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«HYDROCARBON EXPLORATION AND EXPLOITATION»

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MSc Thesis (Μεταπτυχιακή Διπλωματική Εργασία)

<< WELL LOGGING AND FORMATION EVALUATION IN OIL AND GAS EXPLORATORY DRILLING>>

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CONTENTS

1. INTRODUCTION

Well logging is the procedure of extracting extensive records (well logs) of geological formations drilled in a well. It is also referred as borehole logging. There are geological logs as well as geophysical logs. The first are created from visual review of samples to the surface and the second from physical measurements acquired by tools taken down into the hole. During different phases of a well's life, such as drilling, completing, producing, or abandoning, there are some types of geophysical logs that can be run. Generally, well logging is applied in wells interested for the oil and gas, groundwater, mineral and geothermal exploration, in addition to environmental and geotechnical operations.

Well logging is an important contributor to formation evaluation. During hydrocarbon exploration, it is the formation evaluation process that ascertains the capability of a well to produce hydrocarbons. Basically, it is the method to determine or identify if a potential oil or gas field is commercially viable by using all available data for interpretation of reservoir formation. These data come from coring, geological logging (mud logging also known as surface logging), geophysical logging (wireline logging) and Logging While Drilling (LWD).

Wireline logging is used in oil and gas industry in order to get a full record of properties that characterize the rocks of the formations. The process of wireline logging is the acquisition and analysis of valuable information about the formation within a few feet of a wellbore. It is classified into two broad categories: open-hole logging and cased-hole/production logging. The open-hole logs are recorded in the uncased portion of the wellbore. On the other hand cased-hole logs are recorded in the completed/cased well.

In an exploratory well it is crucial to assess the commercial viability of a formation before spending the money to complete the well. So it is important to determine fluid contacts in a formation and obtain geological properties such as porosity and rock type. In order to achieve all these, it is obvious that an uncased (open) hole is required, where the open-hole logging will be applied. Thus, this assignment, which refers to exploratory drilling, is focused on open-hole logging.

2. DEFINITION OF WELL LOG

A Well Log is a detailed record of the geological formation during the drilling of a borehole. A well log is prepared by either taking samples through visual inspections or with the aid of measuring instruments lowered into the borehole. Logs prepared using visual inspections are called geological logs whereas logs prepared with the help of inspection instruments are called geophysical Logs. (https://www.petropedia.com/definition/4271/well-log, From Petropedia for the Energy Industry)

Well log is the measurement compared to depth or/and time of a physical quantity (or more of them) in or around a well. The word ''log'' means a record in engineering language. According to this, the phrase well log signifies a record represented by a graph and corresponding notes. Wireline logs are taken downhole by lowering an electric logging tool-or a string of one or more instruments- on a cable into a well and measuring various responses on the instruments as the tool (also called sonde) is raised back to the surface. In other words measurements are transmitted through this wireline cable up to surface laboratory or computer unit and recorded there on film or paper. In terms of logging while drilling (LWD) and measurements while drilling (MWD) it is necessary to mention that logs are taken downhole too. There are two ways of acquiring data in this occasion. The one is by transmission of the data to the surface directly via mud pulses and the other is by retrieval of the data recorded downhole when the tool is pulled up to the surface. On the other hand, mud logs are taken and recorded on surface exclusively, as they describe samples of drilled cuttings.

Well Logs are generally prepared in order to evaluate hydrocarbon deposits. In order to perform this evaluation, testing of rock and fluid formations at different locations is conducted and the data is recorded on the logs. The device that is used to conduct well testing is called logging tool and it can be attached to a thin wire called wireline, which carries this tool to the necessary depth within the borehole to conduct testing on quantity and location of hydrocarbons beneath the earth's surface. This tool gathers all data and sends it to the control room where the well logs are prepared. (https://www.petropedia.com/definition/4271/well-log, From Petropedia for the Energy Industry) The logging tools can measure electrical resistivity, sonic vibrations and reflections, natural and induced radioactivity, bulk density, hydrogen content and more which are various properties of the subsurface formations.

There is a recording of the data either in real-time mode (at surface) or in memory mode (in the hole) with the help of a computerized data format. The outcome is a printed record or an electronic presentation, the well log, which will be given to the client. Well log files can be generated during the drilling process in LWD for real-time information. On the other hand, in wireline logging, when the well has reached its total depth, measurements can be recorded for all the sections of the well as the instrument is raised up to the surface.

A folded paper of medium length and about 8.5 in. (21.5 cm) wide can represent a typical log. Logging measurements are recorded as function of depth, as illustrated in Figure 2.1. The left hand side of the figure illustrates a well log with two measurement tracks and another with three measurement tracks. Both well logs have a track for depth. The measurement tracks display measurement values relative to a scale that is suitable for the measurement. More than a one measurement may be displayed in each measurement track. The header contains information about the well (such as name, location and owner), the logging run (such as date, logging company and tool description) and the scales for the measurement at the top of the tracks.

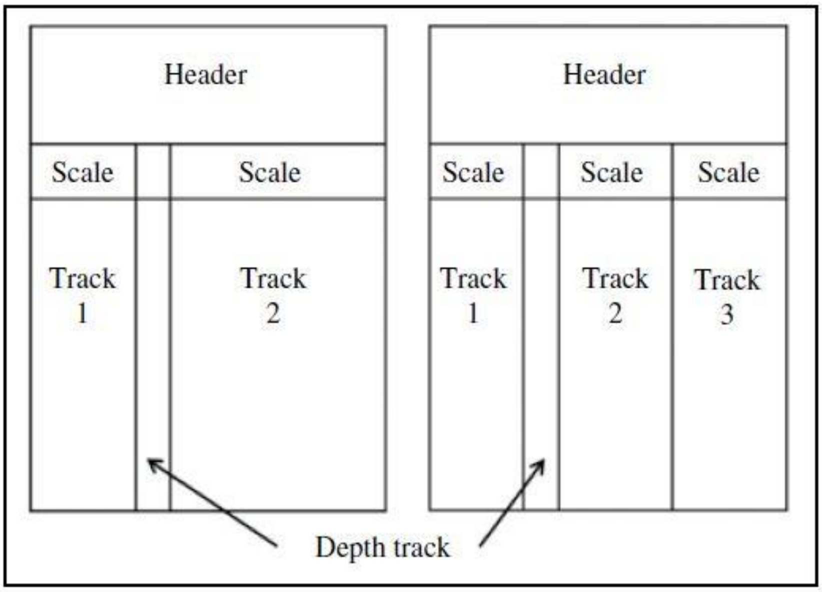


Figure 2.1 Well log format ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering-John Wiley & Sons, Inc. 2017)

