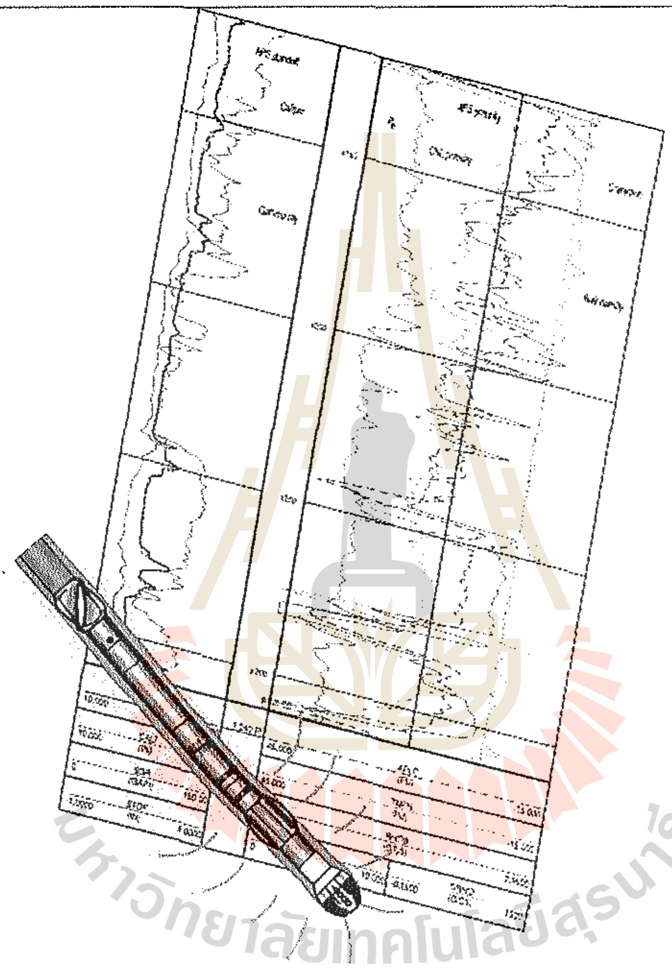
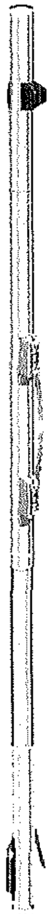
เอกสารประกอบการบรรยาย

รายวิชา

434359 Well Logging





สาขาวิชาเทคโนโลยีธรณี

มหาวิทยาลัยเทคโนโลยีสุรนารี

คำนำ

เอกสารฉบับนี้เป็นเอกสารที่ใช้ประกอบการบรรยายและการเรียนการสอนในรายวิชา 434359 Well Logging ในสาขาวิชาเทคโนโลยีธรณี มหาวิทยาลัยเทคโนโลยีสุรนารี ซึ่งเป็นวิชาที่มีเนื้อหาเกี่ยวกับการแปลความหมายข้อมูลจากการหยั่งธรณีหลุมเจาะ โดยเนื้อหาที่แสดงอยู่ในเอกสารฉบับนี้ จะรวบรวมมาจากหนังสือที่ใช้ในการเรียนการสอนรายวิชา 434359 Well Logging และเอกสารประกอบการฝึกอบรมในหัวข้อ Introduction to Open Hole Logging ของบริษัทเอกชนที่มีความเชี่ยวชาญในธุรกิจด้านหารหยั่งธรณีหลุมเจาะ และสำหรับเนื้อหาทางวิชาการต่างๆที่บรรจุอยู่ในเอกสารประกอบการเรียนการสอนฉบับนี้ ผู้รวบรวมมีวัตถุประสงค์เพื่อใช้ในการเรียนการสอนในรายวิชา 434359 Well Logging เท่านั้น ไม่สามารถนำออกเผยแพร่เพื่อจุดประสงค์ทางพาณิชย์หรือจุดประสงค์อื่นๆที่มิใช้เพื่อประกอบการเรียนการสอนได้ ดังนั้นผู้รวบรวมเอกสารชุดนี้หวังว่าเอกสารชุดนี้ จะสามารถช่วยเพิ่มความรู้ ความเข้าใจของผู้เรียนในรายวิชา 434359 Well Logging และผู้สนใจให้มีความรู้ความสามารถเพียงพอต่อการทำงานที่เกี่ยวข้องกับการหยั่งธรณีหลุมเจาะต่อไปในอนาคต

ด้วยความนับถือ

นายเชษฐา ชุมกระโทก
อาจารย์ประจำสาขาวิชาเทคโนโลยีธรณี
สำนักวิชาวิศวกรรมศาสตร์
มหาวิทยาลัยเทคโนโลยีสุรนารี

WELL LOGGING

(434359)

Course Outline

1. INTRODUCTIONS & ROCK PROPERTIES(2 hrs.)
2. Resistivity and Basic Relationships of Well Log Interpretation(1 hrs.)
3. Resistivity Device(2 hrs.)
4. Spontaneous Potential (SP) Log(2 hrs.)
5. Induction Electric and Dual Induction Logs(2 hrs.)
6. Acoustic , Gamma Ray and Caliper Logs(2 hrs.)
7. Quantitative Analysis -Part I (2 hrs.)

Course Outline

8. Density, and Neutron Logs(3 hrs.)
9. Combined Porosity and Lithology logs Determinations(2 hrs.)
10. Focused Resistivity Logs (2 hrs.)
11. Openhole Log and QUICKLOOK Interpretations(3 hrs.)
12. Shaly Sand Interpretations(3 hrs.)
13. Case Hole Logging(3 hrs.)
14. Computer Processing of well Logs(1 hr.)

Course Outline

15. Fracture Detection with Well Logs(1 hr.)
16. Dipmeter Principles(2 hrs.)
17. Logs Correlations(2hrs)
18. Special Logs, MWD,(2 hrs.)
19. Core & Core Analysis(2 hrs.)

Grading

▪ Homework	?? %
▪ Attendance	?? %
▪ Report and Presentation	?? %
▪ Pre-Test and Post Test	?? %
▪ Quiz	?? %
▪ Mid Term	?? %
▪ Final Exam	?? %

Introduction to Log Interpretation
&
Rock Properties

What Is Well Logging?

Well logging is the process of recording various physical, chemical, electrical, or other properties of the rock/fluid mixtures penetrated by drilling a well into the earth's mantle. A log is a record of a voyage, similar to a ship's log. In this case, the ship is a measuring instrument of some kind, and the trip is taken into and out of the wellbore.

In its most usual form, an oil well log is a record displayed on a graph with the measured physical property of the rock on one axis and depth (distance from the surface) on the other axis. More than one property may be displayed on the same graph.

Why are we Logging Wells ?

Wireline logging can be used in a number of ways by a number of people to provide solutions to questions they have about a particular well.

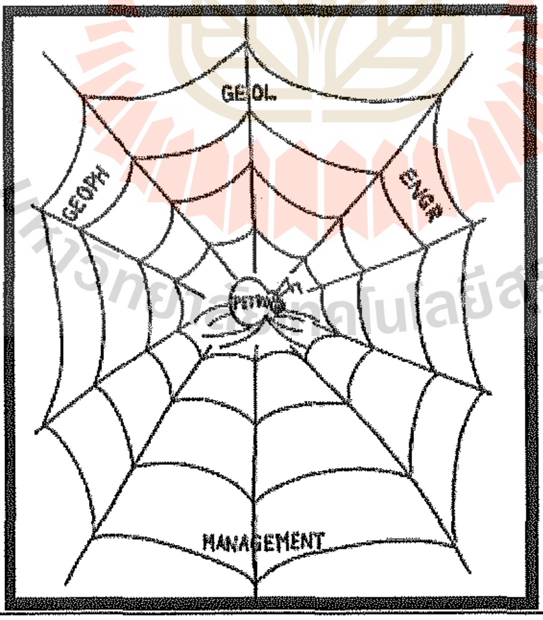
- Some of the ways different people in an office will use these logs are:
- Geophysics look to logs for:
  - Where are my tops (as predicted?)
  - Does seismic interpretation agree with log data?
  - How is my synthetic doing with this new information?

- Geologists look to logs for:
  - Where are my tops ?
  - Do I have any reservoir ?
  - Is there any Hydrocarbon in the well ?
  - What type of Hydrocarbon(s) is there ?
  - How good is my reservoir ?
  - What kind of reserves do I have ?
  - How does this tie in to my offsets ?

- Drilling Engineers are looking for:
  - What is my hole volume (cement) ?
  - What is my dog leg severity ?
  - Where can I get a good packer seat for testing ?
  - Where can I set up my whipstock ?

- Production Engineers are looking for:
  - Where should complete this well ?
  - What will be my expected production rates ?
  - Will I have to deal with water ?
  - How should I complete this well ?
  - Do I need to stimulate this well ?
  - How should I stimulate it ?

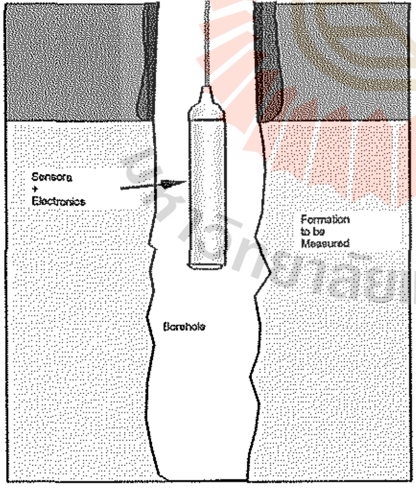
Petro-Physicist



Wireline Well Logging

The Wellbore
Wellbore Fluids
Volumes Under Investigation
Basic Interpretation Technique
Interpretation Procedures

Measuring in the borehole

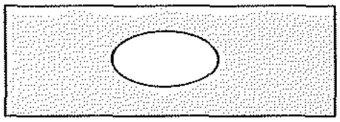


The formation to be measured is masked by the borehole.

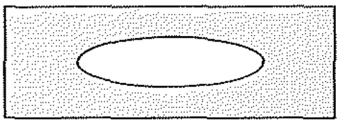
The borehole contains fluids and is of an irregular shape.

The sensor has to be able to measure the formation property accurately and send the information to surface.

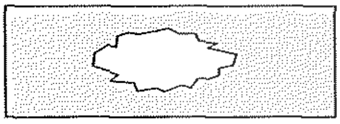
Borehole -Size and Shape



Perfect shape no problems except if very large.



Ovalised hole; will give problems for some tools. Best to run two calipers.

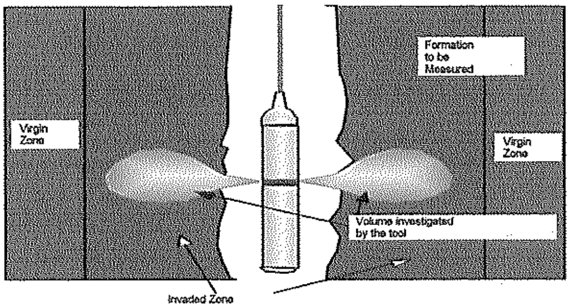


Irregular borehole, gives problems for most tools.

Borehole - Temperature

- Increasing temperature affects the measurements in some tools. The most affected is the thermal neutron devices.
- High temperature also affect the performance of the electronics in the tools.
- Temperature affects the mud resistivity (it decreases with increasing temperature).
- Temperature is measured during each logging run.

Volume of Investigation



The tool shown here measures all around the borehole. It is omni-directional.

An example of this type of tool is the Gamma Ray.

Some of the "signal" is in the borehole. Most comes from the invaded zone.

Wireline Logging Objective in Drilling Operation

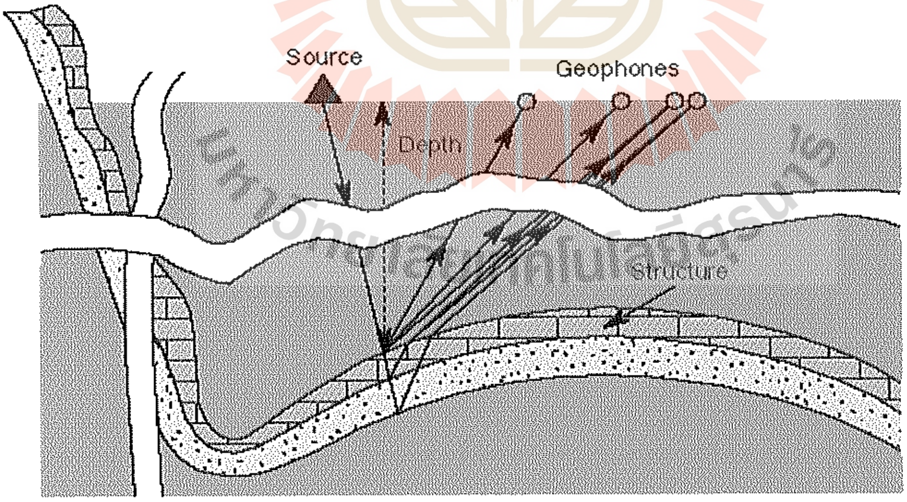
A well is drilled to a pre-determined objective:

- An exploration well targets a suspected reservoir.
- An appraisal well evaluates a discovery.
- A development well is used for production.

Pre-Drilling Knowledge Exploration

- Structural information obtained from surface seismic data.
- Rough geological information can be provided by nearby wells or outcrops.
- Approximate depths estimated from surface seismic data.

Pre-Drilling Knowledge Exploration



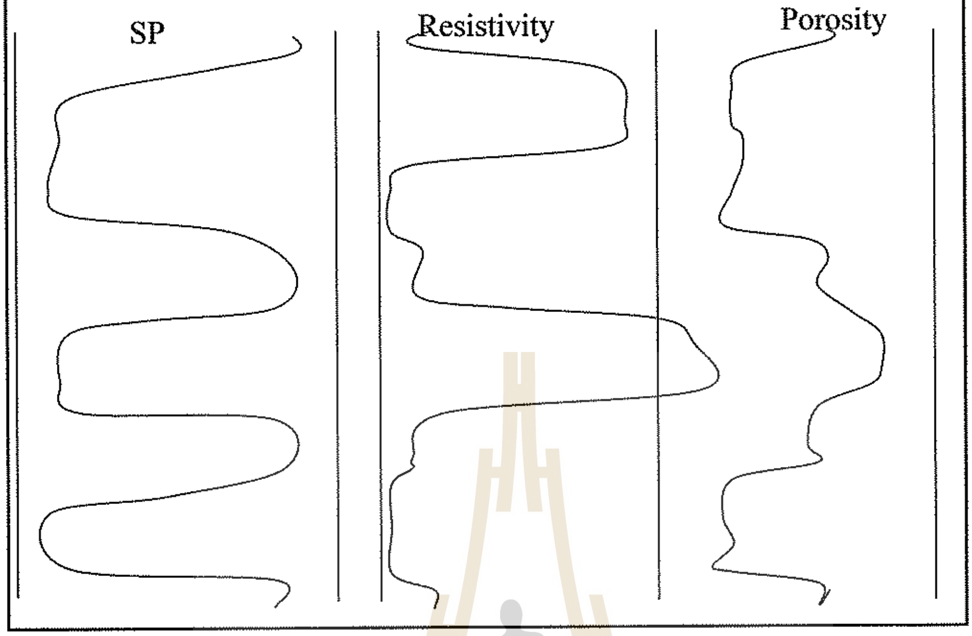
Tool History

- 1927 - First electrical log recorded.
- 1930s - SP, Short Normal, Long Normal and Long Lateral combined, Core Sample Taker.
- 1940s - Gamma Ray and Neutron, 3-arm Dipmeter using SP, then electrical measurements, Induction tool.
- 1950s - Microlog tool, Laterolog tool, Sonic tool, Formation Tester.
- 1960s - Formation Density tool.
- 1970s - Dual Spacing Neutrons, Advanced Dipmeters, Computerised Surface Systems, Repeat Tester tools, Electromagnetic Propagation tool.
- 1980s - Resistivity Imaging tool, Advanced Sonic tools
- 1990s - Advanced testing tools, Induction imaging tools, Azimuthal Laterolog tools, Ultrasonic imaging tools, Epithermal porosity tools, Magnetic resonance tools

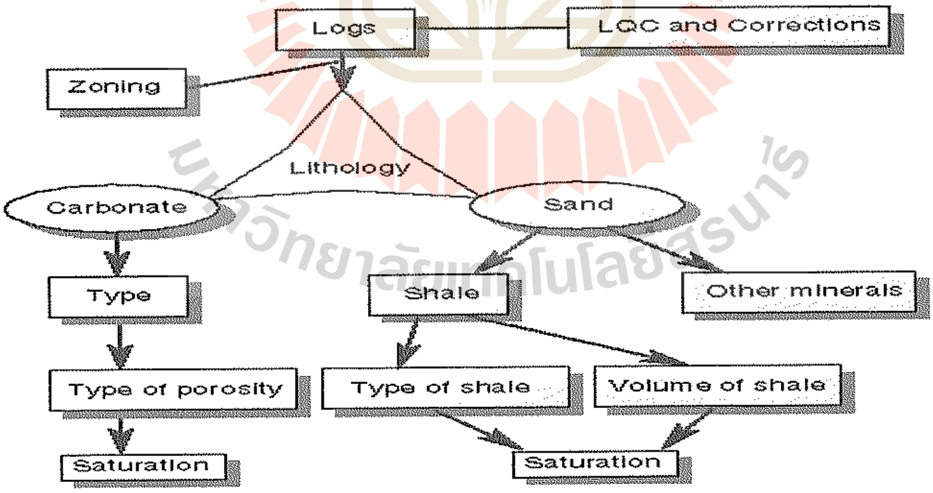
Early Interpretation

- Early resistivity logs were used to find possible producing zones.
- high resistivity = hydrocarbon
- SP was used to define permeable beds, compute Rw and determine shaliness.
- Resistivity was also used to determine "porosity".
- Archie developed the relationship between resistivity, porosity and saturation.

Basic Log Response



Interpretation Procedure



Logs

LQC and Corrections

Zoning

Lithology

Carbonate

Sand

Type

Shale

Other minerals

Type of porosity

Type of shale

Volume of shale

Saturation

Saturation

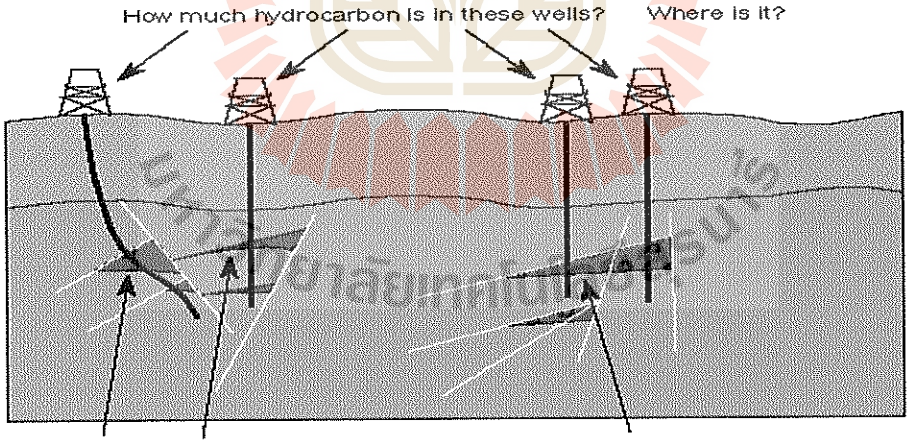
Log Interpretation

Interpretation is defined as the action of explaining the meaning of something.

Log Interpretation is the explanation of logs ρb, GR, Resistivity, etc. in terms of well and reservoir parameters, zones, porosity, oil saturation, etc.

Log interpretation can provide answers to questions on:

Log Interpretation



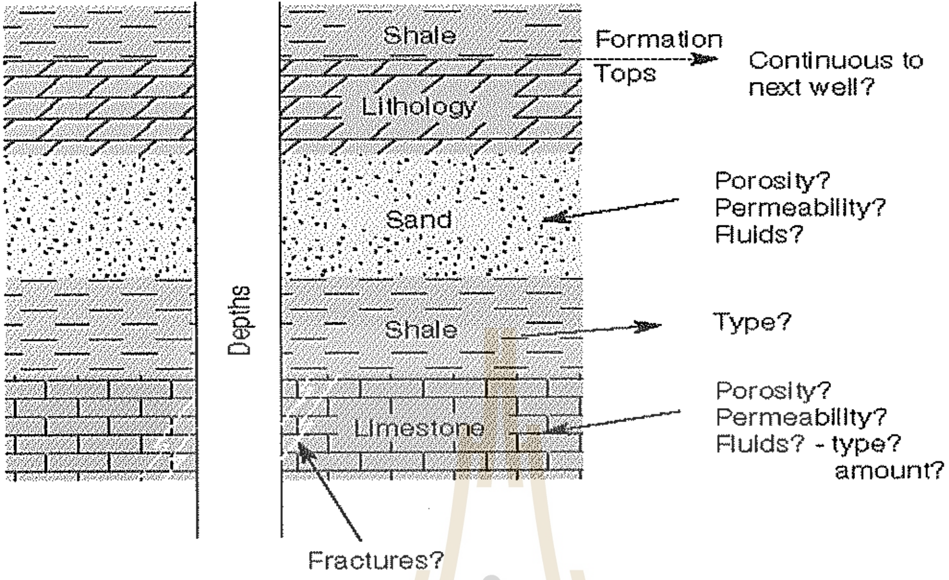
How much hydrocarbon is in these wells?

Where is it?

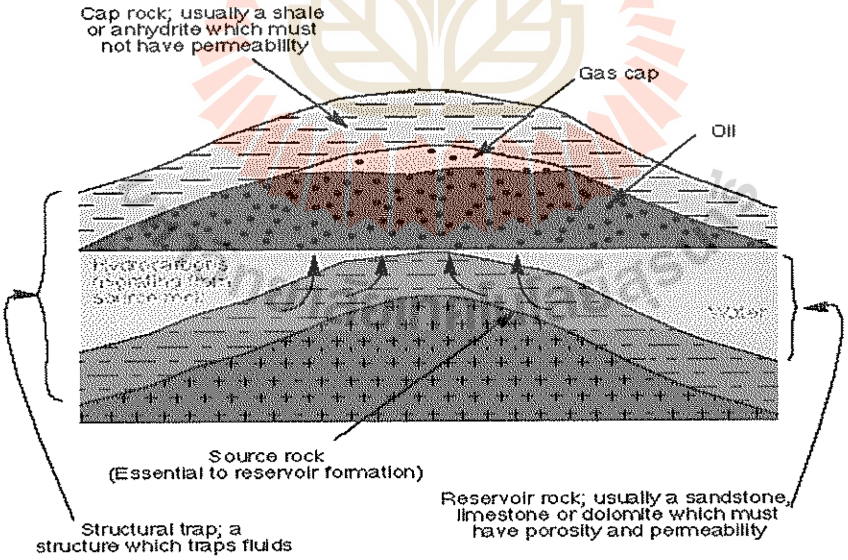
Is there communication between these reservoirs?

What is the extent of this reservoir?
How will it produce?
Will it require enhanced recovery techniques?

Why Run Logs



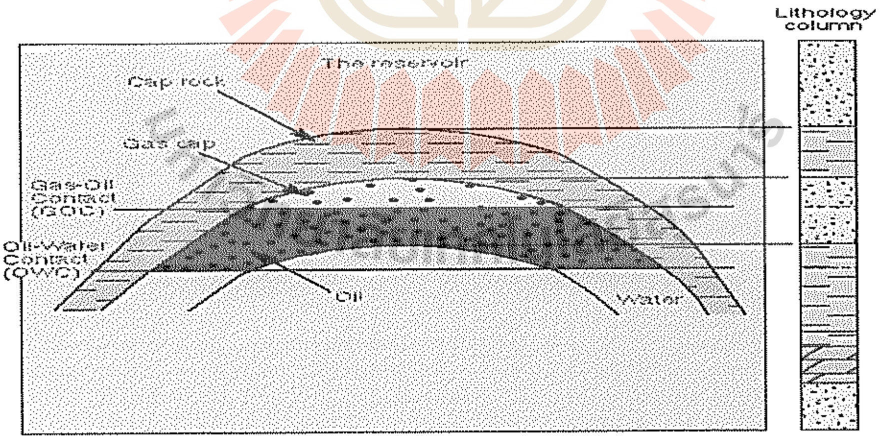
The Reservoir



Requirements of a reservoir

- To form a reservoir needs
- source of organic material (terrestrial or marine)
- a suitable combination of heat, pressure and time
- an oxygen free environment
- a suitable basin

Reservoir Geometry



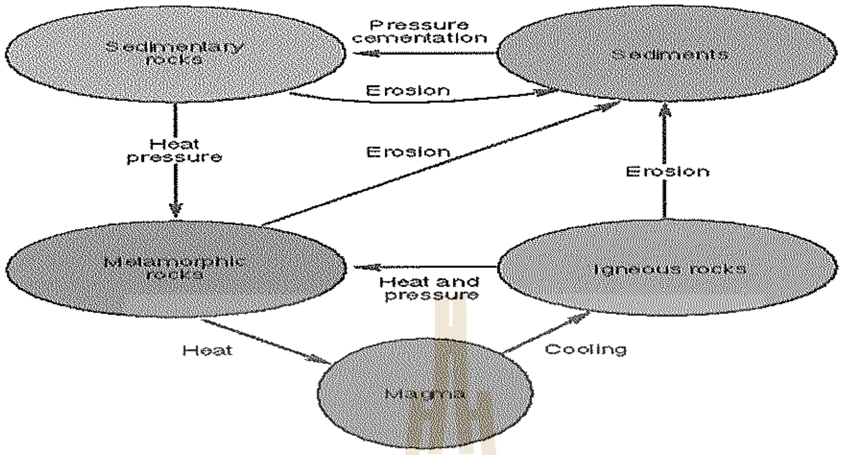
Reservoir Rocks

Rocks General

There are three major classes of rock:

- Igneous: (e.g. Granite).
- Sedimentary: (e.g. Sandstone).
- Metamorphic: (e.g. Marble).

Rock Cycle

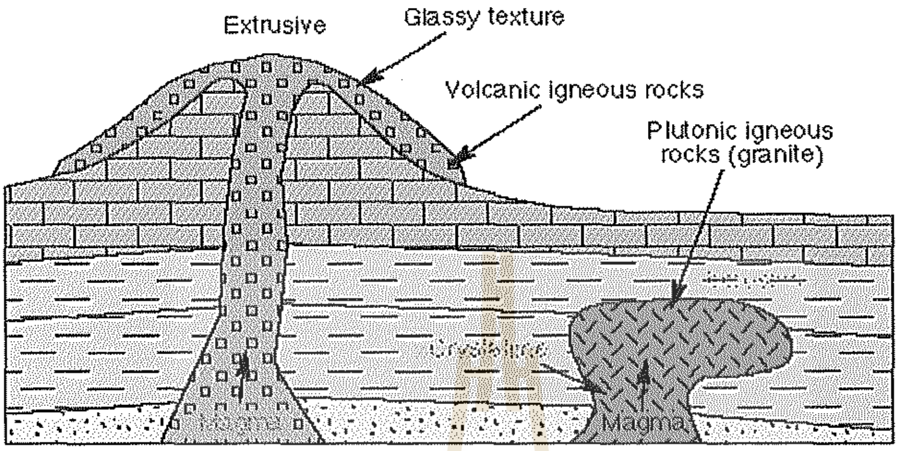


Sedimentary rocks
Pressure cementation
Sediments
Erosion
Heat pressure
Erosion
Erosion
Metamorphic rocks
Heat and pressure
Igneous rocks
Heat
Cooling
Magma

Igneous Rocks

- 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.

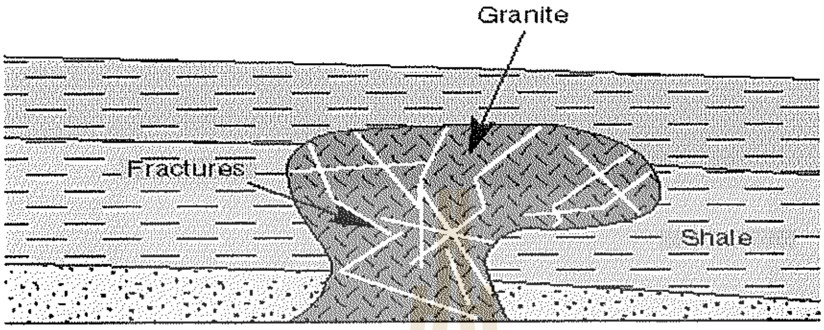
Igneous Rocks



Igneous Rocks and Reservoirs

- Igneous rocks can be part of reservoirs.
- Fractured granites form reservoirs in some parts of the world.
- Volcanic tuffs are mixed with sand in some reservoirs.

Igneous Rocks and Reservoirs



Example: Granite Wash - Elk City, Okla., Northern Alberta,CA

Metamorphic Rocks

- <u>2) Metamorphic rocks</u>
- formed by the action of temperature and/or pressure on sedimentary or igneous rocks.
- Examples are

  Marble - formed from limestone

  Hornfels - from shale or tuff

  Gneiss - similar to granite but formed by metamorphosis

Sedimentary Rocks

- The third category is Sedimentary rocks. These 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.

Sedimentary Rocks

- Clastic rocks - formed from the materials of older rocks by the actions of erosion, transportation and deposition.
- Non-clastic rocks -from chemical or biological origin and then deposition.

Depositional Environments

- The depositional environment can be Shallow or deep water.
- Marine (sea) and lake or continental.
- This environment determines many of the reservoir characteristics

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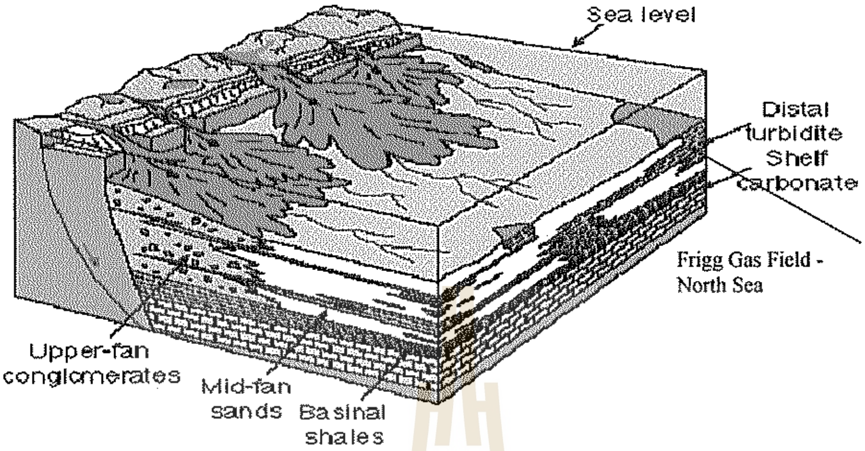
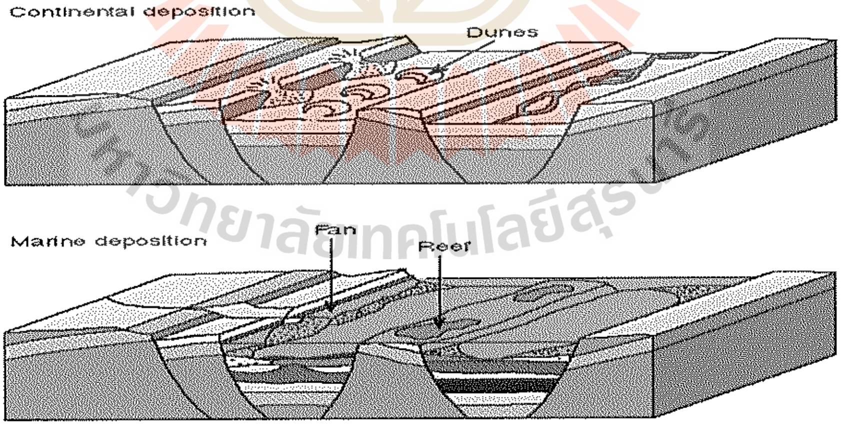
- The depositional characteristics of the rocks lead to some of their properties and that of the reservoir itself.
- The type of porosity (especially in carbonates) is determined by the environment plus subsequent events.
- The structure of a reservoir can also be determined by deposition; a river, a delta, a reef and so on.
- This can also lead to permeability and producibility. of these properties are often changed by further events.

Depositional Environments

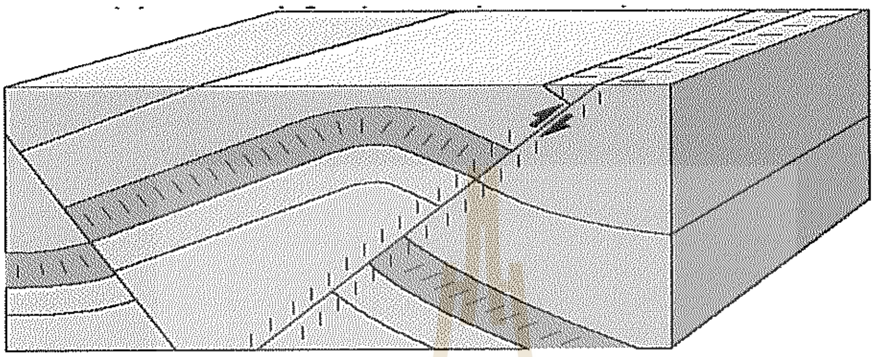


Depositional Environments



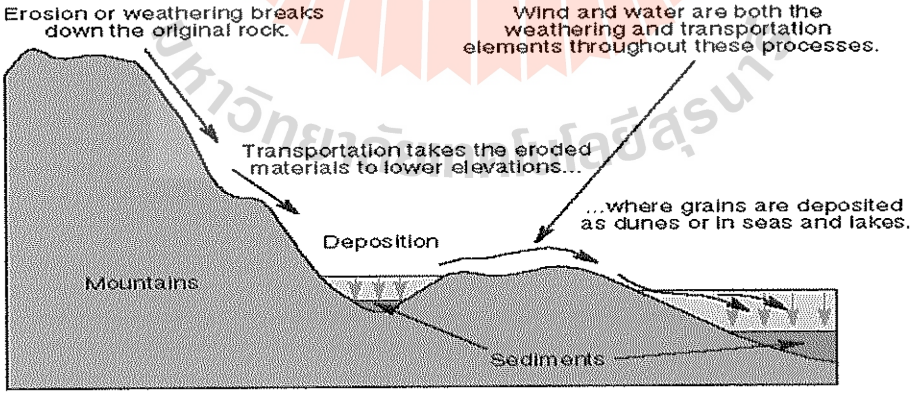
Depositional Environment

- The environment is not static.

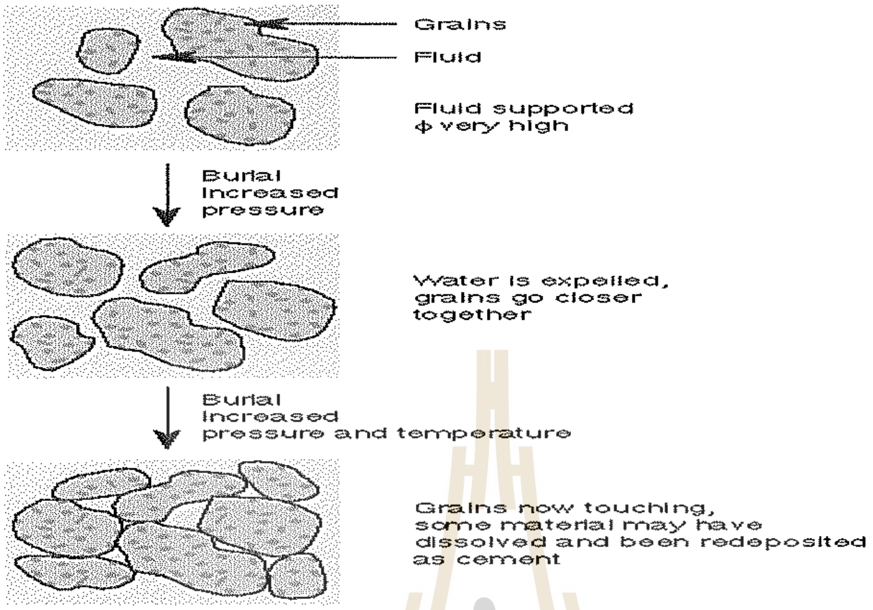


Clastic Rocks

- Clastic rocks are sands, silts and shales. The difference is in the size of the grains.



Sedimentation



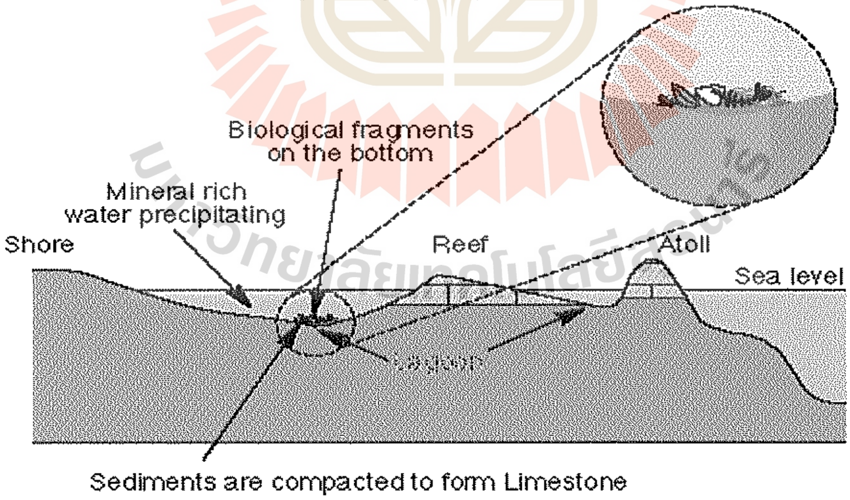
Carbonates

- Carbonates form a large proportion of all sedimentary rocks.
- They consist of:
  - Limestone.
  - Dolomite.
- Carbonates usually have an irregular structure.

Depositional Environment Carbonates

- Carbonates are formed in shallow seas containing features such as:
  - Reefs.
  - Lagoons.
  - Shore-bars.

Depositional Environment Carbonates



Petroleum System

- The factor of petroleum system are compounded 5 factor as shown:
  - Source Rock
  - Migration
  - Reservoir Rock
  - Cap Rock or Seal Rock
  - Trap

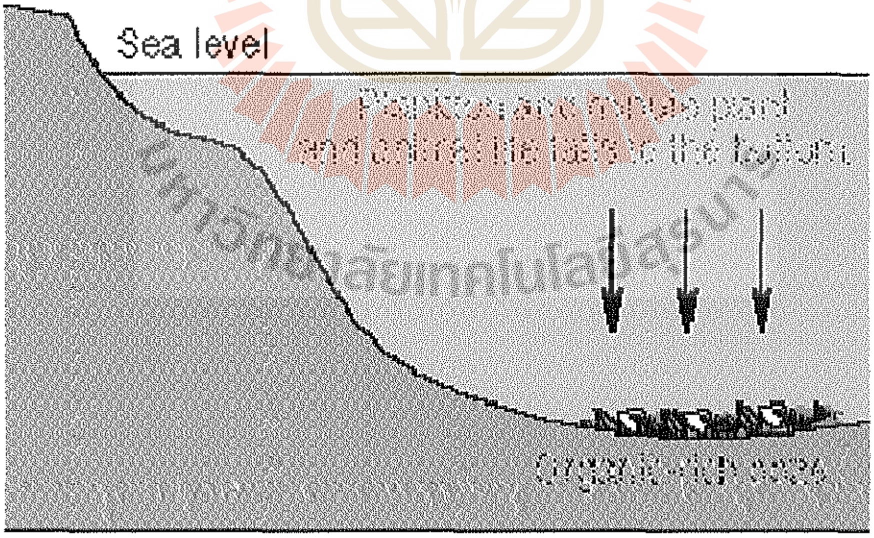
Source Rocks

- Hydrocarbon originates from minute organisms in seas and lakes. When they die, they sink to the bottom where they form organic-rich "muds" in fine sediments.
- These "muds" are in a reducing environment or "kitchen", which strips oxygen from the sediments leaving hydrogen and carbon.

Source Rocks

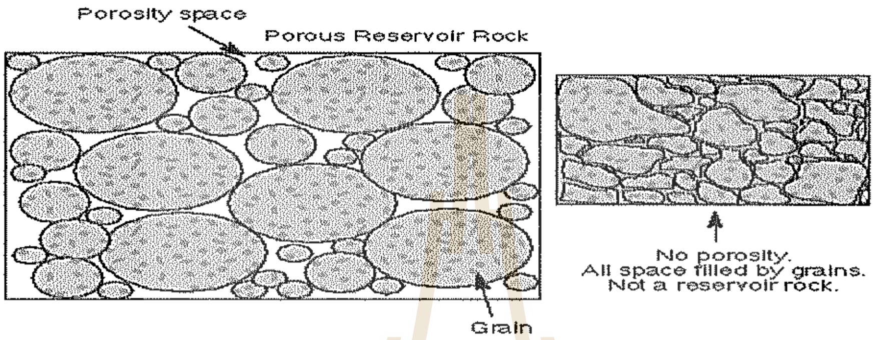
- The sediments are compacted to form organic-rich rocks with very low permeability.
- The hydrocarbon can migrate very slowly to nearby porous rocks, displacing the original formation water.

Source Rocks



Reservoir Rocks

- Reservoir rocks need two properties to be successful:
  - Pore spaces able to retain hydrocarbon.
  - Permeability which allows the fluid to move.



Clastic Reservoirs

- Sandstone usually has regular grains; and is referred to as a grainstone.
- Porosity
  - Determined mainly by the packing and mixing of grains.
- Permeability
  - Determined mainly by grain size and packing, connectivity and shale content.
- Fractures may be present.

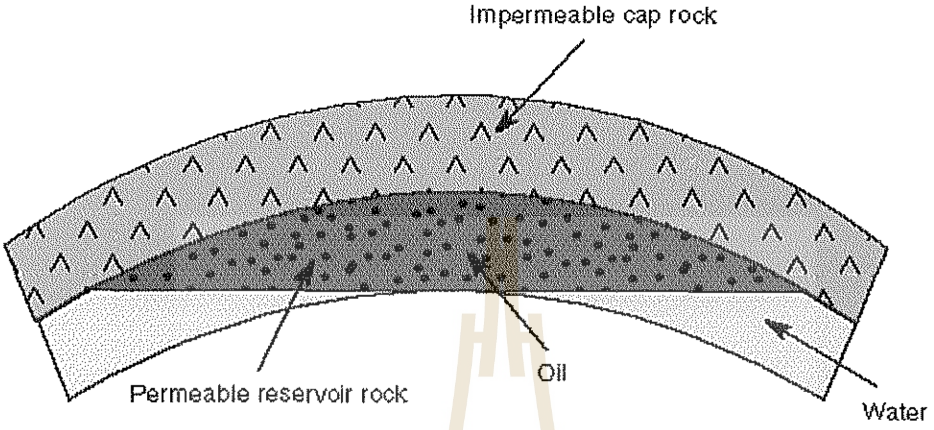
Carbonate Reservoirs

- Carbonates normally have a very irregular structure.
- Porosity:
  - Determined by the type of shells, etc. and by depositional and post-depositional events (fracturing, leaching, etc.).
- Permeability:
  - Determined by deposition and post-deposition events, fractures.
- Fractures can be very important in carbonate reservoirs.

Cap Rock

- A reservoir needs a cap rock.
- Impermeable cap rock keeps the fluids trapped in the reservoir.
- It must have zero permeability.
- Some examples are: Shale, Evaporites such as salt or anhyhdrite, Zero-porosity carbonates.

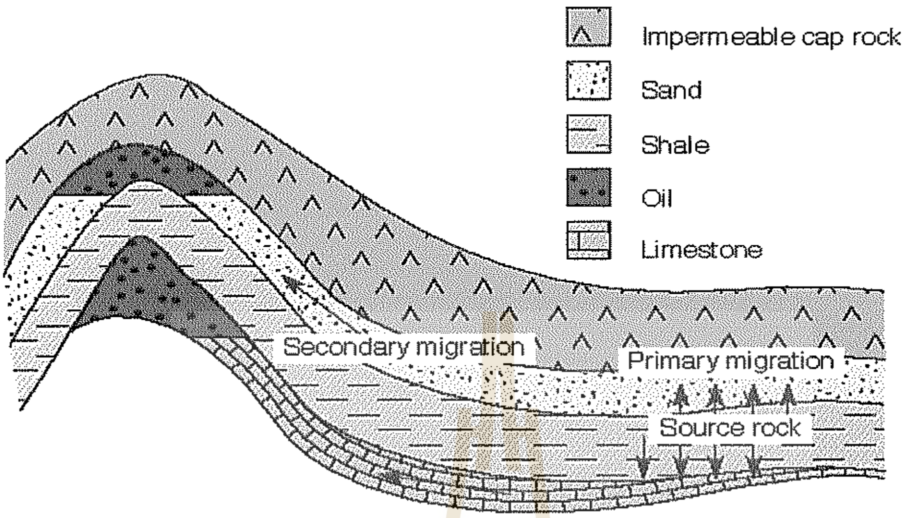
Cap Rock



Hydrocarbon Migration

- Hydrocarbon migration takes place in two stages:
    - Primary migration - from the source rock to a porous rock.
    - Secondary migration - along the porous rock to the trap.

Hydrocarbon Migration



Rock Classification

Clastics

Rock type	Particle diameter	
Conglomerate	Pebbles	2 - 64mm
Sandstone	Sand	.06 - 2mm
Siltstone	Silt	.003 - .06mm
Shale	Clay	<.003mm

Rock Classification

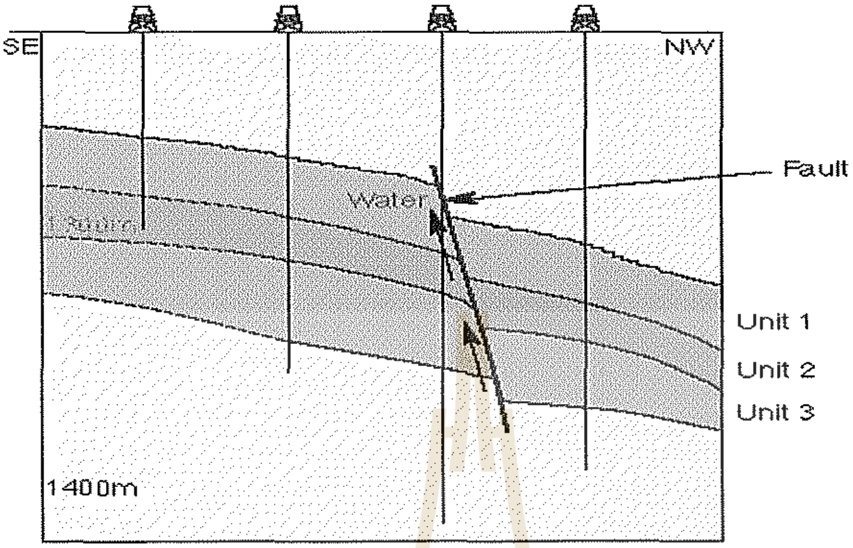
Non-Clastics

Rock type	Composition
Limestone	$CaCO_3$
Dolomite	$CaMg(CO_3)_2$
Salt	$NaCl$
Anhydrite	$CaSO_4$
Gypsum	$CaSO_4.2H_2O$
Coal	Carbon

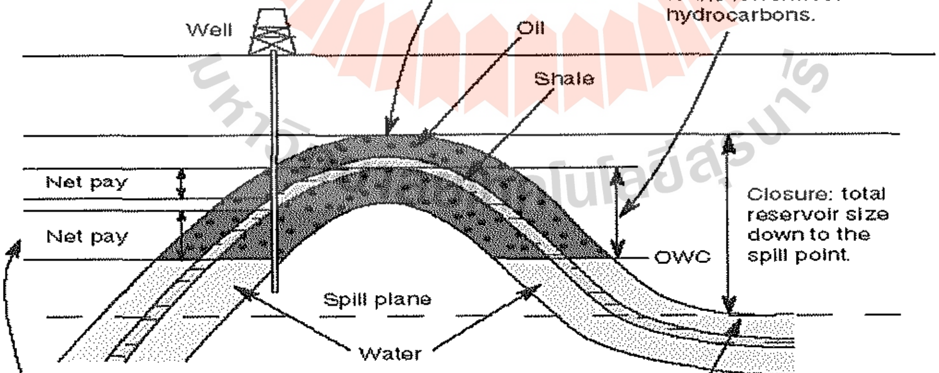
Reservoir Structure

- There are many other types of structure.
- The criteria for a structure is that it must have: Closure, i.e. the fluids are unable to escape.
- Be large enough to be economical.
- The exact form of the reservoir depends on the depositional environment and post depositional events such as foldings and faulting.

Reservoir Structure



Traps General



Crest: the highest point on a structure.

Gross pay: the total thickness of the reservoir zone from the top of the reservoir to the lowermost hydrocarbons.

Closure: total reservoir size down to the spill point.

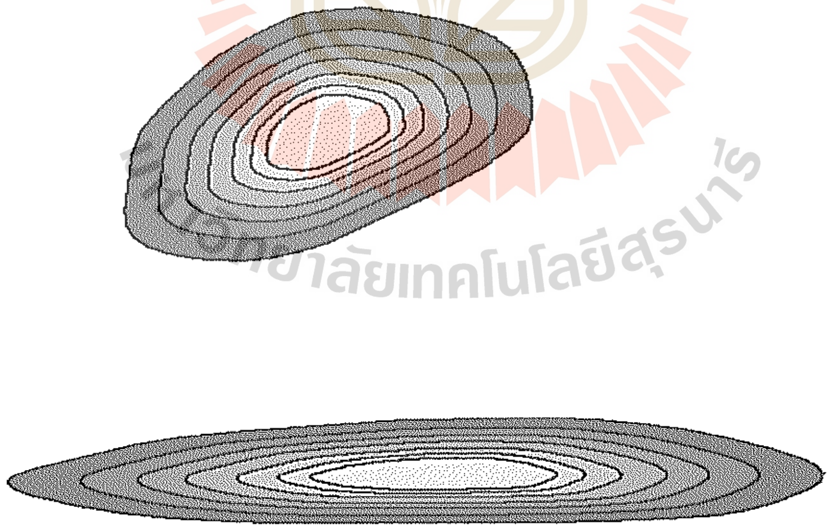
Net pay: the total thickness of producible hydrocarbons.

Spill point: connection to other systems.

Structural Traps

- The simplest form of trap is a dome.
- This is created by upward movement or folding of underlying sediments.
- An anticline is another form of simple trap. This is formed by the folding of layers of sedimentary rock.

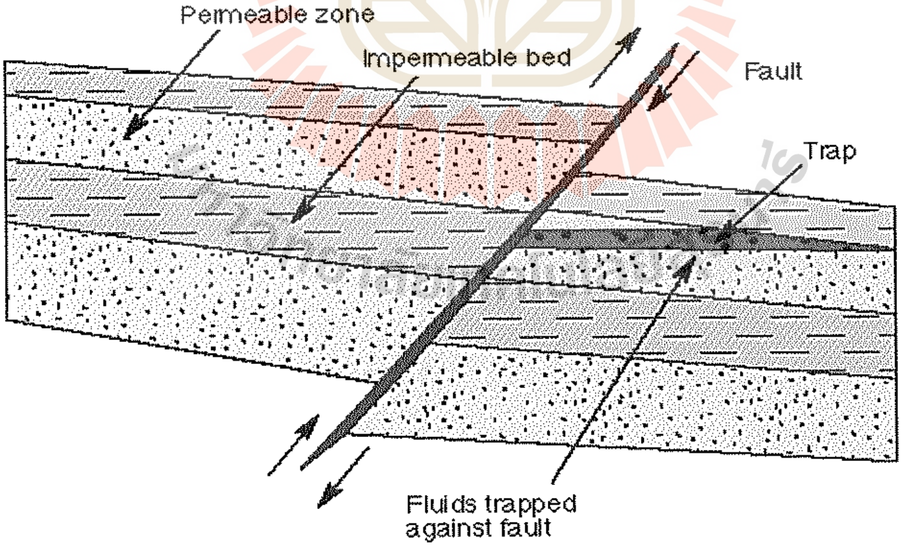
Structural Traps



Fault Traps

- Faults occur when the rock shears due to stresses. Reservoirs often form in these fault zones.
- A porous and permeable layer may trap fluids due to its location alongside an impermeable fault or its juxtaposition alongside an impermeable bed.
- Faults are found in conjunction with other structures such as anticlines, domes and salt domes.

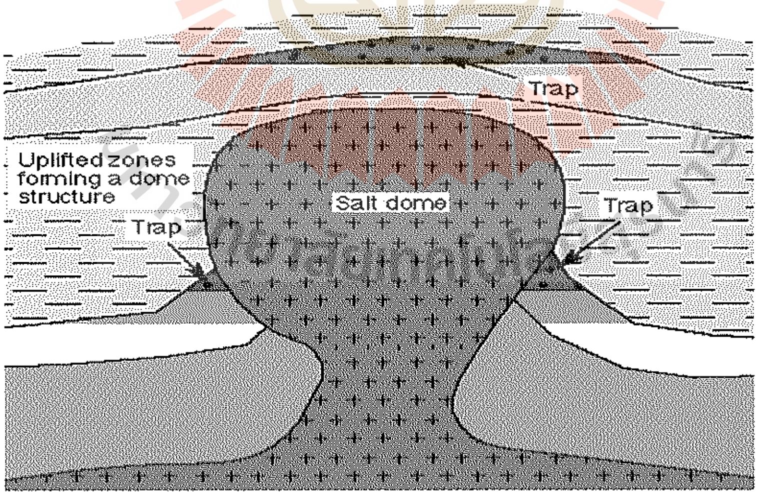
Fault Traps



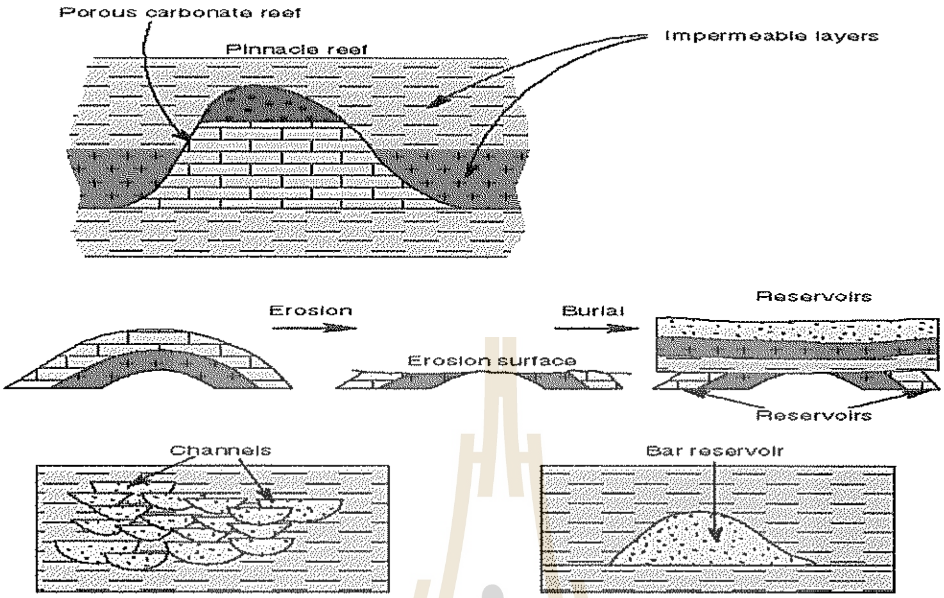
Salt Dome Trap

- Salt Dome traps are caused when "plastic" salt is forced upwards.
- The salt dome pierces through layers and compresses rocks above. This results in the formation of various traps:
- In domes created by formations pushed up by the salt.
- Along the flanks and below the overhang in porous rock abutting on the impermeable salt itself.

Salt Dome Trap



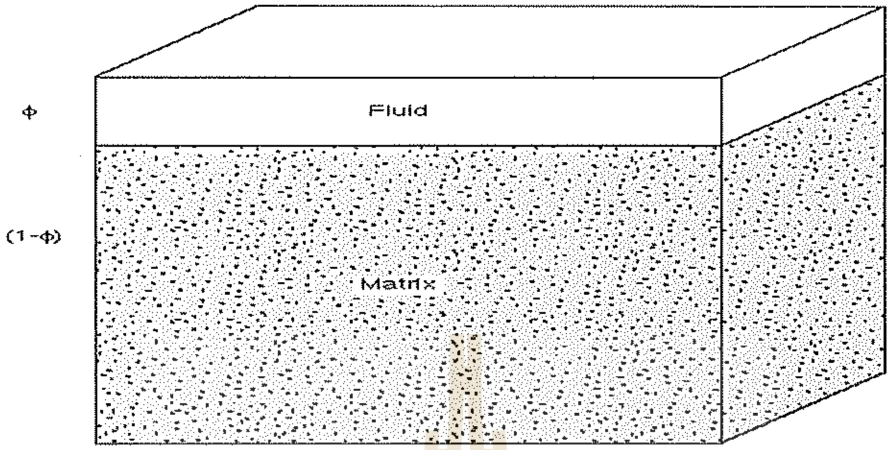
Stratigraphic Traps



Rock Properties

- Rocks are described by three properties:
  - Porosity - quantity of pore space
  - Permeability - ability of a formation to flow
  - Matrix - major constituent of the rock
  - Fluid Saturation – the quantity of fluid in the pore space of rock

Definition of Porosity



ϕ = Fraction of a unit volume occupied by pores or voids

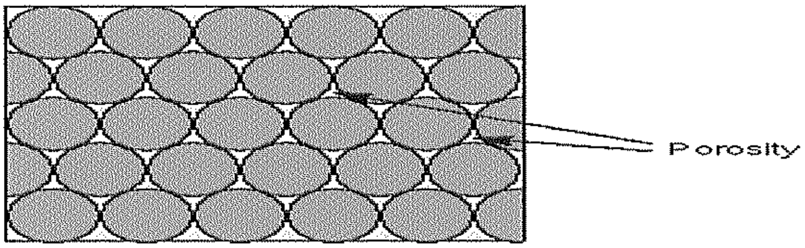
$$= \frac{V_{\text{Fluids}}}{\text{Total volume}}$$

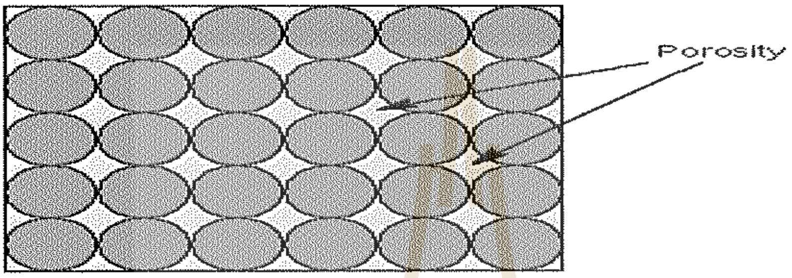
$(1 - \phi)$ = Matrix fraction

Porosity Sandstones

- The porosity of a sandstone depends on the packing arrangement of its grains.
- The system can be examined using spheres.

Porosity Sandstones



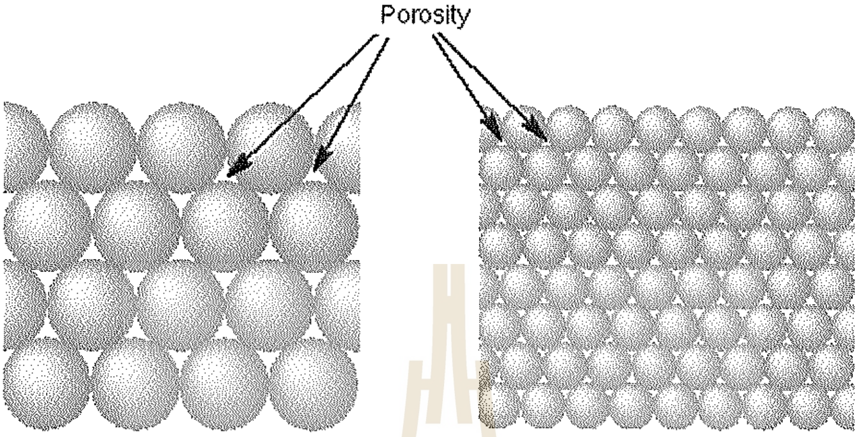


Porosity and Grain Size

- A rock can be made up of small grains or large grains but have the same porosity.

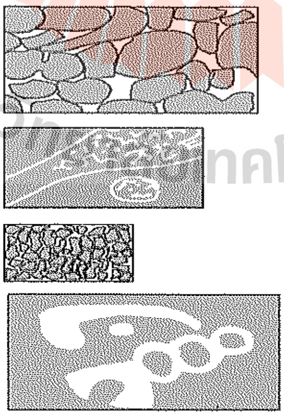
- Porosity depends on grain packing, not the grain size.

Porosity and Grain Size



Carbonate Porosity Types 1

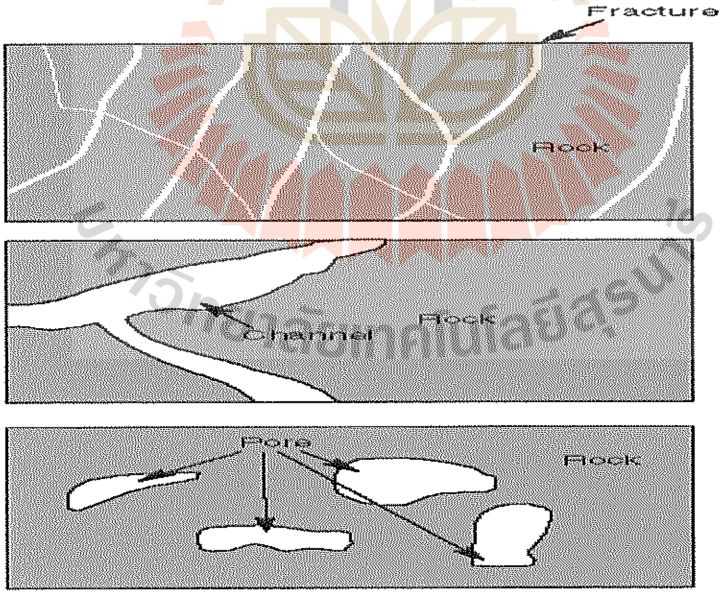
- Carbonate porosity is very heterogeneous. It is classified into a number of types:



Carbonate Porosity Types 2

- Fracture porosity: **Pore spacing created by the cracking of the rock fabric.**
- Channel porosity: **Similar to fracture porosity but larger**.
- Vuggy porosity: **Created by the dissolution of fragments, but unconnected.**

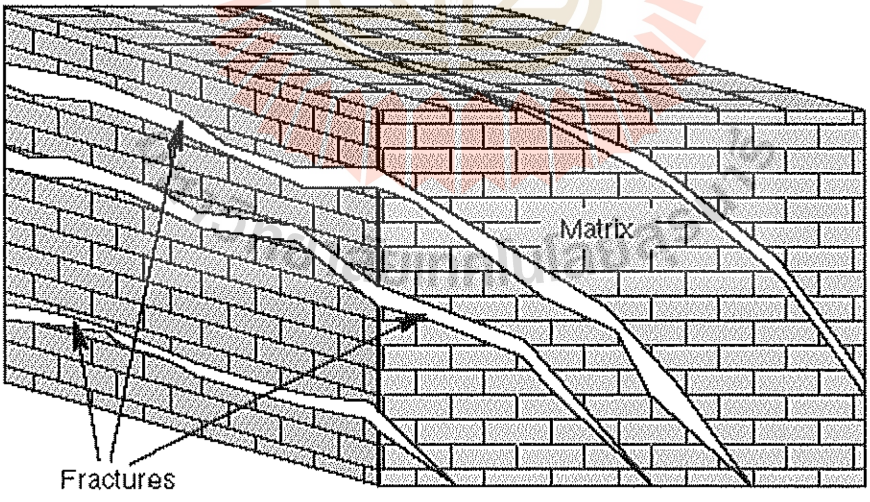
Carbonate Porosity Types 2



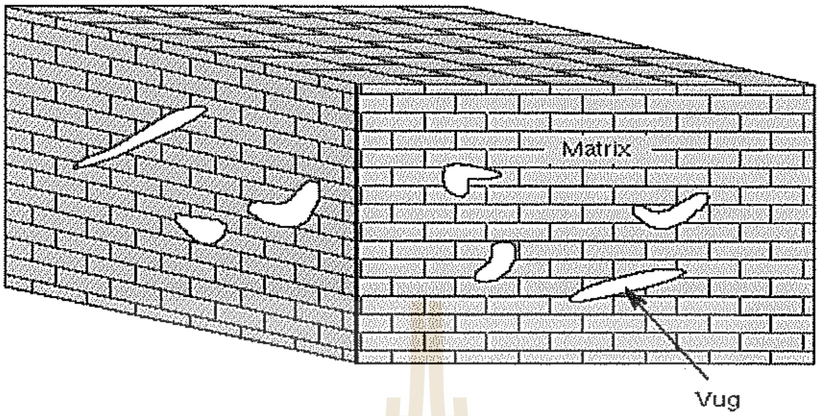
Carbonate Porosity

- Intergranular porosity is called "primary porosity".
- Porosity created after deposition is called "secondary porosity".
- The latter is in two forms:
  - Fractures
  - Vugs.

