



UNIVERSITY OF OSLO  
FACULTY OF MATHEMATICS AND NATURAL SCIENCES

# GEO4250 Reservoir Geology

Basic Well Log Analysis

# Objectives

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To give an insight in the basic well logging methods used to derive petrophysical properties for hydrocarbon exploration



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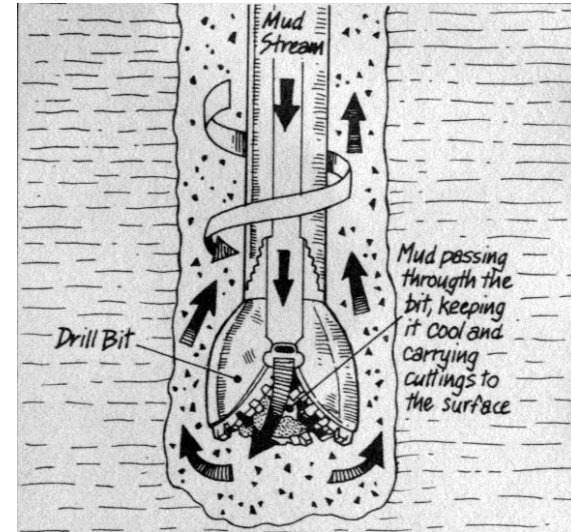
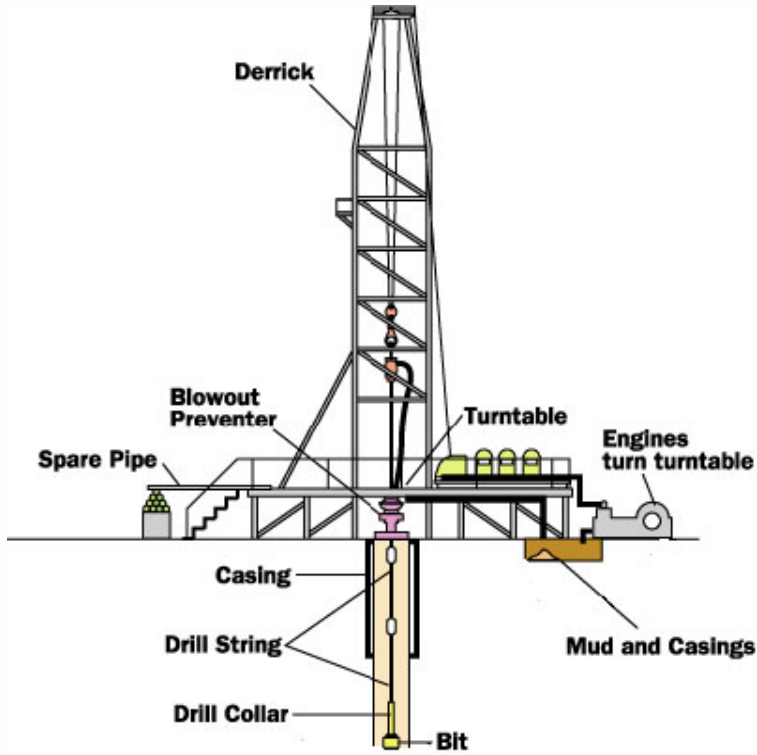
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# Further Reading

- Asquith, G. and Krygowski, D. 2004. Basic Well Log Analysis, 2nd edition. *AAPG Methods in Exploration Series*, 28, 244pp (incl CD)
- Schlumberger, 1989. Log Interpretation Principles/Applications (available through Classfronter)
- Krygowski, D. 2003. Guide to Petrophysical Interpretation. (available through Classfronter)



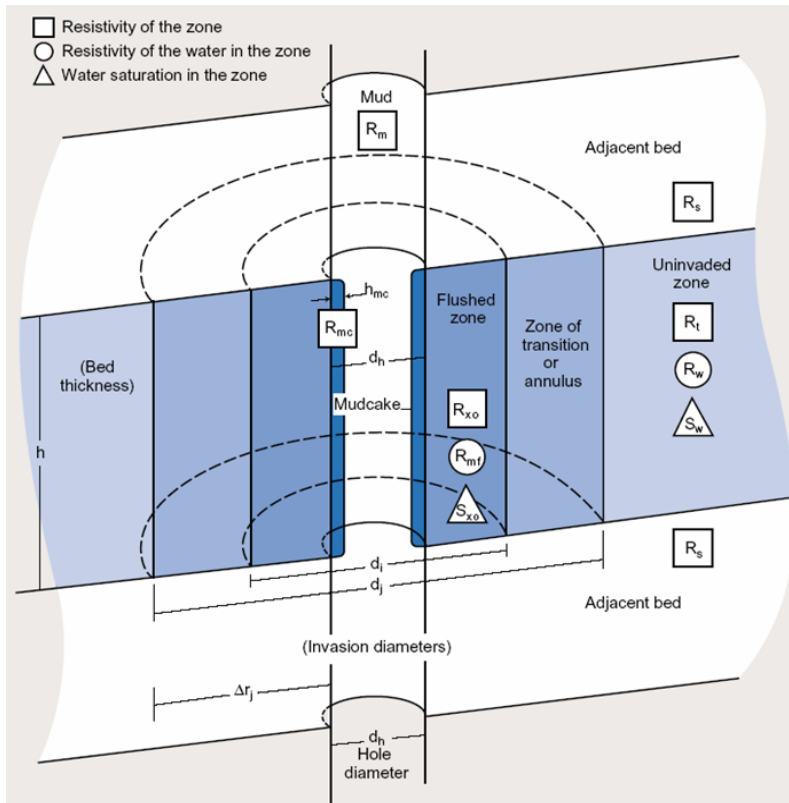
# The borehole



During drilling a liquid mixture containing clays and other natural materials, called **'Mud'** is pumped down the drill string forcing the rock cuttings up to the surface. These cuttings are analysed for indications of oil or gas.



# Invasion

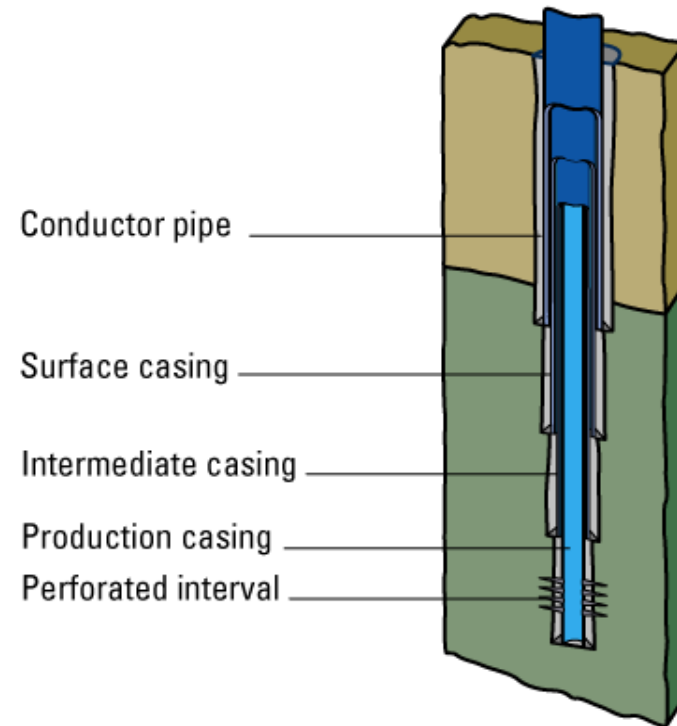


- Hydrostatic pressure of the mud column is usually greater than the pore pressure of the formations
- This forces mud filtrate into the permeable formations and a mud cake on the borehole wall
- The mud cake reduces further infiltration
- Establishment of a
  - Flushed zone
  - Transition zone or Annulus
  - Noninvaded, virgin or uncontaminated zone