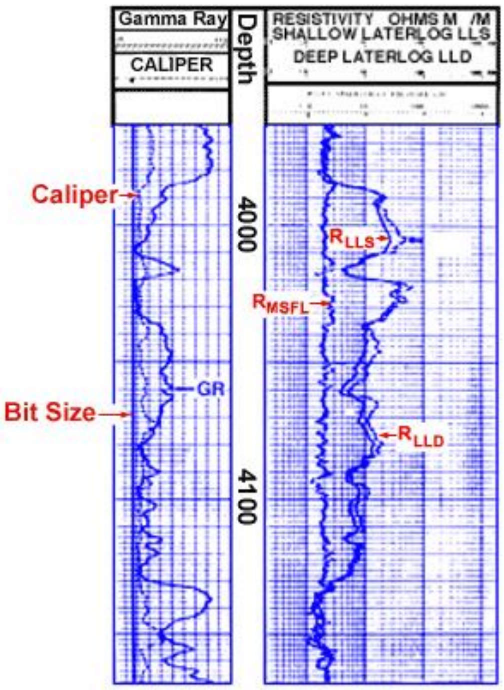


Figure 2.2 Example of a well log ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

Well logs are used by engineers and drillers to determine many characteristics such as formation tops' depths, types of formations found, presence of oil or/and gas, porosity, water saturation, permeability and formation dip. As a result, they will find out if a well is commercial or not. Consequently, they will decide if the next steps (casing, cementing and completion) will be operated or not. It is not only the fact of discovering hydrocarbons in the ground, but mainly to predict the business success.

3. HISTORY

In the early 1800s, the information gathered from the oilfield derricks was written down by the well loggers. Particularly, they wrote chronicles of what happened at certain depths. They were interested in types of formation found, speed of drilling, flows of oil and gas and of course any problem that appeared.

Later, in the early 1900s, it was Conrad Schlumberger who conceived the idea of introducing electrical measurements in hydrocarbon exploration. Especially, these measurements were used for mapping subsurface formations. The first electrical resistivity well log in the world was achieved in France by him and his brother Marcel in 1927. (Resistivity measures how difficult an electric current passes through a formation.) This was the first well log and it was obtained in Pechelbronn field in Alsace, France. The tool, invented by Schlumberger brothers, measured electrical resistance of the earth. Engineers recorded a data point each meter as they retrieved the tool (sonde), suspended from a cable, from the borehole. Their data log of resistivity changes identified the location of oil. ([Mark Andersen] Discovering the Secrets of the Earth, Oilfield Review 2011, From Schlumberger Defining Logging)

Subsequently, two Schlumberger's scientists Henri George Doll and G. Dechatre observed a wiggle of the galvanometer even though there was no passage of current throughout the logging cables down in the borehole. As a result, spontaneous potential (SP) was discovered in 1931. This type of measurement was equally substantial to the measurement of resistivity. Borehole mud produced inherently the SP effect at the boundaries of permeable layers. If SP and resistivity were recorded at the same time, loggers could discern whether permeable oil-bearing zones or impermeable nonproducing zones existed.

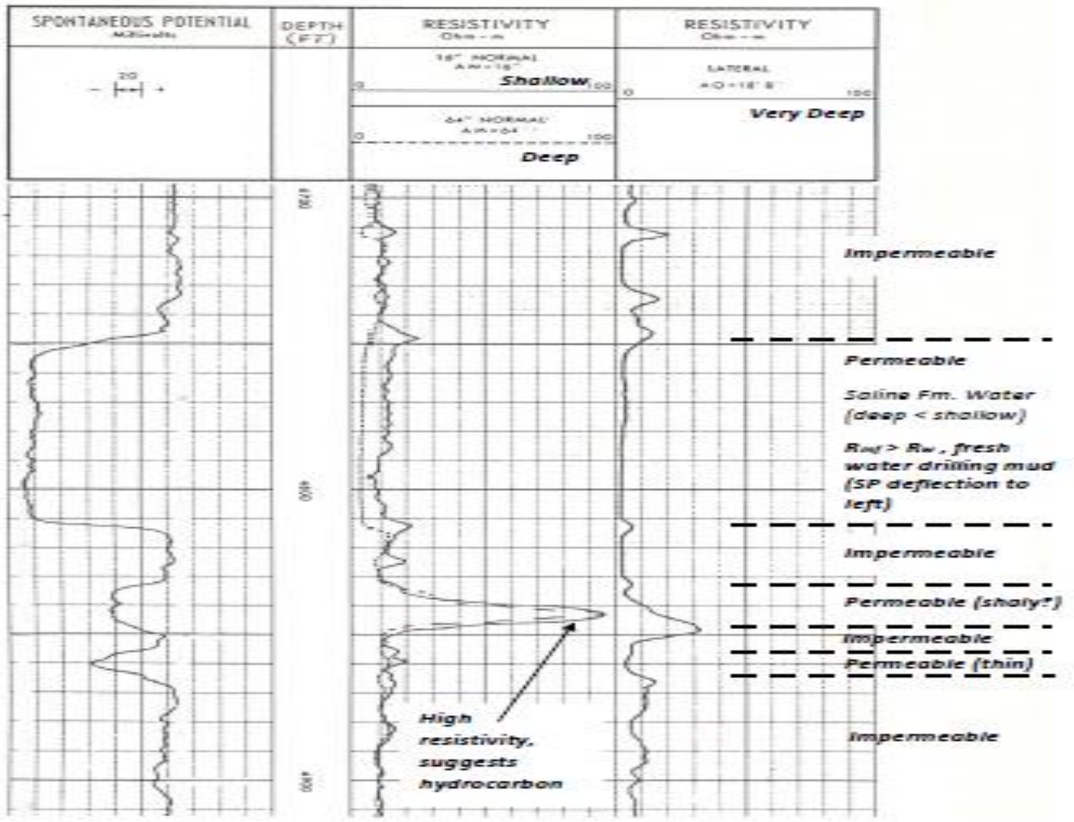


Figure 3.1 Example of resistivity and spontaneous potential (SP) record ([A.Georgakopoulos,V.Kosmidou] MSc Hydrocarbon Exploration and Exploitation, Aristotle University of Thessaloniki, Course Notes, 2017)

Oil-based mud (OBM) was a big problem for the reason that it is non conductive. Until 1948, normal electric logs had been operated with a conductive or water-based mud. That year, OBM was introduced in Rangely Field in Colorado with the use of a new electric log named induction log.

