Al-Karkh University of Sciences
College of Remote Sensing and Geophysics

Geophysics Department

2021 – 2022

Lecture ONE

An Introduction to Well Logging

by

Assistant Professor

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What is a Wireline Log?

A ***log*** is a continuous recording of a geophysical parameter along a borehole. Wireline logging is a conventional form of logging that employs a measurement tool suspended on a cable or wire that suspends the tool and carries the data back to the surface. These logs are taken between drilling episodes and at the end of drilling. Recent developments also allow some measurements to be made during drilling. Well logging primary meaning is electrical coring, which is a continuous record of characteristics of rock formations traversed by a measurement device in the well bore, these devices recording various physical, chemical, electrical, or other properties of the rock or fluid mixtures penetrated by drilling a well into the targeted depth. Well logging, however, means different things for different people.

For a **geologist**, it is primarily a mapping technique for exploring the surface. Moreover, answer the following questions:
What depths are the formation tops?
Is the environment suitable for accumulation of hydrocarbon?
Is there evidence of hydrocarbons in this well?
What type of hydrocarbon?
Are hydrocarbons present in commercial quantities?

For a **geophysicist**, it is a source of complementary data for surface seismic analysis. Moreover, answer the following questions:
Are the tops where you predicted?
Are the potential zones porous as you assumed from seismic data?
What does a synthetic seismic section show?

For a **petrophysicist**, it is a means to evaluate the hydrocarbon production potential of a reservoir.

*"The tools that required to make measurements are attached to the drill string behind the bit, and do not use a wire relying but instead on low band-width radio communication of data through the conductive drilling mud. Such data is called **MWD** (measurement while drilling) for simple drilling data, and **LWD** (logging while drilling) for measurements analogous to conventional wireline measurements. These methods will not be covered by this course, although the logs that are produced in this way have very similar characteristics."*

Of the various types of logs, the ones used most frequently in exploration are called ***open-hole logs***. The name open hole is applied because these logs are recorded in the uncased portion of the wellbore. All the different types of logs and their curves discussed in this text are of this type. ***Open-hole logs*** are made when the drill-bit is removed from the borehole. This can be either between drilling episodes, before casing is laid, or at the end of drilling. Wireline logging can be done when the newly drilled rock formations form the wall of the borehole (***open-hole logs***) or after a concrete lining or casing has been inserted to stabilize the well bore (***cased-hole logs***). However, as may be guessed, the quality of data from the rock is best from **open-hole logs**, and

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some measurements cannot be done at all through casing. Cased-hole logging requires special tools to optimize measurement through the casing, and is a specialist subject not covered by this course.

Remember that a borehole represents a dynamic system; that fluid used in the drilling of a well affects the rock surrounding the borehole and, therefore, log measurements. In addition, the rock surrounding the borehole has certain properties that affect the movement of fluids into and out of it.

Rock properties or characteristics that affect logging measurements are: *porosity*, *lithology*, *mineralogy*, *permeability*, and *water saturation*. Additionally, the resistivity of the rock is important because it is directly measured and is an essential part in the interpretation process. It is essential that the reader understand these properties and the concepts they represent before proceeding with a study of log interpretation.

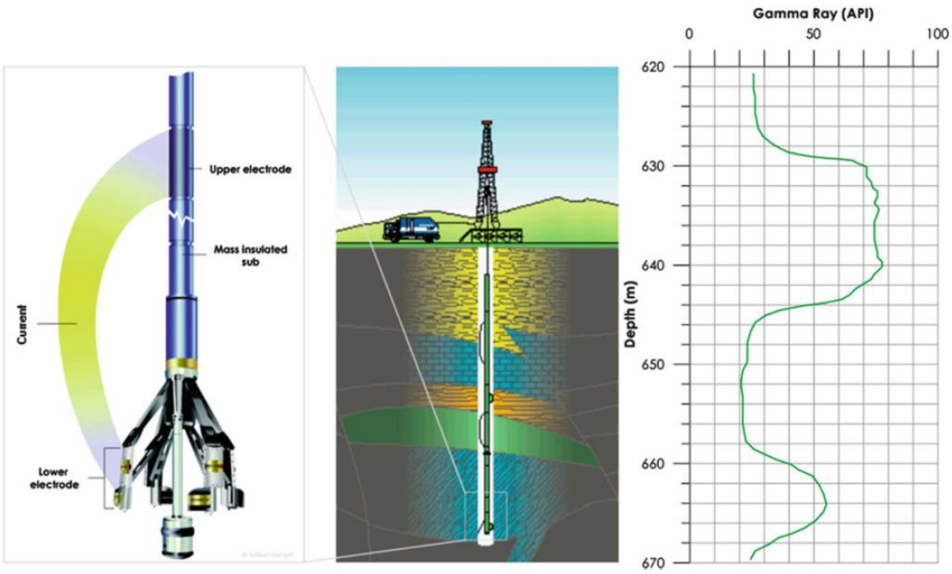

Figure. Example of a logging tool (left, Courtesy of Schlumberger). The wireline logging operation showing logging truck, logging cable strung into the rig, then lowered into the borehole with logging tools at the end of the cable (middle). Example of a recorded gamma ray log display (right).

Use of Logs

Well logging from its origination about 100 years ago, has been proofed an utmost useful technology both in exploration and exploitation. Its measurements occupy a central position in the whole life of a well. The traditional role of well logging lies in two domains: **formation comprehensive evaluation** and **completion evaluation**. For the **formation comprehensive evaluation**, it can be summarized in four key questions of primary phase:

1. Are there any hydrocarbons, and if so are they oil or gas? For this question, resistivity logging, sonic logging and radioactivity logging can answer.
2. Where are the hydrocarbons? That means we must assure the depth of the formations, which contain accumulations of hydrocarbons, must be identified. Based on the GR or

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SP curves, the top and bottom depth of a permeable zone can be delineated, and then, we can know the thickness of a pay zone.

3. How much hydrocarbon was contained in the formation? Well log data are initial approach to give a quantity evaluation of the hydrocarbon in the formation. Two utmost important parameters, porosity, and saturation In addition to these two parameters, thickness of formation which contain hydrocarbon was also needed.
4. How producible are the hydrocarbons? In fact, all questions will come down to this one practical concern, which is just the most difficult one to answer. The reason is a most important parameter, **permeability** of the formation, which is the most uncertainty one. Many empirical methods are used to extract permeability from logging with varying degrees of success.

The researcher can easily find solutions for particular applications in any required field, therefore the main applications of well logs are:

1. ***Groundwater drilling for verifying the construction of a well, maintaining the quality of water, preventing environmental losses, and complying with the regulations.***
2. ***Environmental applications of well logs include a study of borehole geophysics for remediation, monitoring of the subsurface, and compliances with environmental regulations.***
3. ***Well logs are used in mining applications for saving the money required for assessing the core characteristics. In addition, it helps in reducing the downtimes and optimizing the mining sites with a focus on worker safety.***
4. ***A wide array of research organizations uses these logs for studying, measuring, and defining the properties of rocks and fluids. This helps in the progression of scientific knowledge that can resolve the major concerns of many industries.***
5. ***The energy companies also use this data for characterizing the reservoirs and improving the efficiencies.***
6. ***The geotechnical companies use well logging for studying the structural integrity of surface.***

The Presentation of Log Data

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 (horizontal) and depth (distance from the surface) on the other axis (vertical). More than one property may be displayed on the same graph.

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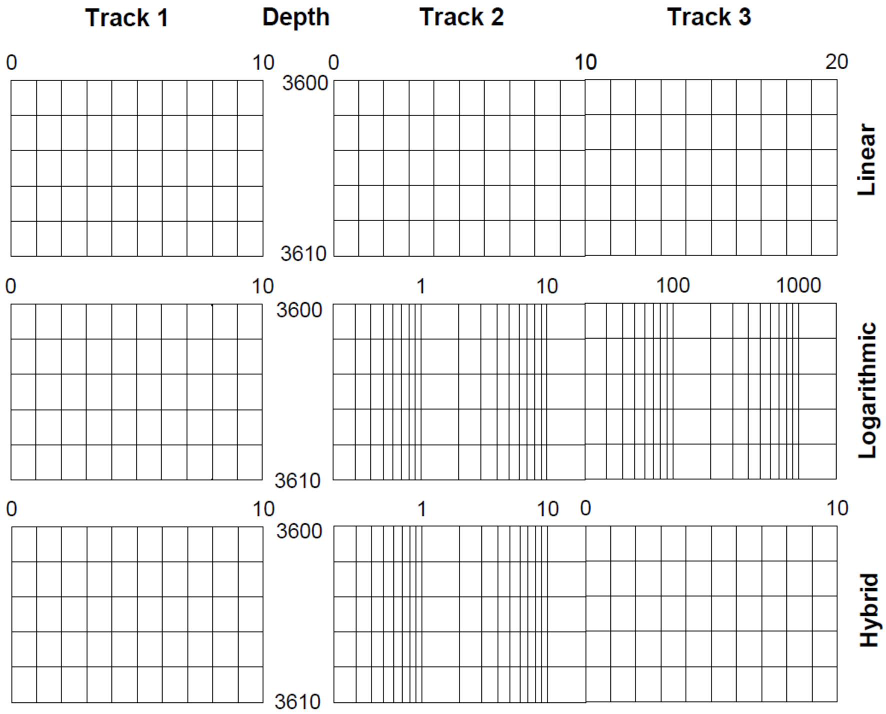

Figure Log presentation grids.

Wireline log tools:

The two primary parameters determined from well log measurements are porosity and the fraction of pore space filled with hydrocarbons (i.e., hydrocarbon saturation). The parameters of log interpretation are determined directly or inferred indirectly and are measured by one of three general types of logs:

The tools of logging can be classified into:

- Electrical Logs:
  Spontaneous Potential Log (SP)
  Resistivity Logs
- Radioactive Logs
  Gamma Ray (GR),
  Neutron (CNL)
  Density (FDC),
- Mechanical Logs:
  Caliper (CALI)
  Bit Size (BS)
- Acoustic Logs
  Sonic (DT)

The Tools:

Tool or "sonde" is an instrument probe that automatically transmits information about its surroundings underground. The tool contains various pieces of equipment to measure the properties of the rock formation. Examples of the basic physical parameters that can be measured down-hole with logs include:

1. The size of the borehole
2. The orientation of the borehole
3. Temperature
4. Pressure

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5. The natural radioactivity of the rocks
6. The acoustic properties of the rocks
7. The attenuation offered by the rocks to radioactivity generated from the tool
8. The electrical properties of the rocks

While examples of information that derived from logs include:

1. Lithology derived from the combination gamma ray and density-neutron logs
2. Shale volume from gamma ray or spontaneous potential (SP) logs
3. Porosity derived from the sonic, neutron or density logs
4. Fluid saturation calculated from the porosity and the electrical logs.

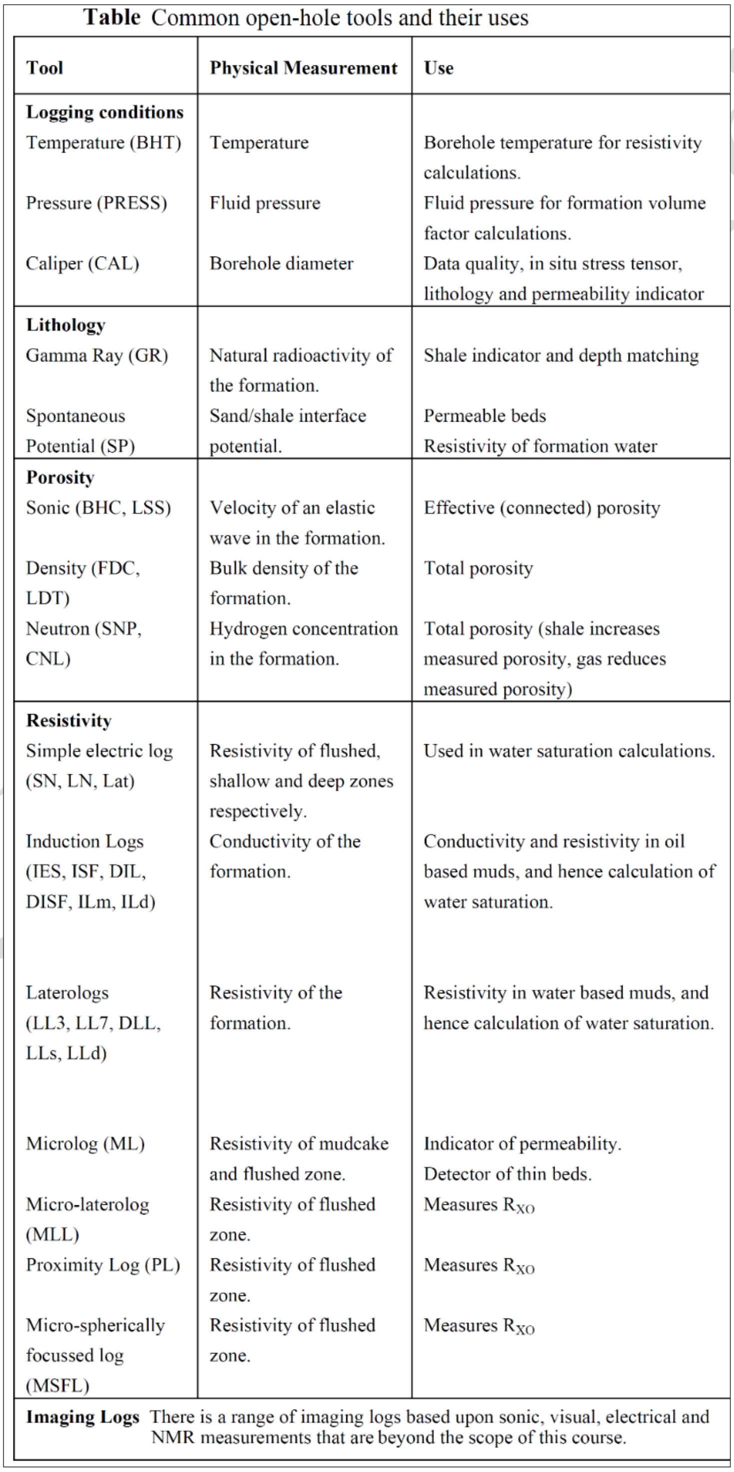

Table Common open-hole tools and their uses

Tool	Physical Measurement	Use
Logging conditions		
Temperature (BHT)	Temperature	Borehole temperature for resistivity calculations.
Pressure (PRESS)	Fluid pressure	Fluid pressure for formation volume factor calculations.
Caliper (CAL)	Borehole diameter	Data quality, in situ stress tensor, lithology and permeability indicator
Lithology		
Gamma Ray (GR)	Natural radioactivity of the formation.	Shale indicator and depth matching
Spontaneous Potential (SP)	Sand/shale interface potential.	Permeable beds Resistivity of formation water
Porosity		
Sonic (BHC, LSS)	Velocity of an elastic wave in the formation.	Effective (connected) porosity
Density (FDC, LDT)	Bulk density of the formation.	Total porosity
Neutron (SNP, CNL)	Hydrogen concentration in the formation.	Total porosity (shale increases measured porosity, gas reduces measured porosity)
Resistivity		
Simple electric log (SN, LN, Lat)	Resistivity of flushed, shallow and deep zones respectively.	Used in water saturation calculations.
Induction Logs (IES, ISF, DIL, DISF, ILm, ILd)	Conductivity of the formation.	Conductivity and resistivity in oil based muds, and hence calculation of water saturation.
Laterologs (LL3, LL7, DLL, LLs, LLd)	Resistivity of the formation.	Resistivity in water based muds, and hence calculation of water saturation.
Microlog (ML)	Resistivity of mudcake and flushed zone.	Indicator of permeability. Detector of thin beds.
Micro-laterolog (MLL)	Resistivity of flushed zone.	Measures R_{XO}
Proximity Log (PL)	Resistivity of flushed zone.	Measures R_{XO}
Micro-spherically focussed log (MSFL)	Resistivity of flushed zone.	Measures R_{XO}
Imaging Logs	There is a range of imaging logs based upon sonic, visual, electrical and NMR measurements that are beyond the scope of this course.	