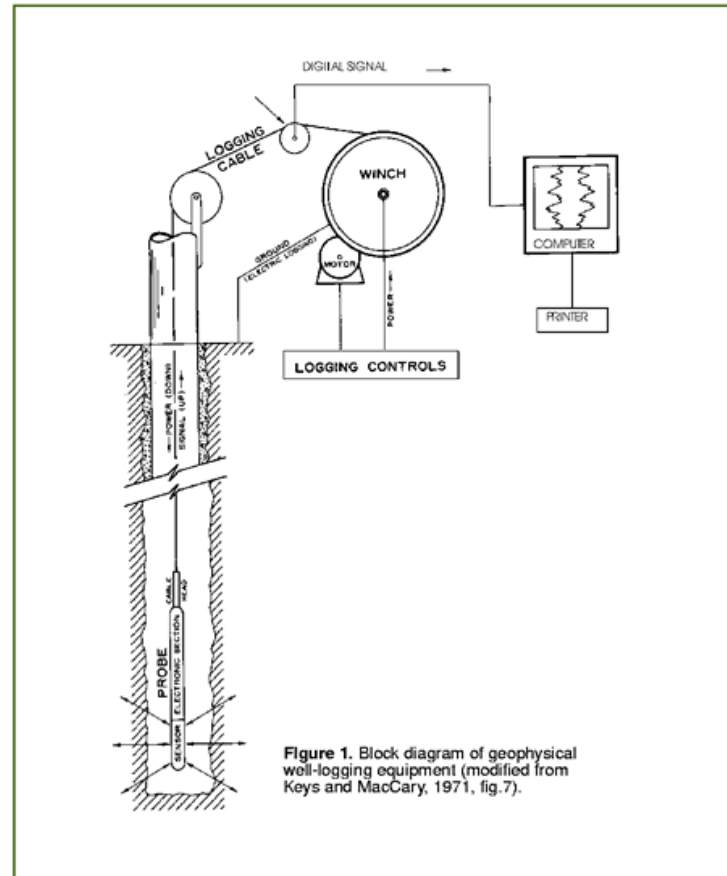


# Open Hole Logs

- Logs recorded in the uncased portion of the well bore
- Most frequently used in HC exploration
- Cased Hole:
  - The portion of the wellbore that has had metal casing placed and cemented to protect the openhole from fluids, pressures, wellbore stability problems or a combination of these



# Logging





# Logging

- Three general types of logs:

- Electrical

e.g.

- Spontaneous Potential
- Resistivity

- Nuclear

e.g.

- Gamma Ray
- Density
- Neutron

- Acoustic / Sonic

e.g.

- Transit time

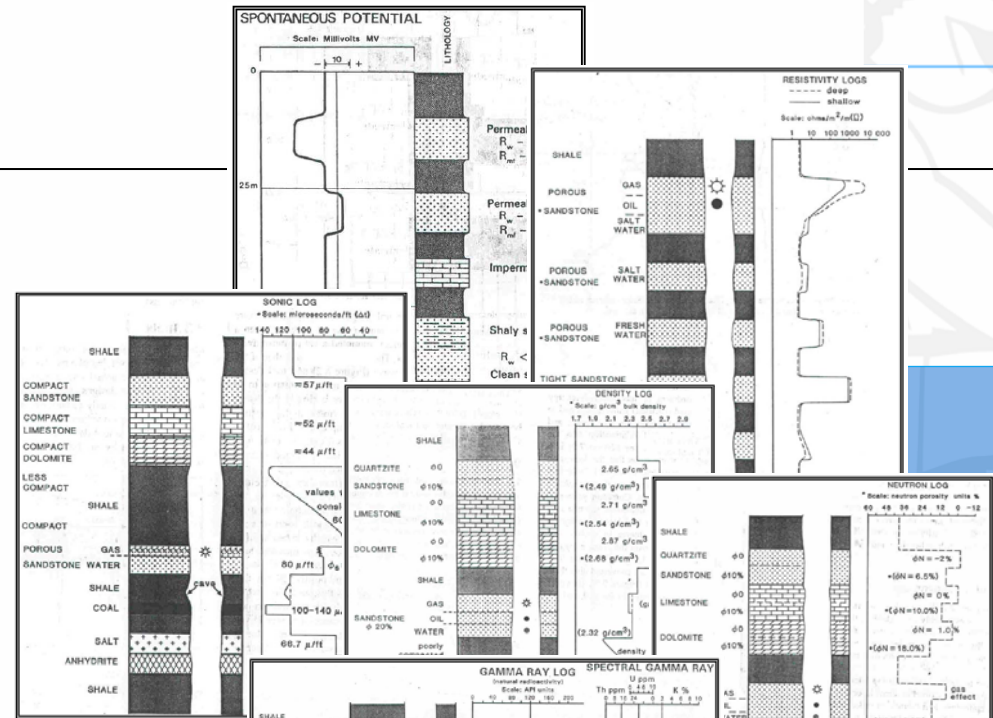


Figure 5-5. Idealized

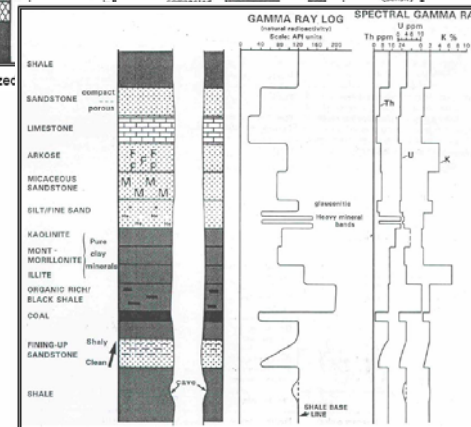


Figure 5-4. Idealized GR and SGR log.

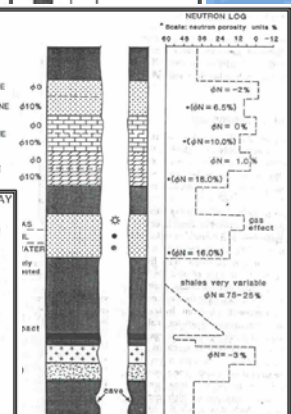


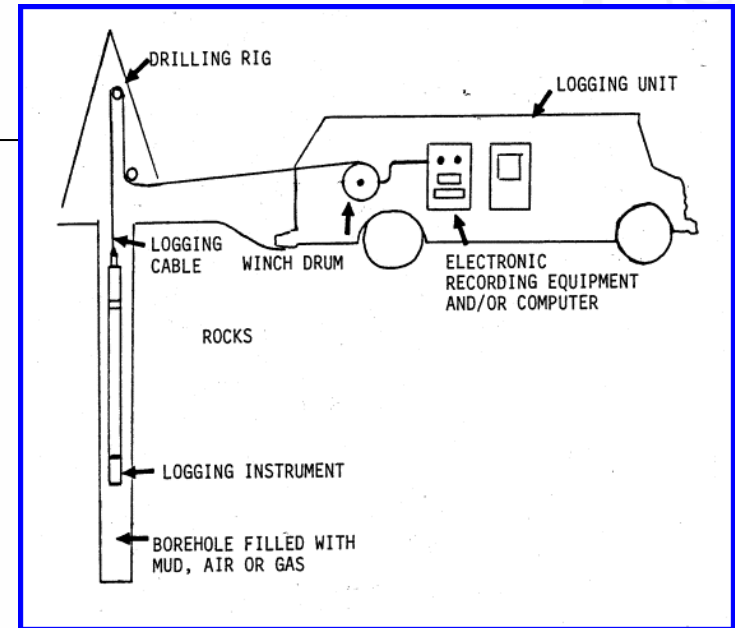
Figure 5-7. Idealized Neutron log.