The reliability of electric logs expanded in the 1960s when transistor and integrated circuits were invented. Computer systems both led to quicker log processing and rapidly enlarged log data-gathering storing. More logs and computers were developed in the 1970s, for instance combo type logs. In these logs, for example, porosity and resistivity logs were recorded in one run in the well.

The logging of formation bulk density, another measurement primarily dependent on formation porosity, was commercially introduced in the early 1960's. An FDC compensated formation density log, which compensated for the mudcake, quickly followed in 1964. In 1981, the Litho-Density log provided an improved bulk density measurement and a lithology-sensitive photoelectric absorption cross section measurement.

Acoustic logs and nuclear logs exist since 1940s. These logs comprise the two types of porosity logs. We know that technology was vastly developed during World War II. Acoustic (also named sonic) logs came from this development. Acoustic logging has been supplemented by nuclear logging. Nevertheless, acoustic logs keep on running on some combination logging instruments.

Subsurface formations emit natural gamma radiation. Nuclear logging was developed at the beginning in order to measure this property. Despite this, new logs appeared in the industry which could energetically bombard formations with nuclear particles. Well Surveys Inc. introduced the gamma ray log in 1939 which measures the natural radioactivity. Some years later, in 1941, the WSI neutron log followed. In terms of gamma ray log, shale layers appear with high gamma radiation. These layers are very important because they are usually the impermeable cap over hydrocarbon reservoirs.

Bloch and Purcell discovered nuclear magnetic resonance in 1946. After some years, in the early 1950s, Chevron and Schlumberger developed the nuclear magnetic resonance (NMR) log that uses the Earth's field. This log was a success for the science but not for the engineers. In the 1990s, NUMAR (a subsidiary of Halliburton) came out with the continuous NMR logging technology after many engineering developments. This technology is applied today in the industry of hydrocarbons as well as in water and metal exploration.

Most of the wells in our days are drilled directionally. Previously, tools had to be attached to the drill pipe by some manner in case of a not vertical well. Nowadays, thanks to modern techniques, non stopping information at the surface has been already permitted. So, today we refer to logging while drilling (LWD) and measurements while drilling (MWD). The data of MWD logs is transferred from the tools of the drill string to the computerized system at the surface via mud pulses.

4. BOREHOLE ENVIRONMENT AND TYPES OF OPEN-HOLE LOGS

Borehole environment

The wellbore and adjacent formations are a complex setting for logging. The desired borehole shape is a cylinder with diameter equal to or slightly larger than the drill bit. In practice, the shape of the borehole may differ substantially from a cylinder because of borehole wall collapse or the presence of cavities in the formation.

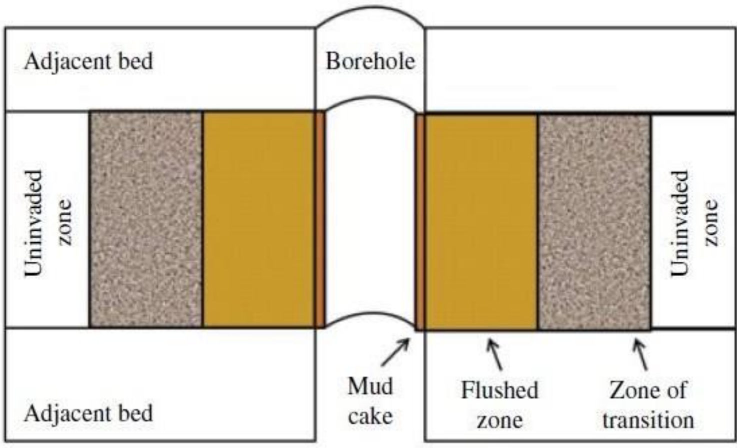


Figure 4.1 Schematic of invasion zones ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering-John Wiley & Sons, Inc. 2017)

An idealized representation of the wellbore and formation is illustrated in Figure 4.1. It is used to make analysis of well log response more tractable. The figure shows several zones near the wellbore: the mud cake, the flushed zone, the zone of transition, and the uninvaded zone. If pressure in the borehole during drilling is greater than pressure in the formation, the pressure difference will drive drilling mud into the permeable formation. Larger particles in the drilling mud will be filtered out at the rock face of the borehole and create a mud cake adjacent to the borehole. The liquid with any small particulates that pass through the mud cake is called the mud filtrate. The mud cake can reduce the flow of fluids between the formation and the well. The formation damage caused by mud cake and filtrate can be quantified by well testing that yields a parameter called “skin.”

During drilling, portions of fluids originally in the flushed zone are displaced by the invading mud filtrate and pushed into the transition zone. During logging, fluids in the flushed zone include mud filtrate with any suspended solids, some native brine and any remaining oil and gas. The flushed zone and the zone of transition are considered invaded zones because original in situ fluids have been displaced by fluids from the borehole. Reservoir rock and fluid properties in the uninvaded zone have not been altered from their original state by fluids from the drilling operation.

Reservoir properties are measured by lowering a tool attached to a wireline or cable into a borehole. The borehole may be filled with water-based drilling mud, oil-based mud, or air. During the drilling process, the drilling mud invades the rock surrounding the borehole, which affects logging measurements and the movement of fluids into and out of the formation. All of these factors must be taken into account while logging and during log analysis. It is important to understand the wellbore environment and the following characteristics: hole diameter, drilling mud, mud cake, mud filtrate, flushed zone, invaded zone and the uninvaded zone.

