturation value from the value that would be calculated if shale effect was ignored.

- This lowering of water saturation can be a problem in log evaluation.
- If an engineer or Geologist overestimates of shale content, a water-bearing zone may calculate like hydrocarbon zone.
- The first step therefore, in shaly sand evaluation or analysis is to determine the volume of shale (V_{sh}) from a gamma ray log.
- The V_{sh} determined is then used to correct the porosity log for shale effect.

- Sonic Log

$$\phi_{sonic} = \left(\frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \times \frac{100}{\Delta t_{sh}} \right) - V_{sh} \left(\frac{\Delta t_{sh} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \right)$$

- Density Log

$$\phi_{Density} = \left(\frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \right) - V_{sh} \left(\frac{\rho_{ma} - \rho_{sh}}{\rho_{ma} - \rho_f} \right)$$

- Neutron-Density Log

$$\phi_{N\_Corrected} = \phi_N - \left(\frac{\phi_{N\_Clay}}{0.45} \times 0.30 \times V_{sh} \right)$$

$$\phi_{D\_Corrected} = \phi_D - \left(\frac{\phi_{D\_Clay}}{0.45} \times 0.13 \times V_{sh} \right)$$

$$\phi_{N-D} = \sqrt{\frac{\phi^2_{N\_Corrected} + \phi^2_{D\_Corrected}}{2}}$$

- After the volume of shale has been determined and the log derived porosity has been corrected for volume of shale, the water saturation can then be calculated using the following correlations:

- **Simandoux (1963)**

$$S_w = \left(\frac{0.4R_w}{\phi^2} \right) \times \left[\frac{V_{sh}}{R_{sh}} + \sqrt{\left(\frac{V_{sh}}{R_{sh}} \right)^2 + \frac{5\phi^2}{R_t \times R_w}} \right]$$

- **Fertl (1975)**

$$S_w = \frac{1}{\phi} \times \left[\sqrt{\frac{R_w}{R_t} + \left(\frac{a \times V_{sh}}{2} \right)^2} - \frac{a \times V_{sh}}{2} \right]$$

- **Schlumberger (1975)**

$$S_w = \frac{-\frac{V_{sh}}{R_{sh}} + \sqrt{\left(\frac{V_{sh}}{R_{sh}} \right)^2 + \frac{\phi^2}{0.2 R_w \times (1.0 - V_{sh}) R_t}}}{\frac{\phi^2}{0.4 R_w \times (1.0 - V_{sh})}}$$

- **Waxman' Smith**

$$S_w^{-n*} = \left[\frac{R_t}{R_w} \times \phi^{m*} \times \left(1 + \frac{R_w B Q_v}{S_w} \right) \right]$$

- B is a constant related to temperature
- Q_v is cation exchange capacity (CEC) per unit pore volume
- m^* and n^* are cementation factor and saturation exponent, respectively.