# Importance of Geophysical Well Logging

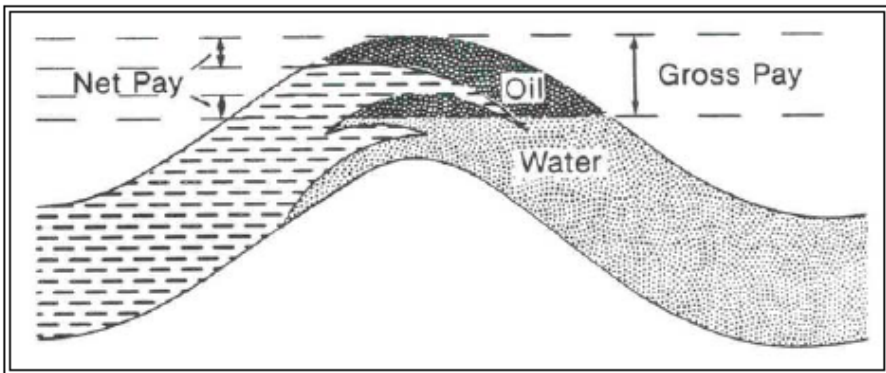
- Zone correlation
- Structure and Isopach mapping
- Defining physical rock characteristics:
  - Lithology
  - Porosity
  - Pore geometry
  - Permeability
- Identification of productive zones
- Determination of depth and thickness of zones
- Distinguish between oil, gas and water
- Estimation of hydrocarbon reserves
- Determination of facies relationships



# Hydrocarbon Reserves

$$N_p = \phi_e S_o h A r$$

$$S_o = 1 - S_w$$



- $N_p$  = Oil Reserves (*stb*)
- $\phi_e$  = effective porosity (*fraction*)
- $S_o$  = Oil saturation (*fraction*)
- $h$  = productive interval thickness (*m/ft*)
- $A$  = drainage area (*acres*)
- $r$  = Recovery Factor



# Logging

- Rock properties that affect logging measurements:
  - Porosity
  - Lithology
  - Mineralogy
  - Permeability
  - Water Saturation
  - Resistivity



# How to measure these properties?

- Unfortunately, few of these petrophysical parameters can be directly measured!
- Derived or inferred from measurements of other physical parameters, such as:

- Resistivity
- Bulk density
- Interval transit time
- Spontaneous potential
- Natural radioactivity
- Hydrogen content of the rock

Wireline well logging



# Porosity

- Defined as the ratio of voids to the total volume of rock. Symbol  $\phi$ , fraction or %

$$\text{porosity, } \phi = \frac{\text{volumes of pores}}{\text{total volume of rock}}$$

- **Total porosity:** total amount of voids in the rock volume
- **Effective porosity:** the amount of void space that is interconnected, and thus able to transmit fluids
- Roughly:  $\phi_e = \phi_t \times (1 - Vsh)$
- **Primary porosity:** The porosity preserved from deposition through lithification.
- **Secondary porosity:** The porosity created through alteration of rock, commonly by processes such as dolomitization, dissolution and fracturing



# Lithology and Mineralogy

- *Lithology* and *Mineralogy* used with some ambiguity
- Lithology is often used to describe the solid matrix, primary mineralogy
- Advanced logging techniques make it possible to estimate mineralogy pairs or triads
- Nuclear measurements made on molecular-level interaction: *Mineralogy*
- Acoustic measurements made on bulk-level interactions: *Lithology*
- Shale and clay are also used with ambiguity





# Permeability

- Is the ability of a rock to transmit fluids
- Symbol: K
- Measured in darcys or millidarcys ( $1 \text{ darcy} = 9.8697 \times 10^{-13} \text{ m}^2$ )
- Related to porosity but not always dependent
- Controlled by the size of the connecting passages between the pores
- Formation waters, held by capillary pressure, may reduce the permeability



# Water Saturation

- The amount of pore volume in a rock that is occupied by formation water. Symbol  $S_w$ , fraction or %

$$\text{water saturation, } S_w = \frac{\text{formation water occupying pores}}{\text{total pore space in the rock}}$$

- Hydrocarbon saturation can be determined by the difference between unity and water saturation

$$S_h = 1 - S_w$$

- Irreducible water saturation ( $S_{w\text{ irr}}$ ) is the term used to describe the water saturation at which all the water is adsorbed on the grains in a rock or is held in the capillaries by capillary pressure



# Resistivity

- Rock property on which the entire science of logging first developed
- Is the inherent property of all materials, regardless of their size and shape, to resist the flow of an electric current
- **Resistance** depends on size and shape
- Resistivity is the reciprocal of conductivity
- Hydrocarbons, rock and fresh water are highly resistive
- Salt water is highly conductive



# Resistivity

- Symbol R, measured in  $\Omega \cdot m$  (ohm·m<sup>2</sup>/m)

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

- With r = resistance; A = area of substance being measured; L = length of substance
- Resistivity is a basic measurement of a reservoir's fluid saturation and is a function of porosity, type of fluid, amount of fluid and type of rock



# Archie's Principle

Experiments (Archie, 1942) show:

- $S_w$  = Water saturation
- $F$  = Formation Resistivity Factor ( $a/\phi^m$ ):
  - Porosity ( $\phi$ )
  - 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
- $R_0$  = Resistivity of the 100% water-saturated rock
- Where there is no knowledge of local parameters the following values can be used:  $n = m = 2.0$ ;  $a = 1.0$