Fractures



Vugs



Permeability Definition

- The rate of flow of a liquid through a formation depends on:
    - The pressure drop.
    - The viscosity of the fluid.
    - The permeability.
- The pressure drop is a reservoir property.
- The viscosity is a fluid property.
- The permeability is a measure of the ease at which a fluid can flow through a formation.

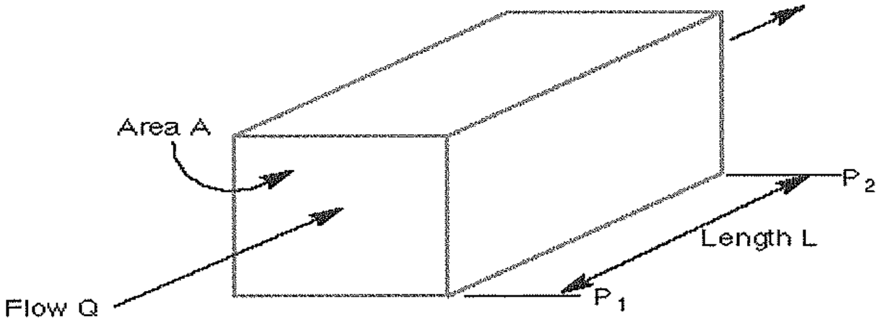
Permeability Definition

- Relationships exist between permeability and porosity for given formations, although they are not universal.
- A rock must have porosity to have any permeability.
- The unit of measurement is the Darcy.
- Reservoir permeability is usually quoted in millidarcies, (md).

Darcy Experiment

- The flow of fluid of viscosity through a porous medium was first investigated in 1856 by Henri Darcy.
- He related the flow of water through a unit volume of sand to the pressure gradient across it.
- In the experiment the flow rate can be changed by altering the parameters as follows:

Darcy Experiment



$Q \propto P_1 - P_2$

$Q \propto 1 / L$

$Q \propto A$

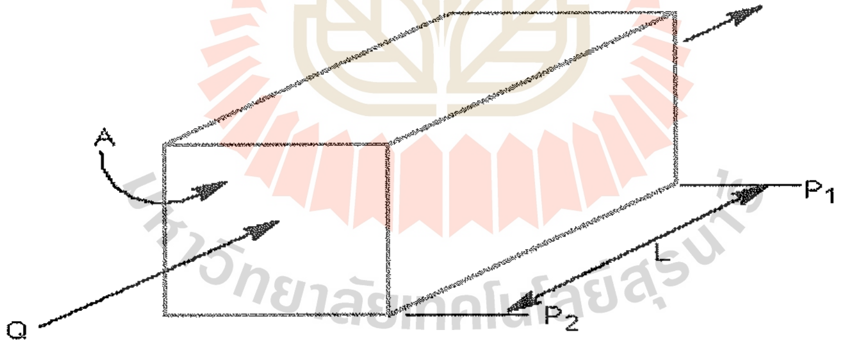
$Q \propto 1 / \mu$

$$Q \propto \frac{A\,(P_1 - P_2)}{\mu L}$$

$$Q = \text{constant} * \frac{A\,(P_1 - P_2)}{\mu L}$$

$$Q = \frac{k}{\mu}\,\frac{A\,(P_1 - P_2)}{L}$$

Darcy Law



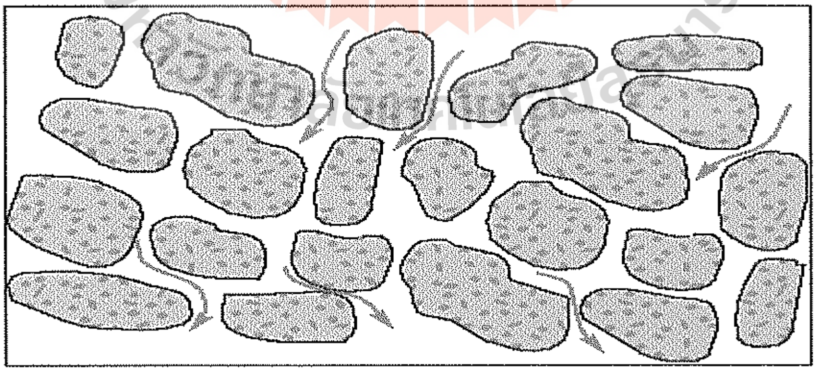
$$K = \frac{Q\mu}{A} \cdot \frac{L}{P_1 - P_2}$$

Darcy Law

- K = permeability, in Darcies.
- L = length of the section of rock, in centimetres.
- Q = flow rate in centimetres^3 / sec.
- P1, P2 = pressures in bars.
- A = surface area, in cm^2.
- μ = viscocity in centipoise.

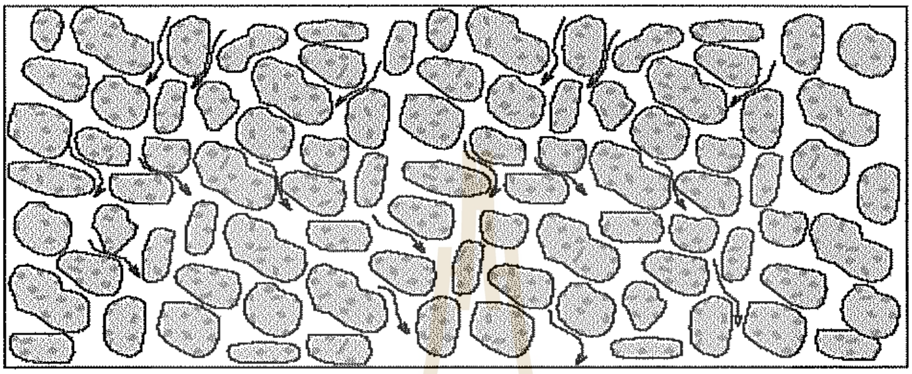
Permeability and Rocks

- In formations with large grains, the permeability is high and the flow rate larger.



Permeability and Rocks

- In a rock with small grains the permeability is less and the flow lower.



Permeability of Fractures

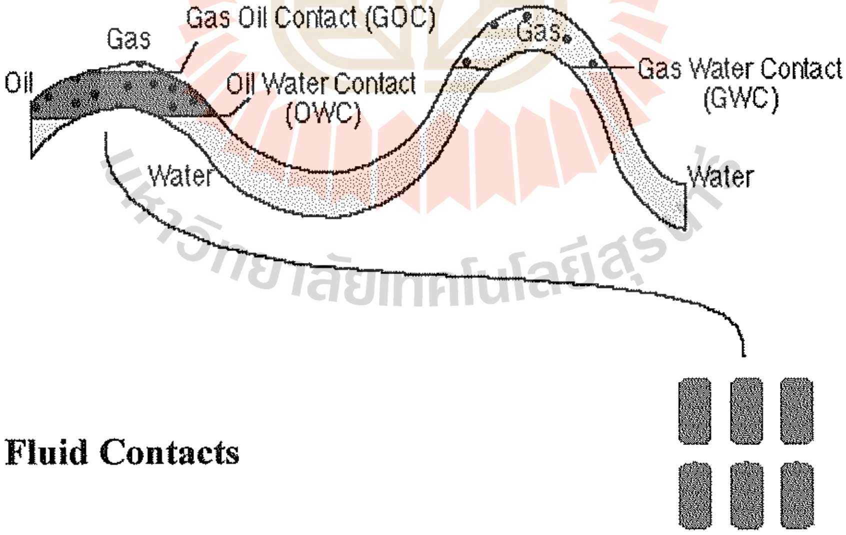
- The permeability of fractures has been estimated to be a function of the fracture width.

$$k = 50000000\,(\text{width})^2 \qquad \text{Eq(1-5)}$$

- Where k is the permeability in Darcys
  and width is in inches

Reservoir Fluids

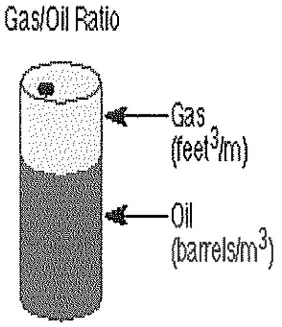
Definitions



Fluid Contacts

Definitions

Oil in Place — **OIP** The volume of oil in the reservoir in barrels or cubic metres.



Gas/Oil Ratio

GOR - The gas content of the oil.

API Gravity — **API** Oil gravity.

Gas/Oil Ratio GOR

GOR is the amount of Gas (ft^3) produced per Barrel of Oil

$$\text{GOR} = \frac{\text{Ft}^3 \text{ gas}}{\text{bbl of oil}}$$

API Gravity

$$^{0}\text{API} = \frac{141.5}{\text{SG}_{\text{oil}}} - 131.5$$

e.g. …. Water has API gravity of 10^{0}API

Fluids in a Reservoir

- A reservoir normally contains either water or hydrocarbon or a mixture.
- The hydrocarbon may be in the form of oil or gas.
- The specific hydrocarbon produced depends on the reservoir pressure and temperature.
- The formation water may be fresh or salty.
- The amount and type of fluid produced depends on the initial reservoir pressure, rock properties and the drive mechanism.

Hydrocarbon Composition

- Typical hydrocarbons have the following composition in Mol Fraction
  - **Dry gas**
  - **Condensate**
  - **Volatile oil**
  - **Black oil**
  - **Heavy oil**
  - **Tar/bitumen**

Hydrocarbon Classification

- Hydrocarbons are also defined by their weight and the Gas/Oil ratio. The table gives some typical values:

	GOR	API Gravity
Wet gas	100mcf/b	50-70
Condensate	5-100mcf/b	50-70
Volatile oil	3000cf/b	40-50
Black oil	100-2500cf/b	30-40
Heavy oil	0	10-30
Tar/bitumen	0	<10

Hydrocarbon Gas

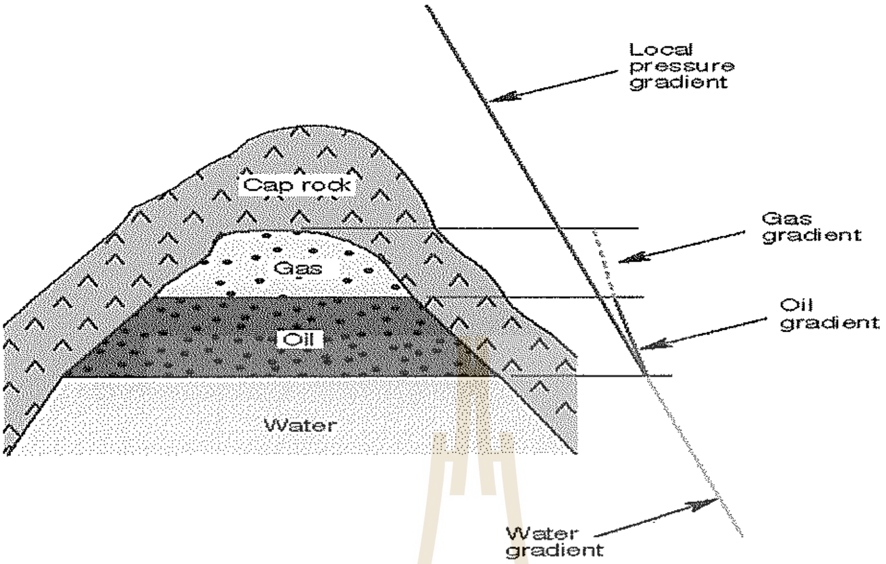
- Natural gas is mostly (60-80%) methane, CH_4. Some heavier gases make up the rest.
- Gas can contain impurities such as Hydrogen Sulphide, H_2S and Carbon Dioxide, CO_2.
- Gases are classified by their specific gravity which is defined as:

  "The ratio of the density of the gas to that of air at the same temperature and pressure".

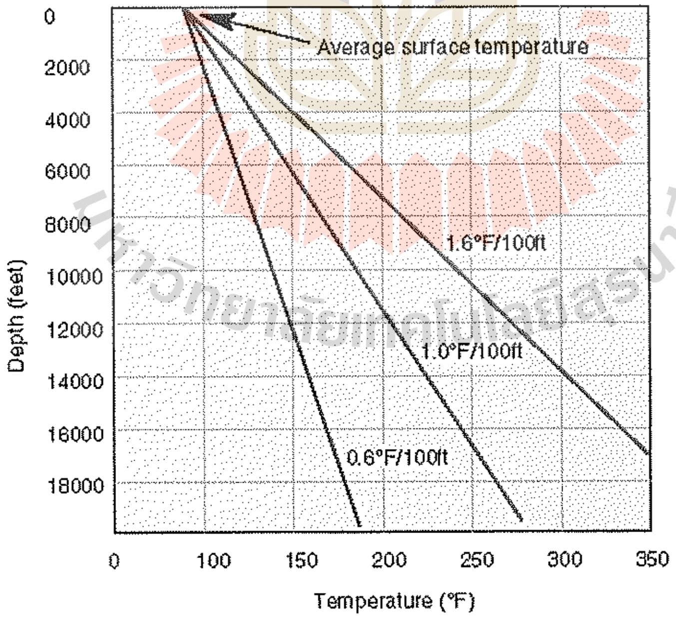
Reservoir Pressure

- Reservoir Pressures are normally controlled by the gradient in the aquifer.
- High pressures exist in some reservoirs.

Reservoir Pressure



Reservoir Temperature Gradient



Reservoir Temperature Gradient

- **The chart shows three possible temperature gradients. The temperature can be determined if the depth is known.**
- **High temperatures exist in some places. Local knowledge is important.**

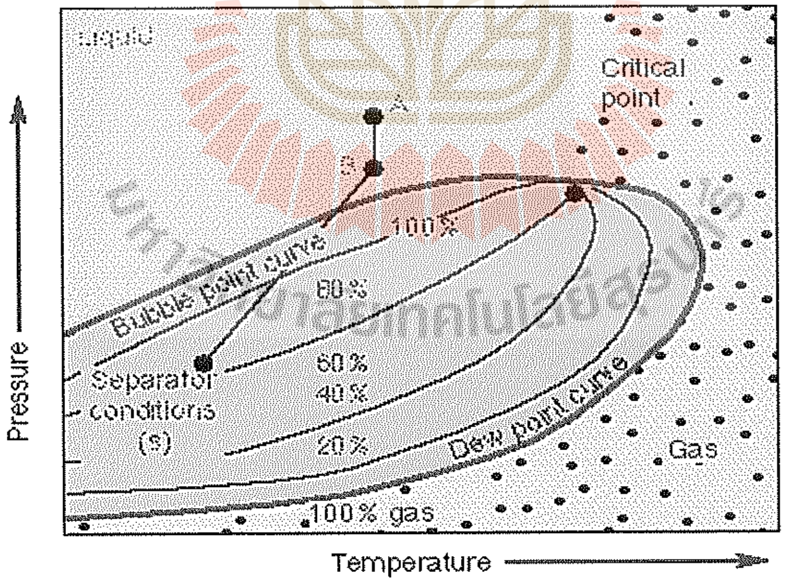
Fluid Phases

- A fluid phase is a physically distinct state, e.g.: gas or oil.
- In a reservoir oil and gas exist together at equilibrium, depending on the pressure and temperature.
- The behaviour of a reservoir fluid is analyzed using the properties; Pressure, Temperature and Volume (PVT).
- There are two simple ways of showing this:Pressure against temperature keeping the volume constant.

Phase diagram Oil

- The Pressure/Temperature (PT) phase diagram for an oil reservoir:
- Point 'A' is the initial reservoir condition of pressure and temperature.
- If the reservoir is produced at a constant temperature until the fluid reaches the wellbore, the line to Point 'B' is drawn. This represents the flow of fluid from the reservoir to the borehole. The fluid travelling to surface now drops in both temperature and pressure arriving at he "separator conditions" (s) with a final volume of oil and gas.

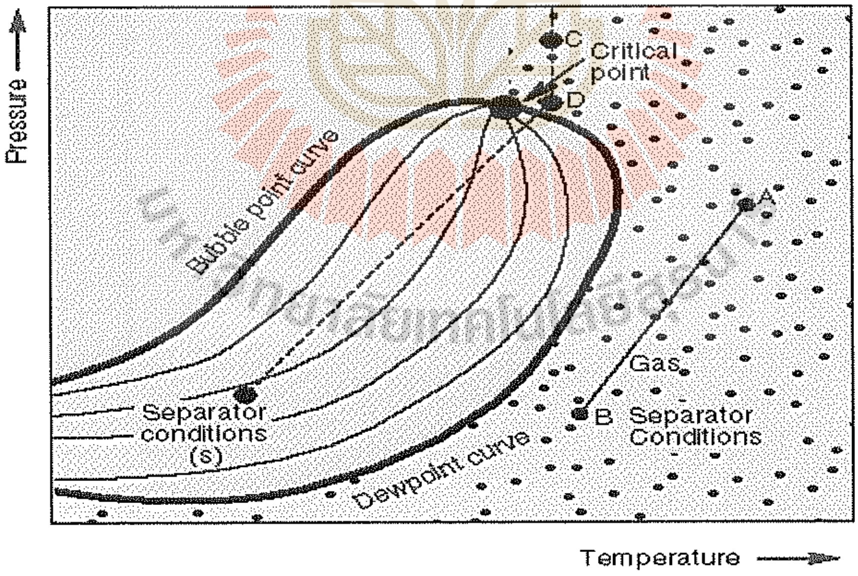
Phase diagram Oil



Phase Diagram Condensate/Gas

- Point 'C' is at the initial reservoir conditions. The reservoir is produced at a constant temperature from C to D. Fluids flowing up the well now drop in temperature and pressure, crossing the Dew point line and liquid condenses out.
- At separator conditions (s) the result in both liquid and gas on the surface.

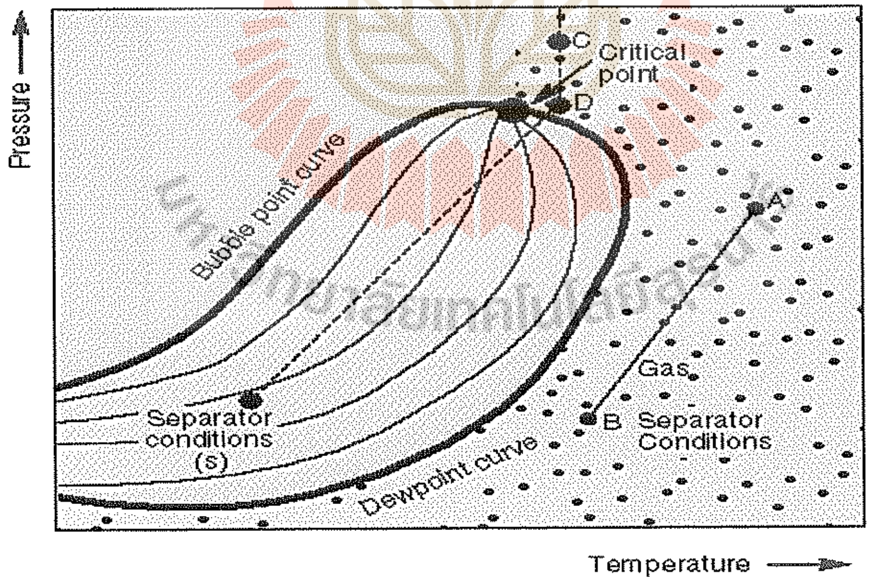
Phase Diagram Condensate/Gas



Gas Reservoir

- In a gas reservoir the initial point is A. Producing the well to separator conditions B does not change the fluid produced.
- The point B is still in the "gas region" and hence dry gas is produced.

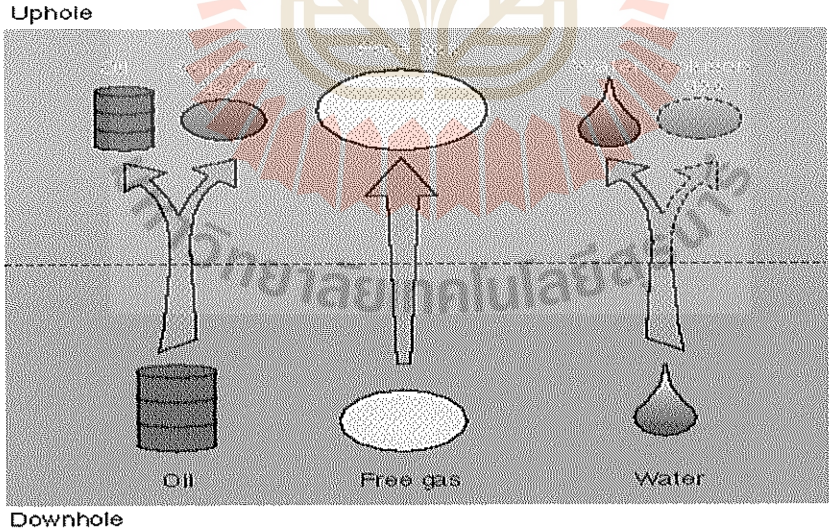
Gas Reservoir



Hydrocarbon Volumes

- Fluids at bottom hole conditions produce different fluids at surface:
  - Oil becomes oil plus gas.
  - Gas usually stays as gas unless it is a Condensate.
  - Water stays as water with occasionally some dissolved gas.

Hydrocarbon Volumes



Saturation

- Formation saturation is defined as the fraction of its pore volume (porosity) occupied by a given fluid.
- Saturation = $\dfrac{\textbf{Volume of a specific fluid}}{\textbf{pore volume}}$

- Definitions

  Sw = water saturation.

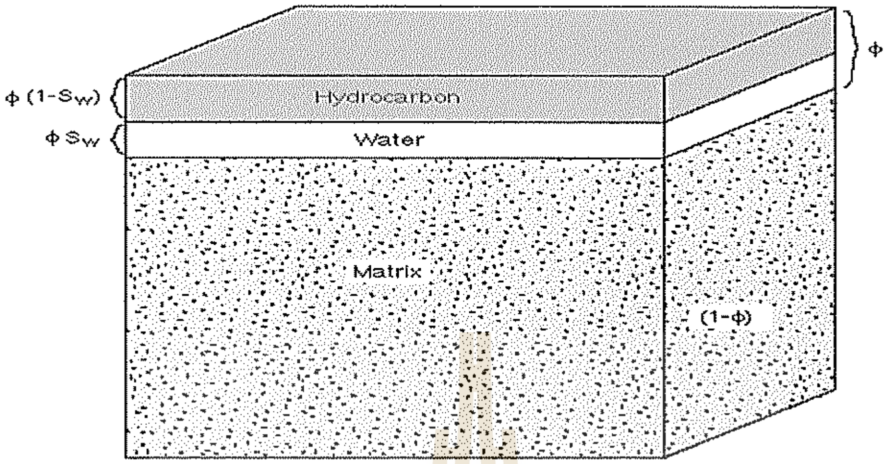
  So = oil saturation.

  Sg = gas saturation.

  Sh = hydrocarbon saturation

  = So + Sg
- Saturations are expressed as percentages or fractions, e.g. Water saturation of 75% in a reservoir with porosity of 20% contains water equivalent to 15% of its volume.

Saturation Definition



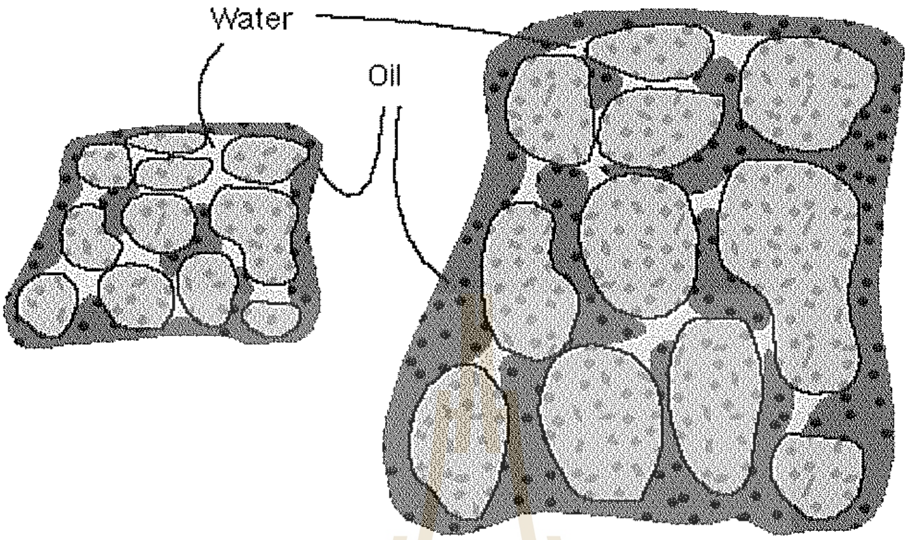
ϕS_W = amount of water per unit volume

$\phi(1-S_W)$ = amount of hydrocarbon per unit volume

Irreducible Water Saturation

- In a formation the minimum saturation induced by displacement is where the wetting phase becomes discontinuous.
- In normal water-wet rocks, this is the irreducible water saturation, Swirr.
- Large grained rocks have a low irreducible water saturation compared to small-grained formations because the capillary pressure is smaller.

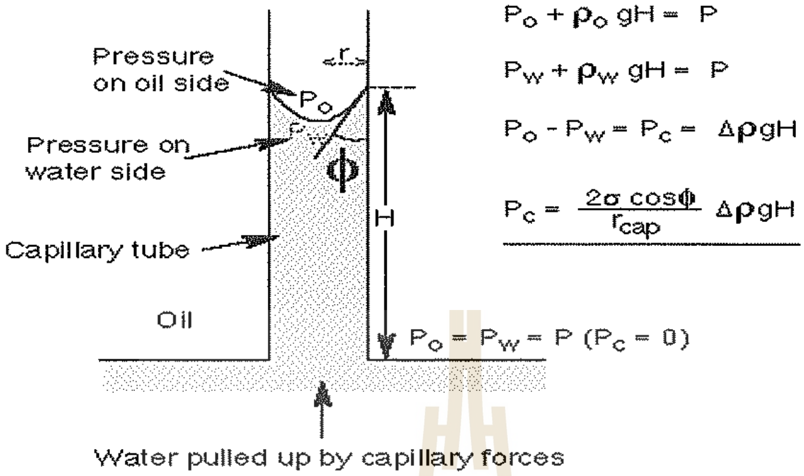
Irreducible Water Saturation



Capillary Forces and Rocks

- In a reservoir the two fluids are oil and water which are immiscible hence they exhibit capillary pressure phenomena.
- This is seen by the rise in the water above the point where the capillary pressure is zero.

Capillary Forces and Rocks



$P_o + \rho_o gH = P$

$P_w + \rho_w gH = P$

$P_o - P_w = P_c = \Delta\rho gH$

$P_c = \frac{2\sigma\cos\phi}{r_{cap}}\ \Delta\rho gH$

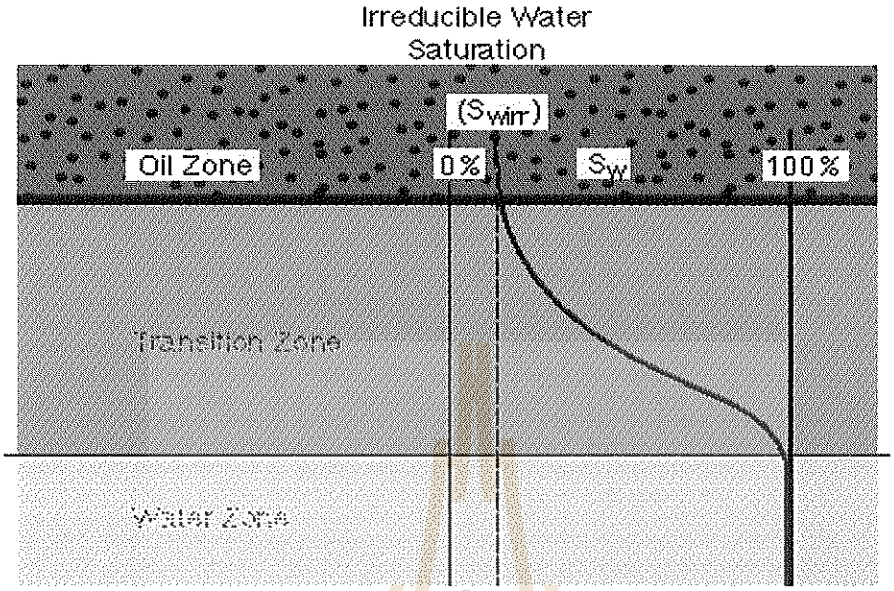
$P_o = P_w = P\ (P_c = 0)$

The height depends on the density difference and the radius of the capillaries.

Transition Zone

- The phenomenon of capillary pressure gives rise to the transition zone in a reservoir between the water zone and the oil zone.
- The rock can be thought of as a bundle of capillary tubes.
- The length of the zone depends on the pore size and the density difference between the two fluids.

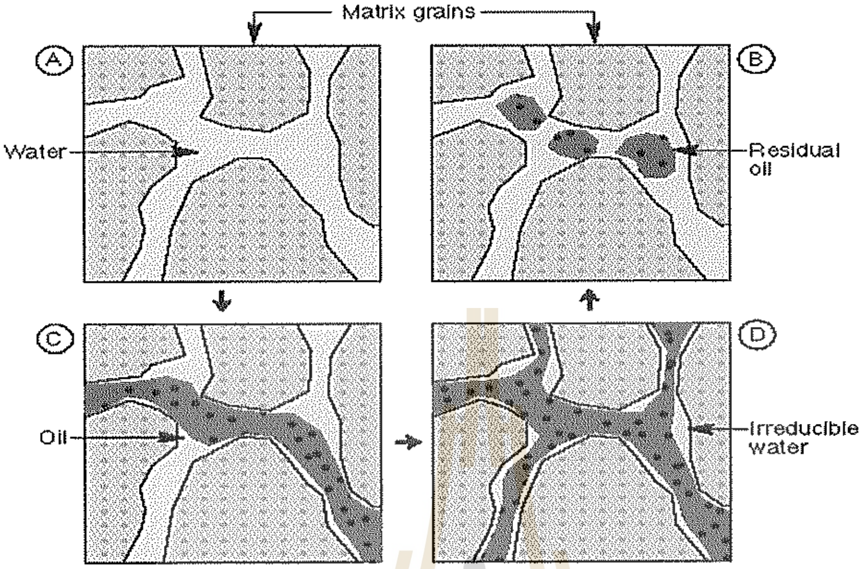
Transition Zone



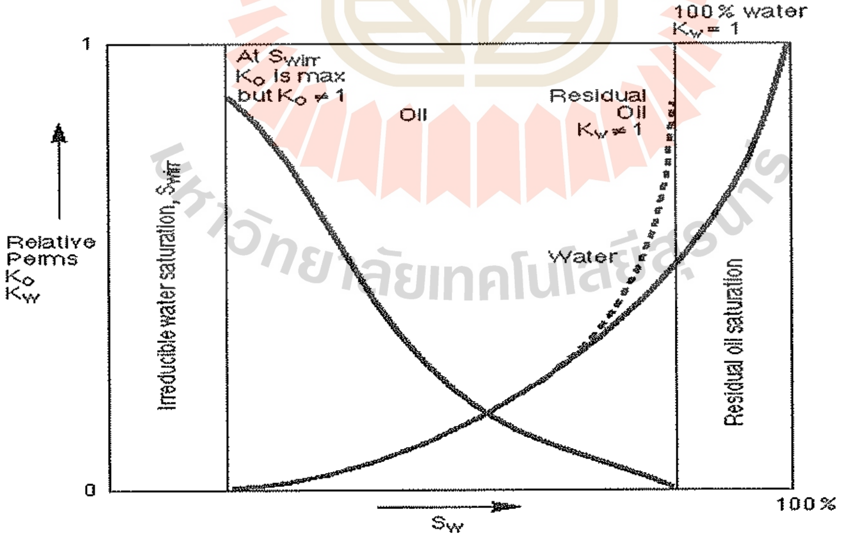
Relative Permeability

- Take a core 100% water-saturated. (A)
- Force oil into the core until irreducible water saturation is attained (Swirr). (A-> C -> D)
- Reverse the process: force water into the core until the residual saturation is attained. (B)
- During the process, measure the relative permeabilities to water and oil.

Relative Permeability



Relative Permeability Experiment



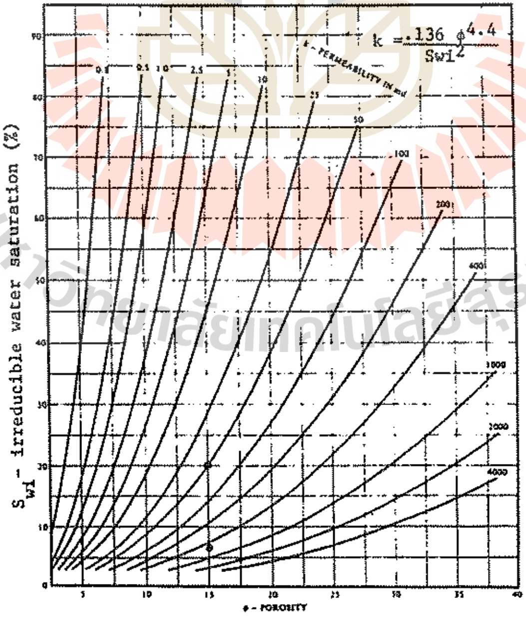
Permeability Estimation

- From figure 1-3, if we have the porosity data and fluid saturation data then we can estimate the value of permeability for granular rocks by figure 1-3 or by equation as shown in below:

$$k = \frac{0.136\phi^{4.4}}{S_{wi}^{2}}$$

**The value of ϕ and Sw are used in percentage

Fig 1-3 Swi-k-ϕ for granular rocks



Drive Mechanisms

A virgin reservoir has a pressure controlled by the local gradient.

Hydrocarbons will flow if the reservoir pressure is sufficient to drive the fluids to the surface (otherwise they have to be pumped). As the fluid is produced reservoir pressure drops.

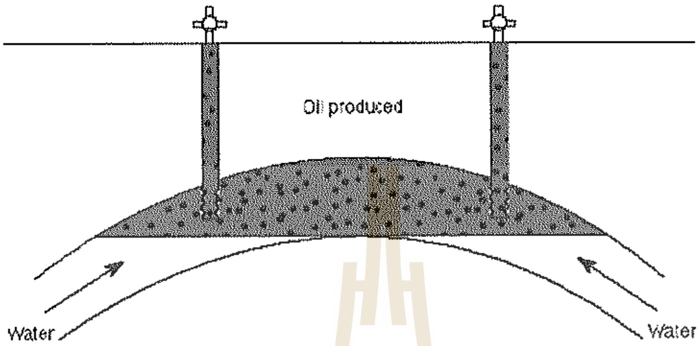
The rate of pressure drop is controlled by the Reservoir Drive Mechanism.

* Drive Mechanism depends on the rate at which fluid expands to fill the space vacated by the produced fluid.

- Main Reservoir Drive Mechanism types are:
  - Water drive.
  - Gas cap drive.
  - Gas solution drive

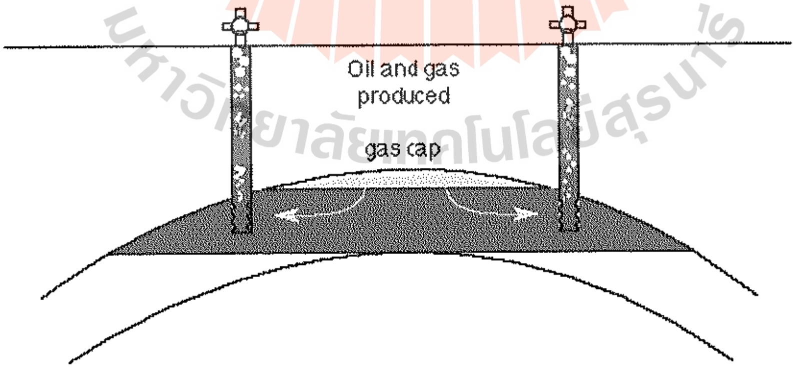
Water Drive

Water moves up to fill the "space" vacated by the oil as it is produced.



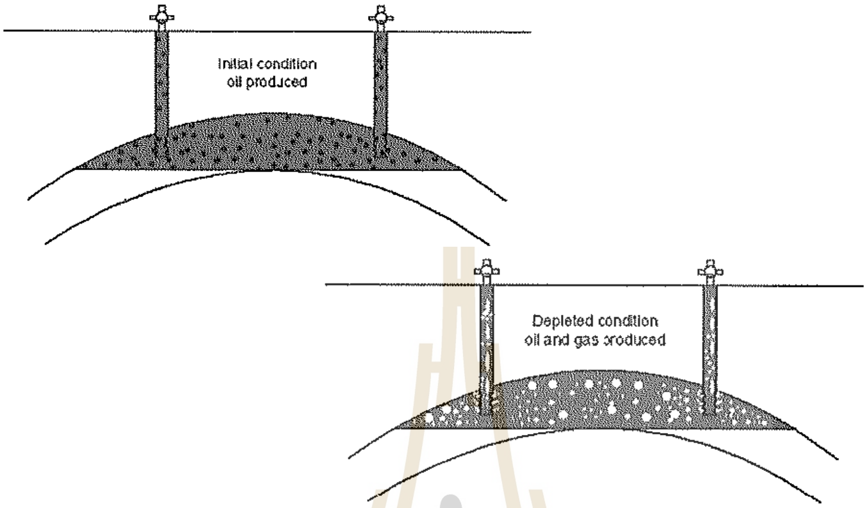
Gas Cap Drive

- Gas from the gas cap expands to fill the space vacated by the produced oil.



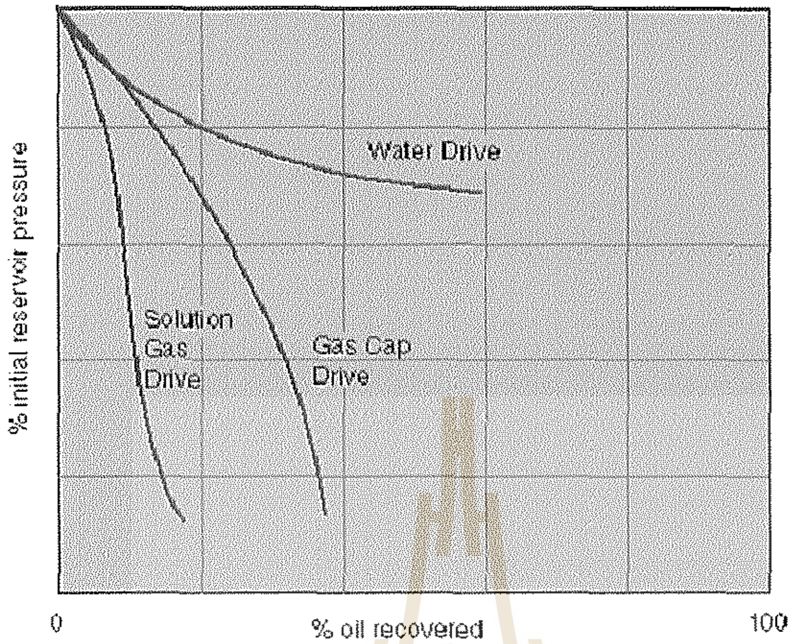
Solution Gas Drive

- After some time the oil in the reservoir is below the bubble point.



Drives General

- A water drive can recover up to 60% of the oil in place.
- A gas cap drive can recover only 40% with a greater reduction in pressure.
- A solution gas drive has a low recovery.



Example 1-1

Example 1-1 shows an analysis of a continuous 100 feet of limestone with no shale breaks. The separate reservoirs are marked as well as the hydrocarbon-water contacts .

- Example 1-1 Interpretation of a Limestone Sw ϕ Data

Sw%	ϕ%	Thickness	Interpretation
100	2	10	wet and non permeability
100	8	5	will probably produce water
100	3	7	non-permeable
30	9	11	hydrocarbon reservoir
80	11	9	will produce water
95	3	22	non-permeable
90	8	16	will produce water

Hydrocarbon/water contact

Introduction to Open Hole Logging

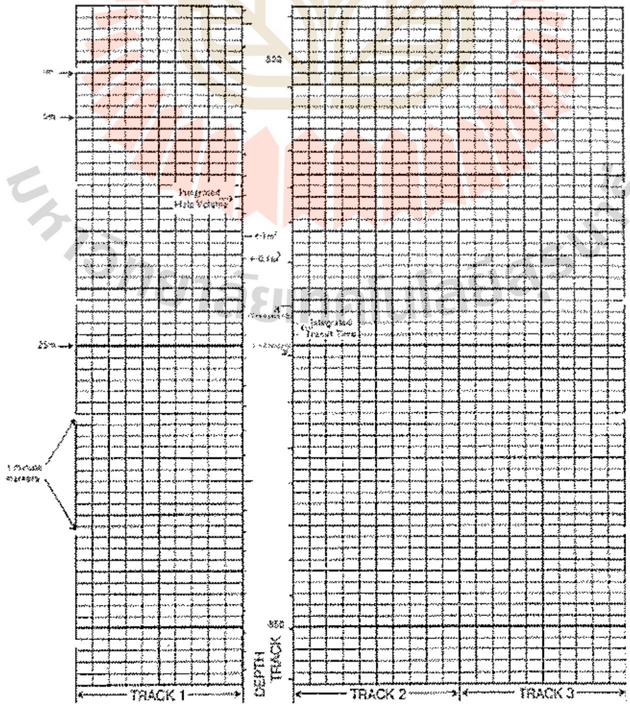
LOG SCALES AND PRESENTATIONS

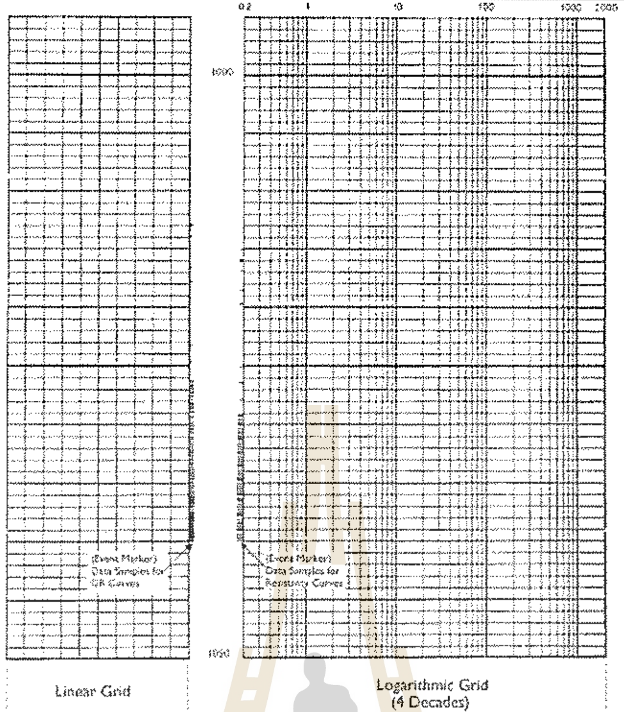
a. Well logs provide a continuous graph of formation parameters versus depth.

Normal depth scales are:

- 1:240 →1 metre of log per 240 metres of measured hole depth.
- 1:600 →1 metre of log per 600 metres of measured hole depth.

- Other scales are available. These include 1:1200, 1:120, 1:48 and 1:5.
- Log grids may be either logarithmic (Resistivity logs) or linear (Porosity logs).

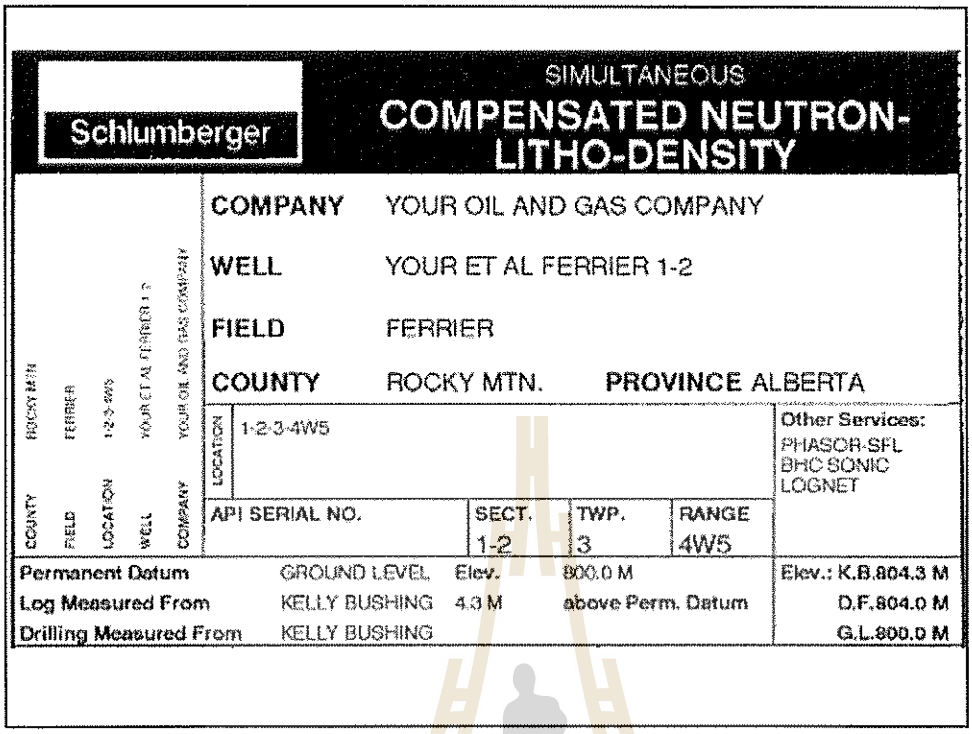




- Logs also have headings and inserts

  - Log headings provide such information as well depth, casing depth, mud parameters, maximum temperature, and other comments pertinent to evaluation of log data.

  - Inserts provide such information as curve scaling, coding, date/time of acquisition, data curve first reading points and constants pertinent to the logging run following the insert. Curve coding on the log data indicates the deepest reading primary measurement (long dashed), to the shallowest reading primary measurement (solid), when two or more measurements are combined.



Schlumberger

SIMULTANEOUS
COMPENSATED NEUTRON-LITHO-DENSITY

COUNTY	ROCKY MTN
FIELD	FERRIER
LOCATION	1-2-3-4W5
WELL	YOUR ET AL FERRIER 1-2
COMPANY	YOUR OIL AND GAS COMPANY

COMPANY YOUR OIL AND GAS COMPANY

WELL YOUR ET AL FERRIER 1-2

FIELD FERRIER

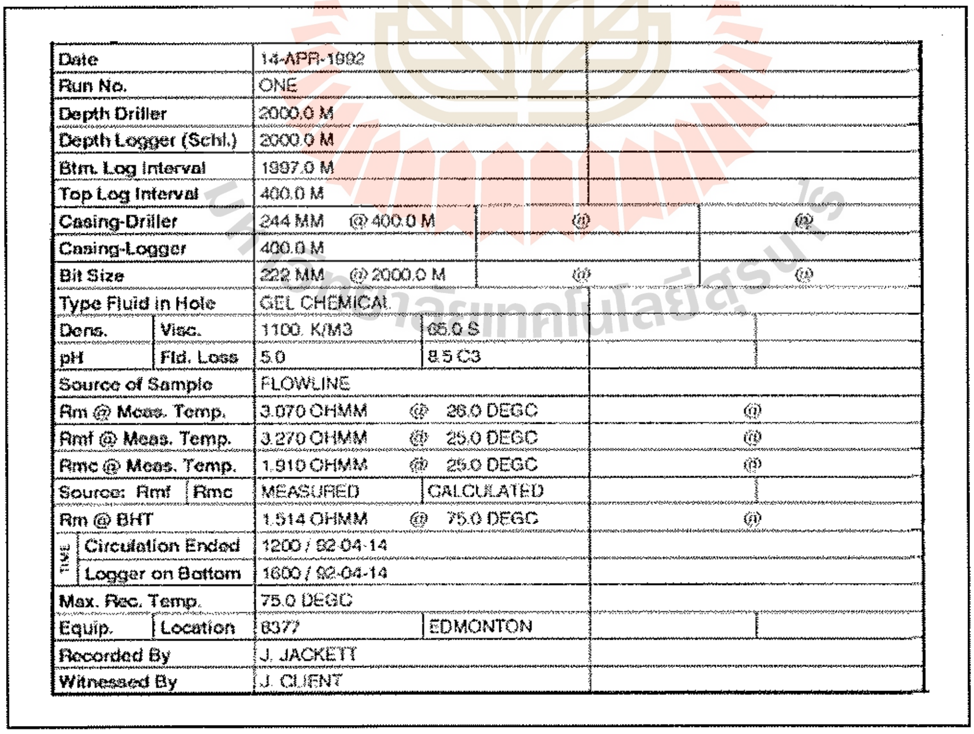
COUNTY ROCKY MTN. **PROVINCE** ALBERTA

LOCATION 1-2-3-4W5

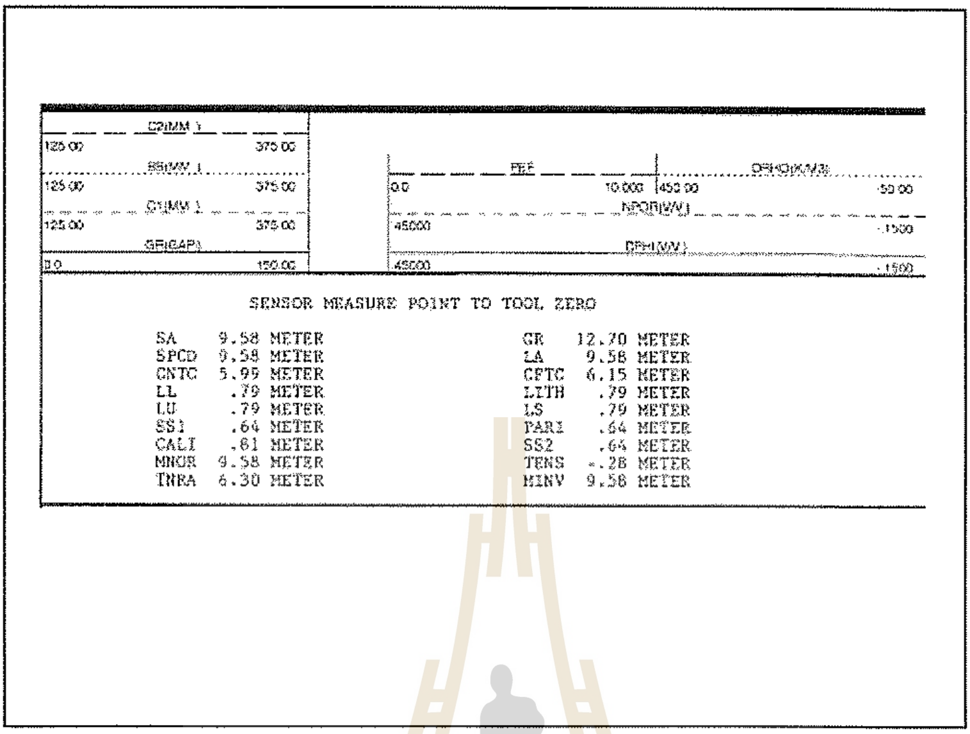
Other Services:
PHASOR-SFL
BHC SONIC
LOGNET

API SERIAL NO.	SECT.	TWP.	RANGE
	1-2	3	4W5

Permanent Datum	GROUND LEVEL	Elev.	800.0 M		Elev.: K.B.804.3 M
Log Measured From	KELLY BUSHING	4.3 M	above Perm. Datum		D.F.804.0 M
Drilling Measured From	KELLY BUSHING				G.L.800.0 M



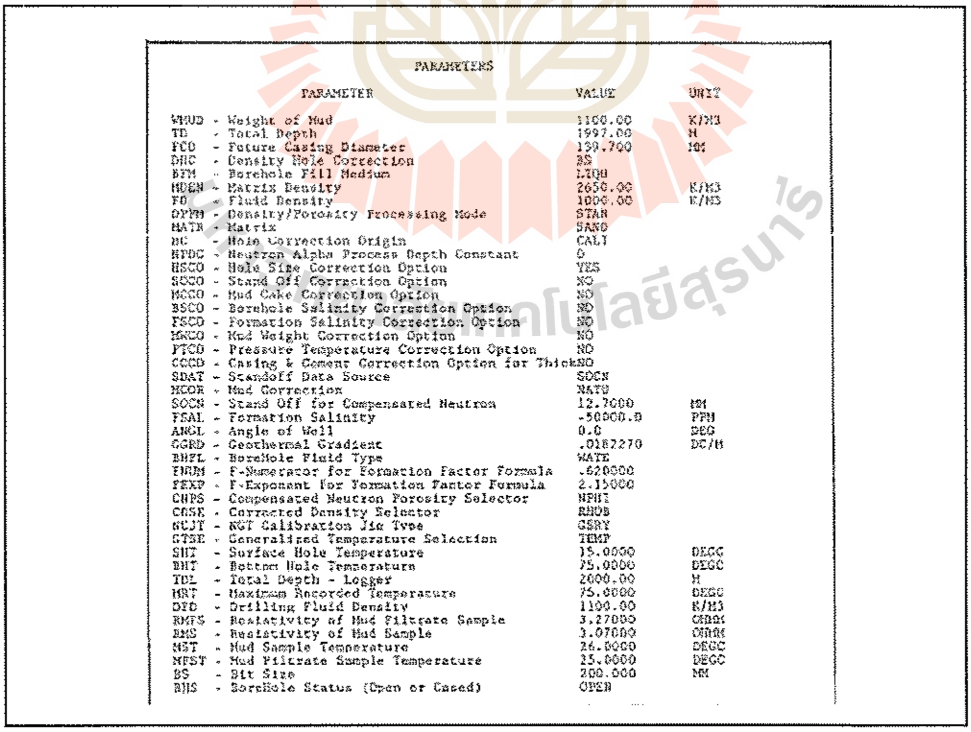
Date		14-APR-1992			
Run No.		ONE			
Depth Driller		2000.0 M			
Depth Logger (Schl.)		2000.0 M			
Btm. Log Interval		1997.0 M			
Top Log Interval		400.0 M			
Casing-Driller		244 MM @ 400.0 M		@	@
Casing-Logger		400.0 M			
Bit Size		222 MM @ 2000.0 M		@	@
Type Fluid in Hole		GEL CHEMICAL			
Dens.	Visc.	1100. K/M3	65.0 S		
pH	Fld. Loss	5.0	8.5 C3		
Source of Sample		FLOWLINE			
Rm @ Meas. Temp.		3.070 OHMM @ 26.0 DEGC		@	
Rmf @ Meas. Temp.		3.270 OHMM @ 25.0 DEGC		@	
Rmc @ Meas. Temp.		1.910 OHMM @ 25.0 DEGC		@	
Source: Rmf	Rmc	MEASURED	CALCULATED		
Rm @ BHT		1.514 OHMM @ 75.0 DEGC		@	
TIME	Circulation Ended	1200 / 92-04-14			
	Logger on Bottom	1600 / 92-04-14			
Max. Rec. Temp.		75.0 DEGC			
Equip.	Location	8377	EDMONTON		
Recorded By		J. JACKETT			
Witnessed By		J. CLIENT			



```
         C2(MM )
125.00              375.00
         BS(MM )                        PEF                    DRHO(K/M3)
125.00              375.00        0.0              10.000 |450.00               -50.00
         C1(MM )                                       NPOR(V/V)
125.00              375.00        .45000                                         -.1500
         GR(GAPI)                                      DPHI(V/V)
0.0                 150.00        .45000                                         -.1500

              SENSOR MEASURE POINT TO TOOL ZERO

     SA     9.58 METER                   GR    12.70 METER
     SPCD   9.58 METER                   LA     9.58 METER
     CNTC   5.99 METER                   CFTC   6.15 METER
     LL      .79 METER                   LITH    .79 METER
     LU      .79 METER                   LS      .79 METER
     SS1     .64 METER                   PARI    .64 METER
     CALI    .81 METER                   SS2     .64 METER
     MNOR   9.58 METER                   TENS   -.28 METER
     INRA   6.30 METER                   MINV   9.58 METER
```



```
                          PARAMETERS

          PARAMETER                              VALUE       UNIT

WMUD - Weight of Mud                             1100.00     K/M3
TD   - Total Depth                               1997.00     M
FCD  - Future Casing Diameter                    139.700     MM
DHC  - Density Hole Correction                   BS
BFM  - Borehole Fill Medium                      LIQU
MDEN - Matrix Density                            2650.00     K/M3
FD   - Fluid Density                             1000.00     K/M3
DPPM - Density/Porosity Processing Mode          STAN
MATR - Matrix                                    SAND
HC   - Hole Correction Origin                    CALI
NPDC - Neutron Alpha Process Depth Constant      0
HSCO - Hole Size Correction Option               YES
SOCO - Stand Off Correction Option               NO
MCCO - Mud Cake Correction Option                NO
BSCO - Borehole Salinity Correction Option       NO
FSCO - Formation Salinity Correction Option      NO
MWCO - Mud Weight Correction Option              NO
PTCO - Pressure Temperature Correction Option    NO
CCCO - Casing & Cement Correction Option for ThickNO
SDAT - Standoff Data Source                      SOCN
MCOR - Mud Correction                            NATU
SOCN - Stand Off for Compensated Neutron         12.7000     MM
FSAL - Formation Salinity                        -50000.0    PPM
ANGL - Angle of Well                             0.0         DEG
GGRD - Geothermal Gradient                       .0182270    DC/M
BHFL - BoreHole Fluid Type                       WATE
FNUM - F-Numerator for Formation Factor Formula  .620000
FEXP - F-Exponent for Formation Factor Formula   2.15000
CNPS - Compensated Neutron Porosity Selector     NPHI
CDSE - Corrected Density Selector                RHOB
NCJT - NGT Calibration Jig Type                  GSRY
GTSE - Generalized Temperature Selection         TEMP
SHT  - Surface Hole Temperature                  35.0000     DEGC
BHT  - Bottom Hole Temperature                   75.0000     DEGC
TDL  - Total Depth - Logger                      2000.00     M
MRT  - Maximum Recorded Temperature              75.0000     DEGC
DFD  - Drilling Fluid Density                    1100.00     K/M3
RMFS - Resistivity of Mud Filtrate Sample        3.27000     OHMM
RMS  - Resistivity of Mud Sample                 3.07000     OHMM
MST  - Mud Sample Temperature                    26.0000     DEGC
MFST - Mud Filtrate Sample Temperature           25.0000     DEGC
BS   - Bit Size                                  200.000     MM
BHS  - BoreHole Status (Open or Cased)           OPEN
```

Chapter 2
Resistivity

INTRODUCTION

The resistivity of a formation is a key parameter in determining hydrocarbon saturation. Electricity can pass through a formation only because of the conductive water it contains. With a few rare exceptions, such as metallic sulfide and graphite, dry rock is a good electrical insulator.

- For the purposes of our discussions we will divide substances into two general categories, ***conductors*** or ***insulators***.
- Conductors are substances which pass electrical current e.g. water, shales, mud.
- Insulators are substances which do not allow electrical current flow e.g. hydrocarbons, or rock matrix.

- The measured resistivity of a formation depends on:

  - Resistivity of the formation water.

  - Amount of water present.

  - Pore structure geometry.

- The units of resistivity are ohm-metres squared per metre, or simply ohm-metres (ohmm).
- Formation resistivities are usually from 0.2 to 1000 ohm-m. Resistivities higher than 1000 ohm-m are uncommon in permeable formations but are observed in impervious, very low porosity formations (e.g., evaporites).

- The electrical resistivity of any material is related to the resistance by:

$$R = \frac{rA}{L} \qquad \text{Eq(2-1)}$$

- Where

  A is the area the current is flowing through

  L is the length of material

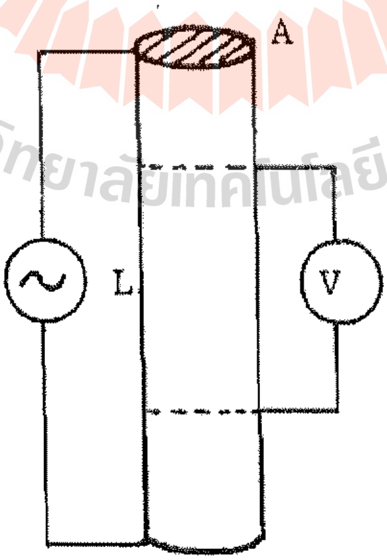
  r is the electrical resistance in ohms

  R is the electrical resistance in ohms meter in normal logging units where A and L are in meter

The resistivity of fluids

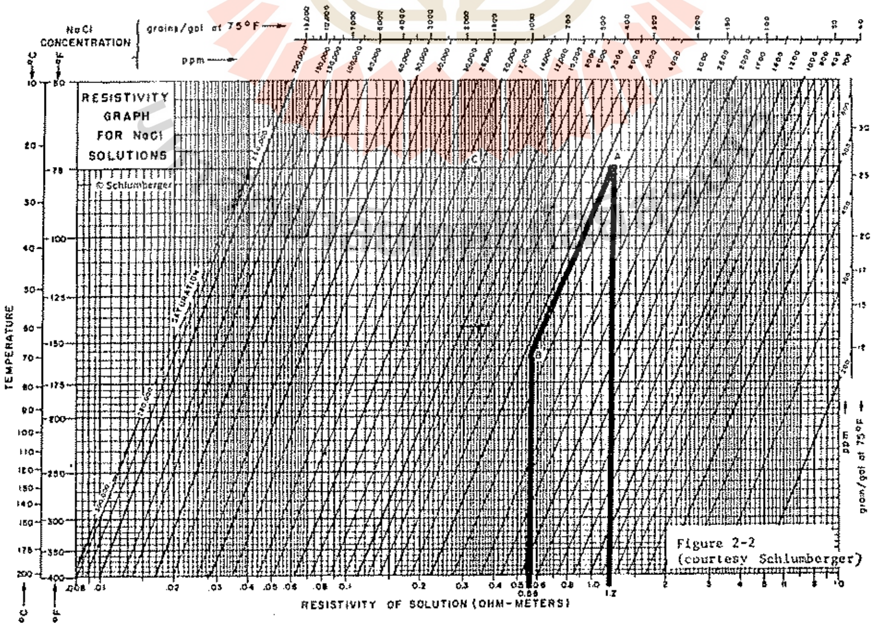
The resistivity of fluids are measured by devices similar to the "mud cup" shown in figure 2-1. The resistivity of hydrocarbons, such as oil and gas, is in the order of millions of ohm meters which makes them electrical insulators.

Fig 2-1

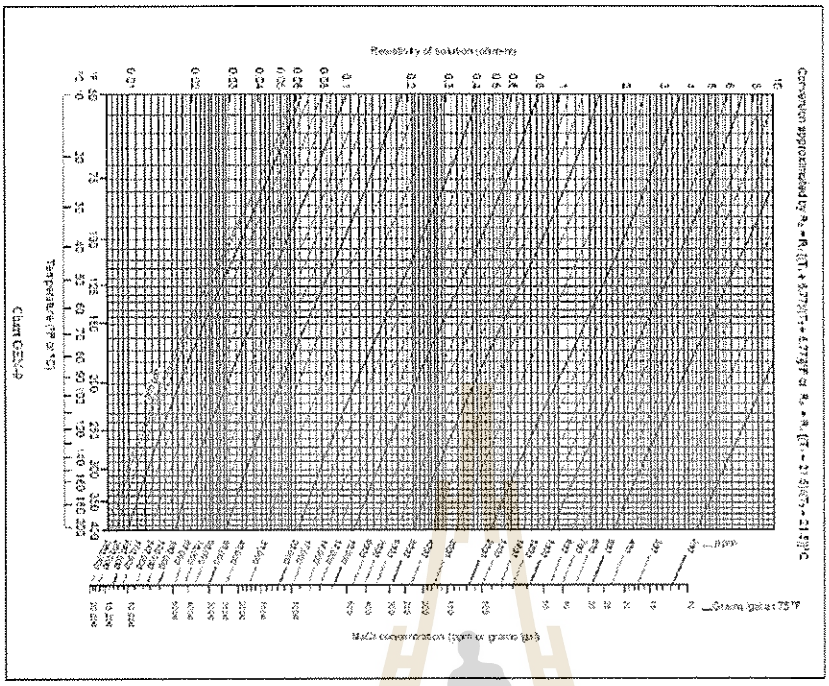


- Water has a variable resistivity depending upon the salinity (amount of salt).
- The resistivity of water is not only a function of the salinity but also a function of temperature. The higher the temperature, the lower the resistivity for a given salinity. Figure 2-2 shows the relationship between water resistivity, salinity and temperature.

Figure 2-2



Resistivity of NaCl Solutions



During a well logging operation a maximum reading thermometer is run which measures the bottom hole temperature. To determine the temperature at any other location in the bore hole it is assumed that geothermal gradient is linear. The relationship between temperatures the geothermal gradient is

$$T_f = T_o + \frac{g_G D_f}{100} \qquad \text{Eq (2-2)}$$

- From equation 2-2, where

  T_f is the temperature of any formation

  T_o is the mean surface temperature

  g_G, is the geothermal gradient in °F/100 feet

  D_f is the depth to the formation.
- The surface temperature is the average of day-by-day, and season-by-season and year-by-year variations.

