Course Title: Wells Log (well logging)

Objectives:

At the end of this course, the students should be able to understand the basics of wells log, theory of measurements, interpretations and applications of the different types of wire line logs. Students should also know how to calculate the petrophysical parameters required for formation evaluation (source and reservoir rocks).

Course construction:

1 Introduction
2 Borehole Environment & Recording Formats of logs
3 Electrical Logs
4 Radioactive Logs
5 Acoustic Logs
6 Thermal Logs
7 Imaging logs
8 Interpretation of Wire line Logs
9 Application of well logging in different fields (formation evaluation)

References:

Asquith, G. and Krygwski, D. (2004): Basic well log analysis" The American Association of Petroleum Geologists, Tulsa, Oklahoma.

Rider, M.H. (1996):"The geological interpretation of well logs" 2nd edition, Blackie and Son Limited, London, UK.

Schlumberger (1987): "Principles and application of well logs" Schlumberger Ltd., France.

REFERENCES

1. Allaud L, Martin M (1977) Schlumberger: the history of a technique. Wiley, New York
2. Segesman FF (1980) Well logging method. Geophysics 45(11):1667–1684
3. Segesman FF (1995) Measurement while drilling. Reprint No 40, SPE Reprint Series, SPE, Dallas, TX
4. Jordan JR, Campbell F (1984) Well logging I – borehole environment, rock properties, and temperature logging. SPE Monograph Series, SPE, Dallas, TX
5. Collins RE (1961) Flow of fluids through porous materials. Reinhold, New York
6. Serra O (1984) Fundamentals of well-log interpretation. Elsevier, Amsterdam, The Netherlands
7. Pickett GR (1974) Formation evaluation. Unpublished lecture notes, Colorado School of Mines, Golden, CO

Introduction

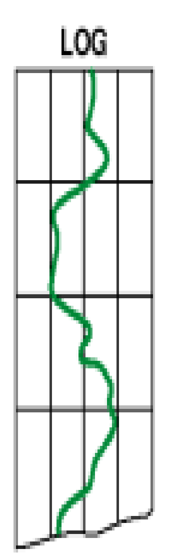
- What is a “Log” and ‘’Well Logging’’.
- Types of boreholes and well logs.
- Well logs; the necessity.
- Advantages and Limitations
- Historical overview on the well logging technique.
- Objectives of wireline logs.

What is a Log?

Definition

According to
4th Edition of **J.A.Jackson's Glossary of Geology**:

Log : A continuous record as a function of depth, usually graphic and plotted to scale on a narrow paper strip, of observations made on the rocks and fluids of the geologic section exposed in the well-bore.

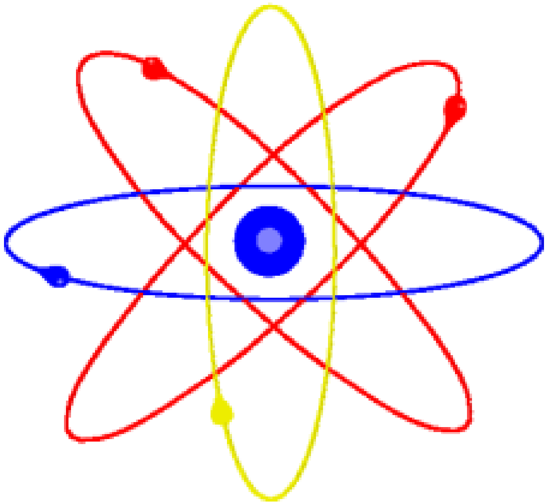


Practical definition of a log

Log is an indirect measurement of formation properties exposed by the well-bore acquired by lowering a device or a combination of devices in the well bore.

- Log is not a direct measurement of formation properties, it is an implied measurement based on one or combination of the following devices

  - Electrical (Resistivity and Induction)
  - Acoustic
  - Nuclear
  - Electromagnetic
  - Magnetic



Well logging

Well logging or borehole logging is the practice of making a detailed record (a well log) of the **geologic formations** penetrated by a **borehole**

The log may be based on:

1. **Visual inspection** of samples brought to the surface (geological logs). Cuttings, extracted from the drilling mud return, are one of the largest sources of subsurface sampling.

2. **Physical measurements** made by instruments lowered into the hole (geophysical logs). Well logs provide continuous indirect measurements of parameters related to porosity, lithology, presence of hydrocarbons, and other rock properties .

Some types of geophysical well logs can be done during any phase of a well's history: drilling, completing and producing. Well logging is performed in boreholes drilled for the **oil and gas, groundwater, mineral**, **environmental and geotechnical studies.**

Well Logging means different things to different people:

For a geologist,
It is primarily a mapping technique for exploring the subsurface.

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

For a geophysicist,
It is a source of complementary data for surface seismic analysis.

In this process, well logging requires the synthesis of a number of diverse sciences: physics, chemistry, geochemistry, acoustics and geology

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Types of boreholes

- According to Casing operation

  - Cased holes

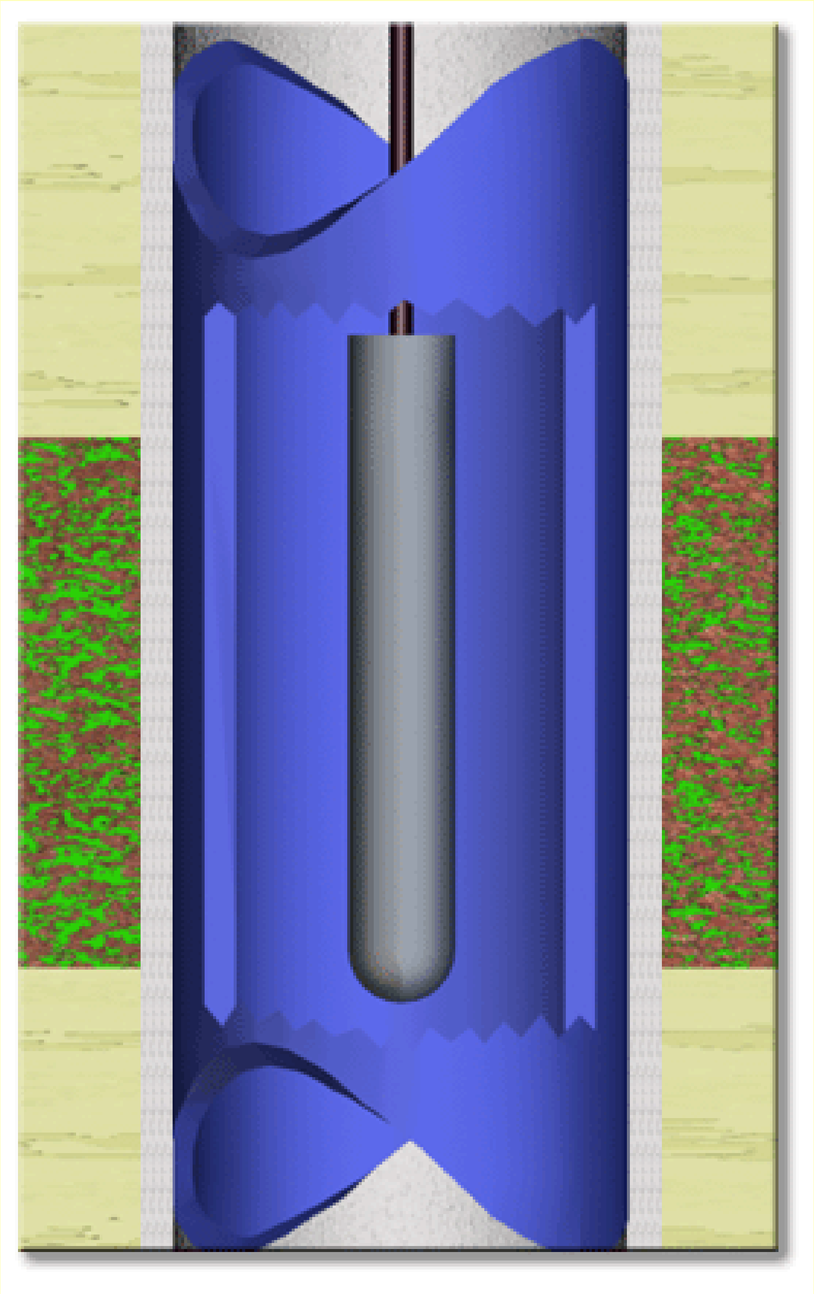
  - Open holes

- According to conductivity of the borehole

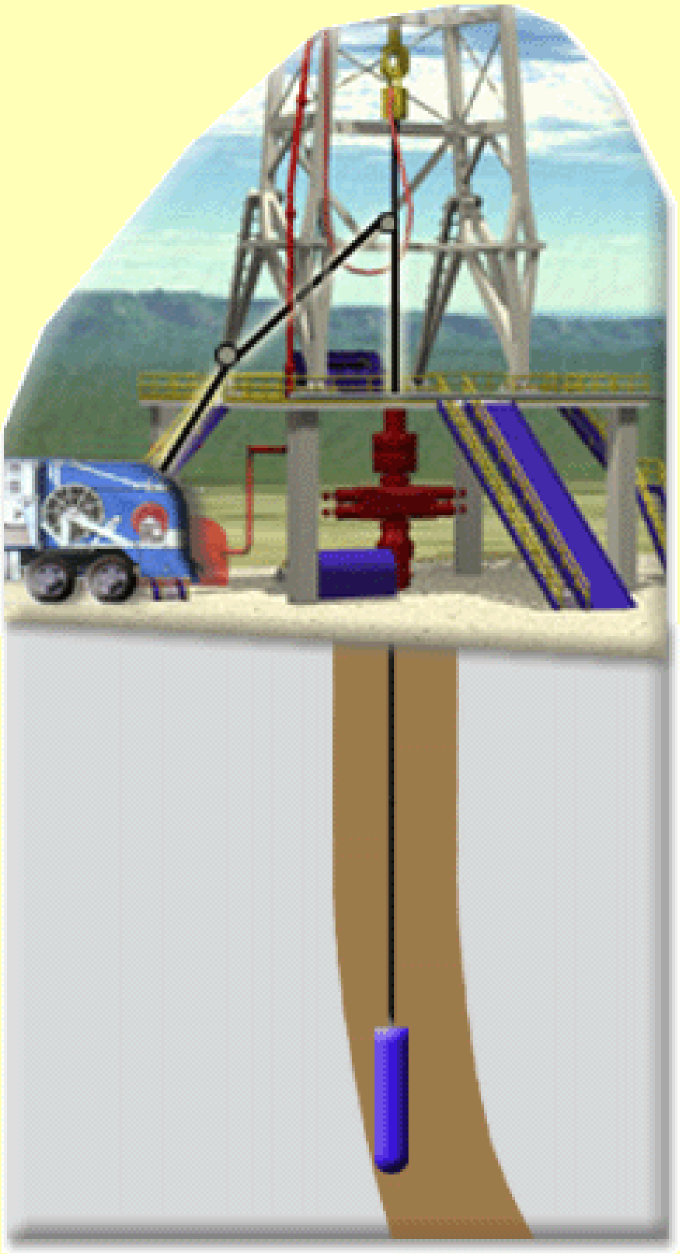
  - Conductive (water base drilling mud)

  - Non-conductive boreholes (oil base mud, air drilled or cased holes)

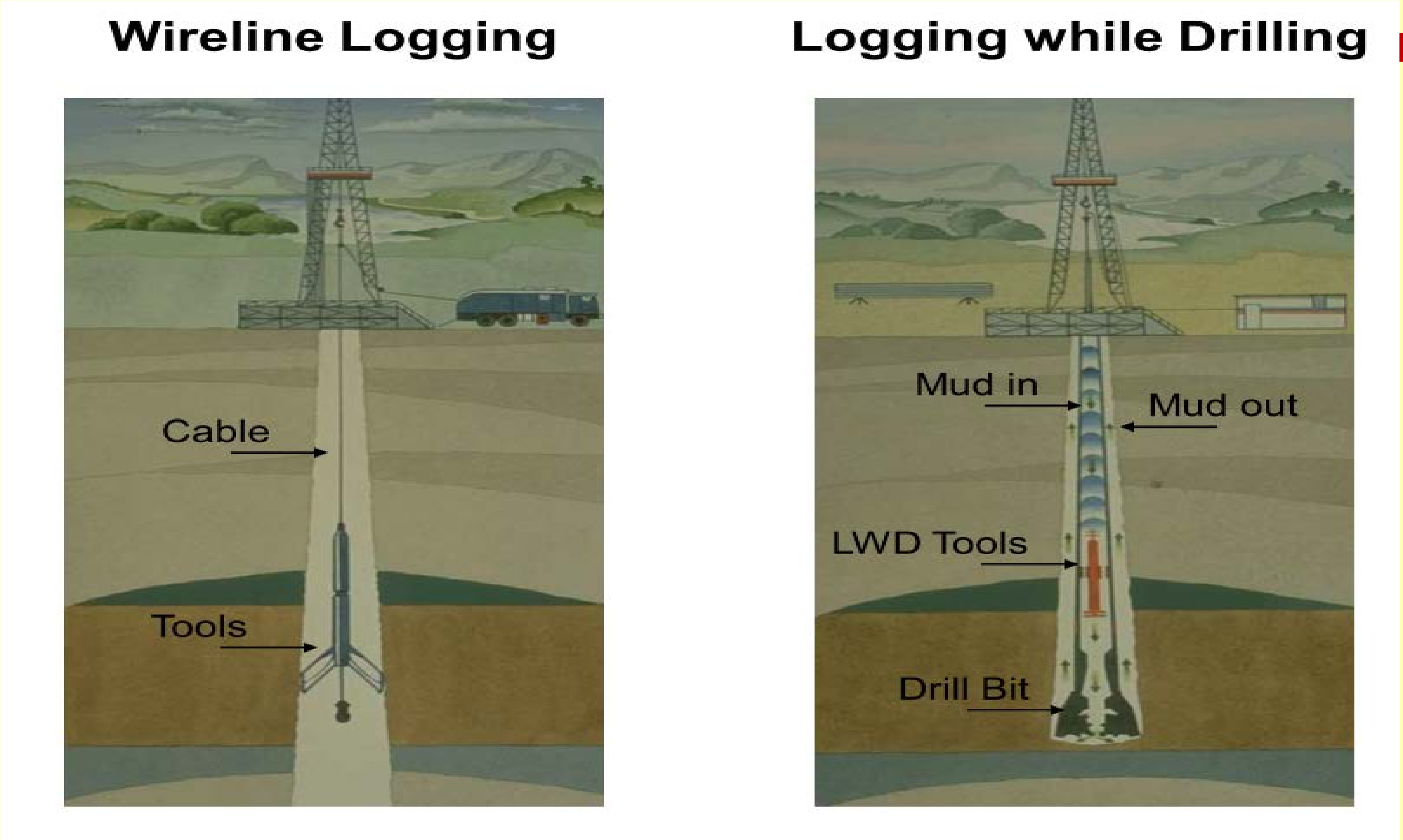
Cased holes



Open holes



Types of well logging



LWD

Wireline refers to the cable by which the measuring devices are lowered and retrieved from the well and, by a number of shielded insulated wires in the interior of the cable, provide for the electrical power of the device and a means for the transmission of data to the surface. More recently, the devices have been encapsulated in a drill collar, and the transmission effected through the mud column. This procedure is known as **logging while drilling (LWD)**.

1) Wire line Logging: The process of logging involves a number of elements

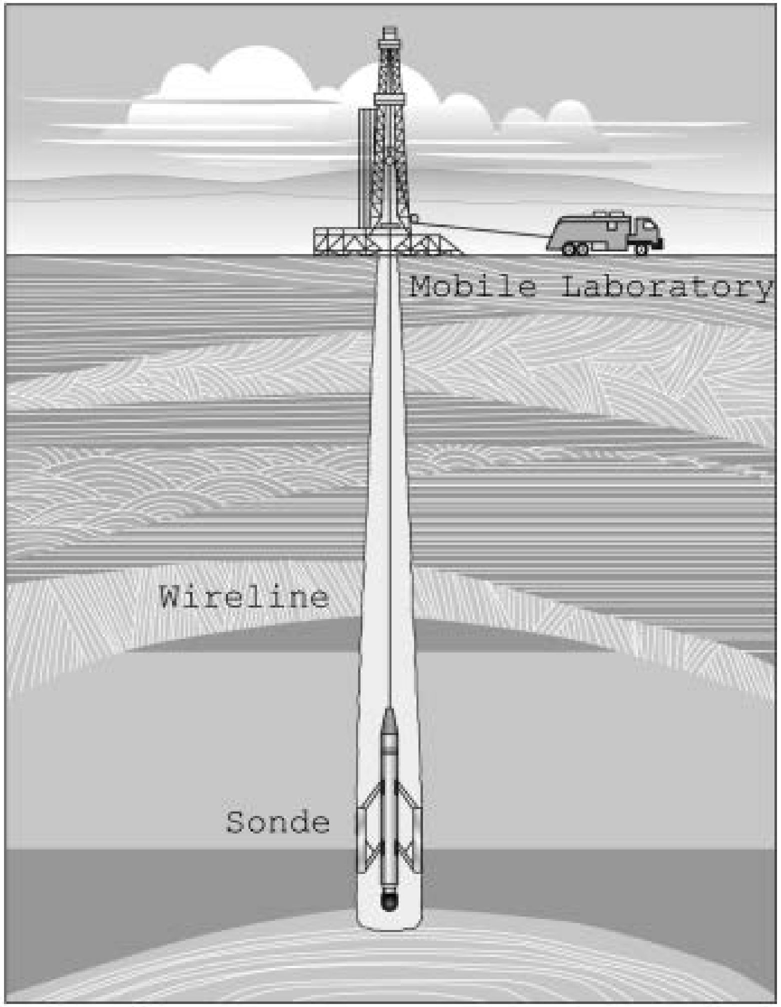
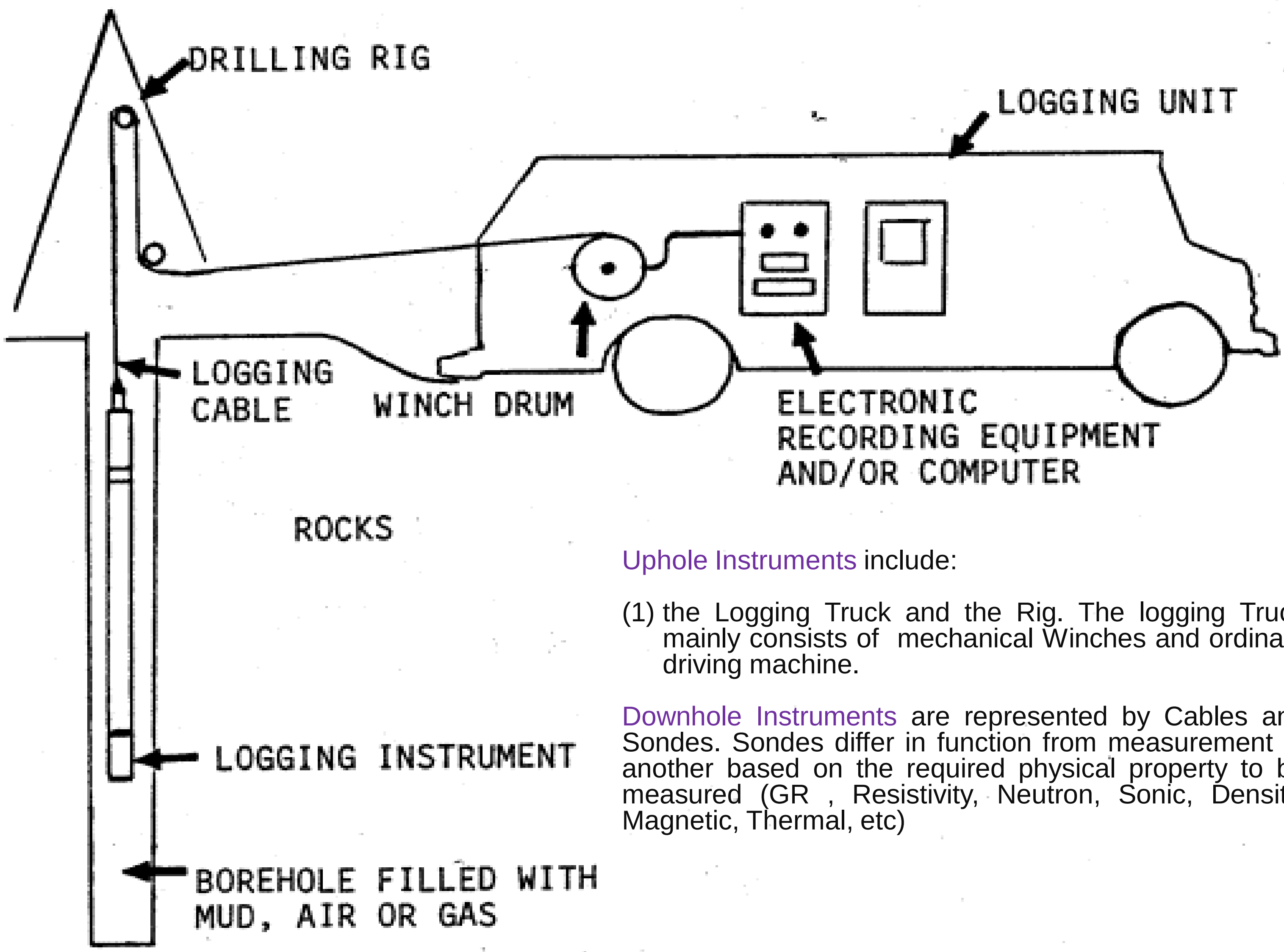


Fig. The elements of well logging: a measurement sonde in a borehole, the wireline, and a mobile laboratory. Courtesy of Schlumberger.

Creating the Well Log “Logging Operation”



Uphole Instruments include:

(1) the Logging Truck and the Rig. The logging Truck mainly consists of mechanical Winches and ordinary driving machine.