CROSS PLOTS

Cross Plots

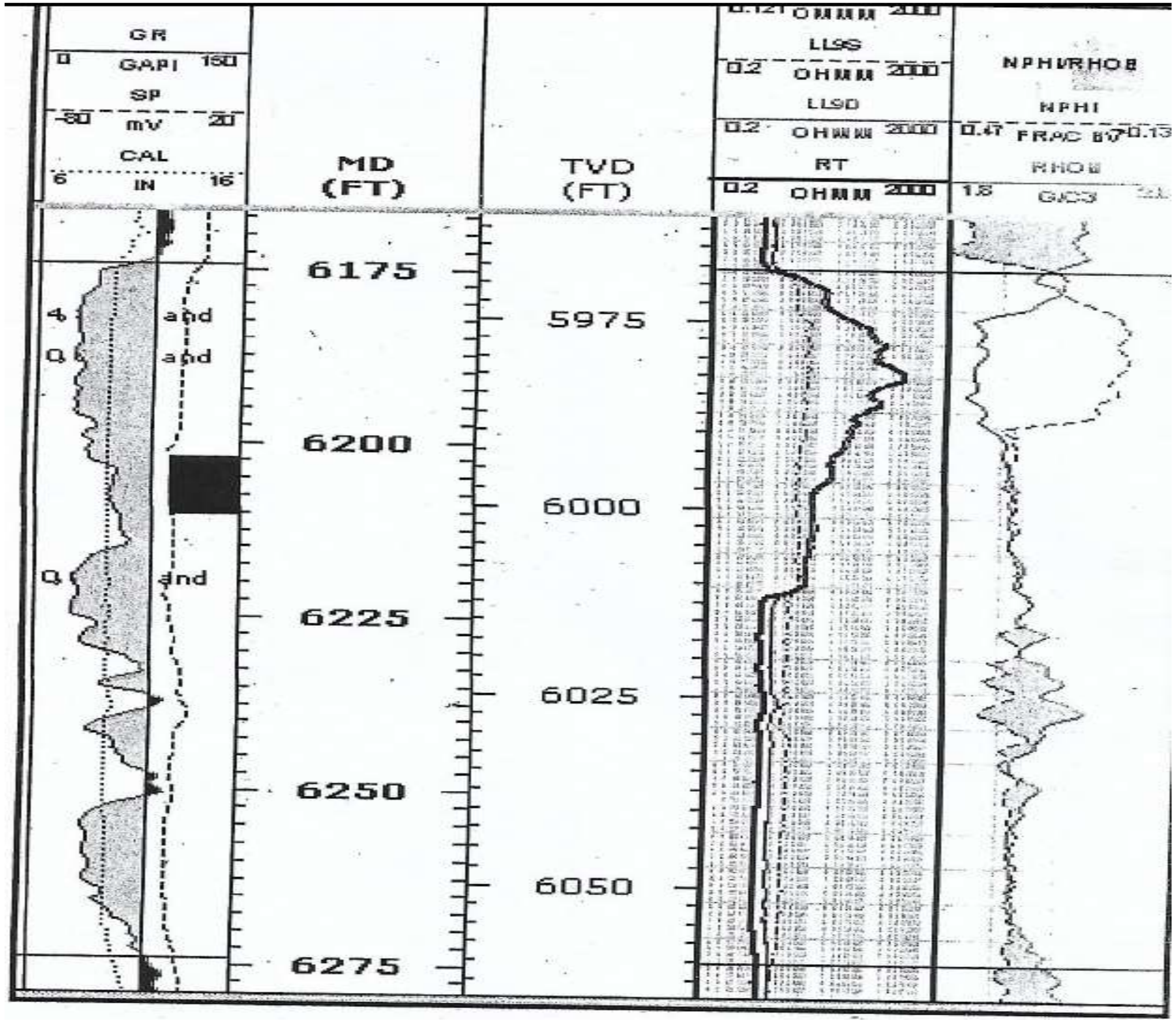
- Are a convenient way to demonstrate how various combinations of logs respond to porosity and lithology
- they provide insight into the type of mixtures that the combination is most useful in unravelling

Porosity determination

- The measurements of the sonic, density and neutron logs depends on porosity, formation lithology, the fluid in the pores and in some instances on the geometry of the pore structure.
- When the lithology or matrix are known, correct porosity values can be derived from these logs.

Neutron-Density Log

- Once the hydrocarbon bearing zones in reservoir intervals have been identified from resistivity log.
- The next step is to differentiate between oil and gas.
- Zones with high N-D separation are identified as gas bearing.
- Zones with little N-D separation are identified as oil bearing.
- Zones with no separation in N-D log is water bearing.



- Accurate porosity determination is more difficult when the matrix lithology is unknown or consists of two or more minerals in unknown proportions.
- Also, porosity determination is further complicated by the type of pore fluids other than water in the formation investigated e.g. light hydrocarbons can significantly influence the response of all three porosity logs.
- The nature and type of pore structure also affects tool response.
- Determination of porosity at the occurrence of any of these complicating situation by a single porosity log is inadequate.
- Sonic, density and neutron logs respond differently to matrix minerals, to the gas or light oils and to the geometry of pore structure.
- Hence, the combination of these logs can be used to unravel complex matrix or fluid mixtures and as a result provide a more accurate porosity determination

- If a formation consists of only two known minerals in unknown proportions, the combination of density and neutron logs or the combination of bulk density (ρ_b) and photo electric logs will define the proportions of the two minerals and a better value of porosity.
- **Go through Charts CP 1a – 21 for:**

i. Porosity determination

ii. Mineral proportions

- Neutron-Density cross Plots
- M-N Plot
- MID Plots

MODERN LOGGING TOOLS IN CASED HOLE

- Thermal Decay Time (TDT) log
- Nuclear Magnetic Resonance (NMR) log
- Temperature Log
- Photo Electric Factor (PEF) log
- Neutron Logs

Thermal Decay Time (TDT) Log

- The thermal decay time (TDT) log is based on a measurement of the rate of decay (absorption) of thermal neutrons in a formation.
- Chlorine is by far the strongest neutron absorber of the common earth elements, and the thermal neutron decay time, T, is determined primarily by the sodium chloride present in the formation water.
- Like the resistivity log, therefore, the thermal neutron decay time measurement is sensitive to the salinity and amount of formation water present in the pore volume.
- Unlike the resistivity log, **this log can be run in cased hole**.
- Also, the TDT log is relatively unaffected by drilling and completion conditions for the usual borehole and casing sizes encountered over pay zones.
- This log can detect the presence of hydrocarbons in formations that have been cased, as well as changes in water saturation during the production life of the well.
- The log is thus useful for evaluating oil wells, for diagnosing production problems, and for following reservoir performance.