Normally, Geothermal gradients of 1 to 2 degrees per 100 feet are common. Equation 2-2 is easily solved by figure 2-3. See the problem worked on the figure. If a calculator is used, equation 2-2 may be rearranged to equation 2-3

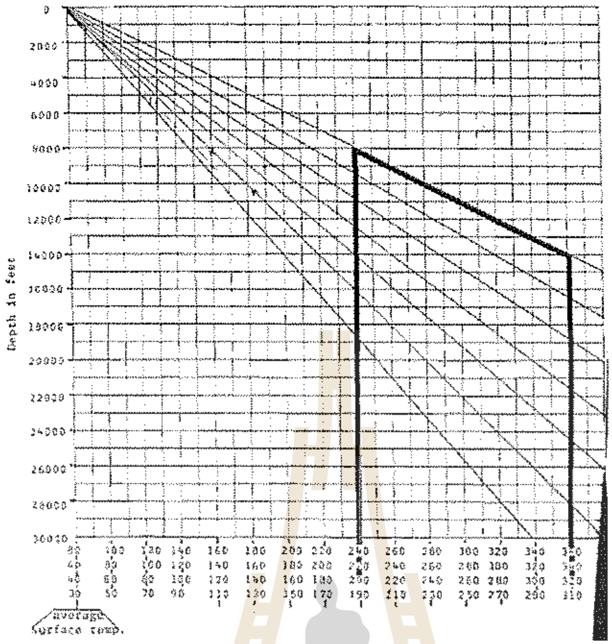
$$T_f = (T_{TD} - T_O)\frac{D_f}{D_{TD}} + T_O \qquad \text{Eq (2-3)}$$

From equation 2-3, where

TD refer to total depth

f refers to the formation in question

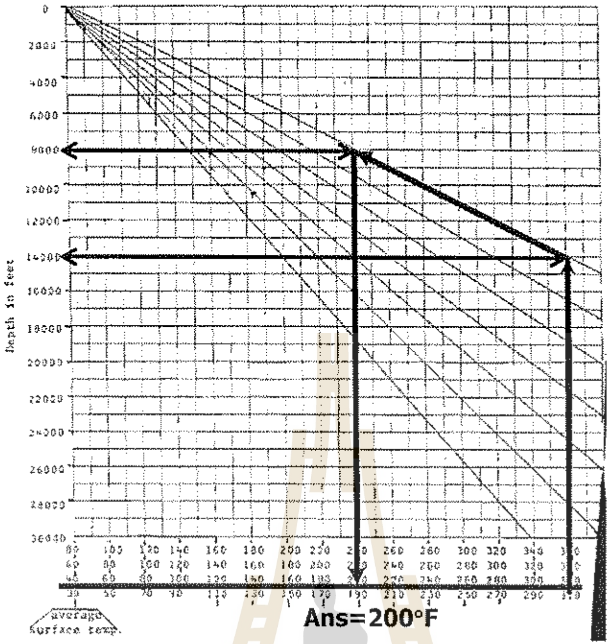
Fig 2-3



Example of Figure 2-3

- The bottom hole temperature is 320°F at 14000 feet. The surface temperature is 40°F. The temperature at 8000 feet is ? °F
- Answer = 200 °F

Fig 2-3

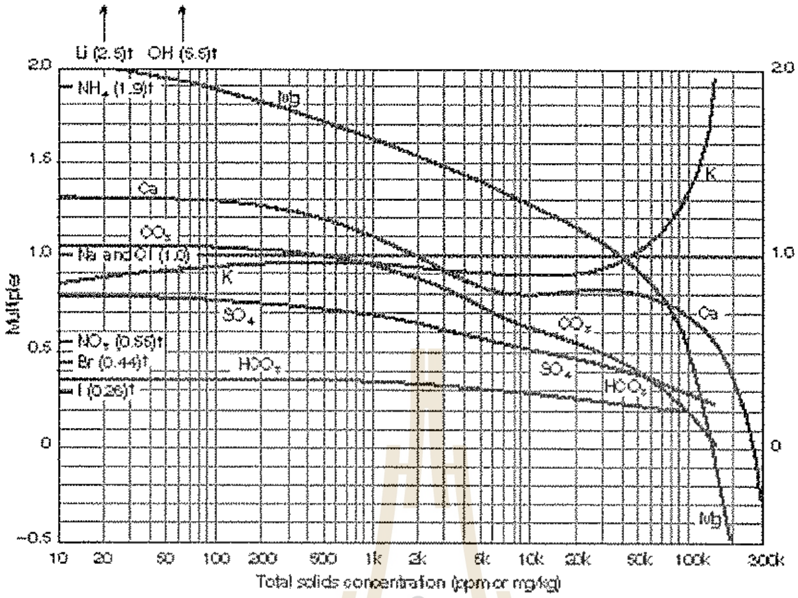


Ans=200°F

Figure 2-4

- From figure 2-4, we can determine the water resistivity from chemical composition.
- The example in the page 2-5.

Figure 2-4



† Multipliers that do not vary appreciably for low concentrations (less than about 10,000 ppm) are shown at the left margin of the chart

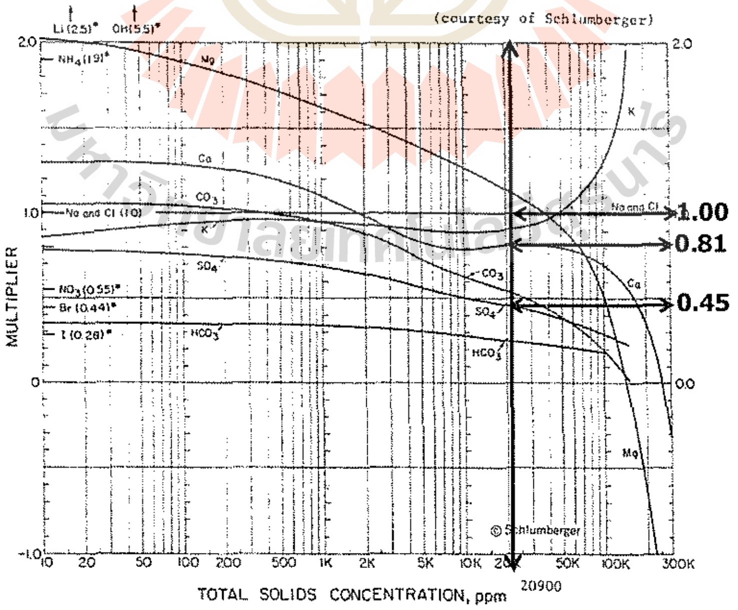
- A formation water sample indicates 400 ppm Ca, 1500 ppm SO_4, 11500 Na and 7500 ppm Cl.
- The total solids concentration = 400+1500+11500+7500 = 20900 ppm
- From Chart (Figure2-4) at total solids concentration = 20900 ppm → the multiplier for all ions are shown in the next slide

Ion	ppm	multiplier	equivalent NaCl ppm
Ca	400	0.81	324
SO_4	1500	0.45	675
Na	11500	1.00	11500
Cl	7500	1.00	7500

total equivalent NaCl ppm ------ 19999 ppm

Using Fig 2-2 the resistivity at 100°F is 0.23 Ω.m

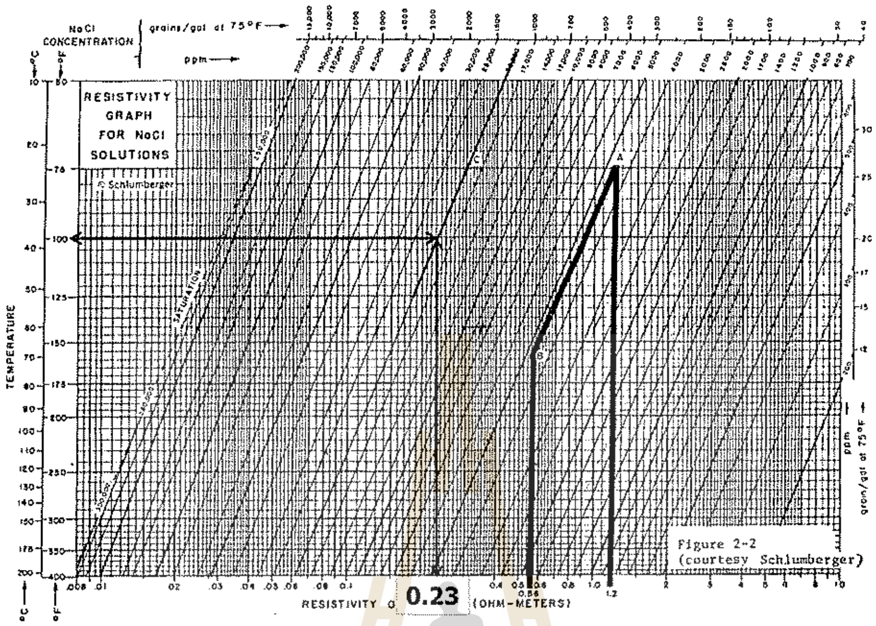
Figure 2-4



(courtesy of Schlumberger)

*Multipliers which do not vary appreciably for low concentrations (less than about 10,000 ppm) are shown at the left margin of the chart.

Figure 2-2



Reservoir Type Rock

The resistivity of a rock or formation can be measured in a similar manner as that used for liquids (mud cup). Reservoir rocks, sandstones, limestones, and dolomites, are made up of mostly materials that are electrical insulators.

RESISTIVITY AS A BASIS FOR INTERPRETATION

- **The usefulness of resistivity logging rests on the fact that:
  - water is a conductor (low resistivity)
  - hydrocarbons and rocks are insulators (high resistivity)

- Consider the following unit cubes (Figure A3):

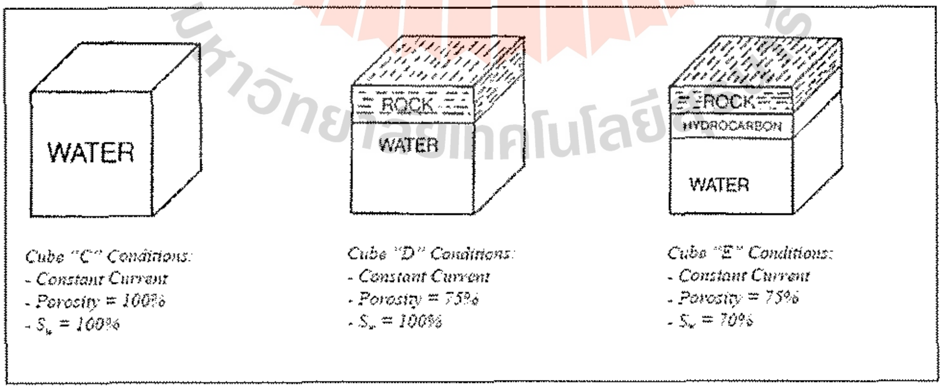


Figure A3

Cube C

The resistivity R_t of the cube will vary with water resistivity R_w (ie: as R_w increases, R_t increases and vice versa.)

Therefore:

$$R_t \alpha R_w. \qquad (1)$$

Where

R_t is Resistivity of the Formation Uncontaminated Zone.

R_w is Resistivity of the Formation Water.

Cube D

Replace 25% of the cube with rock (hence F = 75%) but maintain a constant R_w. Resistivity R_t increases with decreasing porosity F (ie: as F decreases, R_t increases.)

Therefore:

$$R_t \alpha 1/\phi. \qquad (2)$$

Cube E

Replace 30% of remaining porosity F with hydrocarbon. Resistivity R_t increases with decreasing water saturation S_w (ie: as S_w decreases, R_t increases.)

Therefore:

$$R_t \; \alpha \; 1/S_w. \qquad (3)$$

By combining the above observations (1,2 and 3), we can say:

$$R_t \; \alpha \; R_W \times \frac{1}{\phi} \times \frac{1}{S_W}$$

or

$$R_t \; \alpha \; \frac{R_W}{\phi S_W} \qquad (4)$$

- To solve for the constants of proportionality let us first limit the equation as follows:

  1) Let S_w = 100% (ie: There is no hydrocarbon present and the porosity is 100% water filled)

  2) then define $R_o = R_t$ (ie: Ro is the wet resistivity of the formation for the condition S_w = 100%)

  So from equation (4), we will get

$$R_t \; \alpha \; \frac{R_W}{\phi} \qquad (5)$$

  Now let $\phi = 1$, then $R_o \; \alpha \; R_w$

- Now let F = constant of proportionality defined as Formation Factor.

  Therefore: $R_o = F^*R_w$

  or

$$F = \frac{R_O}{R_W} \qquad (6)$$

- Returning to equation 5 and introducing porosity as a variable, it is clear that to equation 2-5

$$F \; \alpha \; \frac{1}{\phi} \Rightarrow F = \frac{a}{\phi^{m}} \text{ or } F = a\,\phi^{-m}$$

And in your book, the resistivity of these dry rock is over a million ohm meters. When these rocks are saturated with salt water (with a resistivity of Rw), the resistivity of the rock (Ro) is related to Rw by;

$$R_O = F_R{}^* R_W \qquad \text{Eq (2-4)}$$

- From equation 2-5, where a and m are empirical constants which are loosely related to the pore geometry.
- Or we can re-write the equation 2-5 as shown in the next slide.

Formation Factor (F_R)

Formation Factor (F_R) is a constant for the formation under consideration. The value of F_R for any particular formation depends on:

- formation porosity
- pore distribution
- pore size
- pore structure

Some recommended F and F relationships are:

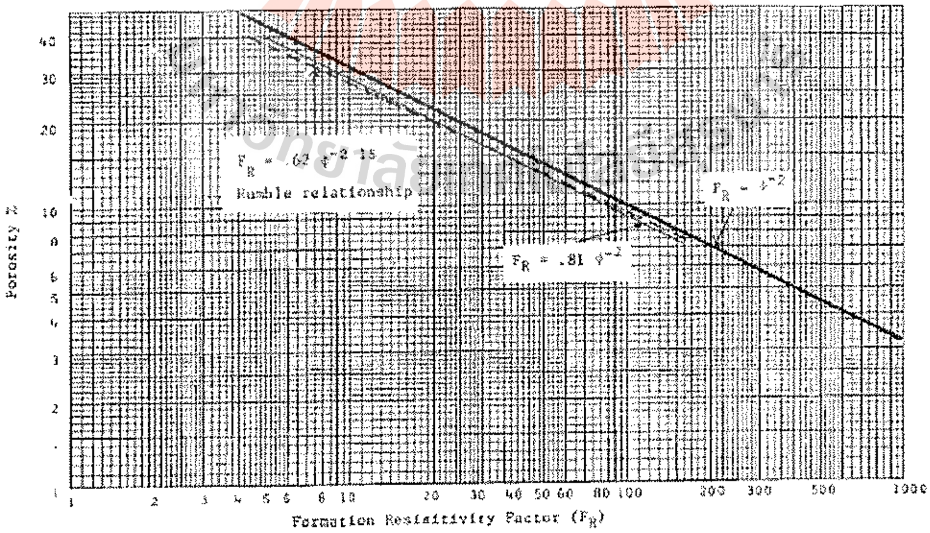
$$F_R = \frac{0.62}{\phi^{2.15}} = 0.62\phi^{-2.15}$$ (for sands) Eq(2-6)

$$F_R = \frac{0.81}{\phi^{2}} = 0.81\phi^{-2}$$ (for sands) Eq(2-7)

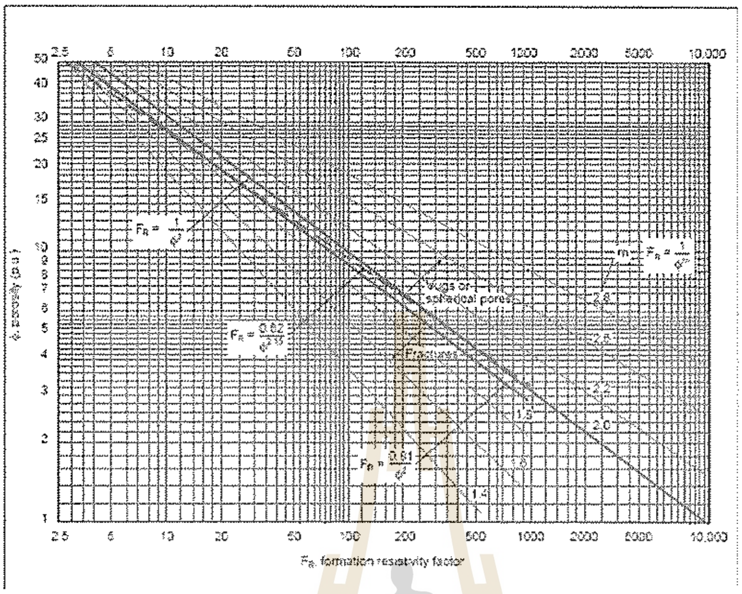
$$F_R = \frac{1}{\phi^{2}} = \phi^{-2}$$ (for carbonates) Eq(2-8)

Not only that equation 2-5 then the value of formation factor (F_R) can be calculated by Figure 2-5 also.

Figure 2-5



Formation Resistivity Factor vs Porosity



Archie Equation

- The Archie equation are the relationship of water saturation, porosity and the resistivity.
- Using the above equations (6)

Recall $R_o = F*R_w$

$$R_t = R_o = \frac{aR_w}{\phi^m} \quad \text{when } S_w = 100\%$$

if $S_w \neq 100\%$, then

$$R_t \ \alpha \ \frac{aR_W}{\phi^m} \times \frac{1}{S_W}$$

Archie Equation

Or

$$R_t \; \alpha \; R_o \times \frac{1}{S_W}$$

Or

$$S_W \; \alpha \; \frac{R_o}{R_t} \qquad (8)$$

Archie Equation

Through laboratory measurements, it was found that this relationship (8) is dependent on the saturation exponent n as

$$S_W^n = \frac{R_o}{R_t}$$

Or

$$S_W^n = \frac{FR_W}{R_t} = \frac{aR_W}{\phi^m R_t} \qquad \text{(9) or Eq (2-10)}$$

** Normally, exponent n = 2

** Equation (2-10) may be solved using Fig 2-6

Equation (9) forms the Archie Relationship that is the basis for all conventional log interpretation techniques. Enhancements and refinements may be applied for the more complicated rock types.

** A more general chart which may be used with different m and n 's is presented in Figure 2-7. An example is worked on the chart.

Figure 2-6

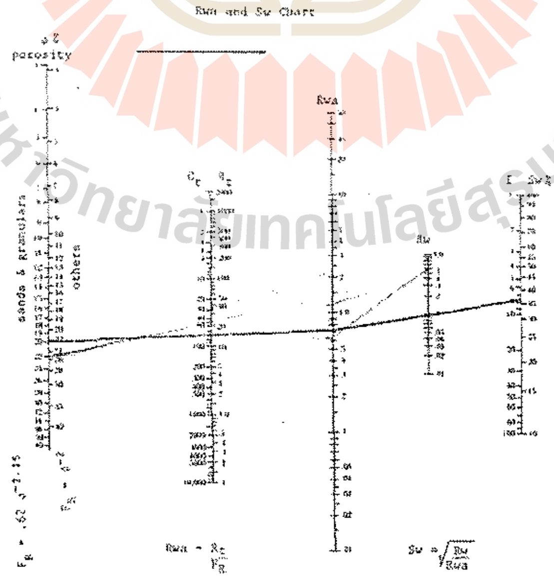
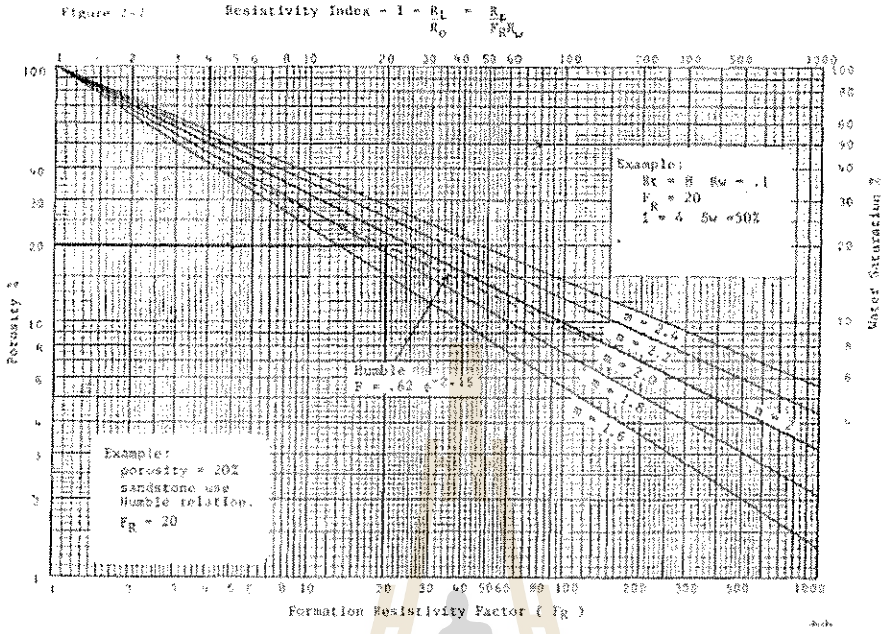
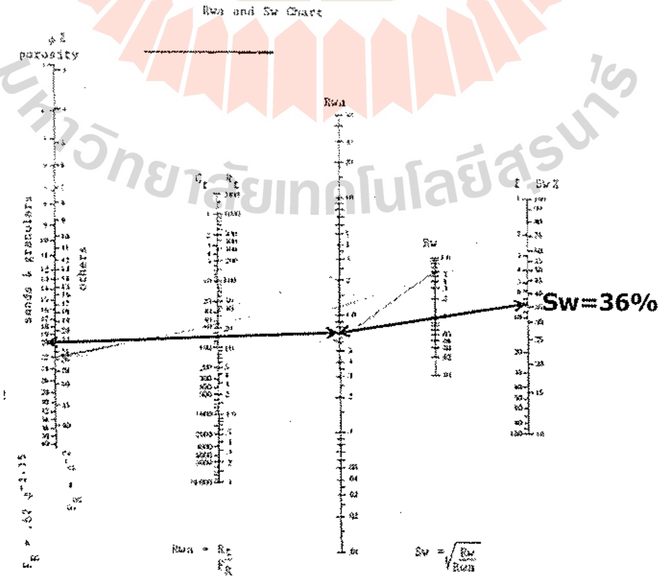


Figure 2-7



The Example of Figure 2-6



Sw=36%

The Example of Figure 2-6

- Porosity is 20% in a sandstone. Rt is 15. These given you an Rwa of 0.72. If Rw is 0.095 Then Sw = ? (Answer → Sw = 36%)

The Borehole Environment

The drilling of a well with mud usually results in the contamination of the permeable formations. This is caused by the need to maintain the mud pressure in the borehole higher than the formation fluid pressure. Failure to do this may result in a "blow out".

The Borehole Environment

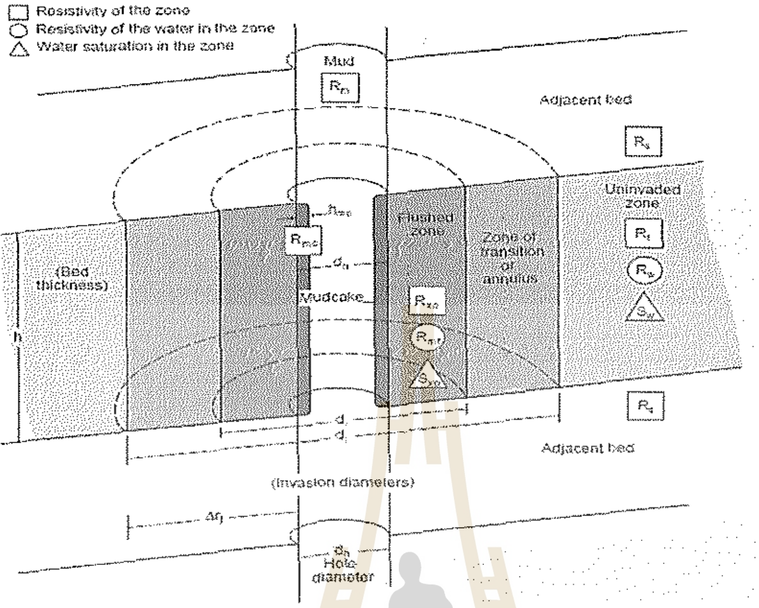
The amount of contamination (usually called invasion) is a function of the mud weight (borehole pressure) and the mud water (filtrate) loss. The mud in the process of filtering into the formation, leaves a mud cake on the wall of the hole. This mud cake (which is formed by the solids in the mud, mostly bentonite) limits the amount of water loss into the formation because of its low permeability.

The Borehole Environment

Relatively deep invasion occurs in low porosity formations because they are drilled generally with high water loss mud. Shallow invasion typically occurs in high porosity formations because they are drilled with low water loss mud. This latter is required to prevent borehole caving in the higher porosity more poorly consolidate formations.

** Figure 2-8 shows a schematic cross section of a wellbore penetrating a permeable formation.

Figure 2-8



The Formula of Figure 2-8

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Resistivity	Rxo	Ri	Rt
Porosity	ϕ	ϕ	ϕ
Water Saturation	Sxo	Si	Sw
Water Resistivity	Rmf	Rz	Rw

The Formula of Figure 2-8

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Equations	$S_{XO} = \sqrt{\frac{F_R R_{mf}}{R_{XO}}}$	$S_i = \sqrt{\frac{F_R R_z}{R_i}}$	$S_W = \sqrt{\frac{F_R R_W}{R_t}}$

** With Invasion $S_{XO} > S_i > S_W$ unless all are 100%
no Invasion $S_{XO} = S_i = S_W$ and R_W in all pores

Flushed Zone

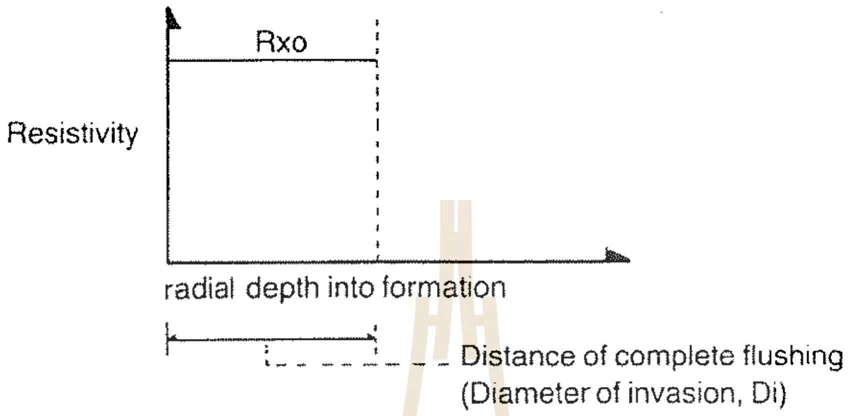
Flushed Zone. Adjacent to the borehole the invasion process flushes out the original water and some of the hydrocarbons (if any were present).

The resistivity of this zone is termed R_{xo}; the water saturation is called S_{xo} where:

$$S_{XO}^2 = \frac{F_R R_{mf}}{R_{XO}}$$

**(for clean formations only)

- Plotting R_{xo} as a function of radial depth into the formation yields Figure.



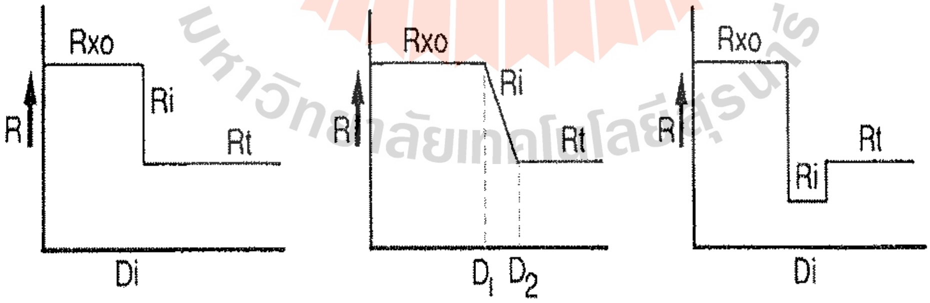
Transition Zone

- Transition Zone. Further from the borehole the flushing action of the mud filtrate may create a variety of situations.
- If the flushing proceeds as a uniform front, we call this a step profile of invasion (Figure B5a). If the intermingling of formation fluids is very gradual, we would call this a transition zone (Figure B5b).

Transition Zone

- Sometimes in oil or gas bearing formations, where the mobility of hydrocarbons is greater than the connate water, the oil or gas move out leaving an annular zone filled with connate water (Figure B5c).
- If Rmf > Rw, then the annular zone will have a resistivity lower than Rxo and Rt and may cause a pessimistic saturation calculation.

Figure B5



Case 1
Step Profile
(a)

Case 2
Transition
Profile
(b)

Case 3
Annulus
Profile
(c)

Uninvaded Zone or Virgin Zone

- True Unaffected Zone. This is the zone which we wish to analyse. it is the formation undisturbed by the drilling process. Its resistivity is termed R_t, water resistivity R_w, and water saturation S_w.
- Plotting R_{xo}, R_i and R_t as a function of invasion:

FORMATION WATER RESISTIVITY (R_W)

As previously indicated, formation matrices are insulators; thus a formation's ability to conduct electricity is a function of the connate water in the formation. Several factors must be considered:

- the volume of the water (porosity)
- the pore space arrangement (type of porosity)
- the temperature of the formation
- the salinity of the water.

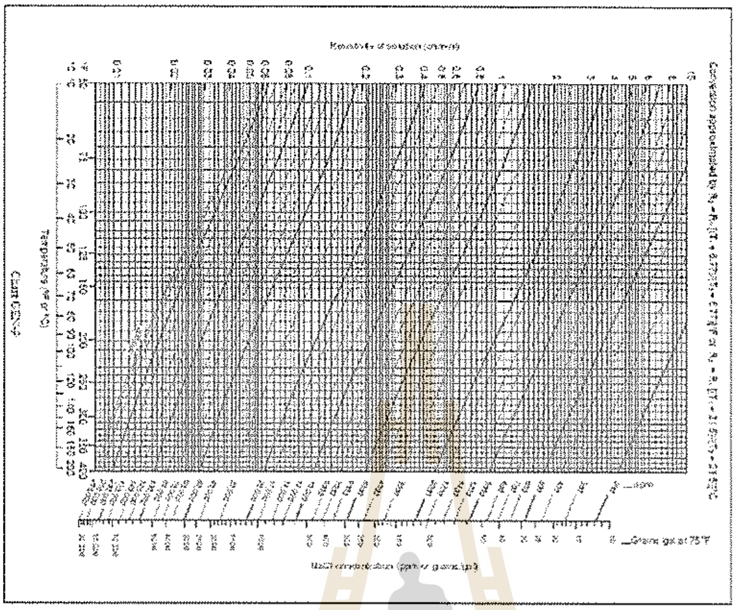
Water Salinity

As salinity increases, more ions are available to conduct electricity so Rw (water resistivity) decreases.

Water Temperature

As water temperature is raised, ionic mobility increases and resistivity decreases. Figure 2-2 in the your Book, illustrates these relationships.

Figure 2-2



Resistivity of NaCl Solutions

Water Volume

As water filled pore space in a rock is increased, resistivity decreases. If some water is displaced by hydrocarbons (insulators), water saturation decreases; resistivity increases.

SUMMARIZE

1. Dry rock formation is an insulator.
2. Formations conduct current because of water in the pore spaces.
3. Knowledge of water resistivity (Rw) is essential for log interpretation.
4. Resistivity used rather than resistance.
5. Formation Resistivity Factor (F) is a porosity related formation characteristic.

SUMMARIZE

6. Relationships:
   - a. $F = (R_t / R_w)$
     $F = (R_o / R_w)$ → 100% water saturated porous rock
   - b. $F = a / \phi^m$
7. Symbols:
   - R_w - resistivity of connate water.
   - R_t - true formation resistivity.
   - R_{xo} - resistivity of flushed zone.
   - a - a constant.
   - m - cementation factor.

Resistivity measuring devices are generally classified by the depth of the measurement. If the device measures only a few inches into the formation it is called an R_{xo} too. If the measurement is in the range of ten 's of inches it is an R_i tool and if the tool reads much deeper than the previously mentioned tools it is an R_t tool. It should be remembered that if the invasion is very shallow or nonexistant all the devices will read R_t.

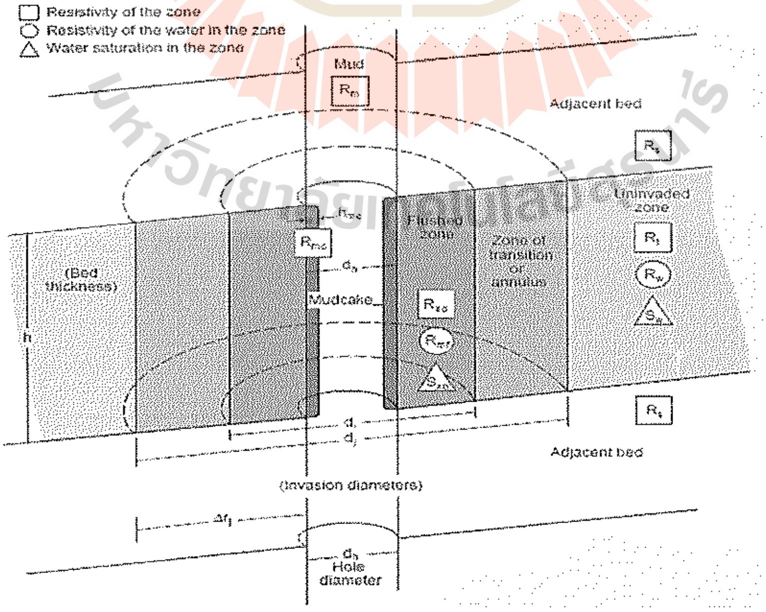
Chapter 3
RESISTIVITY MEASURING DEVICES

This chapter will be limited to discussing the more commonly used induction resistivity type logs and the associated resistivity curves. Induction Electric Logs and Dual Induction Logs are combinations of several curves.

In general one curve is an Rt curve that measures deep into the formation and another is an Ri curve that reads mostly in the invaded zone.

The Dual Induction has another resistivity curve that reads between these two so that corrections for invasion can be made when necessary. The other curve on induction logs is a Spontaneous Potential whicn is the subject of Chapter 4.

Review of Chapter II (Important)



The Formula of Chapter II (Figure 2-8)

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Resistivity	Rxo	Ri	Rt
Porosity	ϕ	ϕ	ϕ
Water Saturation	Sxo	Si	Sw
Water Resistivity	Rmf	Rz	Rw

The Formula of Chapter II (Figure 2-8)

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Equations	$S_{XO} = \sqrt{\frac{F_R R_{mf}}{R_{XO}}}$	$S_i = \sqrt{\frac{F_R R_z}{R_i}}$	$S_W = \sqrt{\frac{F_R R_W}{R_t}}$

** With Invasion	$S_{XO} > S_i > S_W$	unless all are 100%
no Invasion	$S_{XO} = S_i = S_W$	and R_W in all pores

Introduction

- We have two different types or classes of tools designed for the two most common borehole environments:
  1. Non-Conductive Boreholes
  2. Conductive Boreholes

Non-Conductive Boreholes

- including Fresh Mud Systems, Invert Mud Systems and Air-filled holes.
  - a. Dual Induction - SFL (No longer in service)
  - b. Phasor Dual Induction - SFL
  - c. Array Induction Imager

Conductive Boreholes

- including Saline to Salt Saturated Mud Systems
  - a. Dual Laterolog

Induction or Conductivity Concepts

- Induction systems measure conductivity.
- Conductivity is the reciprocal of resistivity and is expressed in mhos per metre. To avoid decimal fractions, conductivity is usually expressed in millimhos per metre (mmho / m), where 1000 mmho/m = 1 mho/m:

$$C = \frac{1000}{R} \qquad \text{Eq (3-1)}$$

INDUCTION LOGGING PRINCIPLES

The induction logging tool was originally developed to measure formation resistivity in boreholes containing oil-base muds and in airdrilled boreholes.

Electrode devices did not work in these nonconductive muds, and attempts to use wall-scratcher electrodes were unsatisfactory.

Experience soon demonstrated that the induction log had many advantages when used for logging wells drilled with water-base muds. Designed for deep investigation, induction logs can be focused in order to minimize the influences of the borehole, the surrounding formations, and the invaded zone.

Principle

Today's induction tools have many transmitter and receiver coils. However, the principle can be understood by considering a sonde with only one transmitter coil and one receiver coil (see Figure 3-1 or Figure B13 in slide).

Figure 3-1

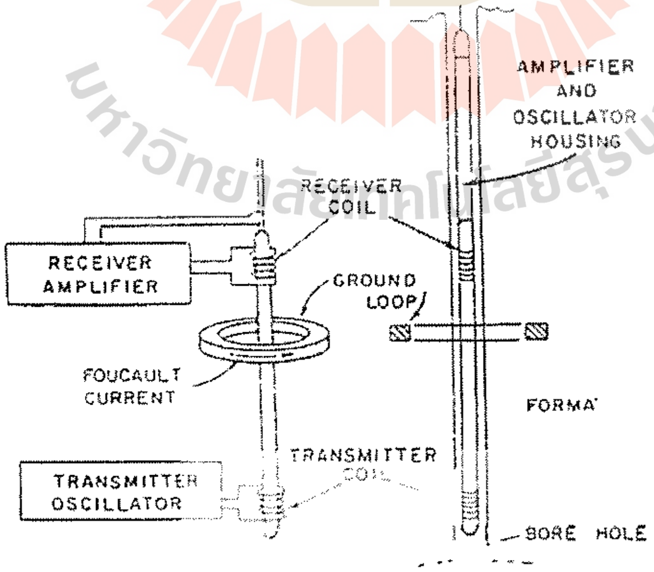
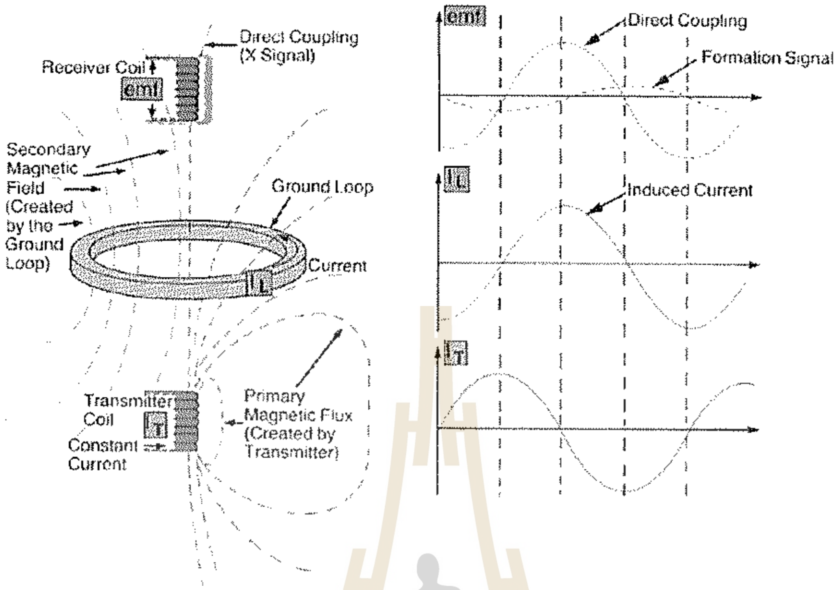


Figure B13



- A high-frequency alternating current of constant intensity is sent through a transmitter coil. The alternating magnetic field created induces currents in the formation surrounding the borehole. These currents flow in circular ground loops coaxial with the transmitter coil and create, in turn, a magnetic field that induces a voltage in the receiver coil.

- Because the alternating current in the transmitter coil is of constant frequency and amplitude, the ground loop currents are directly proportional to the formation conductivity. The voltage induced in the receiver coil is proportional to the ground loop currents and, therefore, to the conductivity of the formation.

The induction tool works best when the borehole fluid is an insulator - even air or gas. The tool also works well when the borehole contains conductive mud unless the mud is too salty, the formations are too resistive, or the borehole diameter is too large.

The example of Resistivity Measurement Devices

- The type of the Resistivity Measurement Device are 3 type up to the type of resistivity value (R_{XO}, R_i ,or R_t) such as:
  - SPHERICALLY FOCUSED LOG (SFL)
  - DUAL INDUCTION - SPHERICALLY FOCUSED LOG (DIL-SFL)
  - Medium Induction (ILM) or Deep Induction (ILD)
  - Short Normal

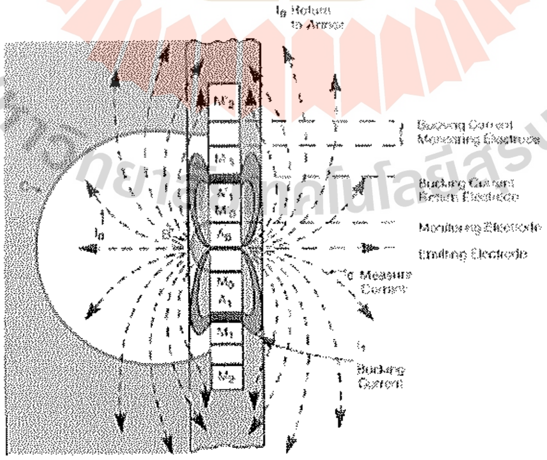
SPHERICALLY FOCUSED LOG (SFL)

The SFL device measures the resistivity of the formation near the borehole and provides the relatively shallow investigation required to evaluate the effects of invasion on deeper resistivity measurements. It is the short-spacing device used in the Phasor Induction – SFL tool.

The SFL system differs from previous focused electrode devices. Whereas systems attempt to focus the current into planar discs, the SFL system establishes essentially constant potential shells around the current electrode.

The SFL device is able to preserve the spherical potential distribution in the formation over a wide range of wellbore variables, even when a conductive borehole is present.

Electrode array of SFL tool



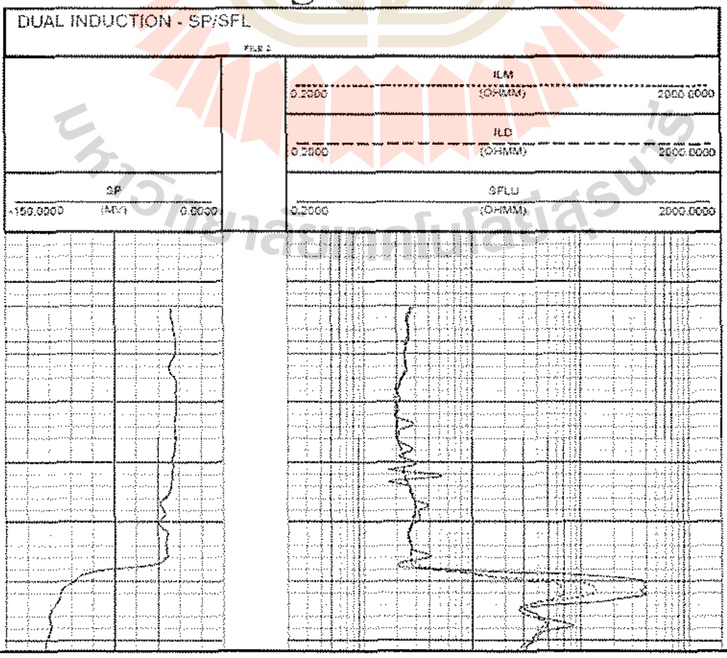
$$R_{SFL} = K\frac{(V_B - V_0)}{I_0}$$

DUAL INDUCTION - SPHERICALLY FOCUSED LOG

This is the most basic of induction devices and was the reference resistivity induction device for 20 plus years until its retirement in 1990.

The tool supplies three focused resistivity curves: two Induction and a shallow investigating Spherically Focused Curve plus the Spontaneous Potential. Each curve has a different depth of investigation (Figure B15).

Figure B15



- Spherically Focused Log - a shallow reading device affected mainly by the flushed (Rxo) zone. (Radial Distance @ 30 cm.)
- Medium Induction (ILM) – depending on the invasion diameter and profile the ILM may be influenced by Rxo or Rt zones ... or both. (Radial Distance @ 60-80 cm.)
- Deep Induction (ILD) - is mostly affected by Rt, unless invasion is very deep. Either or both induction curves may be influenced if an annulus is present. (Radial Distance @ 1.2-1.5 m.)

Ri Companion Curves

Three basic invaded zone resistivity curves are run in conjunction with the deep induction curve. The older logs have a short normal while the newer use a Spherically Focused Log or a laterolog.

Short Normal

The Short Normal is a measuring device which passes current from an electrode on the sonde through the mud into the formation. This device is similar to the mud cup in chapter 2 only it is three dimensional and the electrodes are placed in the borehole.

The deep induction curve (ILd, 6FF40, Deep induction) are Rt type curves. They generally read close to Rt and where no correction for invasion is possible are assumed to be Rt . The value recorded on the curve is usually referred to as Ra (apparent resistivity)

Tool Characteristics and Applications

- The Dual Induction SFL is most effective when used in holes drilled with moderately conductive mud, e.g. where Rmf / Rw > 2.5.
- Vertical Focusing is good, reliable values of Rt may be obtained where bed thickness is > 4.0 metres.

Tool Characteristics and Applications

- Since this tool actually measures formation conductivity and converts the values to resistivity, results are most accurate in zones of low resistivity.
- The recording of three curves which investigate different amounts of formation volume enable us to study invasion profiles, and where invasion is deep, make correction to obtain Rt.

Limitations

- The logging of large diameter holes drilled with saline mud should be avoided, particularly in high resistivity formations. Large borehole signals will add to the formation signals producing anomalously low apparent resistivities.

Limitations

- In zones of high resistivity (low conductivity), e.g. in excess of 250 ohmm, errors in measurement can occur.

The above problems can sometimes be minimized by a system of downhole calibration checks. A thick zero porosity zone, e.g. limestone, or anhydrite for this purpose.

Thus if difficulties in producing a good DIL are expected, it is often advantageous to run a porosity - caliper log before the DIL.

Log Responses

For wells drilled with fresh muds (Rmf/Rw > 2.5, Rxo/Rt>2.5) the following general conclusions can be reached by log inspection:

- When SFL = ILM = ILD; Rt = ILD, this indicates zero or very shallow invasion.

- When SFL > ILM = ILD; Rt = ILD, this indicates moderate invasion.

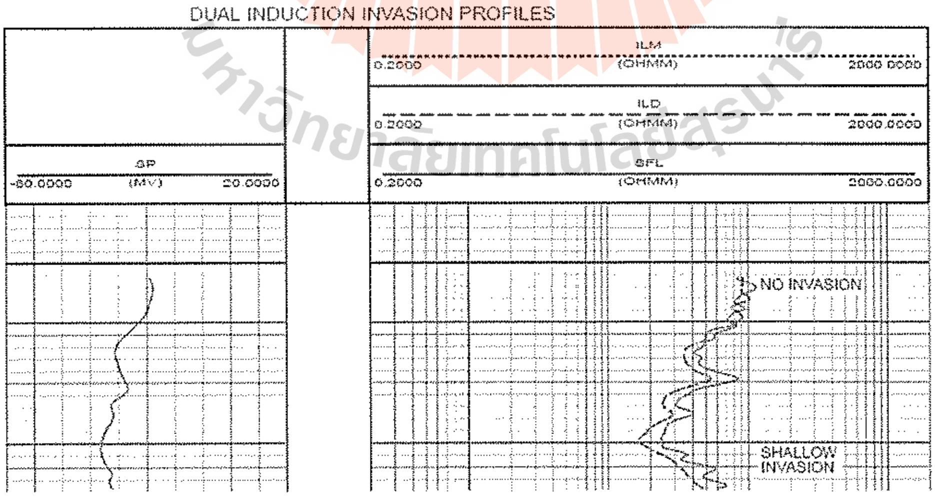
- When SFL > ILM > ILD; and if Rxo = SFL, then Rt < ILD, this indicates deep invasion.

Log Responses

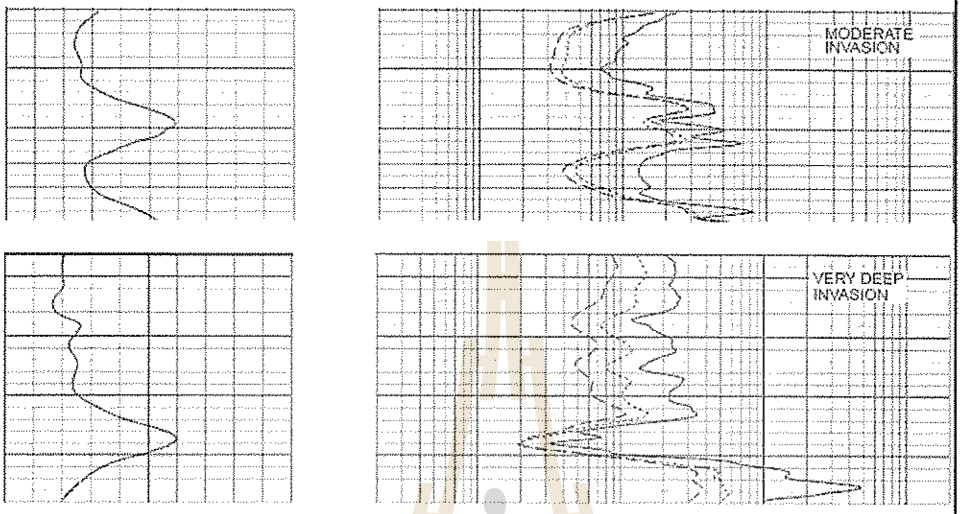
When SFL = ILM > ILD, and if Rxo = SFL we must use chart Rint-2c (Figure B17) to obtain Rt. This response indicates very deep invasion.

In general, the closer the medium curve is to the SFL, the deeper the invasion. The result of correcting for invasion is to obtain an Rt which is lower than ILD. Hence, by using ILD without correction, you will obtain an optimistic Sw.

DUAL INDUCTION INVASION PROFILES



DUAL INDUCTION INVASION PROFILES



Summary

- *Benefits*:
  - Dual Induction SFL can most effectively be used in holes filled with moderately conductive mud, nonconductive mud, and air drilled holes.
  - Vertical focusing is good and gives reliable values of Rt, for beds thicker than three metres.

Summary

- *Benefits:*
  - It measures low resistivities (less than ten ohm-metres) accurately.
  - Recording of three focused resistivity logs, which investigate different volumes of formation enables us to study invasion profile, and good Rt values in the case of deep invasion.

Summary

- Correction charts are available for:

  - Borehole

  - Bed thickness

  - Invasion

Summary

- *Disadvantages:*
  - Not reliable for resistivities > 250 ohm-m (use a Dual Laterolog)
  - Large hole and saline mud results in large borehole signals which give an unusually low apparent resistivity.

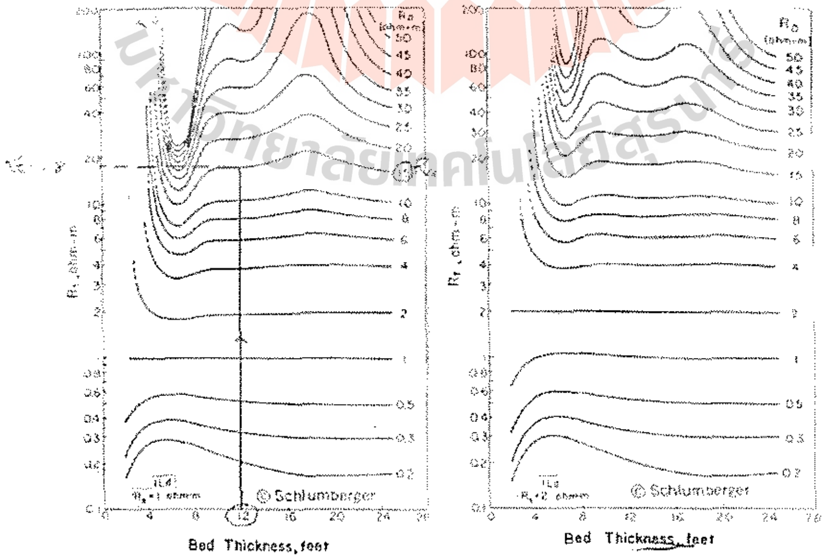
The Example of Correction Chart

Correction charts are available for most logging devices. The correction charts are usually made for ideal situations which you seldom encounter in nature.

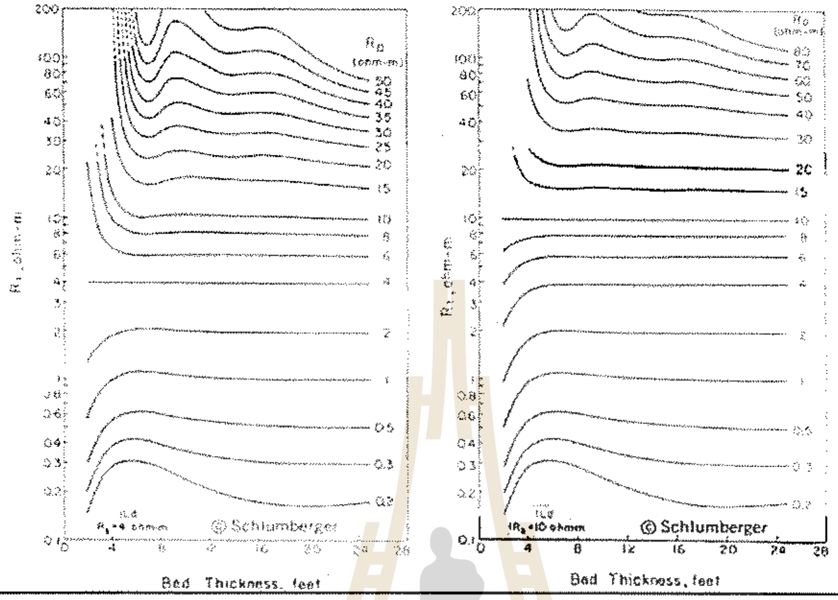
Induction Bed Thickness Corrections

Figures 3-7, 3-8 and 3-9 are bed thickness corrections for induction logs as published by Schlumberger. Figure 3-7 is for thick zones and Figure 3-8 is for thin conductive zones for the ILd or 6FF40 which are the standard tools. Figure 3-8 needs some words as they use R_{ID} instead of the normal R_a for the apparent resistivity from the log. Figure 3-9 is the ILm which is the medium induction on the dual induction log .

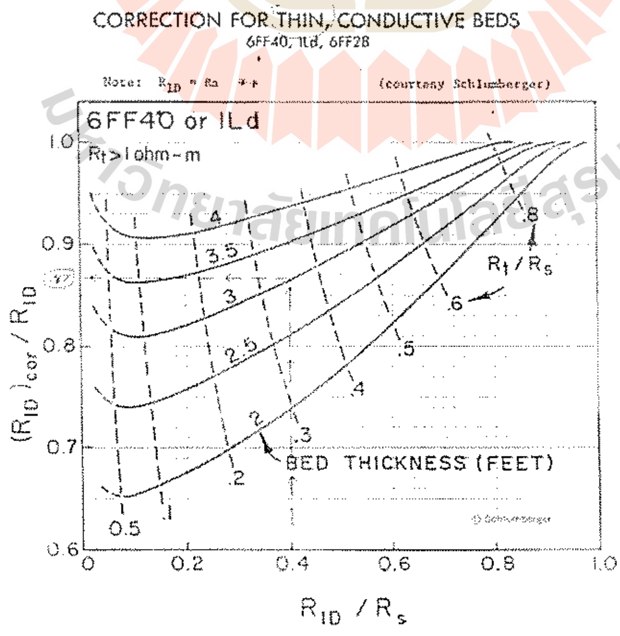
The Example of Correction Chart (Figure 3-7)



The Example of Correction Chart (Figure 3-7)



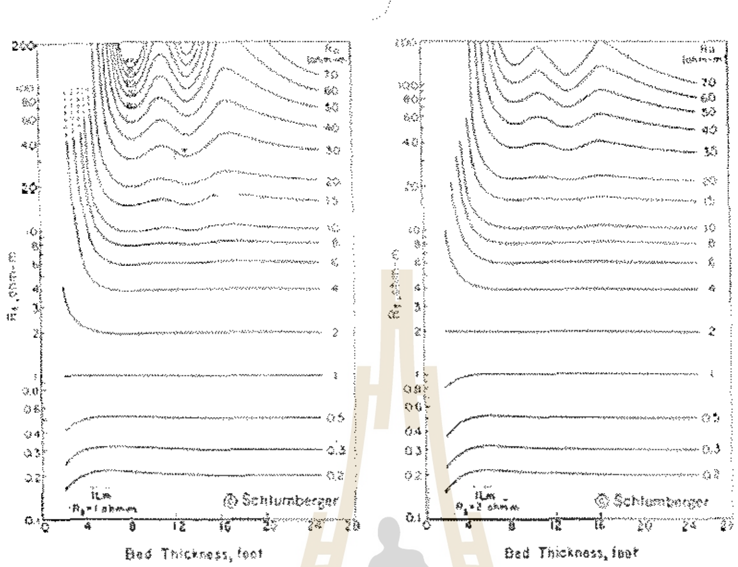
The Example of Correction Chart (Figure 3-8)



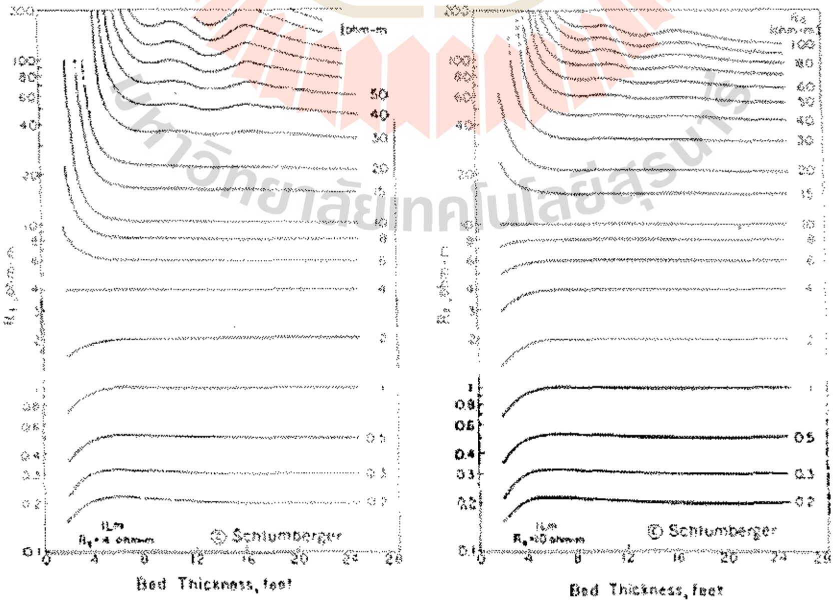
The Example of Correction Chart (Figure 3-9)

INDUCTION LOG BED THICKNESS CORRECTION

ILm



The Example of Correction Chart (Figure 3-9)



The Example of Correction Chart (Figure 3-10)

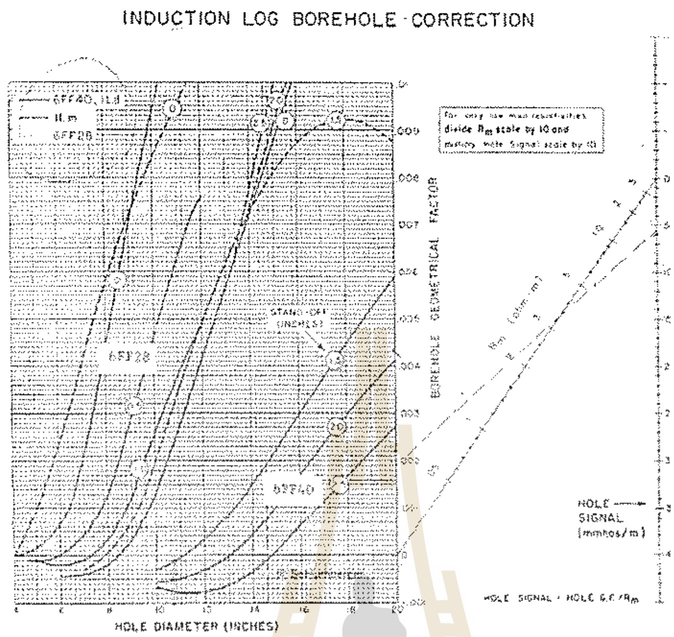
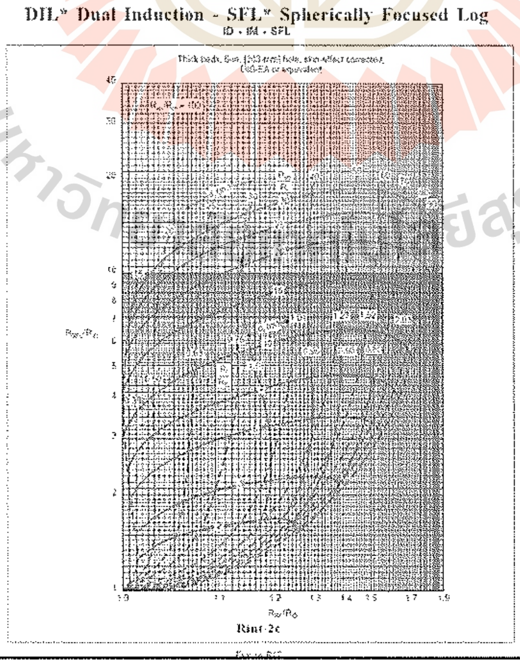


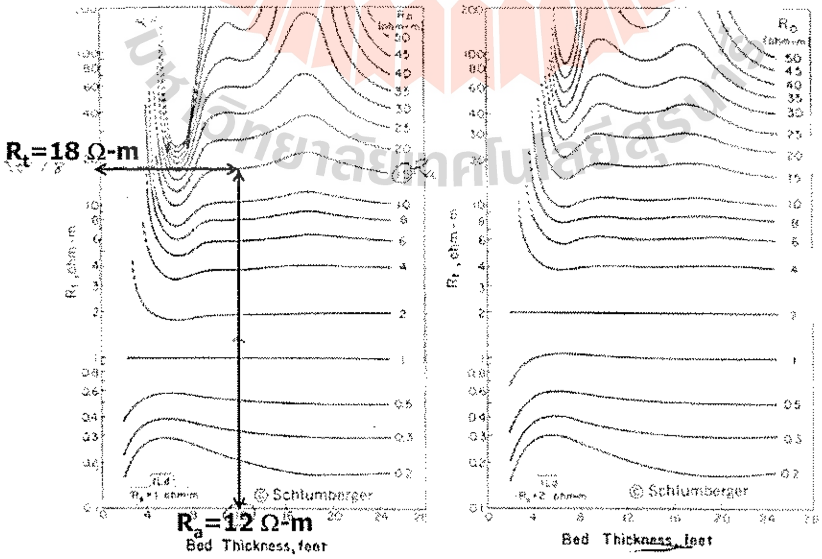
Figure B17 or Figure 3-11



Example 3-1
Bed Thickness Corrections for ILd

- a) For Rs (adjacent bed resistivity) of 1 ohm-m, a bed thickness of 12 feet and the apparent resistivity of 15 ohm-rn see the uper left hand chart of figure 3-7. You follow bed thickness vertical until you reach Ra and then read Rt from the scale on the left as Rt = 18 in this case.

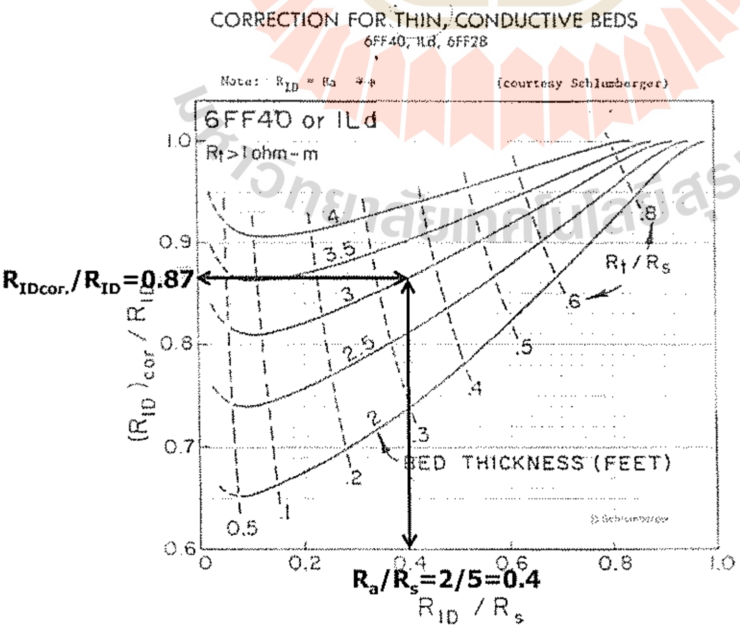
The Example of Correction Chart
(Figure 3-7)



Example 3-1
Bed Thickness Corrections for ILd

- b) For at thin conductive bed where Rs is 5 ohm-m, the bed thickness is 3 feet and the apparent resistivity from the curve is Ra = R_{ID} = 2 ohm-m. The $R_{IDcor.}/R_{ID}$ from the chart is 0.87. Rt or $R_{IDcor.}$ = 1.75 ohm-m.