Downhole Instruments are represented by Cables and Sondes. Sondes differ in function from measurement to another based on the required physical property to be measured (GR , Resistivity, Neutron, Sonic, Density, Magnetic, Thermal, etc)

The measurement device, or **sonde**.
Some of them are passive measurement devices; others exert some influence on the formation being traversed. Their measurements are transmitted to the surface by means of the wire line

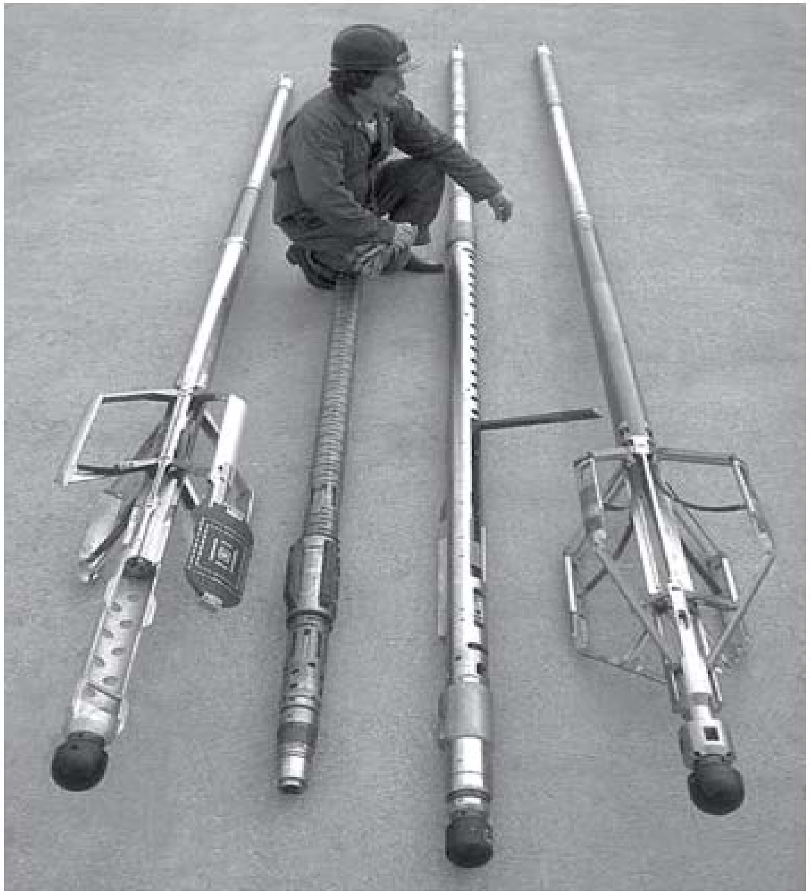
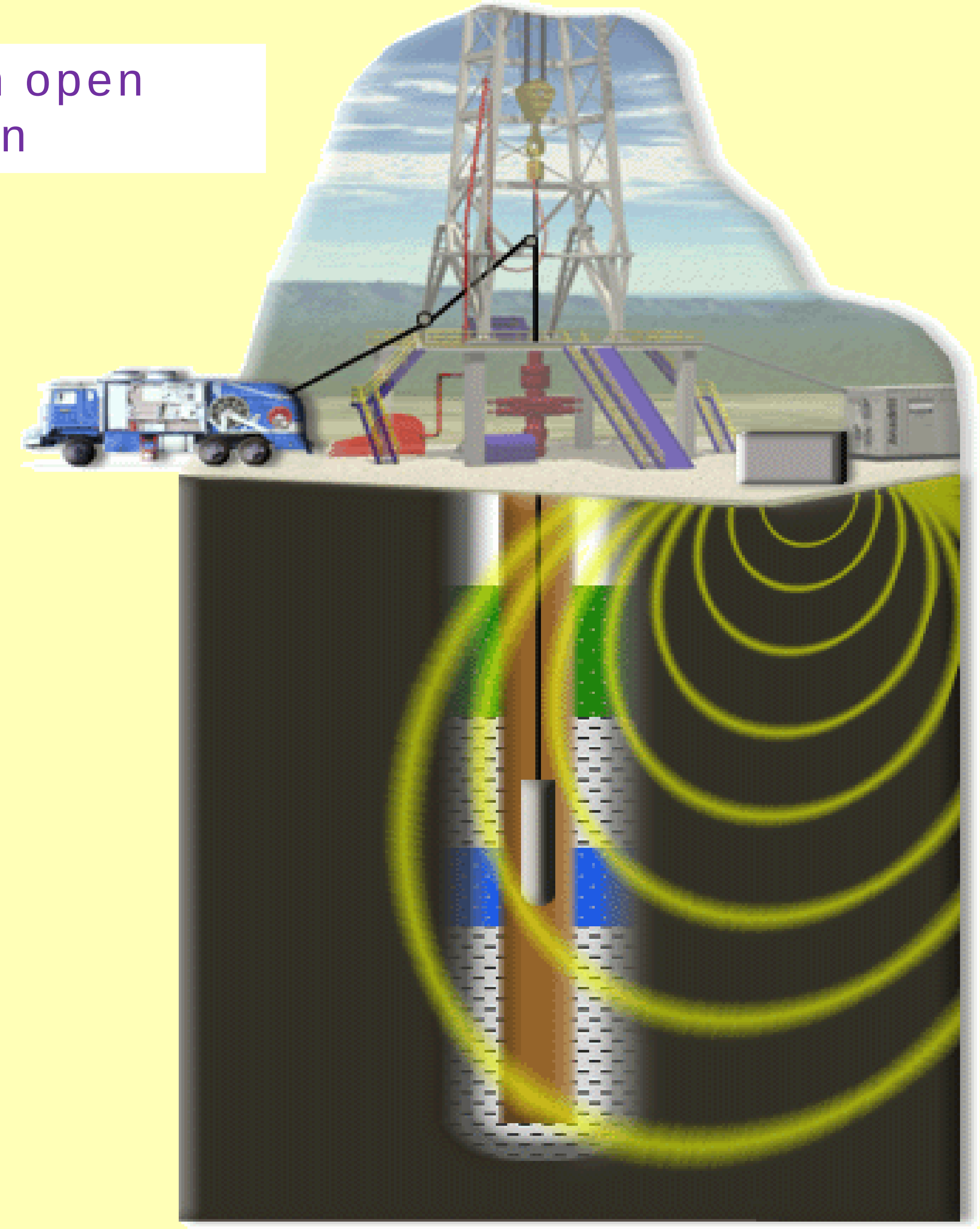


Fig. Examples of four logging tools. The dipmeter, on the left, has sensors on four actuated arms, which are shown in their fully extended position. Attached to the bottom of one of its four arms is an additional electrode array embedded in a rubber "pad." It is followed by a sonic logging tool, characterized by a slotted housing, and then a density device with its hydraulically activated back-up arm fully extended. The tool on the extreme right is another version of a dipmeter with multiple electrodes on each pad. Courtesy of Schlumberger.

Sound waves through open hole logging operation



2) Logging while drilling (LWD) The sensors are built into the wall of the drill collar

The measurement device can be run either "slick" or with an attached clamped-on external "stabilizer." This latter device centralizes the drill collar and its contained sensors. When the unit is run in the "slick" mode it can, in the case of a horizontal well, certainly ride on the bottom of the hole.

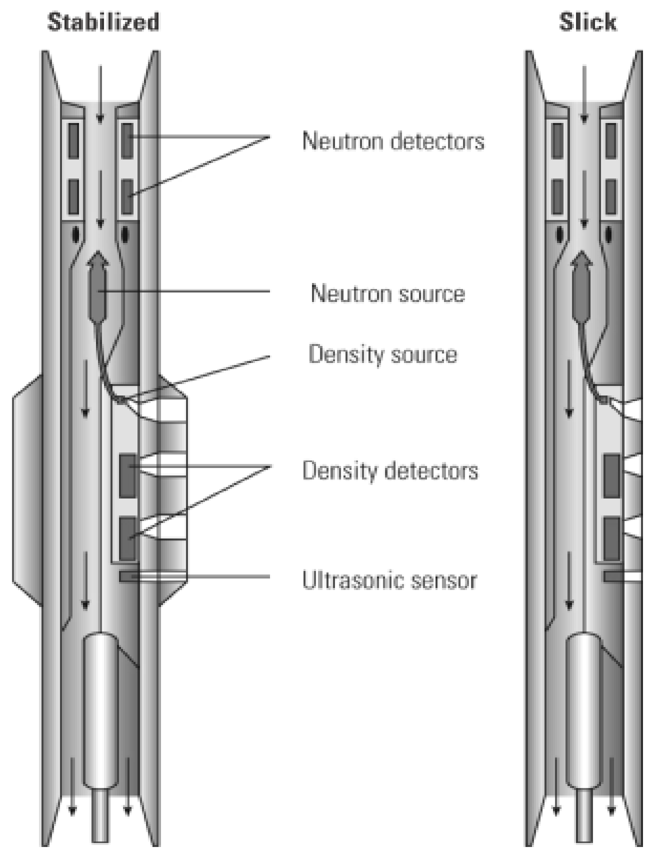


Fig. An LWD device containing a neutron and density measurement. The panel on the left shows the tool with clamp-on wear bands so that the diameter is close to that of the drill bit. In the right panel the tool is shown in the "slick" mode. Courtesy of Schlumberger.

Wireline Logging and LWD difference

1) As the drill collar is rotated, LWD data can be acquired
from multiple azimuths around the borehole, something not often achievable
with wireline logging.

2) Wireline tools are generally of a standard diameter, many of the LWD
tools come in families of sizes (e.g., 4, 6, and 8 in.).
This is to accommodate popular drilling bit sizes and collar sizes since the
LWD device must conform to the drilling string.

3) LWD data acquired with time instead of depth in Wireline Logging.
This arises from the rate of drilling which is not very well controlled in LWD.

4) Wireline is well adapted in vertical drilling than LWD.

Well logs- the necessity

- These measurements are necessary because geological sampling during drilling (cutting sampling) leaves a very imprecise record of the formations encountered.

- Entire formation samples can be brought to the surface by mechanical coring, but this is both slow and expensive.

- The results of coring, of course, are perfect. Logging is precise, but not perfect, in that it needs interpretation to bring a log to the level of geological or petrophysical experience.

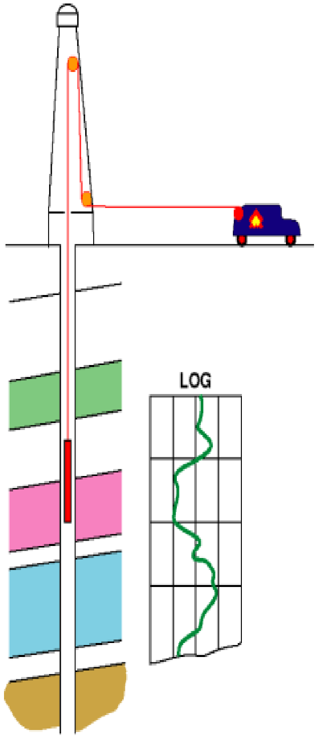
Advantages and Limitations of Well Logging

Advantages:

- Continuous measurements
- Easy and quick to work with
- Short time acquisition
- Better resolution than seismic data
- Economical

Limitations:

- Indirect measurements
- Limited by tool specification
- Affected by environment
- Varying resolution

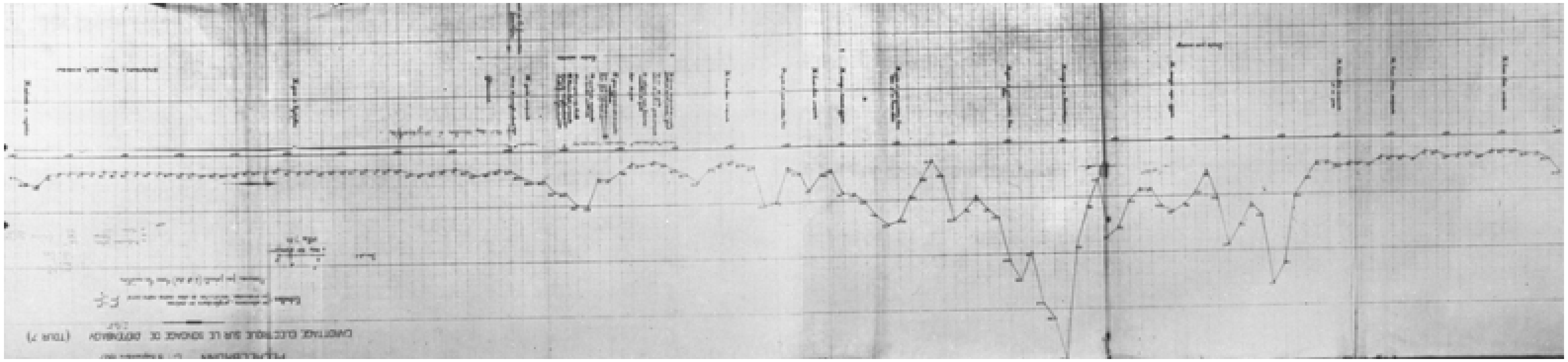


Well Logging History

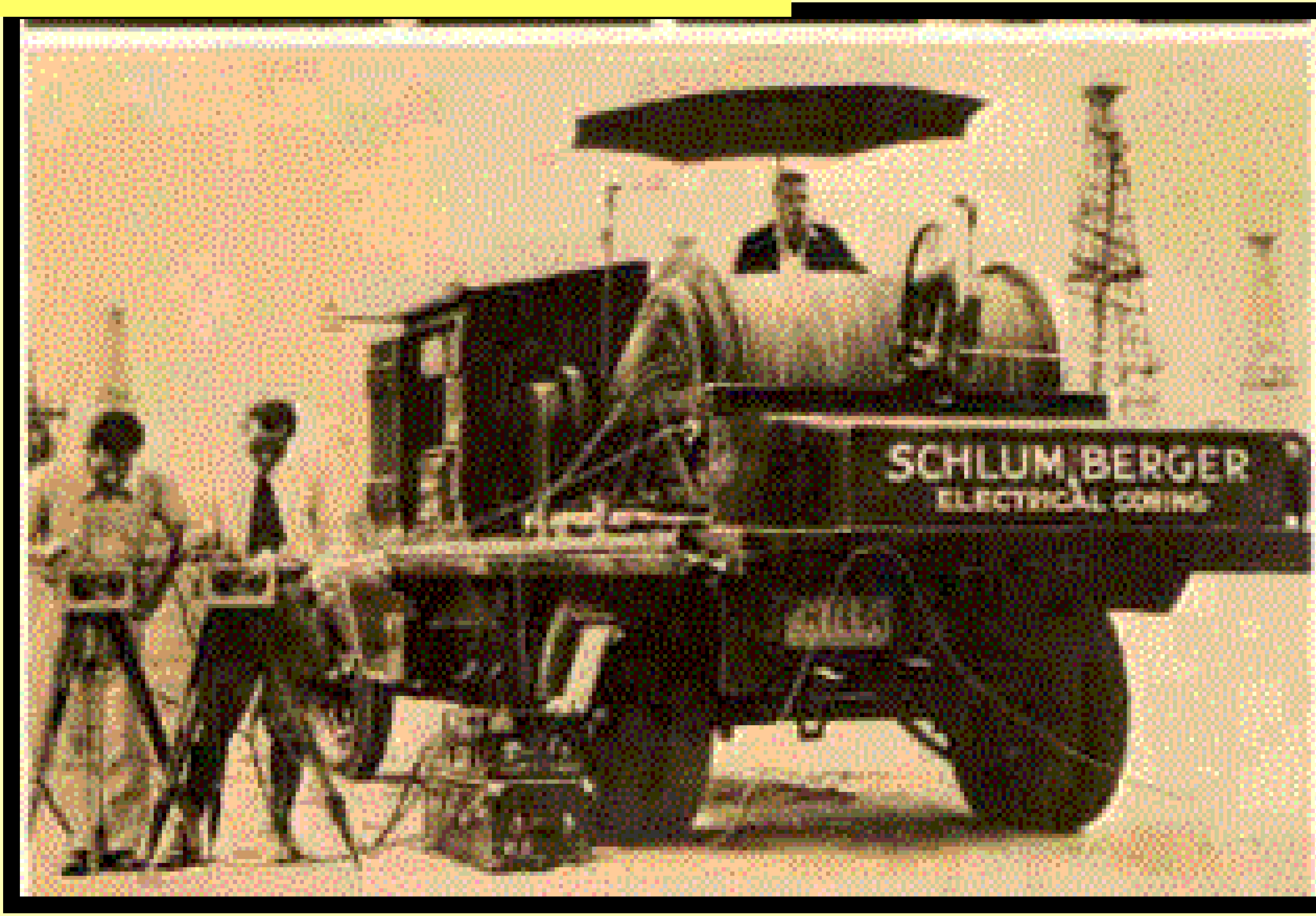
- The first electrical log was introduced in 1927 in France using stationed resistivity method.
- The first commercial electrical resistivity tool in 1929 was used in Venezuela, USA and Indonesia.
- SP was run along with resistivity first time in 1931
- Schlumberger developed the first continuous recording 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, Fomation 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


Well in Pechelbronn - France


Surface Recording Instrument


The “First” Log recorded in 1927

Schlumberger Logging Trucks in the past



Rock properties

(1) **Porosity**: the volume of pores to the total volume of rock.

φ = V(pores) / V (Rock) * 100 %

(2) **permeability** the ability of petroleum to flow through these voids flow through these voids.

(3) **Clay content**: (Rock may be clean or it may contain clay)

Caly content affects the permeability and log readings

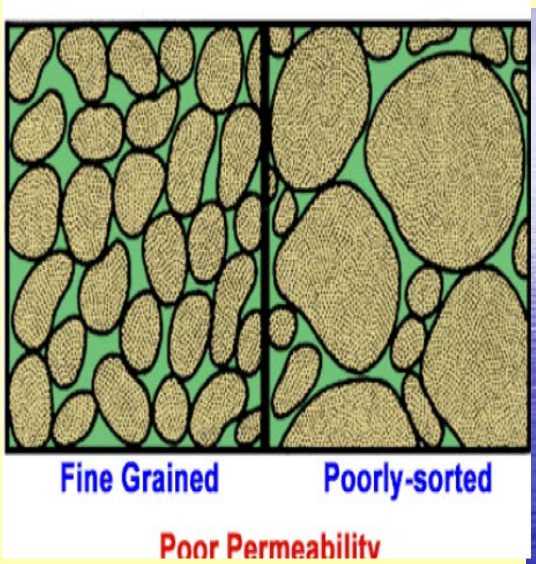
(4) **Saturation**: The fraction of the pore space containing water

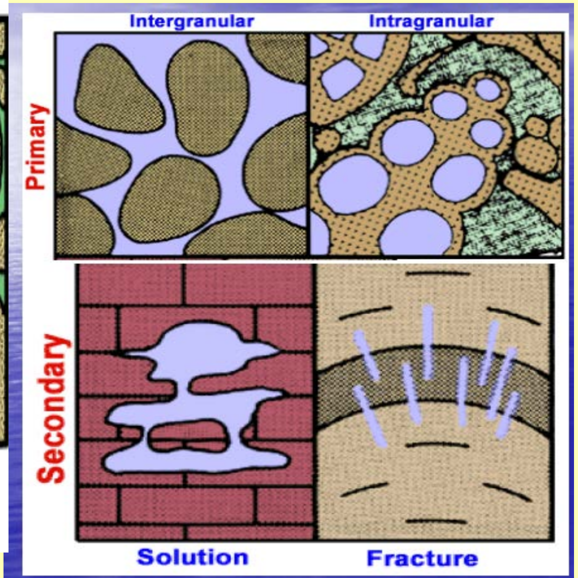
S= V(Liquid) / V (Pores) * 100 %

(5) **Consolidation**: A mechanical property in which reduction in volume takes place by expulsion of water under static loads.

(6) **The existence of fractures**, natural or induced, alter the permeability significantly

(7) **Pressure and Temperature**: important for both the drilling and production phases.





Objectives of wireline logging

1-Lithology identification

2-Determination of reservoir characteristics (e.g. porosity, saturation, permeability).

3-Discrimination between source and non source rocks

4-Identification the fluid type in the pore space of reservoir rock (gas, oil, water)

5-Identification of productive zones.

6-Determination the depth and thickness of productive zones.

7-Locating reservoir fluid contacts.

8-Well to well correlation for determining the lateral extension of subsurface geologic cross sections.

9-Determination formation dip and hole angle and size.

Formation evaluation

The goals of formation evaluation can be summarized by a statement of four questions of primary interest in the production of hydrocarbons:

- Are there any hydrocarbons, and if so are they oil or gas?

  First, it is necessary to identify or infer the presence of hydrocarbons in formations traversed by the wellbore.

- Where are the hydrocarbons?

  The depth of formations which contain accumulations of hydrocarbons must be identified.

- How much hydrocarbon is contained in the formation?

  An initial approach is to quantify the fractional volume available for hydrocarbon in the formation. This quantity, porosity, is of utmost importance. A second aspect is to quantify the hydrocarbon fraction of the fluids within the rock matrix. The third concerns the areal extent of the bed, or geological body, which contains the hydrocarbon. This last item falls largely beyond the range of traditional well logging.

- How producible are the hydrocarbons?

  In fact, all the questions really come down to just this one practical concern. Unfortunately, it is the most difficult to answer from inferred formation properties. The most important input is a determination of permeability. Many empirical methods are used to extract this parameter from log measurements with varying degrees of success. Another key factor is oil viscosity, often loosely referred to by its weight, as in heavy or light oil.

MEASUREMENT TECHNIQUES

Measurement techniques are based on three broad disciplines:

Electrical Measurements:

A porous formation has an electrical conductivity which depends upon:

(1) The nature of the electrolyte filling the pore space. The rock matrix is nonconducting, and the usual saturating fluid is a conductive brine. The contrasts of conductivity are produced when the brine is replaced with nonconductive hydrocarbon.

(2): Porosity: Brine-saturated rocks of different porosity will have quite different conductivities; at low porosity the conductivity will be very low, and at high porosity it can be much large.

Nuclear measurements:

measure the radioactivity of formations. They can be used for identifying lithologies. Shale-free sandstones and carbonates have low concentrations of radioactive material and give low gamma ray readings. As shale content increases, the gamma ray log response increases because of the concentration of the radioactive material in shale.

Acoustic Measurements:

Generates acoustic signals to measure the time travel to pass through a formation.

Rock properties can be studied from sonic measurements:

Porosity, Lithology, Compaction and Rock strength.

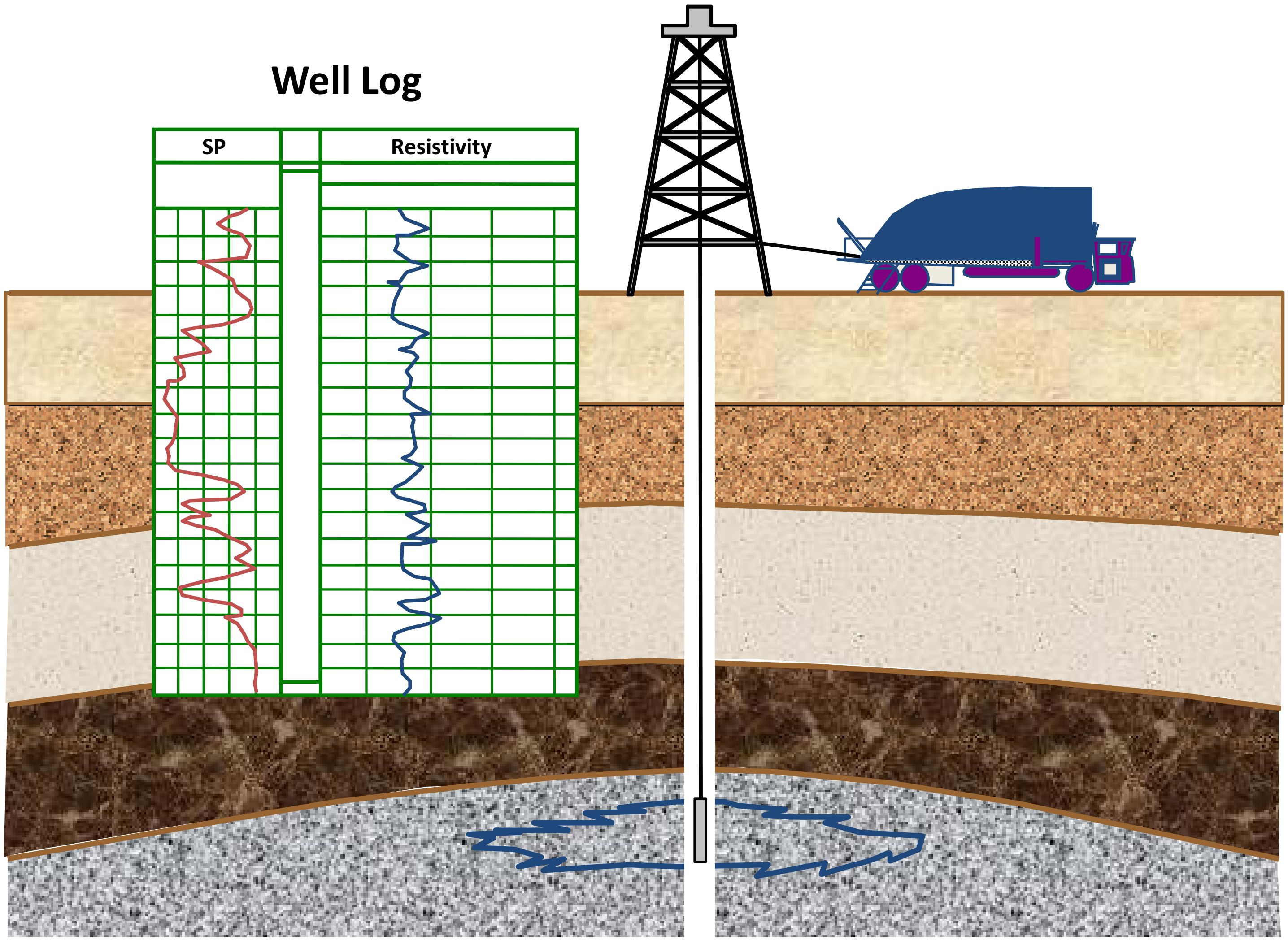
What Logs Can Measure

1. electron density of the rock
2. acoustic travel-time of the rock
3. resistivity, at various distances from the borehole, of the rock
4. neutron absorption rate
5. the self potential of the rock/borehole fluid interface
6. the size of the borehole drilled in the rock
7. the flow rate and density of fluids in the wellbore
8. and other related or derived properties

Electrical Logs

Measure the electrical properties of the formation.

These measurements deal with the resistivity of the formation or the measurement of spontaneously generated voltages.