$$R_0 = F \times R_w$$

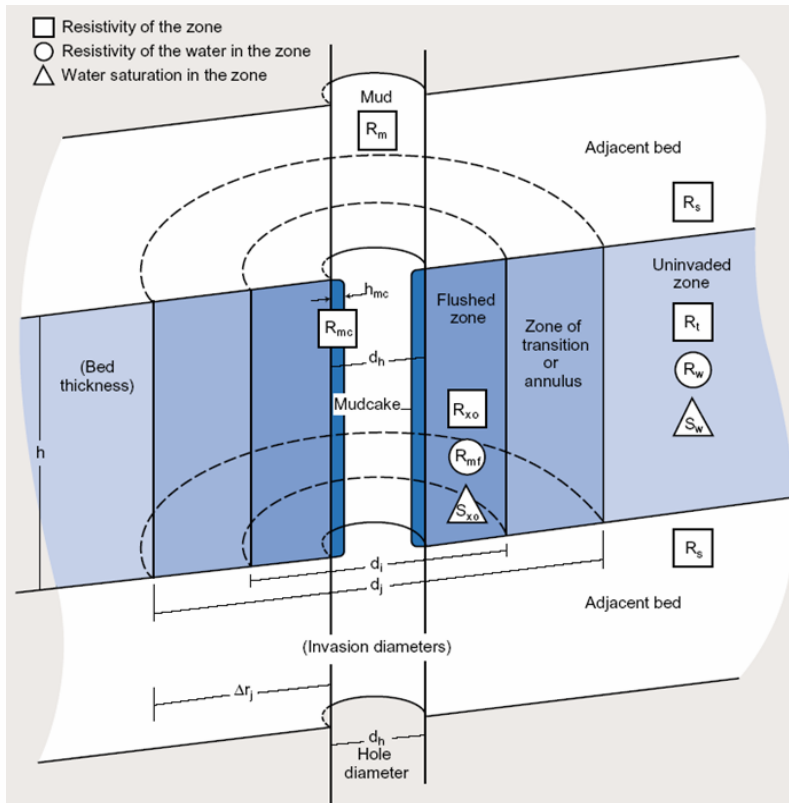
$$F = \frac{a}{\phi^m}$$

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

Archie Equation for Water Saturation



# Borehole Environment

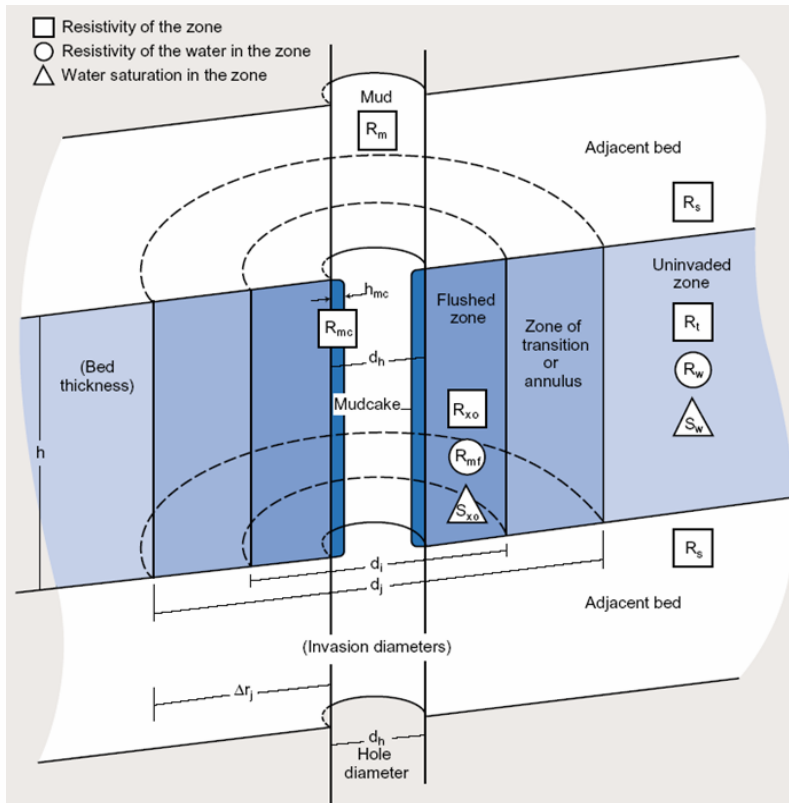


- Rock-fluid system is disturbed and altered during drilling
- Borehole Diameter ( $d_h$ ), c. 7-12 inch
  - Determined by the bit size, but
    - May be larger due to wash out
    - May be smaller due to build up of mud cake





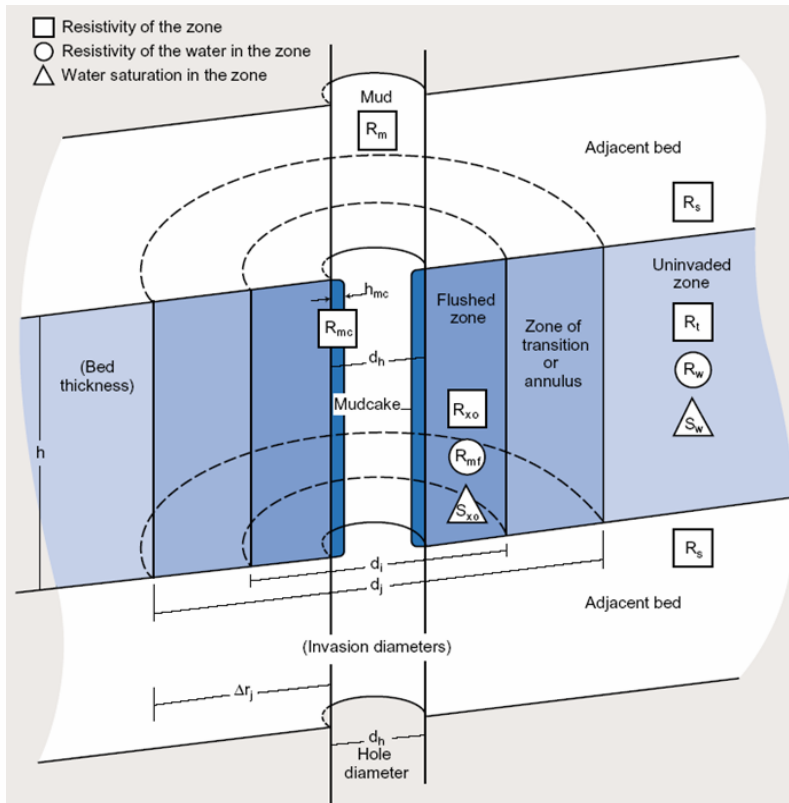
# Borehole Environment



- Drilling mud:
  - Remove cuttings
  - Lubricate and coll drill bit
  - Maintain excess borehole pressure over formation pressure
    - Mud filtrate into formation
    - Build up of mud cake on borehole walls
  - Drilling mud ( $R_m$ ), mud cake ( $R_{mc}$ ) and mud filtrate ( $R_{mf}$ ) resistivities are recorded and used in interpretations



# Borehole Environment

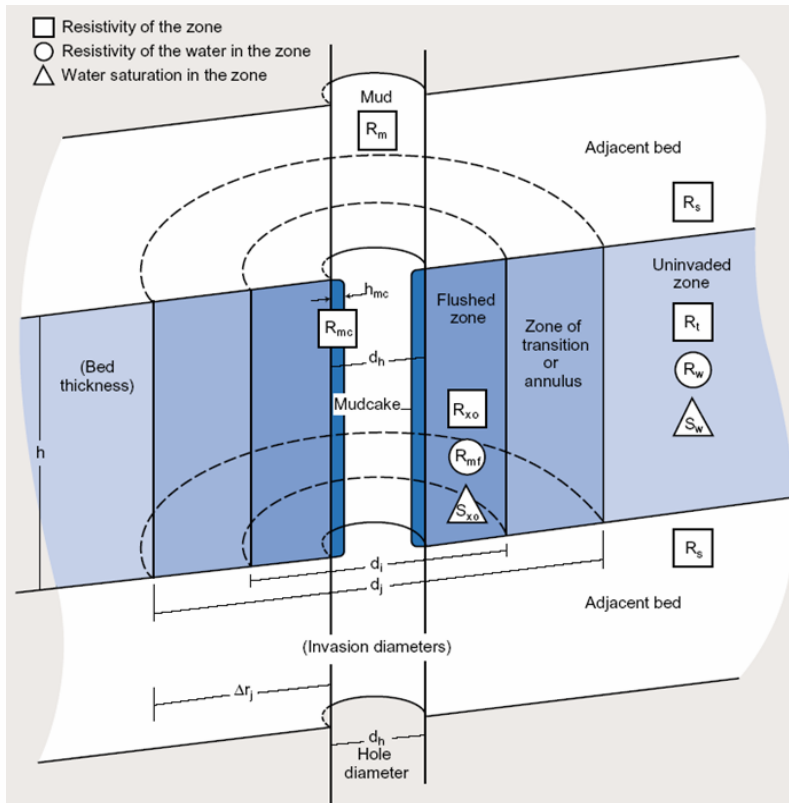


## Invaded Zone

- Zone around the borehole where the original fluid content has completely or partly been replaced by drilling mud.
- Invaded Zone = Flushed Zone + Transition Zone ("Annulus")
- Depth of invasion depends on mud cake. Mud cake formation more efficient in porous rocks, causing less deep penetration of mud filtrate in porous rocks
- Flushed Zone Resistivity;  $R_{xo}$
- Residual oil in flushed zone. Usually 70-95% is flushed out.
- $S_{ro} = 1 - S_{xo}$