The Example of Correction Chart (Figure 3-8)



Example 3-1

$$\frac{Ra}{Rs} = \frac{2}{5} = .4$$

$$R_{ID}\ cor. = \frac{R_{ID}\ cor}{R_{ID}} \times R_{ID} = .87 \times 2 = 1.74\ ohm\ m = Rt$$

or

$$Rt = \frac{Rt}{Rs} \times Rs = .35 \times 5 = 1.75\ ohm\ m$$

Example 3-2
Induction Borehole Correction

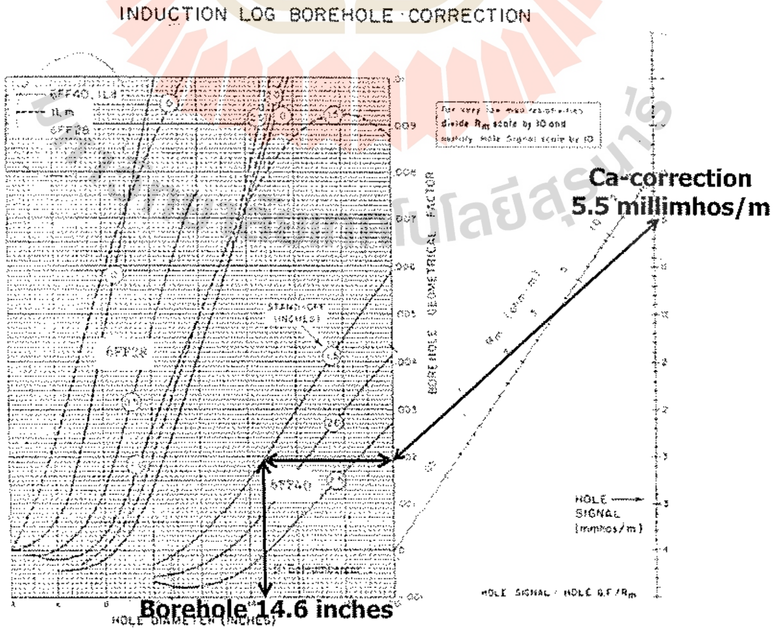
- The apparent formation resistivity from the induction log is 25 ohm-m. The borehole is 14.6 inches in diameter. The mud resistivity at that depth and temperature is -325 ohm-m. The stand-off is 1.5 inches. From figure 3-10 the correction is 5.5 millimhos/m.

- Ca = 1000/Ra = 1000/25 = 40
- Ca (borehole corrected) = Ca - correction

  Ca - correction =40 - 5.5 = 34.5 millimhos/m.
- Ra = 1000/34.5 = 29 ohm-m.

  This example uses a very large borehole and a modestly salty mud so the correction is larger than normally experienced.

The Example of Correction Chart (Figure 3-10)



Ca-correction
5.5 millimhos/m

Borehole 14.6 inches

Example 3-3
DIL-SFL Invasion Correction

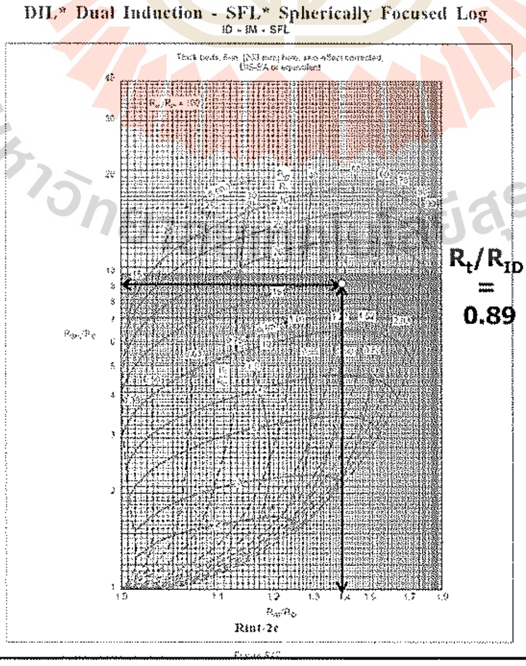
- The deep, medium and SFL readings are 10, 14 and 90 ohm-m respectively

$$\frac{R_{SFL}}{R_{ID}} = \frac{90}{10} = 9 \qquad \frac{R_{IM}}{R_{ID}} = \frac{14}{10} = 1.4$$

R_t/R_{ID} from the chart is 0.89

$R_t/R_{ID} \, x R_{ID} = R_t = 0.89x10 = 8.9$ or 9.0 ohm-m

Figure B17 or Figure 3-11



R_t/R_{ID} = **0.89**

PHASOR INDUCTION SFL TOOL

The Phasor Induction SFL tool (Figure B18) uses a conventional Dual Induction-SFL array to record resistivity data at three depths of investigation.

PHASOR INDUCTION SFL TOOL

The Phasor Induction SFL tool is the new developments in electronics technology, work on computing the response of the induction tool in realistic formation models, and modern signal processing theory have combined to allow the development of a newer tool which is able to overcome the limitations of previous tools.

Figure B18 →

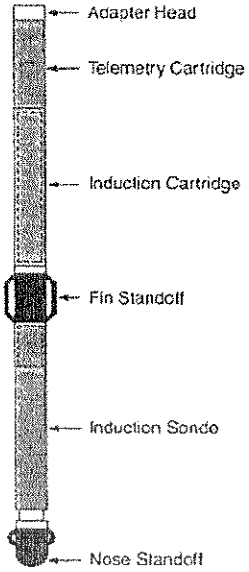


Figure B18: Schematic of the Phasor Induction SFL tool

The Phasor Induction design provides several additional advantages over existing tools. These include improvements in the calibration system, sonde error stability, SFL response, and a reduction of signal and cable noise.

Phasor Tool Description and Features

The Phasor Induction SFL tool can be combined with other cable telemetry tools. Measurements returned to the surface include deep (ID) and medium (IM) R-signals, ID and IM X-signals, SFL voltage and current, SFL focus current, spontaneous potential (SP), SP to-Armor voltage, and array temperature.

Log Presentation

- The same presentation format is used for both generations of induction tools. The two logs can be identified by the following differences (Figure B19) :

  1. Deep Induction (IDPH) - the log inserts use the IDPH acronym to identify Phasor processing.

  2. Medium Induction (IMPH) - the log inserts use the IMPH acronym to identify Phasor processing.

  3. There is a hash mark up the right side of the depth track.

Figure B19

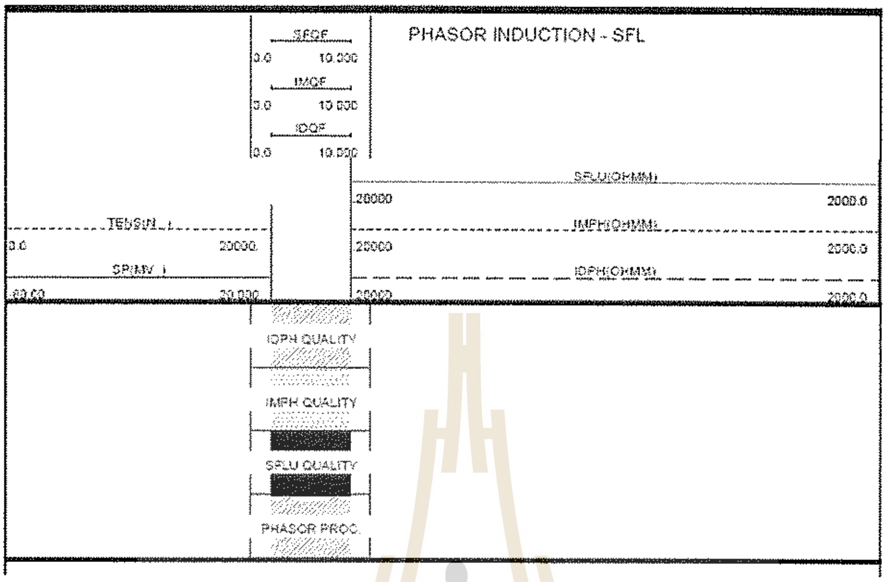
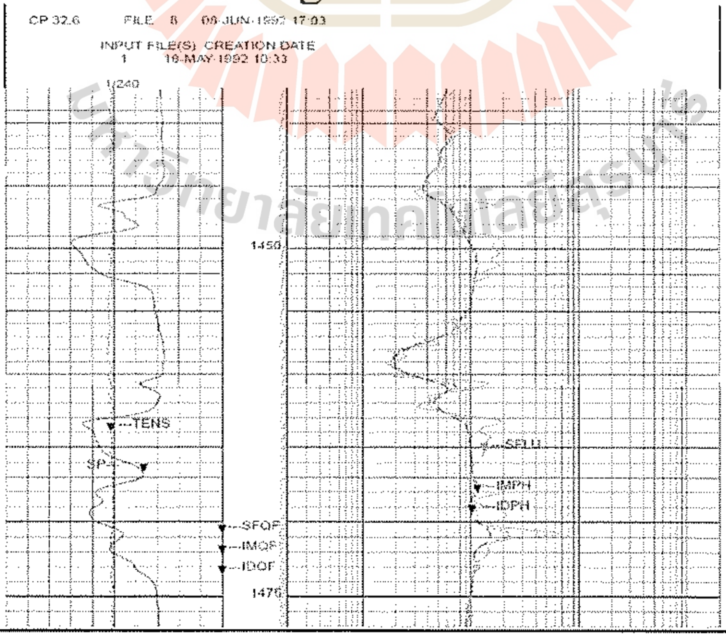


Figure B19



Tool Characteristics, Improvements, and Applications

1. Phasor Induction - SFL can be most effectively used in holes filled with moderately conductive mud, nonconductive mud, and air drilled holes.

2. Vertical focusing is good and gives reliable values of Rt for beds thicker than 2.5 metres with no shoulder bed corrections required.

Tool Characteristics, Improvements, and Applications

3. Measures low resistivities accurately.

4. Recording of three focused resistivity logs, which investigate different volumes of formation.

5. Reliable for resistivities up to 1000 ohm-m versus 250 ohm-m with normal Induction tool.

Tool Characteristics, Improvements, and Applications

6. Gives accurate readings in boreholes up to 66 cm in diameter (Rt/Rm < 1000).

7. Operates at varying transmitter frequencies to improve signal to noise ratios.

8. Uses digital transmission techniques to improve accuracy of calibration and measurement.

- Correction charts are available for:

  - Borehole

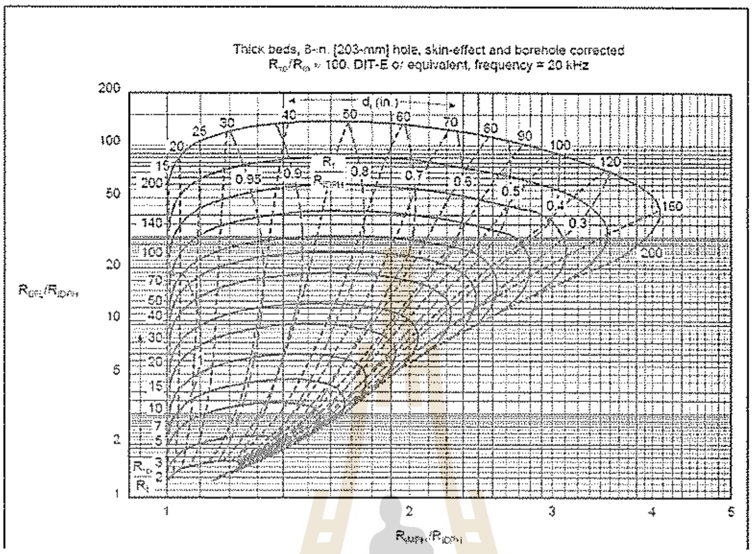
  - Bed thickness

  - Invasion (Chart Rint-11a)

Chart Rint-11a

Phasor* Dual Induction-SFL Spherically Focused Log

ID Phasor - IM Phasor - SFL



Thick beds, 8-in. [203-mm] hole, skin-effect and borehole corrected

$R_{xo}/R_m \approx 100$. DIT-E or equivalent, frequency = 20 kHz

Measurement of Rt by Laterolog Principles

- DUAL LATEROLOG

  The Dual Laterolog is a current emitting electrode device that performs best in saline muds (i.e. where Rt/Rm >>> 100, Rmf /Rw < 2.5). It is designed to extract Rt by measuring resistivity with several arrays having different depths of investigation.

- For best interpretation accuracy, such a combination system should have certain desirable features:
  - Borehole effects should be small and/or correctable.
  - Vertical resolutions should be similar.
  - Radial investigations should be well distributed; i.e., one reading as deep as practical, one reading very shallow, and the third reading in between.

DUAL LATEROLOG

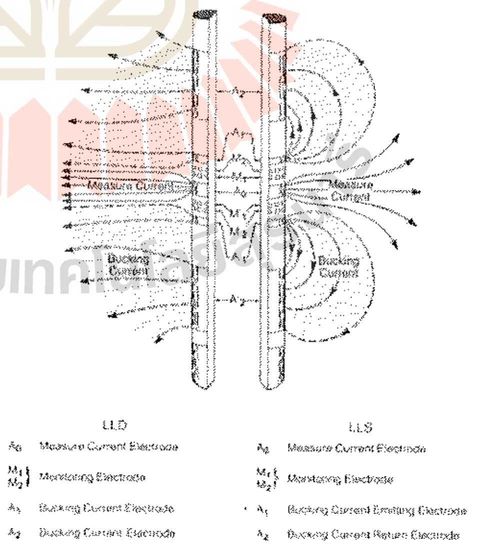


Figure B21: Dual Laterolog
Deep and Shallow Current Patterns

The DLL tool has a response range of 0.2 to 40,000 ohm-m, which is a much wider range than covered by previous laterolog devices.

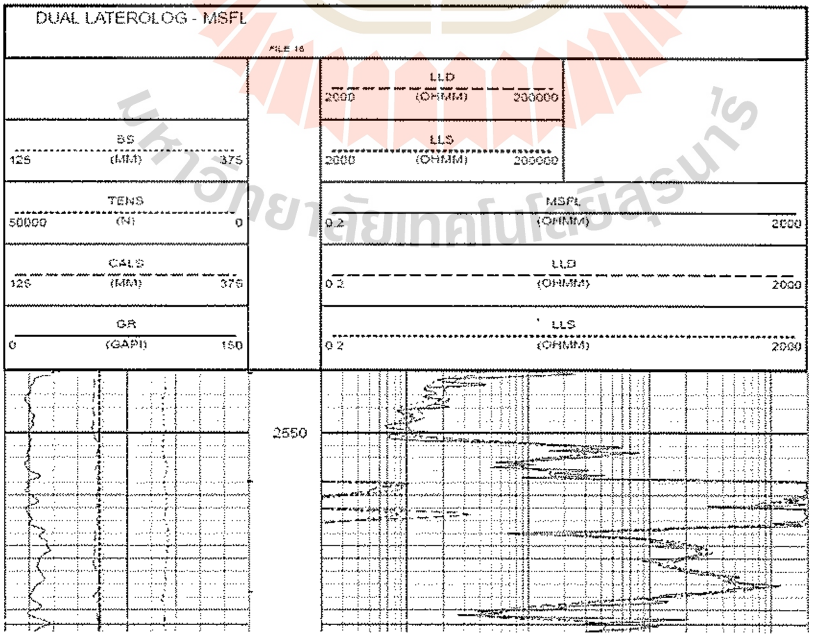
The deep laterolog measurement (LLD) of the DLL tool has a deeper depth of investigation than previous laterolog tools and extends the range of formation conditions in which reliable determinations of Rt are possible.

The shallow laterolog measurement (LSS) has the same vertical resolution as the deep laterolog device 60 cm (2 feet), but it responds more strongly to that region around the borehole normally affected by invasion.

Log Presentation

The DLL-MSFL presentation is very similar to the Phasor Induction. Differences include expanded resistivity scale (0.2-200,000 ohm-m) and the addition of Gamma Ray and Caliper (if MSFL is used). See log in Figure B23.

Figure B23



Tool Characteristics and Applications

1. The Dual Laterolog performs most effectively in saline mud (high Rt/Rm ratios) or where Rmf/Rw < 2.5.

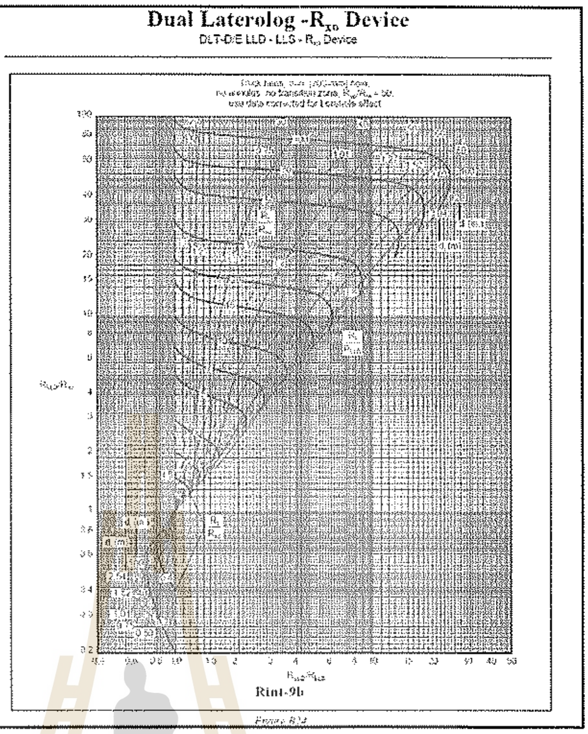
2. The tool has an excellent resistivity range; by utilizing a unique design, resistivity resolution from 0.2 to 40,000 ohm-m is possible.

3. Vertical resolution is excellent, Rt can be obtained in beds as thin as 60 cm (2 feet).

4. The LLd has very little borehole effect in large holes.

5. When combined with an Rxo measurement, the LLd, LLs curves may be used to study invasion profiles and compute a more accurate Rt. See Chart Rint-9 (Figure B24).

Figure B24 →



Limitations

1. The tools should not be used in fresh muds (Rmf/Rw > 2.5.)

2. The tools requires good centralization to minimize borehole influence on the LLs.

3. If invasion is deep, a good value of Rxo (e.g. from a Micro-Spherically Focused Log) is required to correct LLd for invasion influence to obtain an accurate value of Rt.

- Correction Charts are available for the influence of:

  - borehole (diameter and mud resistivity).

  - invasion. (Chart Rint-9b/Figure B24)

  - bed thickness.

Measurement of Rxo by Micro-resistivity Principles

- INTRODUCTION

  As has been mentioned, a measurement of flushed zone resistivity, Rxo, is an important input when attempting to define invasion diameter. Since the flushed zone may only extend a few centimetres from the borehole, a shallow reading device is required. Such tools are the Microlog, Microlaterolog, Proximity log and the Micro-Spherically Focused Log.

Today, the Microlog and Micro-Spherically Focused Log are completely combinable with all main logging services. The Microlaterolog and Proximity log have been discontinued due to their limitations in design.

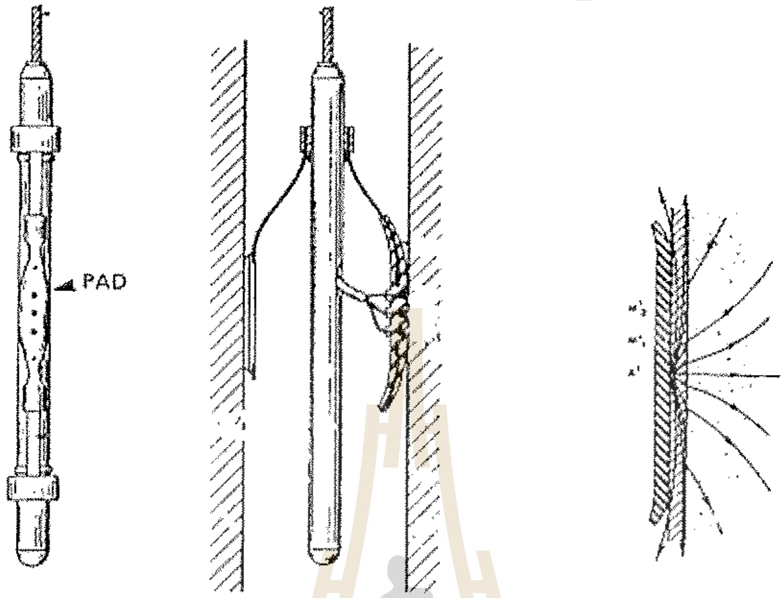
To measure Rxo, the tool must have a very shallow depth of investigation. Since the reading should be affected by the borehole as little as possible, a sidewall-pad tool is used.

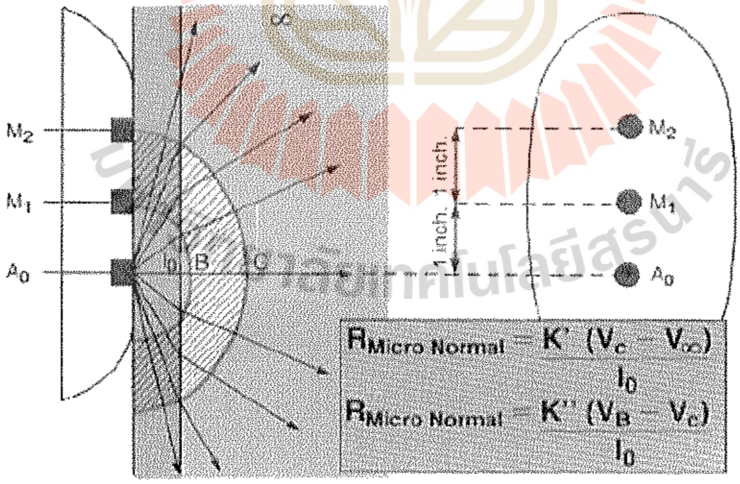
MICROLOG

With the micrólog tool, two short-spaced devices with different depths of investigation provide resistivity measurements of a very small volume of mudcake and formation immediately adjoining the borehole.

Comparison of the two curves readily identifies mudcake, which indicates invaded and, therefore, permeable formations.

Figure B25: Microlog



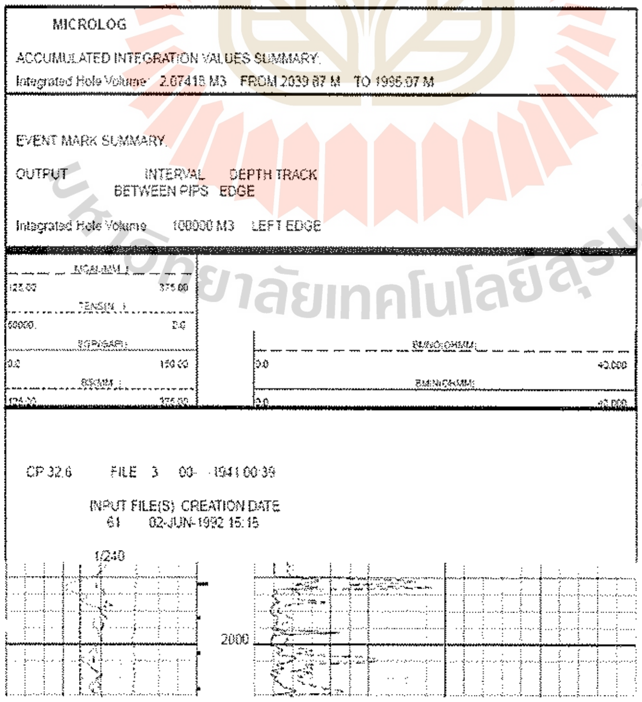


$$R_{\text{Micro Normal}} = \frac{K'\,(V_C - V_\infty)}{I_0}$$

$$R_{\text{Micro Normal}} = \frac{K''\,(V_B - V_C)}{I_0}$$

Figure B26: Microlog ML

As drilling fluid filters into the permeable formations, mud solids accumulate on the hole wall and form a mudcake. Usually, the resistivity of the mudcake is slightly greater than the resistivity of the mud and considerably lower than the resistivity of the invaded zone near the borehole.



MICROLOG

ACCUMULATED INTEGRATION VALUES SUMMARY:

Integrated Hole Volume: 2.07418 M3 FROM 2039.87 M TO 1995.07 M

EVENT MARK SUMMARY:

OUTPUT	INTERVAL BETWEEN PIPS	DEPTH TRACK EDGE
Integrated Hole Volume	100000 M3	LEFT EDGE

CP 32.6 FILE 3 00- 1941 00:39

INPUT FILE(S) CREATION DATE
61 02-JUN-1992 15:15

Microlog Limitations

- Rxo/Rmc must be less than about 15.

- Mudcake thickness < 1.2 cm

- Depth of Flushing > 10 cm, otherwise the microlog readings are affected by R_t.

MICRO – SPHERICALLY FOCUSED LOG

The MicroSFL is a pad-mounted spherically focused logging device that has replaced the Microlaterolog and Proximity tools. It has two distinct advantages over the other Rxo devices. The first is its combinability with other logging tools, including the Phasor Induction, the Array Induction, and Dual Laterolog tools.

The second improvement is in the tools response to shallow Rxo zones in the presence of mudcake.

The chief limitation of the Microlaterolog measurement was its sensitivity to mudcakes. When mudcake thickness exceeded about 3/8 inch, the log readings were severely influenced at high Rxo/Rmc contrasts.

MicroSFL Limitations

- depth of flushing > 12 cm.
- mud cake thickness < 1.2 cm.
- radial investigation 10 cm.

MicroSFL Applications

- Identification of permeable zones.

- An excellent value of Rxo from the MSFL provides a quick look over-lay technique for comparison with an Rt curve after being normalized in a 100% Sw zone. After normalization when curves separate, moved hydrocarbon is indicated.

- Correction charts are available for the influences of:
  - Mudcake (Chart Rxo-3) (Figure B29).

Figure B29

MicroSFL* Mudcake Correction

For Hole Diameter of 8 in. or 200 mm

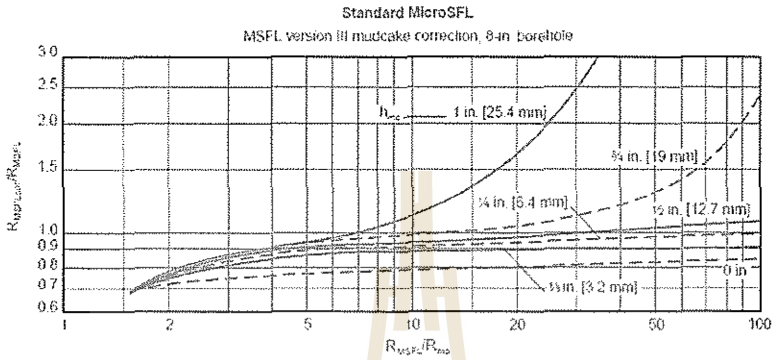
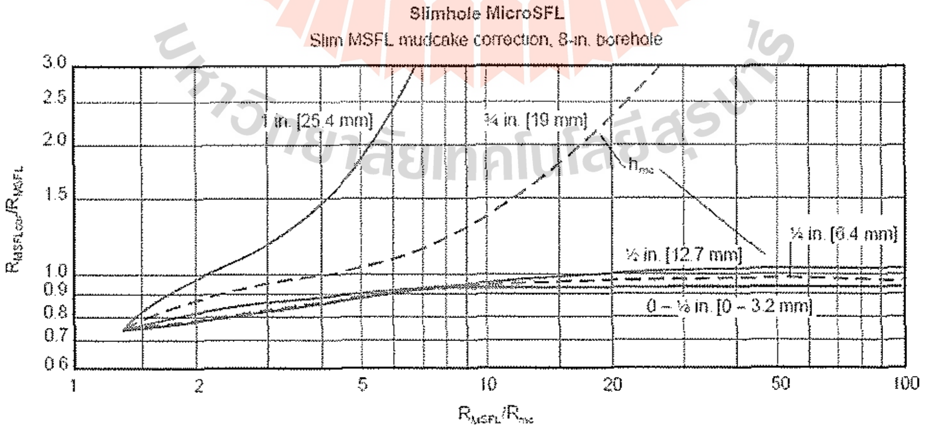


Figure B29 (Cont.)



Chapter 4
SPONTANEOUS POTEXTIAL (SP) LOG

SPONTANEOUS POTEXTIAL (SP) Log

The Spontaneous Potential (SP) curve is a record versus depth of the direct current potential of a moving electrode in the borehole and a fixed reference surface eletrode .

- The SP is used to :

  1) identify permeable beds,

  2) locate the boundaries of permeable beds and to correlate these beds from well to well,

  3) determine the values of formation water resistivity (R_W)

  4) give a qualitative indication of formation shaliness.

  5) give an indication of zone shale content.

  6) indicate depositional environment.

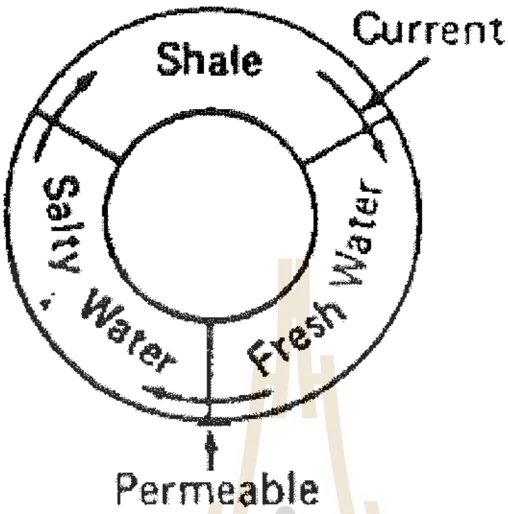
The SP is recorded as a linear relative direct current potential. with no recorded zero. The amplitude of each excursion is recorded in millivolts(mV) with the base reference being the shale baseline . Opposite shales the SP records a relatively constant potential with a small drift either positive or negative.

The SP is normally recorded on the extreme left hand side of the log grid. Typically the shale base line is about two divisions to the left of the depth column.

The Electrochemical Component of the SP

Mounce and Rust used a simple experiment to show that two waters of different salinities and a shale, all separated by permeable membranes, are an electro chemical cell. As shown in Figure 4-1.

Fig 4-1



From Figure 4-1, the current flows from the fresh to the salty water and then through the shale. The voltage created is a function of the salinity difference between the fresh and salty water salinities. If both waters have the same salinity the voltage is zero. If you reverse the two waters, the current flows in the opposite direction. This cell is similar to the conditions existing in the wellbore, where the drilling mud is fresh and the formation water is salty.

Electrochemical Potential

This potential is created by the contact of two solutions of different salinity, either by a direct contact or through a semi-permeable membrane like shales.

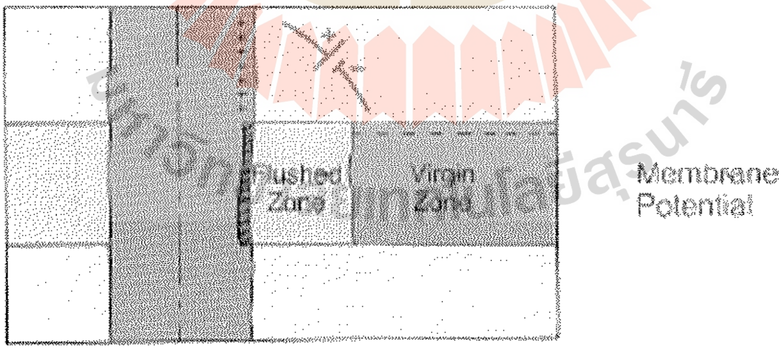


Figure B7: Electrochemical membrane potential of SP

The liquid junction is a result of the salty formation water being in contact with the fresh mud filtrate. The ions migrate from the very salty to the fresher water. The chlorine ion has a much greater mobility than the sodium ion and thus migrates more quickly. A net negative charge is created in the less saline water. The liquid junction represents about 17% of the total potential.

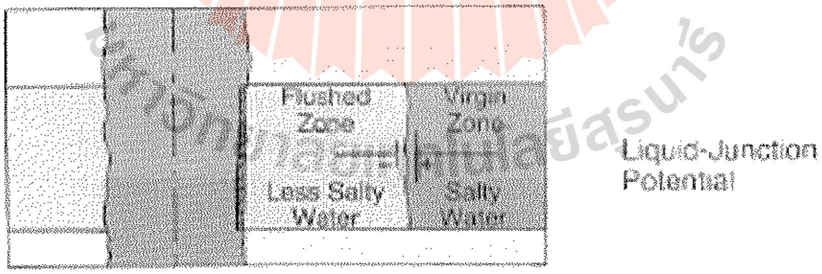


Figure B8: Electrochemical Liquid - Junction Potential of SP

- For a clean (non-shaly) formation the electrochemical potential is

$$E_C = -K_C \log \frac{a_W}{a_{mf}} \qquad (4\text{-}1)$$

where E_C is the potential of the cell in millivolts

a_W is the activity of the formation water

a_{mf} is the activity of the mud filtrate

- and K_C is proportional to formation temperature and is

$$K_C = 0.133T + 61 \qquad (4\text{-}2)$$

Where T is in degrees Fahrenheit (°F).

- When converted to resistivities equation 4-1 becomes:

$$E_C = -K_C \log \frac{R_{mfeq}}{R_{Weq}} \qquad (4\text{-}3)$$

where R_{mfeq} is the equivalent resistivity of the mud filtrate

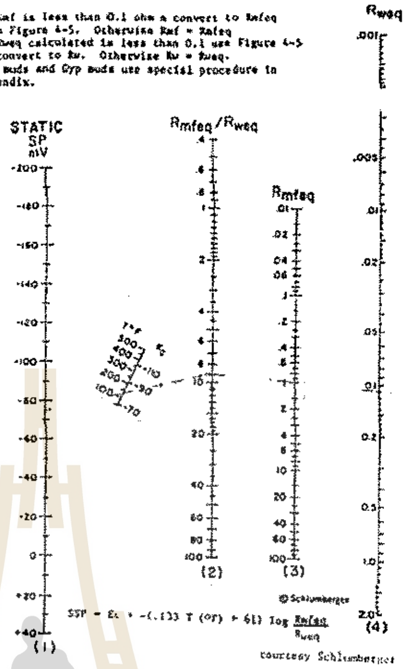
and R_{Weq} is the equivalent resistivity of the formation water.

- Figure 4-4 solves equations 4-2 and 4-3 for R_{Weq}. The SP used should be corrected for bed thickness (if necessary). SSP is E_c or SP (corrected).
- Figure 4-5 shows the relationship between R_{Weq} and R_W, and between R_{mfeq} and Rmf.

Figure 4-4

Figure 4-4 Nomograph for Rweq determination from the SP

a) If Rmf is less than 0.1 ohm m convert to Rmfeq with Figure 4-5. Otherwise Rmf = Rmfeq
b) If Rweq calculated is less than 0.1 use Figure 4-5 to convert to Rw. Otherwise Rw = Rweq.
c) KCl muds and Gyp muds use special procedure in Appendix.



$SSP = E_c + -(.133\ T\ (°F) + 61)\ \log \frac{R_{mfeq}}{R_{weq}}$

courtesy Schlumberger

Figure 4-5

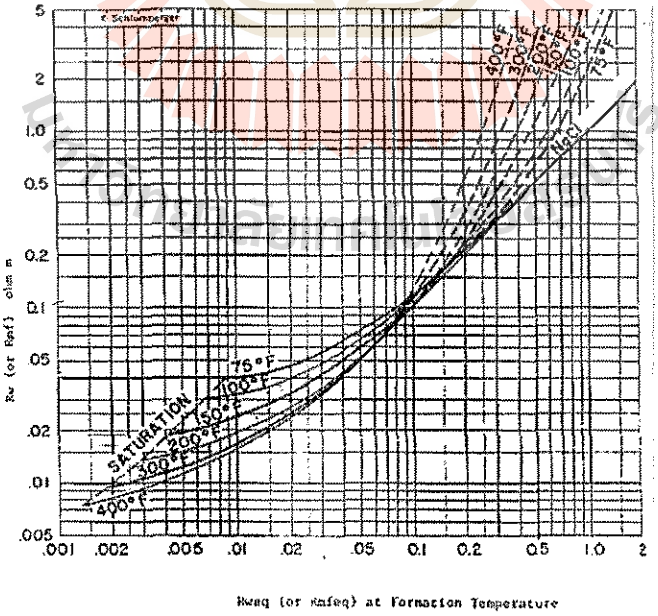
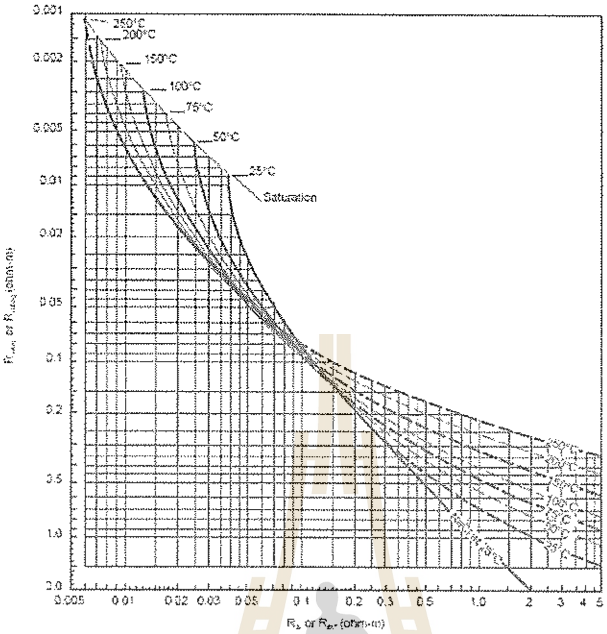
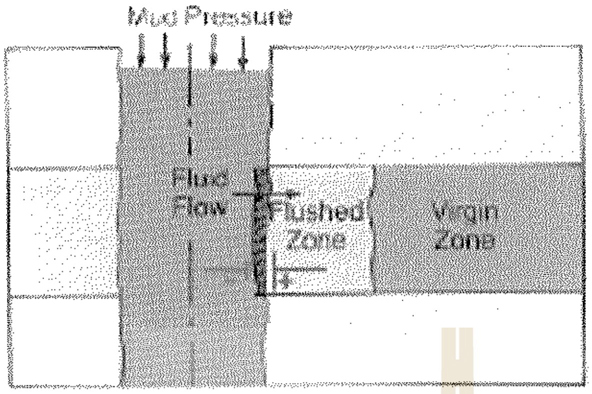


Figure 4-5



The Electrokinetic Component of the SP

The electrokinetic (streaming) potential results from the flow of an electrolyte through a non-metallic permeable medium. The pressure drop across the material and the resistivity of the electrolyte all contribute to the magnitude of this potential. Generally it is considered that the electrokinetic potential is created across the mud cake and also shales. These two potentials are usually equal and thus cancel each other out and thus are ignored.



Electrokinetic
Potential

Figure B6: Electrokinetic Potential of SP

If a solution is forced, by differential pressure, to flow through a membrane, an electrical potential will appear across the membrane (Figure B6). A similar situation occurs when the mud filtrate flows through the mudcake because of the differential pressure between the mud column and the formation. This electrokinetic potential (E_{kmc}) is generally very small.

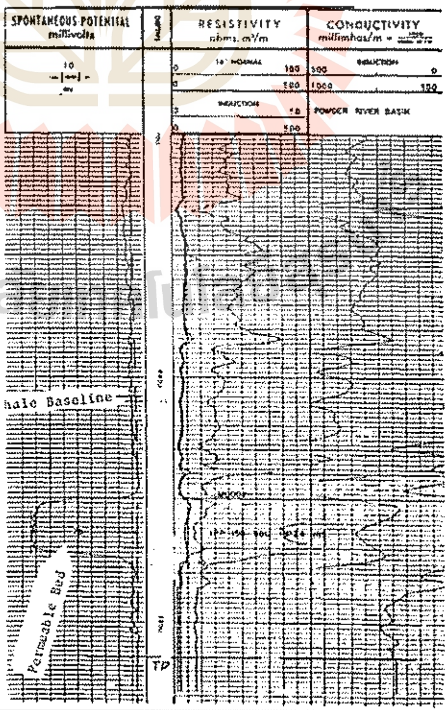
In a very low permeability formation, where the mudcake is only partially built up, this electrokinetic potential may be as high as 20 mV. This situation is, however, very rare and in general the total electrokinetic potential can be neglected.

The SP Log

Figure 4-6 shows a typical SP log in the Lower Cretaceous in Wyoming. The apparent shale baseline is not as smooth as is often seen in the Sulf Coast. This is probably due to much of the shale section being silty. The large anomaly at 6850-6869 is a permeable bed (the Muddy sandstone).

- The SP curve is generally presented in track 1, and usually recorded with resistivity surveys, assuming a conductive mud is in the borehole.
- The maximum available SP in a thick, clean, water-bearing zone is called Static Spontaneous Potential, or SSP

Figure 4-6



Factors Affecting the SP

- The static SP (SSP) refers to the maximum SP that can be obtained for a given shale and the two waters of different salinity.
- The SP, as measured in the borehole, is influenced by bed thichness, bed resistivity. Invasion, borehole diameter, shaliness and of course R_{mf}/R_W ratio.

Factors Affecting the SP

- Bed Thickness : SP decreases when bed thickness decreases.
- Invasion : Reduces SP
- Shaliness: Shale reduces SP
- Hydrocarbons: Hydrocarbons in slightly shaly formations will reduce the SSP
- Mud Filtrate: The magnitude and direction of SP deflection from the shale base line depends on relative resistivities of the mud filtrate and the formation water.
- Fresh Mud - negative SP (Figure 8). Rmf > Rw
- Saline Mud - positive SP (Figure 8). Rw > Rmf
- Rw = Rmf - zero SP (Figure 8).

The Influence of Bed Thickness and Resistivity

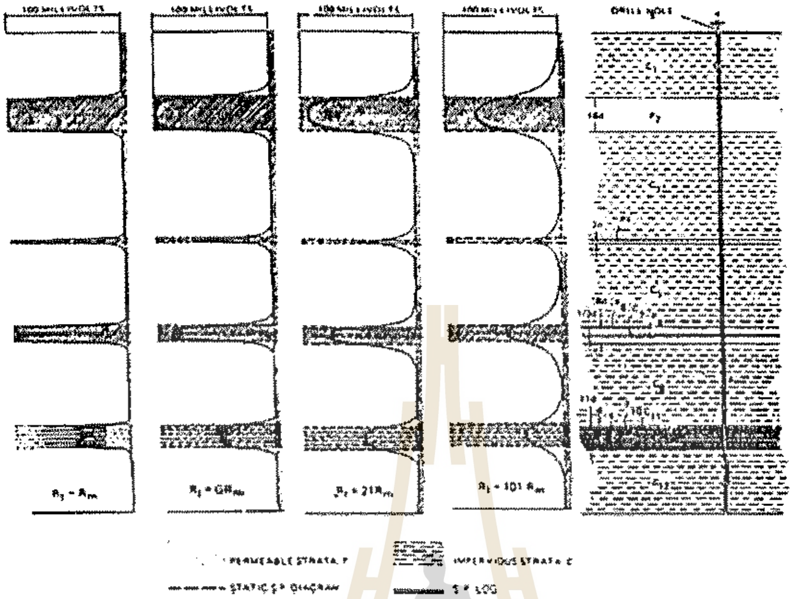
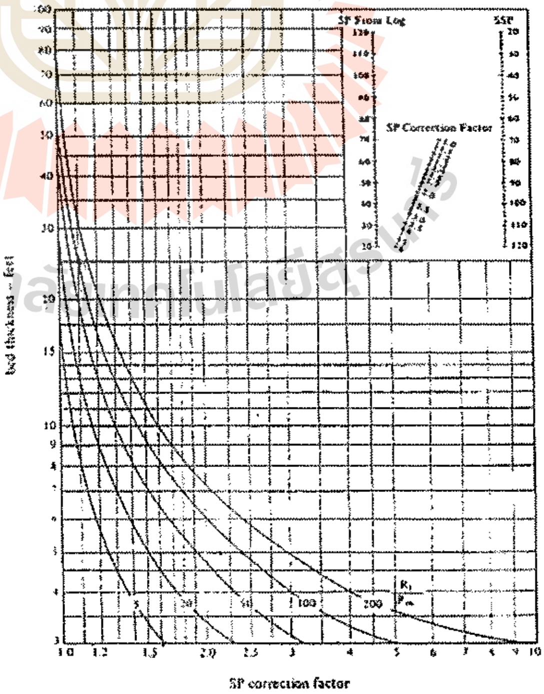


Figure 4-8



Solution of Rw from SP

1. Establish the shalebaseline on the SP curve
2. Pick out permeable zones
3. Do all the thick zones have about the same SP?
   - yes -- pick any thick zone
   - no -- pick thick zone near or the zone you are interested in .
   - - if in transitional zone be very careful.

4. Determine formation temperature --- Fig. 2-3 or Equation (2-3)

5. Determine R_{mf} and R_m at formation temperature --- Fig. 2-2

6. Read SP amplitude from shale baseline to maximum constant deflection.

7. Determine bed thickness from SP deflection points.

8. Do you need to , or can you correct for bed thickness effects, if SP looks like:

needs correction

no correction

9. Using SP from step 8 (corrected if necessary) go to ---Fig. 4-4

R_{mf} less than 0.1 correct to R_{mfeq} --Fig. 4-5

Enter Fig. 4-4 --- with SP, T_f, R_{mf} or R_{mfeq}

Come out with Rweq

---

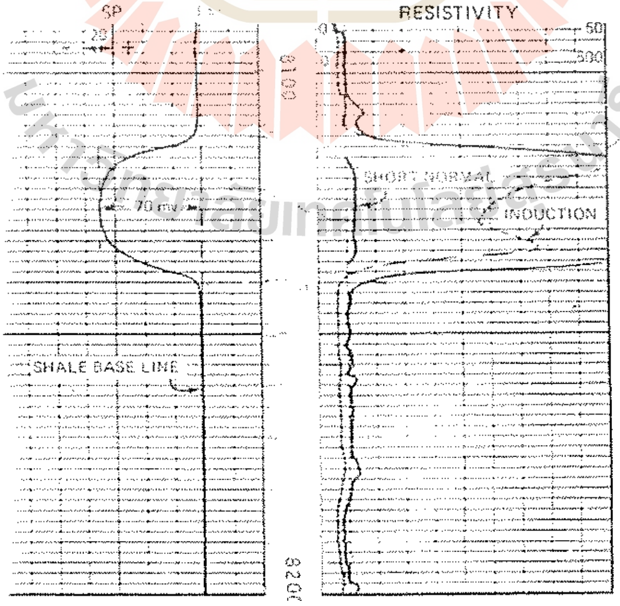
10. Convert R_{weq} to R_w with Fig. 4-5 use solid NaCl lines.

11. Check R_w from SP against another source if available

Example 4-1
Calculation of R_w from SP

- Well Log Heading Data: Formation - Morrow sandstone
- Rmf = 2.0 @ 70 °F surface temp. = 60 °F
- Rm = 2.5 @ 70 °F TD temp. = 164 °F
- TD = 10500 ft

Example 4-1



Example 4-1

1. Shale baseline - see log
2. only one permeable zone -- 8114 top
3. only one zone
4. $T_f = 140$ °F
5. Rmf = 1.0 at 140 °F   Rm = 1.3 at 140 °F
6. SP = -70 mV
7. depth interval = 8114 - 8138 = 24 feet

Example 4-1

8. needs correction Ri (from short normal) = 65 ohm-m → Ri/Rm = 65/1.3 = 50

Depth interval = 24 foot bed

Correction factor = 1.07

SP cor. = SP X corr. Fac.

= 70 X 1.07 = 75 mV.

9. Rweq = 0.114

10. Rw = 0.114 ohm-m.

Rweq > 0.1 = Rw

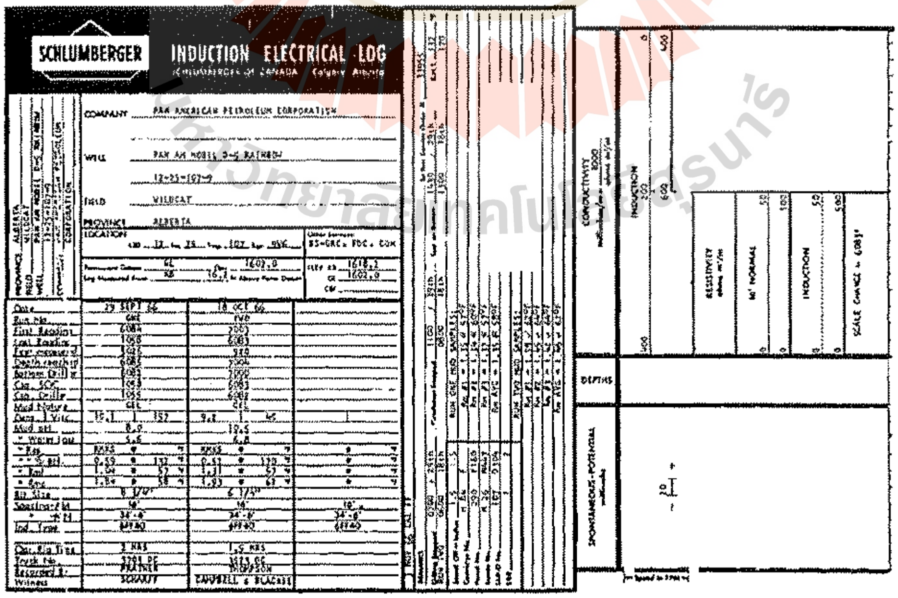
Chapter 5
THE INDUCTION ELECTRIC AND DUAL INDUCTION LOGS

The induction electric log and the dual induction log are combinations of several measurements. The elements that make up each of these logs have already been discussed. In this chapter we will look at the combination of these element and discuss the meanings of the combined data.

The Log Heading

Figure 5-1 shows a typical induction electric log heading. On the log heading are the well name, location , field name or if a wildcat it so states, other logs run on the well, depth reference usually the Kelly Bushing (KB) elevation or ground level (GL), the date the log was run, the total depth according to the log and the driller, the interval logged, the mud properties, tool specifics, operating rig time, truck and logging engineer who made the log and the customer's name who witnessed the log.

Figure 5-1



SCHLUMBERGER

INDUCTION ELECTRICAL LOG

COMPANY PAN AMERICAN PETROLEUM CORPORATION

WELL PAN AM MOBIL D-5 RAINBOW

12-25-107-9

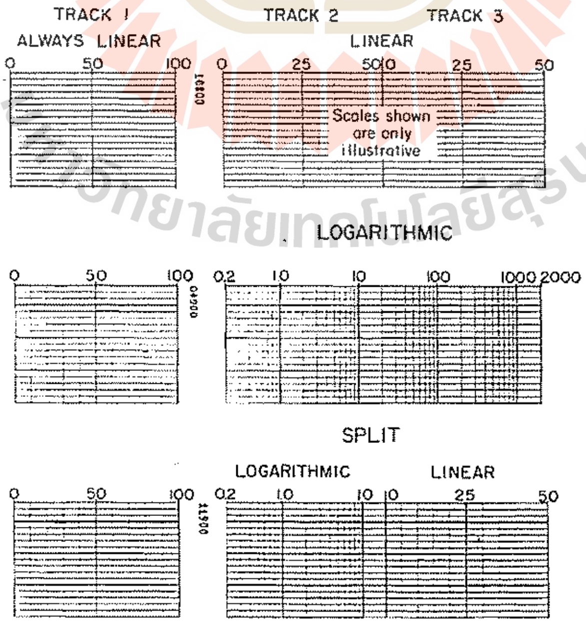
FIELD WILDCAT

PROVINCE ALBERTA

Log Scales and Grids

The log grids most commonly used are shown in Figure 5-2. The linear scale is used on induction electrical logs, porosity type logs and all of the older logs. The logarithmic grid is used on most of the newer resistivity logs such as the dual induction, dual laterolog, Rxo logs, etc. The split grid is used primarily on the induction Spherically Focused Log.

Figure 5-2



Well Log Examples

- Induction Electric Log

  Figure 5-3 shows a typical induction electric log. The SP is, as always, in track 1. The short normal is, as always, in track 2 as a solid line. Actually two short normal curves are showing, one on a 0-2 ohm-m scale and the other on a 0-10 ohm-m scale. And there are two induction curves. The prime data is in track 3 where the induction is displayed on a conductivity scale.

- Dual Induction Log

  The dual induction log is typically run in hard rock areas where the formation are well consolidated and invasion is deeper than in the Tertiary rocks of areas.

- Figure 5-4 shows the detailed and correlation scales usually run with the dual induction.

- Induction Spherically Focused Log

  The induction spherically focused log (ISFL) is shown in Figure 5-6. The SFL is the solid curve, as Ri curves usually are, in track 2 with the induction the dashed curve on the same track 2.

Figure 5-3

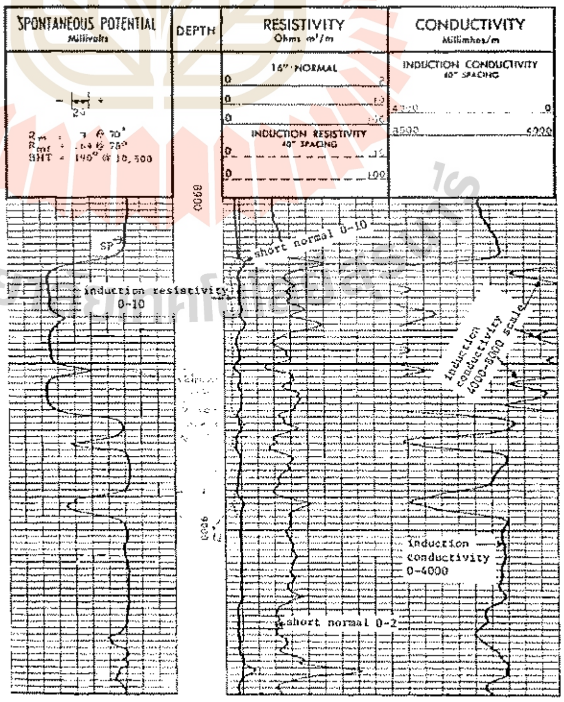


Figure 5-3a

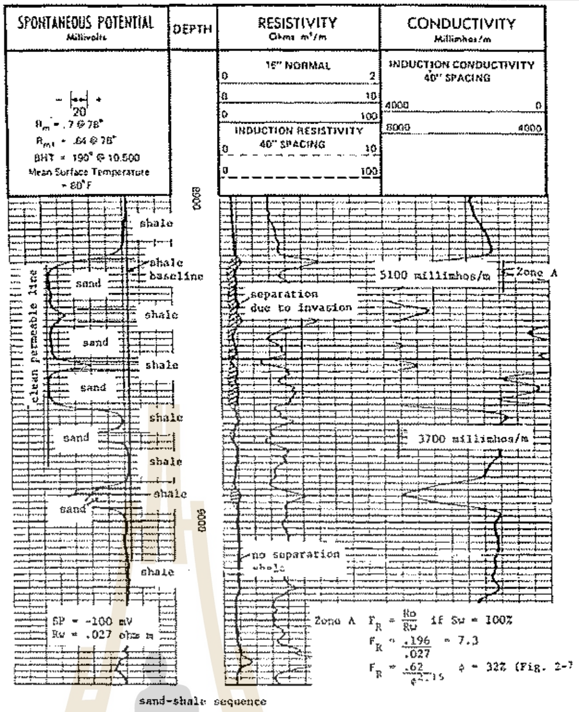
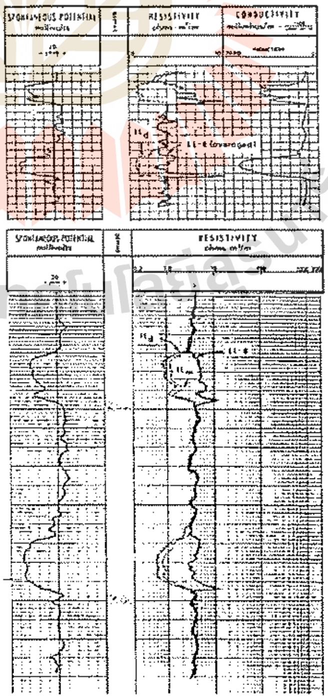
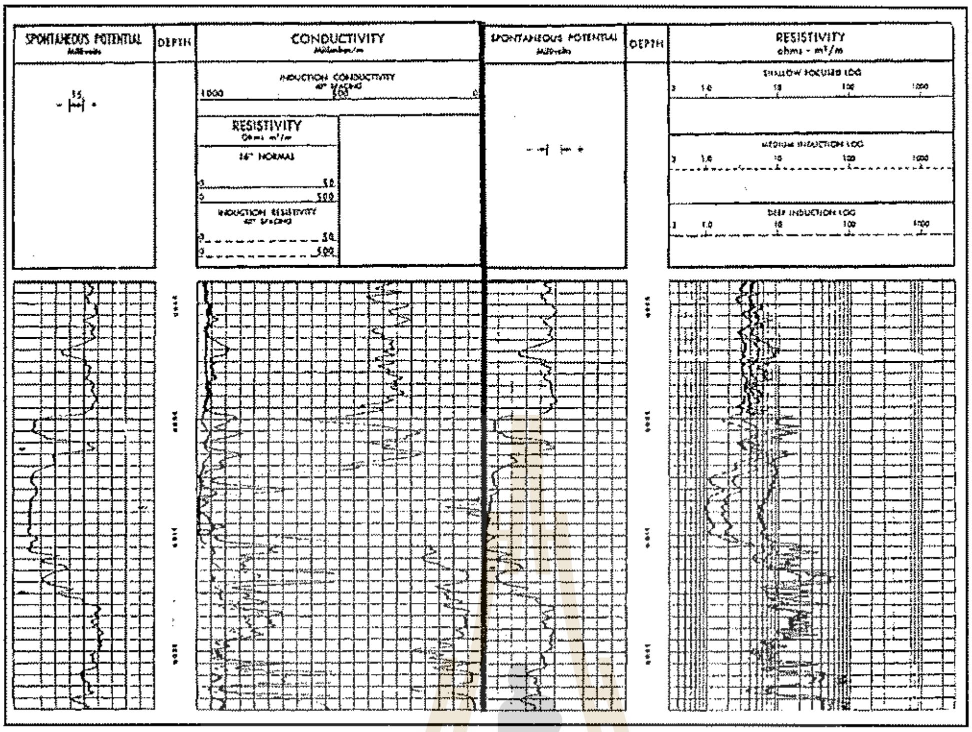


Figure 5-4




SPONTANEOUS POTENTIAL
Millivolts
DEPTH
CONDUCTIVITY
Millimhos/m
INDUCTION CONDUCTIVITY
40" SPACING
1000
0
RESISTIVITY
ohms m²/m
16" NORMAL
INDUCTION RESISTIVITY
40" SPACING
50
500
SPONTANEOUS POTENTIAL
Millivolts
DEPTH
RESISTIVITY
ohms - m²/m
SHALLOW FOCUSED LOG
MEDIUM INDUCTION LOG
DEEP INDUCTION LOG
1.0
10
100
1000

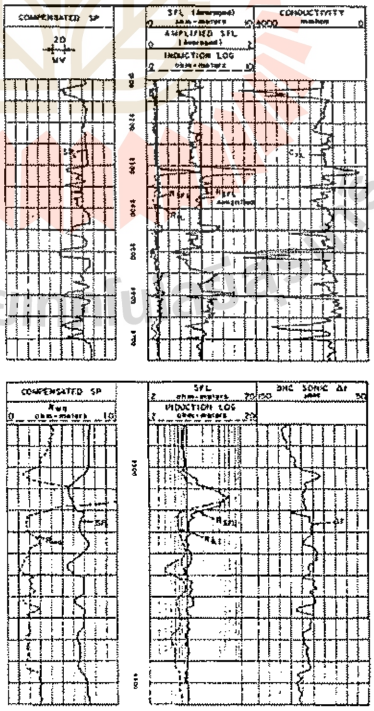

COMPENSATED SP
20
MV
SFL (Averaged)
ohm-meters
AMPLIFIED SFL
(Averaged)
INDUCTION LOG
ohm-meters
CONDUCTIVITY
mmhos
SFL
Rwa
ohm-meters
BHC SONIC Δt

Figure 5-6

Figure 5-7 log reading

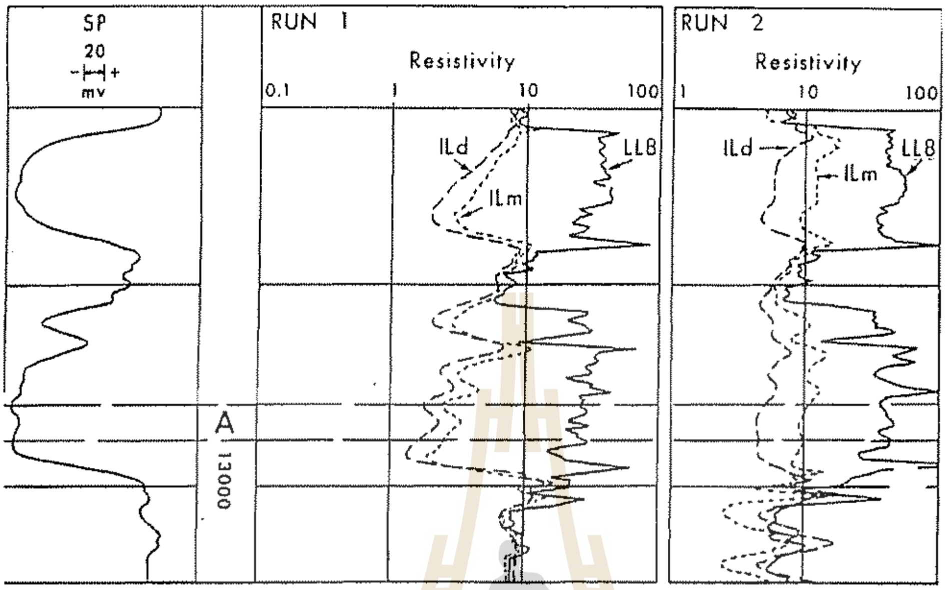


Figure 5-7 log reading

- Zone A 12980 - 12989 ft, Ten days between logging runs

Run	R_{LL8}	R_{IM}	R_{ID}	R_t/R_{ID}	R_t
1	26	2.9	2.0	0.88	1.76
2	40	9.3	4.5	~0.4	1.8

$R_O = 1.5\ \Omega m$ *(Calculated)*

If $R_{ID} = R_t$ *run#1* $Sw = 87\%$

run#2 $Sw = 58\%$

- From Figure 5-7, we can calculated the value of R_t/R_{ID} by Figure 3-11/Figure 5-9.
- From Figure 3-11/Figure 5-9, we will get:

Run	R_{LL8}	R_{IM}	R_{ID}	R_{IM}/R_{ID}	R_S/R_{ID}	R_t/R_{ID}
1	26	2.9	2	1.45	13.00	0.86
2	40	9.3	4.5	2.07	8.89	~ 0.4

Figure 5-9

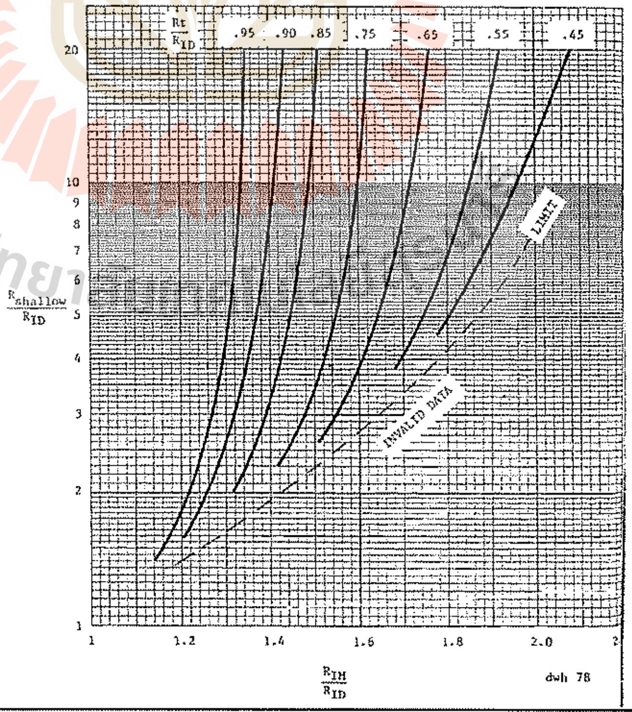


Figure 3-11

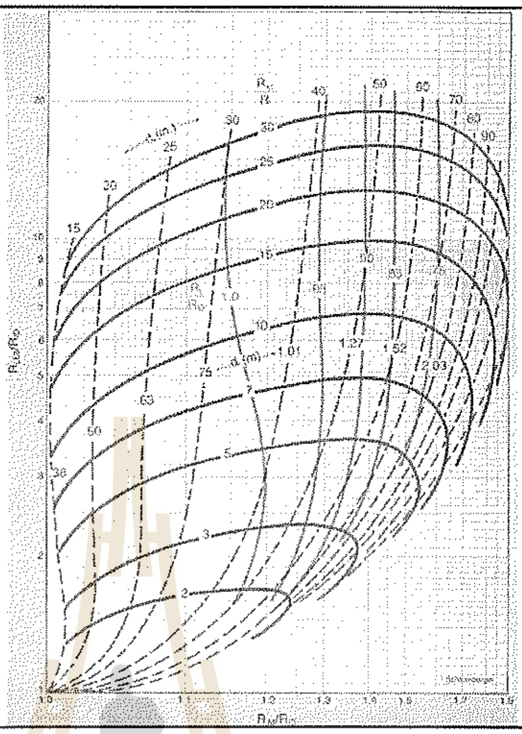
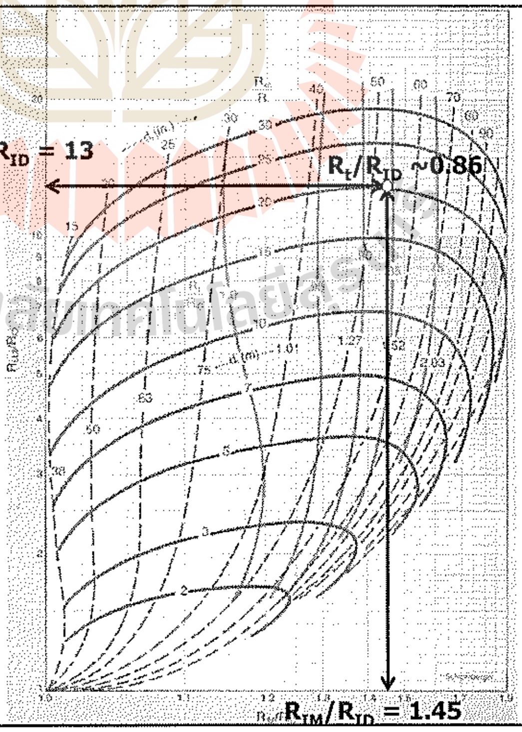


Figure 3-11

Run#1


R_{LL8}/R_{ID} = 13

R_t/R_{ID} ~0.86

R_{IM}/R_{ID} = 1.45

Figure 5-9
Run#2

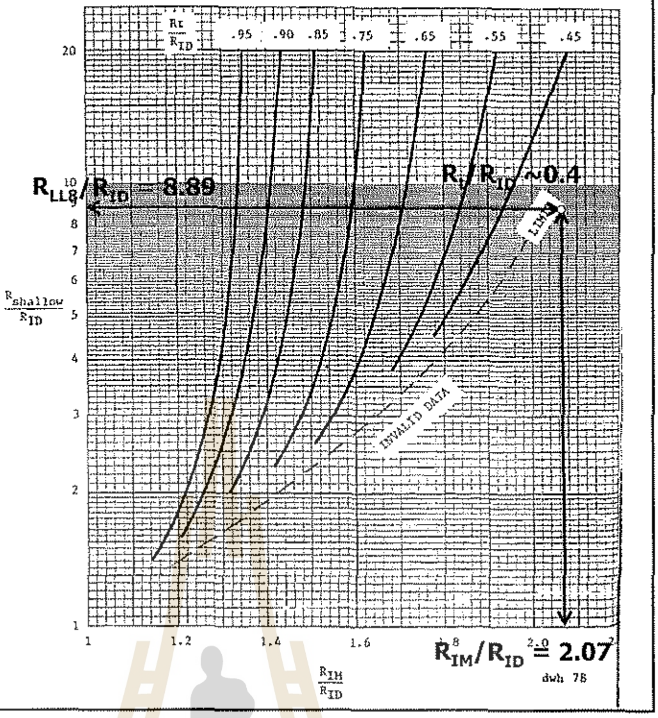


Figure 5-8

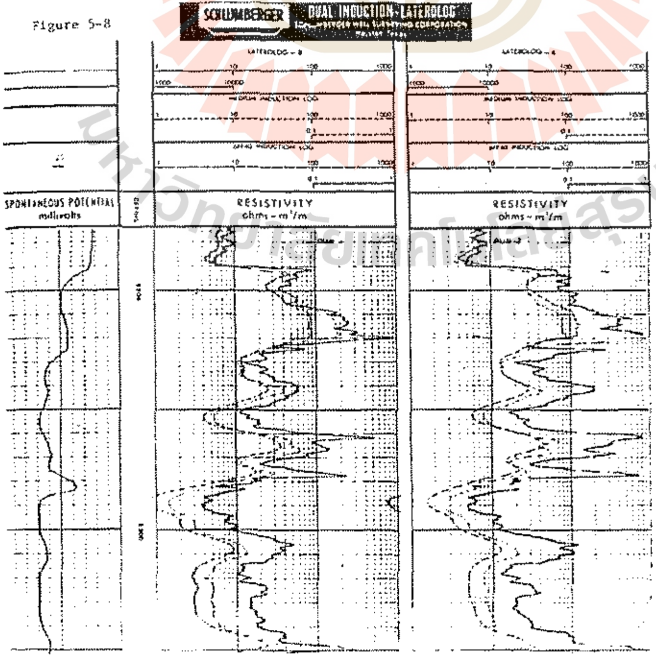


Figure 5-8

Depth	$\frac{LL8}{ILD}$	$\frac{ILM}{ILD}$	D_i	$\frac{R_t}{ILD}$	ILD	R_t	Run#1 R_t
5229-36	2.9	1.0	15"	4.0	13	13	13.0
5244-50	3.9	1.55	71"	0.81	13	10	10.0
5250-55	3.6	1.40	54"	0.90	5.9	5.3	4.0
5286-92	3.5	1.80	160"	0.50	1.6	0.8	0.8
5294-5300	3.9	1.58	78"	0.76	3.0	2.3	2.0
5306-12	7.5	1.6	65"	0.83	12	10	9.0

Example 5-1

Interpretation of an Induction Electric Log with Constant Porosity

- The Gulf Coast log example 5-1 on the next page is a sandstone-shale sequence. The Rw from the SP is 0.042 ohm-m.
  - SP = -100 mV. → From log
  - $R_{mf}/R_{weq} = 18$ → From Figure 4-4
  - Rweq = 0.028 → From Figure 4-4
  - Rw= .042 → From Figure 4-5 (Correction R_W value)

Example 5-1

- From Archie's equation:

$$S_W = \sqrt{\frac{F_R R_W}{R_t}} = \sqrt{\frac{R_O}{R_t}}$$

- We can calculate the value of water saturation as followed:
  - $R_O = 0.2\ \Omega$.m from conductivity log (R_O = is the resistivity of formation that have 100% water in pore volume = $F_R * R_W$)

Example 5-1

- From log, we get the value of $R_t = 15\ \Omega$.m
- From Archie's equation:

$$S_W = \sqrt{\frac{F_R R_W}{R_t}} = \sqrt{\frac{R_O}{R_t}}$$

$$S_W = \sqrt{\frac{0.2}{15}} = 11\%$$

Example 5-1

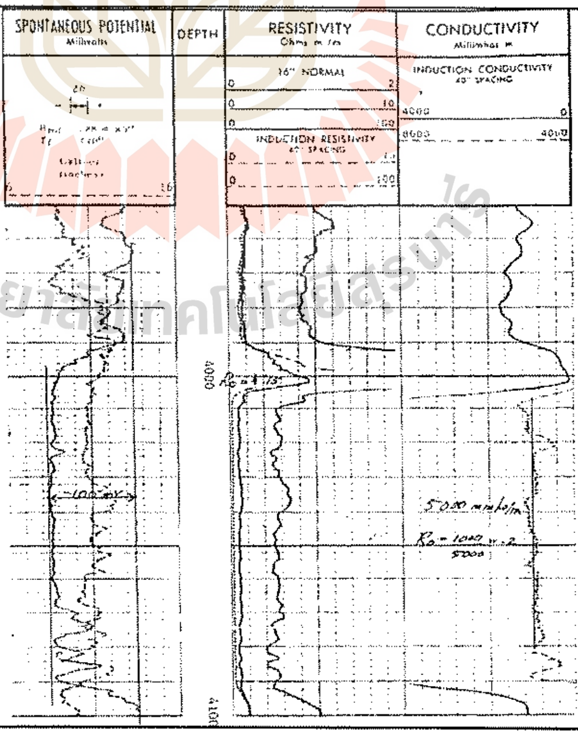
- The porosity in the water bearing zone can be estimated by use of R_W and R_O.

$$F_R = \frac{R_O}{R_W} = \frac{0.2}{0.042}$$

$$F_R = 4.76$$

- If $F_R = 0.62\phi^{-2.15}$ for sandstones then
  $\phi = 39\%$

Log of Example 5-1



Chapter 6
ACOUSTIC AND GAMMA RAY LOGS

Porosity Measurements

Total porosity may be made up of primary and secondary porosity. Effective porosity is the total porosity after the shale correction is applied. Rock porosity can be obtained from the sonic log, the density log, or the 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 or can be determined, the tool response can be determined and related to porosity. Therefore, these devices are often referred to as porosity logs.