From NExT, 1999

Electrical conduction

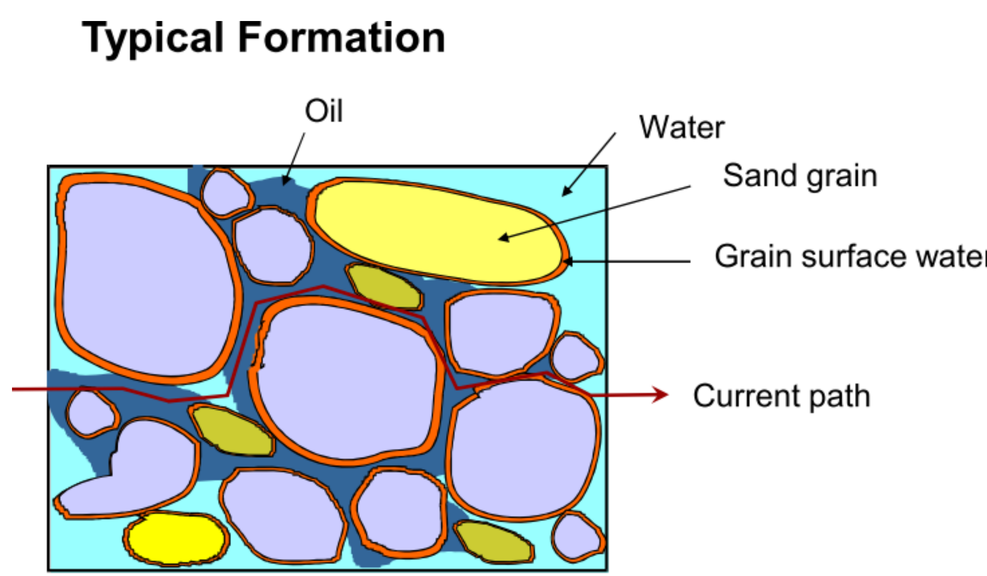
takes place in soil and rocks in three ways:

1. Electrolytic Conduction
2. Electronic Conduction
3. Dielectric conduction

In soils and rocks, electrolytic conduction is the most common method where the current moves through the ions in the pore water. In electronic conduction, the current is carried by the free mobile electrons in the metals. The low resistivity (high conductivity) of metals is, therefore, explained by the large number of free electrons in their structure Dielectric conduction takes place in insulator materials when an external AC current is applied, which makes the electrons shift slightly.

Factors affecting electrical properties of reservoirs

- Salinity
- Temperature
- Saturation
- Presence of hydrocarbons
- Lithology

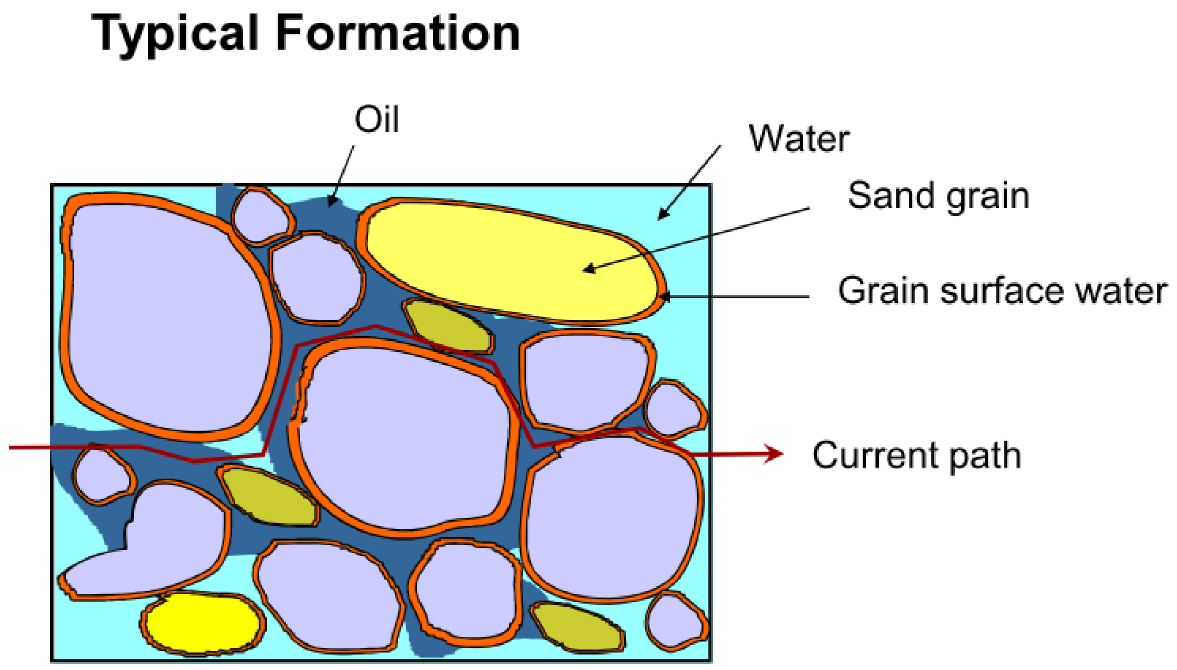


Electrical RESISTIVITY

Definition

Electrical resistivity is a physical property of a material that describes its ability to resist the flow of electrical current. The resistivity method is, therefore, based on the principle that the voltage drop associated with DC or low frequency current injected into the soil is strongly dependent on the resistivity of the soil.

Electrical resistivity of materials



•Electrical properties of reservoirs vary strongly with **porosity** and characteristics of the **fluids** in the pore space; usually, basic properties are determined assuming:

- “clean” reservoir rock (non-shaly)
- S_w = 1.00 (water saturated rock)

Basic theory

Ohm's Law is a fundamental physical law that governs the flow of electrical current in the soil. The electrical resistance R (Ohm) of a conductor is defined as:

$$R = \frac{\Delta V}{I}$$

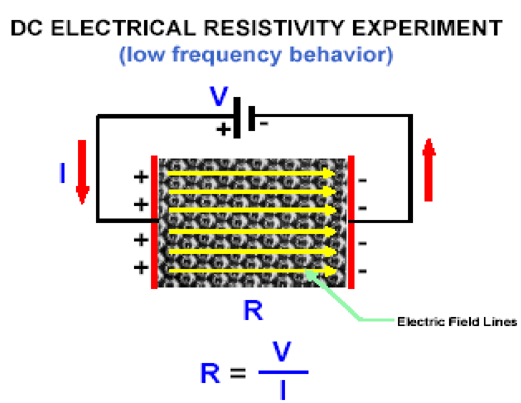
Where ΔV (volt) is the potential difference between two points in the conductor and I is the electrical current (Ampere). The resistance of the conductor (Figure :) is found to be directly proportional to its length L (m) and inversely proportional to the cross-sectional area A (m^2):

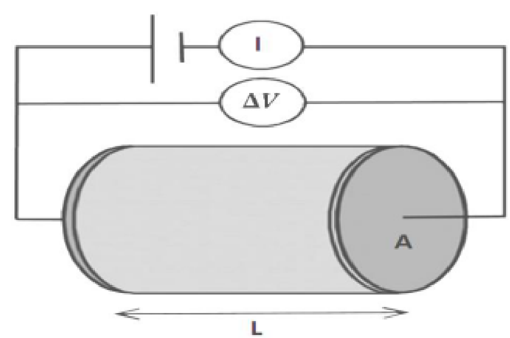
$$R = \frac{\rho L}{A}$$

Where ρ is the resistivity of the conductor (Ohm.m)

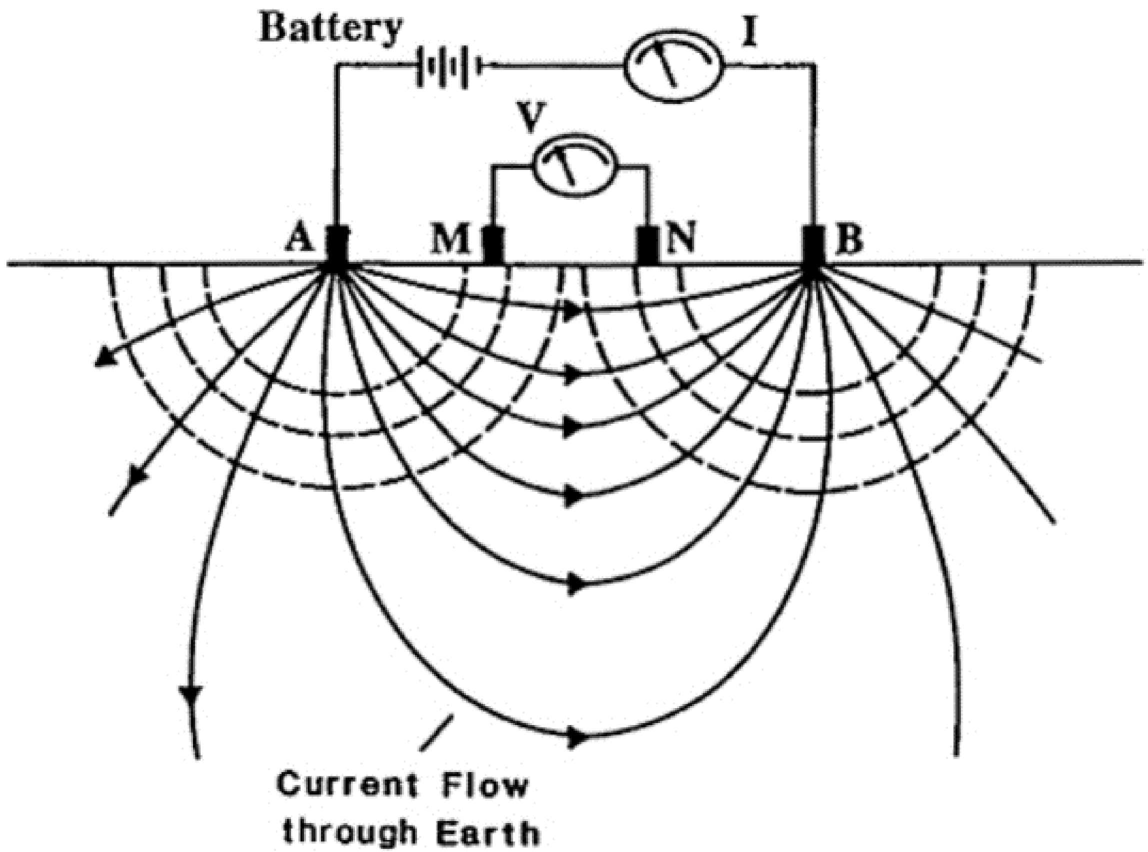
resistivity can be written as:

$$\rho = \frac{\Delta V}{I} \frac{A}{L}$$





Ohm's law on simple conductor of length L and cross-sectional area A^2



Principle: ***Passing a current between two current electrodes (A&B) in the earth and measured the potential drop between two other electrodes (M&N)***

$$\rho = K\frac{\Delta V}{I}$$

1) Resistivity Logs

Resistivity Log is a measurement of a Formation Resistivity (its resistance to passage of electrical current) by resistivity logging tools.

- **Most of rocks are insulators**
- **Gas-insulator**
- **Oil-insulator**
- **Water-conductor**
- **Clay-Conductor**

The resistivity log is fundamental in **formation evaluation** because hydrocarbons do not conduct electricity while all formation waters do. Therefore a large difference exists between the resistivity of rocks filled with hydrocarbons and those filled with water. Clay minerals and a few other minerals, such as pyrite, also conduct electricity, and reduce the difference.

Basic Types: **Normal, Laterolog and Micolog**

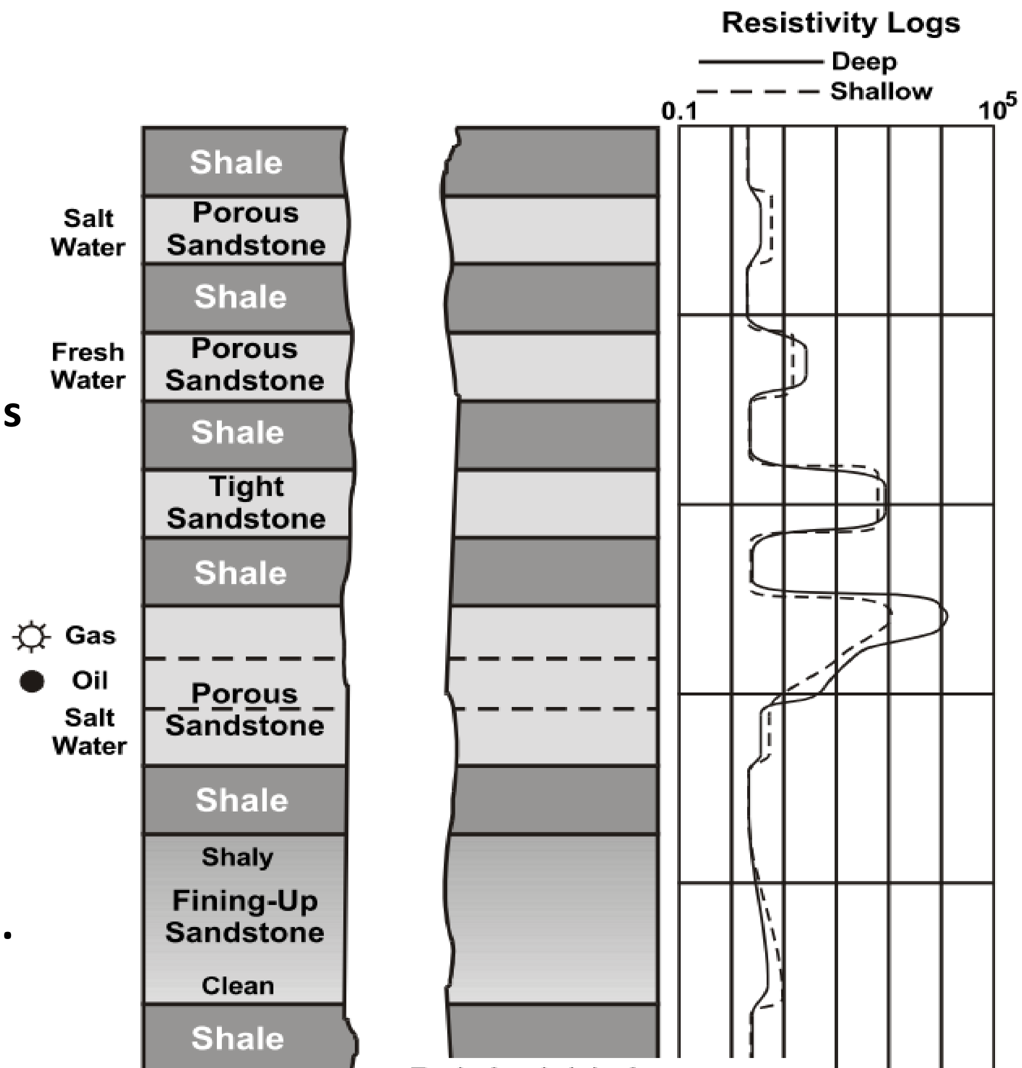
Resistivity Logs

Resistivity Logs are used for:

1.Determination of the hydrocarbon versus water-bearing zones

2. Determine the porosity

3. Determine the permeable formations



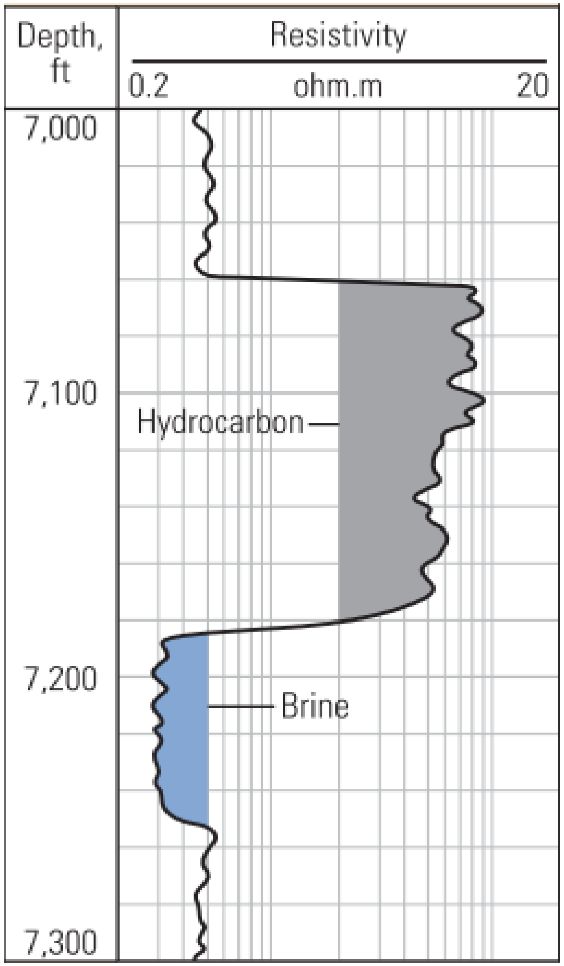
Typical resistivity log responses.

Limitations:

Resistivity tools can only function in boreholes containing conductive mud. They cannot be run in fresh water mud.

Log Format and Scale of resistivity Log:

1. The unit of resistivity is **Ohm.m**.
2. Resistivity logs are plotted on **a logarithmic scale.**
3. The resistivity values (scale) are usually (**0.20-2000**) Ohm.m



Resistivity Log

Principle: ***Passing a current between two current electrodes (A&B) in the earth and measured the potential drop between two other electrodes (M&N)***

1) The Standard Normal Log: The current flow circuit (**the generator circuit**) to be separated from the potential sensing circuit (**the meter circuit**). In this arrangement a constant known current is flowed from A to B (or B to A), and the potential is measured between M and N.

The current emitting electrode (A) and the measure electrode (M) are placed close together on the sonde, and the current return electrode (B) and the measure reference electrode (N) far away. The response is determined mainly by the distance between A and M. The larger AM, the deeper the measurement. Although many distances have been used, the most common are 16 in. [40 cm], known as the short normal, and 64 in. [162 cm], known as the long normal

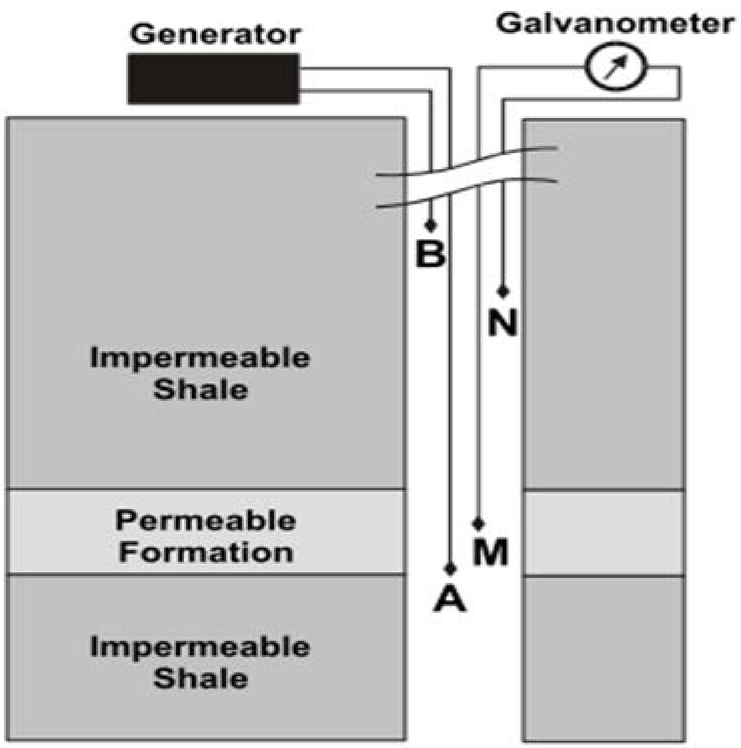


Fig. The standard normal configuration.

2) The standard Lateral Log:

The current electrodes A and B are placed close together on the sonde with the measure electrode (M) several feet away and the measure return (N) far away. This arrangement is sensitive to the potential gradient between A and B. The spacing is defined by the distance from M to the midpoint between A and B. The most common spacing is 18 ft, 8 in. [5.7 m].

The lateral gives a sharper response to a bed boundary than a normal log but also introduces several artifacts that can give misleading results

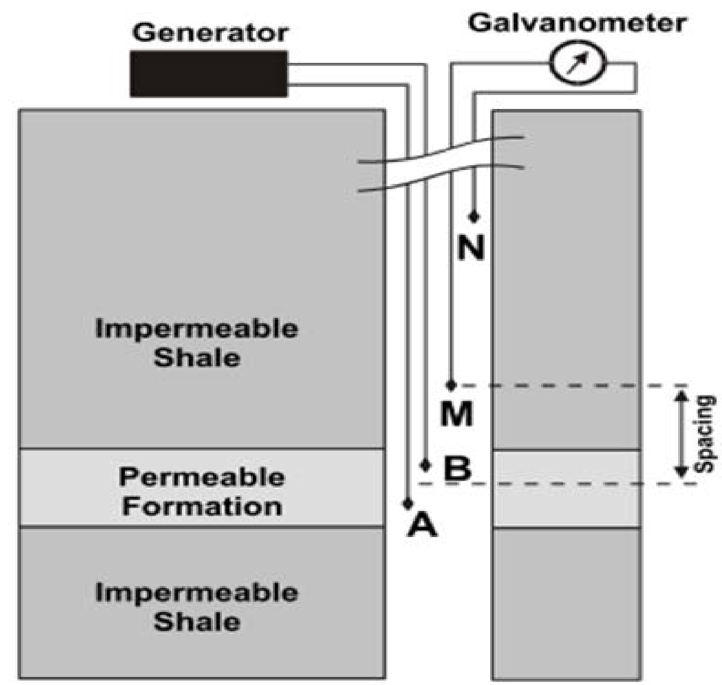
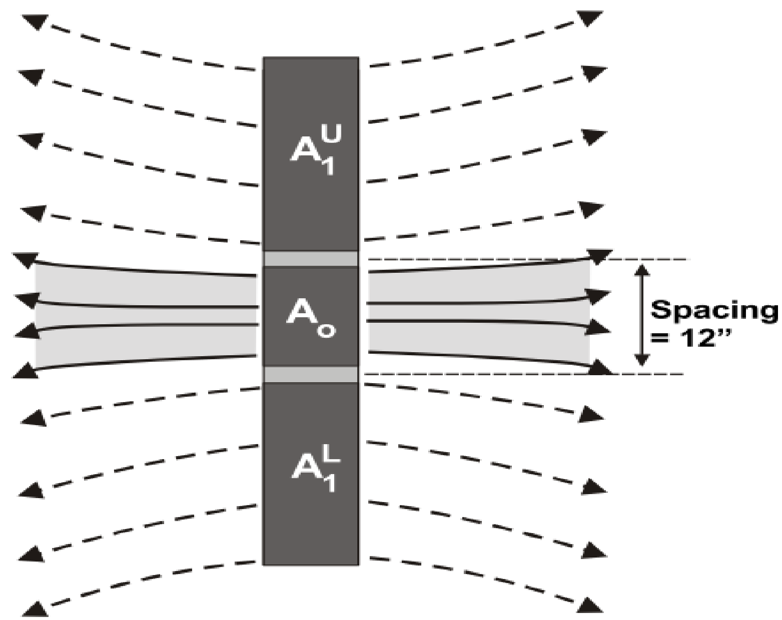


Fig. The standard lateral configuration.