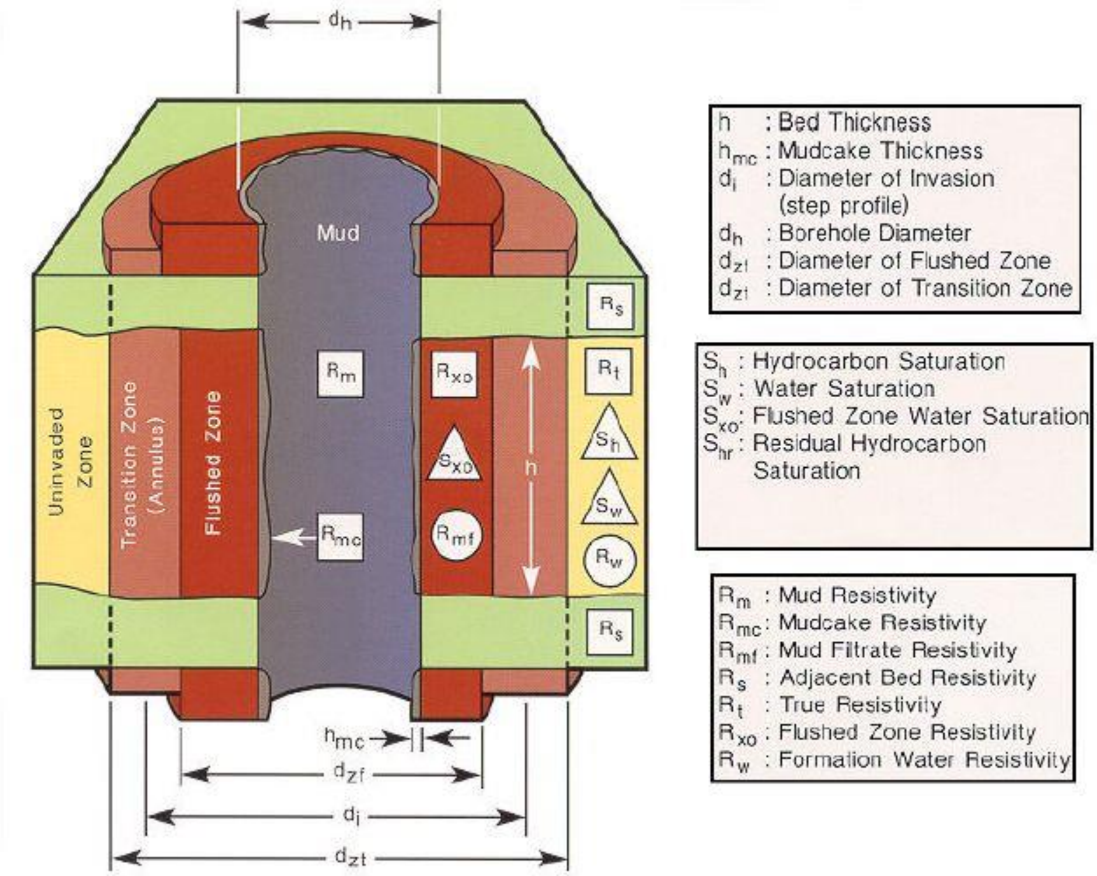


Figure 4.2 Borehole environment ([Halliburton] Basic Log Analysis 2001)

Hole diameter (d_h): The size of the borehole determined by the diameter of the drill bit.

Drilling Mud Resistivity (R_m): Resistivity of the fluid used to drill a borehole and which lubricates the bit, removes cuttings, maintains the walls of the borehole and maintains borehole over formation pressure. Drilling mud consists of a variety of clay and other materials in a fresh or saline aqueous solution and has a measurable resistivity.

Mudcake Resistivity (R_{mc}): Resistivity of the mineral residue formed by accumulation of solid drilling mud components on the wellbore walls as the mud fluids invade the formations penetrated by the borehole.

Mud Filtrate Resistivity (R_{mf}): Resistivity of the liquid drilling mud components that infiltrate the formation, leaving the mudcake on the walls of the borehole.

Resistivity values for the drilling mud, mudcake, and mud filtrate are determined during a full mud press and are recorded on a log's header (the information section at the top of a printed well log).

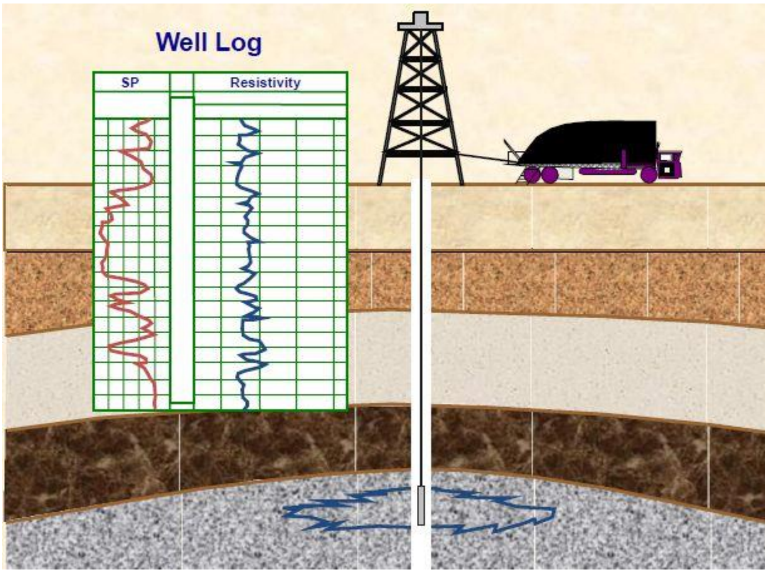
Invaded Zone: The zone which is invaded by mud filtrate. It consists of a flushed zone (R_{xo}) and a transition or annulus zone (R_i). The flushed zone (R_{xo}) occurs close to the borehole where the mud filtrate has almost completely flushed out the formation's hydrocarbons and/or water. The transition or annulus zone (R_i), where a formation's fluids and mud filtrate are mixed, occurs between the flushed zone (R_{xo}) and the univaded zone (R_t).