- As well as porosity, the logs are affected by:

  - volume and nature (lithology) of matrix material.

  - amount and nature of pore space contents (pore geometry, water, hydrocarbons).

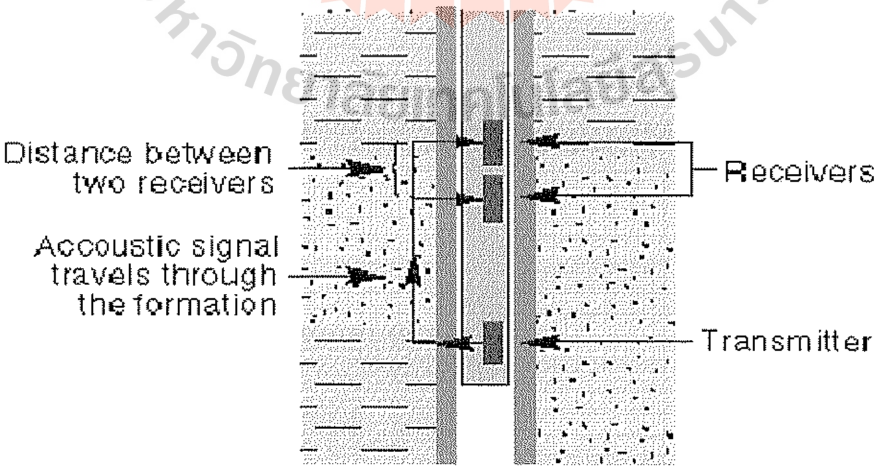
  - volume and nature of shales.

Sonic Tool

- The sonic tools create an acoustic signal and measure how long it takes to pass through a rock.
- By simply measuring this time we get an indication of the formation properties.
- The amplitude of the signal will also give information about the formation.

Sonic Tool

Two receivers eliminates the travel in the borehole



ACOUSTIC LOGS / SONIC LOGS

The acoustic (sonic) log measures the shortest time required for a compressional wave to travel vertically through one foot of formation adjacent to the wellbore. The acoustic (sonic) travel time (per foot) can be related to porosity when the lithology is known.

Additional information can be obtained from this measurement as the acoustic travel time is not only influenced by porosity but also rock elasticity and strength.

The acoustic log is typical of most logs in that the desired rock property is not measured but inferred and empirical relationships have been developed to relate the rock property to the measured parameter.

Wyllie Equation

- The empirical Wyllie equation is used to relate travel time and porosity. In its original form this relationship is:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \qquad \text{Eq 6-1}$$

- Where
  - t is the formation travel time from the well log,
  - t_{ma} is the matrix travel time (at zero porosity)
  - t_f is the fluid travel time (60 microseconds per foot)
- The matrix travel time varies from one rock type to another as shown in Table 6-1.

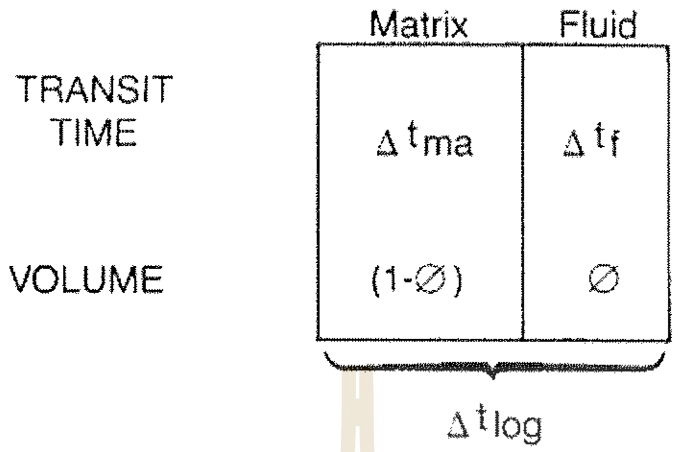


Figure C4: Components of the Wylie Time-Average Equation

Table 6-1

- Table 6-1 Commonly used matrix travel times for different rock types

Mineral	t_{ma} Range	t_{ma} Commonly Used
sandstones	55.5 – 50	55.5 or 51
limestones	47.5 – 43	47.5
dolomites	43.5 – 38	43.5
anhydrites	50	50.0
salt (halite)	67	67.0
casing (iron)	57	57.0

The Wyllie relationship assumes that the porosity is homogeneous. This means that the relationship works well in sandstones and other granular rocks but must be adapted for some vuggy carbonates as will be discussed in the carbonate section of this chapter.

The acoustic log is a plot of acoustic travel time versus depth. Short travel times are on the right hand side of track 3 and longer travel times are on the left hand side of track 2. This format conforms to the general well log format where everything else being constant, porosity increases as the curve moves to the left.

** Shales usually show up as higher travel times. This is not because the porosity is high but because the shales are not elastic and do not react like the other formations.

The acoustic log is usually recorded with a caliper log i n track 1. This caliper is usually a three-armed device in which the three arms go in and out together. An SP or gamma ray is often recorded in track 1. The SP on the acoustic log often looks different than the induction log SP. This is the result of the acoustic log having a metal housing which often results in bimetallic responses on the SP. If there is any variation in the SP use the induction SP.

The Acoustic Measuring Instrument

The acoustic log sonde has at least one sound transmitter and two or more receivers. The transmitter creates a sonic pulse with a frequency centered around 20,000 Hz (cycles per second). The sound goes out in all direction into the bore hole mud. One ray of this sound is refracted into the formation and travels downward as shown in Figure 6-1.

As the sound travels downward it is responsible for part of the energy being refracted back into the bore hole. As the wave passes by the first receiver the refracted wave into the bore hole is received and looks something like the schematic shown in Figure 6-1. As the wave is received at the second and third receive the increased time for the wave to travel the given distance is noted.

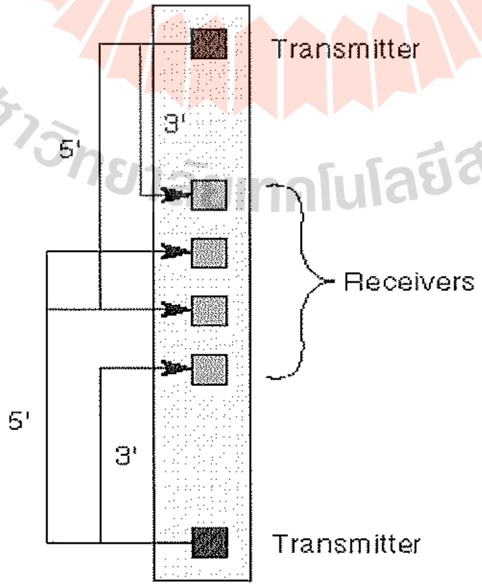
The travel time recorded on the log is either the time difference of the first acoustic wave arrival (the compressional wave) between the first and second receivers (a one foot sonic spacing)

The bore hole compensated (BHC) acoustic log was developed to eliminate the bore hole effects. Figure 6-2 shows a sonic log from West Texas. The section is comprised of anhydrite and salt beds. The anhydrite beds have travel times of 50 microsec./ft. while the salt beds have 67 microsec./ft. The caliper is in track 1 and is the dotted curve and is recorded 5 feet shallow. The hole enlargements are opposite the salt beds. The circled points are caused by change in hole size.

Sonic -BHC

- A simple tool that uses a pair of transmitters and four receivers to compensate for caves and sonde tilt.
- The normal spacing between the transmitters and receivers is 3' - 5'.
- Used for: Correlation, Porosity, Lithology, Seismic tie in, time-to-depth, conversion.

Sonic BHC



BHC Sonic - GR tool distances

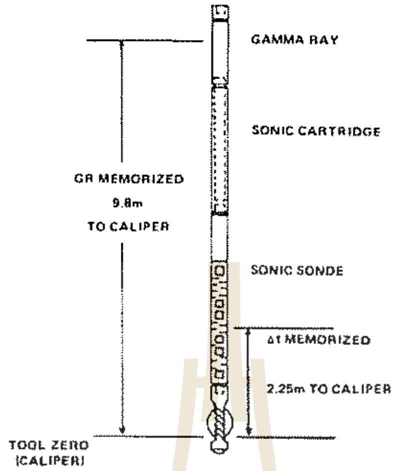


Figure C2: BHC Sonic - GR tool distances

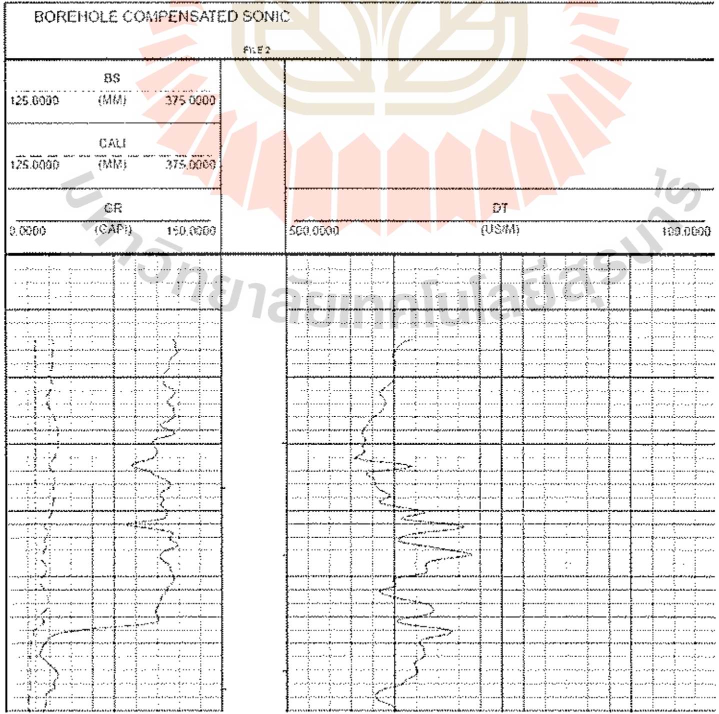


Figure 6-1

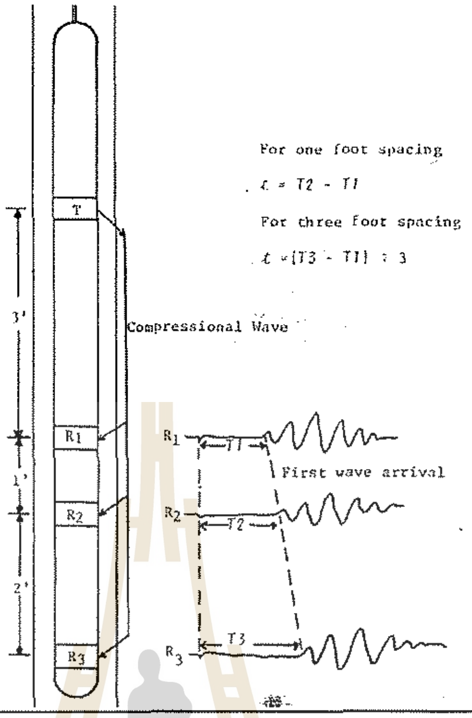
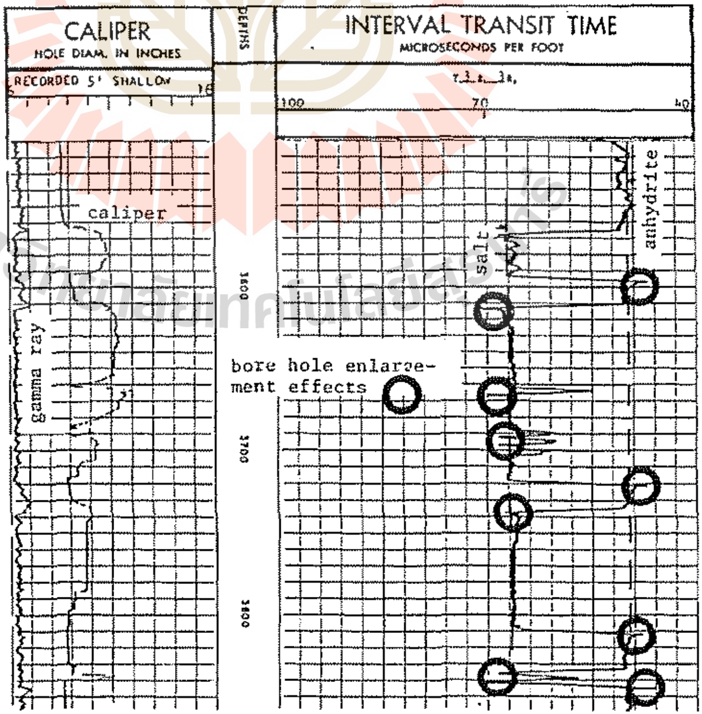


Figure 6-2



- A schematic of this hole enlargement effect is shown in Figure 6-3.

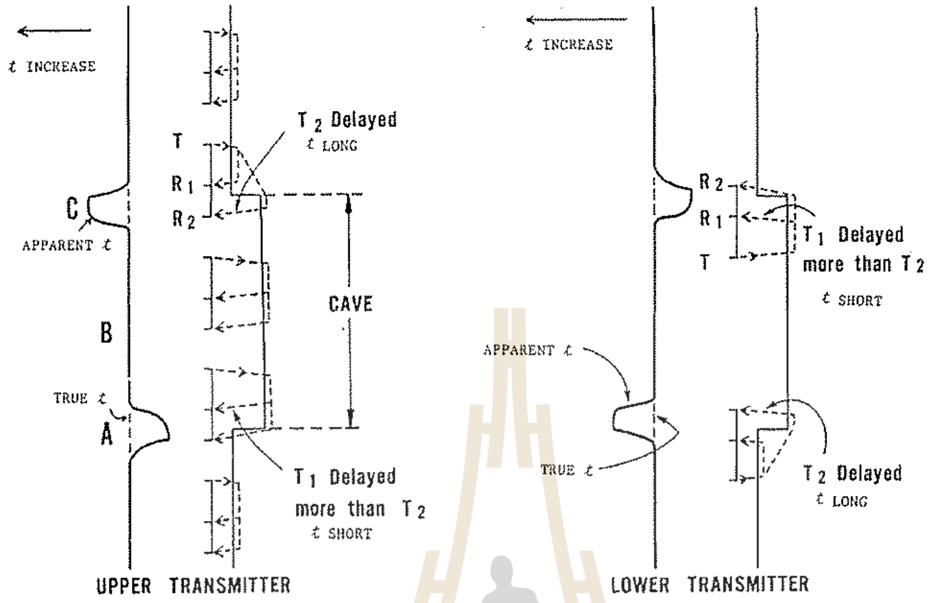
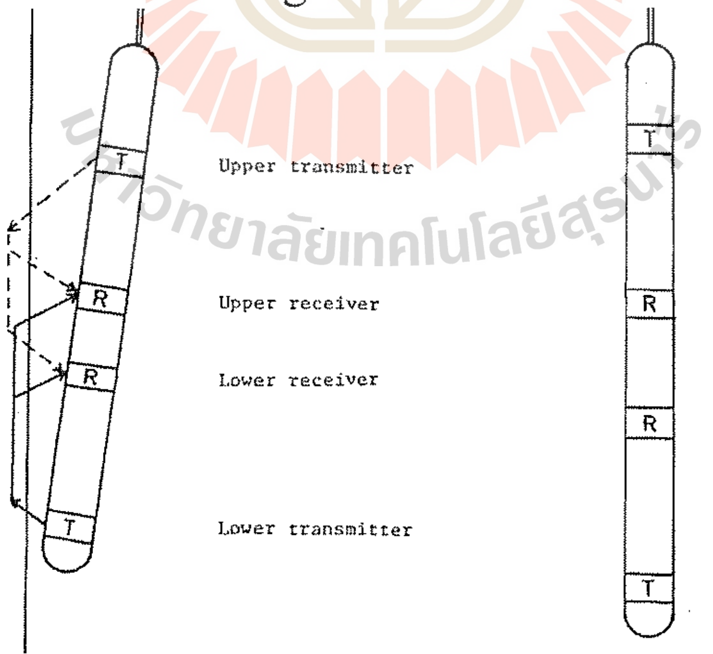
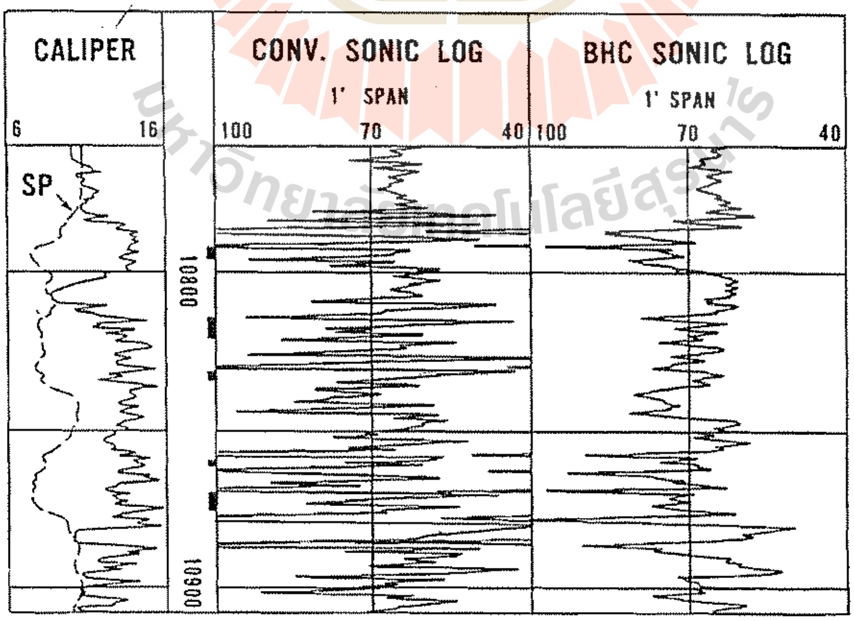


Figure 6-4



- Figure 6-5 shows two sonic (acoustic) logs run over the same bore hole interval. The conventional sonic log shows the effects of the badly caved hole while the BHC sonic essentially eliminates these hole enlargements effects. The conventional sonic in this case is impossible t o read.

Figure 6-5



Porosity

- Compacted and Consolidated Sandstones

  In consolidated and compacted sandstone formations equation 6-1 is used which is solved in a general way in Figure 6-9.

Porosity

- Carbonate

  In carbonates having homogeneous or intergranular porosity equation 6-1 and Figure 6-9 give good porosity results. In carbonates with secondary or moldic porosity in the form of vugs, the travel time is often shorter than would be calculated for that given porosity. This is because the acoustic log measures the fastest travel time through the formation.

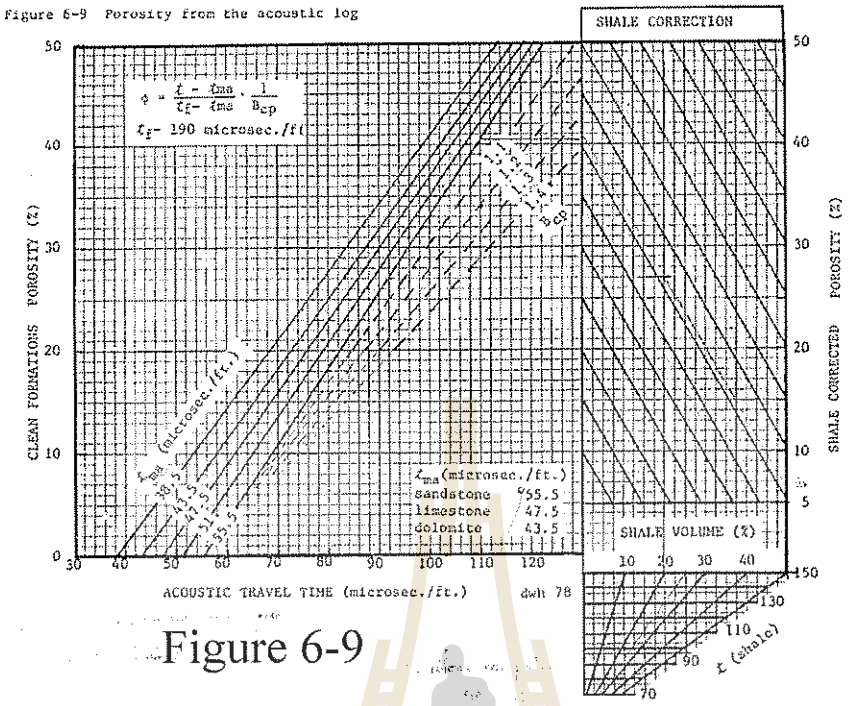


Figure 6-9

Porosity

- Un-compacted Sandstones (Un-consolidated)

  Uncompacted reservoir rocks exhibit longer travel time than the compacted rocks of the same porosity. This longer travel time results in higher calculated porosities than are present. It has been empirically determined that the travel times, in the adjacent shales are relatively good indicators of the net overburden pressure.

If the travel time in the shales are over 100 microsec./ft. the formations are usually uncompacted. The higher the shale travel time the more uncompaced the reservoir rocks are and the greater the deviation in the calculated and true porosity. The equation used to calculate porosity in uncompacted formations (almost always sandstones) is

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \cdot \frac{1}{B_{cp}} \qquad \text{Eq 6-2}$$

where the only addition to equation 6-1 is B_{cp} which is:

$$B_{cp} = \frac{t_{sh}c}{100} \qquad \text{Eq 6-3}$$

where t_{sh} is the travel time in the shale as seen on the log

c is a constant, usually = 1 but can be higher than one if more correction is required.

** Equation 6-2 can be solved with Figure 6-9 for sandstones. The B_{cp} corrections are shown as dashed lines.

- In hydrocarbon bearing uncompacted formations the acoustic porosity even after adequate correction using equation 6-2, is too high. This is due to the response of the measurement to the hydrocarbons. Although at this time it is virtually impossible to correct for these hydrocarbon effects the following empirical corrections are suggested

in gas $\phi \cong \phi(\text{calculated}) \times 0.7$

in oil $\phi \cong \phi(\text{calculated}) \times 0.9$ Eq 6-4

Example 6-1

- Calculation of porosity in an uncompacted gas sand.

  Data: Shale travel time is 120 microsec./ft. The sandstone formation travel time is 110 microsec./ft.

  From equation 6-3 $B_{cp} = 120 \times 1. / 100 = 1.2$

  (if you don't know: better assume c = 1.)

  From equation 6-2 or Figure 6-9 porosity = 34%

Example 6-1

Since this is a gas zone this is probably too high. Check adjacent water zones. If the adjacent water zones are lower porosity then correct for gas effect

$$\phi \cong 34\% \times 0.7 = 24\%$$

$$**\phi = \frac{110-55.5}{190-55.5}\cdot\frac{1}{1.2} = 0.337 = 33.7\%$$

Shales

Shales have relatively high travel times. The shale travel time, as previously mentioned, it a function of the amount of overburden pressure that the shale has been exposed to. I believe shale travel times are longer than reservoir rocks due to the plastic nature of shales. Or if you wish they have low elasticities. As materials such as sand and lime are added to shales (clays) the travel times decrease.

Example 6-2 (Figure 6-13)

- Figure 6-13 An acoustic log example with the associated induction electric log.

  Additional data: Well log Heading

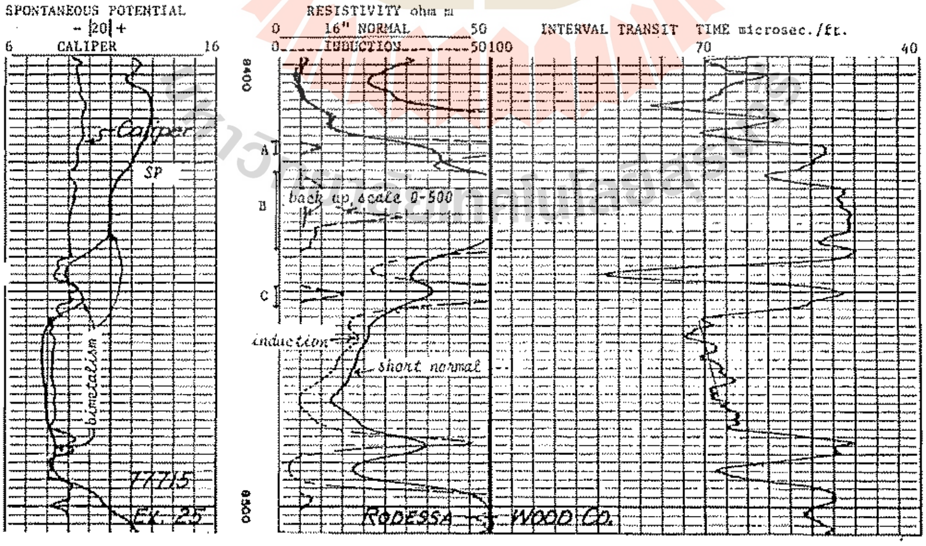
  R_m = 0.62 Ω.m @ 92°

  R_{mf}= 0.56 Ω.m @ 92°

  TD = 8529 ft
- Authors notes: SP run with Sonic log,

  R_W = 0.018 Ω.m at formation temperature

Example 6-2 (Figure 6-13)



Example 6-2 (Figure 6-13)

- From Figure 6-13, we get

	Depth	R_{ind}	t	Permeable	Why?
1	8444-48	22	84	Yes	SP & Caliper
2	8450	150	50.5	No	SP, Caliper, ϕ
3	8456-58	17	70	Yes	SP & Caliper
4	8474-76	5	69	Yes	SP & Caliper
5	8491-93	2.5	68	Yes	SP & Caliper

Example 6-2 (Figure 6-13)

- From Figure 6-13, we get

	Depth	R_{ind}	t	ϕ,%	Fr	Sw%
1	8444-48	22	84	25.6	15.2	11.2
2	8450	150	50.5	2.1	2256.3	52.0
3	8456-58	17	70	15.8	40.1	20.6
4	8474-76	5	69	15.1	43.9	39.8
5	8491-93	2.5	68	14.4	48.3	59.0

FACTORS AFFECTING SONIC INTERPRETATION

- Lithology
- Shale
- Fluid Types
- Compaction
- Secondary Porosity
- Borehole Effect
- Mudcake

Lithology

Lithology must be known to obtain the correct V_{ma}. Incorrect choice of V_{ma} will produce erroneous calculations.

Shale

Shale content generally causes Δt to read too high for a porosity calculation due to the bound water in the shale. The sonic reads primary porosity which may be affected by shale.

Fluid Types

Depth of investigation of the sonic is very shallow; therefore most of the fluid seen by the sonic will be mud filtrate.

- Oil →Usually no effect.
- Water → There is usually no effect except where drilling fluid is salt saturated, and then a different V_f should be used, usually 607 msec/m.

- Gas

  Residual gas causes Δt log to read too high when the formation is uncompacted. The gas between the sand grains slows down the compressional wave resulting in a long Δt. In compacted sands, the wave will travel from one sand grain to another and the gas effect will be reduced.

Compaction

Δt log will read too high in uncompacted sand formations. Compaction corrections can be made if the compaction factor (Bcp) is known.

Secondary Porosity

Sonic generally ignores secondary porosity. For example in vugular porosity, the travel time through the formation matrix is faster than the time through fluid in the vugs, since Δt_f is about three to four times Δt_{ma}.

Borehole Effect

The Compensated Sonic is unaffected by changing hole size except in the case of extremely rough, large holes where the formation signal is severely affected by the noise of the mud signal and formation damage.

Mudcake

Mudcake has no effect on the BHC sonic because the travel time through the mudcake is compensated.

Gamma Ray (Natural) Log

Gamma ray logs are measurements of the naturally occurring gamma rays in the formations. In sedimentary rocks the shales are generally more radioactive than the sandstones, limestones, dolomites, anhydrites, salts , etc.. The exceptions are granite washes and some radioactive sandstones, limestones and dolomites.

The GR Log

The GR log is a measurement of the natural radioactivity of the formations. In sedimentary formations the log normally reflects the shale content of the formations. This is because the radioactive elements tend to concentrate in clays and shales.

Clean formations usually have a very low level of radioactivity, unless radioactive contaminant such as volcanic ash or granite wash is present or the formation waters contain dissolved radioactive salts.

Clean Formation

Clean Formation	GR Reading
Sands	15 to 30 API
Limestones	10 to 20 API
Dolomites	8 to 15 API

The GR log can be recorded in cased wells, which makes it very useful as a correlation curve in completion and workover operations. It is frequently used to complement the SP log and as a substitute for the SP curve in wells drilled with salt mud, air or oil-based muds. In each case, it is useful for location of shales and nonshaly beds and, most importantly, for general correlation.

Gamma Rays

Gamma rays may be thought of as either electromagnetic waves or as particles referred to as photons. They are like light only more energetic. The radiation encountered generally comes from potassium-40 (a radioactive isotope of potassium that is associated with naturally occurring potassium), elements of the uranium-radium series hereafter referred to as the U series and, elements from the thorium series hereafter referred to as the TH series.

Each of these elements emits gamma rays; the number and energies of which are distinctive of each element. Figure C24 shows the energies of the emitted gamma rays: potassium (K40) emits gamma rays of a single energy at 1.46 MeV, whereas the uranium and thorium series emit gamma rays of various energies.

Figure C24

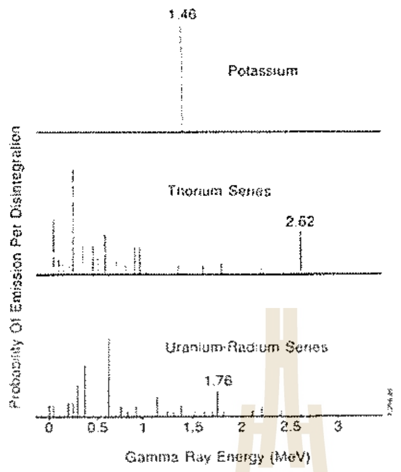


Figure C24: Gamma ray emission spectra of radioactive minerals

In passing through matter, gamma rays experience successive Compton-scattering collisions with atoms of the formation material, losing 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 energies degraded (reduced) as they pass through the formation. The rate of absorption varies with formation density. Two formations having the same amount of radioactive material per unit volume, but having different densities will show different radioactivity levels; the less dense formations will appear to be slightly more radioactive. (Figure C25)

Figure C25

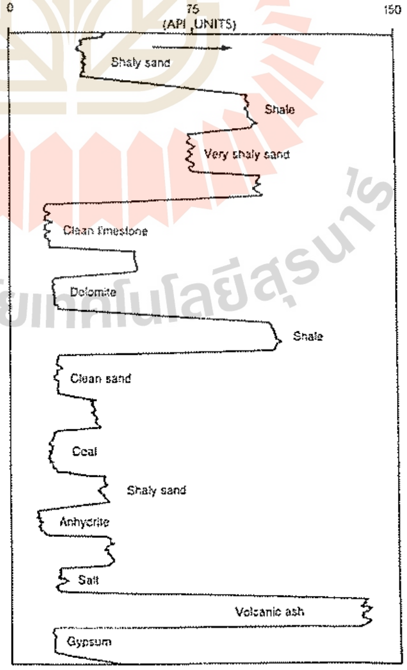
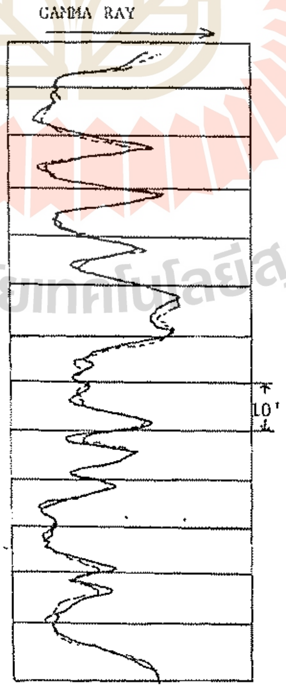


Figure C25: Relative GR response for various rock formations

Figure 6-14

shows an overlay of two gamma ray logs run in the same borehole at different times. The two logs do not repeat exactly (as resistivity, SP and acoustic logs should) due to the statistics.

Figure 6-14



Application of GR log

- Defining shale beds.
- Indicator of shale content.
- Detection of radioactive and nonradioactive minerals.
- Identify formation tops.

Gamma Ray Curve Characteristics

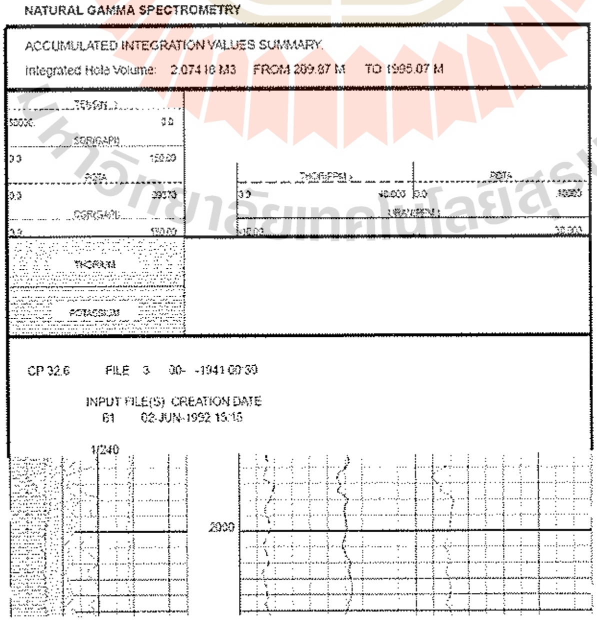
The vertical resolution of the gamma ray is about 2.5 feet and the depth of investigation is in the order of 6 inches.

The borehole generally has little effect on the gamma ray unless the borehole diameter is very large (over 13 inches in diameter) and contains heavy (barite weighted) mud. In a large borehole with KC1 mud, the gamma ray log may be significantly effected by the borehole.

THE NATURAL GAMMA RAY SPECTROMETRY LOG

Like the GR log, the NGS natural gamma ray spectrometry log measures the natural radioactivity of the formations. Unlike the GR log, which measures only the total radioactivity, this log measures both the number of gamma rays and the energy level of each and permits the determination of the concentrations of radioactive potassium, thorium, and uranium in the formation rocks. (Figure C27)

Figure C27


NATURAL GAMMA SPECTROMETRY

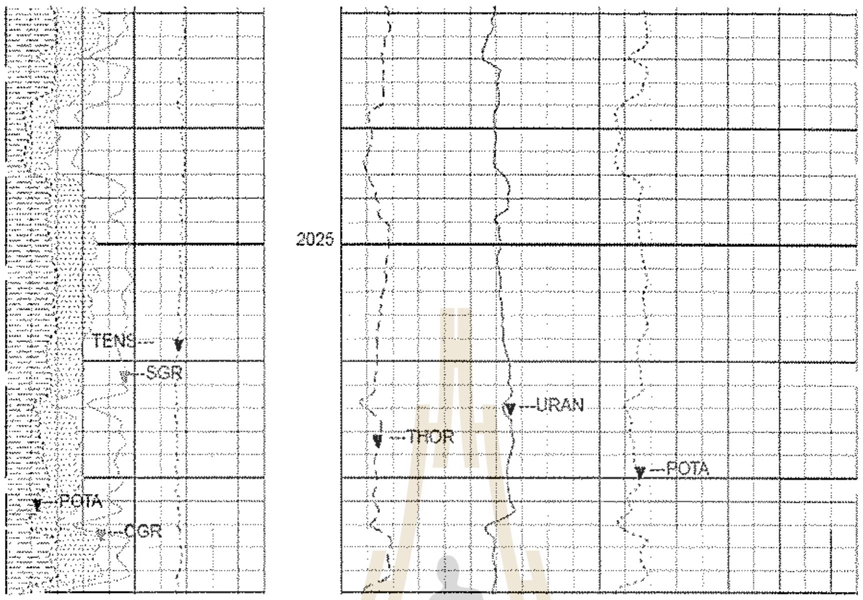
ACCUMULATED INTEGRATION VALUES SUMMARY

Integrated Hole Volume: 2.07416 M3 FROM 209.87 M TO 1995.07 M

CP 32.6 FILE 3 00- -1941 00:30

INPUT FILE(S) CREATION DATE
61 02-JUN-1992 15:15

Figure C27



APPLICATION of THE NATURAL GAMMA RAY SPECTROMETRY LOG

- Identifies radioactive sands which may be misinterpreted as shales.
- Identifies different types of shales/clays.
- Depth correlation (same as Gamma Ray).
- Complex lithology analysis

Borehole Geometry by Caliper Measure

The hole diameter is usually recorded in conjunction with the following surveys:

- Sonic logs (BHC versions, Array Sonic, Dipole Sonic)
- Microresistivity logs (Microlog, Micro-SFL, Electromagnetic Propagation Logs)
- Litho-Density logs
- Dipmeter logs (Stratigraphic HDT, Formation Microscanner, and MicroImager)
- Borehole geometry log

The readings given by different calipers in the same hole, may be different depending on the caliper design combined with the hole cross section.

The following table shows the characteristics of the different calipers:

	No. of Arms	Phasing of the Arms (Degrees)	Maximum Diameter	Remarks
Sonic	3	120	406 mm (16")	3 Arms Coupled 1 Reading
Microlog	1	0	508 mm (20")	1 Arm 1 Reading
Micro-SFL (Option A)	1	0	406 mm (16")	1 Arm 1 Reading
Micro-SFL (Option B)	4	90	558 mm (22")	4 Arms Coupled 2x2 2 pair Reading
Density	1	0	Short Arm 406 mm (16") Long Arm 533 mm (21")	1 Arm 1 Reading
Dipmeters	4	90	FMS/FMI 558 mm (22")	4 Arms Coupled 2x2 2 Independent Readings
Borehole Geometry	4	90	Standard 762 mm (30") Special 1016 mm (40")	4 Arms Coupled 2x2 2 Independent Readings
Dual Axis	2	180	406 mm (16")	2 Arms Coupled 1 Reading

Figure C29: Caliper Specifications for different devices found on the stored logs

The reason of different arm of Caliper tools

1. The mudcake is a good reason to have different calipers reading different values:

- If the arm of the caliper is the blade type, it will cut into the cake and this arm will ignore the thickness of the mud cake.

- If the arm is of the pad type, it will skid over the cake and the mud cake thickness will be taken into account.

2. Assuming no mudcake, the readings of different calipers in a perfectly round hole will be identical. But round holes are not always the case. In clearly ovalized holes, 2-Arm, 3-Arm and 4-Arm calipers will read different hole diameter values, mostly because of the way these arms are coupled together.

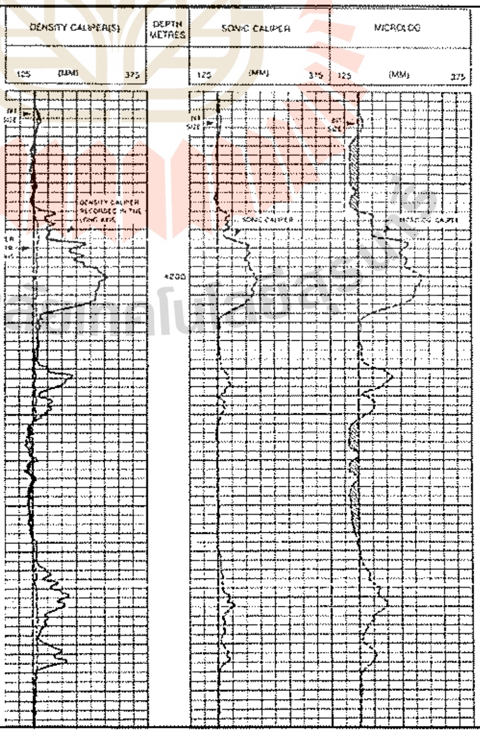
If the logging tool is fairly free to rotate inside the hole:

- Two arm calipers will ride using the larger diameter of the hole.
- Four arm calipers will ride with one pair of coupled arms using the larger diameter of the hole.

3. In deviated wells calipers may partially collapse under their own weight and give readings that are too low.

The following example (Figure C30) shows different calipers in an ovalized hole:

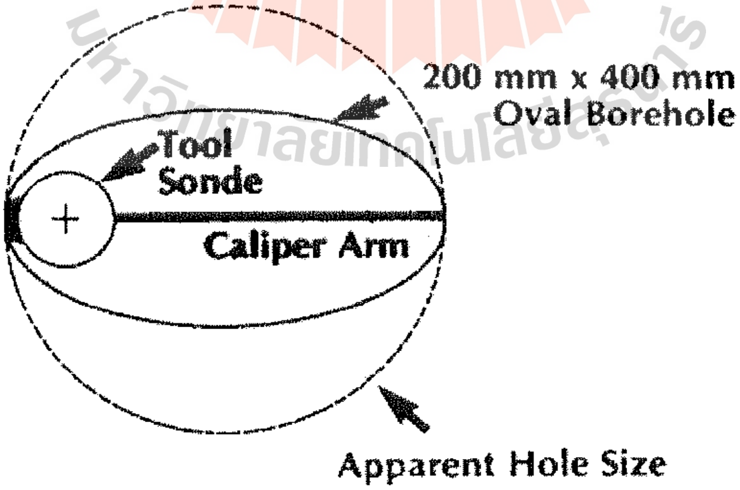
Figure C30



Single Arm Caliper Configuration:

- Records one borehole diameter = 400mm.
- Calculated 100m hole volume = 12.57m3 (+100% error)
- Tool examples:
  - + Litho-Density log. (No short axis hdwe)
  - + MicroSFL (Option A).
  - + Electromagnetic Propagation Log.

Single Arm Caliper Configuration:



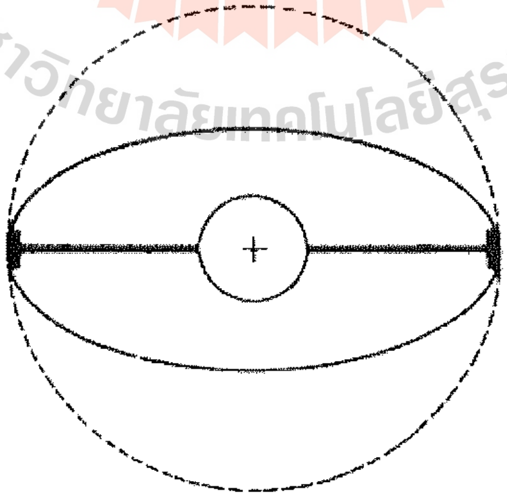
Two Arm Caliper Configurations:

a. Uni-directional

- Records one borehole diameter = 400mm.
- Calculated 100m hole volume = 12.57m3 (+100% error)
- Tool examples:
  - + MicroSFL (Option B).

Two Arm Caliper Configurations:

a. Uni-directional



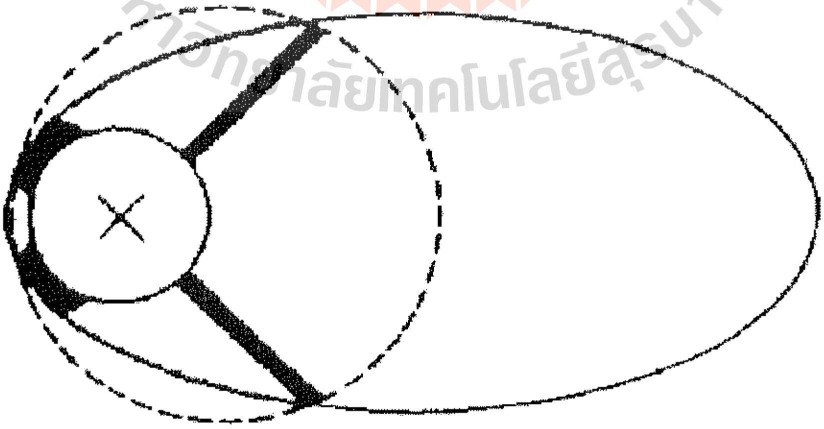
Two Arm Caliper Configurations:

b. Bi-directional Long Axis

- Records one borehole diameter = 195 mm.
- Records a second diameter = 195 mm.
- Calculated 100m hole volume = 2.98m3 (-53%)

Two Arm Caliper Configurations:

- b. Bi-directional Long Axis



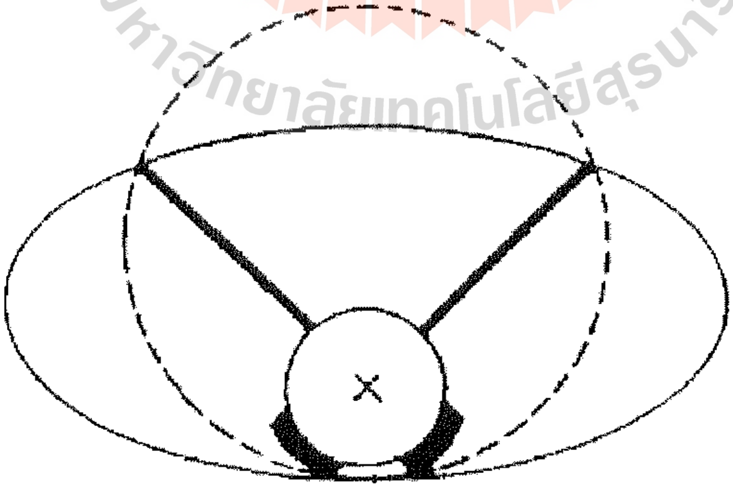
Two Arm Caliper Configurations:

c. Bi-directional Short Axis

- Records one borehole diameter = 273 mm.
- Records a second diameter = 273 mm.
- Calculated 100m hole volume = 5.85m3 (-7%)

Two Arm Caliper Configurations:

c. Bi-directional Short Axis



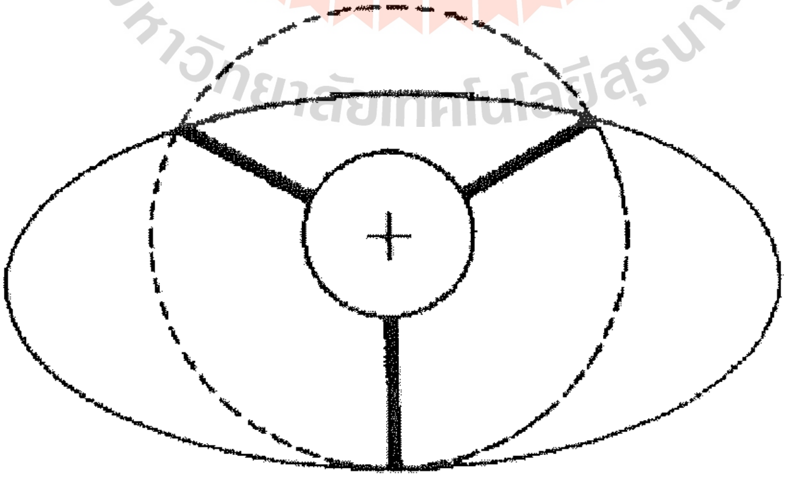
Three Arm Caliper Configurations:

a. Centered

- Records one borehole diameter = 260 mm.
- Calculated 100m hole volume = 5.31m3 (-15%)
- Tool example:
  + Sonic Log.

Three Arm Caliper Configurations:

a. Centered



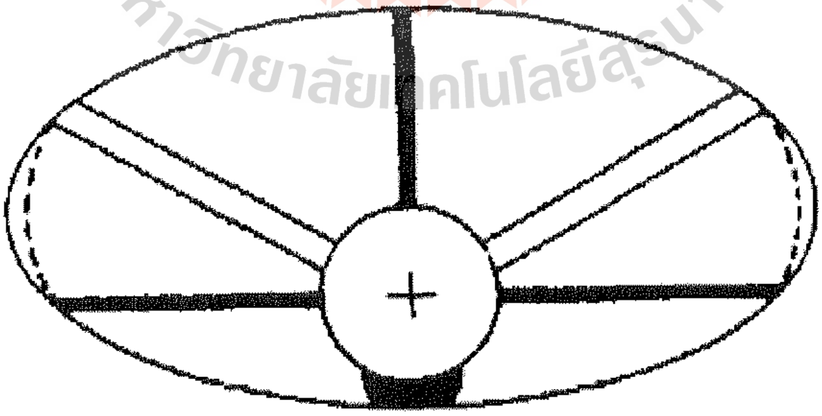
Three Arm Caliper Configurations:

b. 90 Degree Offset

- Records one axis diameter = 200 mm.
- Records a second diameter = 382 mm.
- Calculated 100m hole volume = 6.00m3 (-4%)
- Tool example:
  + Compensated Neutron.
  + Litho-Density Log.

Three Arm Caliper Configurations:

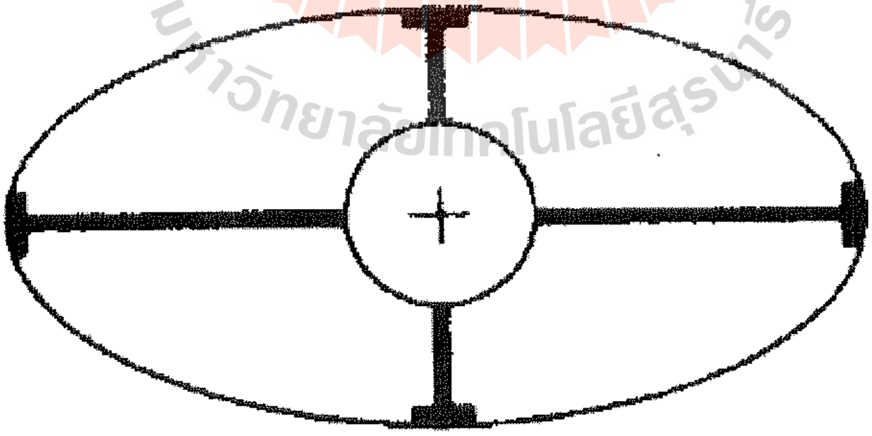
b. 90 Degree Offset



Four Arm Caliper Configuration

- Records one axis diameter = 200 mm.
- Records a second diameter = 400 mm
- Calculated 100 m hole volume = 6.28 m3 (0%)
- Tool example:
  - + Borehole Geometry Log.
  - + Stratigraphic HDT.
  - + Formation Microscanner.
  - + Formation MicroImager.

Four Arm Caliper Configuration



Chapter 7
QUANTITATIVE ANALYSIS-PART I

Water Saturation Calculation and Rwa

The calculation of water saturation requires not only the true formation resistivity and porosity, but also the formation water resistivity. Water saturations can be calculated directly using the Archie equation (2-10) by determining F_R from porosity from the acoustic porosity, R_w from the SP, and resistivity from the induction curve.

The R_{wa} technique is a formalized method of estimating the R_w from water bearing zones so that the analyst has another way of establishing R_w.

The R_{wa} method is probably the single most used analysis approach in the petroleum business. The Archie equation is used, only it is rearranged for convenience as shown in Table 7-1.

Table 7-1 R_{wa} theory

- The Archie equation (2-9) states

$$S_W^2 = \frac{F_R R_W}{R_t}$$

- which becomes after rearranging

$$R_W = \frac{S_W^2 R_t}{F_R}$$

- if you have a water zone ($S_w = 100\%$) Rw may be calculated directly as;

$$R_W = \frac{R_t}{F_R} \qquad (7\text{-}1)$$

- if the zone contains hydrocarbons F_R will be the same, only Rt will increase, so for a general case will change equation 7-1 to a general form

$$R_{Wa} = \frac{R_t}{F_R} \qquad (7\text{-}2)$$

- if you calculate a series of zones and one is a water zone, R_{wa} from equation 7-2 will have its lowest value in the water zone and $R_w = R_{wa}$ for this lowest value in a water zone.

$$S_W^2 = \frac{F_R R_W}{R_t} = \frac{R_W}{\dfrac{R_t}{F_R}} = \frac{R_W}{R_{Wa}}$$

$$\text{so} \qquad S_W = \sqrt{\frac{R_W}{R_{Wa}}} \qquad (7\text{-}3)$$

An Algorithm for the R_{wa} method

1. Correlate porosity and R_t logs

2. Pick out permeable beds to be calculated using SP or R_i /R_t separation on logs.

3. Mark zones on the resistivity (R_t) log. Read resistivity values and correct for invasion if necessary (DIL or DLL)

DIL → Figure 5-9
DLL → Figure 11-8

An Algorithm for the R_{wa} method

4. Mark zones on the porosity logs and calculate porosity. Use density-neutron or acoustic-neutron crossplots, if possible.

t → Figure 6-9 or Equation 6-2
ρ → Figure 8-4 or Equation 8-1

5. Calculate Rwa from Figure 2-6 or Equation 2-6 or 2-7 and 7-2

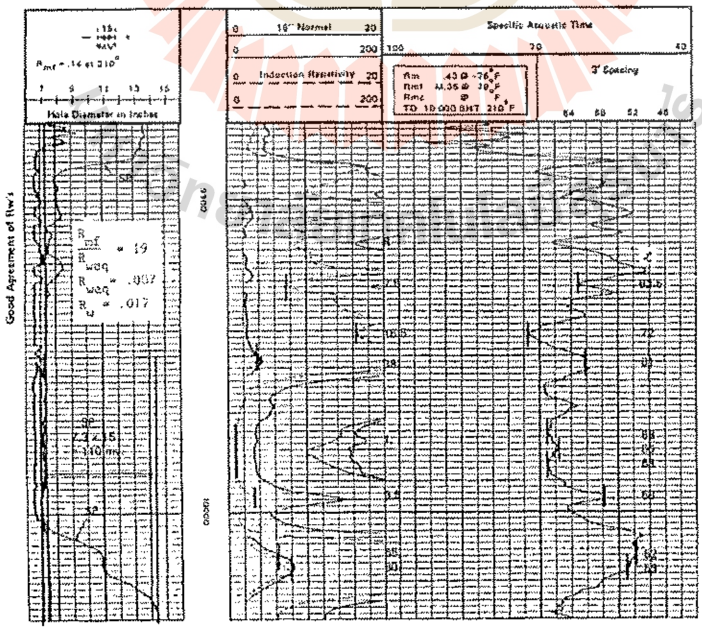
6. Lowest values of R_{wa} are probably R_w

7. Check R_w from step 6 against Rw catalog and calculate Rw from SP. If agreement is good go to step 9 or if agreement is poor go to step 8.

8. Where agreement is poor select lowest R_w from catalog, SP or R_{wa}. If using density logmake sure lowest R_{wa} (R_w) is not in a shaly zone.

9. All zones where R_{wa}>$3R_w$ are potentially hydrocarbon bearing. Calculate S_w for these zones by Figure 2-6 or Equation 7-3

Example 7-1 - The R_{wa} Algorithm



Example 7-1

Zone	SP	Resistivity	Time
A	110	7.5	62.5
B	110	16.5	72
C	110	38	61
D	110	1	68
E	110	1	66
F	110	1	68
G	110	3.5	58
H	110	65	52
I	110	80	53

Example 7-1

Zone	Porosity (ϕ)	R_{Wa}	S_W (%)
A	10.5	0.082	49
B	17	0.47	21
C	9.5	0.34	24
D	14.5	0.02	100
E	13	0.017	100
F	14.5	0.02	100
G	7.5	0.019	100
H	3	?	?
I	4	?	?

Chapter 8
DENSITY LOGS

Introduction

Litho-Density logs are primarily used for porosity and lithology measurements. Other uses include identification of minerals in evaporite deposits, detection of gas, determination of hydrocarbon density, evaluation of shaly sands and complex lithologies, determinations of oilshale yield, calculation of overburden pressure and rock mechanical properties.

DENSITY LOGS

The density log measures the bulk density of the formation using Compton Scattering of gamma rays. Bulk density can be related to porosity when the lithology is known. The equation relating porosity and density is similar to the acoustic equation only in this instance it is theoretically correct.

- The relationship is:

$$\phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \qquad \text{Eq 8-1}$$

where

ρ_b is the formation density from the well log

ρ_{ma} is the matrix density (formation density at zero porosity)

ρ_f is the density of the fluid in the pores which is usually 1.0 gm/cc when fresh muds are used and 1.1 gm/cc when the drilling mud is very salty.

- Table 8-1 is a listing of commonly used matrix densities for commonly occurring rock types.
- Table 8-1 Commonly used matrix densities for different rock types.

Mineral	ρ_{ma} Range	ρ_{ma} Commonly used
Sandstone	2.65-2.70	2.65 or 2.69
Limestone	2.71	2.71
Dolomite	2.83-2.89	2.83 or 2.87
Anhydrite	2.94-3.00	2.98
Salt (halite)	2.03	2.03

ρ_b Values for Common Resevoir Rocks and Fluids

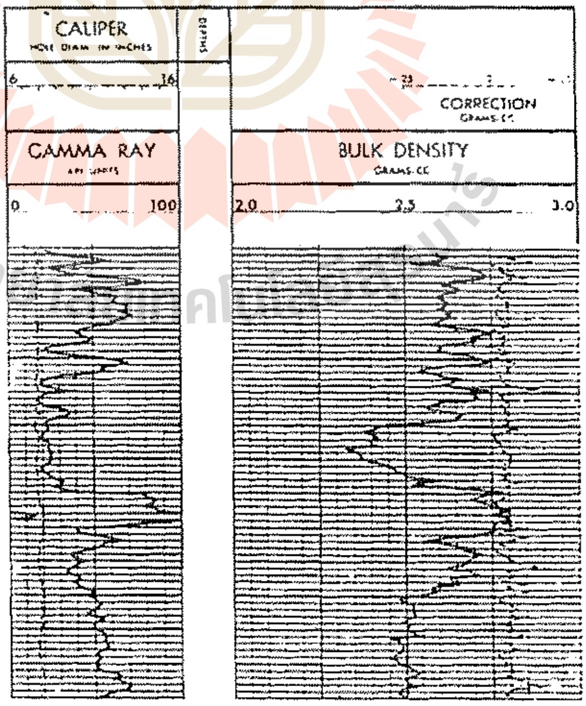
Compound	Formula	Actual] Density ρ	ρa (as seen by tool)
Quartz	$Si0_2$	2654	2648
Calcite	$CaC0_3$	2710	2710
Dolomite	$CaC0_3MgC0_3$	2870	2876
Anhydrite	C_aS0_4	2960	2977
Sylvite	KCI	1984	1863
Halite	NaCI	2165	2032

Compound	Formula	Actual] Density ρ	ρa (as seen by tool)
Fresh Water	H_20	1000	1000
Salt Water	200,00ppm	1146	1135
'Oil'	$n(CH_2)$	850	850
'Gas'	$C_{1.1} H_{4.2}$	ρg	$1.325\rho g$-0188

ρ in kg/m^3

- The bulk density versus depth is plotted on the density log as shown in Figure 8-1
- A caliper log is run simultaneously as is the correction curve. This latter will be discussed in the measurement section. Higher densities, which correspond to lower porosities will be on the right hand side of the log while higher porosities (lower densities) appear on the left hand side of tracks two and three. This conforms to the general well log format.
- Shales are usually indicated as medium to high densities (low porosity).