Well Logging History

- Marcel and Conrad Schlumberger, made the first electrical log that introduced in 1927 in France using stationed resistivity method.
- The first commercial electrical resistivity tool in 1929 was used in Venezuela, USA and Indonesia.
- SP was run along with resistivity first time in 1931.
- Schlumberger developed the first continuous recording in 1931.
- GR and Neutron logs was started in 1941.
- Microresistivity array dipmeter and lateralog were first time introduced in 1950’s.
- The first induction tool was used in 1956 followed by Formation tester in 1957
- Formation Density in 1960’s, Electromagnetic tool in 1978 and most of Imaging
- Logs were developed in 1980’s.
- Advanced formation tester was commercialized in early 1990’s.

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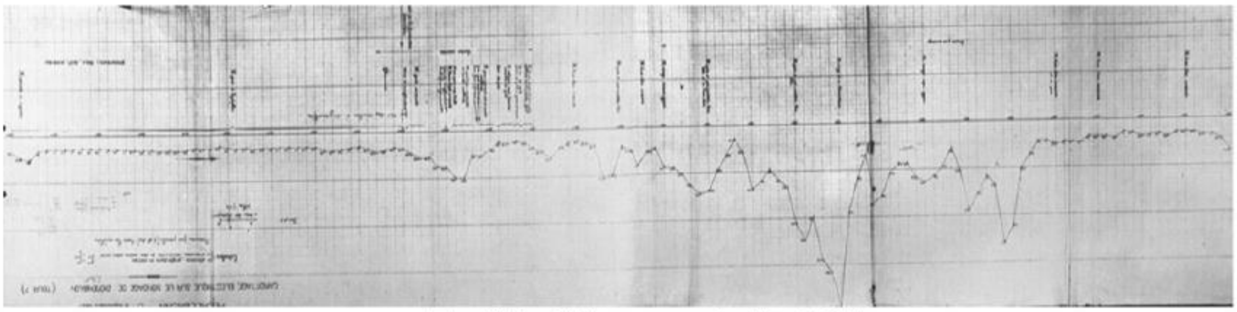
Well in Pechelbronn - France


Surface Recording Instrument


The “First” Log recorded in 1927

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Lecture TWO

Borehole Environments and Invasion

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Borehole Environment:

Where a hole is drilled into a formation, the rock plus the fluids within (the rock-fluid system) are altered in the proximity of the borehole wall. The borehole and the surrounding formations are contaminated by the drilling mud, which affects logging measurements. A schematic illustration of a porous and permeable formation that is penetrated by a borehole filled with drilling mud illustrated in figures below.

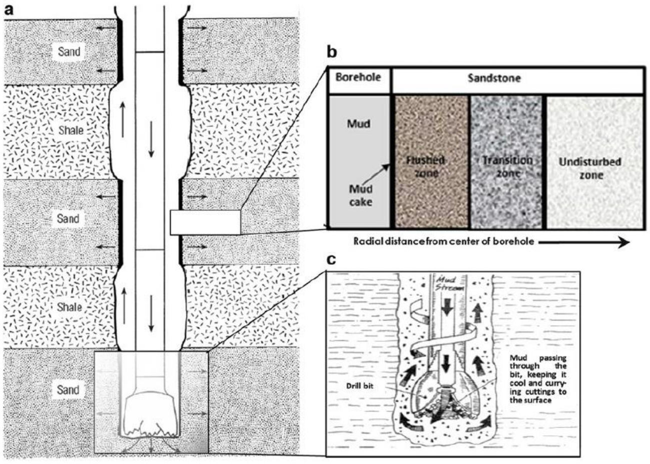

Fig. The schematic diagram illustrates an idealised version of what happens when fluids from the borehole invade the porous and permeable sandstones and low permeability shales. The mud circulation causes borehole washout in the low permeability shale zones (a). Overpressured mud indicates that it is invading porous and permeable sandstones with the formation of a mudcake (a and b). During drilling, mud is pumped down the drill-string, forcing the cuttings up to the surface with the return flow (c)

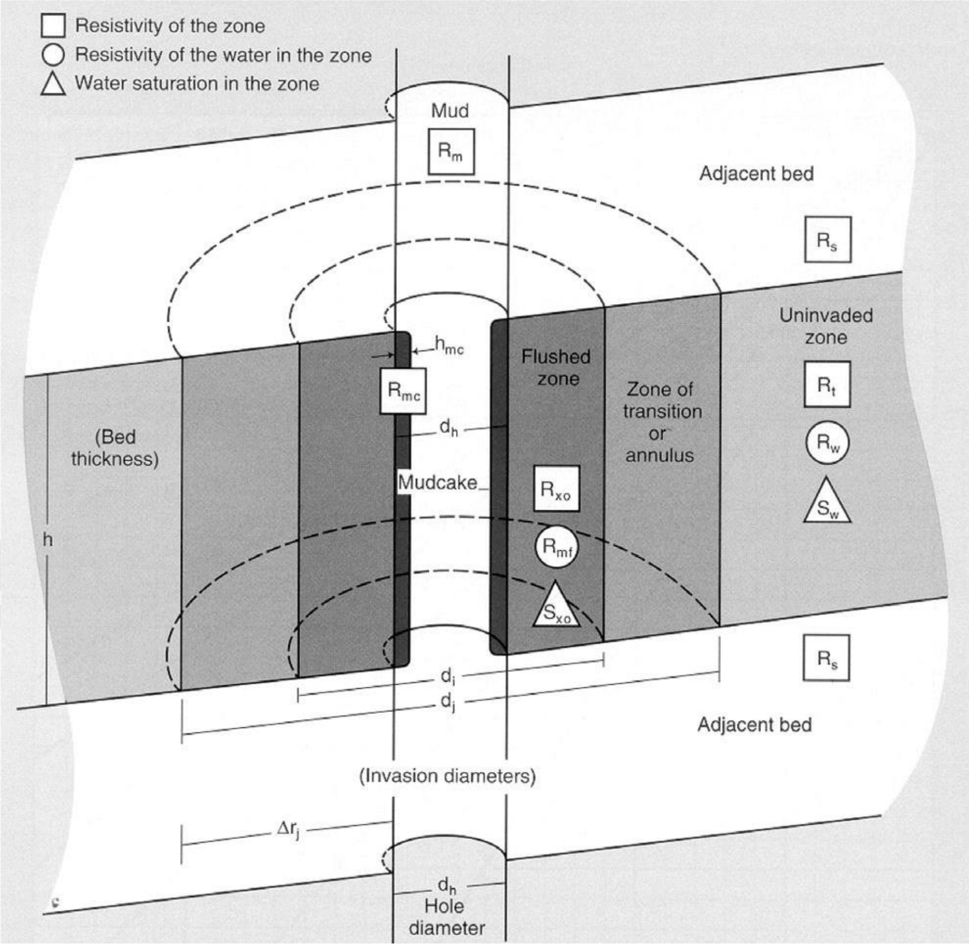

Figure. A schematic illustration of a porous and permeable formation that is penetrated by a borehole filled with drilling mud.

This schematic diagram illustrates an idealized version of what happens when fluids from the borehole invade the surrounding rock. Dotted lines indicate the cylindrical nature of the invasion.

dh = hole diameter.
di = diameter of Flushed zone.
dj = diameter of Transition zone (outer boundary of invaded zone).
Δrj = radius of invaded zone.
hmc = thickness of mud cake.
Rm = resistivity of the drilling mud.
Rmc = resistivity of the mud cake.
Rmf = resistivity of mud filtrate.
Rs = resistivity of the overlying bed (commonly assumed to be shale).
Rt = resistivity of uninvaded zone (true formation resistivity of hydrocarbon-bearing formation).
Ro = resistivity of water-bearing formation
Rw = resistivity of formation water.
Rxo = resistivity of flushed zone.
Sxo = water saturation flushed zone.
***Sh* = hydrocarbon saturation (i.e., the fraction of pore volume filled with hydrocarbons).**
Sw = water saturation of the uninvaded zone (i.e., the fraction of pore volume filled with water).

Hole Diameter (dh)

The borehole size is determined by the outside diameter of the drill bit. Nevertheless, the diameter of the borehole may be larger than the bit size because of washout and/or collapse of shale and poorly cemented porous rocks. Smaller than the bit size because of a build up of mud cake on porous and permeable formations. Common borehole sizes, which is measured by a caliper log normally vary from 8 in. to 12 in., and modern logging tools are designed to operate within these size ranges.

Drilling mud:

During drilling a **water-based**, or sometimes **oil-based**, (Drilling with air or Foam drilling in rare cases) mud containing clays and other natural materials, called **drilling mud (drilling fluid)**, is pumped down the drill-string.

Drilling muds are added to the wellbore to facilitate the drilling process by **suspending** rock fragments **(**cuttings) by providing **buoyancy** that can transport the cuttings to the surface where the cuttings are analyzed for indications of hydrocarbonand prevent cuttings to gather on the drilling bit, and **cooling and lubricating the drilling bit**. Nowadays, drilling deeper, longer and more challenging wells is made possible due to more efficient and effective drilling fluids. High density materials (e.g. **barite, hematite**) are added to the drilling mud to increase its **density** and thereby its **pressure** on the walls of the well that leads to **rock stabilization**. These special additives ensure

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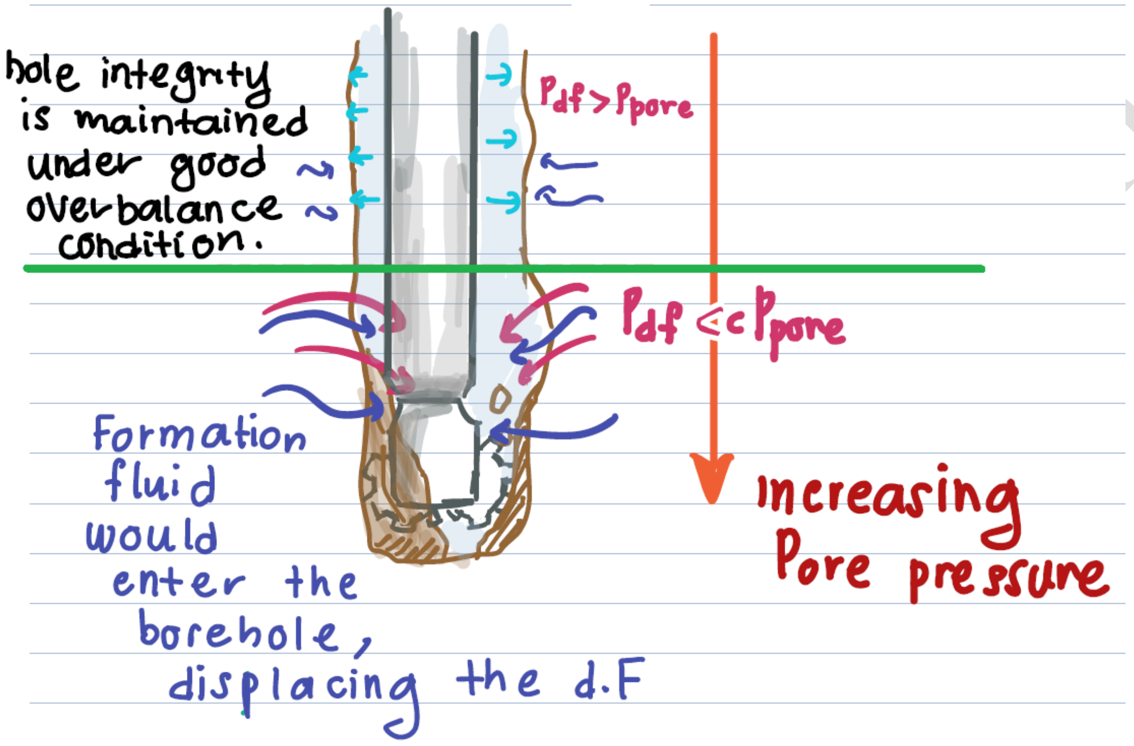
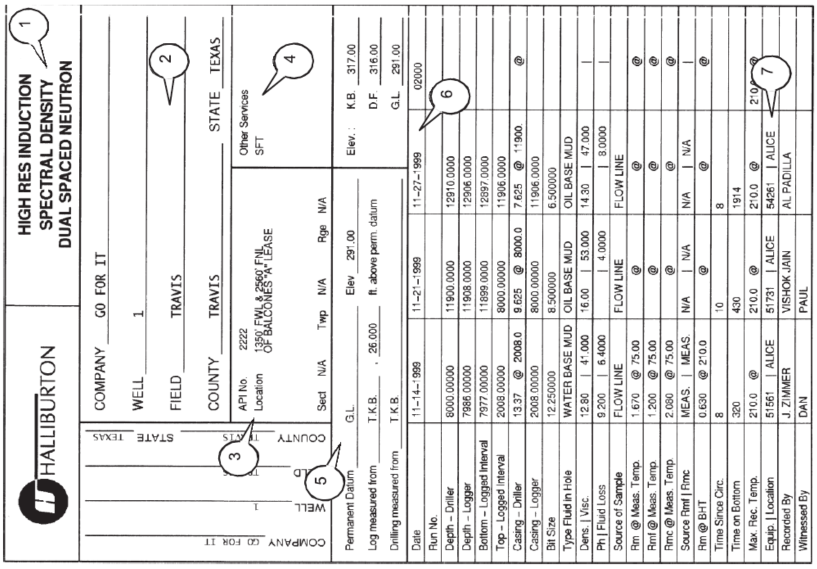
that the drilling fluid is not absorbed by the rock formation in the well and that the pores of the rock formation are not clogged. The drilling fluid pumped down the borehole must ensure that the **hydrostatic pressure** in the wellbore exceeds the **fluid pressure** in the formation pore space to **prevent** disasters such as blowouts (handmade Figure below).



As invasion occurs, many of the solid particles (i.e., clay minerals from the drilling mud) are trapped on the side of the borehole and form **mud cake** (having a resistivity of ***Rmc***). Fluid that filters into the formation during invasion is called **mud filtrate** (with a resistivity of ***Rmf***). The resistivity values for drilling mud, mud cake, and mud filtrate are recorded on a log's header and are used in interpretation as illustrated in the Figure below.



HALLIBURTON

HIGH RES INDUCTION
SPECTRAL DENSITY
DUAL SPACED NEUTRON

COMPANY GO FOR IT
WELL 1
FIELD TRAVIS
COUNTY TRAVIS STATE TEXAS

API No. 2222
Location 1350' FWL & 2560' FNL OF BALCONES "A" LEASE
Sect N/A Twp N/A Rge N/A

Other Services
SFT

Permanent Datum G.L. Elev 291.00
Log measured from T.K.B. , 26.000 ft. above perm. datum
Drilling measured from T.K.B.

Elev. : K.B. 317.00
D.F. 316.00
G.L. 291.00

Date	11-14-1999	11-21-1999	11-27-1999	02000
Run No.				
Depth – Driller	8000.00000	11900.0000	12910.0000	
Depth – Logger	7986.00000	11908.0000	12906.0000	
Bottom – Logged Interval	7977.00000	11899.0000	12897.0000	
Top – Logged Interval	2008.00000	8000.00000	11906.0000	
Casing – Driller	13.37 @ 2008.0	9.625 @ 8000.0	7.625 @ 11900.	@
Casing – Logger	2008.00000	8000.00000	11906.0000	
Bit Size	12.250000	8.500000	6.500000	
Type Fluid in Hole	WATER BASE MUD	OIL BASE MUD	OIL BASE MUD	
Dens. | Visc.	12.80 | 41.000	16.00 | 53.000	14.30 | 47.000	|
Ph | Fluid Loss	9.200 | 6.4000	| 4.0000	| 8.0000	|
Source of Sample	FLOW LINE	FLOW LINE	FLOW LINE	
Rm @ Meas. Temp.	1.670 @ 75.00	@	@	@
Rmf @ Meas. Temp.	1.200 @ 75.00	@	@	@
Rmc @ Meas. Temp.	2.080 @ 75.00	@	@	@
Source Rmf | Rmc	MEAS. | MEAS.	N/A | N/A	N/A | N/A	|
Rm @ BHT	0.630 @ 210.0	@	@	@
Time Since Circ.	8	10	8	
Time on Bottom	320	430	1914	
Max. Rec. Temp.	210.0 @	210.0 @	210.0 @	210.0 @
Equip. | Location	51561 | ALICE	51731 | ALICE	54261 | ALICE	
Recorded By	J. ZIMMER	VISHOK JAIN	AL PADILLA	
Witnessed By	DAN	PAUL		

Figure . Reproduction of a typical log heading.