<u>Lateral Log Types:</u>

The laterolog emits a "measuring" current into the formation from one electrode, and "focussing" currents from a series of auxiliary electrodes positioned symmetrically about the measuring current electrode. This focuses the measuring current into a sheet to obtain the best tool resolution

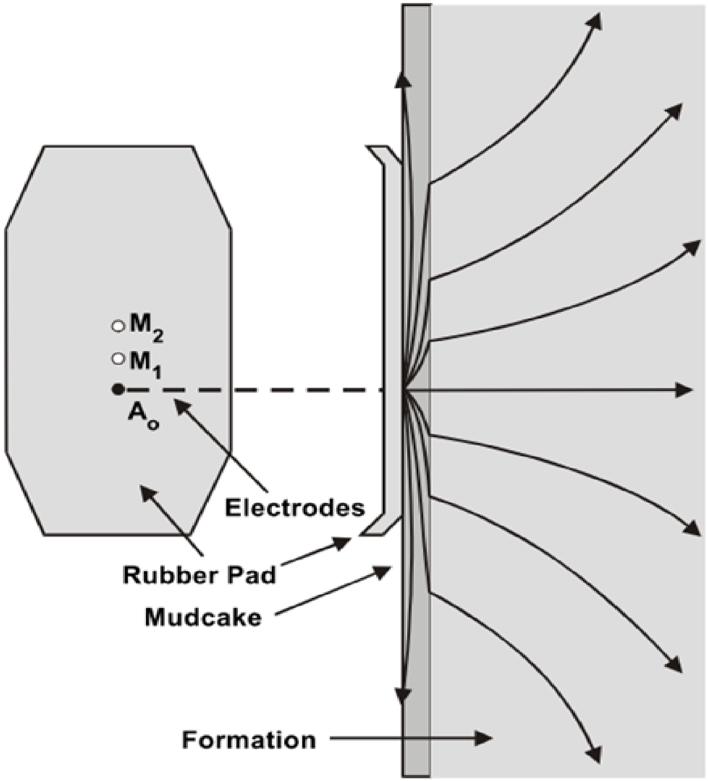
<u>Example: Lateral Log</u> (LL3) has 3 current emitting electrodes. The middle one, which is 1 foot long emits the main current, while the 5 foot long electrodes either side of it emit a current that is designed to help keep the central current more focused, and the potential of the central electrode is measured relative to the potential at infinity to give a potential difference. **This potential difference and the known current from the central electrode are used to calculate the formation resistivity, using a known geometrical factor for the arrangement**. The vertical resolution of the LL3 is 1 ft.



3.The Micro resistivity Log (Microlog)

A shallow resistivity reading can be provided by a microresistivity device.
The measuring device is a rubber pad with rectangular electrodes on it, which is pressed against the borehole wall
The resistivity of essentially only the invaded zone is obtained.
The tool has a very good resolution as a result of the pad geometry .

The tool will not work in oil based mud, because current has to flow from the pad into the formation.



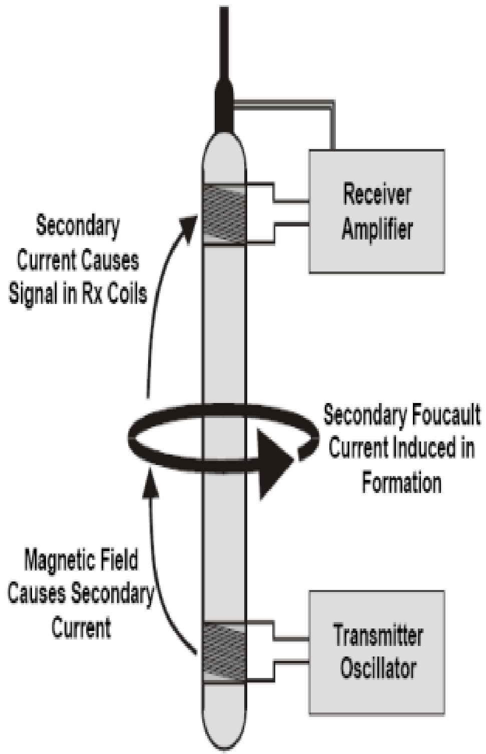
Induction Log

Induction Log measures formation conductivity (its ability to measure conduct the electrical current).

Induction Tools:

These logs were originally designed for use in boreholes where the drilling fluid was very resistive (oil-based muds or even gas). It can, however, be used reasonably also in water-based muds of high salinity, but has found its greatest use in wells drilled with fresh water-based muds.

The sonde consists of 2 wire coils, a transmitter (Tx) and a receiver (Rx). High frequency alternating current (20 kHz) of constant amplitude is applied to the transmitter coil. This gives rise to an alternating magnetic field around the sonde that induces *secondary currents* in the formation. These currents flow in coaxial loops around the sonde, and in turn create their own alternating magnetic field, which induces currents in the receiver coil of the sonde. The received signal is measured, and its size is proportional to the *conductivity* of the formation.

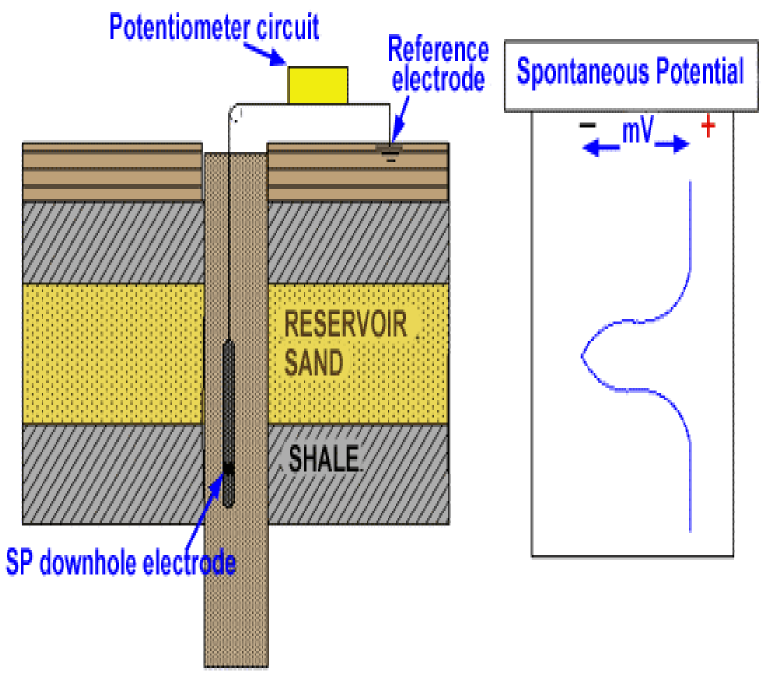


As there is no direct flow of current from the induction tool to the formation, this tool can be used with low conductivity borehole fluids, such as fresh water muds or oil base muds.

The **resolution** of the tool is not as good as that of the laterolog, because the arrangement of the coils does not allow sharp focussing of the measurements

Spontaneous (self) Potential Log (SP)

- The spontaneous potential (SP) Logrecords the naturally occurring electrical potential (voltage) produced by the interaction of formation connate water, conductive drilling fluid, and shale
- The SP curve reflects a difference in the electrical potential between a movable electrode in the borehole and a fixed reference electrode at the surface

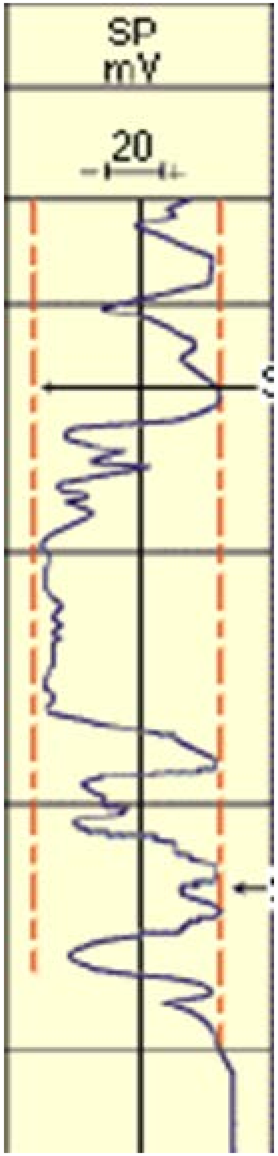


The presence of hydrocarbons will reduce the response on an SP log because the water contact with the well bore fluid is reduced. The SP curve is usually 'flat' opposite shale formations because there is no ion exchange due to the low permeability, low porosity properties thus creating a baseline. Rocks other than shale (e.g. sandstones) will also result in poor or no response on the SP curve because of no ion exchange.

Conductive fluids are necessary in bore hole to create a SP response, so the SP log cannot be used in nonconductive drilling muds (e.g. oil-based mud).

Log Format and Scale of sp Log:

1. The SP is measured in **millivolts** (mv).
2. The scale on the log shows a number of mv per division. For example 20mv/division.
3. The scale across the track is variable and depends on the conditions in the well.



The SP log is used to identify:
-Lithology
- Detect boundaries of permeable beds
-Determination formation water resistivity
-shale volume indicator

RADIOACTIVITY LOGGING (Nuclear logging)

Introduction

Radioactivity Logs also known Nuclear logging comprises methods of measuring the intensity of ***natural*** and ***induced*** radiations emitted in the formation. Nuclear logs have a fundamental advantage over most other logs- they can be made in either cased or open holes filled with any type of fluids (Since many radiation rays can pass through steel casing)

Radioactivity Logs measure the **natural radiation** generated by the formation, such as the total gamma ray logs and spectral gamma ray logs, and those that measure the response of the formation to radiation **generated by the tool**, such as the neutron, density logs.

Types of Nuclear logs:

Nuclear-logging tools use two types of radiation:

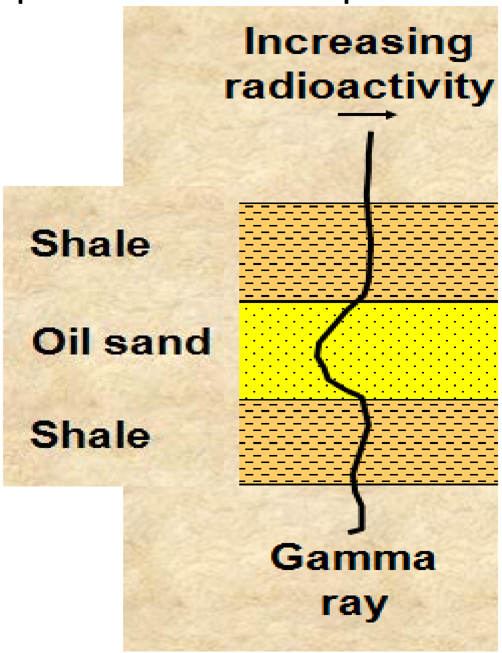
Gamma rays and neutrons: Both follow basic scattering principles but have unique reaction types and cross sections.

1) Gamma ray logs

- Simple (total) gamma ray log
- Spectral gamma ray log
- Density logging

2)Neutron logs

- Neutron porosity logs
- Carbon oxygen logs
- Geochemical logs



Radioactivity of rocks

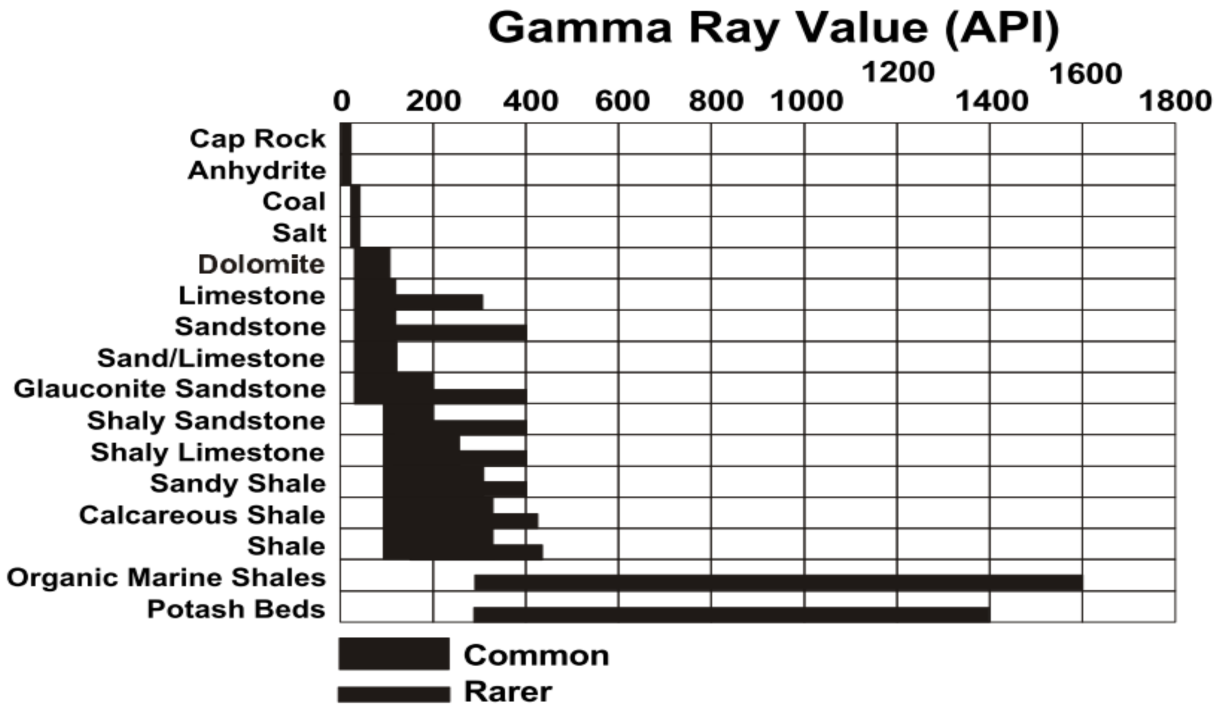
All substances are assemblages of atoms. Each atom comprises of nucleus (made up of neutron and protons) together with electrons revolving around the nucleus. The arrangement of Neutrons and Protons in the atoms is unstable and a natural rearrangement occurs during which protons and neutrons are ejected from the nucleus and energy is emitted in the form of gamma rays.

The Figure shows the distributions of radiation levels observed are plotted for numerous rock types.

All rocks contain radioactive elements. However, Uranium, Thorium and Potassium are common.

*Evaporites (salt, anhydrites) and coals typically have low levels.

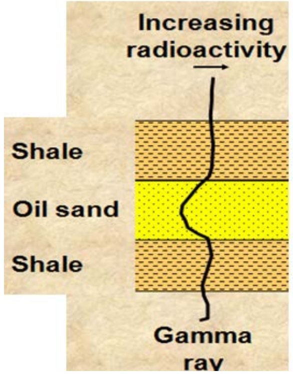
*In other rocks, the general trend toward higher radioactivity with increased shale content is apparent. At the high radioactivity extreme are organic-rich shales and potash (KCl).



Distribution of relative radioactivity level for various rock types

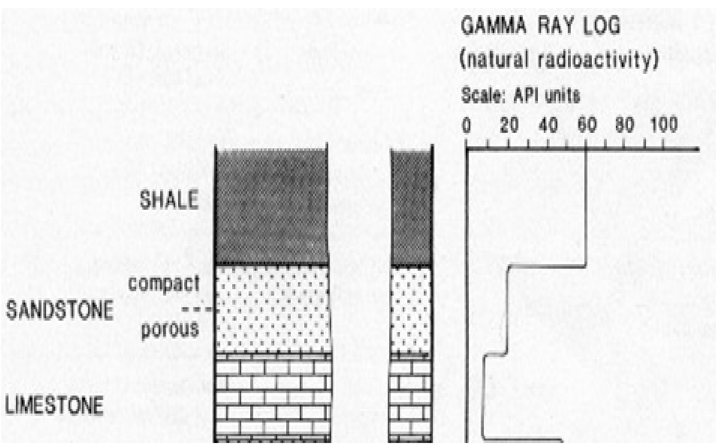
Natural Gamma ray Logs

- **Gamma ray logs** measure natural radioactivity of formations.
  emitted by elements such as Potassium, Uranium and Thorium .
- The gamma ray measures the natural radioactivity of the rocks, and does not measure any hydrocarbon or water present within the rocks.
- The most common gamma emitting Lithology is Shale. This is because Shales are derived from the weathering of Igneous rocks (composed of Quartz, Feldspar and Mica) which contains significant amount of potassium and Uranium.
- Shales: radioactive Potassium is a common component, and because of their cation exchange capacity, Uranium and Thorium are often absorbed as well.
- Therefore, very often Shales will display high gamma ray responses, while sandstones and limestone will typically show lower responses.
- They can be used for identifying **lithologies** and **correlating zones**. Shale-free sandstones and carbonates have low concentrations of radioactive material and give low gamma ray readings. As shale content increases, the gamma ray log response increases because of the concentration of the radioactive material in shale.

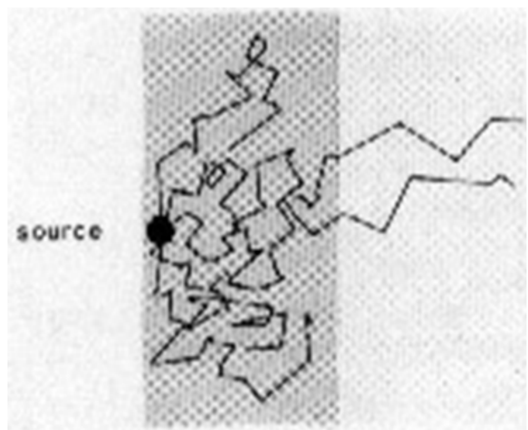


Properties of Gamma Rays

- Gamma rays are high energy electromagnetic waves that are emitted spontaneously by some radioactive elements. Nearly all the gamma radiation encountered in the earth is emitted by the radioactive Potassium isotopes and by the radioactive elements of the Uranium and Thorium series.
- In passing through a 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. *Thus, natural gamma rays are gradually absorbed and their energies degraded 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. The GR log response is proportional to the weight concentrations of the radioactive material in the formation .



Dense Less Dense



Scattering of Gamma ray (the effect is more marked in denser material

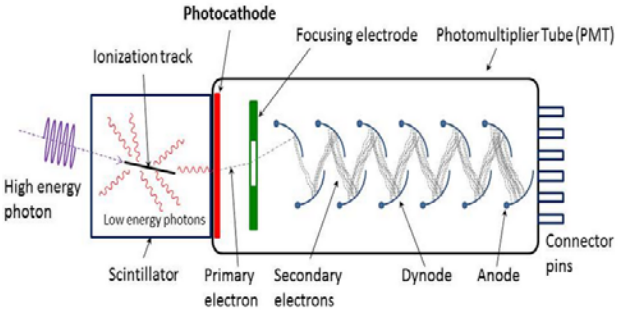
Gamma ray (GR) Log: Basic concept

Gamma logs provides a record of gamma radiation detected in the borehole using GR tool: The GR sonde contains a detector to measure the gamma radiation originating from the volume of formation near the sonde. Scintillation counter (an instrument for detecting and measuring radiation of incident radiation on a scintillator material and detecting the resultant light pulses) are now generally used for this measurement. They are much more efficient than the Geiger-Mueller counters used in the past. Because of its higher efficiency, a scintillation counter, few inches in length is mostly used

Simple Gamma Ray Tool: The tool is a sensitive GR detector consisting of a scintillation counter and photomultiplier: the counter is a sodium iodide crystal 2cm in diameter and 5 cm long in the simple tool. When GR pass through the crystal they cause a flash. Theses are collected by the photomultiplier and stored in attached condenser over period of time.
Spectral Gamma Ray Tool: It also consists of a scintillation counter and photomultiplier. However, the crystal has a much greater volume- typically 5cm in diameter and 20cm long to give the tool a much better counting sensitivity.

The difference between Gamma Ray and spectral Gamma Ray Logs:
In general Gamma ray logs is a record of formations radioactivity from naturally occurring Uranium, Thorium and Potassium.

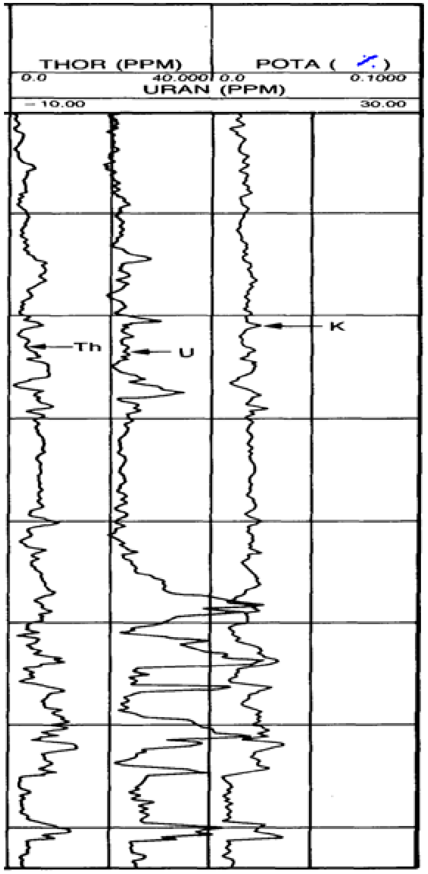
- The simple Gamma Ray logs gives the radioactivity of the three elements combined while The spectral Gamma ray log shows the amount of each individual elements.
- The spectral Gamma ray log has a much better sensitivity.



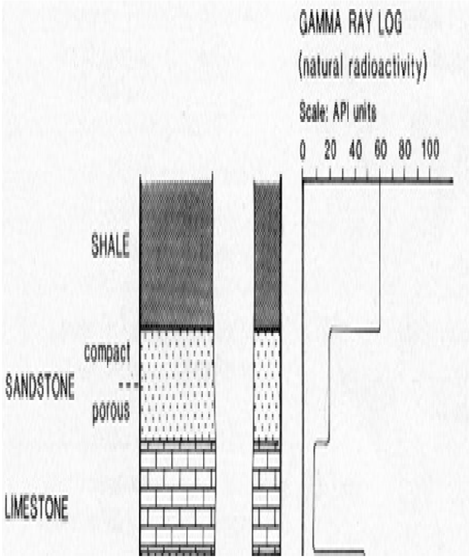
Gamma ray log format and unit

- The radioactivity in well logging is measured using API (American Petroleum Institute) Scale.
- The scale can be from (1-200API)
- For GR Spectral Log, the format of Thorium and Uranium are given in PPM(part per million), Potassium is given Percent %.

➢ 1 ppm U=8.09 API
➢ 1 ppm Th=3.93 API
➢ 1% K= 16.32 API



GR Spectral Log



Simple GR Log

The principles Uses of the radioactivity logs:

1. The gamma ray is quantitatively used to derive the Shale volume.
2. The gamma ray is qualitatively for identification and correlation of lithology.
3. The spectral gamma ray can be used to determine the radioactive minerals and more accurate shale volume.

The difference between Gamma Ray and spectral Gamma Ray Logs:

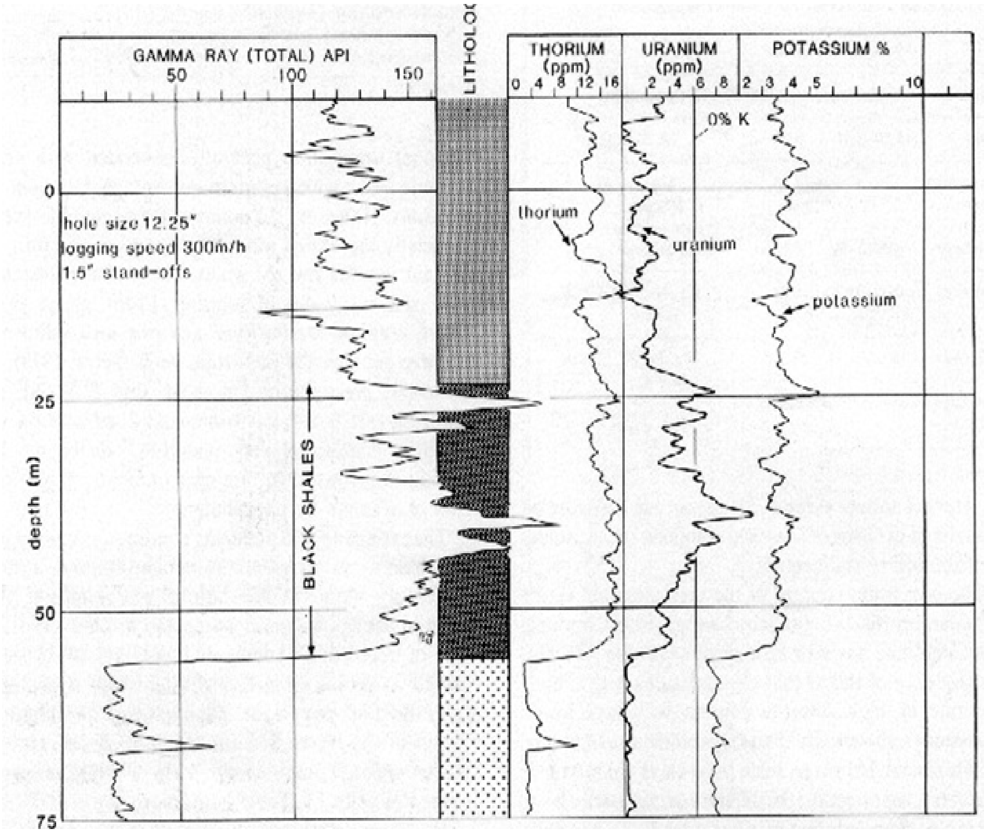
In general Gamma ray logs is a record of formations radioactivity from naturally occurring Uranium, Thorium and Potassium.