Figure 8-1

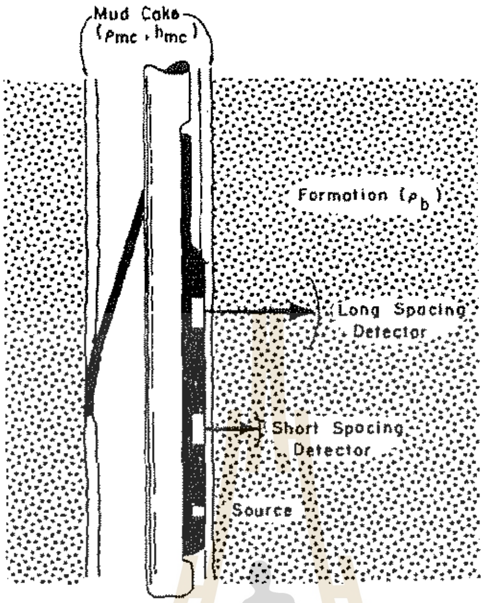


The bulk density does not correlate as well with resistivity logs as other “porosity logs” as the shales show up as low porosity. If you have trouble correlating the density log with the resistivity log, try instead the SP or gamma ray and density log in sandstone - shale sequences.

The Density Measuring Instrument

Density instruments generally consist of a gamma ray source, usually cesium 137 and two detectors. The source and detectors are located on a skid (pad) which is forced against the side of the hole. The long spaced detector reads mostly the formation. The short spaced detector measures a great deal of both the formation and the materials that occur between the pad and the formation. Figure 8-2 shows a schematic of the density log instrument.

Figure 8-2



Litho-Density Tool

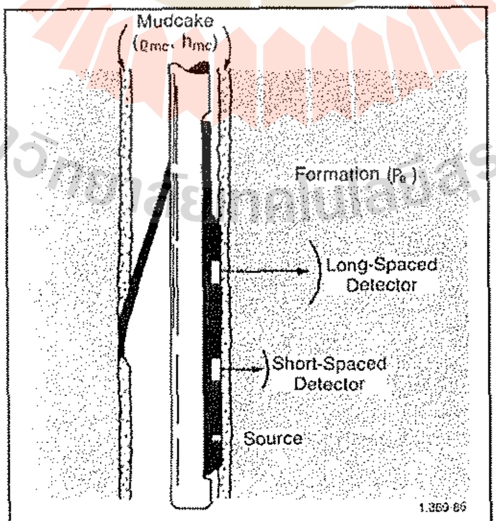


Figure C7: Schematic drawing of the dual spacing Litho-Density Logging Device (LDT).

The gamma rays leaving the source are scattered by the orbital electrons of the atoms in the materials being measured. This Compton Scattering results in the loss of energy of the gamma rays. If the material is very dense (contains many electrons) the gamma rays are scattered more, and more are absorbed by the material due to the low energy.

This absorption near to the source results in fewer gamma rays reaching the detector. In formations with fewer electrons (lower density) the gamma, rays are not slowed down as much and more reach the detector. This phenomena is very much like driving at night in the fog. When the fog is dense your car lights are reflected back into your eyes and little light reaches the road. When the fog is light , only a limited amount of the light is reflected into your eyes. Most of the light reaches the road.

The density log only measures the density on one side of the borehole. If the porosity (density) varies across the borehole and the pad comes up a different path, the densities may vary between different logging passes.

Porosity

In most moderate to low porosity formations invasion of mud filtrate into the formation is sufficiently deep that the measurement is not influenced significantly by the hydrocarbons which generally have lower densities than the water. In general fluid densities (of) equal to 1.0 are used and if the mud is very salty a fluid density of 1.1 is used. The density measured (and thus the porosity) has no influences of compaction or pore geometry as the measurement is at the atomic level.

Porosity

Porosity is calculated from equation 8-1 or from the chart shown in Figure 8-4. The rock type must be known before porosity can be determined from density.

Figure 8-4

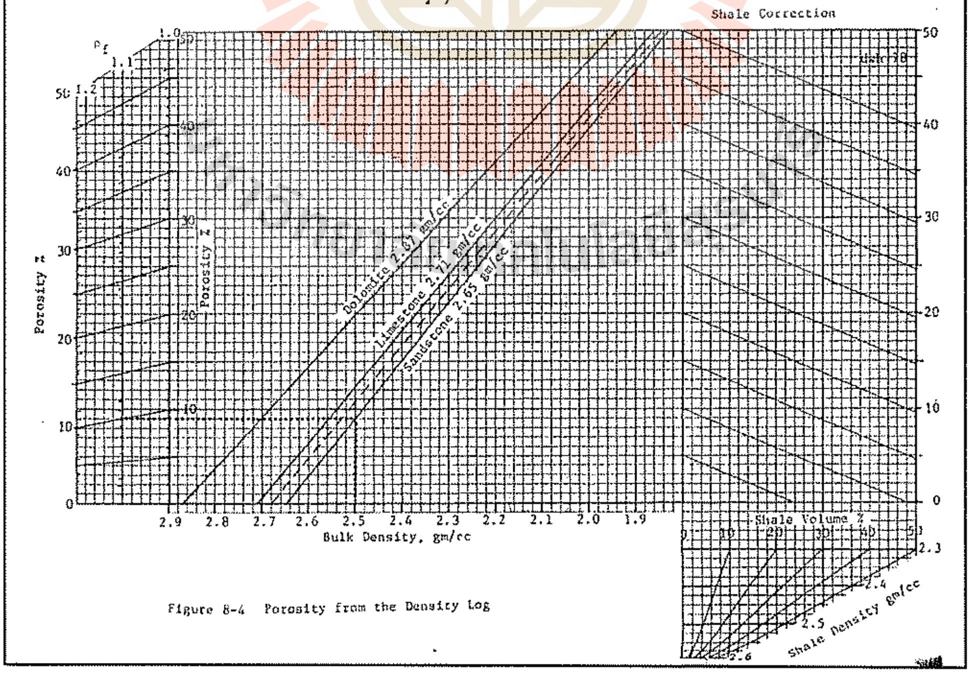


Figure 8-4 Porosity from the Density Log

Example 8-1

- Use of Figure 8-4 for determination of porosity from density
- Given: formation is a sandstone, density is 2.5 gm/cc

Solution

- the porosity for a fluid density of 1.0 gm/cc is 9% if the fluid density is 1.1 (salty mud) porosity is 10%
- Extra: if the formation was a limestone and the mud fresh the porosity would be 12.2% or in realistic terms 12%

Figure 8-4

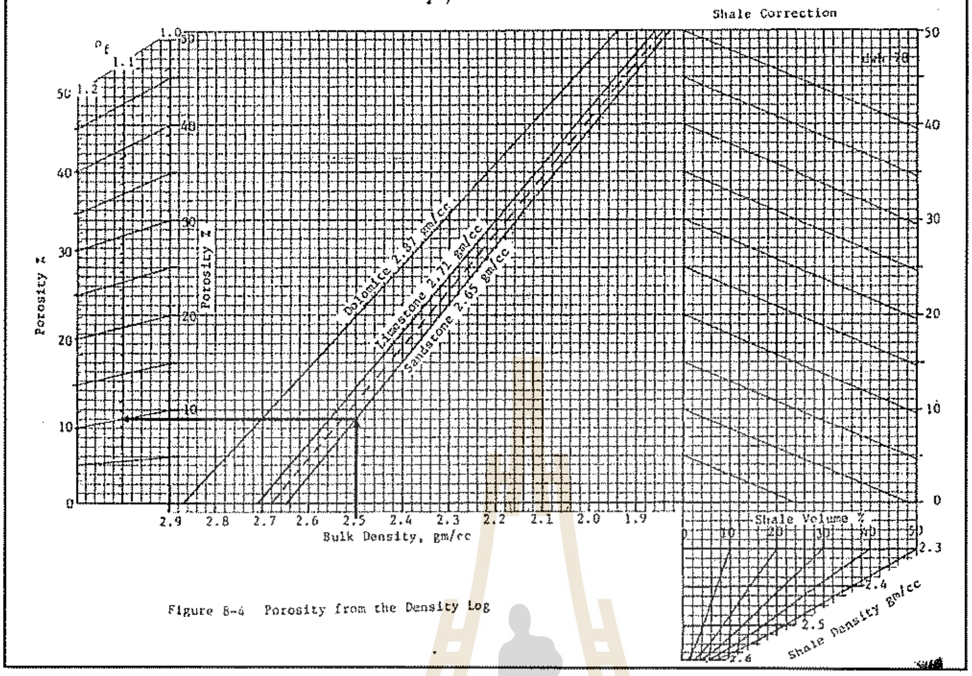


Figure 8-4 Porosity from the Density Log

- The shale correction part of Figure 8-4 will be explained in chapter 13 on shaly sandstone interpretation.
- If the formation has little or no invasion the light density of the formation hydrocarbon can influence the density measured. The effect of oil is not too significant as the density of oil is around 0.8 and this is partially offset by the formation water being over 1.0 gm/cc. Gas significantly effects the density of a formation.

- If a fluid density of 1.0 is assumed, the porosity calculated will be too high in a noninvaded gas sandstone. In a noninvaded sandstone the fluid density will be:

$$\rho_f = S_w \rho_w + (1 - S_w) \rho_h \qquad 8\text{-}2$$

- where the subscript w refers to the formation water and h to hydrocarbons. To find the fluid density it is necessary to know the hydrocarbon density, the formation water density and the water saturation.

- An approximate gas density can be obtained from Figure 8-5. If you do not know the gas specific gravity use 0.7
- The formation water density can be estimated easily once you know the resistivity, which you must know for the interpretation.
- Table 8-2 shows some salt water densities.

Figure 8-5

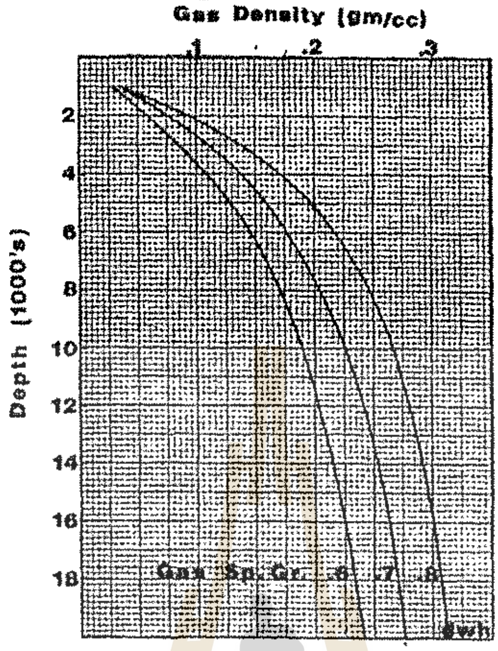


Table 8-2 Density/salinity relationships for aqueous NaCl

Salinity (ppm NaCl)	Density (gm/cc)
0	1.0
20000	1.01
50000	1.03
100000	1.07
150000	1.11
200000	1.15
250000	1.19

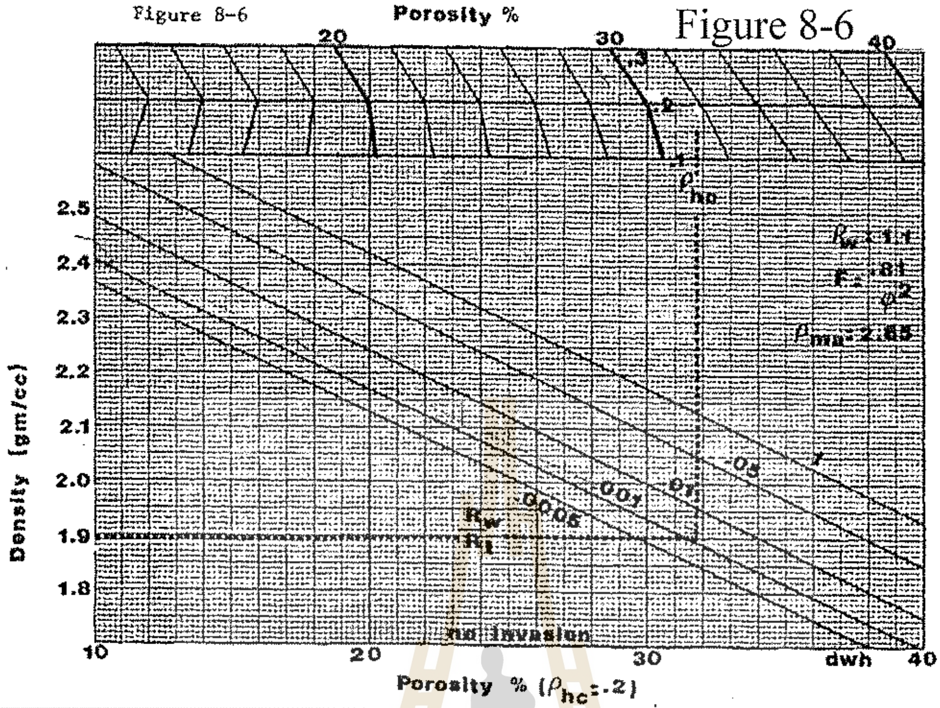
- Equations 8-1 and 8-2 can be solved by trial and error when combined with equation 2-10. If equations 2-7, 2-10, 8-1 and 8-2 are combined

$$\phi = \frac{0.9\sqrt{\frac{R_w}{R_t}}(\rho_w - \rho_h) + \rho_{ma} - \rho_h}{\rho_{ma} - \rho_h}$$

Eq 8-3

- An approximate solution for this equation can be obtained using Figure 8-6.
- Figure-8-6 is accurate for low values of Rw/Rt.
- Figure 8-6 and equation 8-3 assume that there is no invasion.
- The solution is not very sensitive to modest variations in S_w.
- Example 8-2 shows an example of a formation with almost no invasion and illustrates the use of Figure 8-6.

Figure 8-6

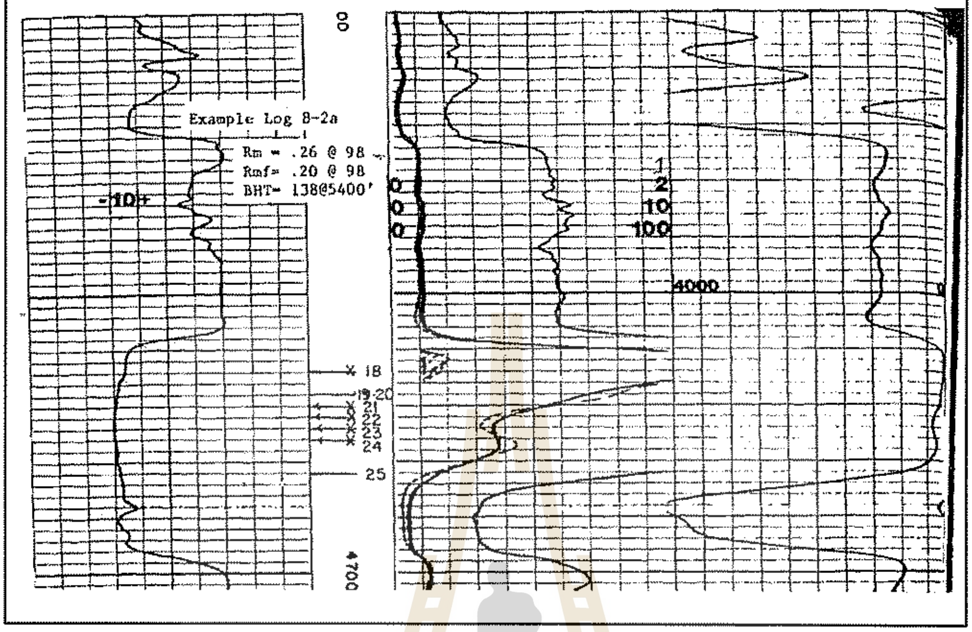


Example 8-2

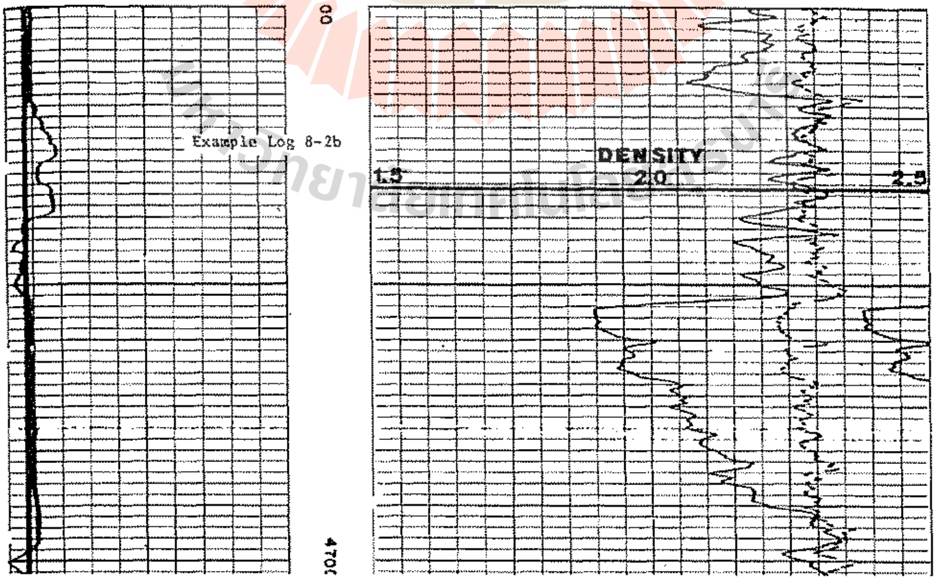
- Interpretation of an induction electric log and density log in a gas zone with no invasion.
- See log examples 8-2a and 8-2b
- Interval induction electric log 4659 - 4665
- density log 4653 - 4659

  (notice that the density and induction log are off depth)

log examples 8-2a



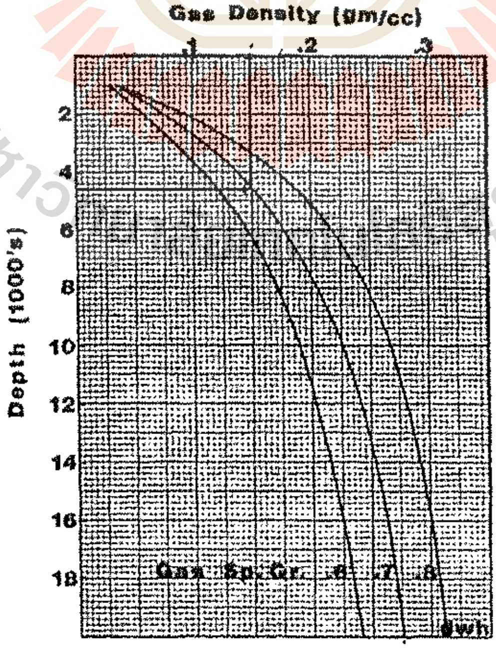
log examples 8-2b



Solution

- Data: density = 1.9 gm/cc from log.
- R_t = 20 ohm-m from induction log.
- R_w = 0.028 from adjacent formation (@ 140°F) (From SP log) this gives water salinity of 170,000 ppm (Fig. 2-2)
- water density is thus 1.12 (from Table 8-2)
- from Fig. 8-5 gas density is 0.15
- R_w/R_t = 0.0014
- porosity from Fig. 8-6 is 31% (slightly over)
- porosity from equation 8-3 is 31.3%
- water saturation is 10%

Figure 8-5



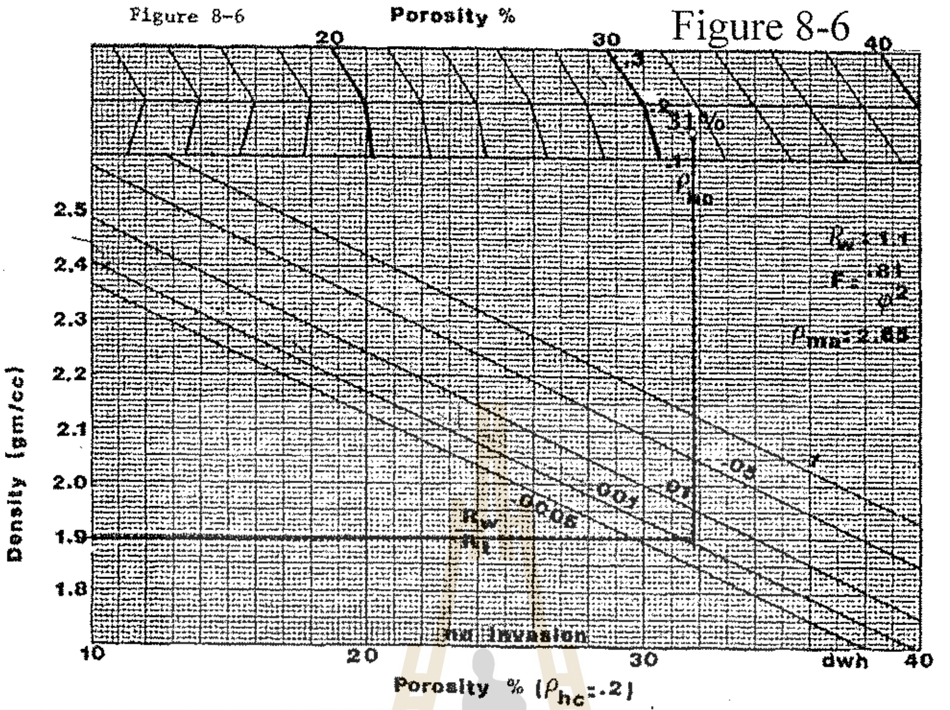


Figure 8-6

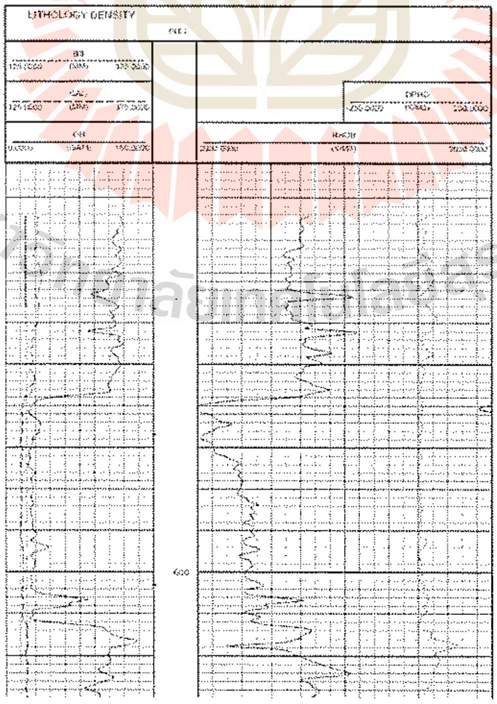


Figure C13

From the example LDT log (Figure C13) at 593 m we read ρ_b = 2180kgm/m3. Given ρ_f = 1000 kgm/m^3, ρ_{ma} = 2650, we can solve for ϕ_D:

$$\phi_D = \frac{2650 - 2180}{2650 - 1000} = 28.5\%$$

- Chart Por-5 (Figure C14) solves this equation graphically. For ρ_b = 2180 kg/m^3 solving for porosity using other matrix values gives:

$\rho_{ma} = 2710$ $\phi_D = 31\%$

$\rho_{ma} = 2870$ $\phi_D = 36.9\%$

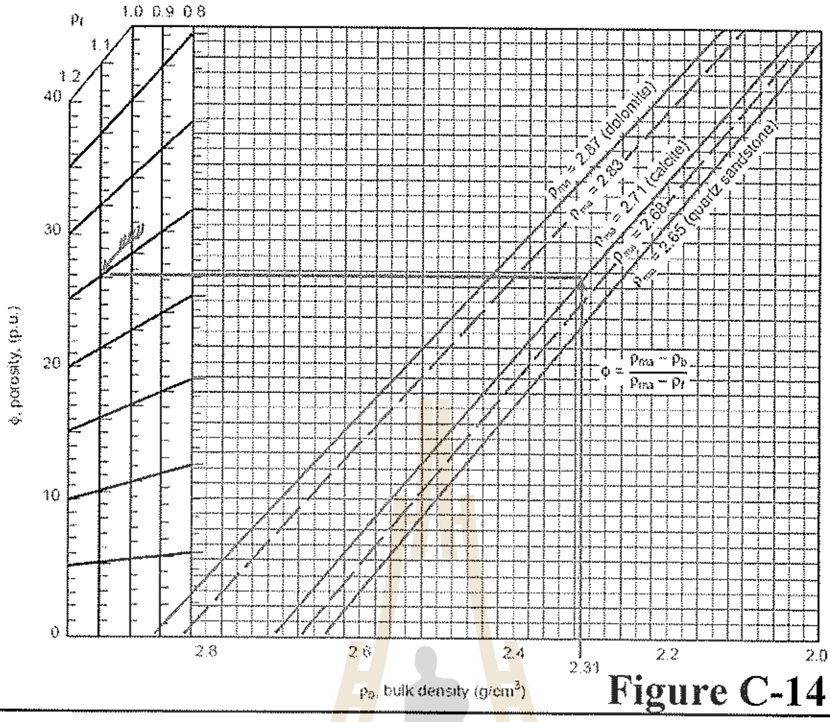


Figure C-14

Miscellaneous

- The vertical resolution of the density log is just over two feet. The depth of investigation into the formation is between 2 and 4 inches.
- The density log maybe run with any fluid in the borehole.
- Shale on the density log appears to be low porosity. This means that shaly sandstone porosities from the density log are very close to the true effective porosity.
- The density log may be used to detect abnormally pressured zones.

FACTORS AFFECTING DENSITY LOG:

- Lithology

  Correct ρ_{ma} must be known to get correct porosity.

- Shale

  Density of shale in sands can range from 2200 to 2650 but is usually close to 2650, the same as sandstone. In shaly sands, the density will usually give a good value of effective porosity regardless of shale content. The shale appears as matrix to the density tool.

FACTORS AFFECTING DENSITY LOG:

- Fluid Type

  Depth of investigation is quite shallow: usually most of the formation fluid is flushed away from the wellbore and the density tool sees drilling fluid or filtrate in the pore space. Hence, the ρ_f to use is that of the drilling mud filtrate rather than the formation water density.

FACTORS AFFECTING DENSITY LOG:

- Oil

  Residual oil will make density porosities slightly high, because the oil is lighter than the drilling mud filtrate.

- Water

  Water density is proportional to the amount of salt content, ρ_f is selected in the computer for porosity determination.

FACTORS AFFECTING DENSITY LOG:

- Gas

  ρ_f of gas is 100-300 kg/m3. Porosity determination in gas zones may be high if there is residual gas near the borehole. Usually most of the gas is flushed and just a little effect is seen on the density log.

- Compaction

  The density tool is unaffected by lack of compaction.

FACTORS AFFECTING DENSITY LOG:

- Secondary Porosity

  The density reads intercrystalline, vugular and fractured porosity. The porosity measured is therefore total porosity.

- Borehole Effect

  Density gives good values for smooth holes up to 381 mm in diameter but a very rough hole will cause the density to read too low densities (high porosities) since the skid to formation contact will be poor.

FACTORS AFFECTING DENSITY LOG:

- Mudcake

  For normal mudcake thickness, there will be no effect since the tool automatically compensates for mudcake.

Chapter 9
NEUTRON LOGS

INTRODUCTION

Neutron logs are used principally for delineation of porous formations and determination of their porosity. They respond primarily to the amount of hydrogen in the formation. Thus, in clean formations whose pores are filled with water or oil, the neutron log reflects the amount of liquid-filled porosity.

Gas zones can often be identified by comparing the neutron log with another porosity log or a core analysis. A combination of the neutron log with one or more other porosity logs yields even more accurate porosity values and lithology identification - even an evaluation of shale content.

NEUTRON LOGS

Neutron logs measure the formations ability to attenuate the passage of neutrons through the formation. This is a measure of the hydrogen content of the formation. The only hydrogen in clean reservoir rocks is due to the presence of water or oil. Both water and oil contain about the same amount of hydrogen. The neutron log is accordingly a porosity device.

Modern neutron logs are plots of porosity (for some particular lithology) versus depth. The neutron log, as is true of the density and acoustic, is affected by lithology. It should be remembered that although the neutron log is presented in-terms of porosity (e.g. apparent limestone porosity) this is only the porosity when the formation is composed of this particular lithology (e.g. limestone)

Figure 9-1 shows the lithology effects for two different Schlumberger neutron logs. The lithology effects are very different for the different logs. Neutron logs are unlike the other porosity logs discussed in that the chart for the particular service company and the particular tool must be used when taking into account different rock types.

Figure 9-1

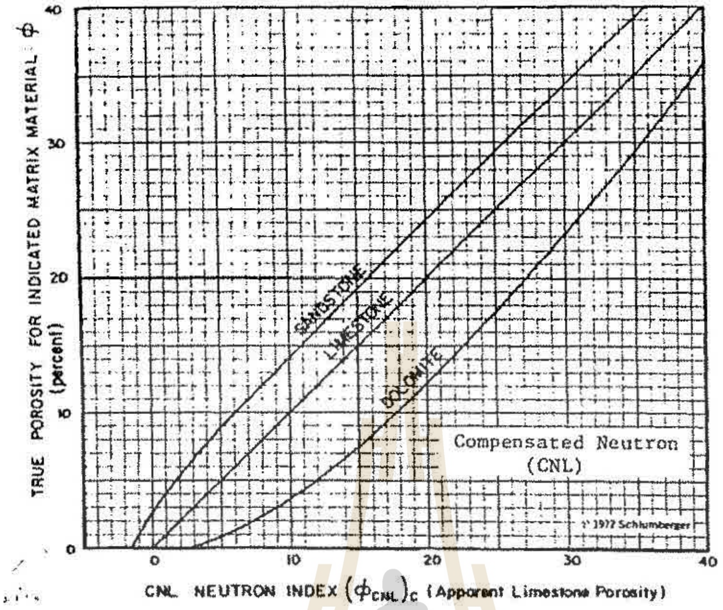
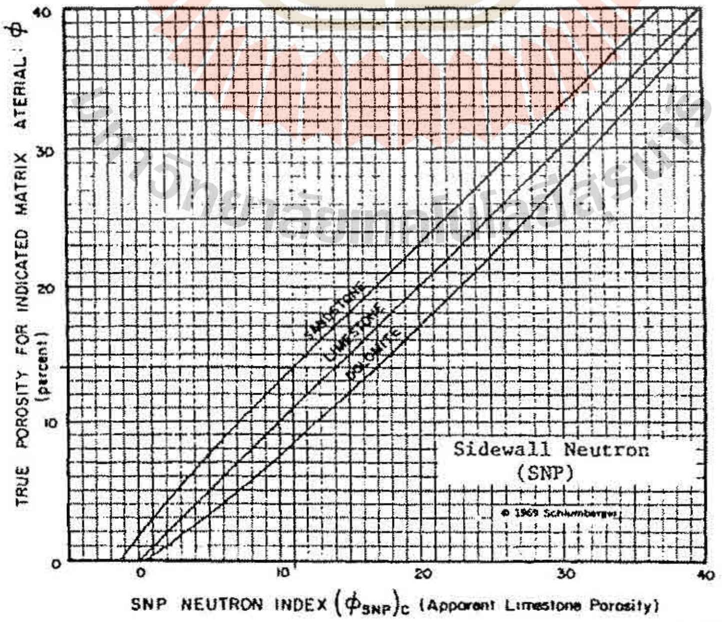


Figure 9-1



Shale on neutron logs appears as apparent high porosity. The value for shales is dependent on the particular neutron log and the particular service company and the type of shale. A caliper log is run with most neutron logs.

Neutron Theory

Neutrons are electrically neutral particles of about the same mass as a hydrogen atom. The sources used in neutron logging are combinations of materials like americium and beryllium and plutonium and beryllium. The neutrons leave the source with high energy (high velocity) and collide with formation materials in an elastic manner. Elastic collisions may be likened to the reaction between billiard balls.

Within milliseconds after leaving the source the neutron is slowed down to what is called the thermal state. In the thermal state the neutrons move randomly neither losing or gaining energy (on the average). In this thermal state the neutrons are captured by various materials the most common of which is chlorine. When the neutron is captured, the nuclei becomes very excited and dissipates the excess energy by ejecting a high energy gamma ray of capture.

The amount of energy lost per collision depends on the relative mass of the nucleus with which the neutron collides. The greater energy loss occurs when the neutron strikes a nucleus of practically equal mass - i.e., a hydrogen nucleus. Collisions with heavy nuclei do not slow the neutron very much. Thus, the slowing of neutrons depends largely on the amount of hydrogen in the formation.

Neutron logging tools may detect fast (epithermal) neutrons with energies just above the thermal level, thermal neutrons, capture gamma rays or combinations of these. Neutron logs are classified as epithermal, thermal or just neutron logs depending upon what energy of neutrons they detect.

Neutron logging tools include the GNT tools series (no longer in use), the SNP sidewall neutron porosity tools (in limited use), and the CNL tool series, which includes the Compensated Neutron and the Dual Porosity Compensated Neutron Log (DNL). The current tools use americium-beryllium (AmBe) sources to provide neutrons with initial energies of several million electron volts.

The type of Neutron Log

- Two types of neutron logs are presently being run, these are:
  - The sidewall neutron
  - The compensated neutron.

The sidewall neutron

The sidewall neutron logs generally measure epithermal neutrons and the curves are put out on apparent limestone, sandstone or dolomite porosities

The instrument itself looks much like the density log device. In fact in most cases the basic sonde is used and only the pad is changed. The pad, with source and detector, is forced against the side of the borehole to reduce borehole effect and t o reduce mudcake effects. These devices are generally run only in openhole. Some of these devices have automatic corrections for temperature, borehole size, mud weight and other such influences.

The major problems these devices have are mudcake between the pad and the formation and rough holes where the pad will not fit snugly against the formation.

The sidewall neutrons have vertical resolutions of just over two feet (somewhat dependent upon the service company) and measure 4 to 12 inches into the formation (again dependent upon the particular service company to some degree) depending upon the hydrogen concentration.

The Compensated Neutron logs

Compensated Neutron logs are generally mandrel type devices with a long and short source to detector spacings. The neutron sources are much stronger as the source to detector spacings are longer. The detectors are generally thermal detectors. Although the detectors are thermal, the measurement bears a close relationship to epithermal measurements as the measurement is a ratio of the long and shorter spaced counting rates. This gradient type measurement is related to the slowing down length of neutrons.

Compensated neutron logs are recorded as apparent limestone porosity, sandstone porosity and dolomite porosity. The depth of investigation of the compensated neutron is from 6 to 16 inches depending upon the porosity (and of course the particular service company). The vertical resolution is just over two feet.

Compensated Neutron Tool

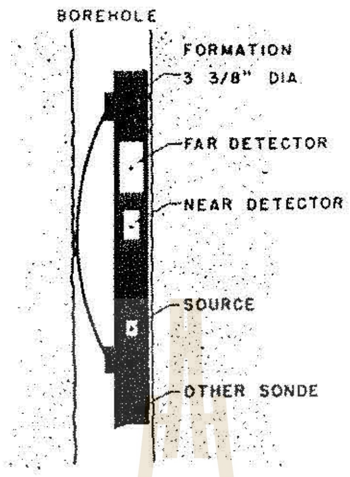


Figure C18: Schematic drawing of the dual spacing Compensated Neutron Tool

- The advantages of the compensated neutron log are:

  1. the borehole influences are significantly reduced, particularly in rough boreholes,

  2. the compensated neutron can be run in cased holes with good results

  3. the compensated neutron can be run simultaneously with some other log, most commonly the density log.

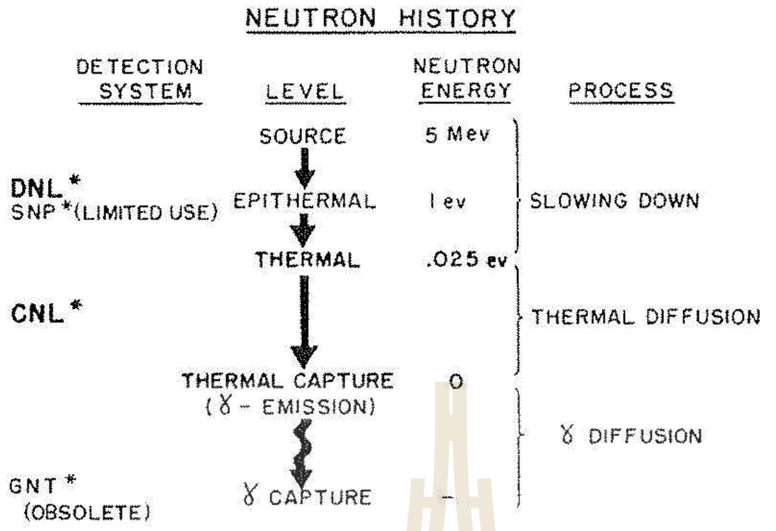


Figure C19: Neutron Energy Travel History

SNP

- detects epithermal neutrons.
- utilizes a skid mounted single detector.
- can be run in open hole only, either liquid-filled or empty.
- most corrections are automatically applied during logging.
- limited use.

CNL

- detects thermal neutrons.
- the CNL uses a two detector system that depth and resolution matches each count rate before the ratio is computed. The ratio value is then converted to porosity on a linear scale (Figure C20), based on the matrix selected for the computation (limestone, sandstone or dolomite).

CNL

- Conversion from one porosity assumption to another can be done via Chart Por-13b (Figure C22). Por-13b converts curves labelled "NPHI" which are not environmentally corrected and also converts for curves labelled "TNPH“ and "NPOR" which are environmentally corrected.
- the CNL is especially designed for use in combination with other devices.
- CNL can be run in liquid-filled holes, either open or cased, but not empty holes (i.e. air or gas filled holes.)

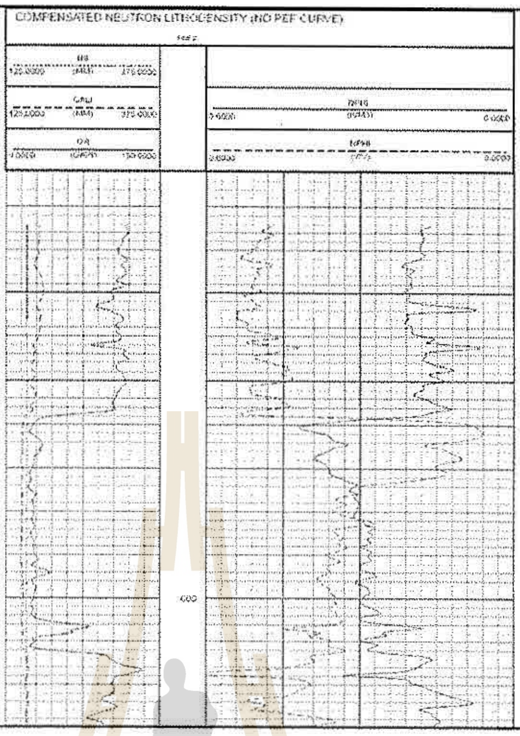
DNL

- detects thermal and epithermal neutrons.
- The DNL tool incorporates two epithermal neutron detectors in addition to the two thermal neutron detectors. Two separate porosity measurements are obtained, one from each pair of detectors.
- To improve the response to gas and to enhance interpretation in the presence of thermal neutron absorbers.

DNL

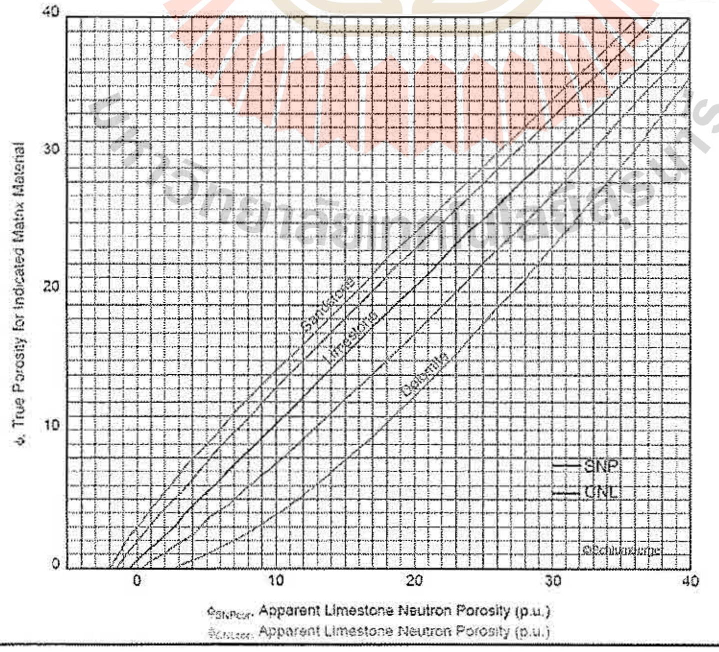
- In shaly formations containing a large number of thermal neutron absorbers, the porosity measured by the epithermal detectors reads lower and agrees more closely with density-derived porosity.
- As with the CNL, the DNL is especially designed for use in combination with other devices. In addition, the DNL can be run in liquid-filled holes, air/gas filled holes (Epithermal Porosity only) and open or cased holes.

Figure C20



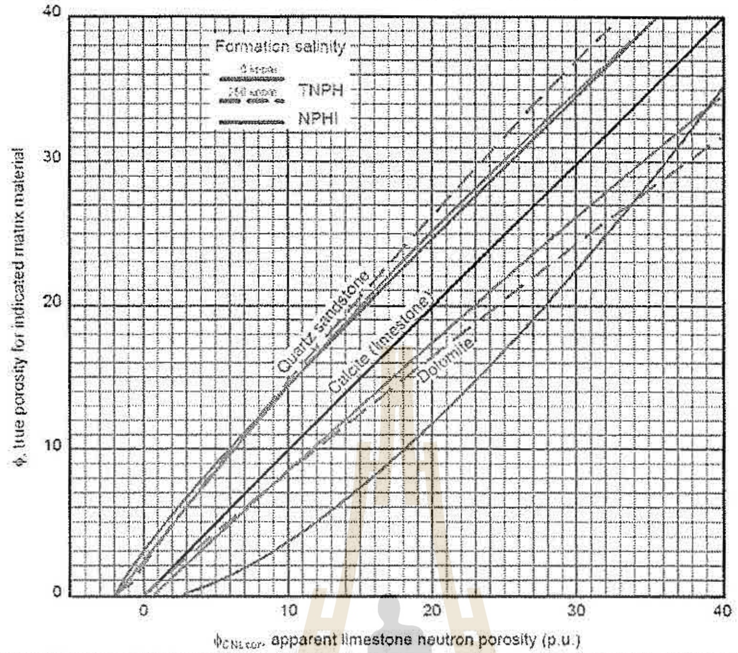
Neutron Porosity Equivalence Curves

Sidewall Neutron Porosity (SNP), Compensated Neutron Log (CNL*)



Neutron Porosity Equivalence Curves

Compensated Neutron Log (CNL*)



- Figure 9-2 shows a comparison of a sidewall and compensated neutron of Dresser Atlas over the same section of borehole.
- The major deviations between the two logs is in the caved sections of the borehole where the sidewall neutron is being significantly affected by the caves.
- Figure 9-3 shows a comparison of a Schlumberger sidewall neutron (SNP) and compensated neutron (CNL) in West Texas.

Figure 9-2

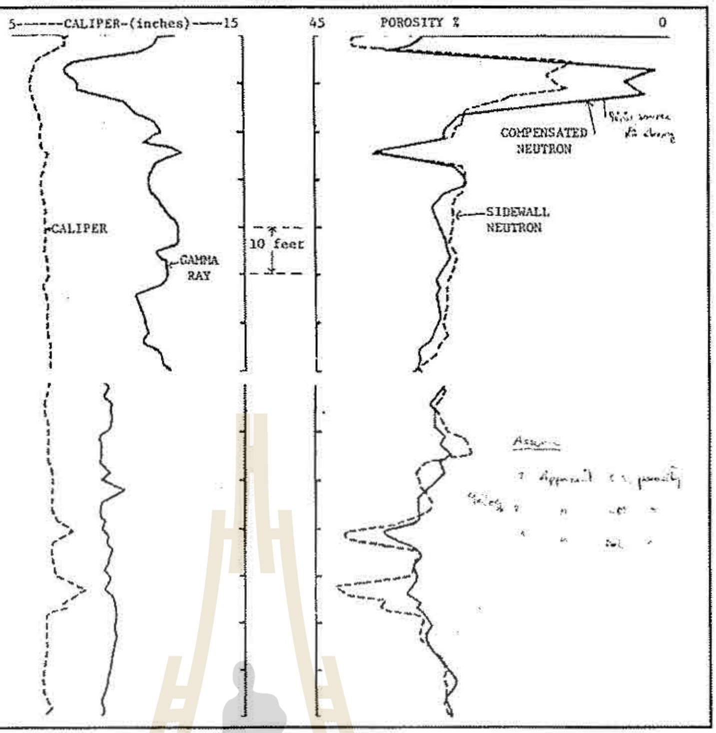
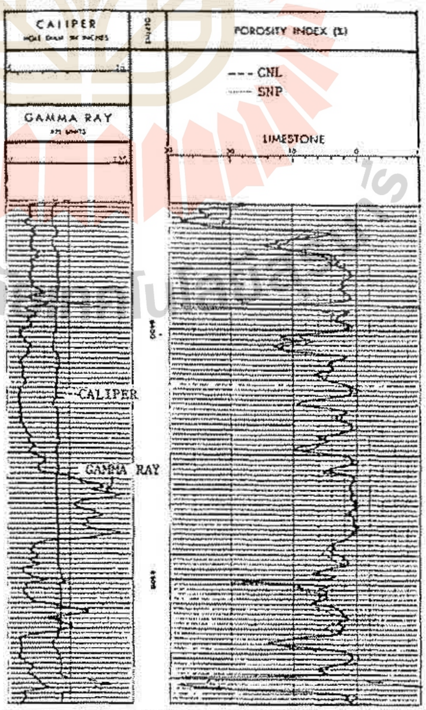


Figure 9-3



General Instrumentation

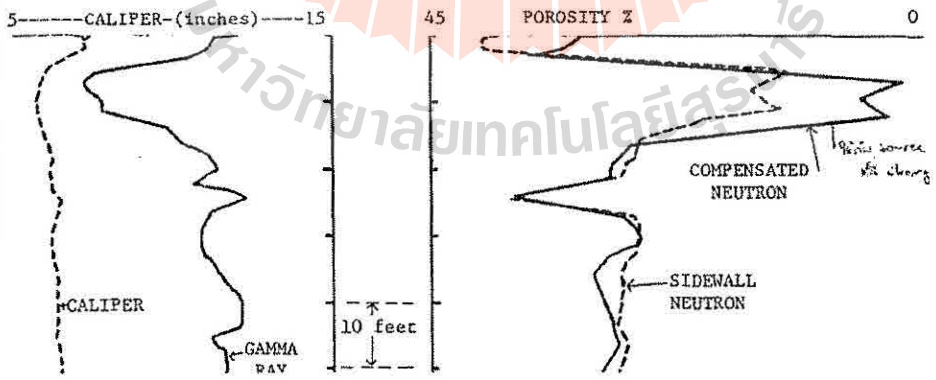
Neutron logs are statistical in nature and thus must be run slowly so that good averages can be obtained. Logging speeds of 20-30 feet per minute are usually adequate.

Porosity

- The neutron logs respond to liquid filled porosity. When gas is in the pore spaces in the materials being investigated, the gas shows up as low-hydrogen content or apparent low porosity.
- In cases where invasion is not deep the gas away from the area around the borehole, the neutron logs will see the gas as lower porosity. If the neutron log is the only porosity log run over a gas zone it may be difficult to determine if the zone is hydrocarbon bearing.

- On Figure 9-2, the zone 10 feet from the top of the shown log is a gas zone. The fact that the sidewall neutron does not read as low a porosity as the compensated neutron is that the formation is invaded and the compensated neutron is seeing deeper into the formation.

Figure 9-2



Neutron logs not only respond to the hydrogen content of the formation but to some degree to the density of the formation. The only place this becomes significant is in gas filled formations. If we have two formations, one with a two percent porosity filled with liquid and another formation with 10 percent porosity of which two percent is filled with water, the neutron log will read lower in the gas case. This is due to a phenomena called "excavation effect".

The neutron measurement is responding to the gas and the lower density of the formation and accordingly indicates lower porosity. This "excavation effect" is usually compensated for in the charts used to interpret the neutron log in gas bearing formations.

The porosity data from the neutron log is used in the same manner as porosity from other porosity logs.

FACTORS AFFECTING CNL LOGS

- Lithology

  A single known matrix must be present to accurately determine porosities. Large errors can occur if matrix selection is incorrect.

- Shale

  The presence of hydrogen in chemically bound water causes the CNL/DNL to read high porosities in shales or shaly formations.

FACTORS AFFECTING CNL LOGS

- Fluid Type

  Water: fresh water, no effects. Saline water has a reduced hydrogen content, CNL/DNL will read low porosity; the correction is in the chart book.

  Liquid Hydrocarbons: hydrogen content is close to that of water, little or no effect.

  Gas: hydrogen concentration is low, CNL/DNL reads low porosity.

FACTORS AFFECTING CNL LOGS

- ***Compaction***

  All neutron logs are unaffected by compaction.

- ***Secondary Porosity***

  All neutron equipment measures total porosity (including primary and secondary).

FACTORS AFFECTING CNL LOGS

- ***Borehole Effect***

  The effects of rough hole are minimized by a large depth of investigation obtained by the use of a high yield source and the two detector system.

  When run in combination with the density tool an automatic caliper correction system is accurate to 356mm. Normally there is zero stand-off correction.

FACTORS AFFECTING CNL LOGS

- ***Mudcake***

  Mudcake, fluid (mud and formation) salinity, mud weight, pressure and temperature correction can be viewed in Chart.

Chapter 10

COMBINED POROSITY LOGS

The acoustic, density and neutron logs, when used separately require a knowledge of lithology to obtain porosity. It should be evident that if each of these logs respond to porosity and lithology that they can be used together in simultaneous equation fashion to solve for porosity and infer lithology without having to know the lithology. If complex lithology is not a problem, then if the logs are responding to gas, gas bearing zones can be identified and porosity determined as well.

- This chapter covers:

  1. Use of multiple porosity logs to obtain porosity in complex lithology

  2. Identification of gas zones and determining porosity of same.

Complex Lithology

- When the formation logged is a combination of, for example limestone and dolomite, the equations and charts presented for the various porosity logs do not apply directly. The equation for the density log becomes:

$$\rho_b = \phi\rho_f + V_{ls}\rho_{ls} + V_{dol}\rho_{dol} \qquad (10\text{-}1)$$

- where ρ_b is the formation density (all densrties in gm/cc)

  ρ_f is the fluid, density that fills the pores @ is the fractional porosity

  V_{ls} is the fractional volume of limestone in the formation

  V_{dol} is the fractional volume of dolomite in the formation

  ρ_{ls} is the matrix density of the limestone

  ρ_{dol} is the matrix density of the dolomite.

- In a functional form equation 10-1 becomes:

  $$\rho_b = f(\phi, V_{ls}, V_{dol}) \qquad (10\text{-}2)$$

  where the matrix densities and the fluid densities are assumed to be known.
- In a functional form the equation for the neutron log is:

  $$\phi_N = f(\phi, V_{ls}, V_{dol}) \qquad (10\text{-}3)$$

  where the lithology effects on the neutron log are known and the ϕ_N is the-.neutron porosity as recorded in an apparent porosity (e.g. apparent limestone porosity). See Figure 9-1 for the lithology effects on the neutron log.

Figure 9-1

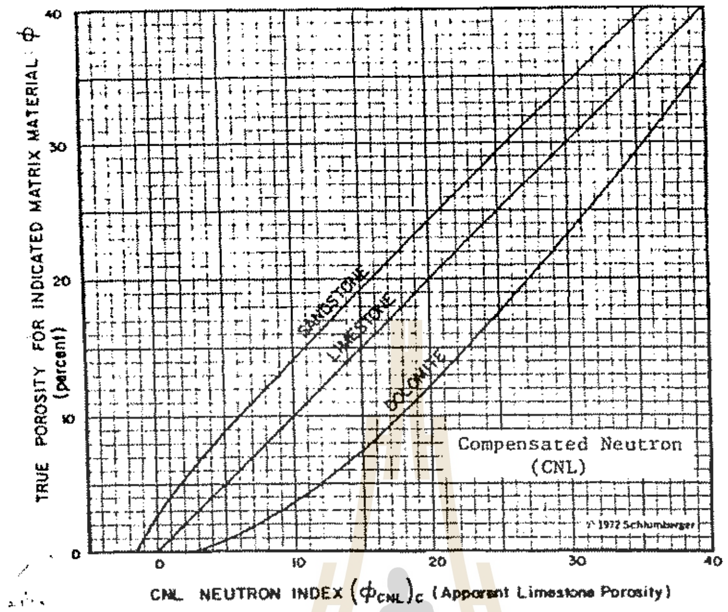
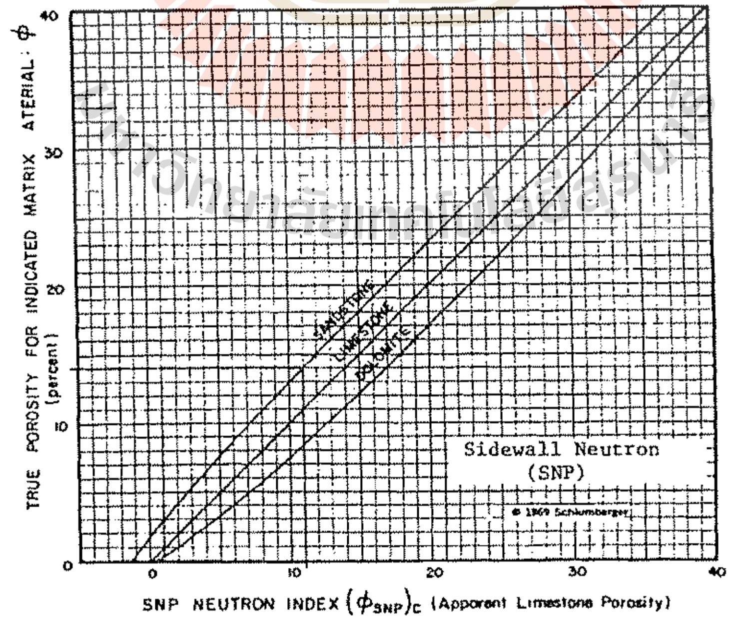


Figure 9-1



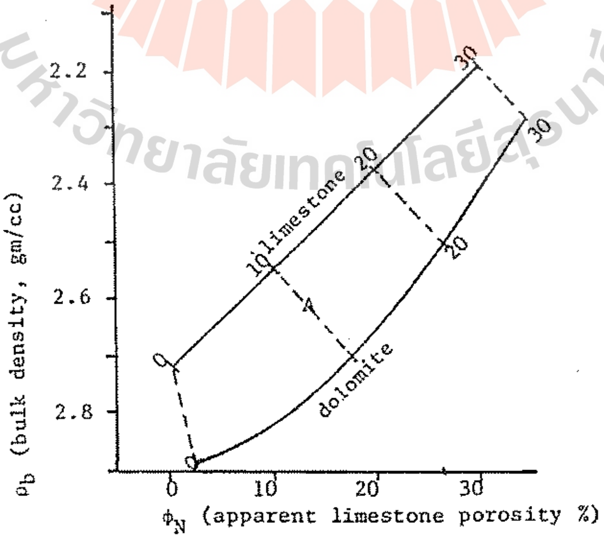
- It should also be recognized that:

$$\phi + V_{ls} + V_{dol} = 1 \qquad (10\text{-}4)$$

Equations 10-2, 10-3 and 10-4 allow us mathematically to solve three equations with three unknowns. This can be done mathematically or may be done graphically. Figure 10-1 shows a porosity log crossplot of a density and compensated neutron for a limestone dolomite mixture.

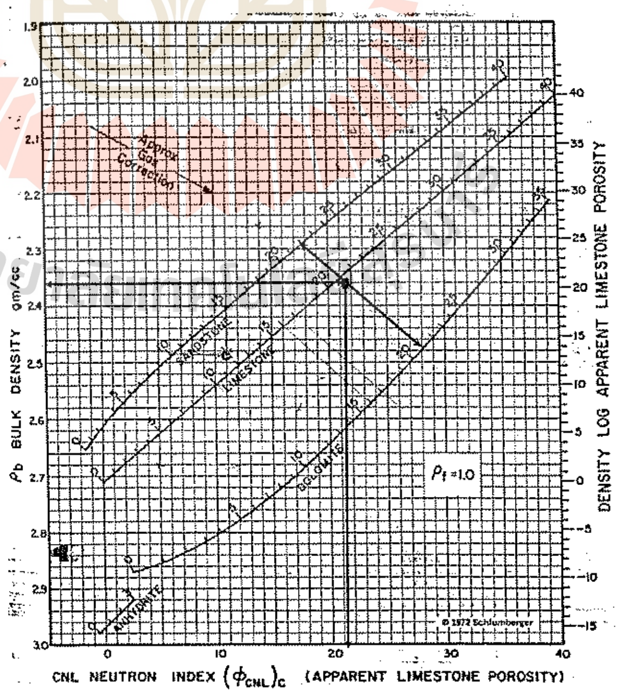
Figure 10-1

Density/Neutron crossplotfor limestone and dolomite



- From Figure 10-1 Point A,which has a bulk density of 2.62 gm/cc and an apparent limestone porosity of 14%,is a limy dolomite with a porosity of 10%.
- Figure 10-2 is a conventional density/neutron (Schlumberger CNL) crossplot chart- In addition to the limestone and dolomite lines are lines for sandstone and anhydrite. The mathematical game is still the same as introduced for Figure 10-1. The crossplot is a solution of three equations and three unknowns. The variables allowed are porosity plus two rock types

Figure 10-2

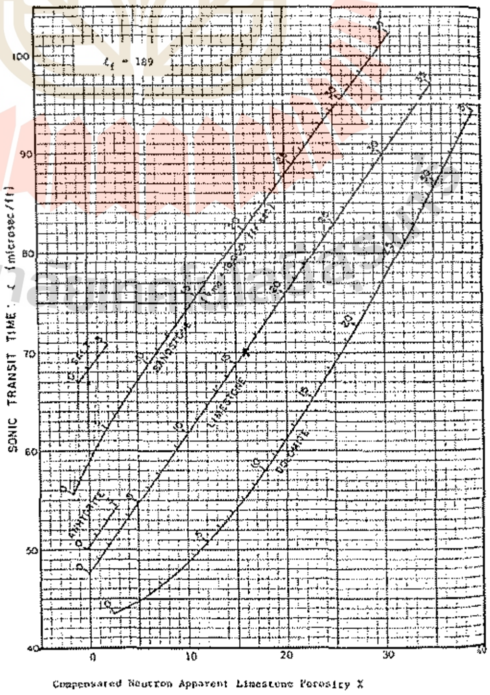


- From fig 10-2, Point B on Figure 10-2 which represents a density of 2.36 gm/cc and a limestone porosity of 21.5% could be a limestone with 21% porosity or it could be a cherty (sandstone) dolomite with a porosity of 21.5%. This latter porosity is obtained by joining the 21 and 22 % porosity lines on the sandstone and dolomite lines and finding B between them.

- Figure 10-2 may be entered with density and compensated neutron limestone porosity or may be entered with density and compensated neutron sandstone porosity. When the density and neutron are run together (sinultaneously) it is common practice to put both logs on a compatible porosity scale.

- Figure 10-3 is a sonic/compensated neutron crossplot (for Schlumberger). The arguments regarding its use are the same as those for the density/neutron crossplot. You determine porosity from this crossplot and the rock types must be limited to two for high quality work.
- If three porosity logs are available (acoustic, density and neutron) both charts (Figures 10-2 and 10-3 for a Schlumberger CNL or equivalents for other service companies) can be used together.

Figure 10-3



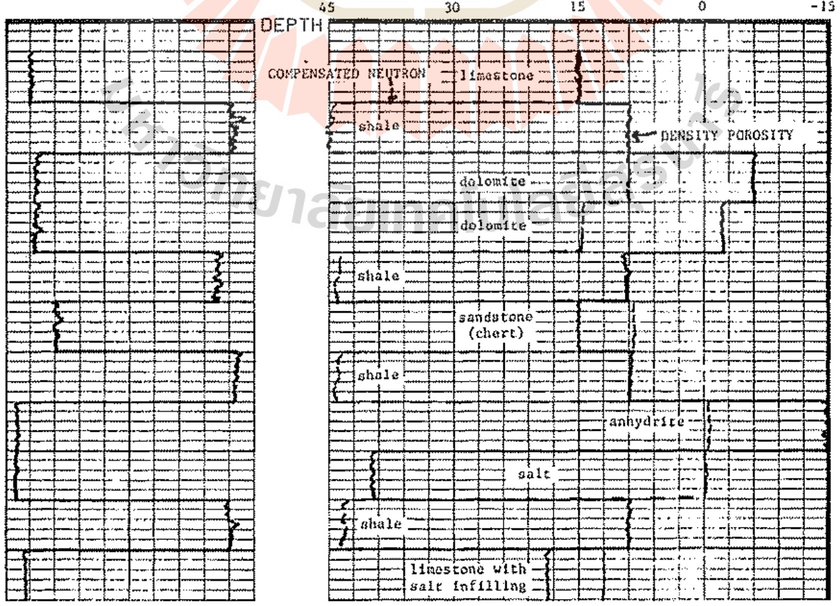
Compatible Porosity Scales

Two logs, such as the density/neutron, run simultaneously on the same lithology porosity scales (compatible porosity scales) show patterns that indicate where on the crossplot the data will fall. Figure 10-4 is a density/CNL (compensated neutron) schematic log. Both logs are recorded on limestone porosity. The logs are designed to be schlumberger logs i n a fresh mud.

- On a limestone scale if both curves record the same value (lie on top of each other) the data point will fall on the limestone line so the porosity can be read directly from the log.
- In a shale the neutron reads apparent high porosity while the density reads lower porosity. Shales are easily picked out on this combination by the large separation and the indication on the gamma ray.

- Dolomites show a density/CNL separation of about 15% porosity with the neutron reading higher porosity. The density often indicates negative porosity. This is caused by the bulk density being larger than the 2.71 g/cc used as matrix density. The two dolomites shown in Figure 10-4 have different porosities.
- Sandstone or chert will show as about 6% porosity difference with the neutron reading lower porosity.

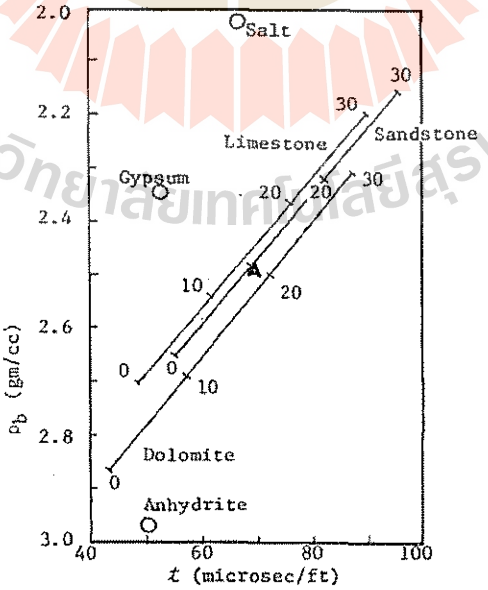
Figure 10-4



Density/Acoustic Crossplot

- The density/acoustic crossplot is not useful for porosity determination for reservoir rocks as can be seen in Figure 10-5. The different reservoir rock curves (sandstone, limestone and dolomite) are so close to each other that the normal data scatter from one laps over on the others.

Figure 10-5



- For example point A could-be any of the three rock types and the porosity would range from 20% if the rock were a dolomite, to 10% is it were a sandstone to 14% if it were a limestone. Accordingly this crossplot is not good for porosity or lithology of reservoir rocks. It can be used to detect other types of rocks as shown on Figure 10-5.