Invaded Zone

It is the zone in which much of the original fluid is replaced by mud filtrate. It consists of a flushed zone (of resistivity *Rxo*) and a transition or annulus zone (of resistivity *Ri*). The flushed zone occurs close to the borehole where the mud filtrate has almost completely flushed out a formation's hydrocarbons and/or water (Rw). The transition or annulus zone, where a formation's fluids and mud filtrate are mixed, occurs between the flushed zone and the uninvaded zone. The uninvaded (with resistivity Rt) zone is defined as the area beyond the invaded zone where a formation's fluids are uncontaminated by mud filtrate.

The depth of mud-filtrate invasion into the invaded zone is referred to as **diameter of invasion** (***di*** and ***dj***). The diameter of invasion is measured in inches or expressed as a ratio ***dj/dh*** (where ***dh*** represents the borehole diameter).

↔ For the **same drilling fluid**, the amount of invasion that takes place is dependent upon the **permeability** of the mud cake and not upon the porosity of the rock.

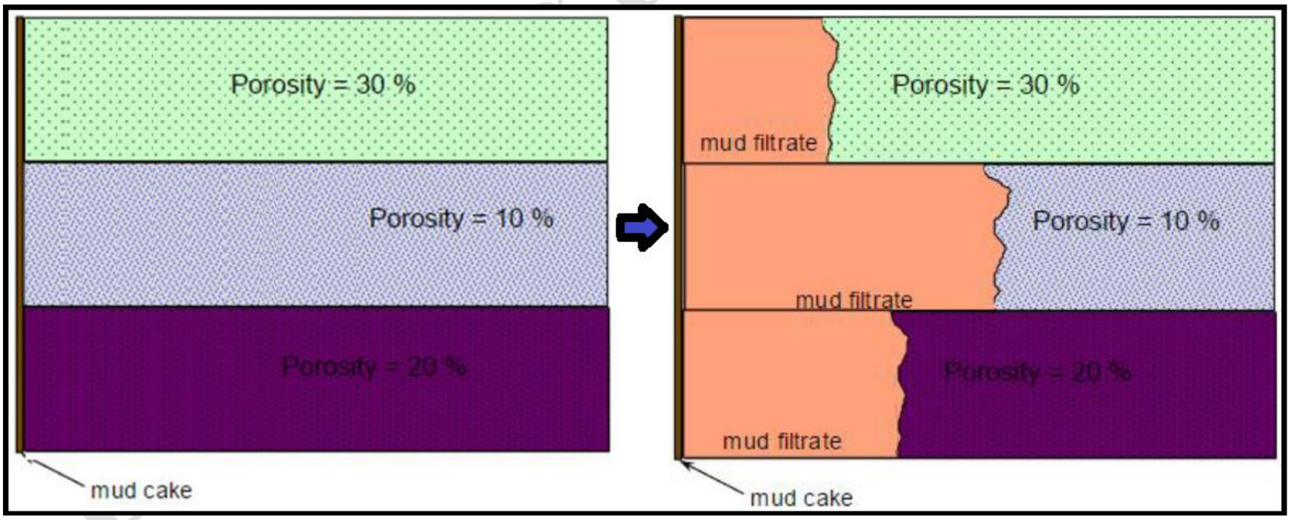
↔ Therefore, an **equal volume** of **mud** filtrate can invade both **low** and **high** porosity rocks.

↔ The **solid particle** in the drilling muds bridge and form an **impermeable** mud cake.

↔ The mud cake then acts as a **barrier** to further invasion.

↔ Because an equal volume of fluid can be invaded before an impermeable mud cake barrier forms, the diameter of invasion will be greatest in **low porosity** rocks.

↔ Low porosity rocks have **less** storage capacity or pore volume to fill with the **same** invading fluid, and, as a result, pores throughout a greater volume of rock will be affected.

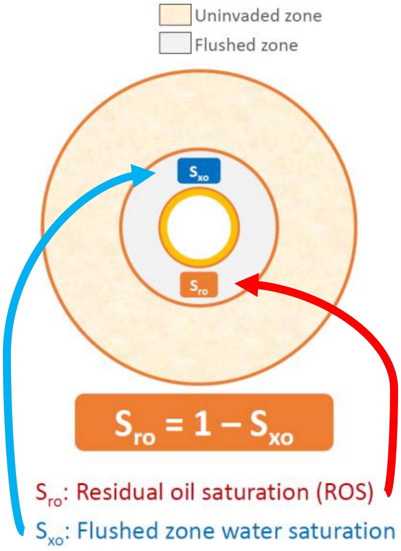


dj/dh= 2 In. for high porosity.
dj/dh= 5 In. for intermediate porosity.
dj/dh= 10 In. for low porosity.

Flushed zone Resistivity (Rxo)

The flushed zone extends only a few inches from the wellbore and is part of the invaded zone. If invasion is deep or moderate, most often the flushed zone is completely cleared of its formation water by mud filtrate *Rmf*.

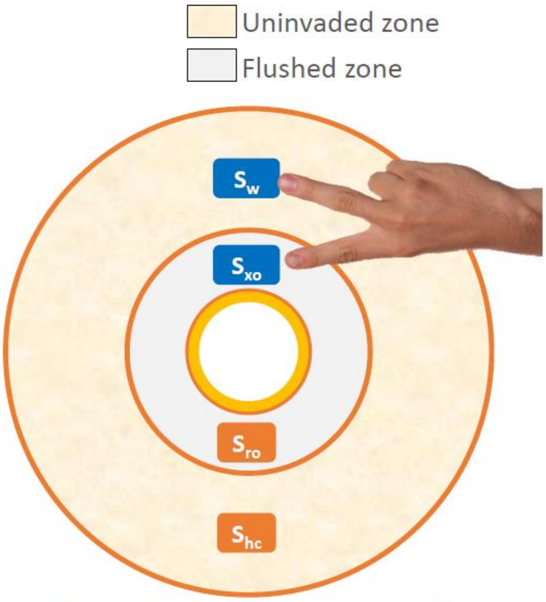
The remaining oil in the flushed zone is called **Residual oil (*Sro*)**. So the Sro is indicated as in the following figure.



Uninvaded zone Resistivity (Rt)

The uninvaded zone is located beyond the invaded zone. Pores in the uninvaded zone are uncontaminated by mud filtrate; instead, they are saturated with formation water (*Rw*), oil, and/or gas. Even in hydrocarbon-bearing reservoirs, there is always formation water envelope the grain surfaces.

Water saturation (Sw) of the uninvaded zone is an important factor in reservoir evaluation.



$$S_h = 1 - S_w$$

Recoverable oil.

$$S_{oR} = S_h - S_{ro} = (1 - S_w) - (1 - S_{xo}) = S_{xo} - S_w$$

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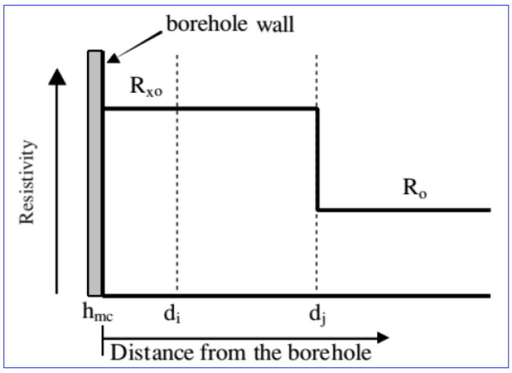
Invasion and Resistivity Profiles

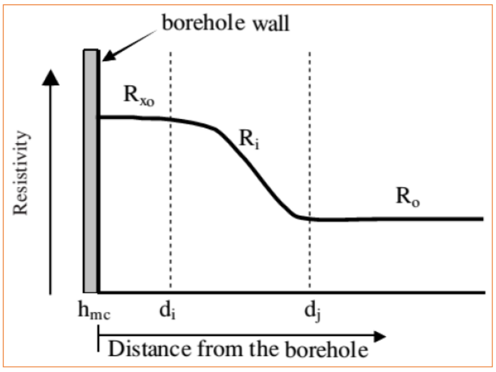
Invasion and resistivity profiles are diagrammatic, theoretical, cross-sectional views of subsurface conditions moving away from the borehole and into a formation. They illustrate the horizontal distributions of the invaded and uninvaded zones and their corresponding relative resistivity. There are three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

- Step profile has a cylindrical geometry with an invasion diameter equal to dj. Shallow-reading resistivity logging tools read the resistivity of the invaded zone (Rxo), while deeper reading resistivity logging tools read true resistivity of the uninvaded zone ($\underline{Rt}$ if the formation is oil-bearing or $\underline{Ro}$ if the formation is water-bearing).
- Transition profile also has a cylindrical geometry with two invasion diameters: di (flushed zone) and dj (transition zone). It is probably a more realistic model for true borehole conditions than is the step profile.
- Annulus profile represents a fluid distribution that occurs between the invaded zone and the uninvaded zone and only exists in the presence of hydrocarbons. In the annulus zone, pores are filled with **formation water** and **residual hydrocarbons**.

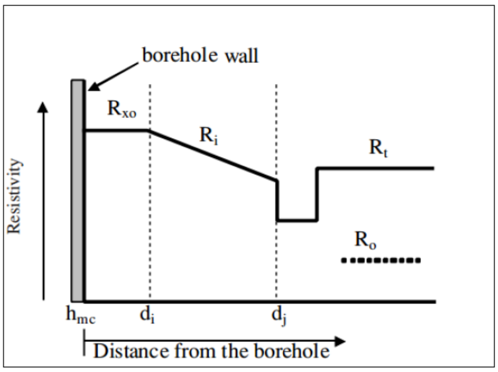
Remember: the true resistivity of the formation is the resistivity of the uninvaded zone due to its virginity. The **Rt** is higher than the water-bearing formation resistivity **Ro** because of the resistivity of **hydrocarbons** is higher than that of **water**.



Step Profile



Transition Profile



Annulus Profile

Water-bearing Zones

Figure below illustrates the borehole and resistivity profiles for water-bearing zones where the resistivity of the mud filtrate (Rmf) for a **freshwater mud** is much greater than the resistivity of the formation water (Ro), and where resistivity of the mud filtrate (Rmf) for a **saltwater mud** is approximately equal to the resistivity of the formation water (Ro).

A freshwater mud (i.e., $Rmf >>> Rw$) results in a *wet* profile where the shallow (Rxo), medium (Ri), and deep (Rt) resistivity measurements **separate** and record **high** (Rxo), intermediate (Ri), and **low** (Rt) resistivities.

A saltwater mud (i.e., $Rw = Rmf$) results in a *wet* profile where the shallow (Rxo), medium (Ri), and deep (Rt) resistivity measurements all read **low** resistivity.

Hydrocarbon-bearing Zones

Same Figure illustrates the borehole and resistivity profiles for hydrocarbon-bearing zones where the resistivity of the mud filtrate (Rmf) for a **freshwater** mud is much

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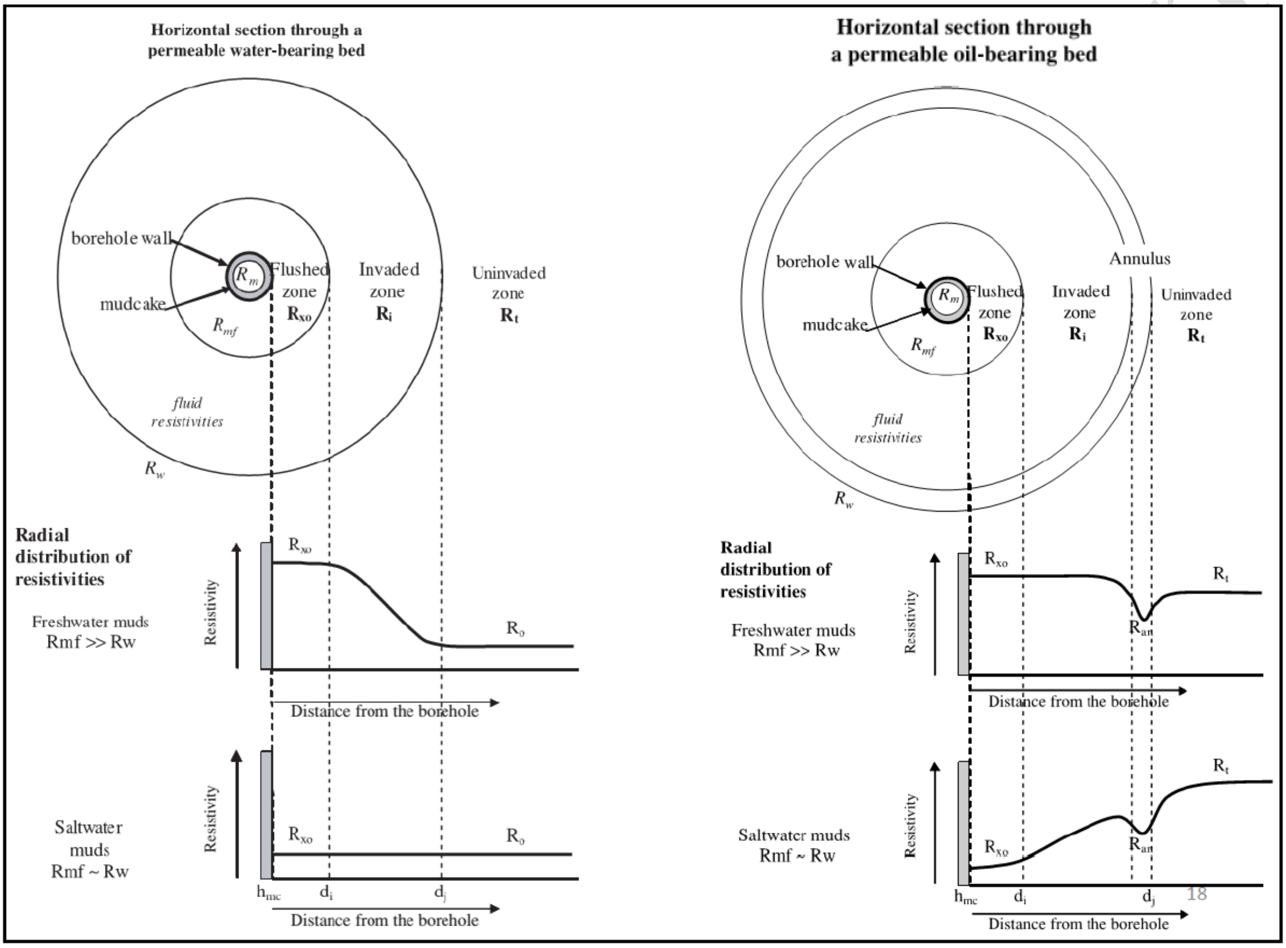
greater than the resistivity of the formation water (*Rw*), and where *Rmf* of a **saltwater** mud is approximately equal to *Rw*.

A hydrocarbon zone invaded with **freshwater** mud results in a resistivity profile where the shallow (*Rxo*), medium (*Ri*), and deep (*Rt*) resistivity measurements all record **high** resistivities.

A hydrocarbon zone invaded with **saltwater** mud results in a resistivity profile where the shallow (*Rxo*), medium (*Ri*), and deep (*Rt*) resistivity measurements **separate** and record low (*Rxo*), intermediate (*Ri*) and high (*Rt*) resistivities.