Uninvaded Zone (Rt): Pores in the univaded zone are uncontaminated by mud filtrate; instead, they are saturated with formation fluids (water, oil and/or gas). ([Halliburton] Basic Log Analysis 2001)

Types of open-hole logs

With the improvement of well logging technology over the years, thousand types of well logs have appeared. Well logging technology continues to improve, so this assignment focuses on the more common open-hole logs.

Immediately after a well is drilled, the formations are exposed to the wellbore. This is an opportune time to determine the properties of the rocks using open-hole logging tools.



Open-hole logging ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

Open-hole logging is a big category of logging which takes place on an ''open'' well; namely a wellbore that has not been yet cased and cemented. That is to say that open-hole logging is carried out through the bare rock sides of the formation.

The traditionally used open-hole logging methods in petroleum exploration are:

- **Electrical logs**. When we refer to electrical logs, we practically speak about resistivity logs. Modern resistivity logs fall into two categories, laterologs or electrode logs and induction logs, having several commercial names, according to each company that provides the logging services.
- **Porosity logs**. Well logs that can be used to obtain porosity include density logs, neutron logs (both of them considered as nuclear logs) and acoustic or sonic logs.
- **Lithology logs**. They are used to determine rock type. We consider three types of lithology logs, gamma ray (GR) logs, spontaneous potential (SP) logs and photoelectric (PE) logs.
- **Miscellaneous logs**. These logs illustrate the variety of logs that are being developed and used to meet industry challenges. They do not fit into the major categories presented previously and are caliper logs, nuclear magnetic resonance (NMR) logs, dipmeter logs and borehole imaging logs.

It is important to mention that the modern logs that can be run only in open-hole well are: dipmeter, borehole imaging, nuclear magnetic resonance (NMR), and spontaneous potential (SP).

5. PRESENTANTION OF EACH LOG

5.1 ELECTRICAL LOGS

Resistivity Logs

Resistivity logs measure the subsurface electrical resistivity, which is the ability to impede the flow of electric current. Rock grains in the formation are usually non conductive, so formation resistivity depends primarily on the electrical properties of the fluid contained in the pore space. We know from physics that resistivity is the inverse of conductivity. This helps to distinguish between formations filled with salty waters-brines (good conductors of electricity, have low resistivity as they contain ions in solution that can support an electrical current) and those filled with hydrocarbons (poor conductors of electricity, have high resistivity as they do not contain ions in solution).

Some logging tools measure properties in the first few inches of the formation, while other tools measure properties deeper into the formation. This depth of investigation is usually characterized as shallow, medium or deep and can range from a few inches to several feet. Resistivity logs are measured at various distances from wellbore axis and different resolutions.

One purpose of resistivity logs is to estimate brine saturation in the formation, as an indication of the presence of oil and gas in the formation. For these estimates to be useful, deep measurements that penetrate beyond the transition zone are needed. Resistivity is measured in units of ohms (or ohms/meter). Due to its large range, it is often charted on a logarithm scale against depth.

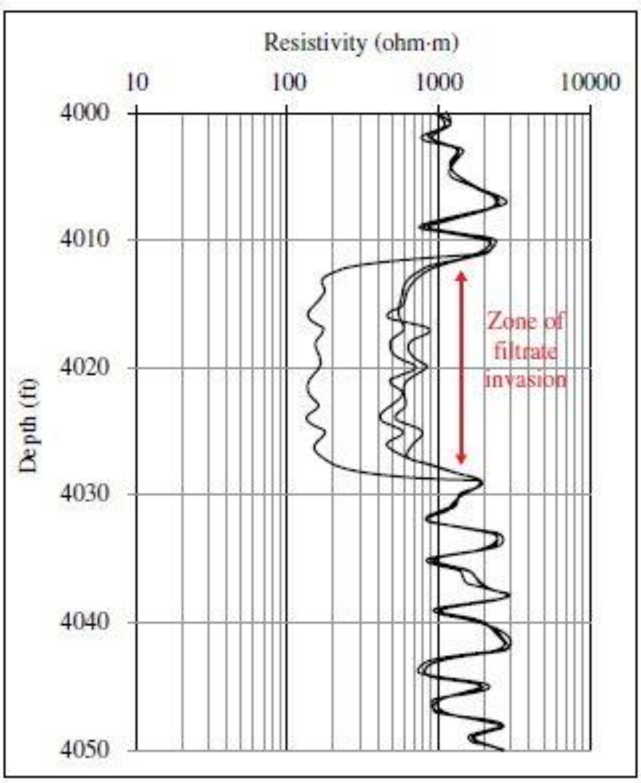


Figure 5.1.1 Illustration of Resistivity Log. The three resistivity traces are shallow, medium and deep resistivity measurements. The zone of mud filtrate invasion (4012ft-4028ft) is the area where there is a separation of the three resistivity traces. ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering-John Wiley & Sons, Inc. 2017)

Oil and gas are more resistive than the salty water that fills most deeply buried rocks. Engineers created two types of electric sondes (tools); both of them measure that difference. As a result, there are two types of resistivity logs: laterologs or electrode logs, and induction logs.

Laterologs or Electrode Logs

This type measures formation resistivity by creating an electric circuit. Electrodes in the electrode tool are connected to a generator. Electrical current passes from the electrodes through the borehole fluid, into the formation and finally to a remote reference electrode. Depth of investigation is controlled by the spacing of electrodes and, more recently, by focusing electrical current into the formation using logs such as the spherically focused log SFL (measures the resistivity of the flushed zone R_{xo}). The observed current gives information about the resistivity of the formation. Electrode logs must be used with conductive ("salty" water-based) mud to allow a current to pass through the borehole fluid.