- The simple Gamma Ray logs gives the radioactivity of the three elements combined while The spectral Gamma ray log shows the amount of each individual elements.
- The spectral Gamma ray log has a much better sensitivity.

Like the GR log, the spectral gamma ray 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

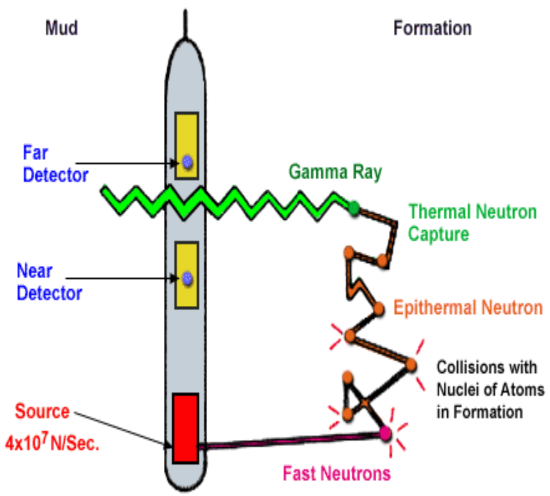
Spectral Gamma ray

- The Spectral Gamma ray tool uses a sodium iodide scintillation detector contained in a pressure housing which, during logging, is held against the borehole wall by a bow spring.
- Gamma rays emitted by the formation rarely reach the detector directly. The high-energy part of the detected spectrum is divided into three energy windows, Wl, W2, and W3; each covering a characteristic peak of the three radioactivity series. **Knowing the response of the tool and the number of counts in each window, it is possible to determine the amounts of Thorium , Uranium, and Potassium the formation**

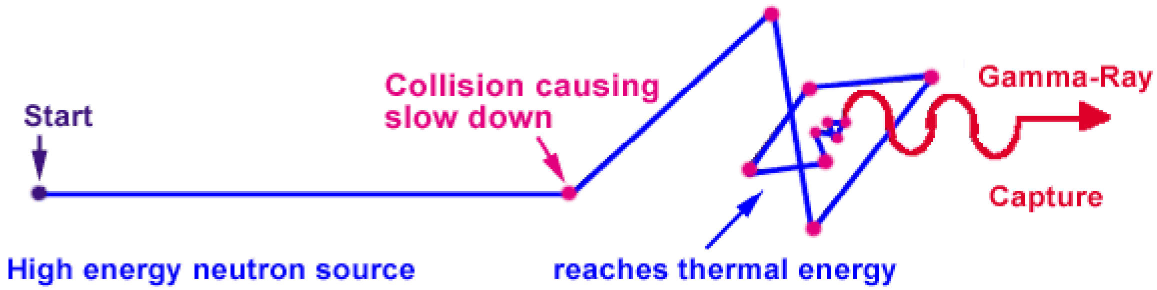


NEUTRON LOG: Basic concept

- Neutron logs are made of a source of Neutrons in the probe detectors. *Logging tool emits high energy neutrons into formation. Neutrons collide with nuclei of formation's atoms. Neutrons lose energy (velocity) with each collision.*
- The most energy is lost when colliding with a hydrogen atom nucleus. Neutrons are slowed sufficiently to be captured by nuclei. Capturing nuclei become excited and emit gamma rays.
- The electrically neutral neutron has a mass that is practically identical to that of the hydrogen atom. The neutrons that are emitted from a neutron source have a high energy of several million electron volts (MeV). After emission, they collide with the nuclei within the borehole fluid and formation materials. With each collision, the neutrons loose some of their energy. The largest loss of energy occurs when the neutrons collide with hydrogen atoms. The rate at which the neutrons slow-down depends largely on the amount of hydrogen in the formation.
- With each collision the neutrons slow down, until the neutrons reach a lower (epithermal) energy state and then continue to lose energy until they reach an even lower (thermal) energy state of about 0.025 eV. At this energy the neutrons are in thermal equilibrium with other nuclei in the formation. At thermal speeds, the neutrons will eventually be captured by a nucleus.
- Log records porosity based on neutrons captured by formation.
- If hydrogen is in pore space, porosity is related to the ratio of neutrons emitted to those counted as captured



The principles of neutron logging are summarized below:



Emission, Traveling and Collisions of a Neutron in a Formation

·A neutron source emits a continuous flux of high-energy neutrons.
·Collisions with formation nuclei reduce the neutron energy -thereby slowing it down.
·At thermal energy levels (approximately 0.025 eV), neutrons are captured.
·Neutron capture results in an emission of gamma rays.

Neutron logging devices contain one or more detectors and a neutron source that continuously emits energetic (fast) neutrons.

Neutron Log applications

- Neutron tools are used primarily to determine:
- porosity, usually in combination with the density tool

  Neutron tool response is dominated by the concentration of hydrogen atoms in the formation. In reservoirs, the neutron log response will provide a good measure of formation porosity if liquid-filled pore spaces contain hydrogen, as is the case when pores are filled with oil or water (hydrogen index =1). By contrast, when logging shaly or gas-bearing formations, a combination of Neutron and Density readings will often be required for accurate porosity assessment.

- Gas detection, usually in combination with the density tool, but also with a sonic tool.

- Shale volume determination, in combination with the density tool

- lithology indication, again in combination with the density log and/or sonic log
- formation fluid type.

Acoustic Log

- The *acoustic* or *sonic* log measures the travel time of an elastic wave (sound) through the formation. This information can also be used to derive the velocity of elastic waves through the formation.
- The sonic log is a porosity log that measures interval transit time (Δt) of a compressional sound wave traveling through one foot of formation.
- The sonic log device consists of one or more sound transmitters, and two or more receivers. Interval transit time time (Δt) in microseconds per foot is the reciprocal of the velocity of a compressional sound wave in foott per second.

main uses:

- To provide information to support and calibrate seismic data.
- To derive the porosity of a formation.
- Stratigraphic correlation.
- Identification of lithologies.
- Facies recognition.
- Fracture identification.
- Identification of compaction.
- Identification of source rocks.

Principles of measurements

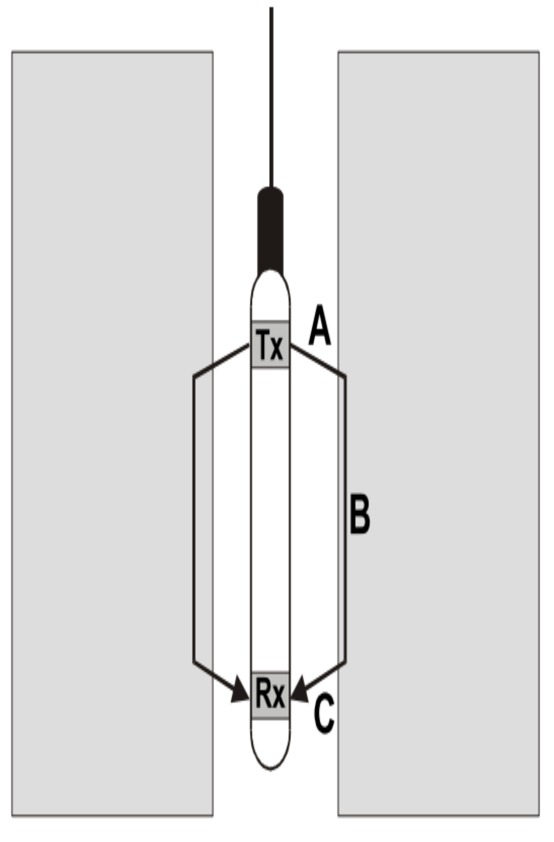
- The Sonic tool measures the time it takes for a pulse of “sound” (i.e., and elastic wave) to travel from a transmitter to a receiver, which are both mounted on the tool.
- If one knows the distance between the Transmitter (Tx) and the Receiver (Rx), the velocity of the wave in the formation opposite to the tool can be found.

Receiver

- The pulse measured is a compression P- wave followed

  by shear and stoneley waves .

Transmitter



Sonic tool

Theory: Waves Types

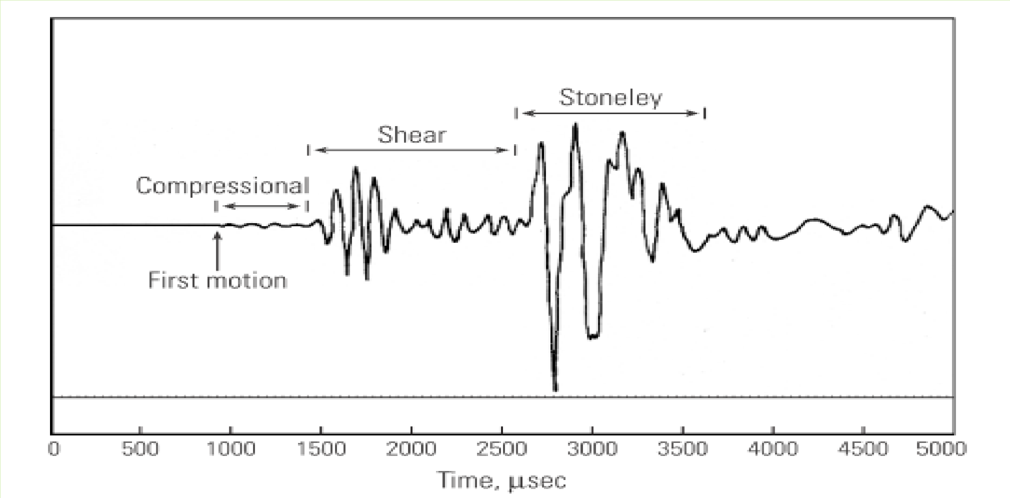
*The transmitted pulse using the Transmitter is very short and of high amplitude (frequency). This travels through the rocks in various different forms while undergoing dispersion (spreading of the wave energy in time and space) and attenuation (loss of energy through absorption of energy by the formations).

- When the sound energy arrives at the Receiver, having passed through the rock, it does so at different times in the form of different types of wave. This is because the different types of wave travel with different velocities in the rock or take different pathways to the receiver. Three waves can be recognized:

1. The first arrived is the compressional wave of low amplitude.

2. The second wave, with a larger amplitude, is the Shear wave of slower velocity.

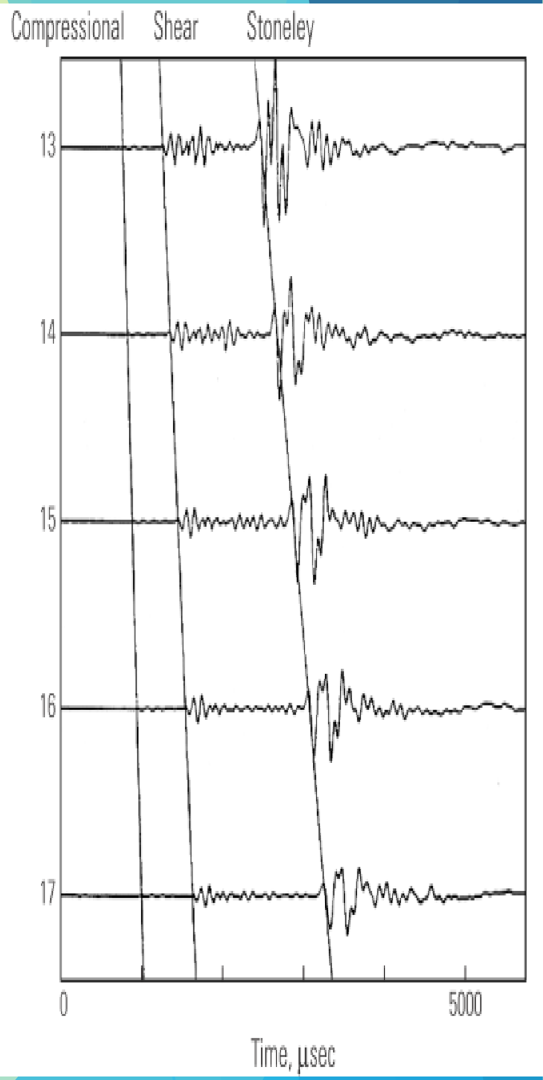
3. Finally, a wave of larger amplitude is arrived, known Stoneley wave.



A typical received train of waves.

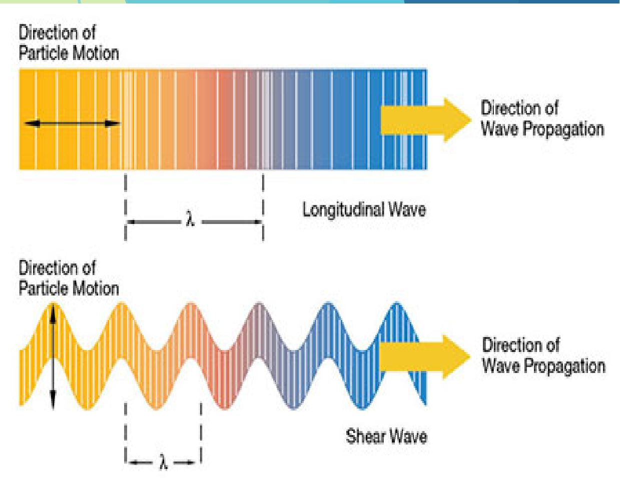
Theory: Waves Types

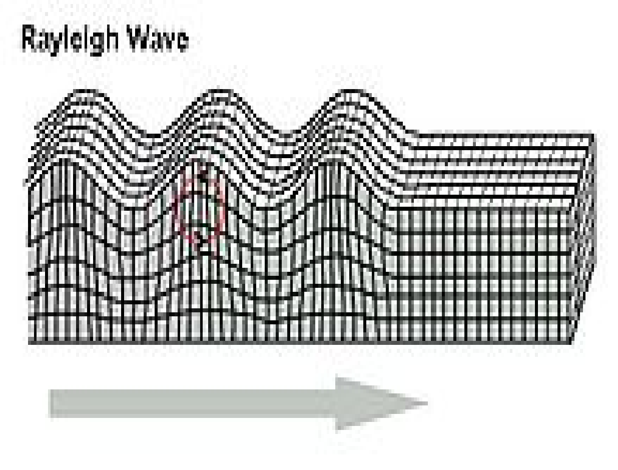
- After some time the first type of wave arrives. This is the ***compressional*** or ***longitudinal*** or pressure wave (**P-wave**). It is usually the fastest wave, and has a small amplitude.
- The next wave to arrive is the ***transverse*** or ***shear wave*** (**S- wave**). This is slower than the P-wave, but usually has a higher amplitude. The shear wave cannot propagate in fluids, as fluids do not behave elastically under shear deformation. These are the most important two waves.
- After them come ***Rayleigh*** waves and **Stoneley** (surface) waves. These waves are associated with energy moving along the borehole wall. They can be high amplitude, but always arrive after the main waves have arrived.
- There may also be unwanted P-waves and S-waves that travel through the body of the tool, but these are minimized by good tool design by (i) reducing their received amplitude by arranging damping along the tool, and (ii) delaying their arrival until the P-wave and S-wave have arrived by ensuring that the pathway along the tool is a long and complex one.



Waves Propagation

- Sound energy used travels in different wave modes based on the direction of the wave and the corresponding motion of molecules. The most commonly modes are longitudinal waves, shear waves, and surface waves.
- **Longitudinal waves:** In a longitudinal wave, particle motion in the medium is parallel to the direction of the wave front. Sound waves are longitudinal waves. Longitudinal waves travel the fastest of the wave modes, approximately 5900 meters per second (0.23 inches per microsecond) in steel.
- **Shear waves:** In a shear wave, particle motion is perpendicular to wave direction. Shear waves have a slower velocity and shorter wavelength than longitudinal waves of the same frequency. Typical shear wave velocity in steel is approximately 3250 meters per second (0.128 inch per microsecond). Shear waves can exist in solids only, not in liquids or gasses.
- **Surface waves:** Surface waves, also known as Rayleigh waves, represent an oscillating motion that travels along the surface. Ocean waves are an example of surface waves.





•**The data of interest is the time taken for the P-wave to travel from the transmitter to the receiver.** *This is measured by circuitry that starts timing at the pulse transmission and has a threshold on the receiver. When the first P-wave arrival appears the threshold is exceeded and the timer stops.*

Velocity V and Δt

- In practice the sonic log data is not presented as a travel time, because different tools have different Tx-Rx spacings. Nor is the data presented as a velocity. The data is presented as a slowness or the travel time per foot traveled through the formation, which is called delta t (Δt or ΔT), and is usually measured in μs/ft. Hence we can write a conversion equation between velocity V and Δt :

$$\Delta t = \frac{10^6}{V}$$

where the **Δt** is in microseconds per foot, and the velocity, **V** is in feet per second

The velocity of the compressional wave depends upon the **elastic properties** of the rock (matrix plus fluid), so the measured ***Δt varies depending upon the composition and microstructure of the matrix, the type and distribution of the pore fluid and the porosity of the rock***.

The velocity of a P-wave in a material is directly proportional to the strength of the material and inversely proportional to the density of the material. Hence, the Δt of a P-wave in a material is inversely proportional to the strength of the material and directly proportional to the density of the material, i.e.;

$$V \propto \frac{\text{Strength}}{\rho} \quad \text{and} \quad \Delta t \propto \frac{\rho}{\text{Strength}}$$

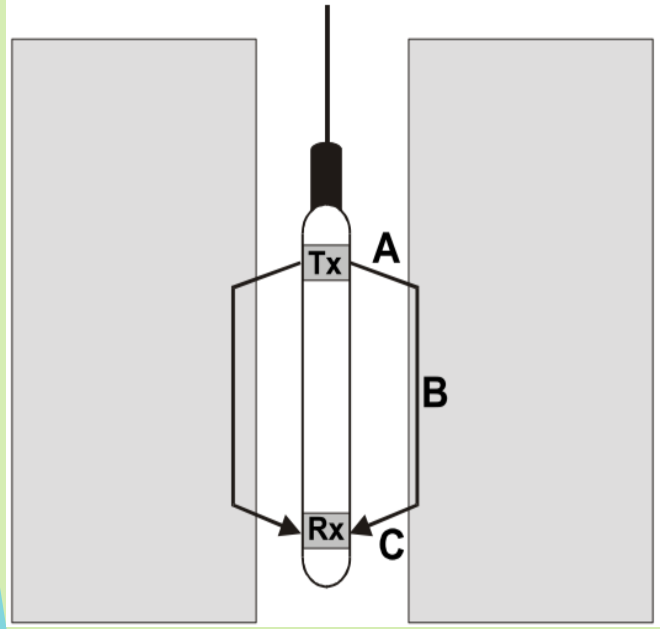
Sonic Log Tools

There are complex tools that make use of both P-waves and S-waves, and some that record the full wave train (full waveform logs).

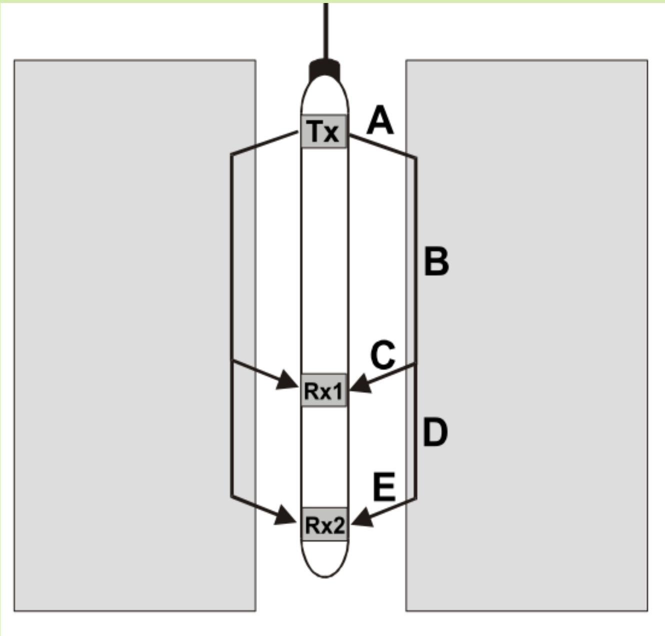
For the simple sonic log that we are interested in, only the first arrival of the **P-wave** is of interest. *The time between the transmission of the pulse and the reception of the first arrival P-wave is the one-way time between the transmitter and the receiver.*

Sonic Tools Types:

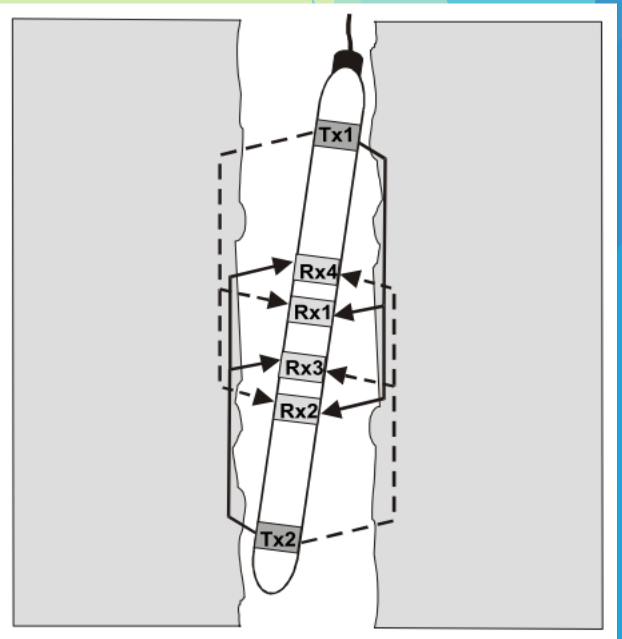
1.Early Tool



2.Dual Receiver Tool



3.Borehole Compensated Sonic(BHC) Tool



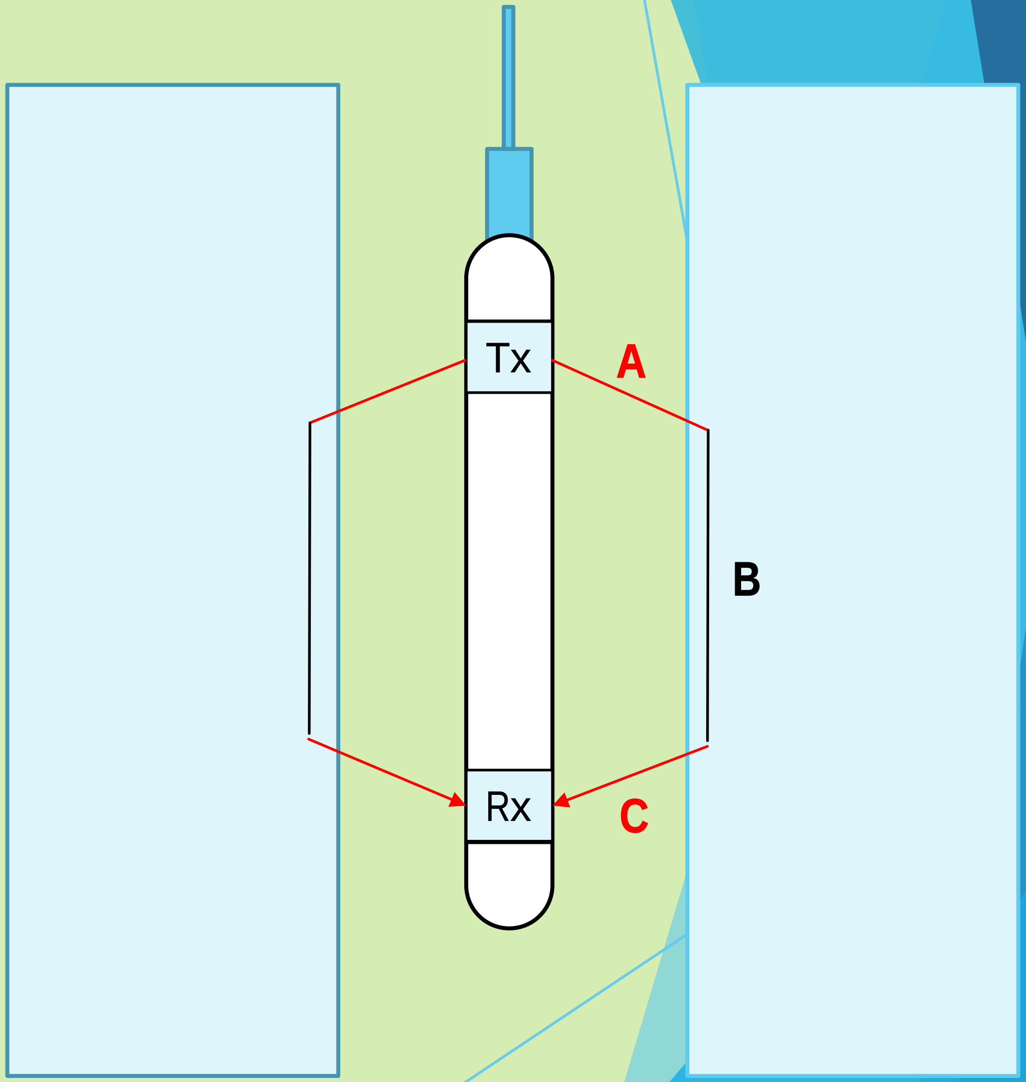
Early Tool

1. Early tools had one Transmitter Tx and one Receiver Rx.

2. The body of the tool was made from rubber (low velocity and high attenuation material) to stop wave travelling preferentially down the tool to the Rx.