# Borehole Environment

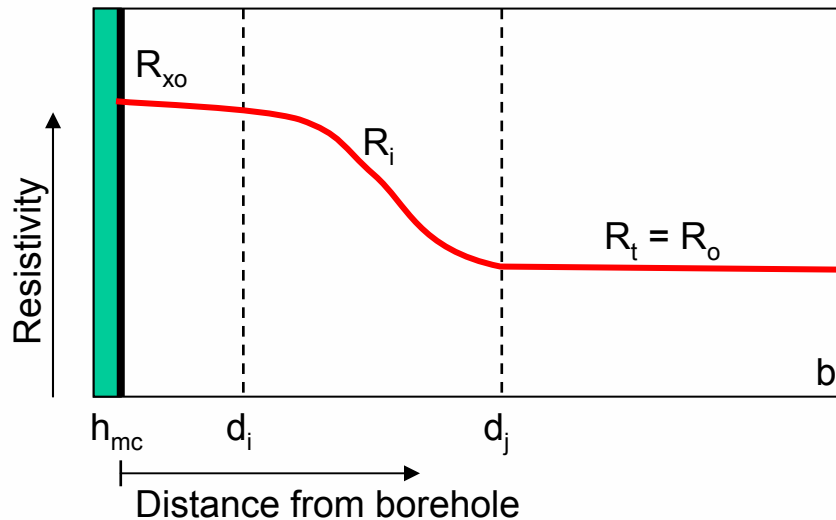
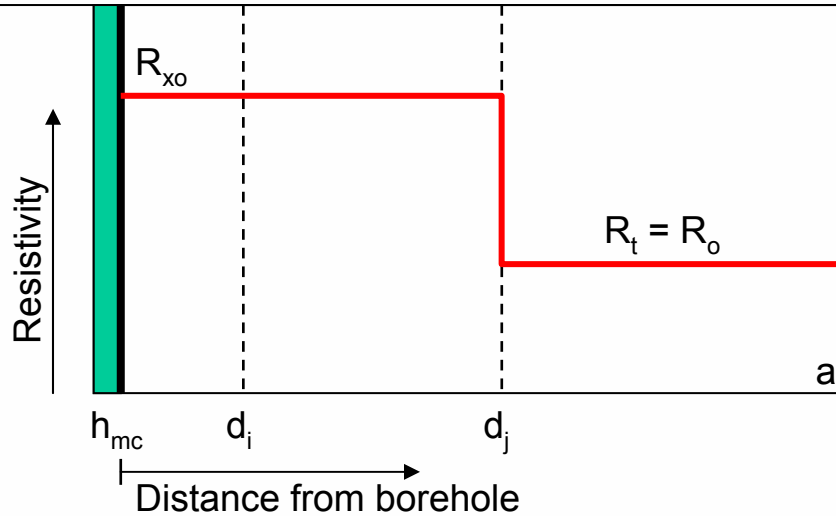


- **Uninvaded Zone**

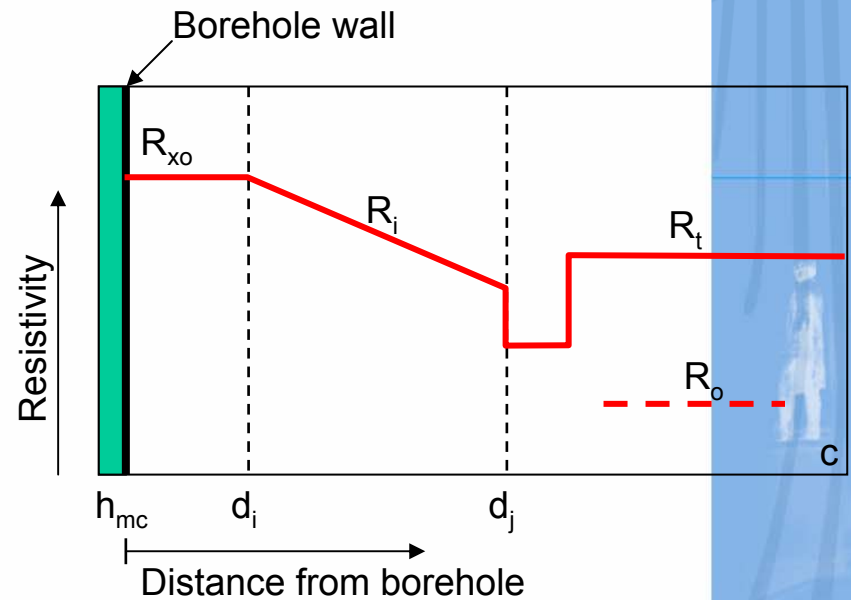
- Pores uncontaminated by the mud filtrate
- Pores contain formation waters, oil and/or gas
- HC bearing reservoir always have some formation water on grain contacts
- Uninvaded zone resistivity;  $R_t$
- Ratio of  $S_w$  to  $S_{xo}$  is an index of HC moveability



# Invasion and Resistivity Profiles



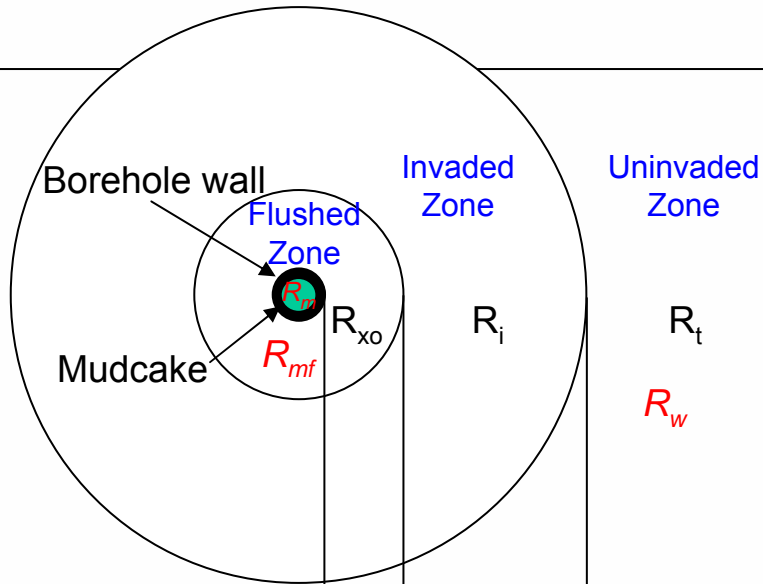
- a) Step Profile
- b) Transition Profile
- c) Annulus Profile



NB: Resistivity profiles for water reservoirs and fresh water muds



# Invasion and Resistivity Profiles



- **Freshwater vs. Saltwater** muds in water bearing formations

- Freshwater:

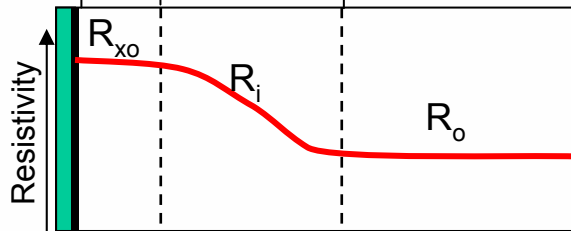
- $R_{x0} > R_i > R_0$

- Saltwater

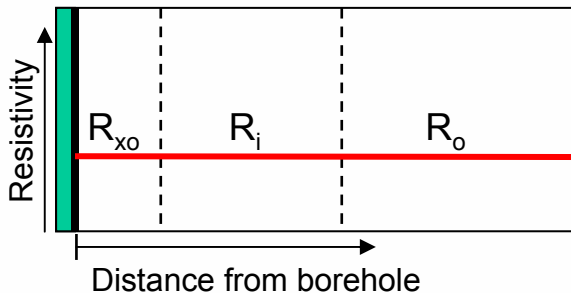
- $R_{x0} \approx R_i \approx R_0$

- NB These examples assume  $S_w$  to be more than 60%

Freshwater muds  
 $R_{mf} \gg R_w$



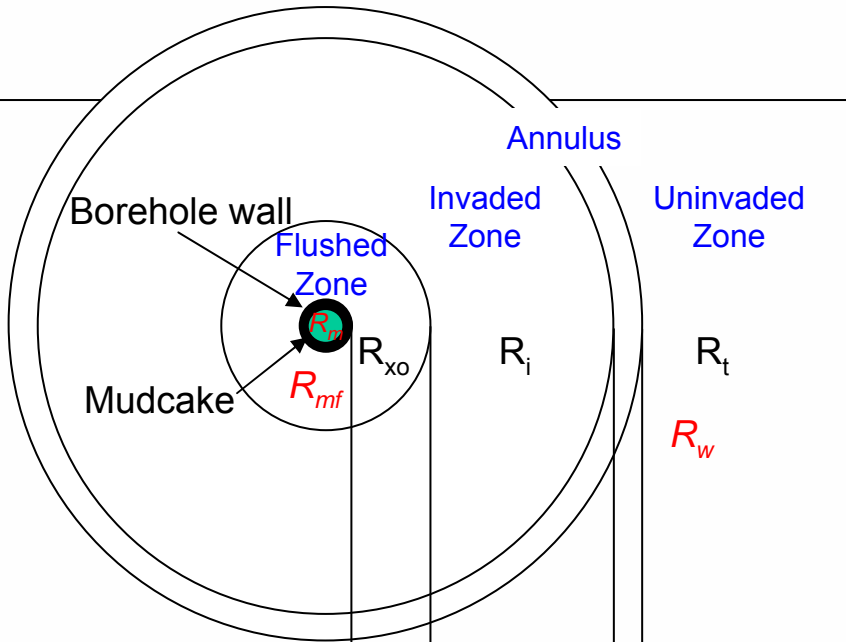
Saltwater muds  
 $R_{mf} \approx R_w$



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# Invasion and Resistivity Profiles



- **Freshwater** vs. **Saltwater** muds in hydrocarbon bearing formations

- Freshwater:

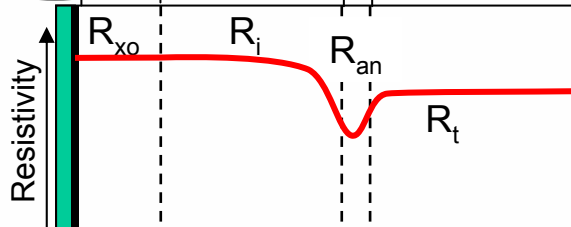
- $R_{xo} > R_i > R_t$  or
- $R_{xo} > R_i < R_t$

- Saltwater

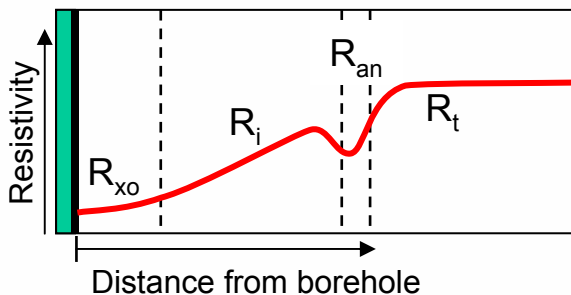
- $R_t > R_i > R_{xo}$

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

Freshwater muds  
 $R_{mf} \gg R_w$



Saltwater muds  
 $R_{mf} \approx R_w$

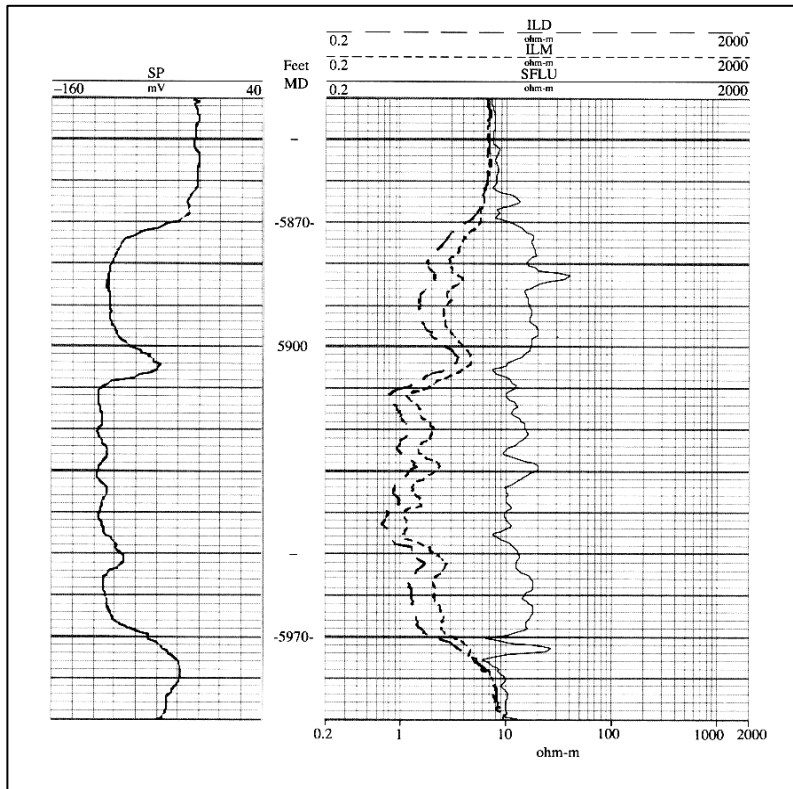


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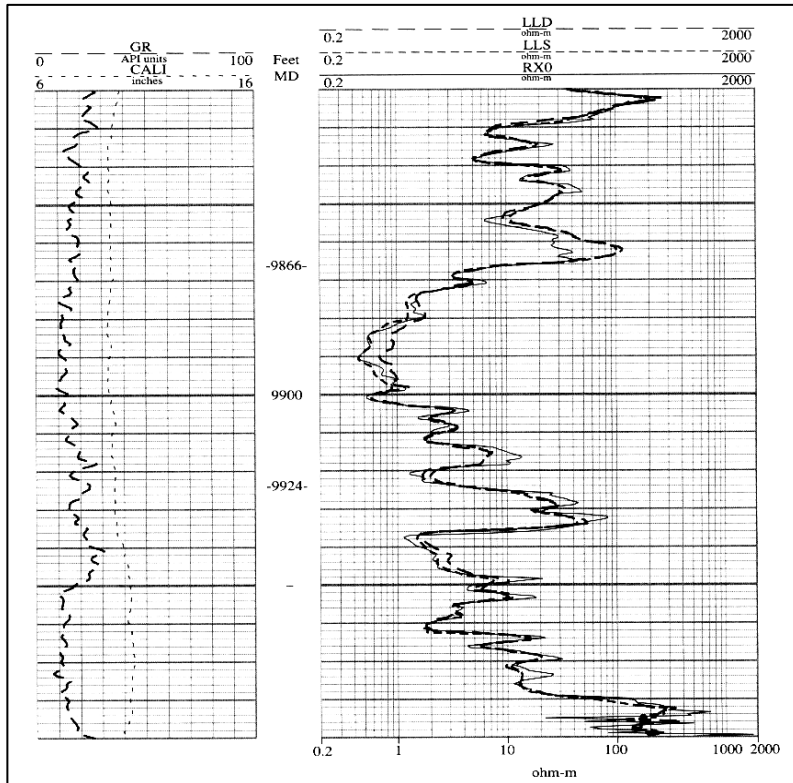
# Examples