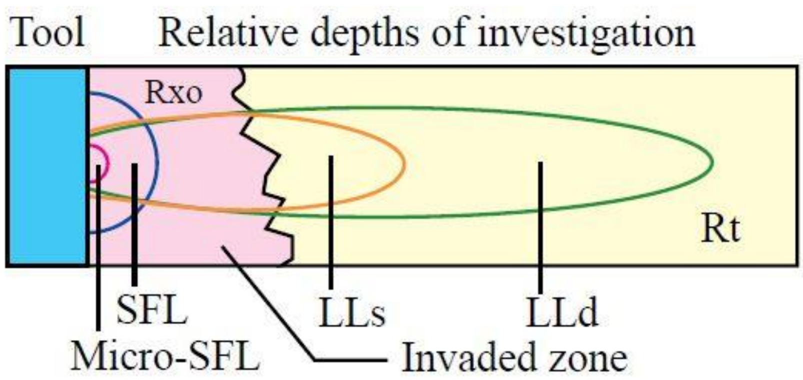


Figure 5.1.2 Electrical currents in the formation of Spherical Focused Logs (Micro-SFL and SFL) and Dual Laterolog (LLs: shallow laterolog and LLd: deep laterolog) (http://www.uio.no/studier/emner/matnat/geofag/GEO4250/v08/Open_Hole_Wireline_logging.pdf)

One common laterolog is the Dual Laterolog (DLL). The DLL instrument simultaneously produces a deep and a shallow resistivity logs. Current path is focused as a horizontal sheet into the formation. One electrode send an electric current from the tool straight into the formation. The return electrodes can be situated in two different places; on surface or integrated on the tool. The current is focused into the formation by two guard electrodes. Thanks to these guard electrodes, current lines are prevented from flowing up and down and spreading to the return electrode through the drilling fluid. The voltage at the main electrode is constantly adjusted during logging so as to support a non changing current intensity. This voltage is analogous to the formation's resistivity.

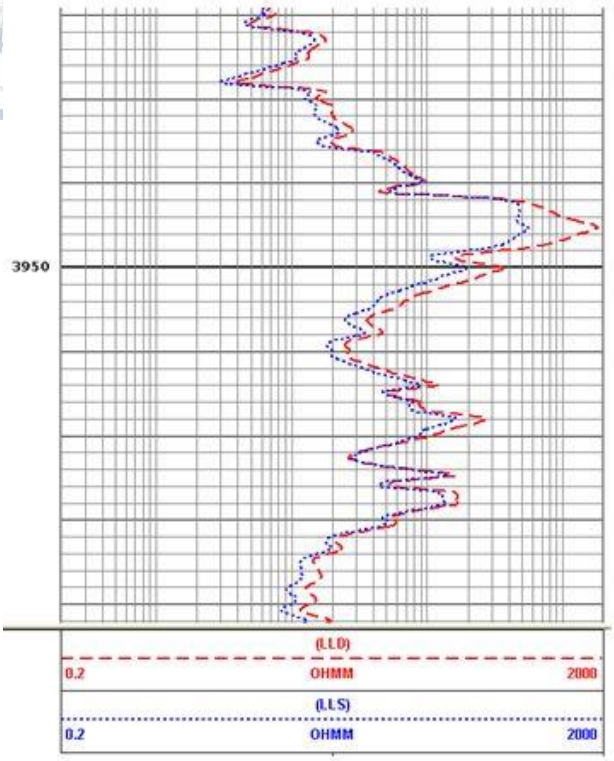


Figure 5.1.3 Example of Dual Laterolog ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

LLD= Deep Laterolog
LLS= Shallow Laterolog

Induction Logs

Induction logs measure formation conductivity, which is the inverse of resistivity. Thus resistivity can be determined because resistivity is the measurement which will be represented on the log. Induction tools have two sets of wire coils: coils for generating magnetic fields that induce current in the formation and coils for sensing the magnetic field produced by the induced current in the formation. This design uses induction coils to measure conductivity and has similar physics to an electric transformer. The conductivity is induced by a focused magnetic field. Transmitting coils in the tool emit a high frequency alternating current signal that creates an alternating magnetic field in the formation. Induced secondary currents are created in the formation by the alternating magnetic field. The secondary currents create new magnetic fields that are recorded by receiver coils. The transmitting and receiving coils are on opposite ends of the tool. Induction log are most accurate when used in wells drilled with non-conductive or low conductivity (oil-based) mud or boreholes filled with air.

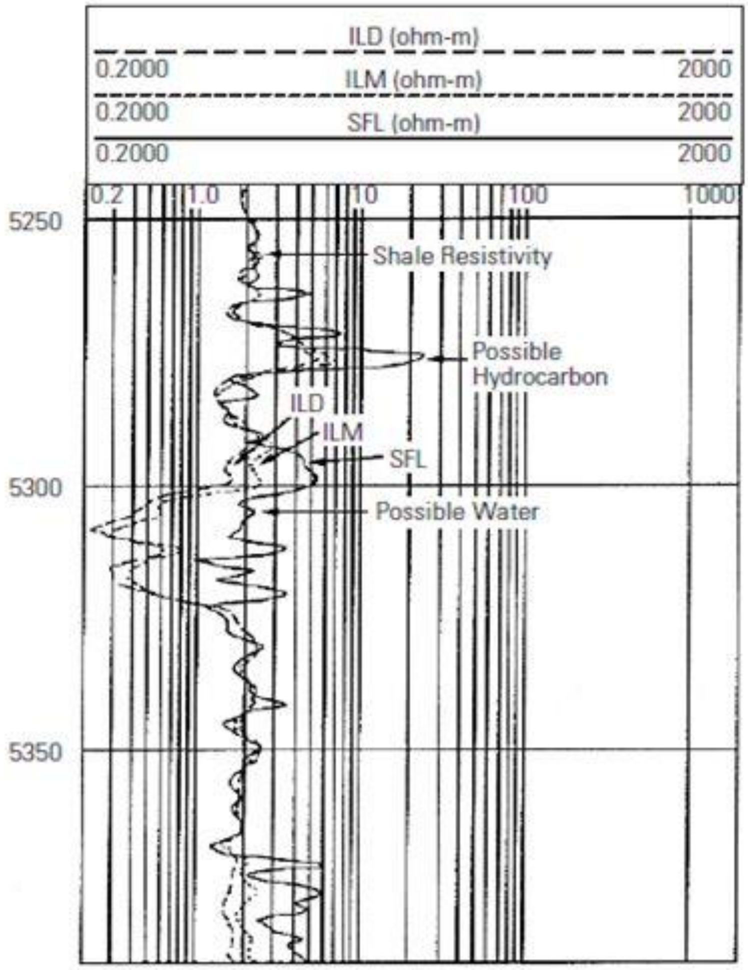


Figure 5.1.4 A section of an Induction Log
([A.Georgakopoulos,V.Kosmidou] MSc Hydrocarbon Exploration and Exploitation, Aristotle University of Thessaloniki, Course Notes, 2017)

ILD= Deep Induction Log
ILM= Medium Induction Log
SFL= Spherically Focused Log (provides a shallow reading)

5.2 POROSITY LOGS

Density and neutron logs are the two main nuclear porosity logs. Another type of porosity (but not nuclear) logs are the acoustic or sonic logs.