➢ The main problems with this tool, The measured travel time is too long.

Δt=A+B+C



Early Sonic Tools

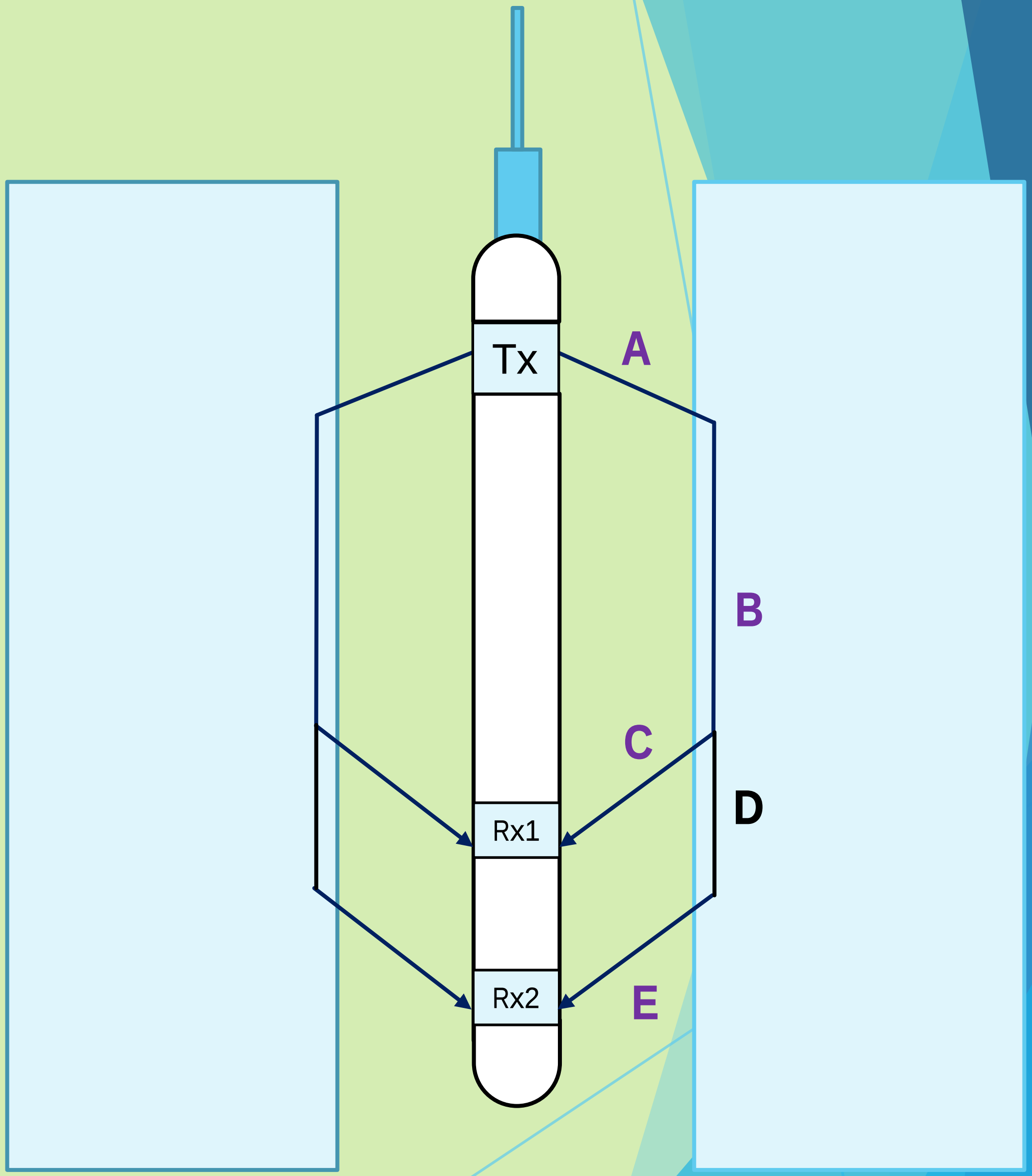
Dual Receiver Tool

- These tools were designed to overcome the problems in the early tools.

- They use two receivers (**RX1 & RX2**) a few feet apart, and measure the difference in times of arrival of elastic waves at each Receiver from a given pulse from the Transmitter **TX**.

This time is called the *sonic interval transit time* (**Δt**) and is the time taken for the elastic wave to travel through the interval D (i.e., the distance between the receivers).

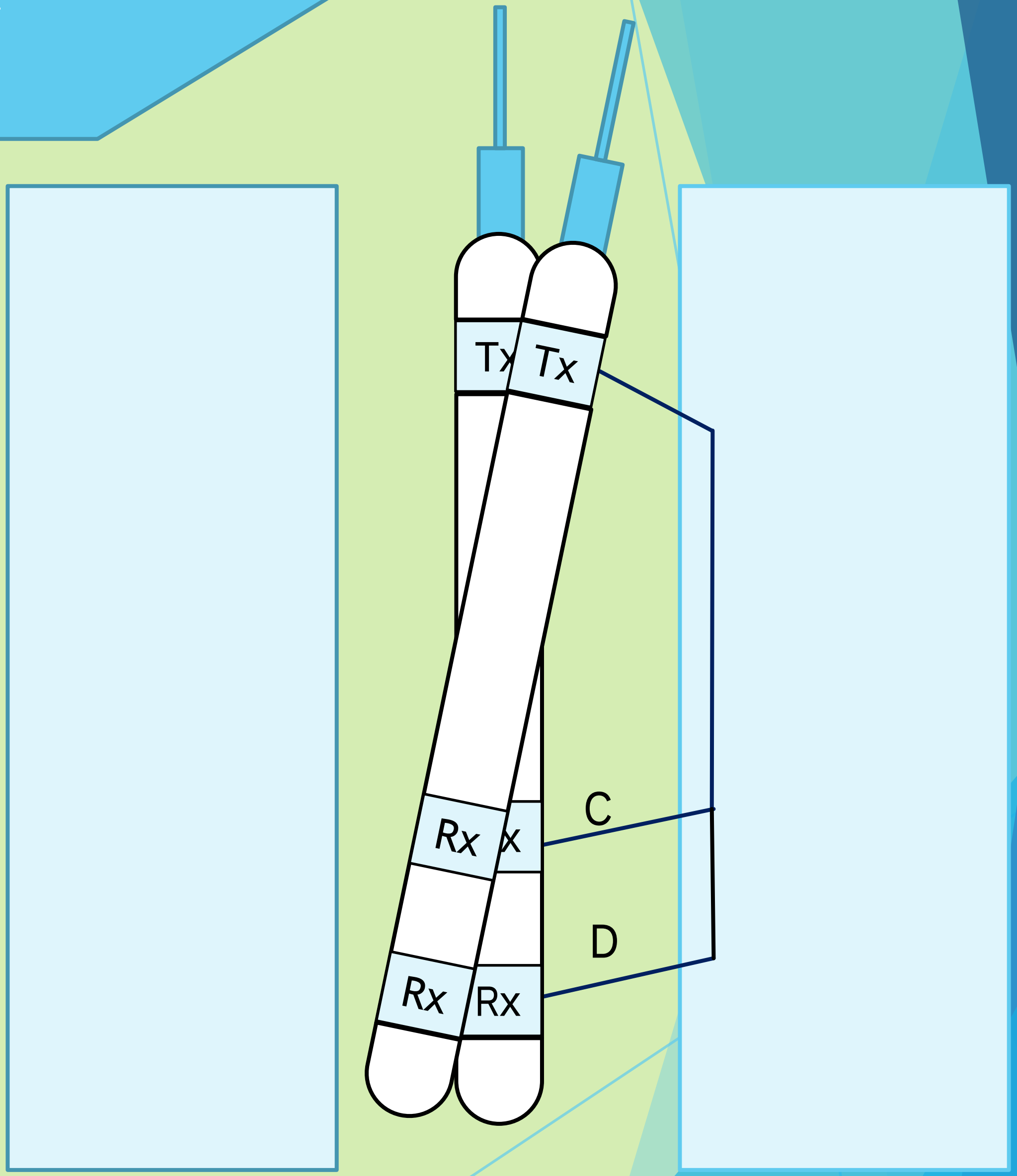
- *TRx1*= A+B+C
- *TRx2*= A+B+D+E
- Δt=(A+B+D+E)-(A+B+C)
- **Δt**=(TRx2-TRx1)=D
- (If tool is axial in borehole **C=E**)



Dual receiver sonic tool

Problem with Dual Receiver Tool

- If the tool is tilted in the hole, or the hole size changes
- Then C≠E
- The two Rx system fails to work.



Dual receiver sonic tools

Borehole Compensated Tool

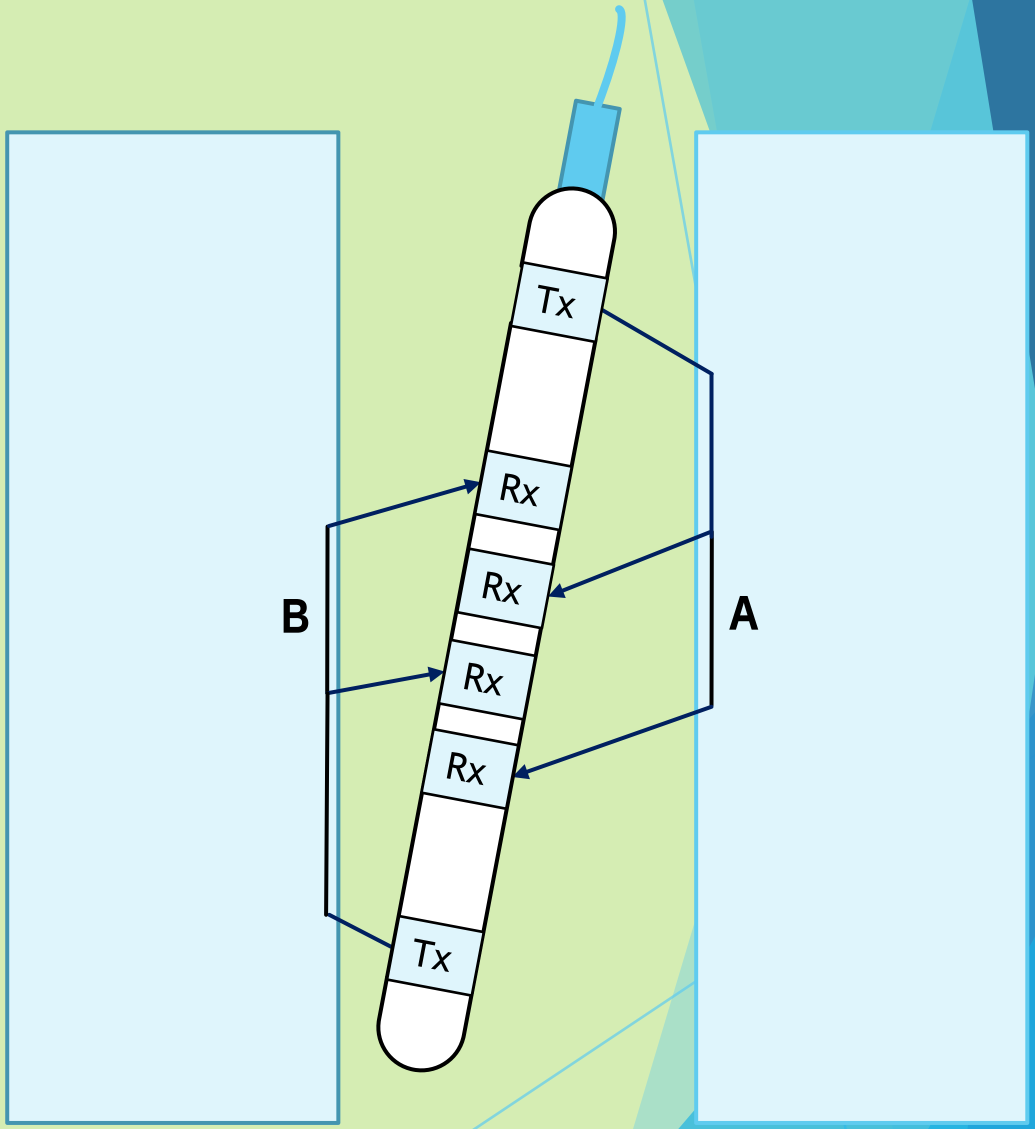
- Automatically compensates for borehole size effects and sonde tilt.

- It has **two transmitters** and **four receivers**, arranged in two dual receiver sets in the opposite direction.

- Each of the transmitters is pulsed alternately, and Δt values are measured from alternate pairs of receivers

- These two values of Δt are then averaged to compensate for tool misalignment

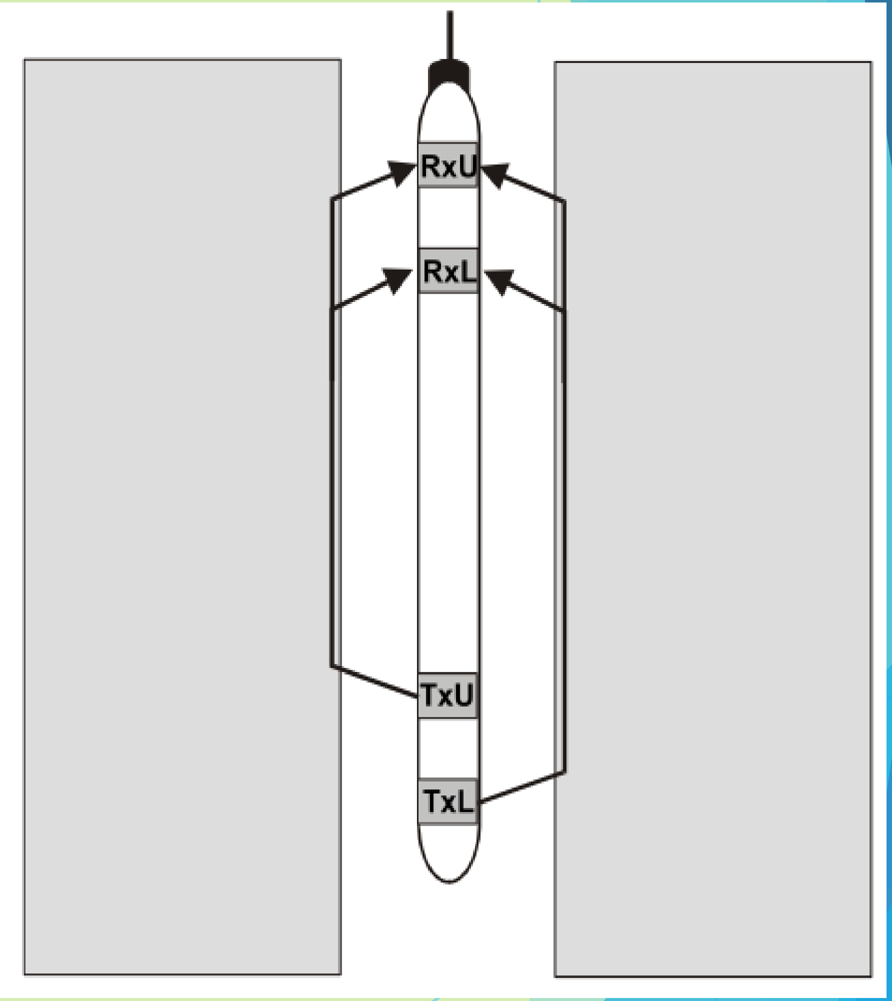
- $\Delta t = A + B/2$



Borehole compensated sonic tools

Long Spacing Sonic (LSS) Tool

- Schlumberger developed the long spacing sonic (LSS), which has two Tx two feet apart, and two Rx also two feet apart but separated from the Tx by 8 feet.
- This tool gives two readings; a near reading with a 8-10 ft. spacing, and a far reading with a 10-12 ft.



Long spacing sonic tools

Sonic Log Format, scale and unit

*The sonic log measures interval transit time (**Δt**) of a compressional sound wave traveling through one foot of formation.

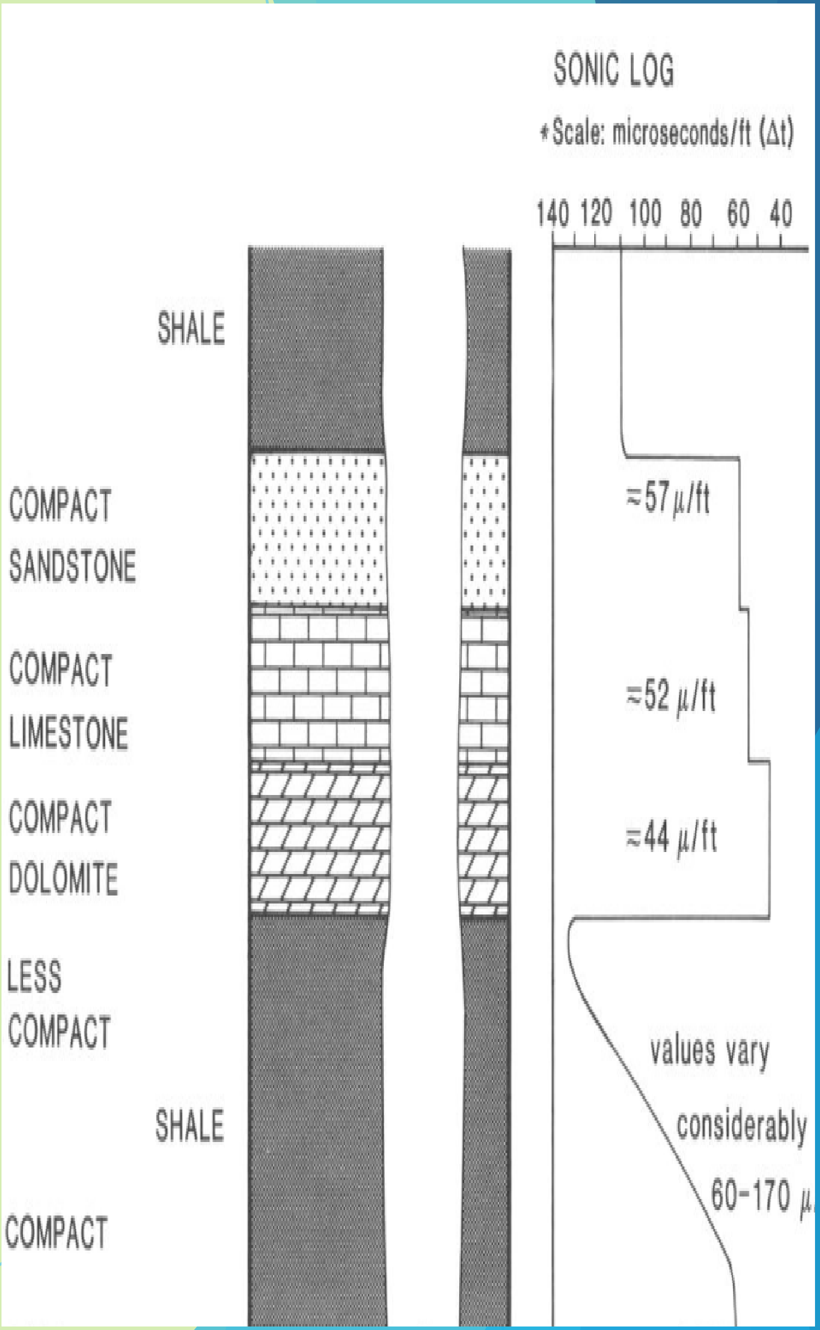
* The units are micro seconds/ft, which is the inverse of velocity.

* Most formations give transit times between 40 µs/ft and 140 µs/ft., so these values are usually used as the scale
* The log is given in arithmetic scale (Normal Scale).

Sonic log units are micro seconds/foot, which is the inverse of velocity.
If Δt= 40µs, then the velocity= 1/ Δt

= 1/(40*10-6)

=25.000ft/sec



Applications

* Seismic Data Calibration: The presence of a sonic log in a well that occurs on a seismic line enables the log data to be used to calibrate and check the seismic data. As the resolution of the sonic log is about 61cm and that of the seismic technique is 10 m to 50 m, the sonic data must be averaged for the comparison to be made. 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. The acoustic log can be used to determine porosity in consolidated formations.

It is also valuable in other applications, such as:

- Indicating lithology (using the ratio of compressional velocity over shear velocity),
- Correlation with other wells
- Detecting fractures and evaluating secondary porosity,
- Determining mechanical properties.
- 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.
- Compaction: As a sediment becomes compacted, the velocity of elastic waves through it increases

CALIPER LOG

<u>Introduction</u>

The *Caliper Log* is a tool for measuring the diameter and shape of a borehole. It uses a tool which has 2, 4, or more extendable arms. The arms can move in and out as the tool is withdrawn from the borehole, The arms are linked to a potentiometer and the movement is converted into an electrical signal by the potentiomet

In 'simple' **<u>the two arm tool</u>** (Figure 1), **the borehole diameter is measured**. This is shown in the log together with the bit size for reference. Borehole diameters larger and smaller than the bit size are possible. Many Boreholes can attain an oval shape after drilling. This is due to the effect of the pressures in the rocks being different in different directions. In oval holes, the two arm caliper will lock into the long axis of the oval cross Section, giving larger values of borehole diameter than expected. **In this case tools with more arms are required.**

Figure 1: two arm caliper tool

Function of the Tool:

- The tool measures variations in bore hole diameter with depth.
- The measurements are made by two (or more) articulated arms pushed against the borehole wall.
- The arms are linked to the cursor of a variable resistance. Lateral movements of the arm is translated into the movements of the cursor along the resistance, and hence variation in electrical out put.
- The variations in output are translated into diameter variations .

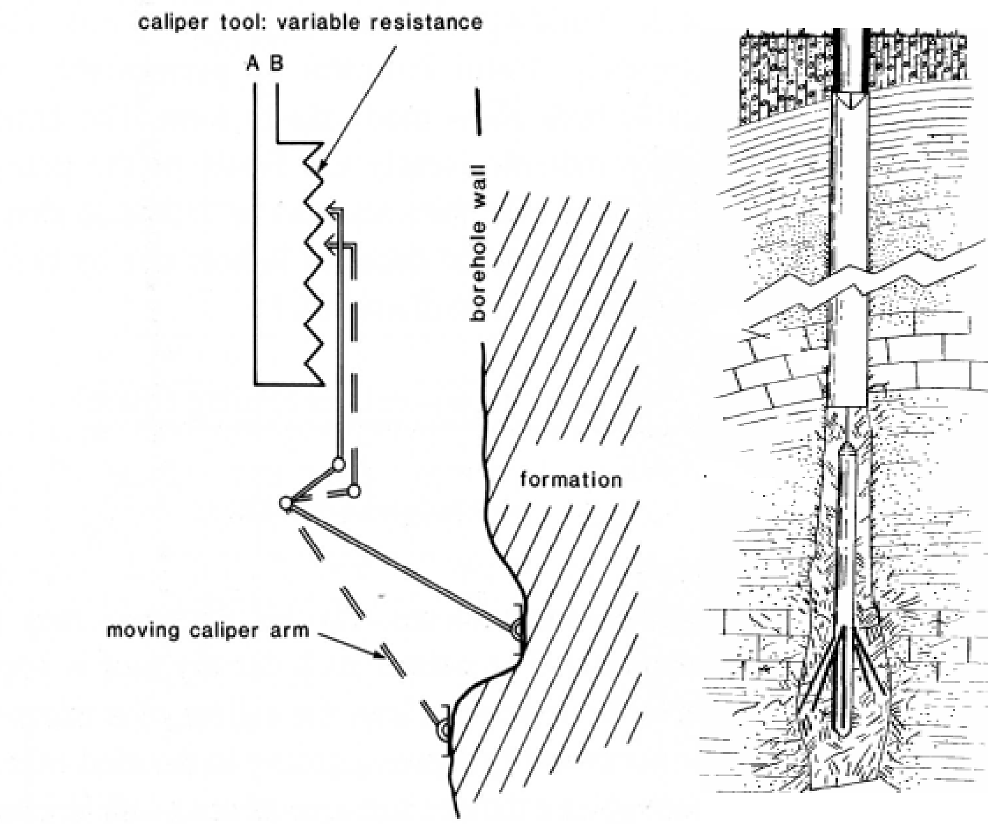


Figure (2) Schematic Caliper tool showing the conversion of a mechanical movement to an electrical signal using a variable resistance

In the **4 arm (dual caliper) tool**, the two opposite pairs of arms (figure 3) work together to give the borehole diameter in two perpendicular directions. An example of a 4 arm tool is the Borehole Geometry Tool (BGT). This has 4 arms that can be opened to 30 inches (40 inches as a special modification), and give two independent perpendicular caliper readings. The tool also calculates and integrates the volume of the borehole and includes sensors that measure the direction (azimuth) and dip of the borehole.