Gas Detection with Porosity Logs

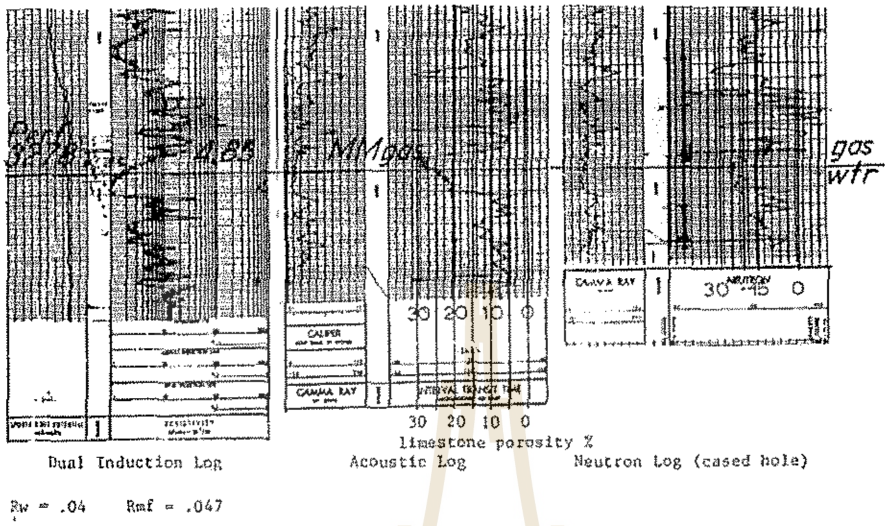
The acoustic, density and neutron logs all respond differently to gas when it is in the field of vision.

Gas Effects on the Acoustic Log

The acoustic log only-responds to gas when the formation is uncompacted or unconsolidated. The gas effect on the acoustic log in uncompacted formations appears to be unpredictable. Gas zones can have porosity (apparent) increases as indicated in equation 6-4 or can have significantly larger effects.

- Figure 10-6 is an example of the gas effect on the acoustic log in an unconsolidated limestone. This is the only unconsolidated limestone, we have ever identified with logs.

Figure 10-6



Gas Effects on the Density Log

The density log sees gas as apparent decrease in density or an apparent increase in porosity. The magnitude of this effect is a direct function of the gas saturation in the field of vision of the log.

- Since the density log only measures 2 to 3 inches into the formation the magnitude of the gas effect is directly tied to invasion. Very shallow or no invasion results in large apparent porosity increases while moderate invasion significantly reduces the gas the density log can detect.
- Shaly formations are trouble some as the shale effects the density log in the opposite way that gas does and the two sometimes cancel the effect.

Gas Effects on the Neutron Log

The neutron log sees gas as an apparent decrease in porosity. This effect is opposite that of the density and acoustic logs. The neutron is generally used with the acoustic or density to maximize the gas effect observed. The neutron log moves to lower porosity while the density and acoustic (in uncompacted formations) move to higher porosity.

Gas Effects on the Neutron Log

The magnitude of the gas effect on the neutron log is controlled by the gas saturation in the neutron log field of vision. The higher the gas saturation the larger the effect.

The neutron log sees much deeper into the formation and thus sometimes can detect gas when the density does not. Shaly formations reduce the apparent gas effect on the neutron logs as the shale effect is opposite to the gas effect.

Gas Detection with the Density and Neutron Logs

The most commonly used gas detection system is the combined density and neutron logs. Generally these logs are run on compatible porosity scales. In gas zones these logs may separate with the neutron log recording a porosity lower than, and the density log reading a porosity higher than the actual porosity.

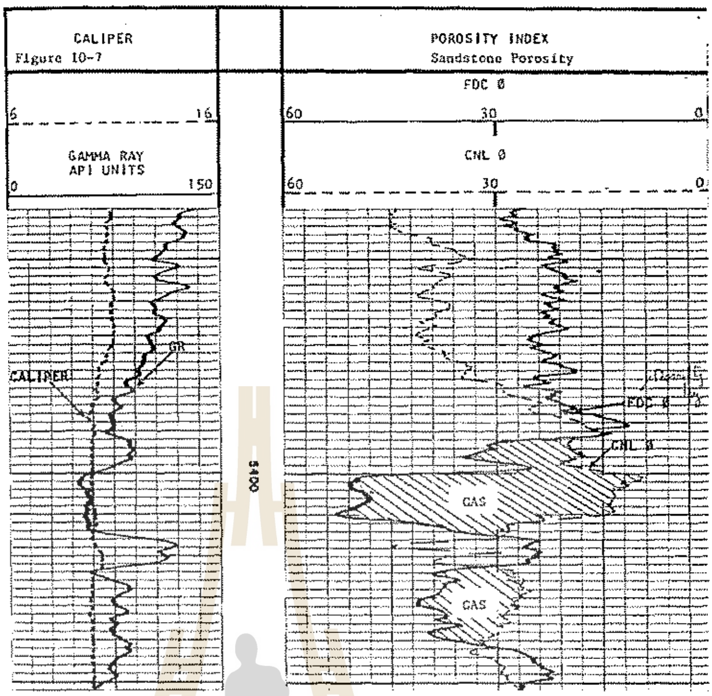
It is important for you to recognize that there are three different situations you may expect when detecting gas with this combination. The first is the case where both logs are seeing the same gas saturztion, the second is where the neutron is seeing more gas due to invasion problems, and the third is the shalv sand case where no "cross-over" occurs.

Crossover is where the neutron reads lower porosity than the density when both logs are on the proper lithology scale. These three situations will be discussed separately.

Case I

- In Case I both the density and neutron are seeing the same gas saturation. This is the case of essentially no invasion or The case of deep invasion. In the former case the logs are seeing the virgin zone while in the latter both are measuring in the invaded zone
- Figure 10-7 shows such an example. The density and neutron read essentially the same in the water zone and separate in the gas zone.

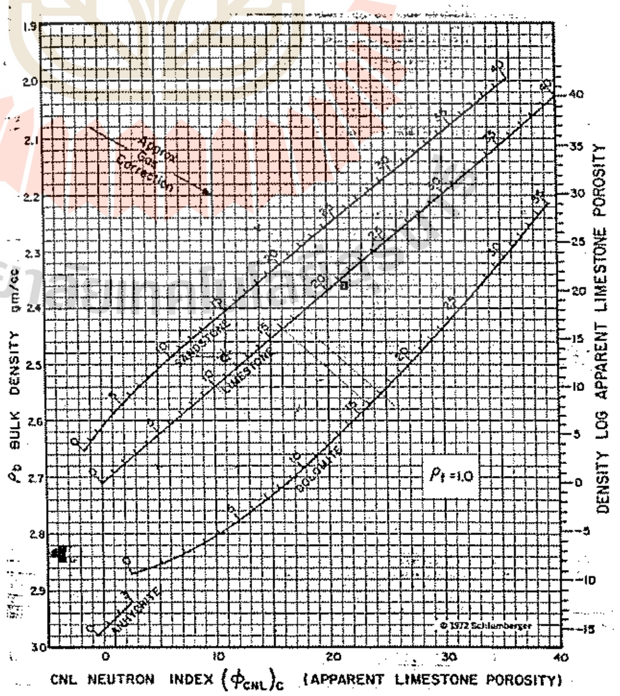
Figure 10-7



- Case I is recognized by the mirror imaging of the density and neutron logs. When the density shows higher porosity the neutron shows lower porosity and vice versa. This means that both logs are responding to the changes in gas (or water) saturation or changes in shale content. The degree of separation is also controlled by the density of the gas which is a function of both temperature, pressure and specific gravity.

- The gas effect correction charts in the service company chart books are primarily for Case I corrections. Density/neutron crossplots such as Figure 10-2 have approximate gas correction arrows.
- This arrow shows the general direction of the gas correction for Case I. Gas points on the crossplot (Case I) fall to the northwest (upper left) of the appropriate lithology line.

Figure 10-2

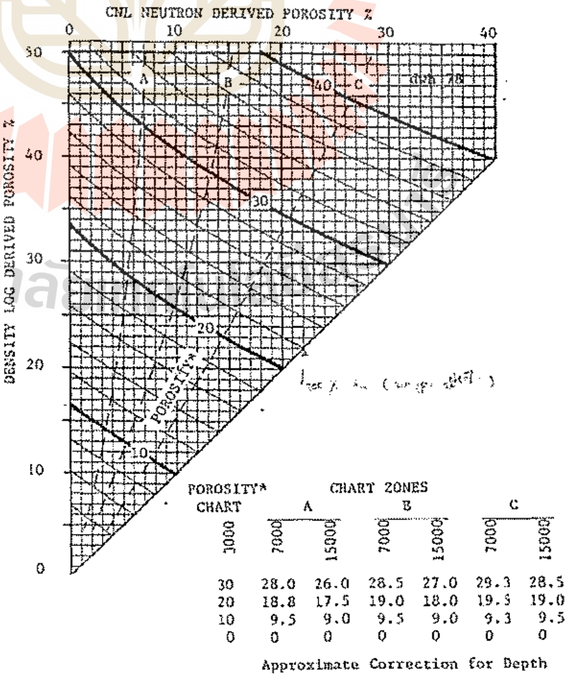


- A close approximation for the crossplot solution is:

$$\phi = \sqrt{\frac{\phi_D^2 + \phi_N^2}{2}} \qquad (10\text{-}5)$$

- where the porosities are for the density (D) and neutron (N) recorded in the appropritate lithology units (e. g. in sandstone porosity when the zone is sandstone)
- A more accurate correction chart is shown in Figure 10-8.
- The chart grid porosities are for an average depth of about 3000 feet.

Figure 10-8

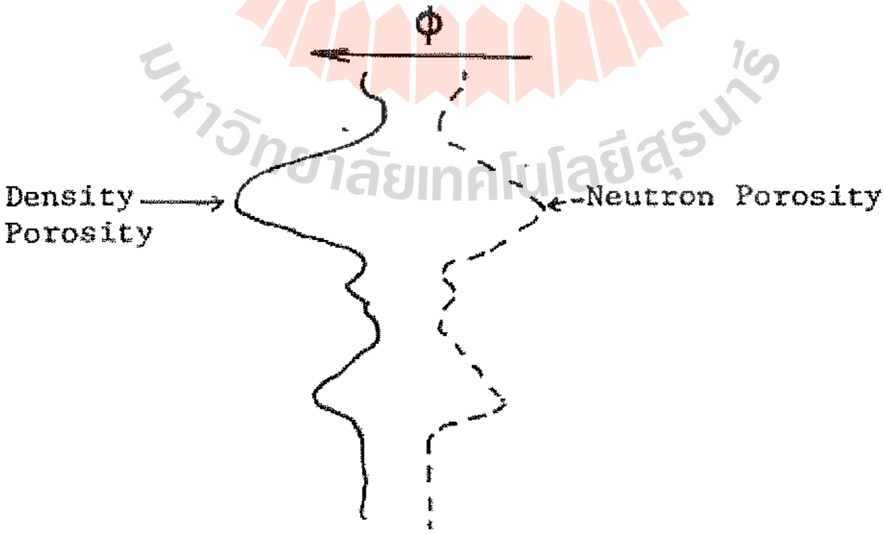


POROSITY* CHART	CHART ZONES A		B		C	
3000	7000	15000	7000	15000	7000	15000
30	28.0	26.0	28.5	27.0	29.3	28.5
20	18.8	17.5	19.0	18.0	19.3	19.0
10	9.5	9.0	9.5	9.0	9.3	9.5
0	0	0	0	0	0	0

Approximate Correction for Depth

- Note: The use of the crossplots, equation 10-5 and Figure 10-8 require that the logs be exhibiting Case I characteristics. That is the density and neutron must be mirroring each other as shown schematically in Figure 10-9.

Figure 10-9



Case II

- Case I1 is the situation where the gas cross-over occurs but the two logs (density and neutron) do not mirror image each other. two examples are shown in Figure 10-10.
- The reason for this best explained using Figure 10-11. Figure 10-11 shows the sampling depths of the Schlumberger density, compensated neutron and sidewall neutron for a sandstone with 35% porosity.

Figure 10-10

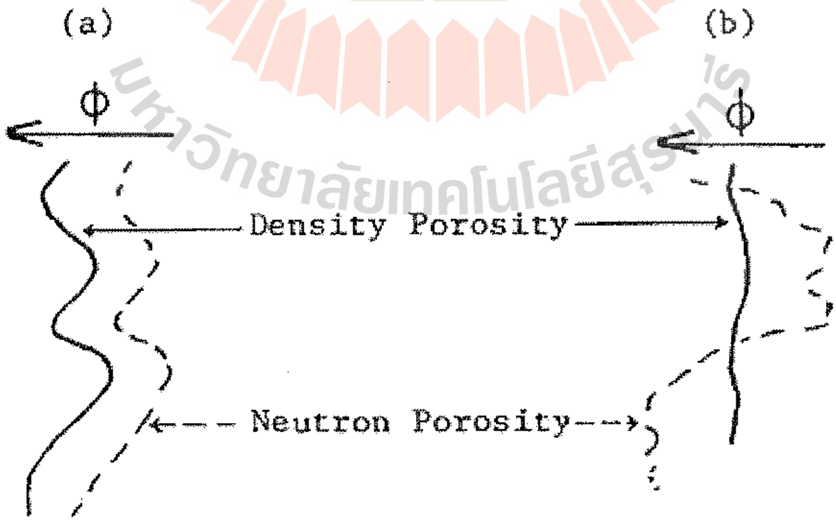
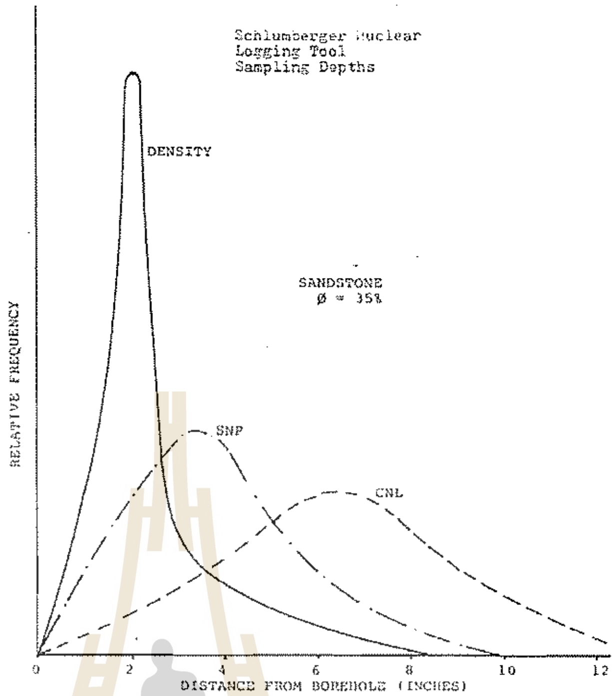


Figure 10-11

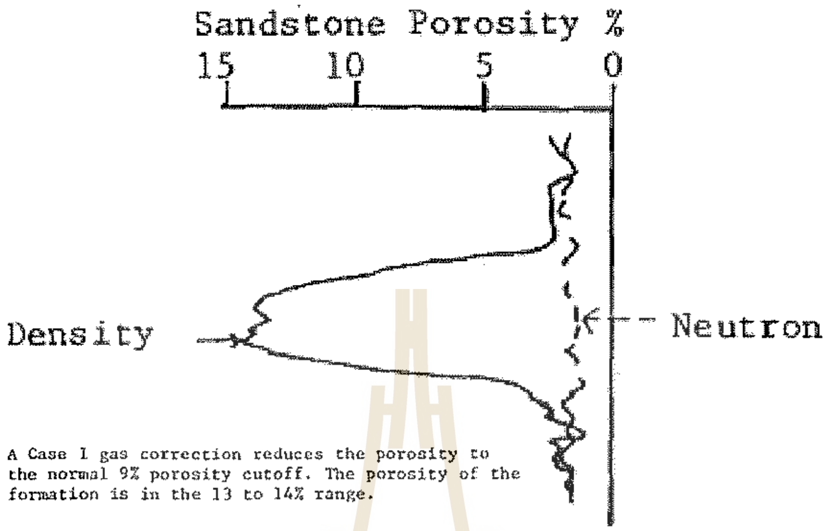


The area under each of the curves represents the total response of the logging system. The figure shows most of the density log measurement occuring between one and three inches behind the formation face. The compensated/neutron by comparison measures between three and ten inches from the borehole wall. This means that the neutron log is measuring much deeper into the formation. As the porosity (or hydrogen content) is reduced the neutron logs depth of investigation increases.

- If invasion is between three and about eight inches from the borehole wall (for an eight inch borehole these are invasion diameters of 14 to 24 inches) the density log will be measuring in the invaded zone and the neutron will be reading mostly behind the invasion zone. The logs will be seeing different gas saturations. Figure 10-10(a) shows this type of situation. Figure 10-10(b) is a similar situation only the zone with separation cleaned up enough (shale content reduced) so that the gas can be seen. Both these situations are common.

- For Case II, I recommend using the density log for porosity and ignoring the neutron log, other than to recognize the gas zone. Using the density for porosity will result in porosities that are a little high. This is better than pushing the porosities to lower values as would be done if a Case I correction were used. Figure 10-12 is a schematic of a real example in which a Case I correction actually eliminated the pay indication on the logs.

Figure 10-12



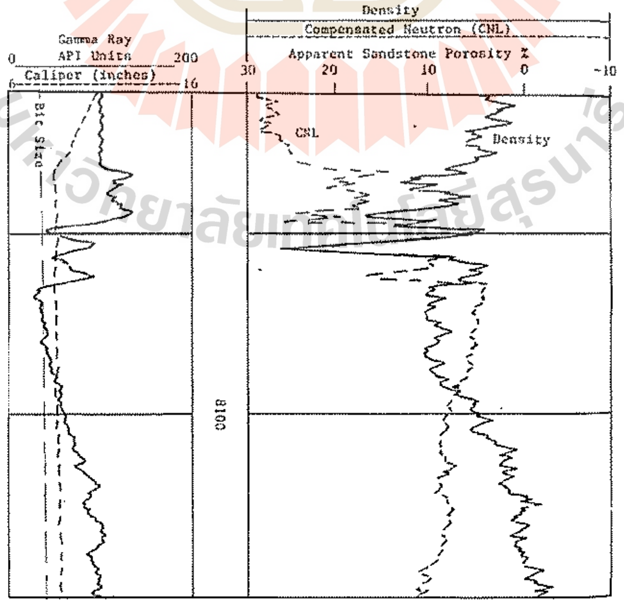
A Case I gas correction reduces the porosity to the normal 9% porosity cutoff. The porosity of the formation is in the 13 to 14% range.

Case III

Case III covers the use of the density/compensated neutron in shaly formations. Shale effects on both the neutron and density logs are opposite to that of gas. Figure 10-13 shows an example of a density/ compensated neutron is a gas sand that becomes progressively more shaly with depth.

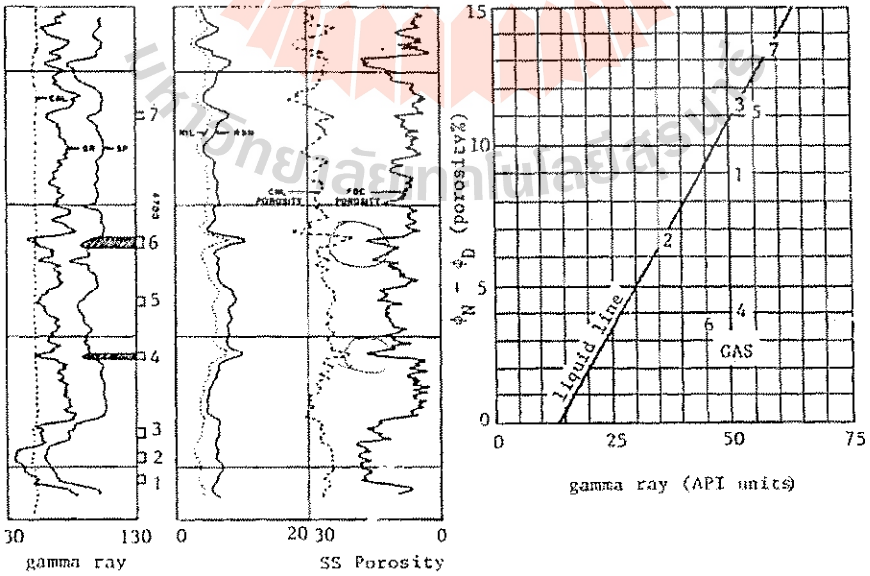
- The gas causes separation in the cleaner upper portion of the sand. The core porosity was essentially the same as that calculated from the density log.
- Below that point (about 8094) the density and CNL do not exhibit the "gas cross over" although the formation still contains gas. This is the type of log response considered in Case III.

Figure 10-13



- Case III is a part of shaly sandstone interpretation as covered in Chapter 13. Case III deals with identifying potentially productive shaly sandstones is a qualitative manner.

Figure 10-14
Case III gas identification approach

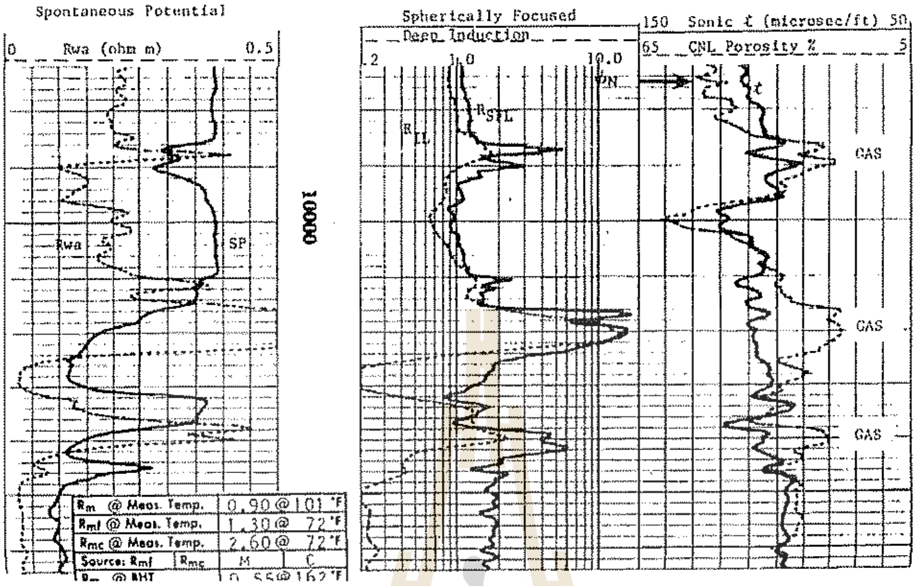


Gas Detection with the Acoustic and Neutron Logs

Gas detection with the acoustic and neutron logs can be made. The best environment is a shallow uncompacted formation. In the compacted formation the acoustic log often overresponds to the gas and shows it as very high apparent porosity. In deeper uncompacted formations the acoustic is not as influenced by the gas and you have to rely on the neutron log to pick up the gas.

- Figure 10-15 shows such an example. In this example the CNL was normalized to the acoustic travel time in the water zones. On this particular set of logs this implies a matrix travel time for the acoustic of 50 microsec/ft. This is not an unusual situation for the Louisiana Gulf Coast .

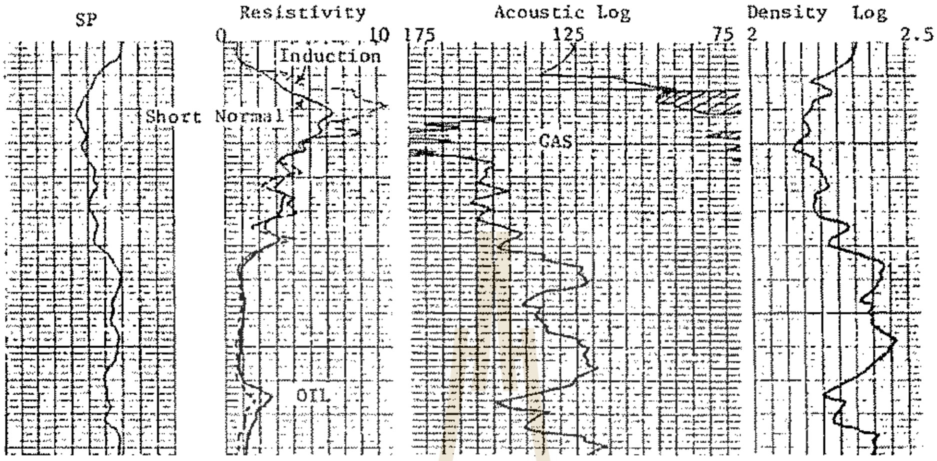
Figure 10-15



Gas Detection with the Acoustic and Density Logs

The only reliable detection of gas with the acoustic/density combination is when the acoustic log responds to the gas (in an uncompacted formation) and the invasion is significant enough to prevent the density from responding . Figure 10-16 shows such an example from offshore Louisiana..

Figure 10-16
An acoustic/density log showing a gas zone



Chapter 11
FOCUSED RESISITIVITY LOGS

This chapter covers all focused resistivity devices commonly used which are designed to measure Rt and Ri as well as the pad (micro) resistivity devices designed to measure in the flushed zone (Rxo). These are all electrode devices that pass current through the borehole liquid or mudcake - into the formation.

The Rt type devices discussed will be laterologs (sometimes referred to as guard or focused logs). The term laterolog will be used in lieu of one of the other names because of the popular acceptance of this term as a generic or near generic name. Laterolog is a chlumberger trademark.

The Ri type devices discussed will be latero logs (slightly different than the Rt laterologs), and Spherically Focused Logs (SFL is a Schlumberger trademark).

The pad or micro-resistivity devices covered will be the Microlog* (competitor names are Contact, Minilog and Microcontact), Microlaterolog* (competitior term FoRxo), Proximity* and Micro-Spherically Focused Log. * refer to Schlumberger trademarks.

The Borehole Environment

The drilling of a well with mud usually results in the contamination of the permeable formations. This is caused by the need to maintain the mud pressure in the borehole higher than the formation fluid pressure. Failure to do this may result in a "blow out".

The Borehole Environment

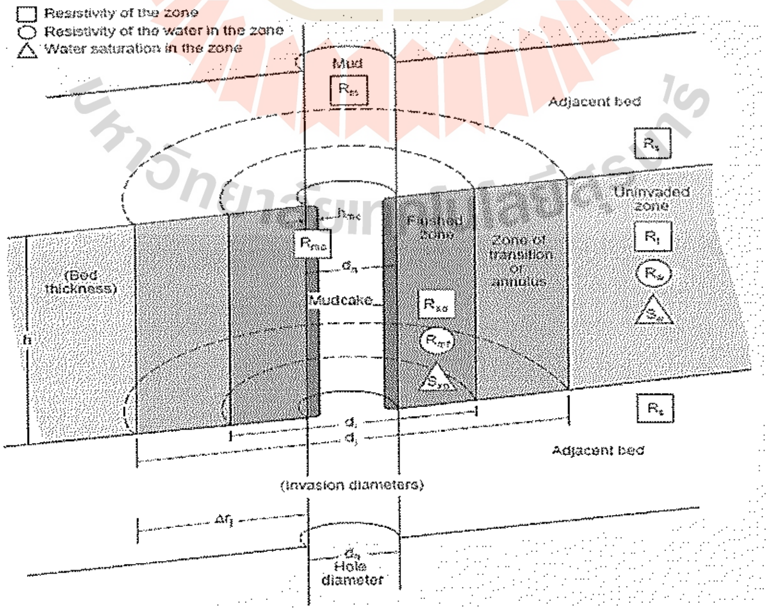
The amount of contamination (usually called invasion) is a function of the mud weight (borehole pressure) and the mud water (filtrate) loss. The mud in the process of filtering into the formation, leaves a mud cake on the wall of the hole. This mud cake (which is formed by the solids in the mud, mostly bentonite) limits the amount of water loss into the formation because of its low permeability.

The Borehole Environment

Relatively deep invasion occurs in low porosity formations because they are drilled generally with high water loss mud. Shallow invasion typically occurs in high porosity formations because they are drilled with low water loss mud. This latter is required to prevent borehole caving in the higher porosity more poorly consolidate formations.

** Figure 2-8 shows a schematic cross section of a wellbore penetrating a permeable formation.

Figure 2-8



The Formula of Figure 2-8

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Resistivity	Rxo	Ri	Rt
Porosity	ϕ	ϕ	ϕ
Water Saturation	Sxo	Si	Sw
Water Resistivity	Rmf	Rz	Rw

The Formula of Figure 2-8

Parameter	Flushed Zone	Total Invaded Zone	Virgin Zone
Equations	$S_{XO} = \sqrt{\frac{F_R R_{mf}}{R_{XO}}}$	$S_i = \sqrt{\frac{F_R R_z}{R_i}}$	$S_W = \sqrt{\frac{F_R R_W}{R_t}}$

** With Invasion $S_{XO} > S_i > S_W$ unless all are 100%

no Invasion $S_{XO} = S_i = S_W$ and R_W in all pores

Flushed Zone

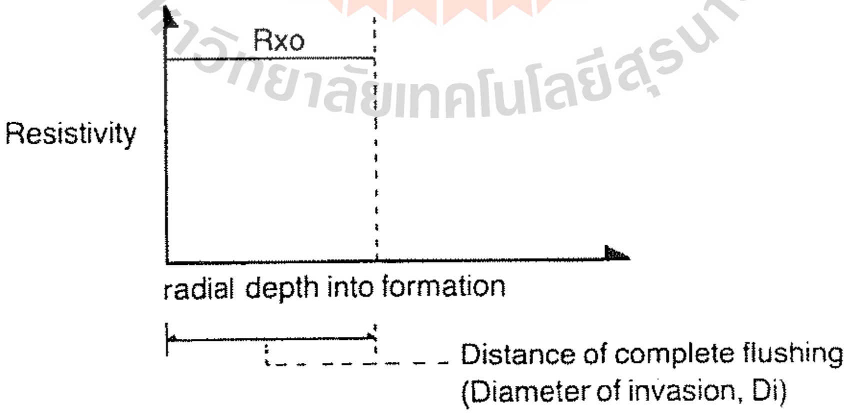
Flushed Zone. Adjacent to the borehole the invasion process flushes out the original water and some of the hydrocarbons (if any were present).

The resistivity of this zone is termed R_{xo}; the water saturation is called S_{xo} where:

$$S_{XO}^2 = \frac{F_R R_{mf}}{R_{XO}}$$

**(for clean formations only)

- Plotting R_{xo} as a function of radial depth into the formation yields Figure.



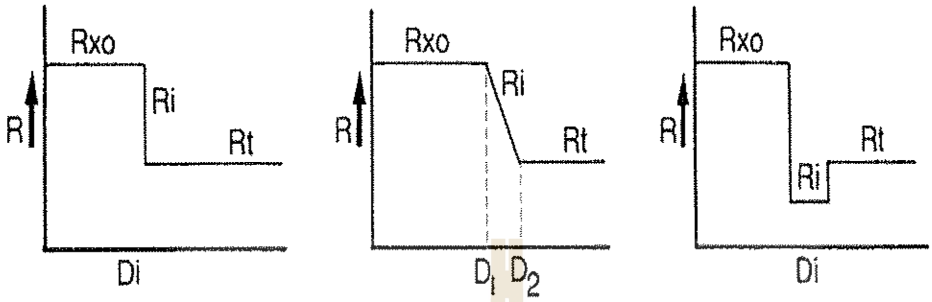
Transition Zone

- Transition Zone. Further from the borehole the flushing action of the mud filtrate may create a variety of situations.
- If the flushing proceeds as a uniform front, we call this a step profile of invasion (Figure B5a). If the intermingling of formation fluids is very gradual, we would call this a transition zone (Figure B5b).

Transition Zone

- Sometimes in oil or gas bearing formations, where the mobility of hydrocarbons is greater than the connate water, the oil or gas move out leaving an annular zone filled with connate water (Figure B5c).
- If Rmf > Rw, then the annular zone will have a resistivity lower than Rxo and Rt and may cause a pessimistic saturation calculation.

Figure B5



Case 1
Step Profile
(a)

Case 2
Transition
Profile
(b)

Case 3
Annulus
Profile
(c)

Uninvaded Zone or Virgin Zone

- True Unaffected Zone. This is the zone which we wish to analyse. it is the formation undisturbed by the drilling process. Its resistivity is termed R_t, water resistivity R_w, and water saturation S_w.
- Plotting R_{xo}, R_i and R_t as a function of invasion:

SUMMARIZE

6. Relationships:

a. $F = (R_t / R_w)$

$F = (R_o / R_w) \rightarrow$ 100% water saturated porous rock

b. $F = a / \phi^m$

7. Symbols:

R_w - resistivity of connate water.

R_t - true formation resistivity.

R_{xo} - resistivity of flushed zone.

a - a constant.

m - cementation factor.

Resistivity measuring devices are generally classified by the depth of the measurement. If the device measures only a few inches into the formation it is called an R_{xo} too. If the measurement is in the range of ten 's of inches it is an R_i tool and if the tool reads much deeper than the previously mentioned tools it is an R_t tool. It should be remembered that if the invasion is very shallow or nonexistant all the devices will read R_t.

Introduction

- We have two different types or classes of tools designed for the two most common borehole environments:

1. Non-Conductive Boreholes
2. Conductive Boreholes

Non-Conductive Boreholes

- including Fresh Mud Systems, Invert Mud Systems and Air-filled holes.
  - a. Dual Induction - SFL (No longer in service)
  - b. Phasor Dual Induction - SFL
  - c. Array Induction Imager

The example of Resistivity Measurement Devices

- The type of the Resistivity Measurement Device are 3 type up to the type of resistivity value (R_{XO}, R_i ,or R_t) such as:
  - SPHERICALLY FOCUSED LOG (SFL)
  - DUAL INDUCTION - SPHERICALLY FOCUSED LOG (DIL-SFL)
  - Medium Induction (ILM) or Deep Induction (ILD)
  - Short Normal

SPHERICALLY FOCUSED LOG (SFL)

The SFL device measures the resistivity of the formation near the borehole and provides the relatively shallow investigation required to evaluate the effects of invasion on deeper resistivity measurements. It is the short-spacing device used in the Phasor Induction – SFL tool.

DUAL INDUCTION - SPHERICALLY FOCUSED LOG

This is the most basic of induction devices and was the reference resistivity induction device for 20 plus years until its retirement in 1990.

The tool supplies three focused resistivity curves: two Induction and a shallow investigating Spherically Focused Curve plus the Spontaneous Potential. Each curve has a different depth of investigation (Figure B15).

Measurement of Rt by Laterolog Principles

- DUAL LATEROLOG

  The Dual Laterolog is a current emitting electrode device that performs best in saline muds (i.e. where Rt/Rm >>> 100, Rmf /Rw < 2.5). It is designed to extract Rt by measuring resistivity with several arrays having different depths of investigation.

- For best interpretation accuracy, such a combination system should have certain desirable features:
  - Borehole effects should be small and/or correctable.
  - Vertical resolutions should be similar.
  - Radial investigations should be well distributed; i.e., one reading as deep as practical, one reading very shallow, and the third reading in between.

DUAL
LATEROLOG

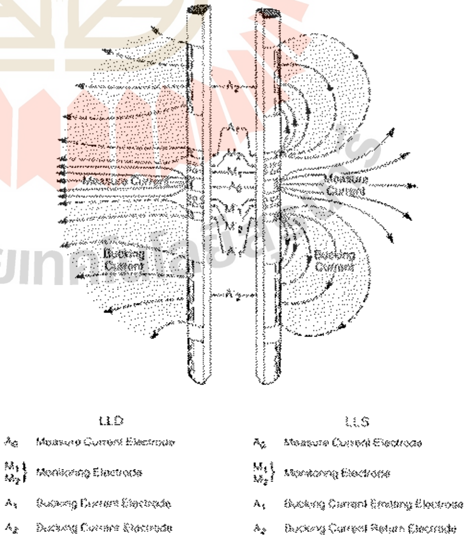


Figure B21: Dual Laterolog
Deep and Shallow Current Patterns

The DLL tool has a response range of 0.2 to 40,000 ohm-m, which is a much wider range than covered by previous laterolog devices.

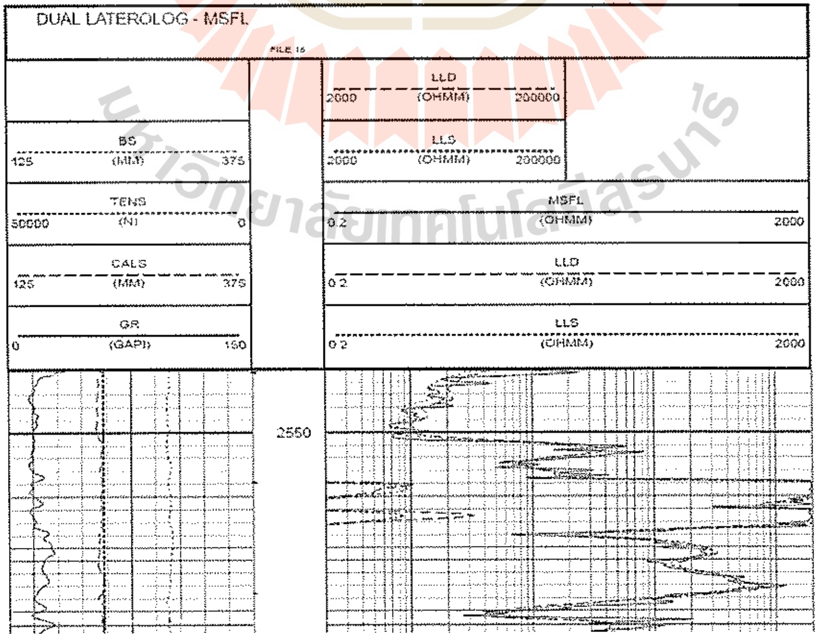
The deep laterolog measurement (LLD) of the DLL tool has a deeper depth of investigation than previous laterolog tools and extends the range of formation conditions in which reliable determinations of Rt are possible.

The shallow laterolog measurement (LSS) has the same vertical resolution as the deep laterolog device 60 cm (2 feet), but it responds more strongly to that region around the borehole normally affected by invasion.

Log Presentation

The DLL-MSFL presentation is very similar to the Phasor Induction. Differences include expanded resistivity scale (0.2-200,000 ohm-m) and the addition of Gamma Ray and Caliper (if MSFL is used). See log in Figure B23.

Figure B23



Tool Characteristics and Applications

1. The Dual Laterolog performs most effectively in saline mud (high Rt/Rm ratios) or where Rmf/Rw < 2.5.

2. The tool has an excellent resistivity range; by utilizing a unique design, resistivity resolution from 0.2 to 40,000 ohm-m is possible.

3. Vertical resolution is excellent, Rt can be obtained in beds as thin as 60 cm (2 feet).

4. The LLd has very little borehole effect in large holes.

5. When combined with an Rxo measurement, the LLd, LLs curves may be used to study invasion profiles and compute a more accurate Rt. See Chart Rint-9 (Figure B24).

Limitations

1. The tools should not be used in fresh muds (Rmf/Rw > 2.5.)
2. The tools requires good centralization to minimize borehole influence on the LLs.
3. If invasion is deep, a good value of Rxo (e.g. from a Micro-Spherically Focused Log) is required to correct LLd for invasion influence to obtain an accurate value of Rt.

Measurement of Rxo by Micro-resistivity Principles

- INTRODUCTION

  As has been mentioned, a measurement of flushed zone resistivity, Rxo, is an important input when attempting to define invasion diameter. Since the flushed zone may only extend a few centimetres from the borehole, a shallow reading device is required. Such tools are the Micrology, Microlaterolog, Proximity log and the Micro-Spherically Focused Log.

Today, the Microlog and Micro-Spherically Focused Log are completely combinable with all main logging services. The Microlaterolog and Proximity log have been discontinued due to their limitations in design.

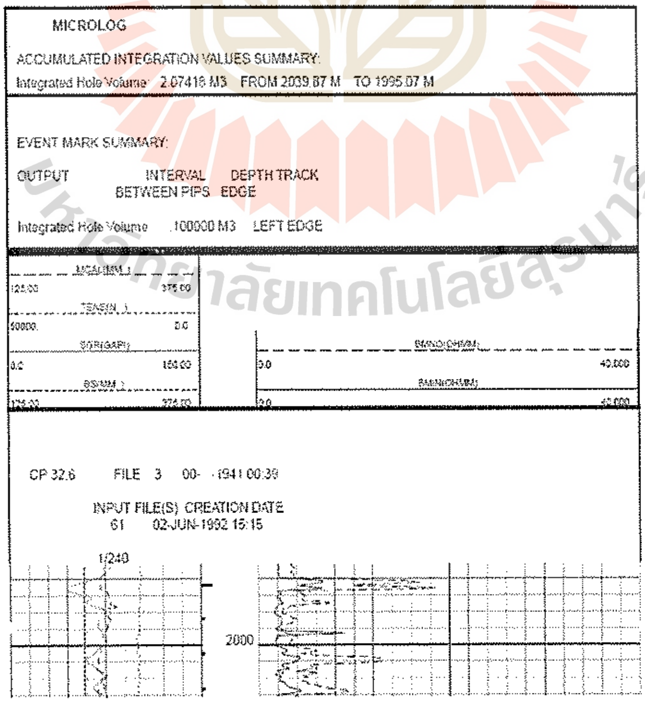
To measure Rxo, the tool must have a very shallow depth of investigation. Since the reading should be affected by the borehole as little as possible, a sidewall-pad tool is used.

MICROLOG

With the microlog tool, two short-spaced devices with different depths of investigation provide resistivity measurements of a very small volume of mudcake and formation immediately adjoining the borehole.

Comparison of the two curves readily identifies mudcake, which indicates invaded and, therefore, permeable formations.

As drilling fluid filters into the permeable formations, mud solids accumulate on the hole wall and form a mudcake. Usually, the resistivity of the mudcake is slightly greater than the resistivity of the mud and considerably lower than the resistivity of the invaded zone near the borehole.



```
MICROLOG

ACCUMULATED INTEGRATION VALUES SUMMARY:
Integrated Hole Volume:  2.07418 M3   FROM 2039.87 M   TO 1995.07 M

EVENT MARK SUMMARY:

OUTPUT                  INTERVAL      DEPTH TRACK
                  BETWEEN PIPS   EDGE

Integrated Hole Volume    .100000 M3    LEFT EDGE

CP 32.6        FILE   3    00-   -1941 00:39

          INPUT FILE(S)  CREATION DATE
            61       02-JUN-1992 15:15
```

Microlog Limitations

- Rxo/Rmc must be less than about 15.

- Mudcake thickness < 1.2 cm

- Depth of Flushing > 10 cm, otherwise the microlog readings are affected by R_t.

MICRO – SPHERICALLY FOCUSED LOG

The MicroSFL is a pad-mounted spherically focused logging device that has replaced the Microlaterolog and Proximity tools. It has two distinct advantages over the other Rxo devices. The first is its combinability with other logging tools, including the Phasor Induction, the Array Induction, and Dual Laterolog tools.

The second improvement is in the tools response to shallow Rxo zones in the presence of mudcake.

The chief limitation of the Microlaterolog measurement was its sensitivity to mudcakes. When mudcake thickness exceeded about 3/8 inch, the log readings were severely influenced at high Rxo/Rmc contrasts.

MicroSFL Limitations

- depth of flushing > 12 cm.

- mud cake thickness < 1.2 cm.

- radial investigation 10 cm.

MicroSFL Applications

- Identification of permeable zones.

- An excellent value of Rxo from the MSFL provides a quick look over-lay technique for comparison with an Rt curve after being normalized in a 100% Sw zone. After normalization when curves separate, moved hydrocarbon is indicated.

- Correction charts are available for the influences of:

  - Mudcake (Chart Rxo-3) (Figure B29).

Chapter 12
QUANTITATIVE ANALYSIS - PART II

This chapter will cover some additional clean formation interpretation techniques. It is well recognized by "experts" in the field of log analysis that there are many ways of handling well log data.

"Quick Look" well site techniques will also be covered. These quick look techniques are procedures done by the logging company while logging and are meant to assist the interpretor in selecting zones that are hydrocarbon bearing.

Quick Look Techniques → R_{XO}/R_t

- The Rxo/Rt quick look curve that is presented on many well logs is an overlay curve on the SP. The SP equation, 4-3 may be simplified to:

$$SP = E_c = -K \log \frac{Rmf}{Rw} \qquad \text{Eq12-1}$$

- If you remember that for a water bearing zone (Sw = 100%)

$Rxo = F_R\ Rmf$ and $Ro = F_R\ Rw$ (Sw = 100%)

- Then

$$SP = E_c = -K \log \frac{Rxo}{Ro}$$

Eq 12-3

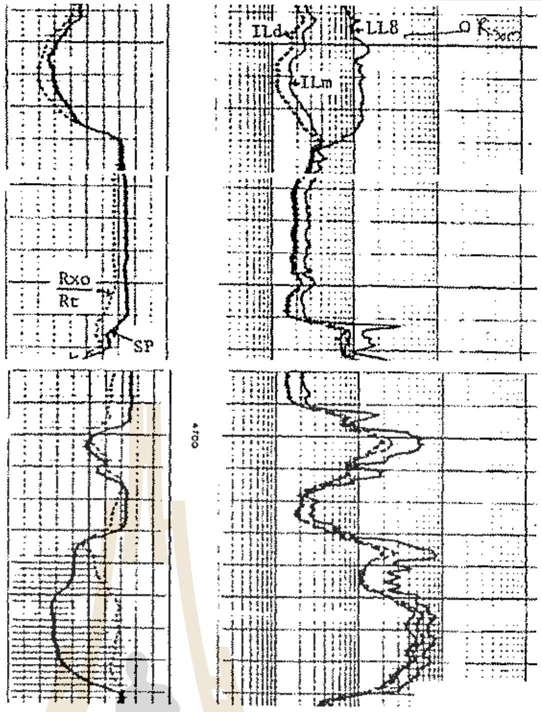
if you multiply both R_{mf} and R_w by F_R. This means that in water bearing zones.

if you measured Rxo and Ro (Rt for Sw = 100%) you could calculate the SP that should be produced. The SP calculated would duplicate the one measured. The Rxo could be obtained from an Ri log (e.g. LL8,SFL or LL3) if average invasion corrections were made, and Rt could be obtained directly from the deep induction log

- In a hydrocarbon zone the SP equivalent calculated from Rxo/Rt would not be correct. The Rt would increase more than Rxo (Sxo > Sw) and the SP calculated would be less than the actual SP.
- The interpretation of Rxo/Rt follows this logic; in water zones the Rxo/Rt curve should look just like the SP and should lay on top of it, in hydrocarbon bearing zones the Rxo/Rt will read less than the SP and this indicates hydrocarbons.

- Figure 12-1 shows an example from Oklahoma. The zones around 4700 and 4750 are hydrocarbon bearing. At 4700 the Rxo/Rt curves looks like the SP, which it is not supposed to, at 4750 the Rxo/Rt curve indicates hydrocarbons.

Figure 12-1



F and Ro Logs

The F and Ro quick look logs are closely related. The first part of the process is to create an F curve, on a logarithmic grid, from a porosity log. On a logarithmic grid a shift is the equivalent of multiplying or dividing. This is how a slide rule works. Thus if the F curve is shifted so that it overlays the Rt curve in a water zone (Ro) the amount of shift is Rw and the F curve is now an Ro curve (resisitivity of formation at Sw = 100%) as in:

$$R_O = F_R R_W \qquad \text{Eq 12-4}$$

Example 12-1 F and Ro logs

Figure 12-2 shows a dual induction and density log for the Gulf Coast. The formations are sands and shales. Porosity is calculated from the density log and then F_R is calculated. In this particular example, the F_R curve on Figure 12-3 was calculated using $F = \phi^{-2}$ probably due to the lack of instrumentation to use the proper equation.

- The F value of 10 overlays the resistivity value of 0.2 just as the F value of 100 overlays 2 on the resistivity curve. As shown in equation 12-4 the constant that connects F (actually F) and Ro is Rw. Thus:

$$Rw = \frac{Ro}{F_R} = \frac{.2}{10} = \frac{2}{100} = .02 \text{ ohm m.}$$

- Rw for this water zone is thus .02 ohm m.

- The Ro (former F curve) will lie on top of the deep induction curve when Sw = 100%. if water saturation drops below 100% the Rt device (deep induction in this case) will read higher than Ro and thus higher than the Ro curve. See the zone around 4130 on Figure 12-3 (marked A).
- The water saturation can be calculated as:(for zone A on Figure 12-3)

$$Sw = \sqrt{\frac{Ro}{Rt}} = \sqrt{\frac{.14}{14.}} = .10 \quad \text{or} \quad 10\%$$

Figure 12-2

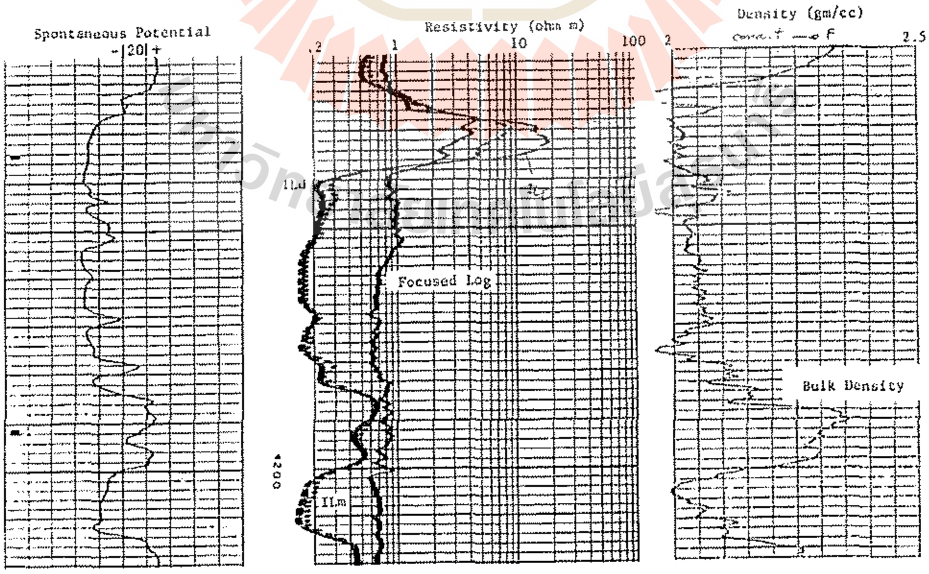
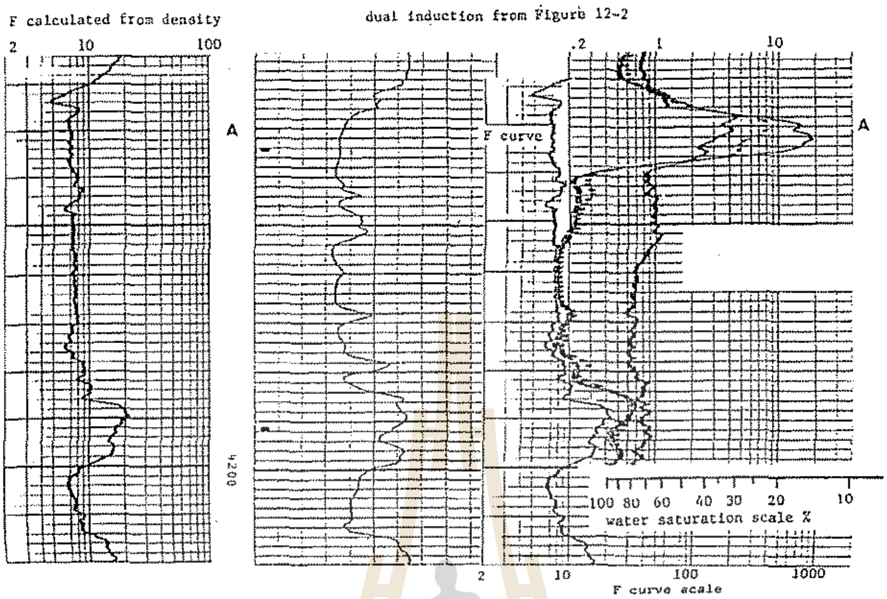
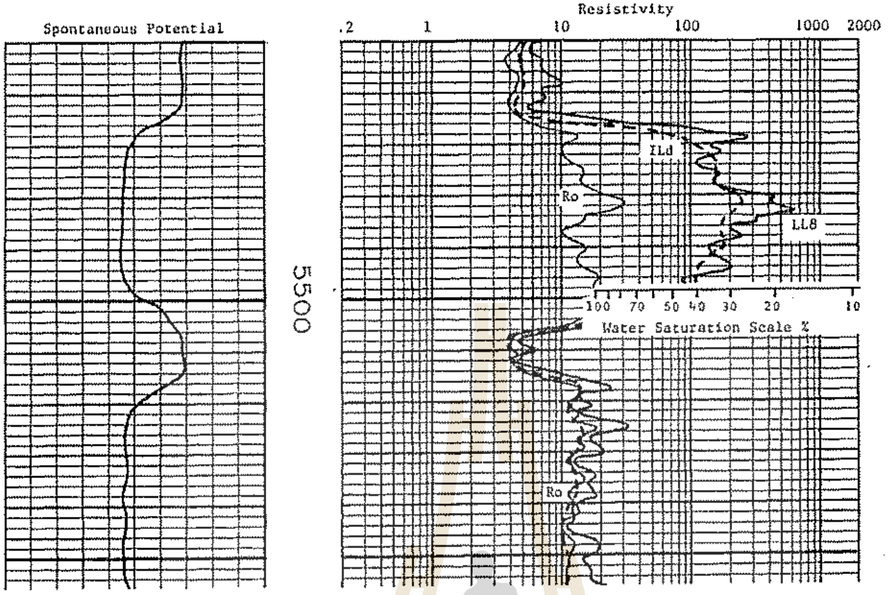


Figure 12-3



- Figure 12-4 shows an Ro overlay from a Sonic log. It should be remembered that to put an Ro on a log requires a knowledge of Rw. If no water zones are present the logging engineer must use a good value of Rw or the Ro curve is no good.

Figure 12-4



Resistivity Porosity Crossplots (RPC)

The RPC requires special graph paper designed for the particular F_R - ϕ relationship used. There are numerous different F_R - ϕ papers available but I will only present the two for the relationships used most often: $F_R = \phi^{-2}$ (for nongranular rocks) and $F_R = 0.62/\phi^{2.15}$ for granular rocks.

The basic concept behind this RPC graph is that the relationship between resistivity and porosity is linear. This makes possible the extrapolation of the resistivity curve to zero porosity or infinite resistivity. If water bearing zones exist the plot defines both matrix property of the rock and the water resistivity. This plot works best when there is a wide range of porosity in the water zone

- Figures 12-5 and 12-6 are the special graph paper for $F_R = \phi^{-2}$ (for nongranular rocks) and $F_R = 0.62/\phi^{2.15}$. Both conductivity and resistivity scales are included for convenience

Figure 12-5

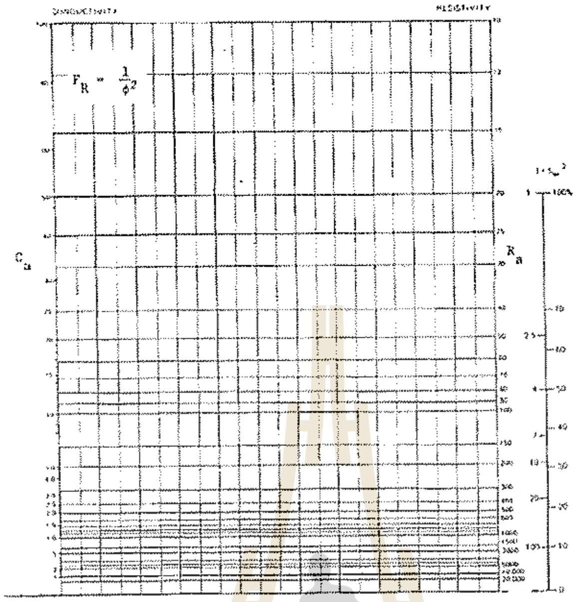
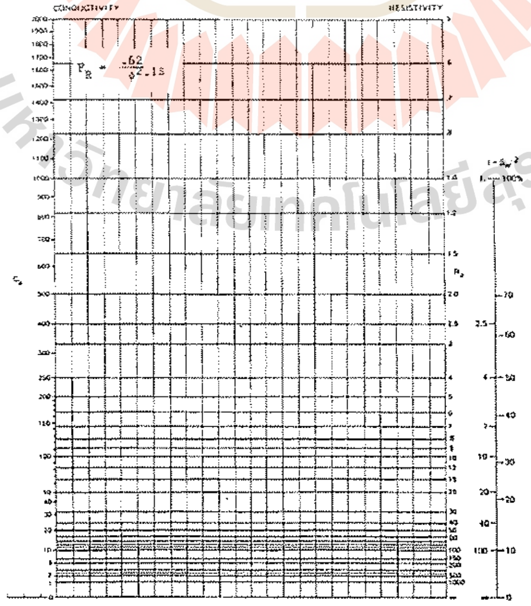


Figure 12-6



RPC Procedure

1. Read resistivity (or conductivity) and travel time, density or neutron porosity from logs. Be sure to cover as wide a range of resistivity and porosity as possible.

2. Set up scales on appropriate graph paper (Figure 12-5 or 12-6)

3. Read data from logs and plot on graph paper. Use a number for each zone (so you can later find any given zone) and plot each level as a number. If you have two porosity logs, go to a porosity log crossplot and obtain a crossplot porosity and plot that porosity.

4. Water zones (if any) will form the upper left hand edge of the the data envelope. This data should form a straight line that extends from the bottom of the graph to the top, sloping to the right (if porosity is plotted increasing to the right) Draw a straight line along the average left edge of the data and extrapolate the line to infinite resistivity. (Figure 12-7)

The point where the line cuts the infinite resistivity line (conductivity equals zero) defines the matrix value for the density and acoustic logs, zero porosity for the neutron log and zero porosity for the porosity crossplot data. If the latter two do not agree with the zero point shift the scale so that zero porosity is at the line cutting infinite resistivity point.

5. Lay out the porosity scale (for the acoustic or density log) or shift the scale (for the neutron porosity or crossplot porosity cases). (Figure 12-8)

6. The slope of the line drawn on the graph is controlled by Rw. To check Rw for line drawn through edge of data (Ro line) assume some porosity, enter bottom of chart and go vertical to the Ro line. Read resistivity at point of intersection of line for assumed porosity. Rw = Ro/F (F for assumed porosity). If you assume a convenient porosity you will have no trouble calculating F_R e.g. for Figure 12-5 a porosity of 10% has an F_R of 100, for 12-6 a porosity of 20% has an F_R of 20.

If the Rw agrees with the Rw from the SP or the catelog value of Rw you can go to the next step. If Rw disagrees you must change slope of line. An approximate method is as follows: for correct Rw calculate Ro, plot this value on graph for assumed porosity, draw a straight line from matrix through this new Ro point, shift this new Ro line parallel until you touch the edge of the data envelope, this is then the new Ro line with resulting new matrix travel time etc. See Figure 12-9 for an example

7. All zones with water saturations less than 100% will fall below the Ro line. Water saturation lines may now be put on graph. Move Sw scale on right hand side (just off graph) to left until top touches Ro line and bottom is on infinite resistivity line. Plot points represented on scale as 10, 20, 30, etc. Join these points with the matrix point. These straight lines represent water saturation lines. See Figure 12-10.

You can now find the water saturation for any plotted point.

Comments: If you use only one porosity log the matrix must have a constant composition. Rw must be constant. Data picks in zones too thin for the resistivity log (e.g. the induction) will move vertically on the graph and may make the determination of the Ro line difficult.

Figure 12-7

Figure 12-7 RPC (drawing of Ro line)

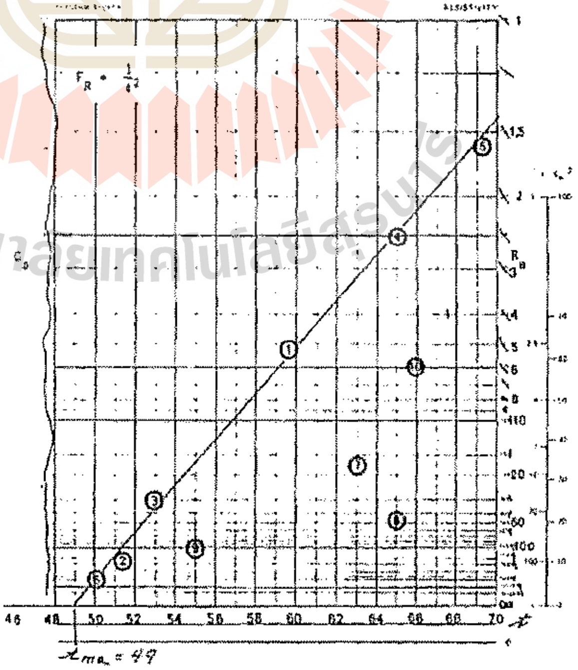
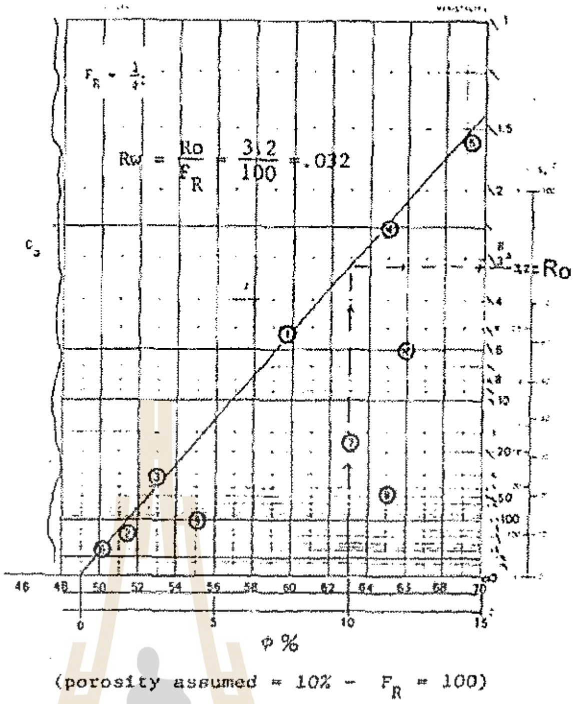
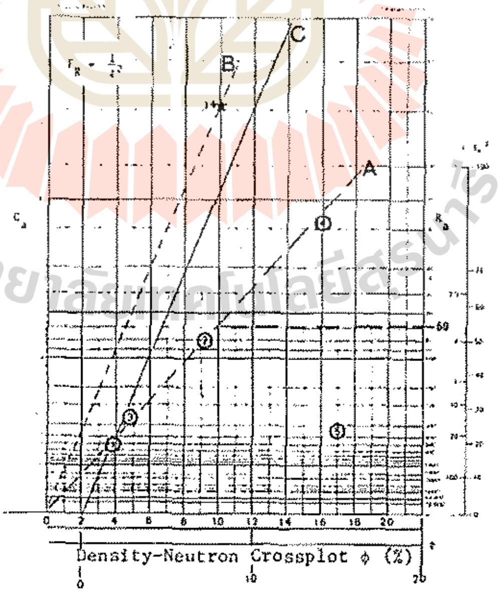


Figure 12-8



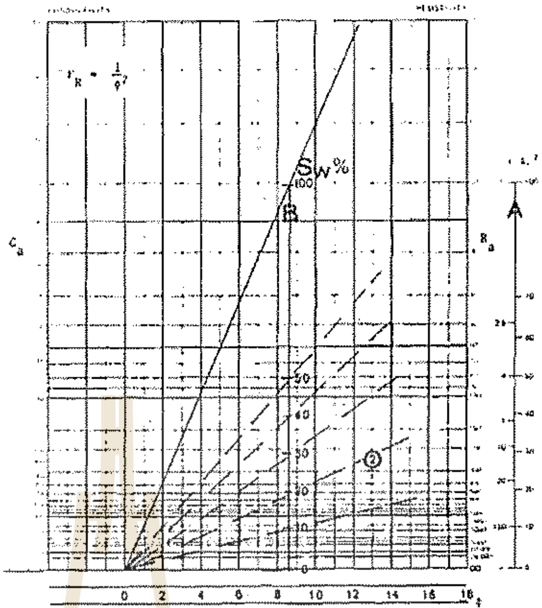
(porosity assumed = 10% - F_R = 100)

Figure 12-9



(A line drawn first. Rw from A =.69)
(B line drawn for correct Rw =.14 Ro=14)
(C line - B line shifted with same slope
C is proper Ro line--porosity scale adjusted)

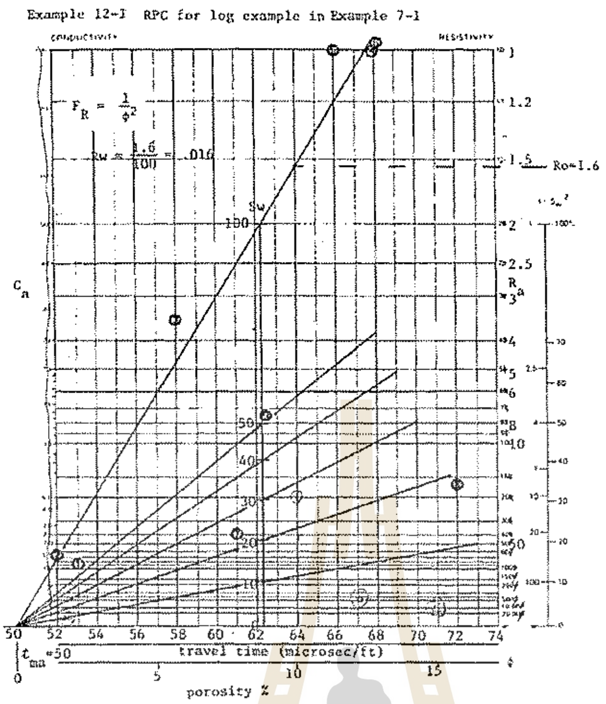
Figure 12-10



(Shift line A to B where Sw=100% touches Ro line and Sw =0% touches R = ∞)

Example 12-1 (again)

Figure 12-11 is a RPC for the log example in Example 7-1. The points are numbered from bottom to top in the example. Number 1 is the bottom most point. In drawing the Ro line point number 3 was ignored as it was too thin for the induction log to read properly. The matrix travel time was 50 microsec/ft. For an assumed porosity of 10% the Ro was 1.6 which results in an Rw of 0.016 (F_R = 100). This is close to the SP derived Rw. The water saturation lines were constructed and the results are close to that of the Rwa analysis because the matrix travel time is close.