Density Logs

The density logs measure the bulk density of a formation by bombarding it with a radioactive source. A focused radioactive source carried in the density tool emits gamma rays of medium energy into the formation. As gamma rays travel through the formation they collide with electrons and are scattered, losing energy in the process, until captured. Detectors mounted in the tool count the number of gamma rays at a fixed distance from the source. The gamma ray count rate is inversely proportional to the electron density of the formation. Electron density is the number of electrons in a volume of the formation and is proportional to bulk density.

The bulk density ρ_b can then be used to determine porosity. Combining ρ_b from the density log with rock matrix density ρ_{ma} and pore fluid density ρ_f yields porosity ϕ:

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

Knowledge of the density of the matrix material ρ_{ma} and the density of the pore fluid density ρ_f is required.

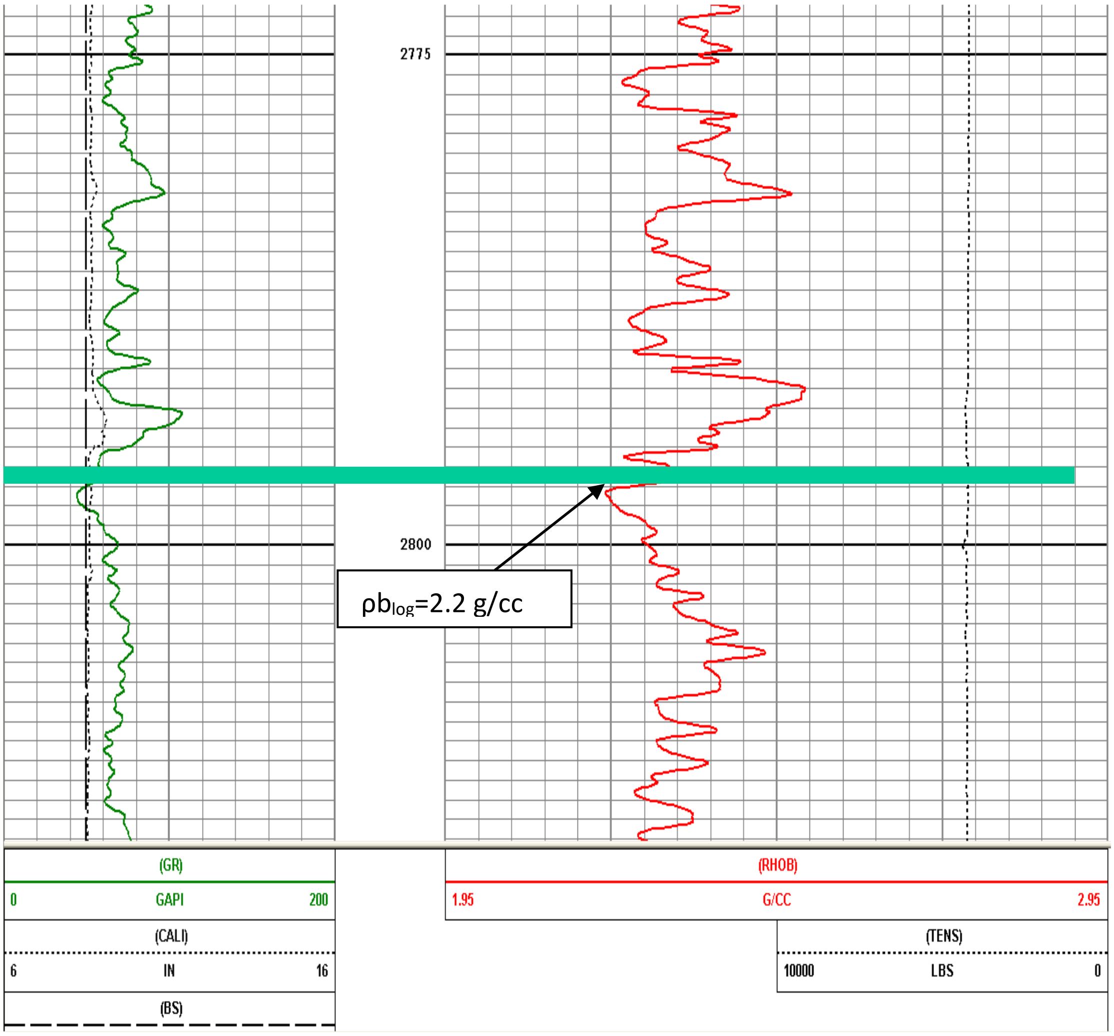


Figure 5.2.1 Example with a Density Log ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

RHOB= Measured Bulk Density curve in g/cc or g/cm^3
TENS= Tension of the cable in lbs
GR= Natural Gamma Ray in API units
CALI= Caliper in inches
BS= Bit Size in inches

From log, ρb_{log}=2.2 g/cc. ρ_{ma}=2.65 g/cc for sandstone ρ_f=1 g/cc for water

$$\phi = \frac{2.65-2.2}{2.65-1} = \frac{0.45}{1.65} = 0.27 = 27\%$$

The presence of a mudcake can seriously affect formation density measurement so the tool is constructed with the source and detectors mounted on skid which, when pushed against the borehole wall, ploughs through the mudcake. The remaining mudcake influence is corrected by comparing count rates at a short and a long spacing detector. The correction applied to the density measurement is also displayed as a separate curve on the log. If this correction exceeds 0.05 g/cc, it is considered less reliable and confidence attached to the log reading at that point is reduced. This situation commonly occurs when the hole is rugose or washed out so that low density mud is present between the tool and the formation. High density barites laden mudcake can also significantly effect the density reading in the opposite sense. The density correction curve therefore serves as a quality check on the density measurement. (http://www.uio.no/studier/emner/matnat/geofag/GEO4250/v08/Open Hole Wireline logging.pdf)