- Water bearing zone with Freshwater muds
  - High resistivity in the flushed zone, a lesser resistivity in the invaded zone and a low resistivity in the uninvaded zone



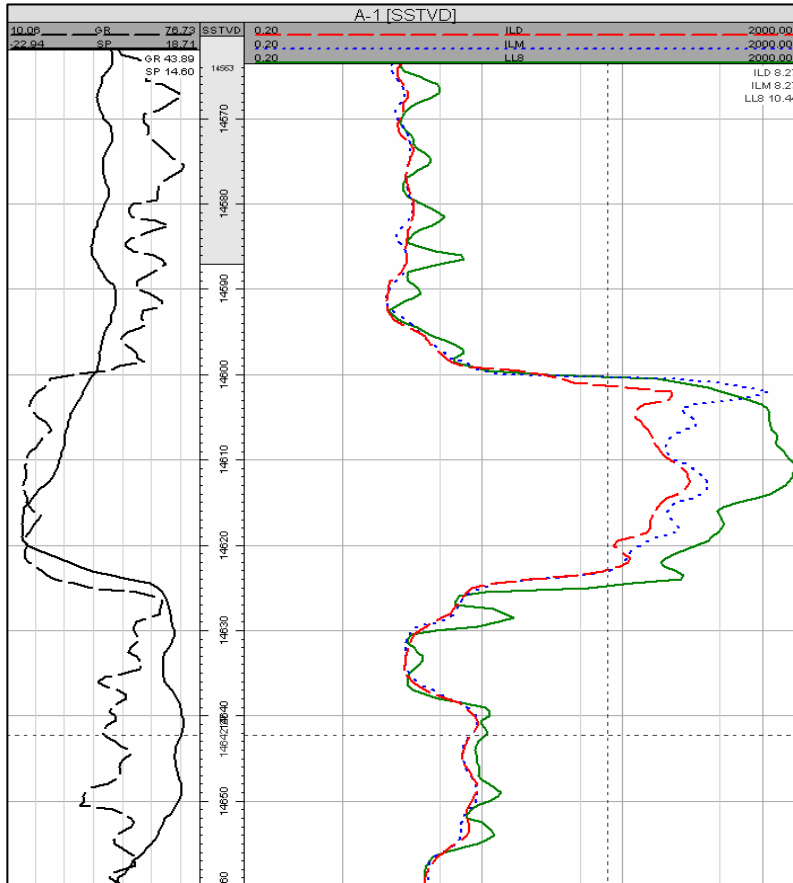
# Examples



- Water bearing zone with Saltwater muds
  - Low resistivity in the flushed, invaded and uninvaded zones



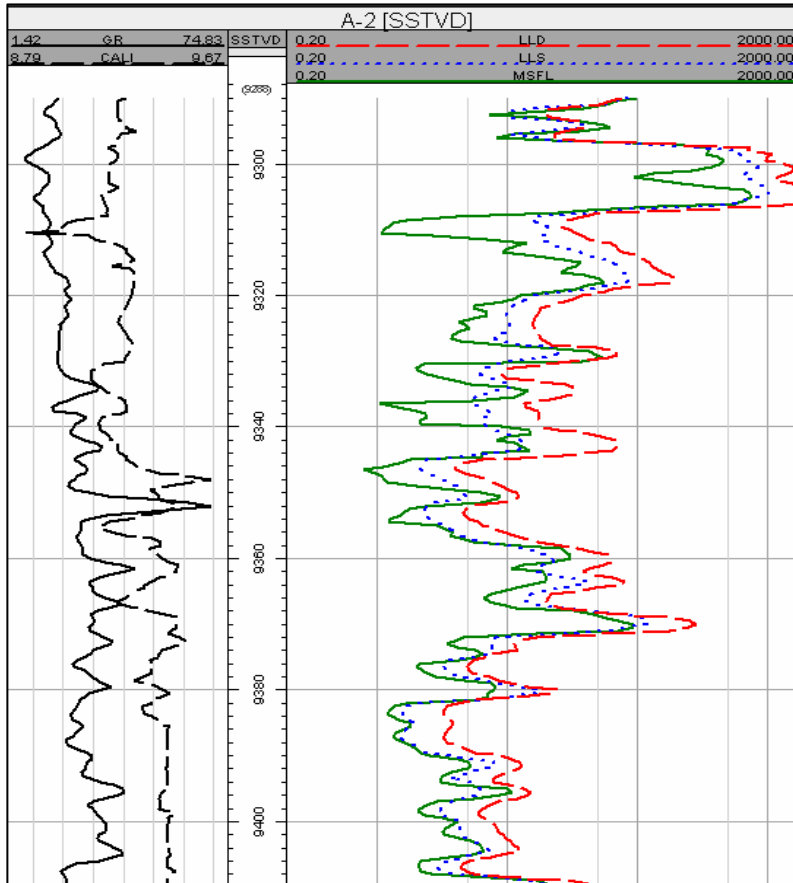
# Examples



- Hydrocarbon bearing zone and Freshwater muds
  - High resistivity in the flushed, invaded and uninvaded zone
  - Normally, the flushed zone has a slightly higher resistivity than the uninvaded zone



# Examples



- Hydrocarbon bearing zone with Saltwater muds
  - Low resistivity in the flushed zone, intermediate resistivity in the invaded zone and high resistivity in the uninvaded zone



# Lithology

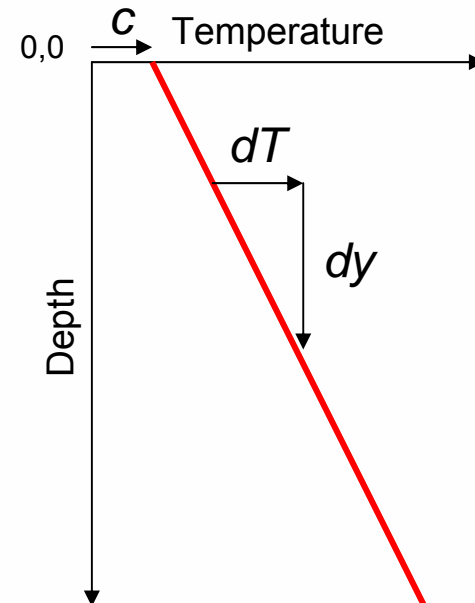
Proper choice of tortuosity and cementation factors depends on the lithology, therefore an estimate of lithology is important

a: Tortuosity factor	m: Cementation factor	Comments
1.0	2.0	Carbonates <sup>1</sup>
0.81	2.0	Consolidated sandstones
0.62	2.15	Unconsolidated sands (Humble formula)
1.45	1.54	Average sands (after Carothers, 1968)
1.65	1.33	Shaly sands (after Carothers, 1968)
1.45	1.70	Calcareous sands (after Carothers, 1968)
0.85	2.14	Carbonates (after Carothers, 1968)
2.45	1.08	Pliocene sands, southern California (after Carothers and Porter, 1970)
1.97	1.29	Miocene sands, Texas-Louisiana Gulf Coast (after Carothers and Porter, 1970)
1.0	$\phi^{(2.05-\phi)}$	Clean, granular formations (after Sethi, 1979)