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LECTURE THREE

Aware of Hulk

Gamma Ray log

by

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Timing is everything; do not miss the best by losing it. (*Rami*)

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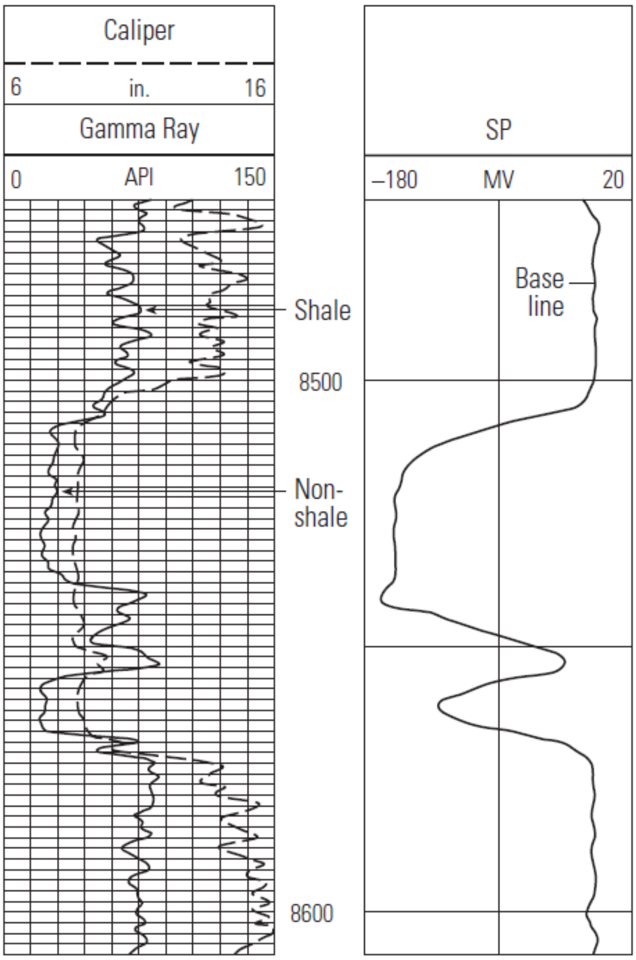
Introduction

The *gamma ray log* measures the total natural gamma radiation emanating from a formation. The radiation arises from three elements present in the rocks, isotopes of potassium, uranium and thorium. It is also known as **shale log** due to Shales are derived from the weathering of igneous rocks (composed of Quartz, Feldspar and Mica) which contains significant amount of potassium and Uranium. The gamma ray log is commonly given the symbol ***GR***.

As is evident from its name, the gamma ray responds to the natural gamma radiation in the formation. It measures the natural radioactivity of rocks surrounding the borehole and does not measure any hydrocarbon or water present within the rocks.

The association of measurable quantities of radioactive isotopes in shales is primarily due to the presence of **clay minerals**, some of which are naturally radioactive or have radioactive ions associated with them. It reflects shale or clay content within a formation, because K, U and Th are largely concentrated in association with clay minerals. In addition, dense formations such as (shales) absorb many gamma rays, while low-density formations such as (sandstones and limestone) absorb fewer.



Comparison of the gamma ray curve with the SP and caliper over clean and shale zones.

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Different types of shale have different total gamma ray activity, depending on the K, U, and Th concentrations associated with them, this activity are measured totally by the **total gamma ray**. While **Spectral gamma ray** devices employ the same basic type of detection system as the total gamma ray devices, but instead of using one broad energy region for detection, the gamma rays are analysed into a number of different energy bins. The usage of total or spectral GR is depending on the calibration in standard formations, where the concentrations of K, U, and Th are known.

Old fashion GR was subjected to many corrections. Some of these corrections are likely to be the borehole environment and diameter. Note that the gamma ray measurement device accepts gamma rays from almost a hemisphere that includes the formation and the drilling mud between the formation and the sensor. Therefore Gamma rays may come from the formation at any angle from horizontal to almost vertically, and indeed may come from the drilling mud itself (beware: some drilling muds are very radioactive, especially that contain mud additives such as barite or KCl. Barium in the mud is a very efficient absorber of low-energy gamma rays emanating from the formation). The density of the drilling mud (*mud weight)* are also effects the signal, so the higher density muds, the higher attenuated gamma rays.

The new devices of GR are corrected within the device itself. The gamma ray log is combinable with all tools, and is usually used as part of every logging combination run because of its ability to match the depths of data from each run. **Spectral gamma ray** can present in two ways in logging as follow:

Standard Gamma Ray (**SGR**): Which gives the summation of the K, U, and Th radiation in API units, that it is similar to the simple Total Gamma Ray but the values of the radioactive elements in separate curves.

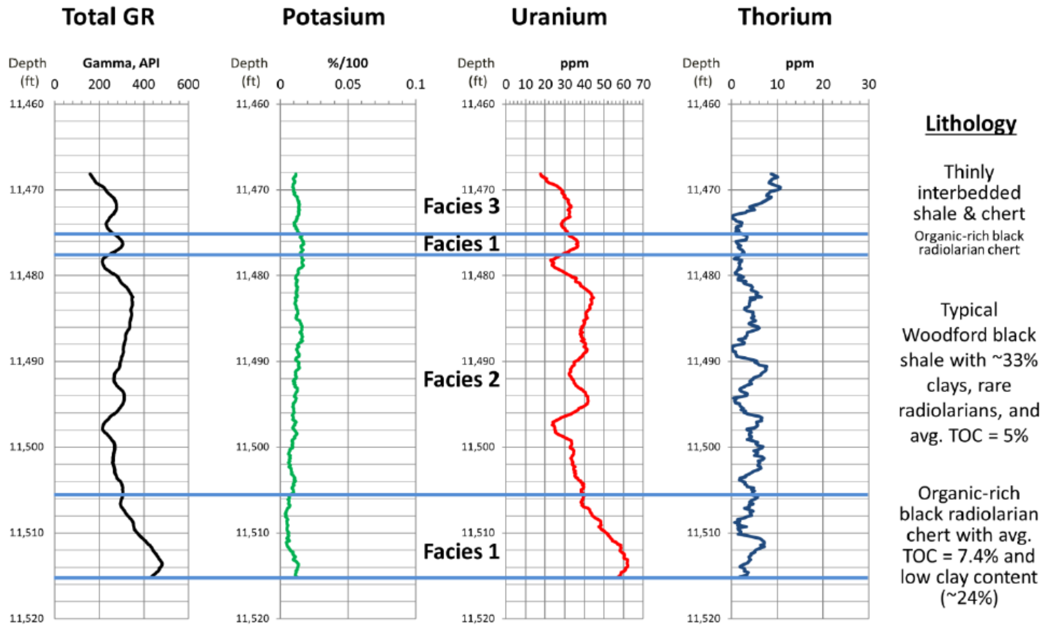

Figure Spectral gamma-ray logs for Woodford Shale core from the Hentz Family 7-1.

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Computed Gamma Ray (**CGR**): Which represents Th and K radiation only, calculated in API units. The difference between the two curves represents the U readings.

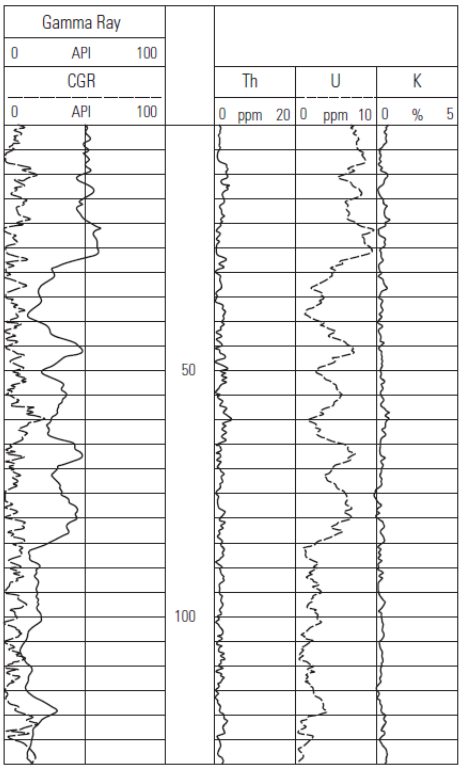
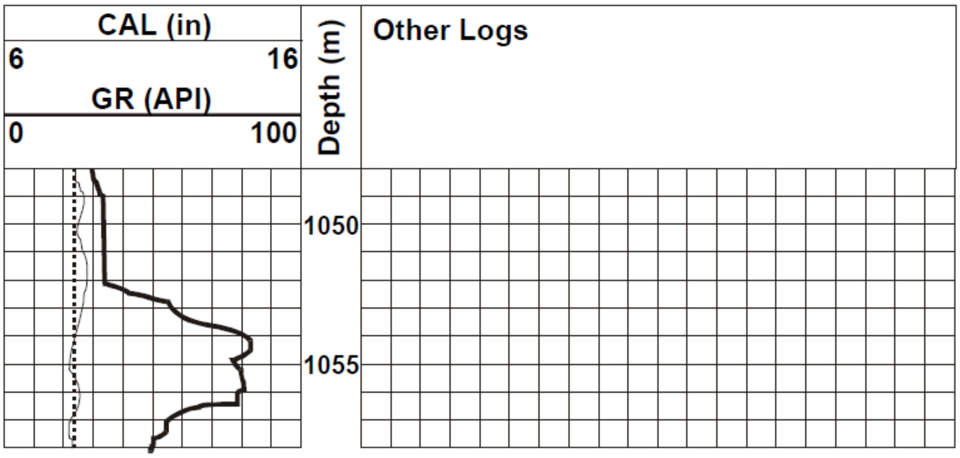


Fig. Decomposition of the natural gamma ray activity of a carbonate section into concentrations of Th, U and K. The total gamma ray (GR) signal has considerable activity, seen to correlate with fluctuations in U content. The CGR trace is computed from the GR trace by subtracting the contribution of uranium. The CGR curve is more consistent with the knowledge that this is a largely clay-free zone. Adapted from Luthi

Log Presentation

The total gamma ray log is usually recorded in track 1 with the caliper log, bit size and SP log. In this case, the other tracks most often include resistivity, density, neutron or sonic logs. Although the API scale goes from 0 to 200 API, it is more common to see 0 to 100 API and 0 to 150 API used in log presentations, as data greater than 150 API is not common, and can always be handled by the use of wrap-around (log back-off).



Gamma log presentation.

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Depth of Investigation

Compton scattering attenuates the gamma rays *(Once the gamma rays are emitted from an isotope in the formation, they progressively reduce in energy as the result of collisions with other atoms in the rock (compton scattering). Compton scattering occurs until the gamma ray is of such a low energy that it is completely absorbed by the formation.)* by all materials between the atom that emitted the gamma ray and the detector, which includes the rock itself and the drilling mud. The degree of attenuation depends upon the number density of atoms in the material, and this is related to the density of the material. The distribution of gamma ray energies, but at distance from the emitting atom increases, the energy of the gamma rays decreases but Compton scattering until they are too low to be measured by the device counter. Therefore, there is a maximum depth of investigation for the tool depends upon **formation and mud density**. For average values of drilling mud and formation density, we can say that approximately 50% of the gamma ray signal comes from within **18 cm** of the borehole wall, increasing to 75% from within **30 cm**. Hence, the depth of investigation, if defined at **75%** of the signal, is 30 cm. However, this will decrease for denser formations of the same radioactivity, and increase for less dense formations of the same radioactivity. Note that the zone of sensitivity is almost **hemispherical**, so the 30 cm depth of investigation applies both horizontally (perpendicular to the borehole wall) and sub-vertically (sub-parallel with the borehole wall). This has implications for the vertical resolution of the tool.

Borehole Quality

The gamma ray log usually runs centred in the borehole. If the borehole suffers from caving, the gamma ray log can be badly affected. In intervals that suffer from caving, there is more drilling mud between the formation and the gamma ray detector to attenuate the gamma rays that produced by the formation. Hence, the log is underestimated, as shown in Figure below. The corrections of these cases depended on cross plots intersections, but nowadays, the correction became automatically within the tool itself and while the logging.

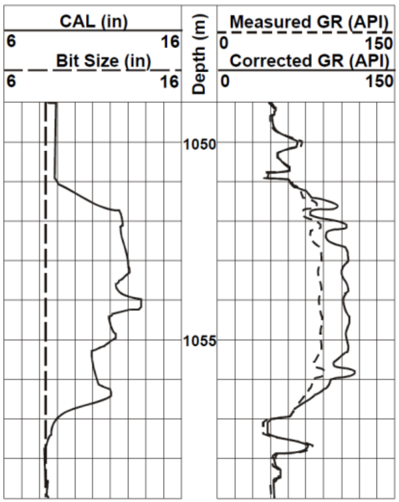

Figure Effect of caving on the gamma ray log.

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Uses of the Total Gamma Ray Log

The gamma ray log is an extremely simple and useful log that is used in all petrophysical interpretations, and is commonly run as part of almost every tool combination. Consequently, every well may have as many as independent sets of gamma ray log data. The high vertical resolution of the gamma ray log makes it extremely useful for depth matching and fine scale correlation. The main uses of the gamma ray log are outlined in the following sections. The first three applications are by far the most important.

Determination of Lithology

The gamma ray log is an extremely useful tool for discrimination of different lithologies. While it cannot uniquely define any lithology, the information it provides is invaluable when combined with information from other logs.

Its main use is the discrimination of shales by their high radioactivity. Figure below shows how different lithologies affect the total gamma ray log. Note that shales, organic rich shales and volcanic ash show the highest gamma ray values, and halite, anhydrite, coal, clean sandstones, dolomite and limestone have low gamma ray values. Care must be taken not to generalize these rules too much. For example a clean sandstone may contain feldspars (arkose sandstones), micas (micaceous sandstones) or both (greywackes), or glauconite, or heavy minerals, any of which will give the sandstone higher gamma ray values than would be expected from a clean sandstone.

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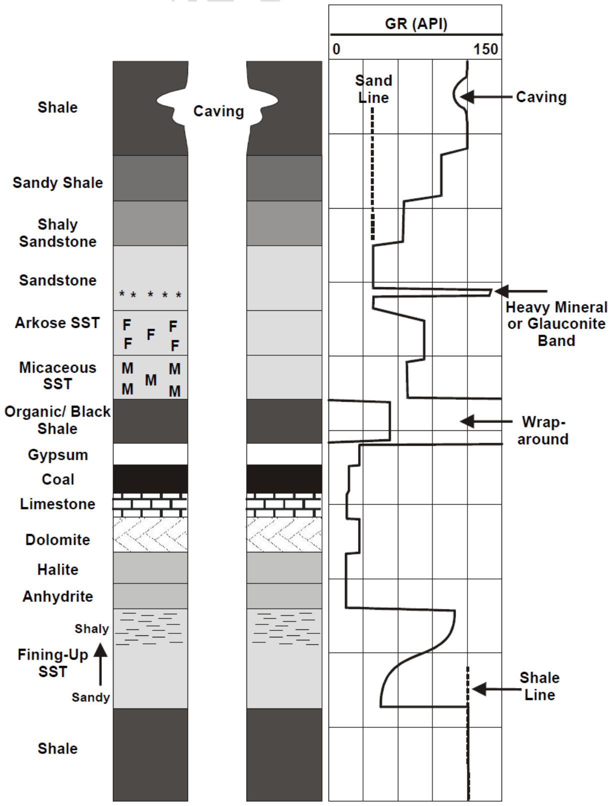

Figure Effect of different lithologies on the gamma ray log.

Determination of Shale Content

In most reservoirs, the lithologies are quite simple, being cycles of sandstones and shales or carbonates and shales. Once the main lithology have been identified, the gamma ray log values can be used to calculate the shaliness or *shale volume* ***Vsh*** of the rock. This is important as a threshold value of shale volume is often used to help discriminate between reservoir and non-reservoir rock. Shale volume is calculated in the following way: First the *gamma ray index IGR* is calculated from the gamma ray log data using the relationship

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

where: IGR = the gamma ray index
GRlog = the gamma ray reading at the depth of interest.
GRmin = the minimum gamma ray reading. (Usually the mean minimum through a clean sandstone or carbonate formation.)
GRmax = the maximum gamma ray reading. (Usually the mean maximum through a shale or clay formation.)

Many petrophysicists then assume that *Vsh* = *IGR*. However, to be correct the value of *IGR* should be entered into the chart shown as Fig. below, from which the corresponding value of *Vsh* may be read.

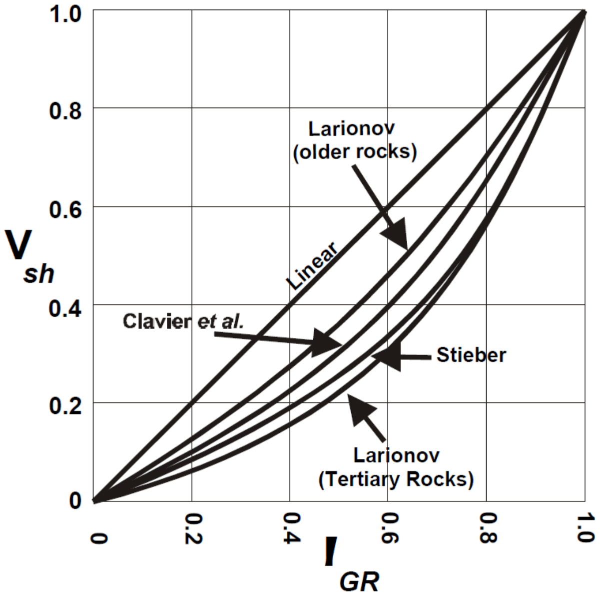

Figure Calculation of shale volume.