Log-Log Resistivity-Porosity Crossplot

The log-log resistivity-porosity crossplot, hereafter called the log-log plot, takes advantage of the use of logarithmic multicycle graph paper and the following logic:

$$Rt = \frac{F_R R_w}{S_w^{\,n}}$$

becomes with the use of 1ogarithmS and assuming $F_R = \phi^{-m}$

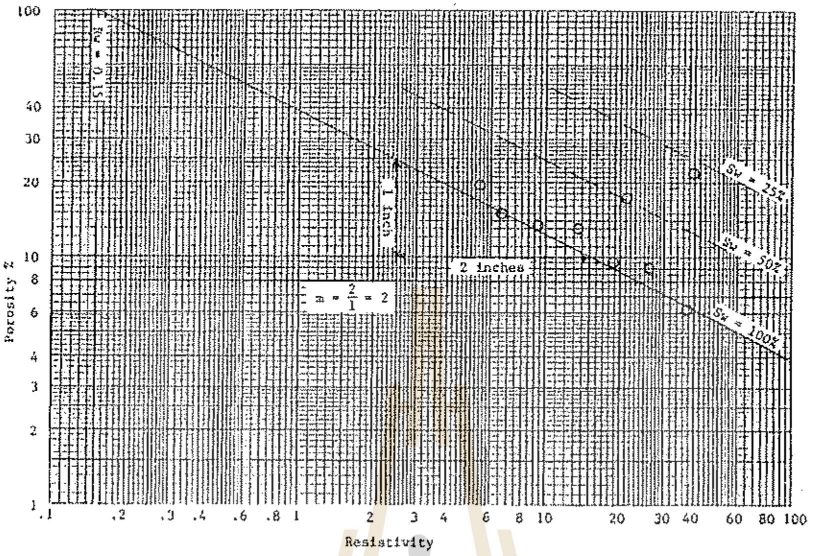
- $\log Rt = - m \log \phi + \log Rw - n \log Sw$ (12-5) where log is the logarithm to the base 10.
- Equation 12-5 becomes, for water saturations of 100%

  $\log Rt = - m \log \phi + \log Rw$ (12-6)

  which is the equation of a straight line on log-log paper. The line for Sw=100% passes through Rw at 100% porosity and the-slope of the Ro line is -m. Thus for d plot of resistivity (Rt) and porosity in a water bearing zone m can be determined if Rw is known.

Figure 12-11 shows an example of a log-log plot of Rt versus porosity. The Ro (Sw = 100%) line passes through Rw at 100% porosity and through the lower resistivity points on the graph. he slope as calculated is -m. Points with water saturations less than 100% will lie above the Ro line. If n (the water saturation exponent) is equal to m, as some analysts claim, the constant water saturation lines will be parallel to the Ro line. If n = 2, as is usually assumed, the slope of the water saturation lines will be 2. Example 12-2 shows the log from Example 7-1 on a log-log plot

Figure 12-11



Example 12-2

The logs inExample7-1 and used in Example 12-1 were crossplotted on loglog paper as shown in Example 12-2. The matrix travel time of 50 microsec/ft and the Rw = .016 obtained in Example 12-1 were used. Point 3 again was a maverick point, probably because it is too thin to have a good resistivity. The Sw lines were constructed with a slope of 2 (n=2). To determine the location of the Sw lines it should be remembered that:

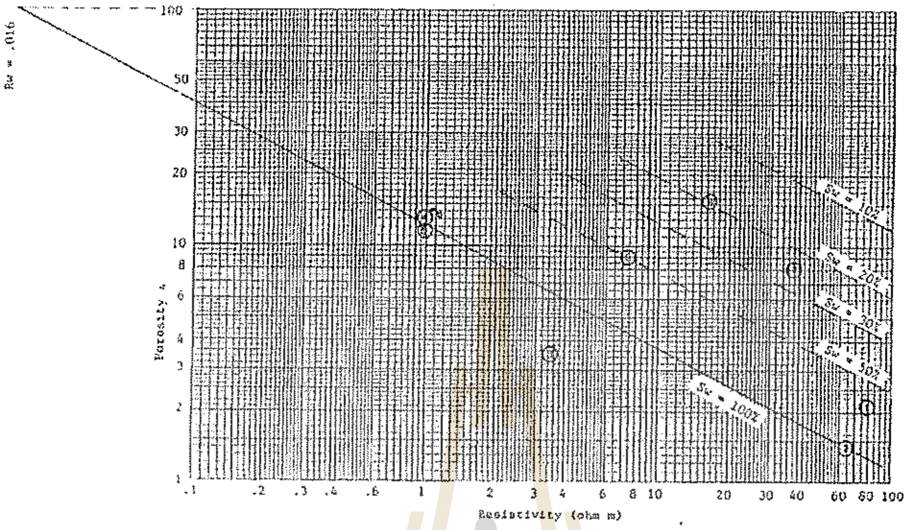
$$Rt = \frac{Ro}{Sw^2}$$

To find a point on the Sw lines assume some porosity like 12%. Ro from the Sw = 100% line is 1.0 ohm m for Example 12-2. For an Sw = 50% at the same 12% porosity

$$Rt = \frac{Ro}{Sw^2} = \frac{1.0}{.50^2} = 4 \text{ ohm m.}$$

In the same manner the Rt ' s for Sw's of 30, 20 and 10% for the same 12% porosity are: 11.1, 25 and 100 ohm m. To obtain another point on each of the lines (Sw) assume another porosity and go through the same routine. Since the Sw lines are straight lines just draw a line through the two points constructed for each Sw line and you have the crossplot constructed. On a log-log crossplot the low porosity points are very sensitive to the matrix travel time (or density). A small change in the matrix will shift the low porosity points up or down

Figure 12-12


Rw = .016
100
50
30
20
10
8
6
4
3
2
1
Porosity φ
.1
.2
.3
.4
.6
1
2
3
4
6
8
10
20
30
40
60
80
100
Resistivity (ohm m)
Sw = 10%
Sw = 20%
Sw = 30%
Sw = 50%
Sw = 100%

Chapter 13

SHALY SANDSTONE INTERPRETATION

The occurrence of shale (clay) materials in reservoirs rocks (whether they are sandstones, limestones or dolomites) can result in erroneous values of water saturation and porosity as calculated from well logs. Shaly sandstones are just more important problem

Effective Shale

Effective shales, those rocks referred to in the literature as shales are usually predominately the multilayer clays such as smectites (montmorillonite, bentonite, etc) and illite. They have significant CEC (cation exchange capacities).

Non Effective Shales

The non effective shales are the kaolinites and chlorites which have essentially zero CEC. The conventional shaly sandstone interpretation deals with effective shales.

The problems encountered with shaly sandstones are several. The porosity logs are all affected to some degree. The resistivity of the formation is affected by the effective shales and probably most significantly, the contrast between oil (or gas) and water bearing zones is reduced.

As the formations become very shaly it is difficult (often times impossible) to determine if the zones are productive. This is primarily due to the shale influence on the permeability:

Shaly sandstone corrections all tend to reduce the water saturation you would calculate if the shale is ignored in the calculation. This can be a problem in that if you over estimate the shale content to a large degree you can change the water saturation calculated enough to make a water bearing zone look like a hydrocarbon bearing zone.

Shale Influences On Logs

- In this section I will discuss the influences of shales on the logs commonly used in shaly sandstone interpretation. I will first discuss effective shales and then noneffective shales.

Effective Shale Influences On Logs

- Resistivity

  Effective shales have relatively low resistivitie and thus lower the resistivity of reservoir rocks if they are hydrocarbon bearing. Patchett determined the resistivity of montmorillonite to be about 1.5 - 0.7 ohm m @ 77° F when the shale had a porosity of under 20%. Illite using the same approach has a resistivity of about 1 – 3 ohm m @ 77 ° F. The resistivity of an effective shale is controlled by porosity, water salinity and of course temperature.

In a water bearing zone shale can reduce or increase the resistivity depending upon the formation water salinity (Rw) and porosity. Effective shales with higher CEC of course have greater influence in changing the resistivity as the formation becomes shalier. Shaliness in this discussion should be considered to be a product of the volume of shale (Vsh) and the resistivity (or CEC) of the shale involved. In short effective shales influence the water saturation calculated and result in higher water saturations.

- SP

  The SP "sees" effective shales in that the SP amplitude is reduced. The Rw calculated from an SP in a shaly sand is thus higher than it would be from the equivalent clean sand. In hydrocarbon zones the reduction in the SP would increase due to Hydrocarbon Suppression. Thus the SP sees the maximum amount of shale present.

- Gamma Ray

  An increase in effective shale will result in an increase in the formation radioactivity. Be careful of radioactive zones that are not shaly. Again the reduction is a production of Vsh and CEC.

- Density Log

  The influence of shale on the density log can be solely blamed on the density of the shale. Montmorillonite has a density of 2.33 gm/cc. Shale will thus look like higher porosity. For example a 20% porosity sand to which is added 20% montmorillonite results in a calculated porosity of 23%. If on the other hand your clay is illite with a matrix density of 2.76 gm/cc the calculated porosity would be 19%. Thus in this case the type of clay is the influence.

- Neutron Log

  The reasons for the neutron log looking like high porosity is not completely clear to the author but we know that the effective shales look like high porosity. Montmorillonite usually shows up as porosities greater than 40%. Illite shows up as porosities greater than 30%.

Non-effective Shale Influences On Logs

- Resistivity

  Non-effective shales such as kaolinite have very high resistivities just like sand grains. This is due to their very low CEC. The higher the CEC the lower the resistivity and vice versa. So on a resistivity log you do not notice kaolinite as a direct influence. It only shows up as a decrease in resistivity because of the increase in water saturation due to the finer grained matrix. In short kaolinite looks like a fine grainedd sand.

- SP

  The noneffective shales (chlorite and kaolinite) have no influence on the SP. They look like sand grains to the SP because to behave like a shale they must lpve significant CEC.
- Gamma Ray

  The noneffective shales look like clean sand on the gamma ray because of the lack of CEC and potassium.

- Density Log

  The effect of noneffective clays on the density log is solely a function of the clay density. Kaolinite with a 2.69 gm/cc density cannot been seen when it coexists with sand. At 100% kaolinite the change in porosity is only 2% porosity.

  Chlorite with its 2.77 gm/cc density tends to make the porosity look a little lower than if it were not there. If there were 100% chlorite the porosity calculated assuming the rock were a sand would be low by 7% porosity. This chlorite effect becomes significant when the reservoir porosities are low (around 9%).

- Neutron Log

  The neutron log sees both of our noneffective shales as having apparent porosities of over 40%. This is apparently due to the large amount of water associated with these rhales. Presently the neutron log is the only way we can detect kaolinite from sand.

- Acoustic Log

  The acoustic log should see both effective and noneffective shales the same. If the clays (either effective or noneffective) are a dispersed type (in the pores only) the acoustic log will not see them. If the clays are structural or laminated the acoustic log will indicate a higher porosity than the true porosity.

Quicky Shaly Sand Method

A study of shaly sandstone interpretations show that the reduction in water saturation is a function of the volume of shale present. In the Quicky technique the volume of shale is estimated (in the same manner as will be discussed later in this chapter) and the water saturation is reduced proportionally based on the following estimates:

Volume of Shale (Vsh)	Water Saturation Reduction
15%	5%
30%	10%
45%	15%

- It should be recognized that if you have a shaly sandstone your water saturations should be greater than about 30+%.

Simplified Shaly Sand Interpretation

Simplified Shaly Sandstone Interpretation recognizes the relative response of the resistivity and porosity tools and uses the appropriate tools with no shale corrections applied directly.

Resistivity is reduced by the existence of shale. Acoustic and neutron logs see shale as having high porosity.

- The use of the resistivity and acoustic (or neutron if you exclude the Schlumberger CNL) will result in water saturations that are, close to the actual water saturations you would get if you went through all the corrections for shale to determine water saturation.
- The logs tend to self compensate for the shale and the water saturation (and Rwa) are close to correct. The porosities from the neutron and acoustic logs are typically too high.

- In a shaly sandstone, the use without corrections, of the density log and resistivity log result in water saturations that are too high(Rwa is too low). The porosities are about right.

- The interpretation scheme is this. Calculate the real porosity from the density log with no shale correction. Use the acoustic (or neutron -- not Schlumbergers CNL) porosity to calculate water saturation using the clean sand relations already introduced. If you must run an Rwa analysis to obtain Rw use the acoustic (or neutron) with the resistivity log. (If you have a Schlurnberger CNL --average the Schlumberger CNL and density porosities and use these in place of the acoustic log porosity).

Complete Shaly Sandstone Interpretation

Shaly sandstone interpretation requires that all log data be corrected for shale effects. To correct log data the volume of shale and the respective property of the shale must be know. For example, to correct the density log for shale you must know the volume of shale and the density of the shale. All data should be corrected as to correct only part of the data, e.g. resistivity, will result in poorer answers than . if none of the data are corrected.

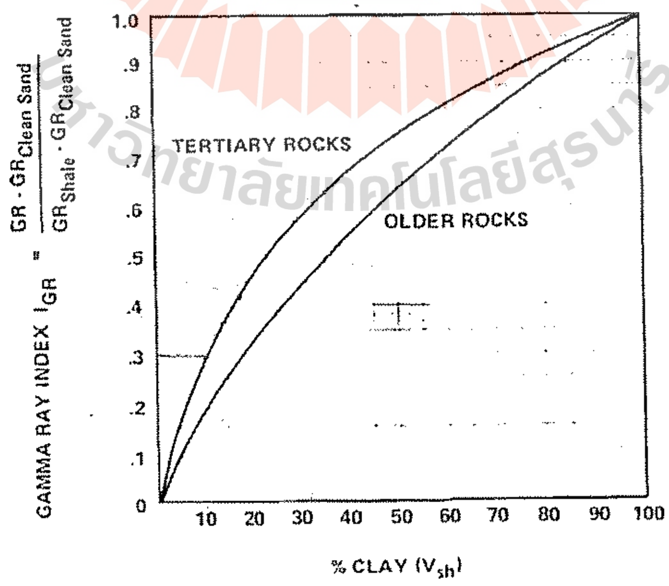
Shale Volume Determination

Shale volume may be determined easily by one of three-ways. These are the gamma ray, the SP and the density-neutron crossplot. It is common to do all three and choose the lowest shale volume of the three. This reduces the chances of error due to noneffective shales, radioactive sandstones or other type problems. Noneffective shales should not be considered as they do not influence the resistivity values and we only wish to correct for the shales that effect the resistivity.

Gamma Ray Shale Volume

A relationship between shale volume and the relative gamma ray deflection (gamma ray index) is shown in Figure 13-1. The gamma ray index is a mathematical means of-normalizing the gamma ray deflection between a clean sand (gamma ray index =0) and a shale (gamma ray index = 1). This prevents units and calibration problems

Figure 13-1



To use Figure 13-1 the analyst must first establish a shale line for the gamma ray log. Sometimes this is easy and other times it is not. An inconsistant shale baseline indicates that the shales are either not clean or that the organic material or clay type is changing. Any of these cases may result in a poor interpretation. A clean sand line must also be established for the gamma ray log. This can usually be done anywhere in the well bore where the bit size is the same as the zone to be interpreted.

If no clean sandstones are available, in many places a clean coal is a good substitute. Clean limestones, dolomites, anhydrites o r salts may not be used as correlations such as Figure 13-1 are based on clean sandstones.

SP Shale Volume

The volume of shale (maximum) is obtained from the SP using:

$$V_{sh} = \frac{SSP - SP}{SSP} \qquad \text{Eq 13-1}$$

where SSP is the SP amplitude in a clean sand or the calculated SP from the Rw,

SP is the SP actual from the zone of interest.

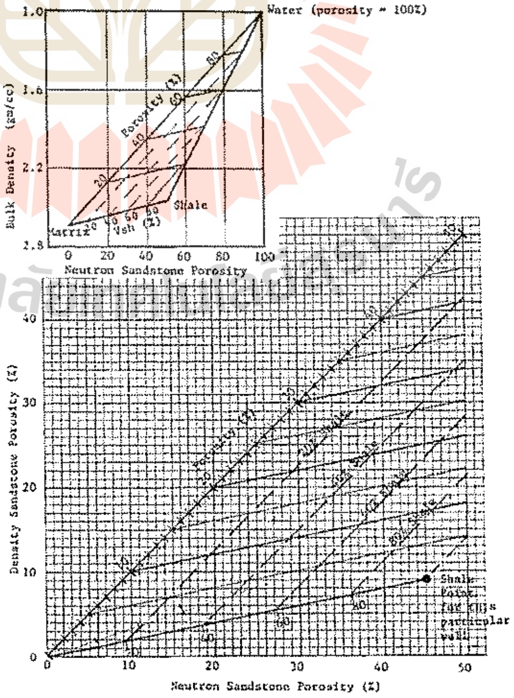
Vsh from the SP is considered the maximum Vsh as in hydrocarbon zones the SP is usually reduced over and above the shale reduction by the hydrocarbon suppression.

Density-Neutron Crossplot for shale Determination

The density and neutron log can be crossplotted to determine porosity and shale content is the zone is composed of only effective shales and sandstone. If gas is present the shale volume will be too low. The existence of noneffective shales or other reservoir rocks will result in too high a calculated effective shale volume. Porosity determination will also suffer a decrease in accuracy.

- Figure 13-2 shows a density-neutron crossplot for shale content.
- Any point plotted on the crossplot (based on data from both the density and neutron logs) will show the shale corrected porosity and the volume of shale.

Figure 13-2



- This crossplot is the simultaneous solution of the two applicable equations :

$\phi = \phi_{\text{density}} - V_{\text{sh}}\ \phi_{\text{sh density}}$ Eq 13-2

and $\phi = \phi_{\text{neutron}} - V_{\text{sh}}\ \phi_{\text{sh neutron}}$ Eq 13-3

where ϕ is the shale corrected porosity

ϕ_{density} is the porosity from the density log in proper lithology 'density

ϕ_{neutron} is the porosity from the neutron log in proper lithology neutron

$\phi_{\text{sh density}}$ is the porosity from the density log in the shale

$\phi_{\text{sh neutron}}$ is the porosity from the neutron log in the shale

V_{sh} is the volume of shale.

The only unknowns are 4 and Vsh. The other values are obtained from the logs.

Porosity Log Correction for Shale Content

All the porosity log shale corrections are graphically and mathematically the same. As in the previous section the correction involves the volume of shale and a shale value from the log. The latter is again a value obtained from the log in a clean shale. Equations are 13-2 and 13-3 for the density and neutron logs and an equivalent equation for the acoustic log.

- Figure 13-3 (which is the same as Figure 8-4) may be used to correct the density log for shale content of the formation.
- Figures 13-4 and 13-5 are used in the same manner.

Figure 13-4

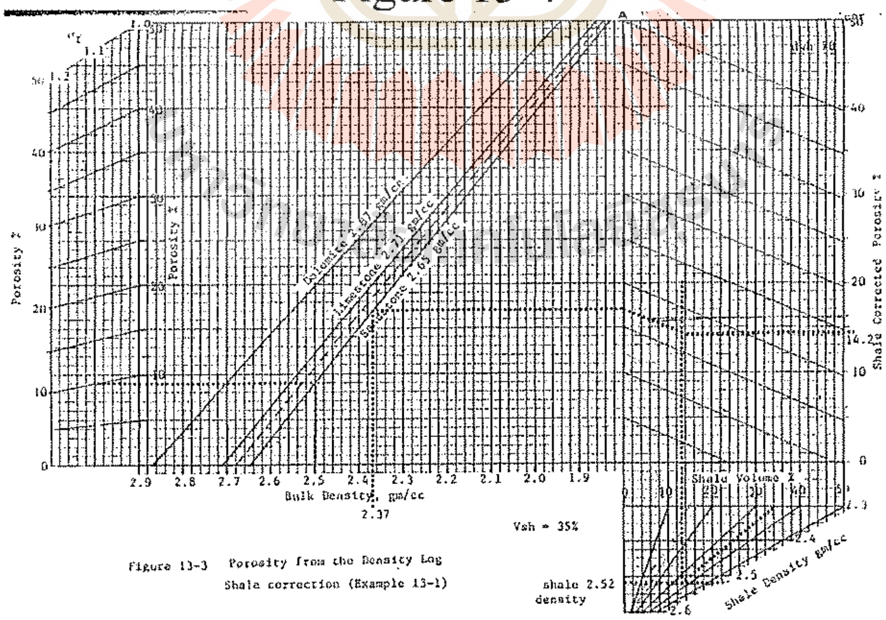


Figure 13-3 Porosity from the Density Log
Shale correction (Example 13-1)

Figure 13-5

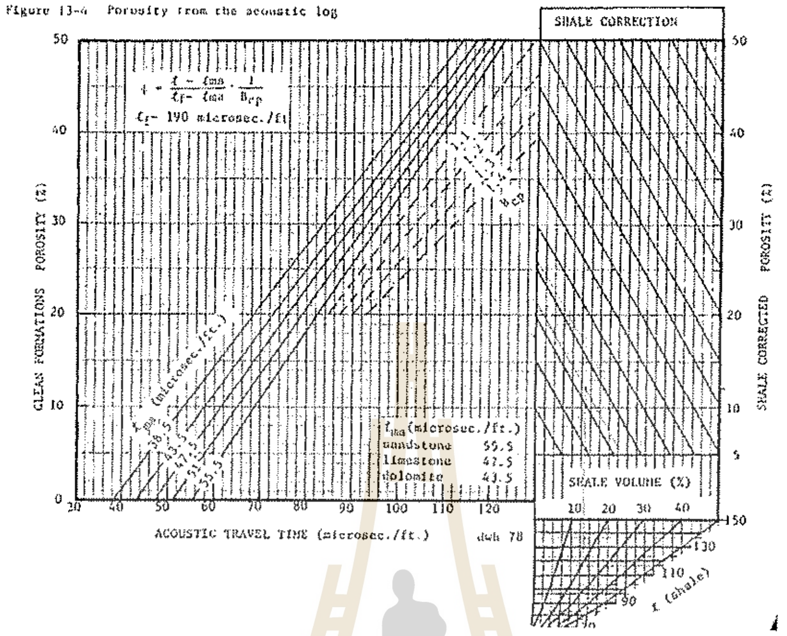
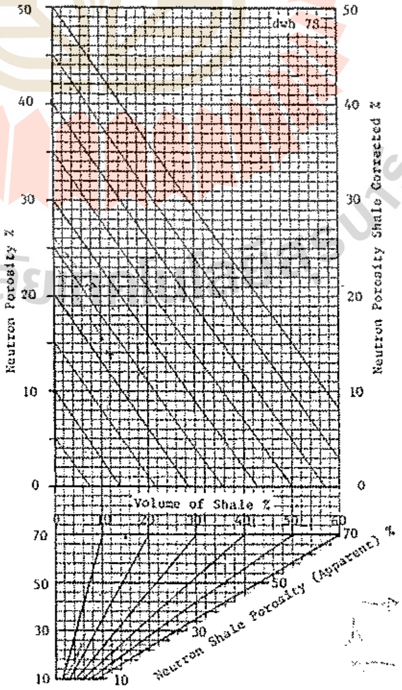


Figure 13-6



A Complete Shaly sandstone Interpretation

Fertl and Hammack suggested the following shaly sand model after a review of many of the models suggested in the literature:

$$S_W = \sqrt{\frac{F_R R_W}{R_t}} - \frac{V_{sh} R_W}{0.4 R_{sh} \phi} \qquad \text{Eq 13-4}$$

where R_{sh} is the shale resistivity (usually from a close shale bed)

and ϕ used is the porosity corrected for shale influences

Equation 13-4 gives about the same results as the most popular Simandoux equation but is simplier to use in that it is not a quadratic equation. The two equations deviate at low shale volumes but I again suggest at for shale volumes less than 15% a clean sand interpretation is more than adequate.

The first part of the equation 13-4 can be solved using Figure 13-6 (the same as Figure 2-6) and the second- part of the equation 13-4 can be solved using Figure 13-7. The final water saturation is the water saturation from Figure 13-6 reduced by the water saturation from Figure 13-7.

Figure 13-6

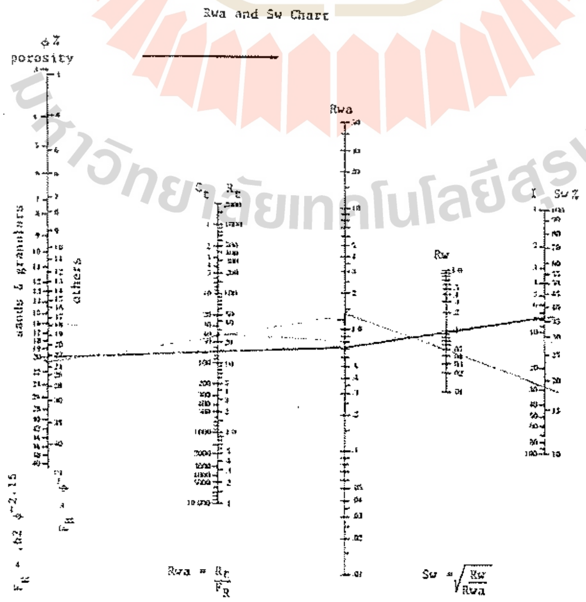
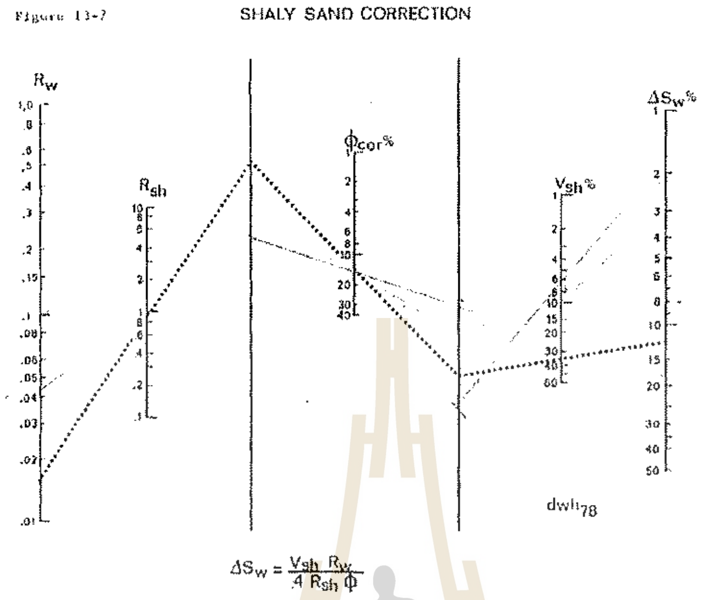


Figure 13-7

SHALY SAND CORRECTION



$$\Delta S_w = \frac{V_{sh}\ R_w}{.4\ R_{sh}\ \phi}$$

ALGORITHN 3 Shaly Sandstone Interpretation

1. Correlate the logs.
2. Do clean sand analysis as in Algorithm 2
3. Establish clean and shale line for gamma ray, SP and porosity logs if crossplot to be done.
4. Establish shale values for resistivity log
5. Determine volume of shale from:

	Figure #	Equation #
Gamma ray	13-1	
SP		13-1
Porosity log Crossplot	13-2	13-2,3

ALGORITHN 3 Shaly Sandstone Interpretation

6. Use the lowest Vsh from step 4.
7. Correct the porosity log for shale effects

	Figure #	Equation #
density	13-3	13-2
neutron	13-5	13-3
acoustic (if your desperate)	13-4	

If you crossplotted density - neutron and this was the shale volume used read porosity off of crossplot-----otherwise use density porosity.

ALGORITHN 3 Shaly Sandstone Interpretation

8. Determine Rw from nearby clean sand or catalog.
9. Calculate Sw

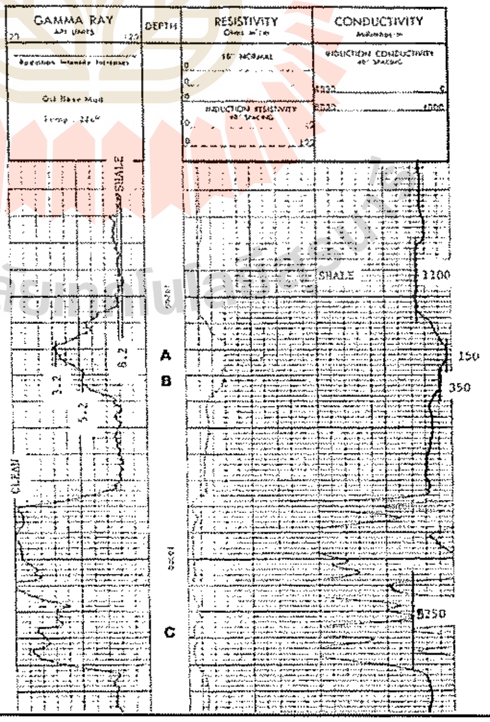
Figure#	Equation#
13-6	13-4
13-7	

10. Compare Sw from step 2 to that of step 9. Step 9 should be lower.

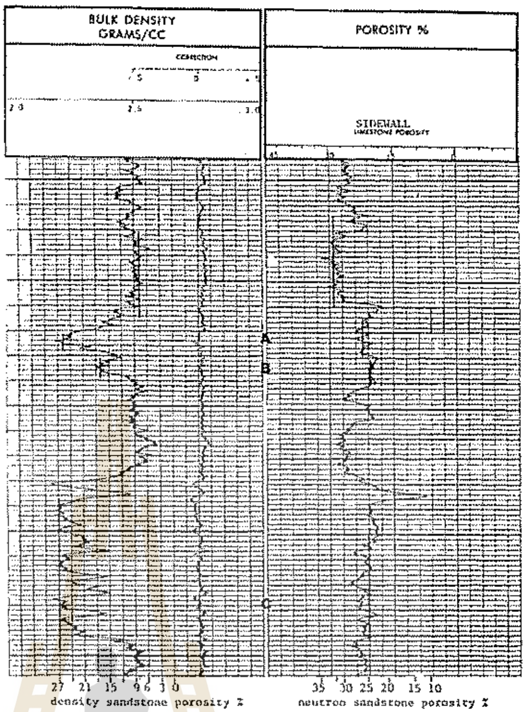
Example 13-1 Shaly Sandstone Interpretation

General: The logs (example logs 13-la, b and c) are over Tertiary sandstones in the Louisiana Gulf Coast. The well was drilled with an oil base mud and thus there is no short normal or SP. The logs are from Dresser Atlas and the neutron log is a sidewall neutron. At the bottom of both the density and neutron a sandstone porosity scale has been put on to ease the calculations.

Example log 13-1a



Example log
13-1b & c
b – Left
c - Right



Simplified Shaly Sand Interpretation

In this technique only the raw data are used with the water saturation being calculated from the induction and neutron and the porosity being determined from the density log.

Rw We will determine Rw from the clean sandstones from 10300 to 10340. The porosity from the density and neutron over this interval are 27% and 25% respecively. We will assume the porosity is 26%. The conductivity of the induction log is about 5250 millimhos/m which is 0.19 ohm m.

We will interpret two zones:

A at 10218 - 10224

(induction log depths) B at 10228 - 10234

Data Read from the logs

conductivity n$^{R_w = \frac{R_t}{F_R} = \frac{.19}{11.2} = .017\ \text{ohm m}}$ density porosity

A	150 (R=6.7)	26%	26%
B	350 (R=2.86)	24%	17%

Sw = 17% for zone A and = 28% for zone B (using induction & neutron)

Complete Shaly Sand Interpretation

We will use the Rw from above of 0.017 ohm m. We will also interpret the same zones and thus can use the same log readings.

1. The density and neutron logs are about two feet deeper than the induction log.
2. The same zones A and B will be used.

3. A R = 6.7 Neutron SS. Porosity = 26%
Den. SS. Por. = 26%
B R = 2.86 Neutron SS. Porosity = 24
Den. SS. Por. = 17

As both porosities in zone A are the same this zone will appear to be clean. The cleaner zone at 10300 showed the density 2 porosity units (pu) greater than the neutron which indicates one of the logs is a little off of calibration. In a clean -zone the two porosities should agree while in a shaly zone the density porosity should be lower.

4. At 10180-10200 the shale values are:
Rsh = 0.91 (C = 1100),
Density = 2.52 gm/cc (ϕ_{ss}= 8%)
Neutron LS. porosity = 234 ((ϕ_{ss} = 32%)

5. The gamma ray shale base line is at 8.2 divisions from the left side of the log. The clean sand line is at 0 divisions. GR for A is 3.2 divisions, for B is 5.2 divisions.

6. We will interpret the porosity logs separately and afterwards will go back and use both logs together.

7 . From Figure 13-1 I_{GR}= A 3.2/8.2 = -39
B 5.2/8.2 = .63

Vsh = A 15%
B 35%

Porosities corrected for shale (neutron Fig.13-5, density Fig. 13-4

A neutron = 21% density = 25%
B neutron = 13% density = 14%

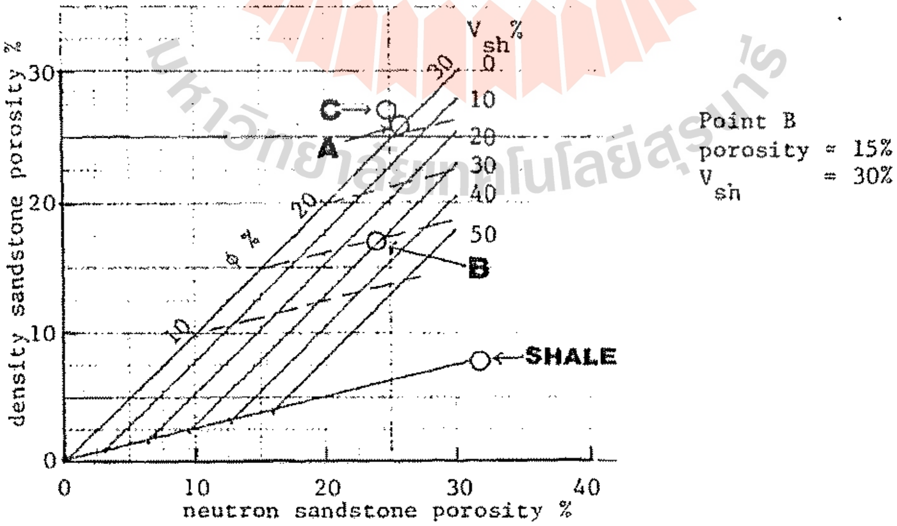
9. The results of the water saturation calculations will be listed as Sw = Sw (Fig. 13-6) - ΔSw (Fig. 13-7)

	Density Log	Neurron Log
A	14.8% = 17.6-2.8	18%=21.3-3.3
B	37.5% = 49.5-12	41.8%=54.4-12.6

The water saturations are close from both the density and neutron log calculations. In zone B which is very shaly there is a significant difference between the simplified and more complete approach.

Under the number 8 is a crossplot of the density and neutron on a sandstone porosity basis. The disagreement in porosities as noted in step 3 causes the shale volumes and porosities to differ from those using only one porosity log. The agreement is still acceptable.

8. Neutron-density crossplot for example 13-1



Shaly Formations

Shales are one of the most important common constituents of rocks in log analysis. Aside from their effects on porosity and permeability, this importance stems from their electrical properties, which have a great influence on the determination of fluid saturations.

Archie's water saturation equation relating formation resistivity to water saturation, assumes formation water to be the only electrically conductive material in the formation. The presence of another conductive material (e.g. Shale) requires changes to either Archie's equation, or the model relating resistivity to water saturation.

As well, the presence of clay in the formation complicates the concept of porosity. The water associated with the clays can represent a very significant amount of porosity. However, this porosity is not available as a potential reservoir for hydrocarbons. To this point, we have dealt with tool responses from our porosity devices that yield total porosity ϕ_T. At this time we have to introduce a new term, effective porosity, ϕ_e, which is that portion of the formation porosity available to contain and produce fluids.

The presence of shale in formations generally affects the response of the logging devices. In our discussions we usually speak of shaly sands, however the presence of shale in carbonates can often be treated in a similar manner.

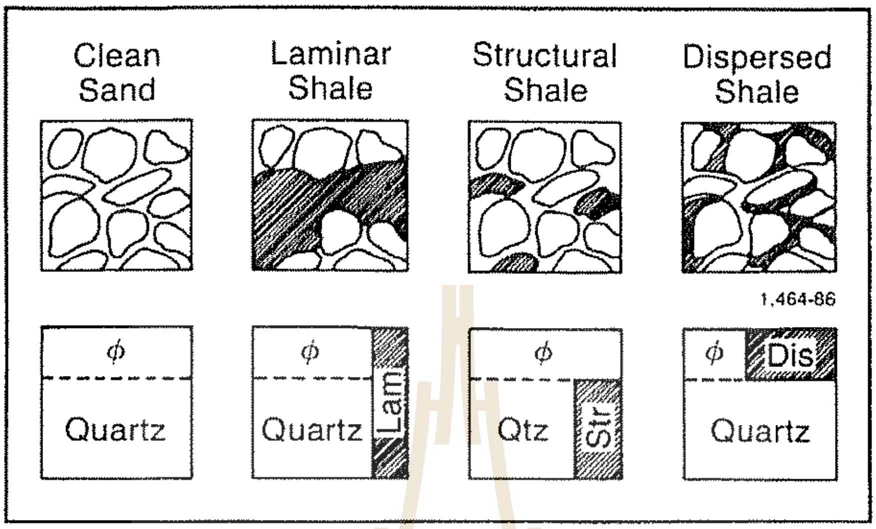
As briefly mentioned before, we categorize the distribution of shaly material in formations in three possible ways (See Figure E1):

1. Laminar Shale: occurs when shale exist in the form of laminae or thin layers between thin layers of sand. The shale streaks do not actually influence the effective porosity of the sand layers in the formation; however, as the bulk volume of shale increases, the overall formation porosity decreases. The presence of the shale may have considerable influence on the logging tool responses.

2. Structural Shale: is defined as the type of shale that exists as grains or nodules in the formation matrix. It is considered to have properties similar to laminar shale.

3. Dispersed Shale: occurs when the shaly material is dispersed through the sand where it occupies part of the intergranular space. This type of dispersed shale reduces the pore space available for fluid accumulation and also reduces formation permeability.

Figure E1



When shales consist of wet clay and silt, the bulk volume fractions may be expressed as:

$$V_{sh} = V_{silt} + V_{clay}$$

Another commonly used expression is Silt Index (I_{silt}) where:

$$I_{silt} = V_{silt}/V_{sh}$$

also

$$V_{clay} = V_{sh}\,(1-I_{silt})$$

EVALUATION OF SHALE VOLUME (V_{SH})

Basic methods of shale (clay) volume calculation use the following indicators:

- Gamma Ray
- NGT
- Spontaneous Potential
- ϕ_N vs ϕ_D Cross Plot
  ϕ_N vs ϕ_S Cross Plot

Gamma Ray

If the radioactivity of the shale content is constant, and if no other mineral in the formation is radioactive, the Gamma Ray reading may be expressed as a function of clay content. The formula can be written:

$$V_{sh} = \frac{GR_{(zone)} - GR_{(clean)}}{GR_{(shale)} - GR_{(clean)}}$$

NGT-Natural Gamma Ray Tool

By using only thorium and potassium components of the Gamma-Ray signal, the radioactive uranium element not associated with shales will be eliminated. The same method is then applied to the NGT as that for a regular Gamma-Ray.

$$*V_{sh} = \frac{CGR_{(zone)} - CGR_{(clean)}}{CGR_{(shale)} - CGR_{(clean)}}$$

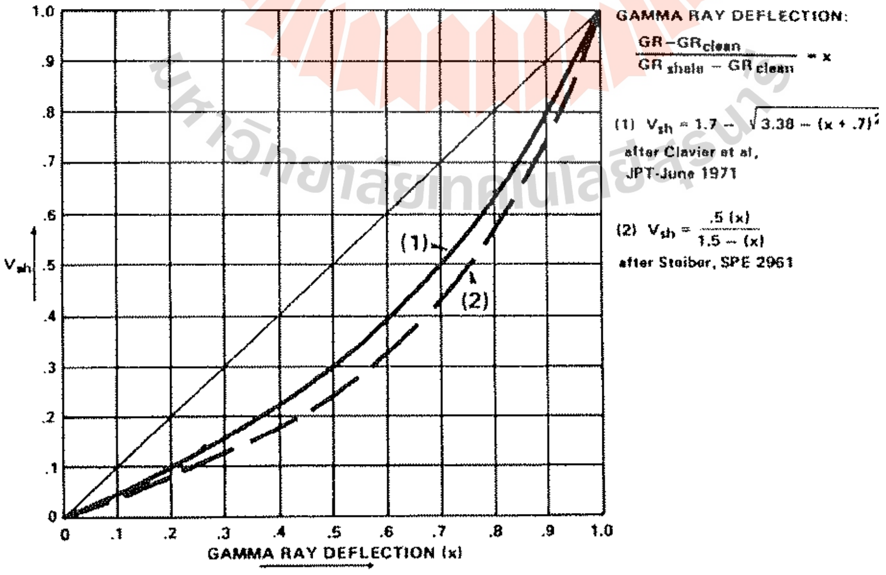
Some typical values for formations are:

- Clean Sandstone - GR = 15-30 A.P.I.
- Clean Carbonates -
- Dolomite - GR = 10-20 A.P.I.
- Limestone - GR = 8-15 A.P.I.
- Shallow Cretaceous Shale - GR = 100-140 A.P.I.

Chart Calculation

The linear equations in (a) and (b) are good first estimates of shale volume. Chart Vsh-1 (Figure E2) allows us to correct for the nonlinear relationship between Vsh and the GR deflection denoted as 'X'. Line (1) is generally used yielding good interpretation results.

Figure E2



Spontaneous Potential (SP)

In water bearing sands of low to moderate resistivity the ratio of SSP (static S.P.) to PSP (pseudostatic S.P.) is indicative of clay content, where:

$$\alpha = PSP/SSP \text{ and } Vsh = 1 - \alpha$$

If the hydrocarbon is present α will be decreased due to the further reduction of PSP by the hydrocarbon. Also, when using this method to calculate Vsh, suitable bed thickness must be present to obtain PSP and SSP.

Shaly Sand Porosity

- CALCULATING ϕ_T, ϕ_e, AND Sw IN SHALY SANDS by GRAPHICAL CALCULATION

ϕ_T and ϕ_e can be found graphically on a ϕ_N - ϕ_D crossplot; the steps are outlined below. This method will help identify gas bearing zones with resistivity input (See Figure F4).

1. Calculate Vsh from Gamma Ray opposite zone of interest.
2. Determine ϕ_D shale and ϕ_N shale from average responses above the zone of interest.
3. Plot ϕ_D shale and ϕ_N shale on crossplot (Shale point).
4. Draw shale line from shale point to clean matrix line at zero porosity.
5. Plot ϕ_D and ϕ_N for zone of interest (point A).

6. Move the shaly sand point parallel to the shale line a distance proportional to Vsh (Point B).

7. If the corrected point falls above the clean matrix line, gas is present.

8. Gas correct point (if necessary) by moving to the clean matrix in the direction of the approximate gas correction arrows (Point E).

9. After shale and gas corrections have been made, you have graphically calculated ϕ_e (Point E).

10. If a gas correction of total porosity is required, shifting the original point in an identical manner will produce ϕ_T (Point C).

11. Using ϕ_e, therefore

$$S_{we}^2 = \frac{FR_w}{R_t}$$

EXAMPLE CALCULATION

- Using the log below for the zone 444m to 447m calculate:
  1) Vsh
  2) ϕ_T
  3) F e

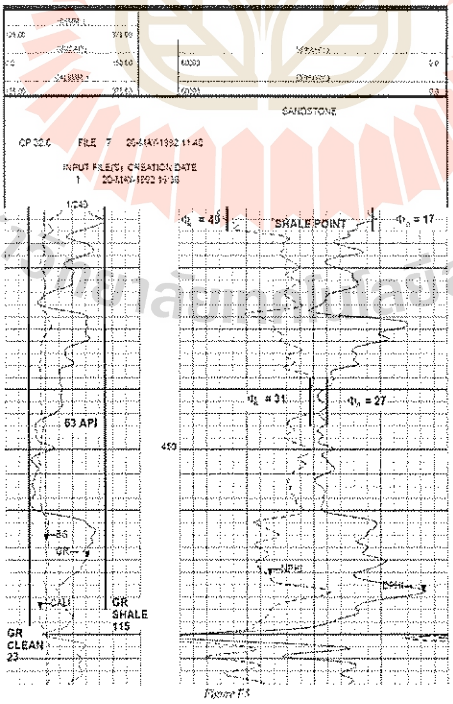
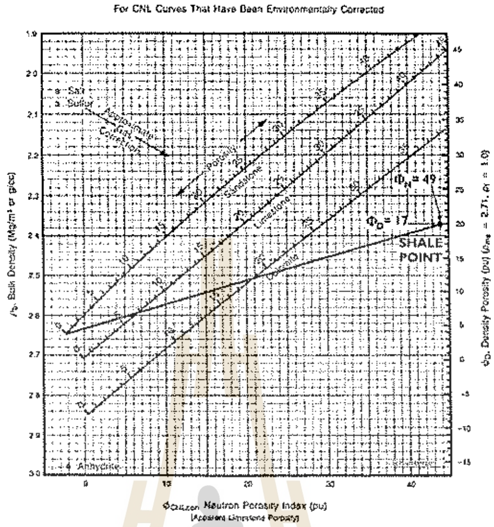


Figure F5

EXAMPLE CALCULATION (continued):

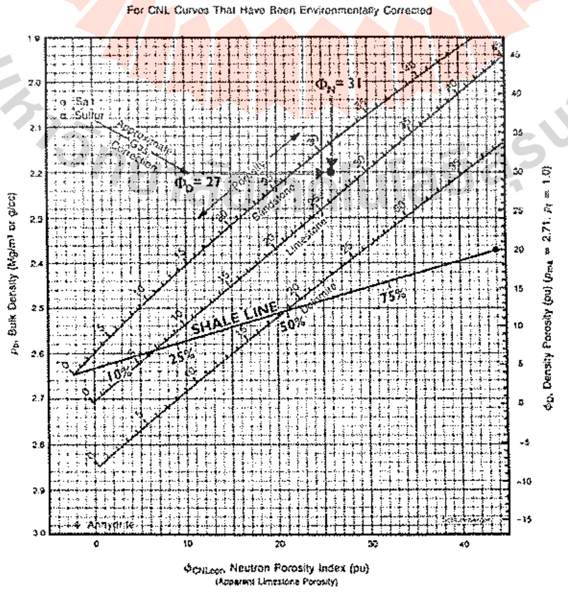
1. Calculate V_{sh}. $X = \dfrac{GR - GRCL}{GRSH - GRCL} = \dfrac{63 - 23}{115 - 23} = .435$ Using V_{sh-1}: $V_{sh} = 25\%$

2. Plot the shale point.

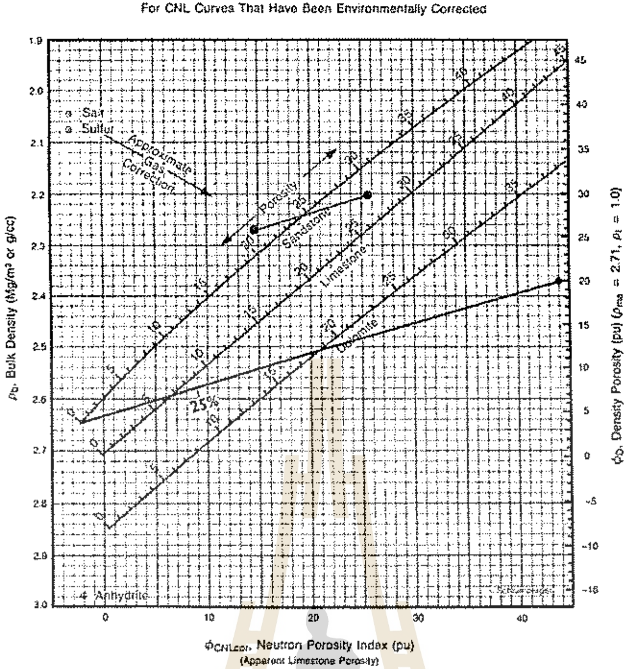


3. Plot the shale-sand point.

4. Draw the shale line.

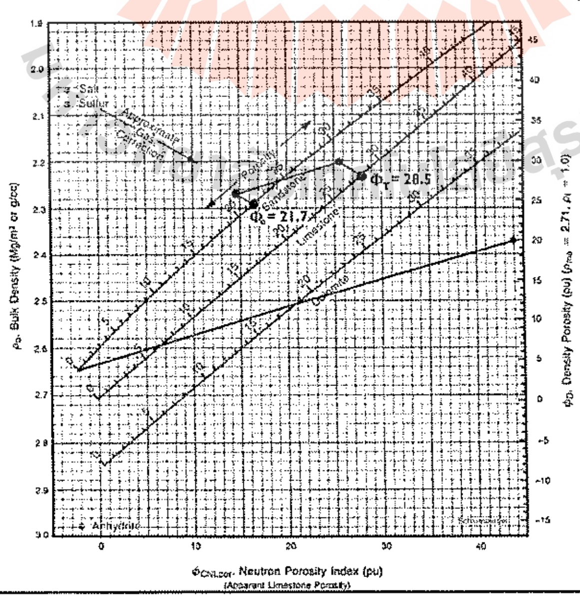


5. Make the shale correction.



6. Make the gas correction and read ϕ_e.

7. Gas correct the log value and read ϕ_T.



Chapter 15

ABNORMAL PRESSURE DETECTION WITH WELL LOGS

Abnormal pressures, sometimes called surpressures, are those formation pressures which exceed the normal .433 to .465 psi/ft gradients. These abnormal pressures are important to drilling engineers and evaluation technologists. The drilling engineer must combat high formation (pore) pressures with high mud pressures (high mud densities) or risk a blowout. The evaluationist may see severely high pressures as an indication of a very limited reservoir volume.

Normal formation pressures are those which are the equivalent of a column of water of the appropriate salinity (.433 psi/ft in the Rocky Mountains and .465 psi/ft in the Gulf Coast) equal to the depth of the formation in question.

Pressures greater than this are abnormal while those less are subnormal. The gross overburden pressure is the weight of all rocks and fluids. This is usually about 1 psi/ft of burial. The net overburden pressure is the gross overburden pressure less the fluid (pore) pressure in the rock. The net overburden pressure is reduced when the fluid (pore) pressure is greater than normal. Subnormal pressures usually result from lower than normal surface ground waters or depletion of reservoir fluids by production.

Origins of Abnormal Pressure

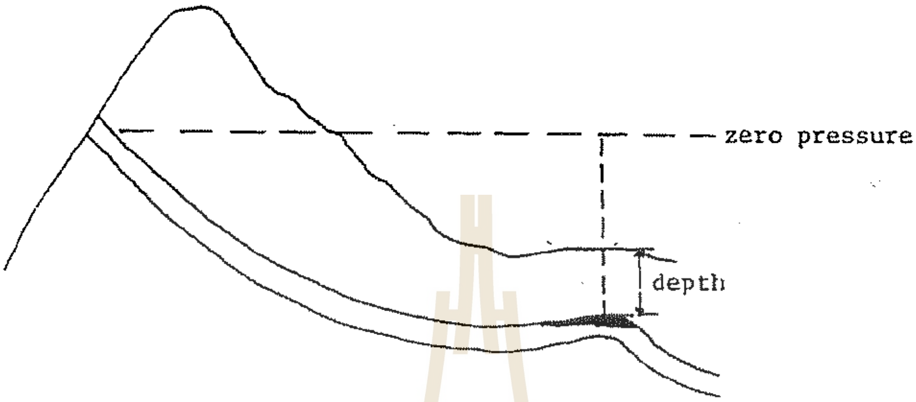
Four common origins of abnormal pressure are presented here. Only one of these types may be detected with well logs before the abnormally pressured permeable bed is penetrated by the drill bit. Abnormally pressured impermeable shales will cause drilling problems but will not result in a blowout.

Artesian

The Artesian type of abnormal pressure is typical of some Rocky Mountain reservoirs. As shown in Figure 1 the permeable bed outcrops at some higher elevation and is fed water. The pressure head is created by the structural relief. As in all artesian wells, the pressure is sufficient to raise the water well over the surface level.

Figure 15-1

A Schematic of an Artesian Overpressured Zone



Burial and Excavation

In this model the formation is buried and has normal pressure. The depth of the reservoir is then reduced by erosion, or by lifting, by faulting or some other tectonics. The pressure in the reservoir remains the same but the depth from the surface has been reduced. The pressure gradient is now higher than normal. This type and the Artesian type of abnormal pressures are not detectable using well logs or other geophysical measurements.

Figure 15-2

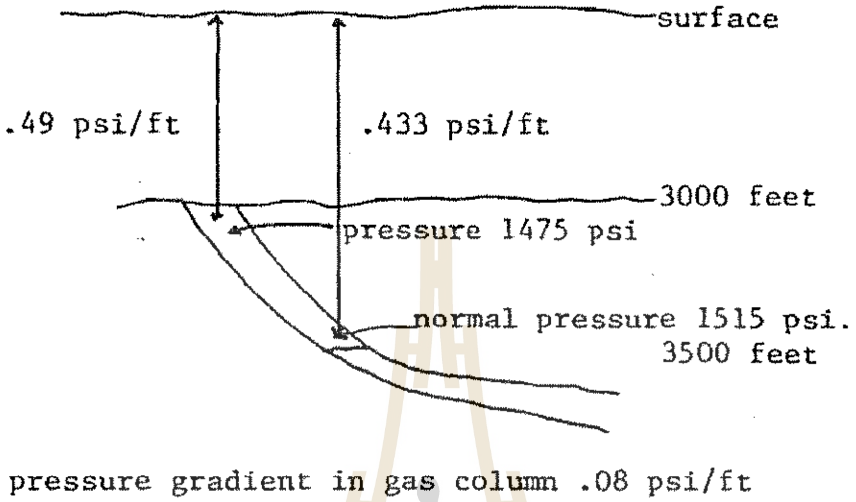
A Schematic Burial and Excavation Overpressured Model

Large Structural Relief of a Gas Reservoir

If a gas-bearing reservoir, as shown in Figure 15-3, has a normally pressured aquifer the top of the reservoir will be abnormally pressured. Gas because of its very low density has a very low pressure gradient. If the water zone is normally pressured it will maintain the pressure at the gas/water contact. The pressure at the top of the gas structure is this pressure minus the gradient of the gas. As shown in Figure 15-3 the pressure at the top of the structure is abnormal.

Figure 15-3

Overpressure Due to Structural Relief of a Gas Reservoir



Excessively Rapid Deposition

If during the rapid deposition of sediments a sand lense is sealed so that the liquids cannot migrate to the surface the zone becomes overpressured. The seal stops or limits the migration of the fluids in the reservoir and the adjacent shales. The seal can be a limy shale, an evaporate or anything that is not permeable.

As the shales and adjacent permeable sand are loaded from above the fluids cannot migrate and thus they start supporting some of the overburden. The shales and reservoir sand thus maintain a higher porosity than would exist if the fluids could escape. The weight of the overburden is about 1 psi/ft and thus the pressure of the fluids in the pores can approach 1 psi/ft . The shales and sands thus are truly uncompacted.

Since the shale above the permeable sands is uncompacted it is often possible to detect the existence of the abnormally pressured zone before a permeable zone is entered. The shales generally cave and cause many drilling problems but do not blow out as the sands can. This is the only type of abnormal pressured zone that can be detected before entering the permeable reservoirs.

Detecting Abnormally Pressured Zones

The methods of detecting abnormally pressured zones generally rely on the uncompacted and higher porosities of these zones. The methods of detecting these zones are listed chronologically from before the well is drilled to detecting after the zone has been drilled. It is of course better to detect the zone before drilling it than after drilling and having had to already control the pressure.

Surface Geophysics

The only surface geophysical measurement that has successfully detected abnormally pressured zones at some depth is the seismic survey. The high porosity (low density) and low velocities of uncompacted abnormally pressured zones are detected by the good reflection created by this significant change in acoustic impedance and the determination of the low velocity of the formation. A t great depths the size of the anomally must be large to be seen.

While Drilling

The abnormally pressure formations, because they are not as well compacted as the beds above drill more easily. Normalized drilling rate correlations which take into account the rotating speed of the bit, the mud weight, the weight on the bit, the bit size and the actual penetration rate are used to detect the entrance into an abnormally pressured zone.

These relationships are used to determine the weight of mud to hold the fluids in the abnormally pressured zones. If the zone is too over pressured it is generally necessary to set casing so that the formations above are not fractured by the mud weight which would result in lost circulation and the inevitable blow out.

Shale Cuttings

Some period of time after the formation has been drilled the cuttings reach the surface and may be picked off the shale shaker. The shale cuttings have a lower density (higher porosity) in an abnormally pressured zone. The measurement of the shale densities versus depth provides a means of detecting the entrance into an abnormally pressured zone. The shale cuttings must be clean and free of contaminants such as lime, sand and other heavy minerals.

Flowline Temperatures

At the same time or just before the cuttings come up the mud comes out of the flowline. In an abnormally pressured zone the geothermal gradient increases due to the decreased thermal conductivity of the formations. Water has about one-third the thermal conductivity of shales and sands. Since in an abnormally pressured zone the porosity increases, the amount of water increases resulting in an increase in temperature versus depth (geothermal gradient).

This results in an increase in the mud temperature. When this mud reaches the surface the flowline temperature increases. Increase in flowline temperature after penetrating an abnormally pressured zone can be five or more degrees F. On some occasions the temperature can decrease due to entrance of gas into the mud and the cooling that occurs as it expands.

Well Logs

The logs most commonly used to detect abnormally pressured zones are the resistivity (either short normal or induction), the acoustic and the density. Other logs such as the neutron and pulsed neutron logs may be used but are not as sensitive to the variations as the former logs.

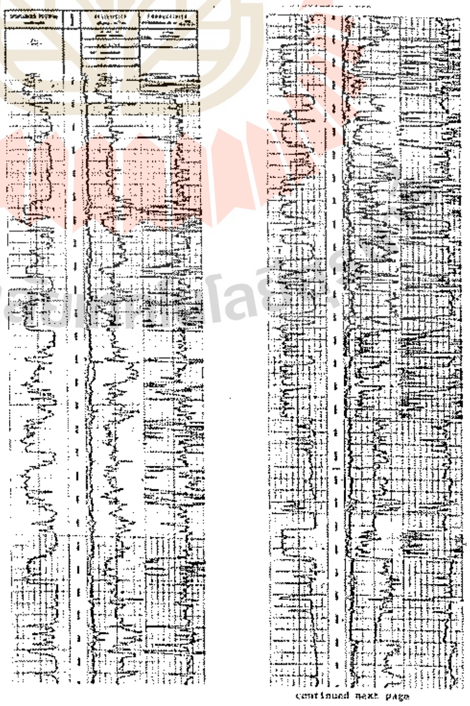
The detection of abnormally pressured zones relies on the values obtained from the logs in shales. Under a normal compaction sequence the shale porosity is reduced with depth. This is due to the continually increasing overburden pressure. The increase in porosity of the shales in the overpressured zone shows up as an apparent increase in porosity of the shales on the logs.

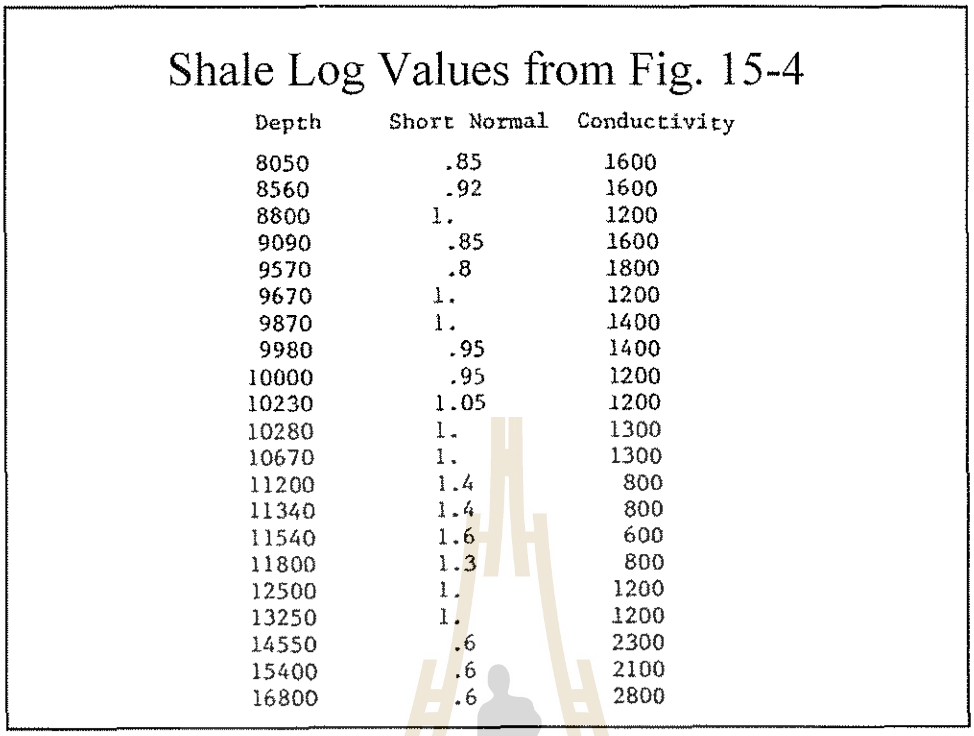
The shale resistivity normally increases with depth. In an abnormally pressured zone the shale resistivity decreases. The greater the decrease in shale resistivity, the.greater the abnormal pressure. The shale ,travel time (acoustic) decreases with depth under normal pressure conditions. In an abnormally pressured zone, the travel time increases. Again the greater the abnormal pressure the more the travel time increases.

The shale density increases with compaction. Abnormal pressures result in increased shale porosity and thus decrease shale density. The lower the porosity, relative to the normal trend, the more the abnormal pressure.

Figure 15-4 is an Induction Electric Log from South Louisiana in a well that was abnormally pressured. The short normal and induction conductivity were read in the better shale zones and are listed on Figure 15-4.

Figure 15-4





Shale Log Values from Fig. 15-4

Depth	Short Normal	Conductivity
8050	.85	1600
8560	.92	1600
8800	1.	1200
9090	.85	1600
9570	.8	1800
9670	1.	1200
9870	1.	1400
9980	.95	1400
10000	.95	1200
10230	1.05	1200
10280	1.	1300
10670	1.	1300
11200	1.4	800
11340	1.4	800
11540	1.6	600
11800	1.3	800
12500	1.	1200
13250	1.	1200
14550	.6	2300
15400	.6	2100
16800	.6	2800

Chapter 16

Fracture Detection With Well Logs

Fractures are important in hydrocarbon. production as they are the source of high permeability in some reservoir rocks that have insufficient matrix permeability to produced without the fractures. Fractures, by my experience, contribute only from 0.5 to 1.5 porosity percent to the porosity of the reservoir. This is generally too low to be detected by the existing porosity logs. Fracture detection from well logs is often more of an art than a science. Fractures are hard to detect from shale beds, porosity developments and thin permeability developments.

Fractures - Natural and Induced

When a well is drilled, the fractures encountered maybe natural, in that they were there before the borehole or they may be created by the drilling of the borehole. The natural fractures are often short in length (inches to feet) and may be vertical or horizontal. Fractures in this discussion are assumed to be open and capable of carrying fluids. Sealed fractures may be sometimes detected, but have no commercial value. Natural fractures are usually oil stained if the reservoir is an oil reservoir.

Drilling induced fractures are usually vertical if the well is over 2000 feet deep. The fractures are not oil stained. These fractures can occur in the cores as I suspect some of the fracturing occurs ahead of the bit.

Fracture Detection

- Direct Detection of Fractures
- Well Log Detection of Fractures

Direct Detection of Fractures

The direct detection of fractures may be from cores, photographic systems or impression packers. Detection of fractures in a core requires a knowledgeable geologist who can recognize a natural fracture from an induced fracture from a place where the core was split during handling.

Photographic techniques, a camera and a lighting system lowered down the borehole, require clean borehole liquid or no borehole liquid and have severe depth limitations. Most of these devices have been developed for water wells.

Well Log Detection of Fractures

- The detection of fractures by well logs are mostly acoustic although some more recent techniques use resistivity measurements.
- Caliper devices with sharp borehole wall contacts often pick up fractures as roughness of the borehole wall. These are not conclusive and require confirmation from some other log.

Well Log Detection of Fractures

- Density and neutron logs generally do not see fractures conclusively.
- The resistivity of a rock is greatly reduced when the current flow is parallel to the fracture The use of induction logs to detect fractures is poor as the current flows around the borehole (in the formation) and does not flow parallel to the fracture for more than a very short distance. Laterologs and micro-focused resistivity logs are most influenced by fractures.