# Formation Temperature

- Formation temperature is an important factor to know, since the resistivities of the drilling mud ( $R_m$ ), the mud filtrate ( $R_{mf}$ ) and the formation water ( $R_w$ ) vary with temperature
- Can be calculated by knowing
  - Formation depth
  - Bottom hole temperature
  - Total depth of the well
  - Surface temperature
- Calculation of Formation Temperature:
$$y = mx + c$$
  - With
    - $x = \text{depth}$
    - $y = \text{temperature}$
    - $m = \text{slope (?)}$ 
      - geothermal gradient ( $dT/dy$ )
    - $c = \text{constant (?)}$ 
      - mean annual surface temperature



# Formation Temperature

- Temperature Gradient Calculation

- Assume:

- $y$  = BHT (bottom hole temperature) = 120 °C
- $x$  = TD (total depth) = 4575m
- $c$  = Mean ann. surface temperature = 20 °C

$$\frac{dT}{dy} = \frac{120 - 20}{4575} = 0.022 \text{ } ^\circ\text{C} / \text{m}$$

- Formation Temperature Calculation

- Assume:

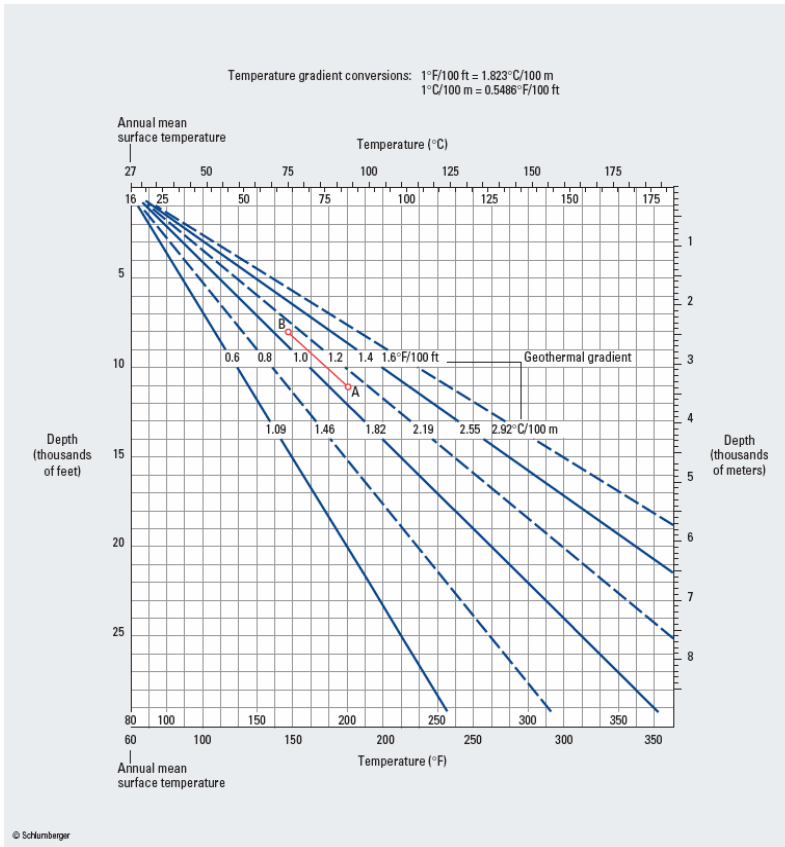
- $M$  = Geothermal gradient = 0.022 °C/m
- $X$  = Formation depth = 2440m
- $C$  = Mean ann. Surface temperature = 20 °C

$$y = (0.022 \times 2440) + 20 \approx 74^\circ\text{C}$$



# Formation Temperature

## By Chart



### Example

Given: Bottomhole depth = 11,000 ft and bottomhole temperature =  $200^{\circ}\text{F}$  (annual mean surface temperature =  $80^{\circ}\text{F}$ ).

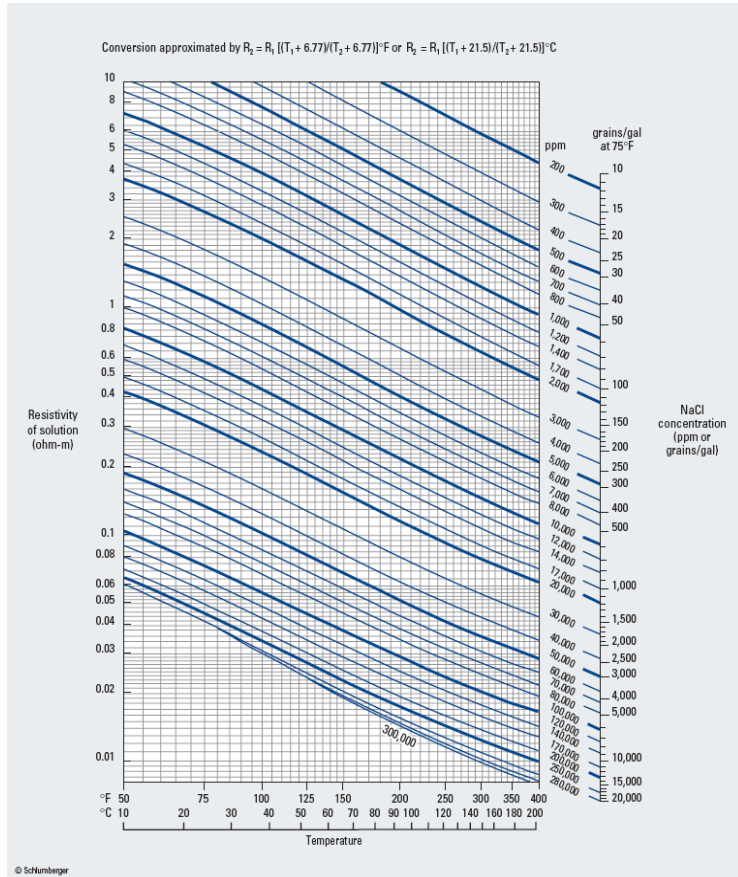
Find: Temperature at 8,000 ft.

Answer: The intersection of 11,000 ft on the y-axis and  $200^{\circ}\text{F}$  on the x-axis is a geothermal gradient of approximately  $1.1^{\circ}\text{F}/100\text{ ft}$  (Point A on the chart). Move upward along an imaginary line parallel to the constructed gradient lines until the depth line for 8,000 ft is intersected. This is Point B, for which the temperature on the x-axis is approximately  $167^{\circ}\text{F}$ .





# Correction of $R_m$ , $R_{mf}$ and $R_w$ for Formation Temperature



## Ex. 1: [NaCl] given

Given: NaCl equivalent concentration = 20,000 ppm. Temperature of concentration = 75°F.

Find: Resistivity of the solution.

Answer: Enter the ppm concentration on the y-axis and the temperature on the x-axis to locate their point of intersection on the chart. The value of this point on the left y-axis is 0.3 ohm-m at 75°F.

## Ex. 2: Resistivity given

Given: Solution resistivity = 0.3 ohm-m at 75°F.

Find: Solution resistivity at 200°F [93°C].

Answer 1: Enter 0.3 ohm-m and 75°F and find their intersection on the 20,000-ppm concentration line. Follow the line to the right to intersect the 200°F vertical line (interpolate between existing lines if necessary). The resistivity value for this point on the left y-axis is 0.115 ohm-m.