On the other hand, we can use the following equations for large data.

$V_{shale} = 0.33\ (2^{2*IGR} - 1)$ ....Old (consolidated) rocks
$V_{shale} = 0.083\ (2^{3.7*IGR} - 1)$........ Tertiary (Unconsolidated) rocks

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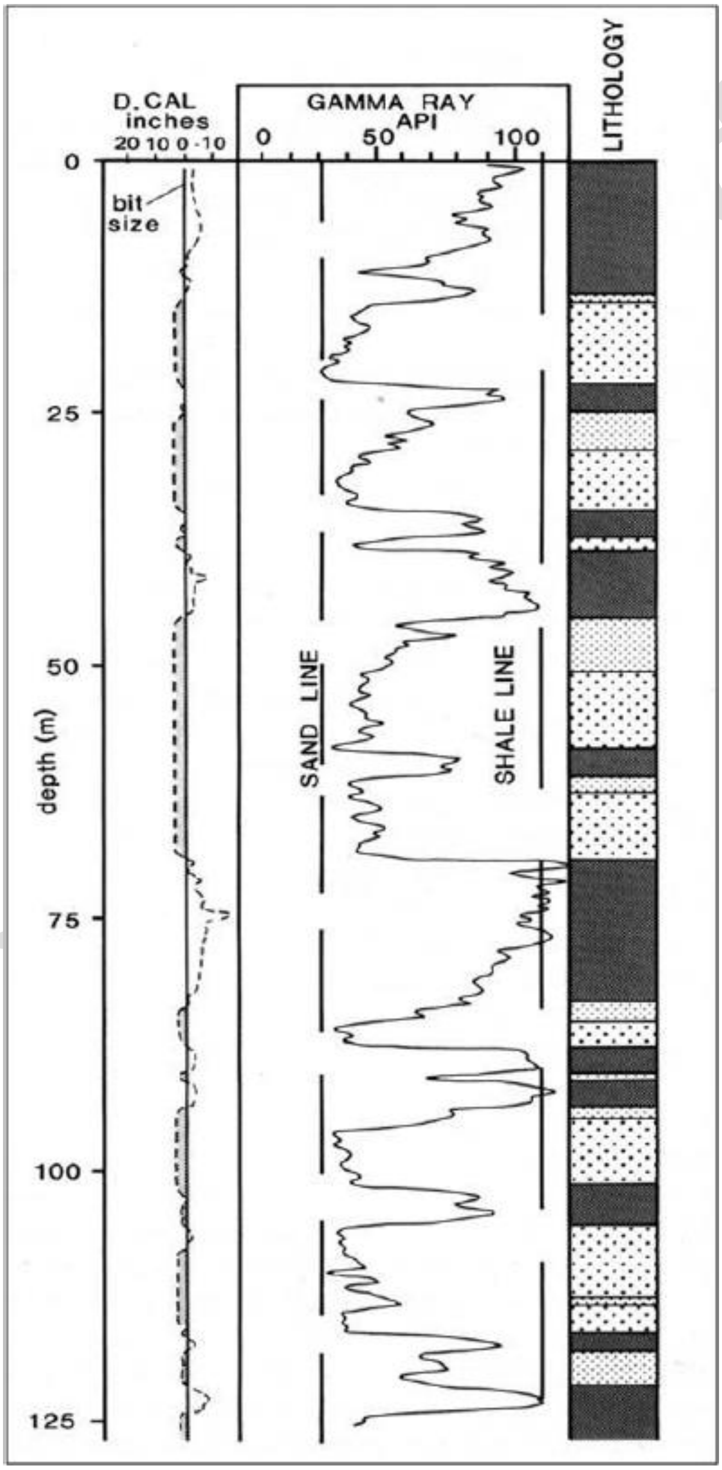
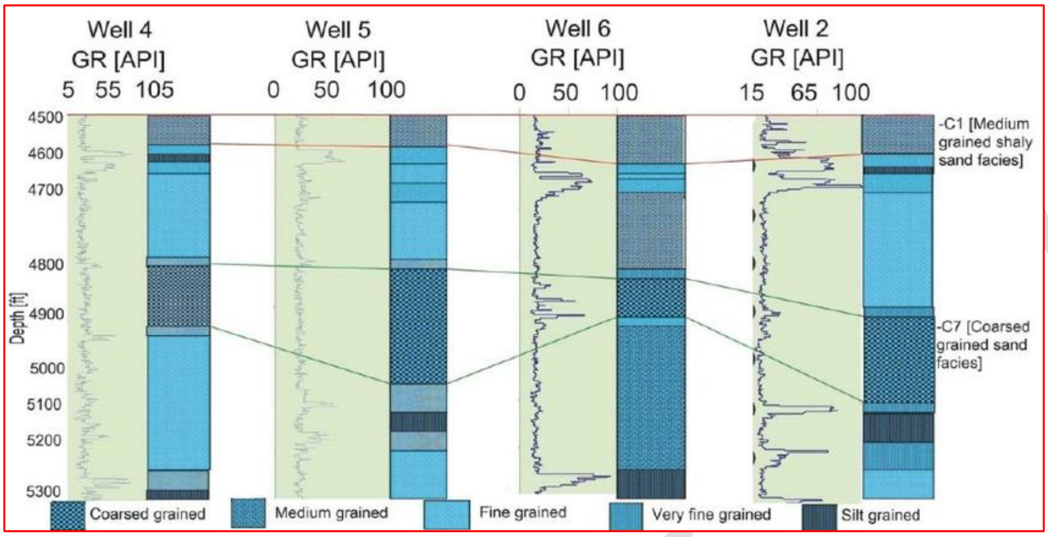
Depth Matching

The gamma ray tool is ❶ run as part of almost every tool combination. It ❷ has a high reliability and a ❸ high vertical resolution. The tool will also ❹ show a useful decrease when opposite casing. For all these reasons, the tools is commonly used to match the depths of data from a given depth interval made at different times with different tool combinations. The depth matching may rely on the characteristic sudden reduction in gamma ray values when the tool encounters the casing of the section of borehole above the interval of interest, but more usually relies on matching the patterns in the gamma ray response from the gamma ray tools run with each tool combination.



Correlations

GR is one of the logs that is used a lot in the similarity of its characteristics and repetition because it is not affected by the depths, its simplicity and giving it some clues about the rocks (Figure below). Because of its use in the correlation.



Recognition of Radioactive and Non-Radioactive Mineral Deposits

The gamma ray log can be used to recognize certain radioactive deposits, the most common of which are potash deposits and uranium ores.

Particular deposits have a very low natural radioactivity. The gamma ray log can also be used to indicate non-radioactive mineral. Formations with extremely low natural radioactivity are the non-radioactive evaporites (salt, anhydrite and gypsum), and coal beds. Note that some evaporites have a large concentration of potassium and can be radioactive.

Facies and Depositional Environment Analysis

We have seen that the gamma ray log is often used to measure the shaliness of a formation. In reality the shaliness often does not change suddenly, but occurs gradually with depth. Such gradual changes are indicative of the litho-facies and the depositional environment of the rock, and are associated with changes in grain size and sorting that are controlled by facies and depositional environment as well as being associated with the shaliness of the rock. Figure below analyses the shape of gamma ray log responses for various depositional environments. All possible combinations of these shapes may be encountered.

The *cylinder shapes* represent uniform deposition and are interpreted as aeolian dune, tidal sand, fluvial and turbidite channel and proximal deepsea fan deposits. The *bell shapes* represent the fining-upward sequences and are interpreted as tidal sand, alluvial sand, fluvial channel, point bar, lacustrine, delta, turbidity channel and proximal deep-sea fan deposits. The *funnel shapes* represent coarsening-upward sequences that are interpreted as barrier bar, beach sand and crevasse splay, distributary mouth bar and distal deep-sea fan deposits.

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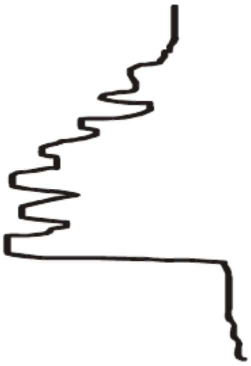
Shape	**Smooth**	**Environments**	**Serrated**	**Environments**
Cylinder Represents uniform deposition.		Aeolian dunes Tidal sands Fluvial Channels		Deltaic distributaries Turbidite channels Proximal deep-sea fans
Bell Shape Fining upwards sequences.		Tidal sands Alluvial sands Braided streams Fluvial channels Point bars		Lacustrine sands Deltaic distributaries Turbidite channels Proximal deep-sea fans
Funnel Shape Coarsening upward sequences.		Barrier bars Beaches Crevasse splays		Distributary mouth bars Delta marine fringe Distal deep-sea fans

Figure The gamma ray log and depositional environments.

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Geophysics Department

2021 – 2022

LECTURE FOUR

Be aware, gamma still radiates

The Formation Density Compensated Log

by

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Introduction

The density log belongs to the group of active nuclear tools, which contains a radioactive source and two detectors.

The formation density log (FDC) is a porosity log, measuring the bulk density of the formation. Its main use is to:

❶ Derive a value for the total porosity of the formation.
❷ It is useful in the detection of gas-bearing formations.
❸ In the recognition of evaporites.
❹ Determine the hydrocarbon density.
❺ Investigate the high-pressure intervals and compaction-depth relationship.
❻ Evaluate the shale and sandstone reservoirs and complicated lithology. Shale, coal, and bentonite beds commonly have low densities and sandstones, and carbonates generally have higher densities. Some typical values are the following:

Grain density of shale: 2.4-2.6 g/cm3
Grain density of sandstone: 2.65 g/cm3
Grain density of limestone: 2.71 g/cm3
Grain density of dolomite: 2.87 g/cm3
Grain density of salt: 2.03 g/cm3
Density of drilling mud: 1-1.1 g/cm3
Density of water: 1.0 g/cm3

The formation density tools are induced radiation tools. They bombard the formation with radiation and measure how much radiation returns to a sensor.

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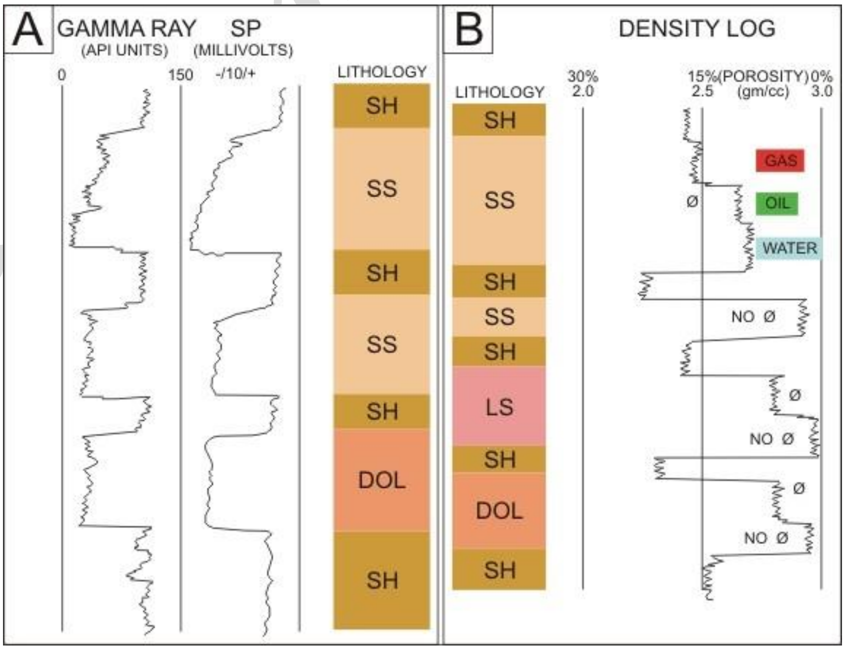

Theory:

The tool of density measurement consist of radioactive source, mainly Ce^{137} or Co^{60} *(Caesium-137 and Cobalt-60)* to detect the formation density (ρ_b or **RHOB**), with two detectors. One of these detectors is near from the source to detect the mudcake density (ρ_{mc}) or very shallow depth in the formation and is placed 7 inches from the source, while the other is far that detect the ρ_b, and is placed 16 inches from the source. This tool depended on two sensors to compensate the effects of the wellbore diameter, where the two values of the two sensors are combined and compared to calculate the radiation ratio. The near sensor records the effects of the contaminated area of the well that will be removed from the far sensor reading to represent the formation density. This operation will compensate the wellbore diameter variations, and as a result the **environmental effects**.

The gamma rays enter the formation and undergo Compton scattering by interaction with the electrons in the atoms composing the formation. Compton scattering reduces the energy of the gamma rays in a step-wise manner, and scatters the gamma rays in all directions. When the energy of the gamma rays is less than 0.5 MeV ***(1 MeV, 1 megaelectronvolt = 1,000,000 eV)*** they may undergo photo-electric absorption by interaction with the atomic electrons. The flux of gamma rays that reach each of the two detectors is therefore attenuated by the formation, and the amount of attenuation is dependent upon the density of electrons in the formation.

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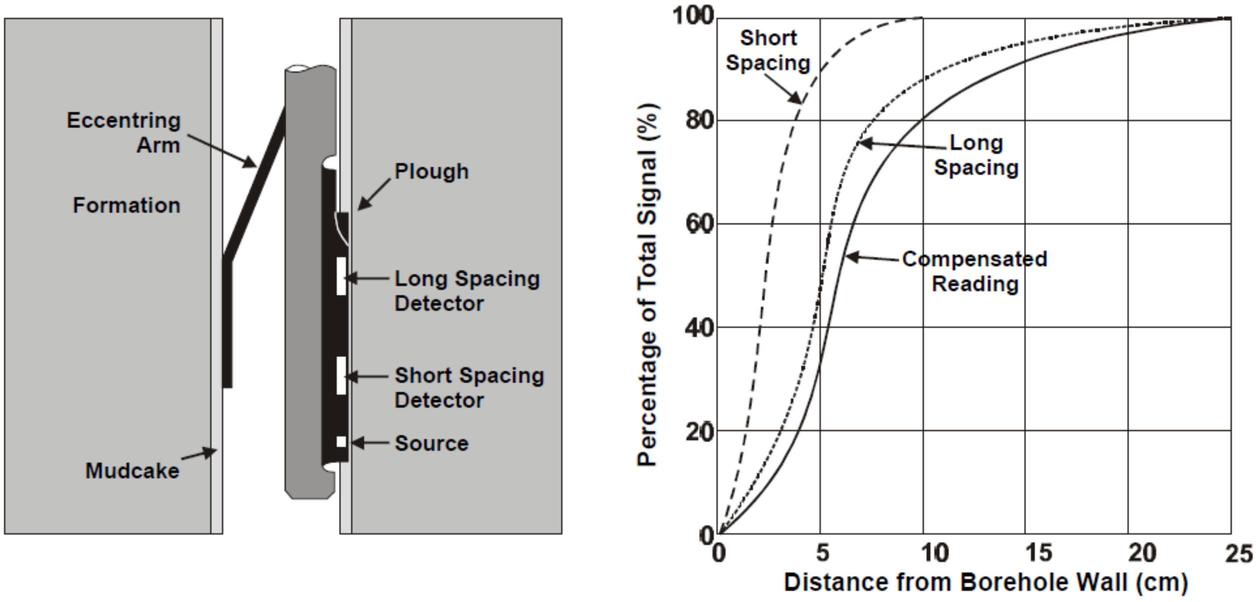

Schematic diagram of a formation density tool.

A formation with a high bulk density has a high number density of electrons. It attenuates the gamma rays significantly, and hence a low gamma ray count rate is recorded at the sensors. A formation with a low bulk density has a low number density of electrons. It attenuates the gamma rays less than a high-density formation, and hence a higher gamma ray count rate is recorded at the sensors.