Figure 3: Four arm caliper tool

In **the multi-arm tools**, Figure (4) up to 30 arms are arranged around the tool allowing the detailed shape of the borehole to be measured. Some of the other tools have sensors attached to pads that are pressed against the borehole wall. The pressing device is also a form of caliper, and so caliper information can sometimes also be obtained from these tools.

Figure 4: Multi- arm caliper tool

Log Presentation

The ***caliper logs*** are plotted with the drilling bit size for comparison, or as a differential caliper reading, where the reading represents the caliper value minus the drill bit diameter (Figure 5). ***The scale is generally given in inches***, which is standard for measuring bit sizes.

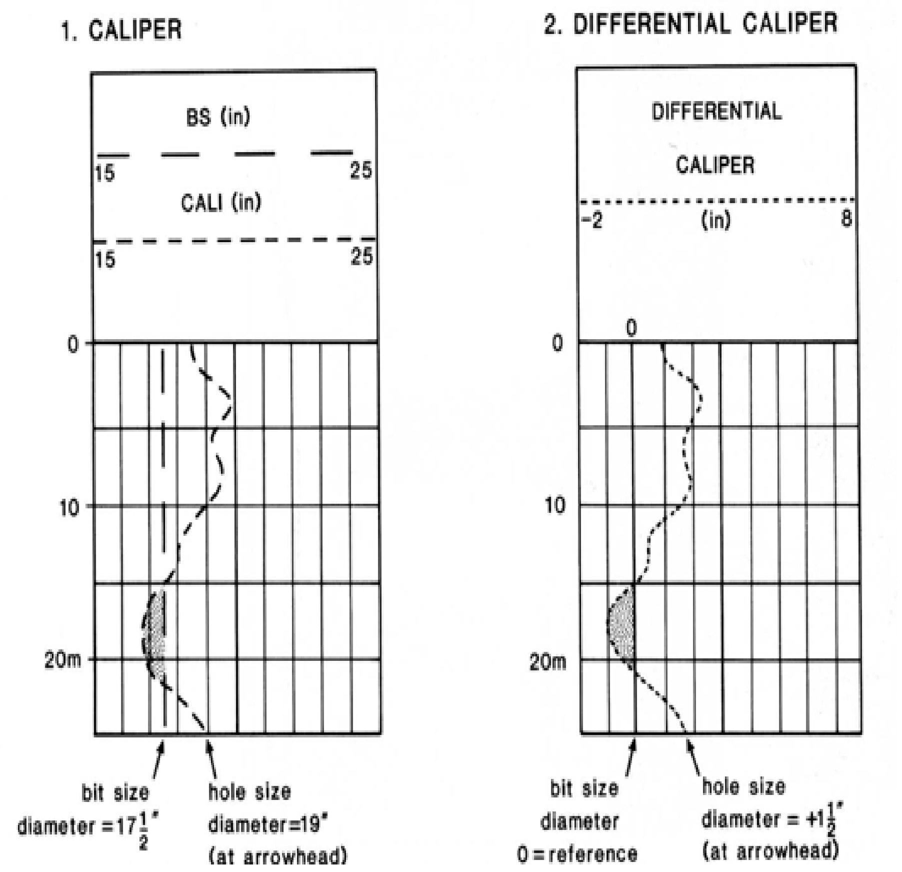


Figure 5 Presentation of 2 arm caliper log data: Caliper Logs: 1. in ordinary format; 2. in differential format; BS = Bit size

The 4 arm (or dual caliper) tools are presented in a range of formats, an example of which is given in Figure 6. Note that data from the caliper pairs are shown together, and that they are different indicating an oval hole.

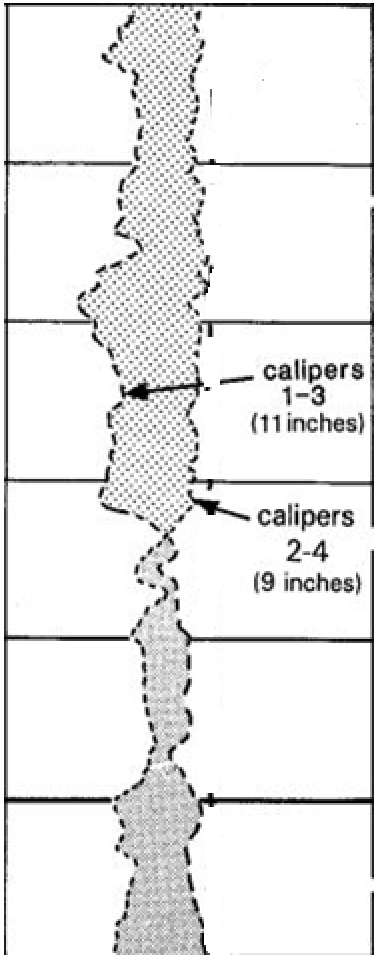


Figure 6 Presentation of 4 arm caliper log data

Caliper Log Interpretation

Figure 7 shows a schematic hole with caliper information, and Table 1 describes the main influences on caliper values. Note that when a hole is the same diameter as the bit-size it is called *on gauge.*

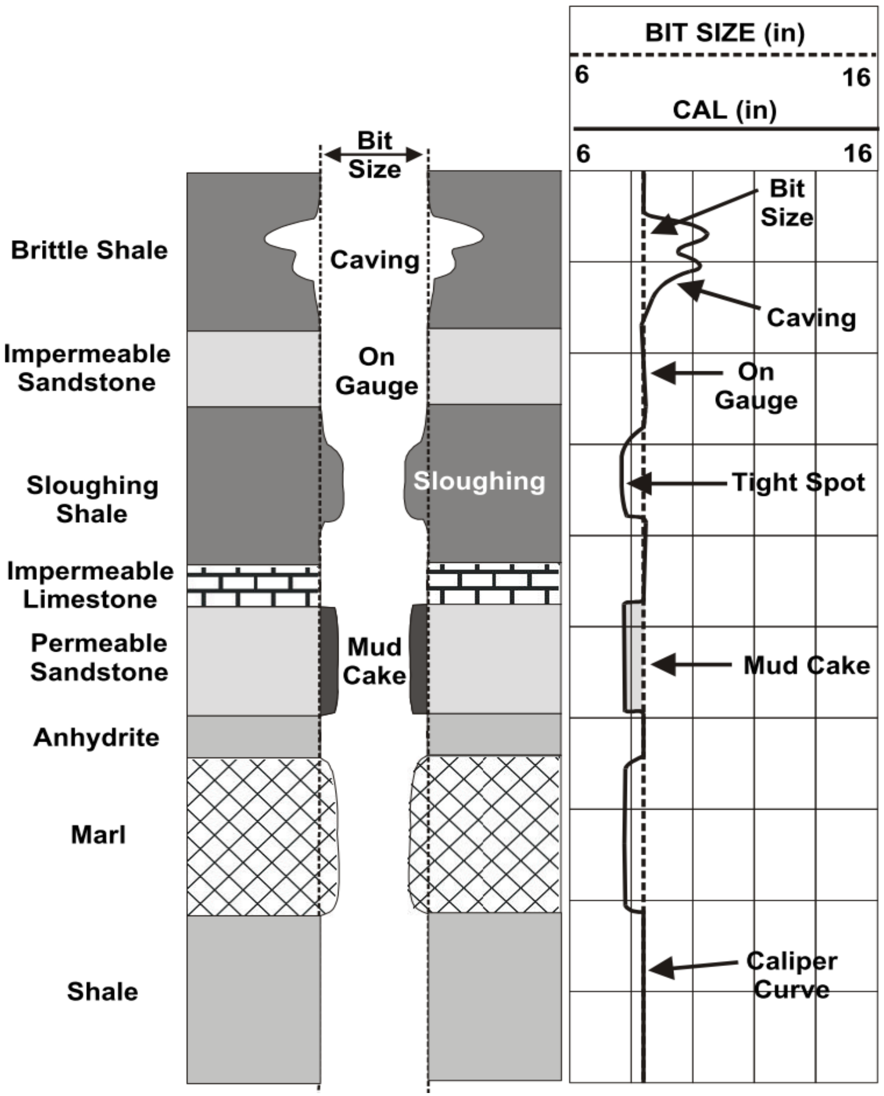


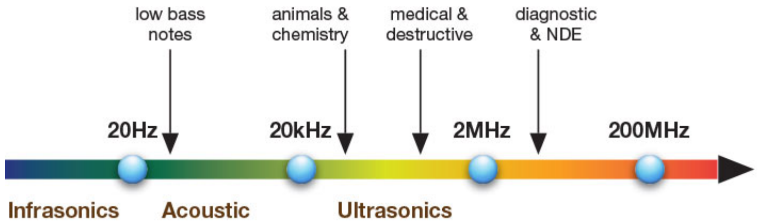
Figure 7 A schematic hole with caliper information

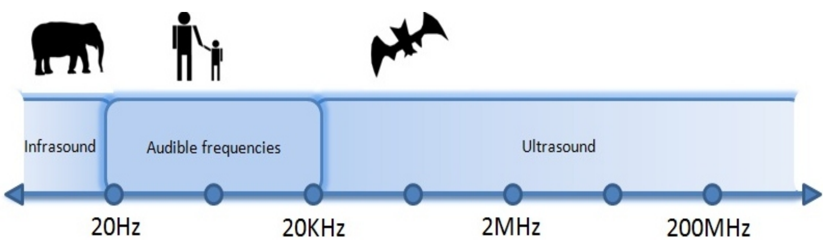
Hole Diameter	Cause	Possible Lithologies
On Gauge	Well consolidated formations Non-permeable formations.	Massive sandstones Calcareous shales Igneous rocks Metamorphic rocks
Larger than Bit Size	1. Formation soluble in drilling mud. 2. Formations weak and cave in.	1. Salt formations drilled with fresh water. 2. Unconsolidated sands, gravels, brittle shales.
Smaller than Bit Size	1. Formations swell and flow into borehole. 2. Development of mudcake for porous and permeable formations.	1. Swelling shales. 2. Porous, permeable sandstones.

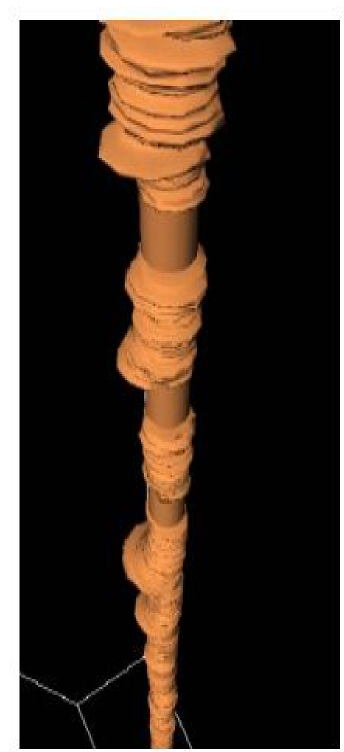
Table 1 The main influences on caliper values

Various types of caliper logs

- Mechanical Caliper -arm averaging.
- Ultrasonic Caliper -An Ultrasonic transducer scans around the borehole walls, and the reflected travel time is converted to the distance between the sonde and the wall.
- Acoustic caliper – calculated from acoustic transit time and velocity







3D image of the ultrasonic caliper. (From Schlumberger)

FLUID TESTING AND PRESSURE LOGS

Introduction

Formation fluid testing involves taking fluid samples from the formation and measuring their pressures.

It gives information on:

1) the types and properties of fluids in the formation,

2) indicates the presence of hydrocarbons, and

3) provides information on the pressures of the fluids within the formation.

4) measure the productivity of the formation.

There are three generic types of test. The three measurement types are as follows, and are described in the order that they are performed, in their complexity, and therefore their cost:

1. **A drill stem test**
2. **Wireline Formation Testing.**
3. **Production Testing**

The second of which will be discussed in detail as it is a wireline method.

Drill Stem Test DST

Drill stem test (DST) is a procedure for isolating and testing the pressure and productive capacity of a geological formation during the drilling of a well. A portion of **perforated drill pipe** and one or two devices for sealing the interval of the well of interest off (**inflated packers**) are lowered down the well to the required depth. The packer is then expanded to make a **seal** between the borehole wall and the drill pipe. If the bottom of the well is being tested, only one packer is needed. If an interval further up the well is being tested, two packers are needed, one above the interval and one below. A **valve** is then opened to reduce the pressure within the drill stem and the fluids will flow from the formation to the surface through the perforations in the drill pipe and up to the surface (Figure. 1).

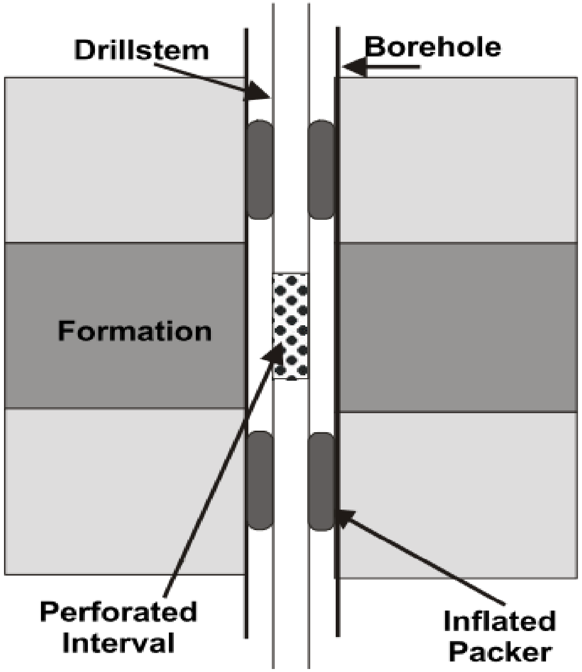


Figure 1: The drill stem test

Wireline Formation Test

A wireline tool used to sample fluid formation and to measure formation pressure quickly and accurately at specific points on the borehole wall . This operation is carried out in an open hole during wireline logging operations. The tool is lowered down the uncased hole to the point of interest. It is then jacked and sealed against the borehole wall. Samples of fluids and measurements of the fluid pressures are then taken. Note that this form of logging is not continuous, and is carried out at a few previously defined depths in the reservoir zone of the well only (Figure 2).

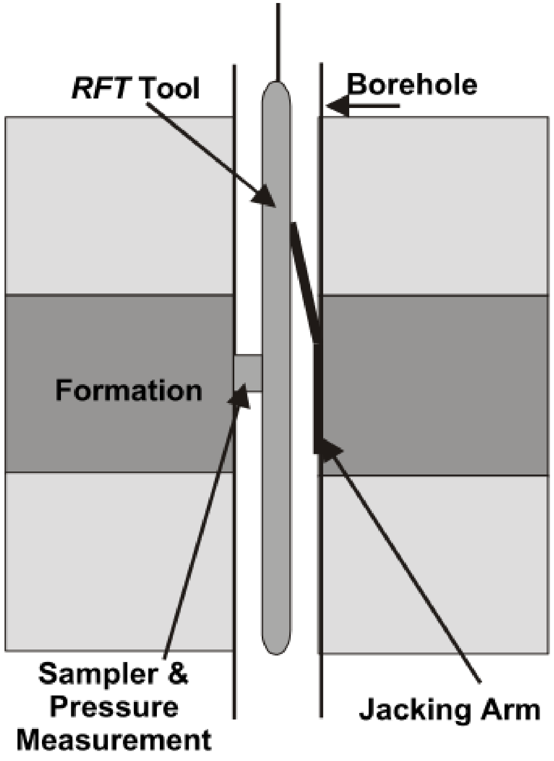


Figure 2: Wireline Formation test

Production Testing

Production tests are run to obtain an indication of well productivity and to determine reservoir properties . This is carried out in **a cased hole** and completed hole with a packer that has been set in place between the cased borehole and a production pipe. The casing is perforated using a wireline perforation gun. As the pressure inside the production pipe is held at a value that is lower than the formation pressure, the formation will produce fluids, which by this stage in the well completion, should be hydrocarbons. If the test produces sufficient hydrocarbons, the production may be allowed to continue as a fullycompleted well (Figure 3).

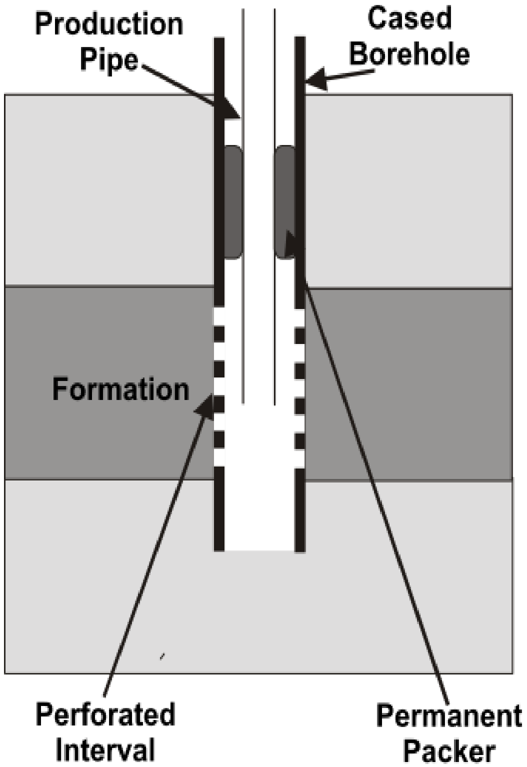


Figure 3: The production test

Wireline FormationTesting

There are a range of wireline formation testing tools now available, such as:

1) The Repeat Formation Tester (RFT)

2) Repeat Formation Sampler (RFS)

3) The Formation Multi-Tester (FMT).

Specifications:

- These tools are capable of taking multiple samples of fluids and pressure measurements in the borehole without withdrawal.
- These testers can mix the fluids sampled in one chamber, or take two separate samples and keep them separate.
- Fluids can be maintained at high pressure, which is important in some volatile oils as a sudden pressure drop causes a change in the composition of the oil.
- Time is saved by the tool and the tool can be reset at another depth for another try.
- It enables the first part of the sample (mud filtrate) to be stored separately from the latter part of the fluid sample (reservoir fluids), or enable the first part to be ignored, so that the sample reliably samples only the reservoir fluid.
- The tools can cope with consolidated and unconsolidated formations, and provide very accurate fluid pressure readings. The tools also require very little time between runs for re-dressing the tool, i.e., unloading the sampled fluids and preparation for the next run.

Operation of Repeat Formation Tester (RFT)

The tool is designed to measure formation pressure quickly and accurately. It measures pressure at specific points on the borehole wall. The tool is run into the well to the depth required, the tool is then attached securely to the wall of the borehole:

- The packer seals the sampling head from the drilling mud and mudcake surrounding the tool (Figure 4. a).
- The probe containing the piston is then pressed through the mudcake into the formation (Figure 4.b).
- The piston is withdrawn, allowing fluids to pass from the formation into the tool (Figure 4.c). This fluid is made to enter a chamber (first pre-test chamber) through a special valve that limits the flow rate to about 60 cm3/min. The sampling pressure is measured. When the first chamber is full, it is closed-off and a second pre-test chamber is filled at a higher rate (150 cm 3/min), while measuring the fluid pressure. When this chamber is full the flow-line fluids are at the same pressure as the fluids in the formation, and this pressure is measured.
- The fluid sample is commonly between 5 and 20 liter. If another sample or more pressure data is required from further depths, the pre-test chambers are emptied and the tool progresses. Finally, the tool is removed with both its sampling chambers full, and having taken a number of pressure readings at sampled or un sampled depth points. The samples are usually sent to a specialist laboratory where the compositions, physical properties and relative volumes of oil, gas, mud filtrate, and formation water can be measured.

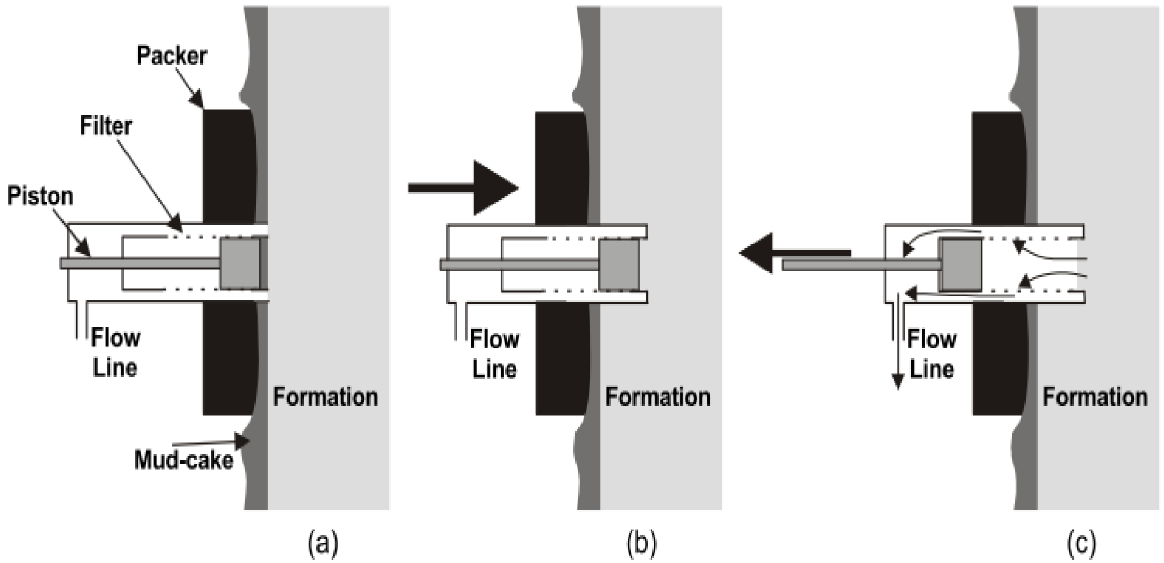


Figure 4: RFT operation

Analysis of Pressure Measurements

A typical RFT recording of pressures from one depth is shown in Figure 5.

1. The hydrostatic pressure is that of the drilling mud, and is recorded while the tool is at the required depth, but has not been pressed against the wall by the packer (A). This is constant for a given depth in the borehole, and depends upon the weight of the column of mud above it.
2. When the tool penetrates the mud-cake, some mud is compressed between the probe and the formation wall, leading to a transient pressure increase (B).
3. The piston is open, and fluid flows into pre-test chamber 1 at 60 cm3/min. The pressure drops because an additional volume has been added to the system (the chamber). The pressure pushing the fluid into the chamber is ΔP1 (C).
4. When the chamber is approaching full the measured pressure begins to increase towards the formation pressure again (D).
5. The second chamber is opened up, and the pressure once again drops because fluid now flows at 150 cm 3/min into the second chamber. The pressure pushing the fluid into the chamber is ΔP 2 (E).
6. When both chambers are full the measured pressure increases towards the formation pressure, which may take some time for low permeability formations (F).
7. After the pressure measurement, the tool is retracted and the mud pressure is measured again (G).