Log Presentation

The formation density log is recorded in tracks 2 and 3 of the standard API log presentation on a linear scale. The scale is in g/cm3, and usually spans **1.95 to 2.95 g/cm^3** as this is the normal range for rocks. The automatic compensation (correction) for mudcake is often shown in either track 2 or track 3 on a linear scale (**DRHO**). This curve is included as a quality control curve. If the correction curve is greater than ±0.15 g/cm3, the data in the main curve will not be very reliable. As the formation density tool is a log that is commonly used to calculate porosity, a pseudo-porosity that has been calculated from the density data may be shown together with the bulk density curve and correction curve. This is a pseudo-porosity curve because it will assume a matrix and fluid density to be constant throughout the logged interval. Matrix densities of 2.65 g/cm3 (for quartz) and fluid densities of 1.1 g/cm3 (for salt water) are often used.

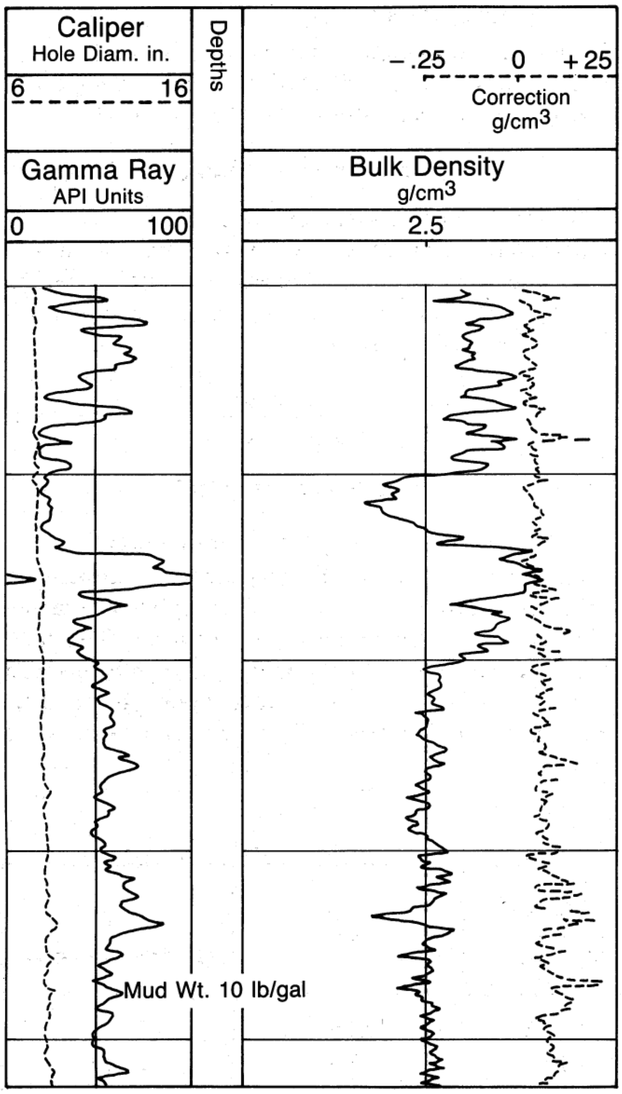

Figure Formation density tool log presentation.

The formation density tool is most often run in combination with ❶ a gamma ray log, for depth matching, ❷ a caliper log, for borehole quality control, and ❸ a neutron log,

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because the interpretation of the formation density tool together with the results from the neutron log provide one of the two best lithological assessment techniques for a reservoir.

Depth of Investigation

The depth of investigation of the tool is very shallow. For Schlumberger's FDC tool 90% of the response comes from the first 13 cm (5 inches) from the borehole wall for a 35% porosity sandstone (which has low density compared with most reservoir rocks). In higher density rocks the depth of investigation is even less, and a value of about 10 cm (4 inches) can be taken as an average value for reservoir rocks. In the first figure in this lecture shows the percentage of the signal that comes from different depths into the formation.

The shallow depth of investigation of the tool makes it sensitive to borehole quality, and it is therefore necessary to interpret the formation density log together with the caliper log to ensure that the measured values is not an artefact (unsubstantial) of bad hole quality. The shallow depth of investigation also implies that in porous and permeable formations, where its main use lies, it only measures the invaded zone. This should be taken into consideration when deciding on a fluid density (mud filtrate density) to use for porosity calculations.

The fact that the tool only measures the invaded zone in porous formations makes the tool little use for distinguishing between formation oil and formation water. However, gas may still be detected because ❶ the greater difference in density between gas and oil or water, and ❷ the fact that mud filtrate invasion into gas bearing zones is never complete, and always leaves a significant amount of gas behind in the invaded zone.

Vertical Resolution

The vertical resolution at the typical logging speed (1300 ft/hr) is good (about 26 cm, 10 inches), which is defined by the distance between the two detectors. The measurement point is taken to be half way between the two detectors. The reaction of this logging tool to very thin beds of anomalously high or low density is sometimes encountered for thin (5 – 10 cm thick) layers of calcareous nodules. *The high vertical resolution means that the log is useful for defining formation boundaries.*

Uses of the Formation Density Log

There are two main uses of density log, which they quantitative and qualitative. The former mainly represent by porosity determination, in addition to hydrocarbon density and acoustic impedance calculation. While the later, contains many uses will be explained later in this lecture.

Determination of Porosity

The porosity φ_{den} of a formation can be obtained from the bulk density if the mean density of the rock matrix and that of the fluids it contains are known. The bulk density ρb from log readings of a formation can be written as a linear contribution of the density of the rock matrix ρma and the fluid density ρf, as:

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

The fluid densities are usually available from RFT sampling, but values of 1.0 g/cm3 for fresh water and 1.1 g/cm3 for salt water are often used. Remember that the tool measures the invaded zone, so the relevant fluid is the mud filtrate in most circumstances. If available, the fluid densities should be corrected to borehole temperature conditions.

The value of the matrix density taken depends upon the lithology of the interval under question. For sandstones, the density of quartz is 2.65 g/cm3, and for limestones, the density of calcite is 2.71 g/cm3. Clay minerals have varied grain densities. Often core data is used to provide accurate matrix densities for particular intervals. Table below gives the matrix densities of some common minerals.

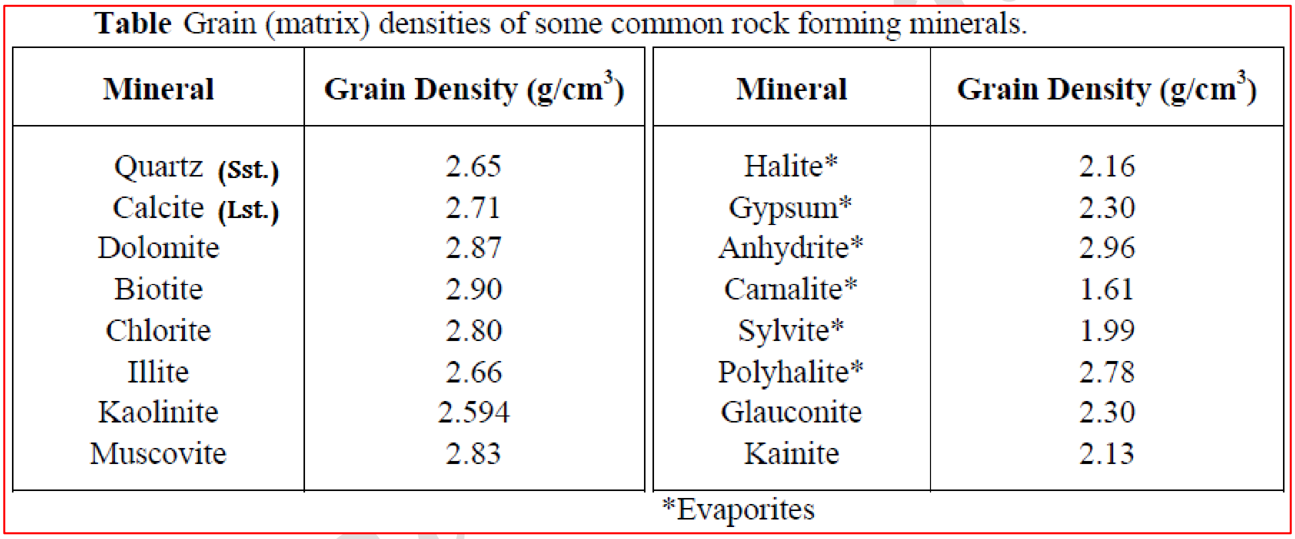

Table Grain (matrix) densities of some common rock forming minerals.

Mineral	Grain Density (g/cm^3)	Mineral	Grain Density (g/cm^3)
Quartz **(Sst.)**	2.65	Halite*	2.16
Calcite **(Lst.)**	2.71	Gypsum*	2.30
Dolomite	2.87	Anhydrite*	2.96
Biotite	2.90	Carnalite*	1.61
Chlorite	2.80	Sylvite*	1.99
Illite	2.66	Polyhalite*	2.78
Kaolinite	2.594	Glauconite	2.30
Muscovite	2.83	Kainite	2.13

*Evaporites

Care must be taken within some lithological intervals because the composition of the matrix may change. For example, the grain density for a clean sandstone is that of quartz (2.65 g/cm3). However, if there is a variable amount of biotite present mixed in with the sand, the bulk density of the rock can rise to 2.84 g/cm3 because biotite has a density of 2.9 g/cm3.

The Effect of Gas

If gas is present in the formation, porosities can be overestimated. The density of gasses is very low (approximately 0.0001 g/cm3) compared to aqueous fluids. If the formation is gas-bearing a significant amount of gas is always left in the invaded zone. This gas will reduce the mean fluid density of the invaded zone, and will cause overestimations of the porosity if a fluid density of 1.0 or 1.1 g/cm3 is used. While in oil-bearing zones, (the density of oil approximately 0.7 g/cm3) this problem is less take place.

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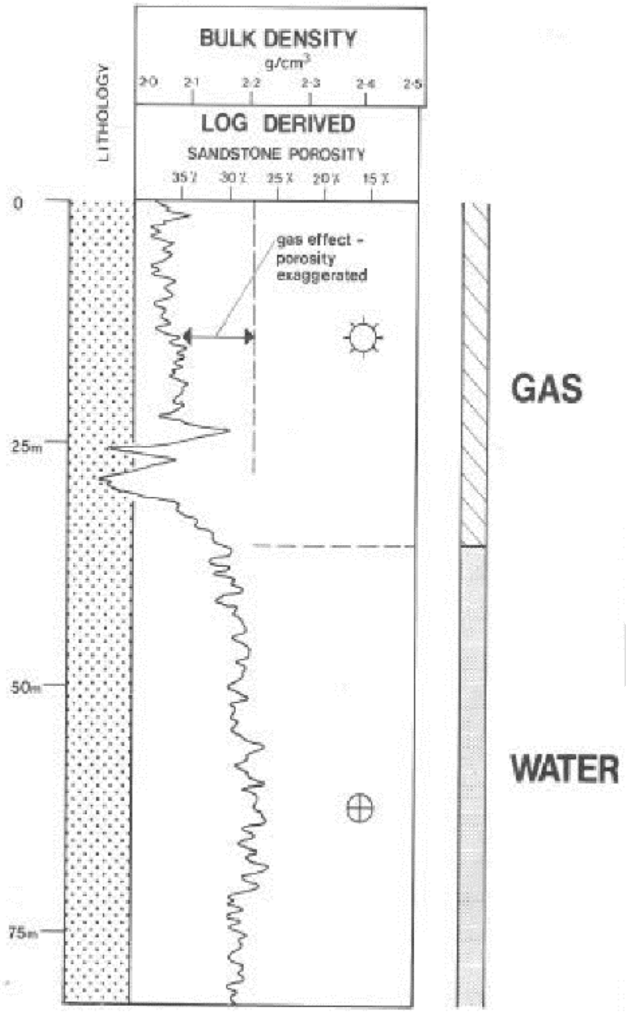

Figure The effect of gas on the formation density log.

Identification of Lithology

When used alone, the density log is not a good tool for identifying most lithology types. This is because most rocks have a wide range of densities resulting from their varied mineralogical compositions and their variable porosities. For example, shales have bulk densities ranging from 1.8 to 2.8 g/cm3 and have variable clay mineral densities. Sandstones, limestones and dolomites all have bulk density ranges that overlap each other. *However, when used with the neutron log, the combination is a very good lithological determination method*. On the other hand, evaporites are often found in a very pure state, and have clearly defined densities.

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2021 – 2022

LECTURE FIVE

CNL

by

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The last stand of exploration

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Introduction

The *neutron* log is sensitive mainly to the amount of **hydrogen** atoms in a formation. Its main use is in the determination of the **porosity** of a formation.

The tool operates by **bombarding** the formation with **high-energy neutrons**. These neutrons undergo scattering in the formation, **losing** energy and **producing high-energy gamma rays**.

The scattering reactions occur most efficiently with hydrogen atoms. The resulting **low energy neutrons** (i.e. gamma rays) can be detected, and their count rate is related to the **amount of hydrogen atoms in the formation**.

In formations with a large amount of hydrogen atoms (i.e. **high-porosity** intervals), the neutrons slow down and absorb very quickly and in a short distance. The count rate of slow neutrons or capture gamma rays is **low** in the tool. Hence, the **count rate will be low** in **high porosity** rocks or formations.

In formations with a small amount of hydrogen atoms (i.e. low-porosity intervals), the neutrons are slowed down and absorbed more slowly and travel further through the rock before being absorbed. The count rate of slow neutrons or capture gamma rays in the tool is therefore higher. Hence, the count rate will be higher in low porosity rocks.

Theory

The neutrons are electrically neutral and their mass approximates the mass of the hydrogen nucleus, and it interacts with the material in two ways:

- Collision, when the neutrons have high energy.
- Absorption, in low energy case.

Neutrons are characterized by three states depending on their velocity, as they are initially very fast and then diminish after that due to the loss of part of their energy, these stages are:

1. Neutron Emission when they released in a **fast state**.
2. In a collision, **slowing** speed takes place in an epithermal state.
3. In the thermal state the **spreading** lead to diffusion and capture of the neutrons.

Hence, in neutron logging, there are three processes of interest: ***neutron emission***, ***neutron scattering*** and ***neutron absorption*** depending on the stage and velocity.

Tool Operation

There are three main types of neutron tool, which are:

1. The Gamma Ray/Neutron Tool (GNT)
2. The Sidewall Neutron Porosity Tool (SNP)
3. The Compensated Neutron Log (CNL)

   This tool is designed to be sensitive to thermal neutrons. It has two detectors situated 15 and 25 inches from the source.

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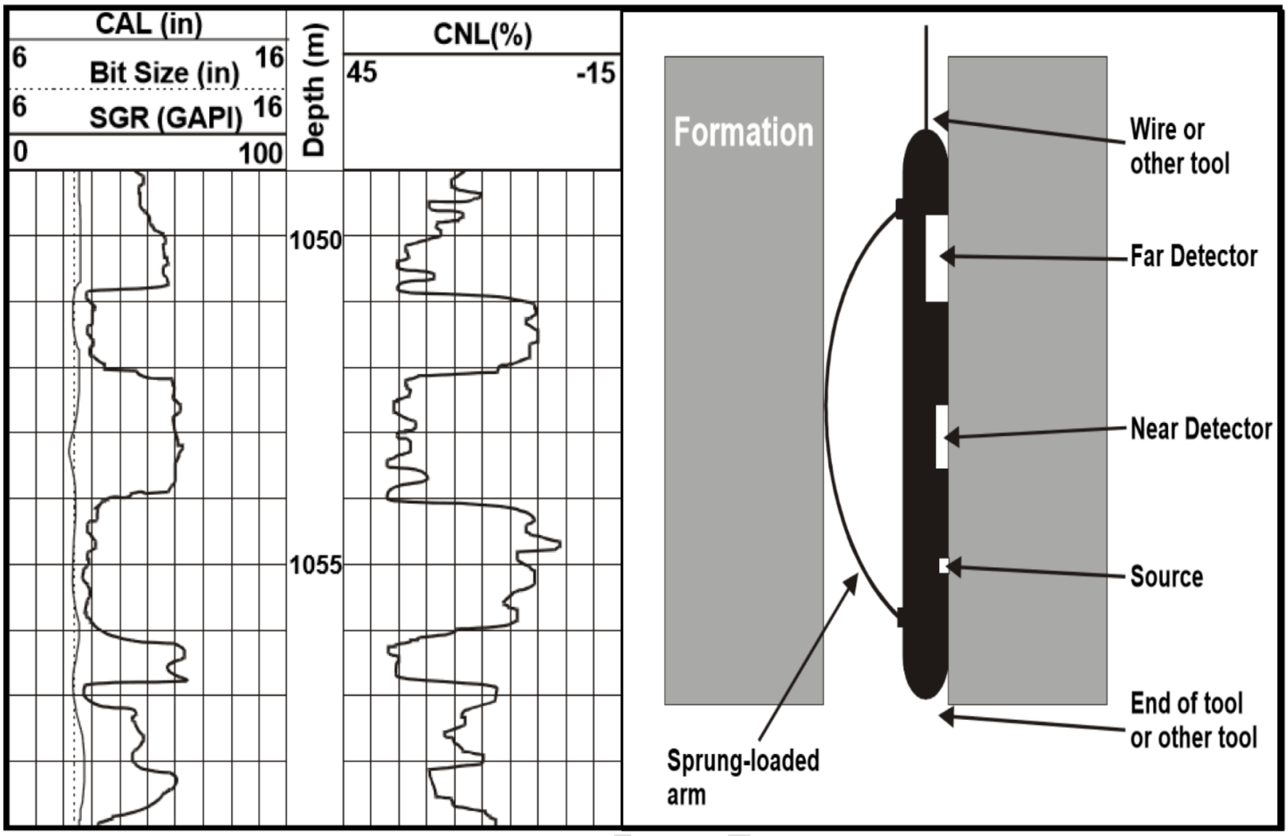
Tool Details and Log Presentation



Depth of Investigation

- The depth of penetration of the tool readings depends directly upon the amount of hydrogens in the formation. Thus, for porous rocks that contain water or hydrocarbons (i.e., **many hydrogens**), there is **much** neutron **scattering** and **absorption**, and hence the **depth of investigation is small**. For low porosity rocks containing water or hydrocarbons, there are fewer hydrogens in the formation and the depth of investigation is larger.
- The presence of gas in a formation increases the depth of investigation because, although the gas may contain hydrocarbons, the gas has a **very low density** compared to liquid water and oil, and hence a **very low hydrogen index**.
- The presence of shales decreases the depth of investigation because even low porosity shales contain many waters (i.e., hydrogen) that are bound to the surface of the clay crystals.

The depth of investigation of the CNL tool in a water saturated formation of 35% porosity is about 12 inches.

Uses of the Neutron Log

A neutron tool is used quantitatively to measure porosity, either qualitatively the log is excellent in distinguishing gas from oil as well as recognition of the gross lithology of rock like evaporites and volcanic rocks, and when used with the density log it is one of the best detectors of subsurface rock, as illustrated in the Table below.

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Table. The principal uses of the neutron log.

	Discipline	Used for	Knowing
Quantitative	Petrophysics	Porosity	Matrix Hydrogen index
Qualitative	Petrophysics	Identification of gas	Lithology
	Geology	Lithology – shales Evaporites Hydrated minerals Volcanic and intrusive rocks General lithology	Gross lithology Neutron evaporite values Calibration Combined with density*

*using neutron log combined with density log on compatible scales.

Determination of Porosity

The main use of the neutron log is to provide porosity information. The tool is sensitive to the amount of hydrogens in the formation and to a less extent upon other elements. It is assumed that the measurement of elements is negligible, and that the contribution to the measurement from hydrogen comes entirely from the fluids fully occupying the pore space.

There are some effects that are not corrected for the log data, that need to be briefly mentioned.

Gas Effects. However, has a much lower hydrogen index resulting from its low density, and its presence will give rise to *underestimations* in porosity (Fig. below). While the presence of hydrocarbon as **liquid** (**oil**) does not affect the tool response as it has approximately the same hydrogen index as fresh water.

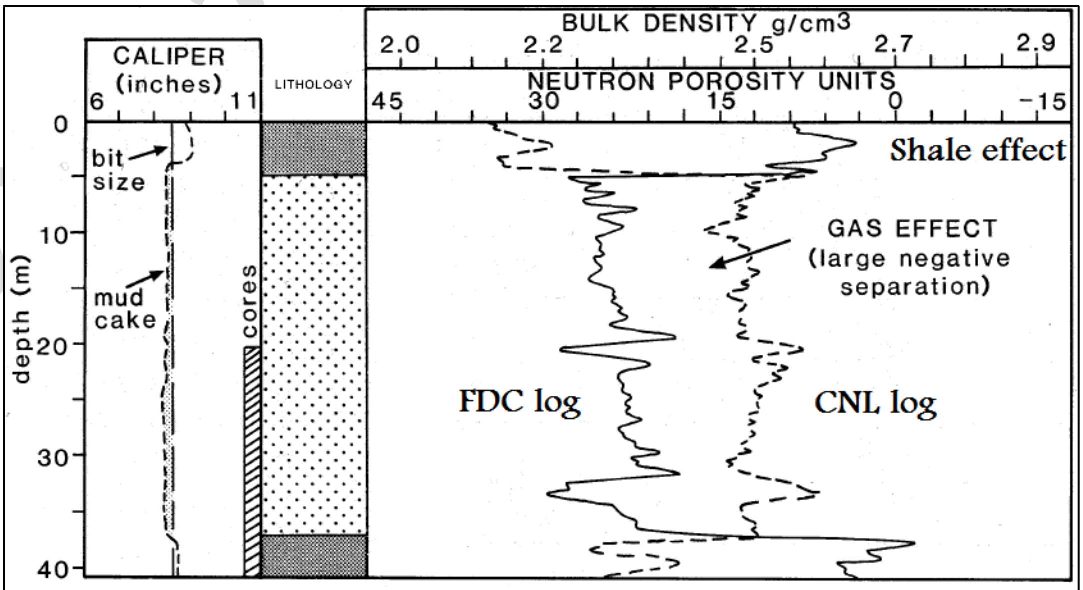

Figure The Hydrocarbon gas effect in the neutron log.

The Shale Effect. Shale contain clays that have a significant amount of bound water molecules on their surfaces. This increases the hydrogen index of the formation. Even very low porosity shales can give erroneously high porosity readings due to the presence of these bound waters.

Determination of Lithology

The direct use of the neutron log to identify lithology depends upon the recognition of which lithology may contain hydrogen atoms (Figure below shows typical log responses in common lithology).

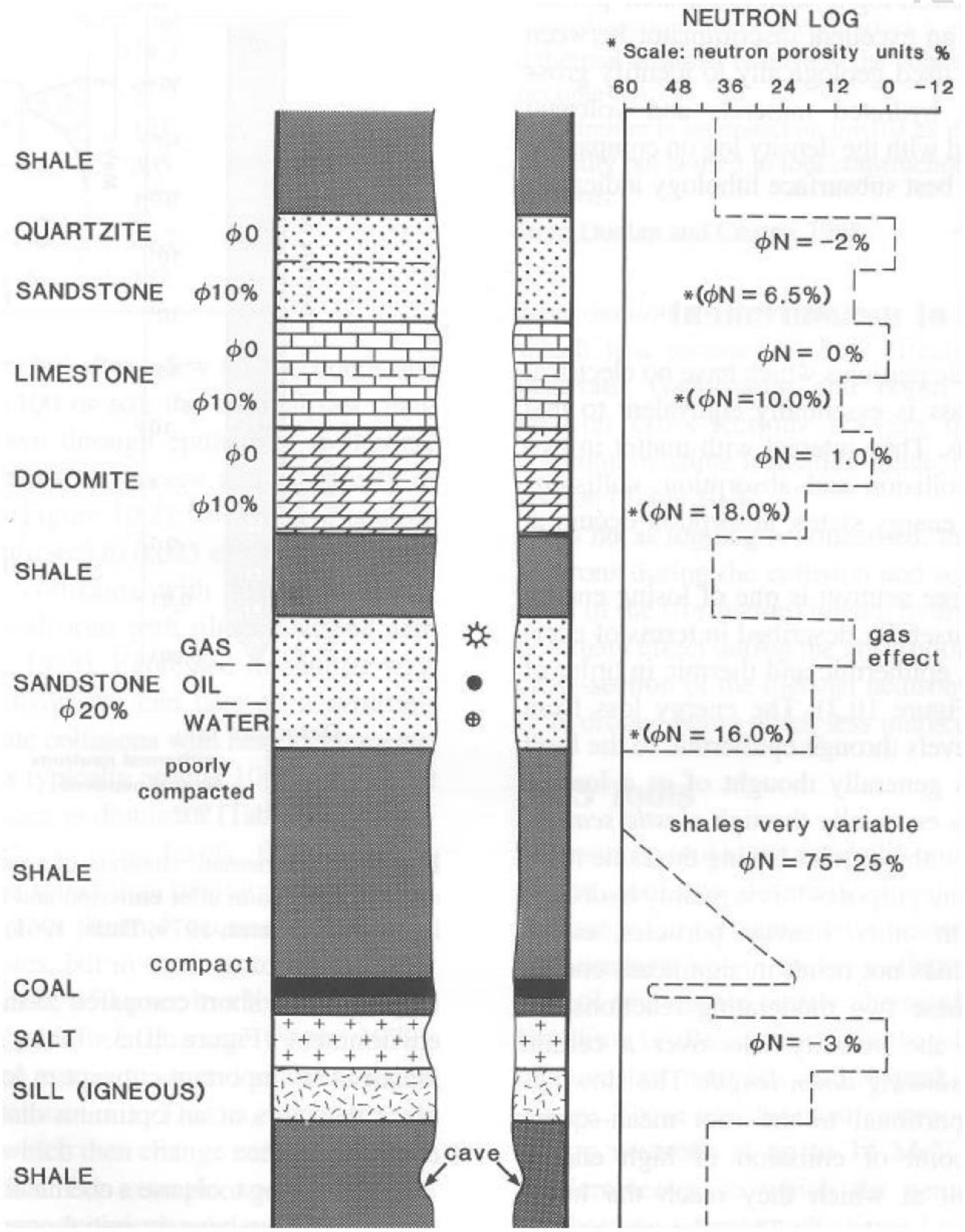

Figure Typical neutron log responses in common lithologies.

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LECTURE SIX

BHC

by

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The last stand of exploration

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Introduction:

The *sonic* or *acoustic* log measures the travel time of an elastic wave through the formation. This information can also be used to derive the velocity of elastic waves through the formation. Its main use is to provide information to support and calibrate seismic data and to derive the porosity of a formation. The main uses are:

Provision of a record of “seismic” velocity and travel time throughout a borehole. This information can be used to calibrate a seismic data set (i.e., tie it in to measured values of seismic velocity).

- Provision of “seismic” data for the use in creating synthetic seismograms.
- Determination of porosity (together with the FDC and CNL tools).
- Stratigraphic correlation.
- Identification of lithologies.
- Facies recognition.
- Fracture identification.
- Identification of compaction.
- Identification of over-pressures.
- Identification of source rocks.

Theory:

The Sonic Log records the average time needed to pass a compressional sound wave one-foot of strata. This time is known as ***Interval Transit Time*** **(Δt, delta t, or DT)** and measure in **μsec/ft.** The interval transit time is dependent upon both lithology and porosity. Therefore, a formation's matrix velocity (Table below) must be known to derive sonic porosity either by chart or by equation.

Table. Sonic Velocities and Interval Transit Times for Different Matricies. These constants are used in the Sonic Porosity Formula.

	V_{ma} (ft/sec)	Δt_{ma} (μsec/ft)	Δt_{ma} (μsec/ft) commonly used
Sandstone	18,000 to 19,500	55.5 to 51.0	55.5 to 51.0
Limestone	21,000 to 23,000	47.6 to 43.5	47.6
Dolomite	23,000 to 26,000	43.5 to 38.5	43.5
Anhydrite	20,000	50.0	50.0
Salt	15,000	66.7	67.0
Casing (Iron)	17,500	57.0	57.0

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Borehole Compensated Sonic (BHC) Tool

These devices greatly reduce the spurious effects of borehole size variations, as well as errors due to tilt of the sonic tool. The tool compensates automatically for problems with tool misalignment and the varying size of the hole (to some extent) that were encountered with the dual receiver tools. It has two transmitters and four receivers, arranged in two dual receiver sets, but with one set inverted (i.e., in the opposite direction). Each of the transmitters is pulsed alternately, and Δt values are measured from alternate pairs of receivers (Fig. below). These two values of Δt are then averaged to compensate for tool misalignment, at to some extent for changes in the borehole size. A typical pulse for the BHC is 100 ms to 200 ms, with a gap of about 50 ms, giving about 20 pulses per second. There are four individual readings per measurement, so 5 measurements can be made per second. At a typical logging speed of 1500 m/h (5000 ft/h), gives one reading per 8 cm (3 inches) of borehole.

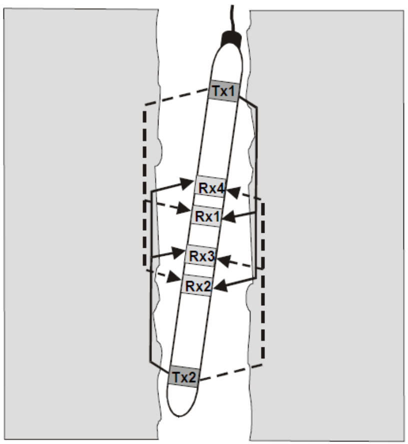

Fig. Borehole compensated sonic tools.

Log Presentation

The interval transit time **Δt** is recorded on the log in microseconds per foot (ms/ft.). If the log is run on its own, the log takes up the whole of Track 2 and 3, if combined with other logs, it is usually put in Track 3 (Fig. below). Most formations give transit times between 40 ms/ft. and 140 ms/ft., so these values are usually used as the scale.

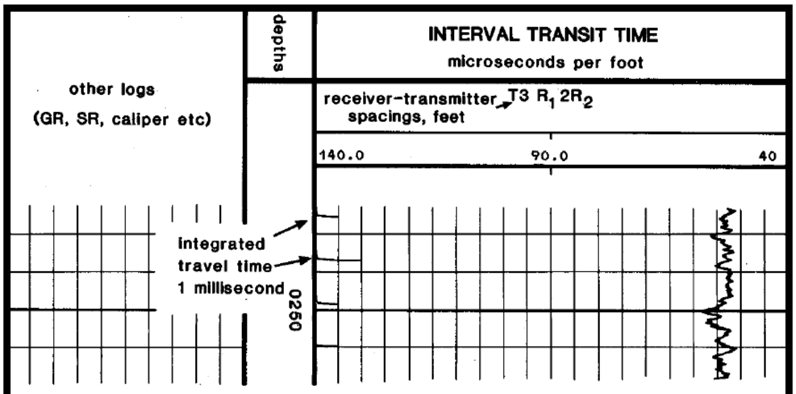

Fig. Presentation of the sonic log.

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Vertical and Bed Resolution

The vertical resolution is equal to the Rx-Rx spacing, and hence is 2 ft. Beds less than this thickness can be observed, but will not have the clear and fully developed signal.

Uses of the Sonic Log

Seismic Data Calibration

The presence of a sonic log in a well that occurs on a seismic line or in a 3D survey enables the log data to be used to calibrate and check the seismic data. However, the higher resolution of the sonic log may enable the log information to resolve indications of beds that are just beyond the resolution of the seismic technique.

Seismic Interval Velocities

The time-depth curve of the sonic can be compared against the velocity analyses from the seismic data, or can be used in place of velocity analyses in seismic processing.

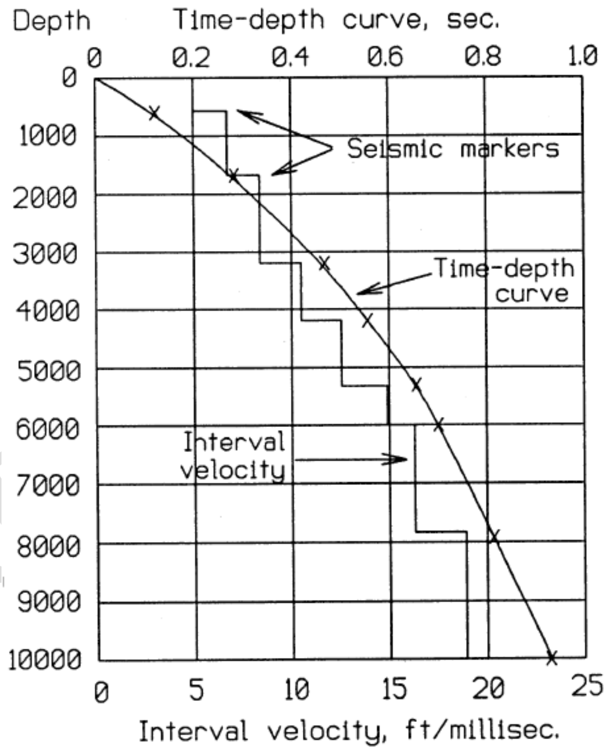

Fig. Interval velocity and time-depth graphs.