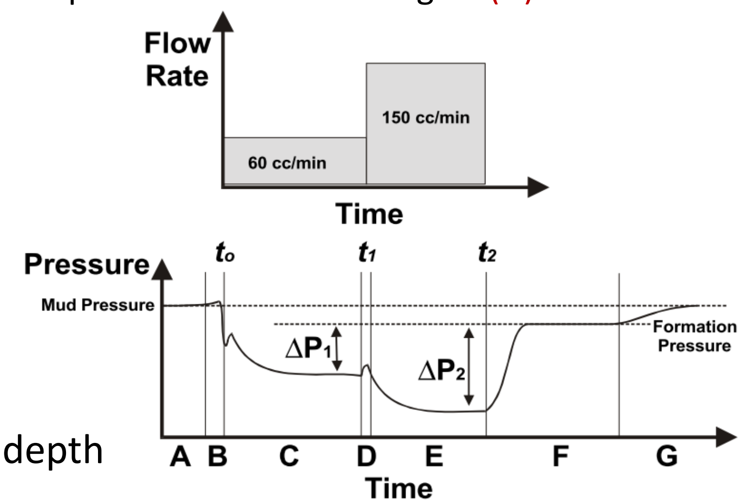


Figure 5: A typical RFT recording of pressures from one depth

Log Presentation

- Pressure is given in psi (**pound-force per square inch**).
- The pressures are given in analogue and digital form. Track 1 usually contains the analogue pressure data
- The vertical scale is in **TIME.**

A typical RFT log for one depth is given as Figure 6

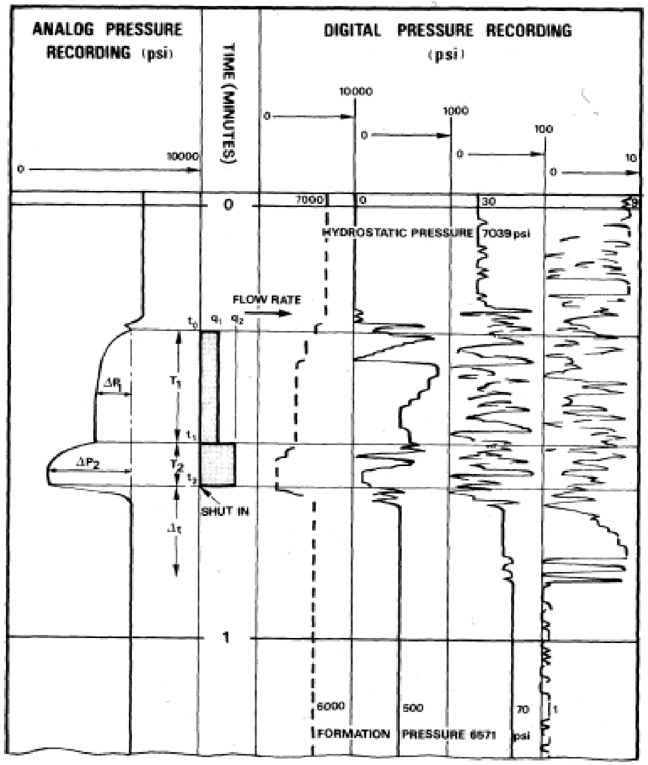


Figure6: An example RFT pressure log

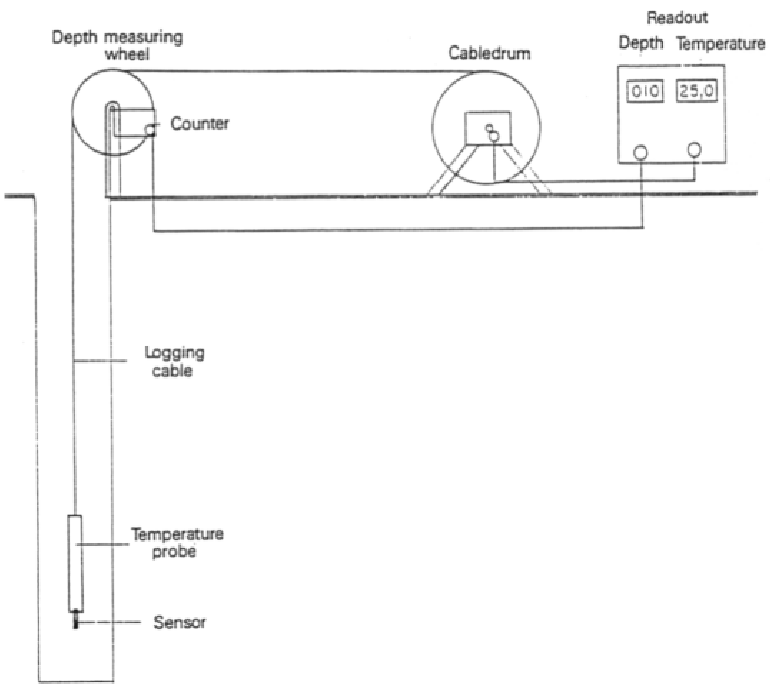
Temperature Logging

Introduction

The ***Temperature Log*** is a record of the ***temperature gradient*** in a well.

Temperature sensors are attached to every tool combination that is run in a well for the measurement of the maximum temperature (assumed to be at the bottom of the well), and a few modern tools exist that can continuously measure temperature as the tool travels down the well.). Readings from a number of the maximum thermometers attached to different tool combinations and run at different times are analyzed to give the corrected temperature at the bottom of the borehole (bottom hole temperature, BHT).

A portable logging unit for temperature measurement is drawn schematically in Figure. A temperature sensor (resistance) is connected to an electric single conductor logging cable. Part of the sensor and the connection is encased in a pressure steel pipe (water tight). A sheave on well head guides the cable into the hole but act as a depth meter as each rotation moves the cable 1 meter. The electronic package and batteries are encased in a box displaying the depth and the sensor reading



Portable temperature logging unit

Theory

Temperature in the sub-surface increases with depth. The rate of increase in temperature per unit depth in the Earth is called the ***geothermal gradient*** or ***geotherm***. Typical geotherms for reservoirs are about 20 to 35 $^oC/km$, although significantly higher values (up to 85 $^oC/km$) can be found in tectonically active areas, and lower ones (0.05C/km) in stable continental platforms. Hence, the **bottom hole temperature** (BHT) for a 3000 m well with a geotherm of 25 ^oC and a surface temperature of 15 ^oC is 90^oC.

Note that this assumes that the geothermal gradient is constant. In practice this is rarely the case because of differences in the thermal conductivities of rocks between the bottom of the hole and the surface, and fluctuations in the surface temperature which penetrate the sub-surface and perturb the sub-surface temperature. Low thermal conductivity rocks, such as shale, act as a thermal insulator and have a large temperature gradient across them, while high thermal conductivity rocks, such as salt, permit the conduction of heat efficiently, and have a small temperature gradient across them.

The temperature log is interpreted by looking for anomalies, or departures, from the reference gradient. This reference might be the geothermal gradient, a log recorded before production started. Most anomalies are related to the entry of fluids into the borehole or fluid exit into the formation.

Temperature logging instruments Types

A wide range of instruments have been used to measure temperature in boreholes:

1) Thermometers

The first thermometers used were ***mercury meters***, which were lowered repeatedly into the well on a line and stopped at one depth in each run. Several runs were therefore needed in order to have a temperature profile for the well.

2) **Temperature Resistors**

Temperature sensing electric resistors (***thermistors/platinum***) became common in logging in the 1950 for well temperatures up to 150°C. The most primitive method is to hook the sensor with waterproof connection to an electric cable and lower it into the well and measure the electric resistance in the sensor at regular intervals. The resistance measured is converted to temperature using a known from calibration curve correlating the resistance of the sensor to the temperature. Later an electronic package was placed in the logging probe and the information on the temperature (the resistance in the sensor) sent through the logging cable as a pulsed signal where the temperature was given by the pulse frequency.

3) Mechanical temperature gauges

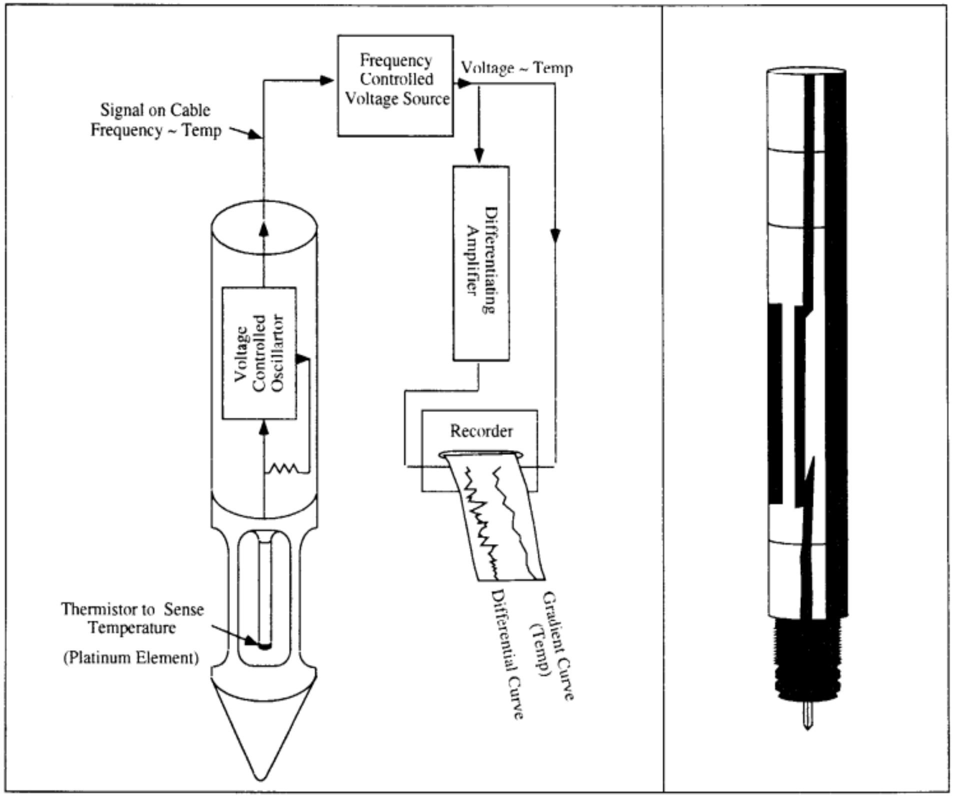
Mechanical temperature gauges for high temperature use were developed in the oil industry in the 1930 by an American company Geophysical Research Corporation. These gauges sense the borehole with a bourdon tube containing a special liquid which boils in the tube and build up pressure through a temperature interval (typically 100-300°C). The gauges were lowered into the well on a slick-line (steel wireline) and temperature (or pressure) recorded with a pen needle on a carbon coated brass foil inside a clock driven recorder. Several data points (20-30) could be recorded during one run. Typically the measurements were done at 100 m interval from top of the well to bottom. The gauges are robust and fairly reliable with an accuracy of +/- 2°C for temperature. Their limitation is mainly the few number of data point obtained. In modern logging we require data points at a couple of meters interval.

4) High temperature electronic logging tools

Since the mid 1980s several high temperature electronic logging tools with surface readout have been developed. A memory tool to be lowered into wells on a slick-line and the data information stored in a memory inside the tool. The down-hole electronics, memory and battery package are encased in a pressure housing and a Dewar flask (heat shield) which protects the electronics from the hot environment for several hours. The tool is typically lowered into the well at a speed of 30 m/min (0.5 m/s) and the data is collected into the memory every few seconds or at ~1 meter depth interval compared to every 100 m with the mechanical tool. The accuracy is also far better or +/- 0.5°C for temperature.

Temperature Measurement: principle

The temperature-logging tool includes a cage, which is open to the borehole fluid, is located at the bottom of the tool. Inside the cage is a thermistor that senses the surrounding fluid temperature. The preferred sensor is a platinum element (either a tiny coil of platinum wire or a platinum-film resistor) because the electrical resistance of the sensor varies linearly with temperature over a wide range and is stable over time. The circuitry of the tool is designed so that the voltage across the sensor is proportional to the sensor's electrical resistance. Platinum is an ideal temperature sensor because its resistivity is stable and increases linearly with temperature over a wide range. Thus, the tool makes a continuous measurement of the resistance of the thermistor, which by calibration id directly related to the temperature of the sensors environment. The voltage drop across the sensor is directly proportional to its resistance. this voltage is used is used to control the frequency output of a voltage-controlled oscillator, the 'pulses'' from which are transmitted up the logging cable to be counted at the surface.



(A) Schematic of Tool (B) Actual Tool

Figure (1) Modern wire line thermometer

Thermistors

Thermistors are temperature-sensitive resistive elements made of semiconductor material The physical effect governing a thermistor's change of resistance is the increased number of conducting electrons for a corresponding increase in temperature. Thermistors can be built up to 100 times more sensitive to temperature change, for the same resistivity change, than resistance temperature detectors (RTDs), which are described next. The main drawback of thermistors is their operating temperature limitation of approximately 300°F.

Logging procedure:

Temperature measurements are always made at the bottom of the well . This allows the sensor to contact fluid that has not been mixed vertically by the passage of the tool and wireline, and sometimes the measurements are made at intervals up the well. The temperature measuring devices can be as simple as a number of maximum temperature monitors that are attached to the outside of a tool string, and this was commonly the case until recently. In this case only the highest temperature (assumed to be at the bottom of the borehole) is measured. Recently a several special temperature logging sondes have been developed (the AMS of Schlumberger and the Temperature Survey of Western Atlas), which read temperature continuously up the well using a thermistor, and sometimes also read the temperature difference between two probes spaced along the tool. The absolute accuracy of temperature measurements is low (±2.5 °C), but the resolution is good (0.025°C).

Temperature logging:

Two Types of recording

1) Analog recording

In analog recording, the transmitted pulses per minute are converted to a voltage by a counting circuit. This voltage is recorded on a pen-and-ink strip chart recorded as the temperature (or gradient) trace. This is Trace 1 on the **Figure 2.**

The scale of the trace shows the temperature in degrees Fahrenheit °F.

As shown in the **Figure 1**, an amplified trace of temperature changes can be generated by the output of a differential amplifier whose input is the same voltage that gives the temperature record. The resulting ''differential'' trace magnifies the changes in slop on the temperature curve as shown in curve 2.

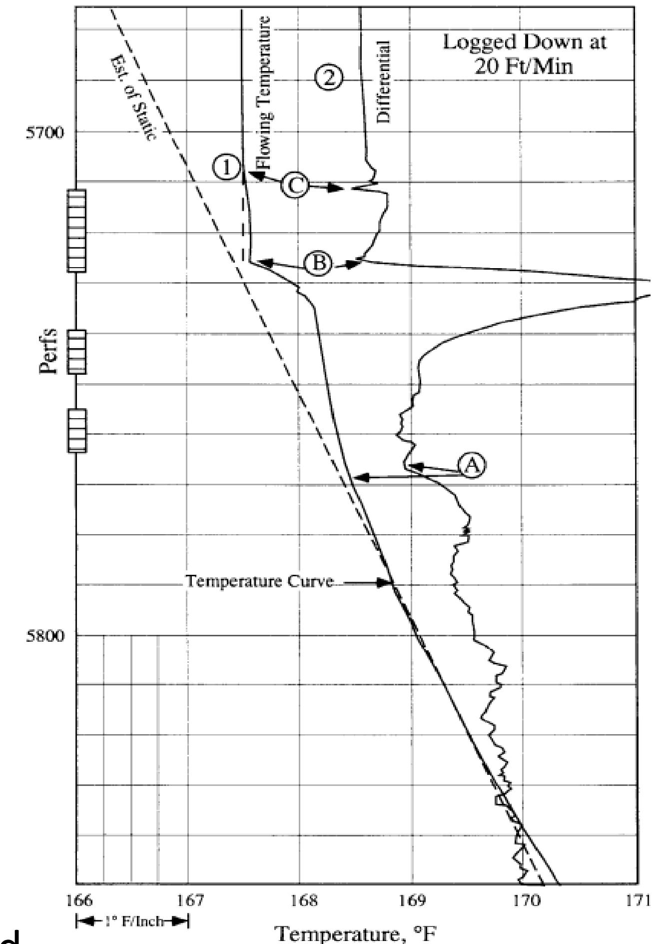


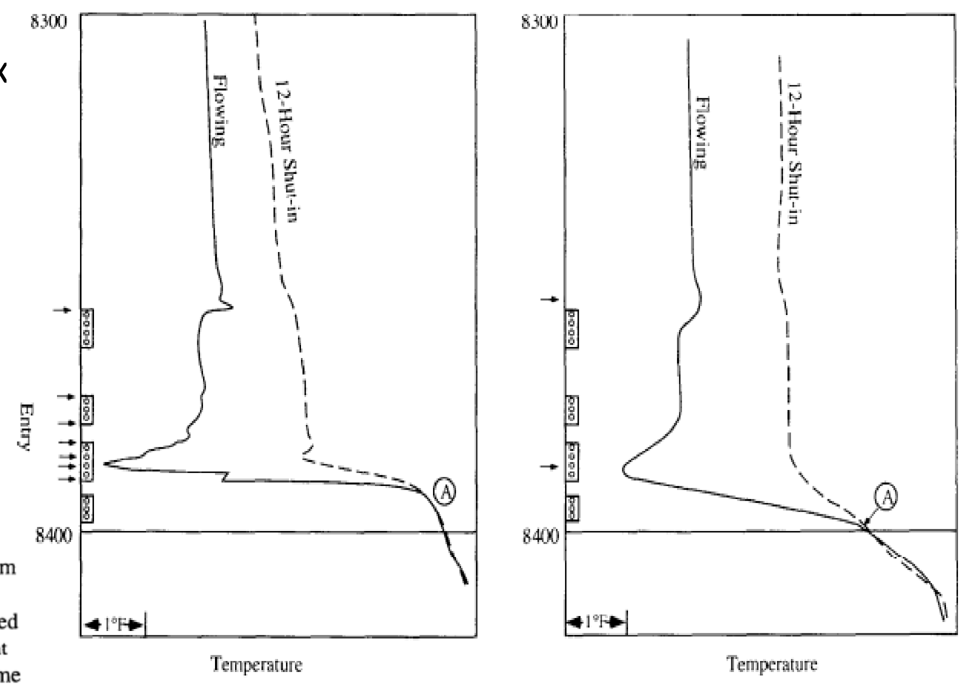
Figure (2) A section of a temperature record

2) Digital recording

In digital recording, the pulses from the logging cable are stored digitally on a storage tape at the surface, and the resulting count rate is converted to a temperature trace by the computer's program. Digital recording degrades the sensitivity of the differential trace from that available with analog recording. The conversion from pulses per minute to binary digits introduces errors. Thus, the digitally determined differential trace is not as useful for highlighting important changes of the temperature curve's slope.

The temperature tool is most effective when located at the bottom of a tool string. In a production well, the tool should always be logged downward so as to enter undisturbed fluid. The log should be recorded at a constant logging speed not to exceed 30 ft/min. With digital recording, the max logging speed should be reduced to 20 ft/min.

On digital logging trucks, the pulses transmitted up the logging cable are processed for tape storage by a binary coded digit unit (BCD). This is essentially a counting device with its own separate clock that is not synchronized with the downhole "clock" or tool. The conversion from pulses per minute to binary coded digits therefore introduces a sampling error that is considerable relative to the resolution of the downhole tool. Before display, this noise is filtered from the record with "suppressor" filters. The resulting degradation in signal quality is evident from a comparison of frames A and B of Figure 3 which show the results of processing the same temperature log by analog and digital panels, respectively.



(A) Analog Panel (B) Digital Panel with "Suppressor"

Borehole Temperature Corrections

* The actual temperature measured is that of the drilling fluid not the formation. The drilling mud is circulated during drilling and prior to inserting the wireline tool, and this drilling mud is cold compared to the formation. The cold drilling fluid invades the formation and cools it down very efficiently via heat convection. During circulation of drilling fluid the temperature of the borehole reaches an equilibrium defined by the cooling effect of the drilling fluid and the heating effect of the formation. When the circulation of the drilling mud stops (for example, in preparation for the insertion of a wireline tool), the borehole gradually regains the true formation temperature, because the large mass of formation around the borehole heats the drilling fluid up to its ambient temperature. This process is slow because it occurs via heat conduction which is less efficient than heat convection. Equilibrium may only be attained after several months after stopping the circulation of the drilling fluid.
* Hence, temperature measurements made during drilling consistently underestimate the formation temperature because drilling mud is being circulated. Temperature measurements made on wireline logs sometime after the drilling fluid circulation has stopped also underestimate the formation temperature, but less than the MWD/LWD case as the formation is now in the process of reheating the borehole. Measurements of temperature made by wireline logs at increasing times after fluid circulation has stopped are closer and closer to the real formation temperature.

Various methods have been adopted in the past to correct the logged BHT to real formation temperatures. The most common method is the Horner plot. The Horner method, plots the measured temperature (at a given depth) from each of several logging runs, against log(T/(t+T)), where T is the time since circulation of the drilling fluid was stopped (usually in hours), and t is the length of time of circulation of drilling fluid prior to this. The parameter t represents the length of time that the borehole was subjected to the cooling effects of the fluid, and T represents the time after circulation that the borehole has had to partially reheat. This plot is a straight line that intersects T/(t+T)=1 at the formation temperature.

For example, The Table gives the drilling, logging, and temperature data for three tool combinations that were run in a single hole one after another. Figure shows the Horner plot generated with this data, and the resulting formation temperature.

Time	Operation	Temperature (°C)	T (hours)	t (hours)	$T/(t+T)$ (-)
00:00	Circulation started	-	-	6	
06:00	Circulation stopped	-	0	6	
13:00	Run IEL log	100	7	6	0.538
17:30	Run Sonic log	105	11.5	6	0.671
01:30	Run FDC-CNL log	108	19.5	6	0.765

Table: Horner plot example.

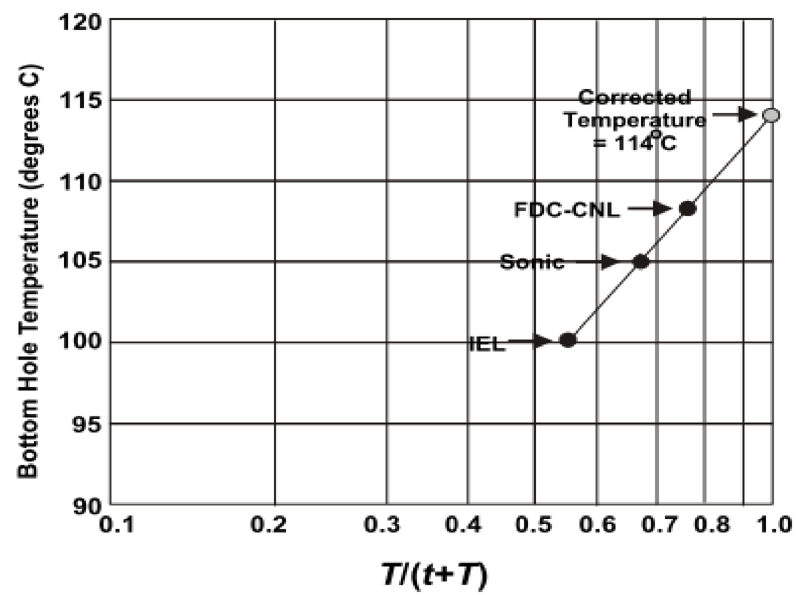


Figure The Horner plot for correction of BHT at 3200 m in a well using data in Table 8.1.

Uses of Temperature Logs

Use	Comment
Correction of other tools	The sensors of other logging tools are sensitive to temperature. The temperature measurement can be used to correct for this, or to recognize temperatures that are outside the operating range of the tool and likely therefore to be erroneous..
Correction of measurements	Some parameters measured by other tools are sensitive to temperature. The best example is resistivity logs. The temperature data is used to correct ALL resistivity data to a standard 24°C (75°F) so they are not depth dependent and can be compared.
Hydrocarbon maturation	The maturity of hydrocarbons depends upon the maximum temperature that the organic remains have been subjected to, as well as time and pressure.
Correlation	Continuous temperature logs record differences in thermal gradient that result from differences in the thermal conductivity of the formations. These difference can be used for correlation.
Fluid movement	Continuous logs can observe intervals of raised (or lowered) temperature caused by the influx of hotter (or colder) fluids into the borehole through the rock matrix, or more usually, through patent fractures. This effect may also be due to cold drilling fluid escaping into the rock.
Overpressured zones	Continuous logs also note the presence of overpressured zones, where the hot overpressured fluids escape into the borehole and are noted by a rise in the measured temperature.

Table: Uses of the temperature log