Synthetic Seismograms

A synthetic seismogram is a seismic trace that has been constructed from various parameters obtainable from log information. It represents the seismic trace that should be observed with the seismic method at the well location. It is useful to compare such a synthetic seismogram with the seismic trace actually measured at the well to improve the picking of seismic horizons, and to improve the accuracy and resolution of formations of interest. It should be remembered that the observed seismic trace is

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primarily a record of the ability of interfaces between formations to reflect elastic waves. This ability is called the **reflection coefficient *R***. The reflection coefficient depends upon the properties of the rock either side of the interface, and in particular on its acoustic impedance. The acoustic impedance is the product of the seismic velocity and the density of the rock.

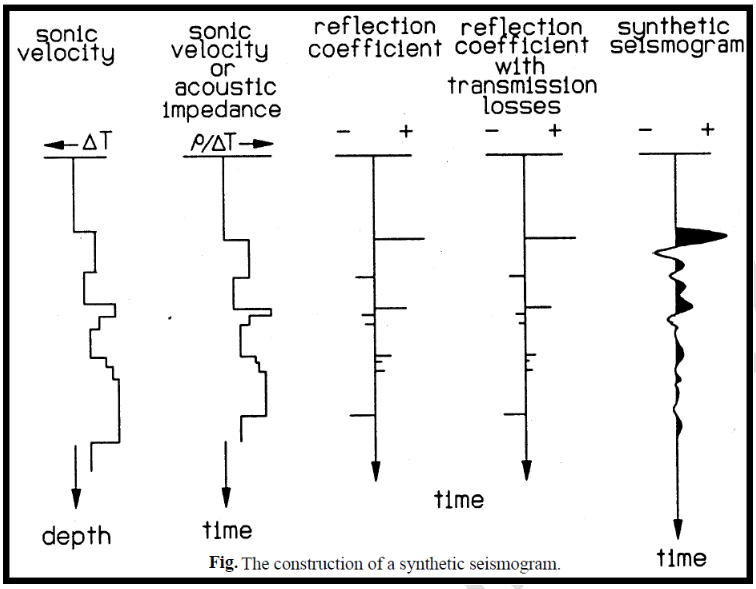

Fig. The construction of a synthetic seismogram.

Porosity Determination

As previously detailed, the sonic log is commonly used to calculate the porosity of formations, however the values from the FDC and CNL logs are superior. It is useful in the following ways:

- As a quality check on the FDC and CNL log determinations.
- As a robust method in boreholes of variable size (since the sonic log is relatively insensitive to caving and wash-outs etc.).
- To calculate secondary porosity in carbonates.
- To calculate fracture porosity.

The Wyllie Time Average Equation:

The porosity formula for calculating sonic porosity can be used to determine porosity in consolidated sandstones and carbonates with intergranular porosity (grainstones) or intercrystalline primary porosity (dolomites). However, when sonic porosities of carbonates with vuggy or fracture porosity are calculated by the this formula, porosity values will be too low. This will happen because the sonic log only records matrix porosity rather than vuggy or fracture secondary porosity. The percentage of vuggy or fracture secondary porosity can be calculated by subtracting *sonic porosity* from *total porosity*. Total porosity values are obtained from one of the nuclear logs (i.e. density or neutron). The percentage of secondary porosity, called SPI or secondary porosity index, can be a useful mapping parameter in carbonate exploration. So the formula is

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used perfectly in consolidating sandstone rock, while in limestone the secondary porosity is the dominant, the porosity values will be too low than the real.

$$\phi_{sonic} = \frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

- Φ_{sonic} = sonic derived porosity.
- **Δt** $_{ma}$ = interval transit time of the matrix (Table above).
- **Δt** $_{log}$ = interval transit time of formation.
- **Δt** $_f$ = interval transit time of the fluid in the wellbore (fresh mud = 189; salt mud = 185).

Where a sonic log is used to determine porosity in unconsolidated sands, an empirical compaction factor or Cp should be added to the equation:

$$\phi_{sonic} = \left(\frac{\Delta t_{log} - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}\right) \times 1/Cp$$

Where:

- Φ_{sonic} = sonic derived porosity.
- **Δt** $_{ma}$ = interval transit time of the matrix (Table above).
- **Δt** $_{log}$ = interval transit time of formation.
- **Δt** $_f$ = interval transit time of the fluid in the wellbore (fresh mud = 189; salt mud = 185).
- **Cp**= compaction factor

The compaction factor is obtained from the following formula:

$$Cp = \frac{\Delta t_{sh} \times C}{100}$$

Where:

- Cp = compaction factor
- **Δt** $_{sh}$ = interval transit time for adjacent shale
- C = a constant which is normally 1.0.

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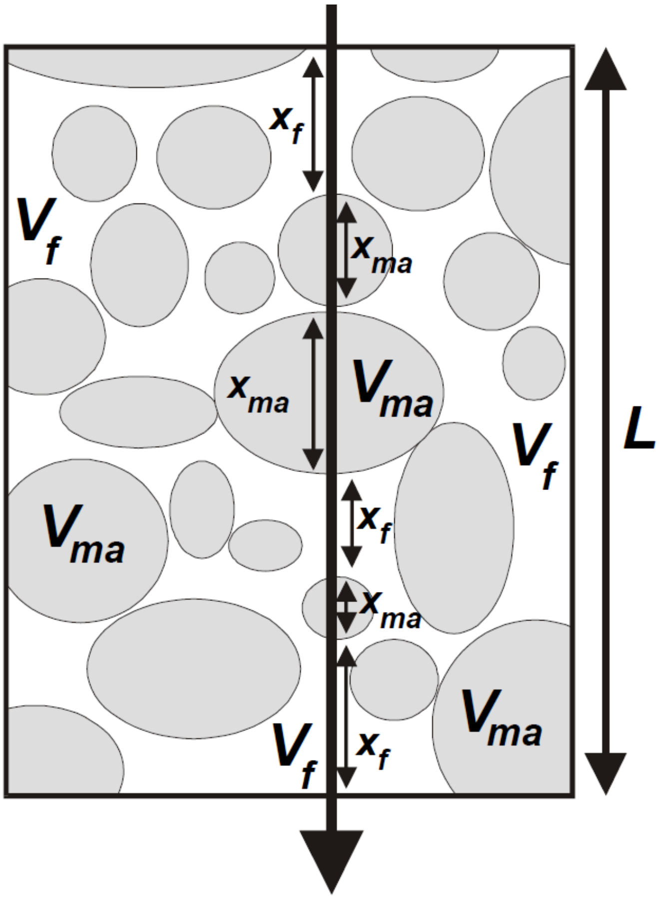

Fig. The wave path through porous fluid saturated rocks.

The Raymer-Hunt Equation:

Another method for calculating the porosity from the sonic log was proposed by Raymer. This is expressed as:

$$\frac{1}{\Delta t} = \frac{\phi}{\Delta t_f} + \frac{(1-\phi)^2}{\Delta t_{ma}}$$

Where:

- Φ = sonic derived porosity.
- **Δt** $_{ma}$ = interval transit time of the matrix (Table above).
- **Δt** = interval transit time of formation.
- **Δt**$_f$ = interval transit time of the fluid in the wellbore (fresh mud = 189; salt mud = 185).

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This provides a much superior accuracy porosity over the entire range of geologically reasonable **Δt**. Figure below shows the Raymer-Hunt equation for some typical lithologies.

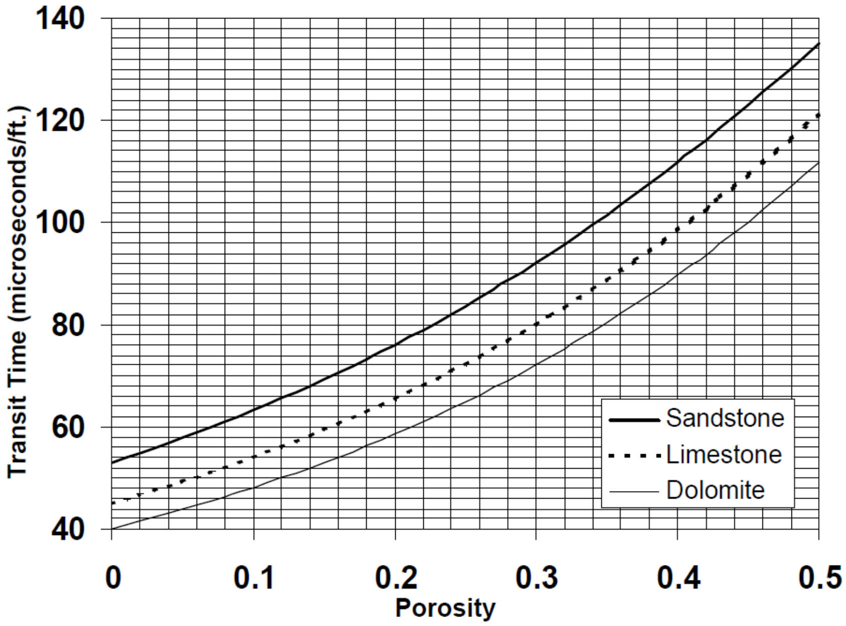
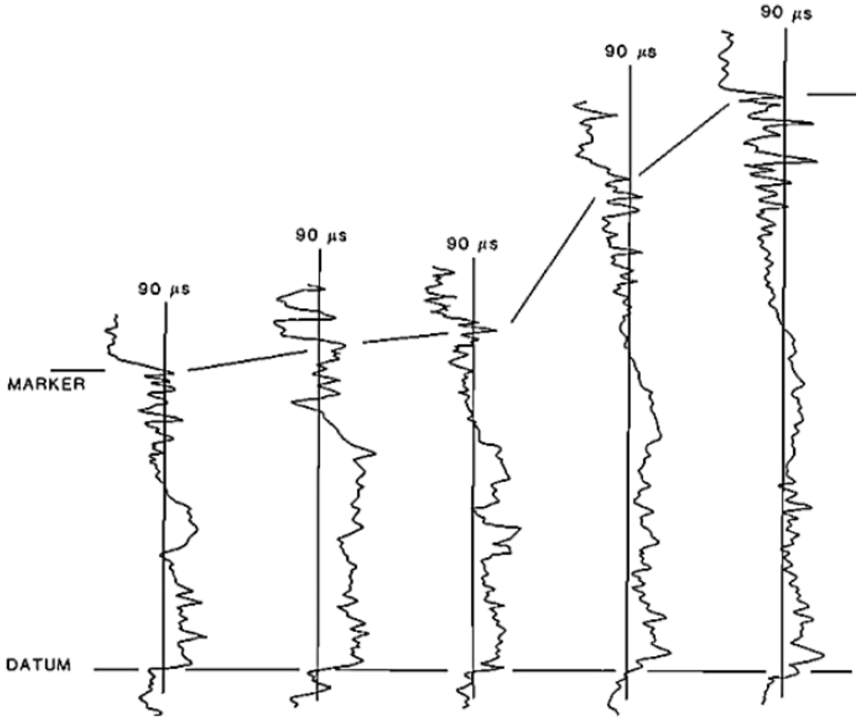


Fig. The Raymer-Hunt equation for calculating porosity from transit time. Here the following data have been used: $\Delta t = 53$ (sandstone matrix), 45 (limestone matrix), 40 (dolomite matrix), 186 (fluid), all in µs/ft.

Stratigraphic Correlation

The sonic log is sensitive to small changes in grain size, texture, mineralogy, carbonate content, quartz content as well as porosity. This makes it a very useful log for using for correlation and facies analysis (Fig. below).



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Identification of Lithology

The velocity or interval travel time is rarely diagnostic of a particular rock type. However, high velocities usually indicate carbonates, middle velocities indicate sands and low velocities, shales. The sonic log data is diagnostic for coals, which have very low velocities, and evaporites, which have a constant, well recognized velocity and transit time (see Table above). It is best to use the sonic log with other logs if lithological identification is important. The main characteristics of the sonic log are shown in Fig. below.

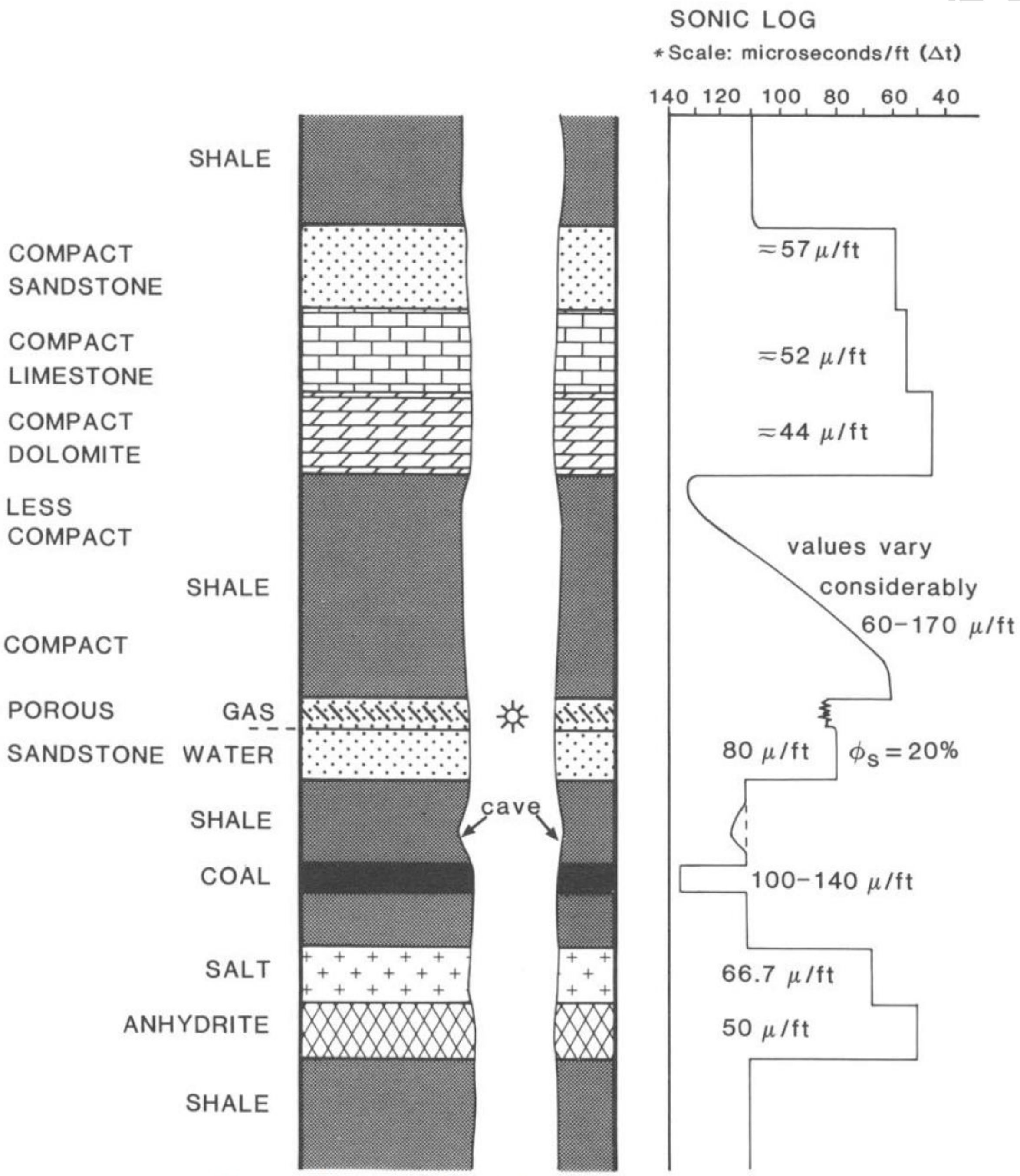

Fig. Typical responses of the sonic log.