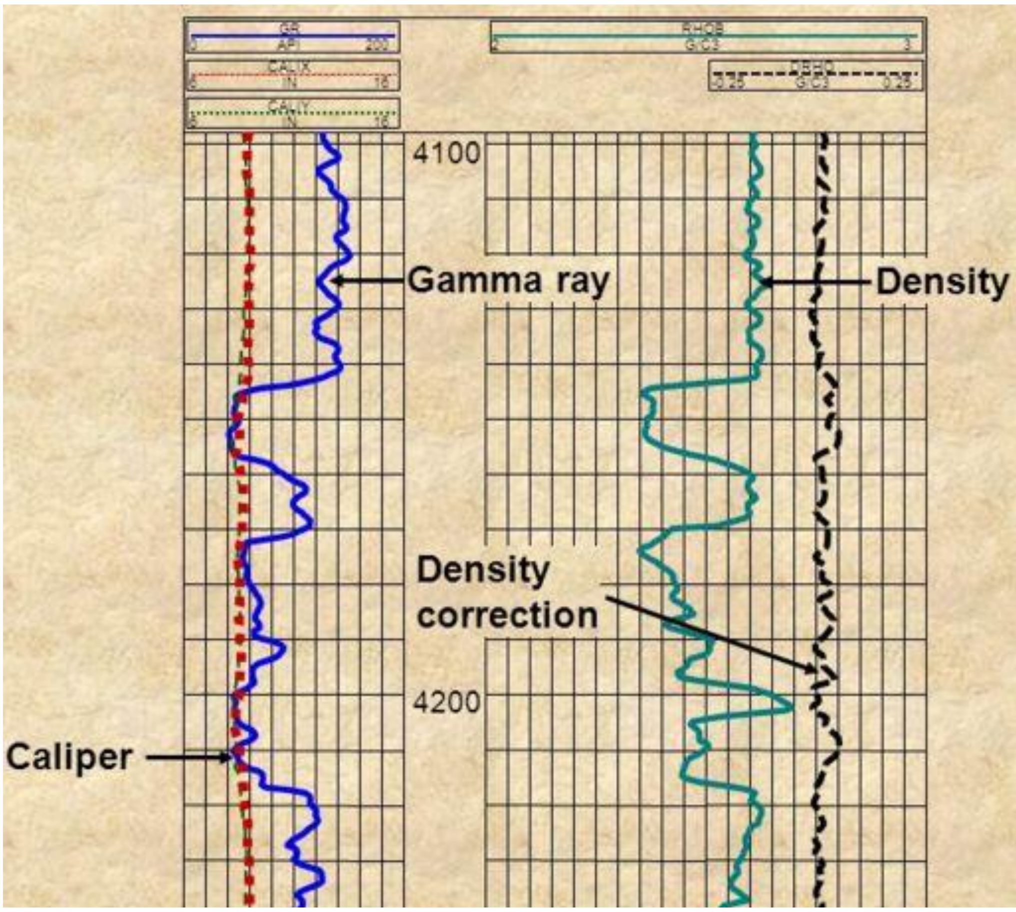


Figure 5.2.2 Density correction
(https://slideplayer.com/slide/8547224/ Porosity Determination from Logs)

Neutron Logs

The neutron logs provide information about the formation by emitting fast high energy neutrons, from a radioactive source in the logging tool, into the formation. The source monitors the population of neutrons, at some distance from the source, which have been slowed down (lost energy and so velocity) to thermal energy levels during passage through the formation. The neutrons are slowed down through elastic collision with atomic nuclei in the formation and can be captured by nuclei. Hydrogen atoms' nuclei are especially effective at capturing thermal neutrons as they have essentially the same mass as the neutron. These hydrogen atoms' nuclei after they have captured the thermal neutrons, become excited and emit detectable gamma rays. Thus, the neutron log response indicates the concentration of hydrogen in the fluid-filled pore space. Hydrogen is mainly present as water or hydrocarbon in the pore spaces. Oil and water have about the same concentration of hydrogen, while gas has a relatively low hydrogen concentration. The presence of a significant amount of hydrogen will appear as a large gamma ray response. A small response suggests a low hydrogen concentration. Gas filled formation has a low hydrogen population which the logging tool records as low apparent porosity and then is represented on the neutron log.

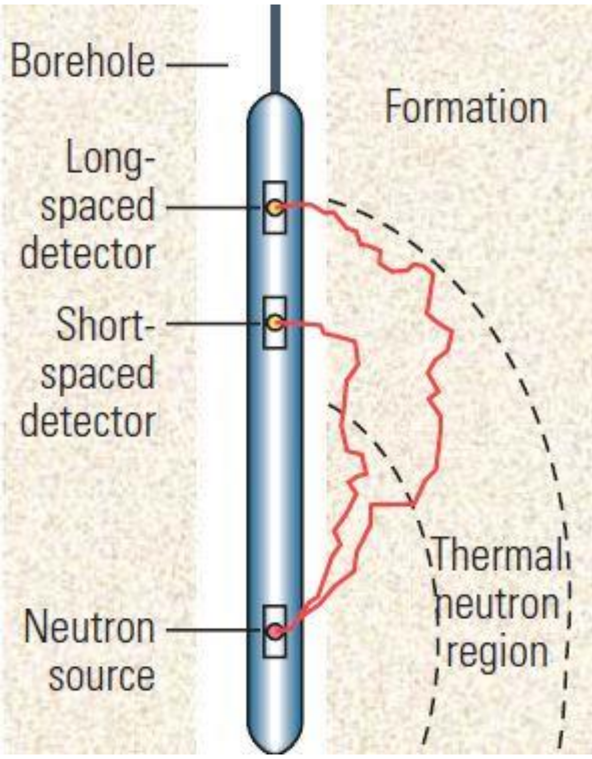


Figure 5.2.3 Neutron Porosity Tool ([Tony Smithson] How Porosity is Measured, Oilfield Review 2012, From Schlumberger Defining Porosity)

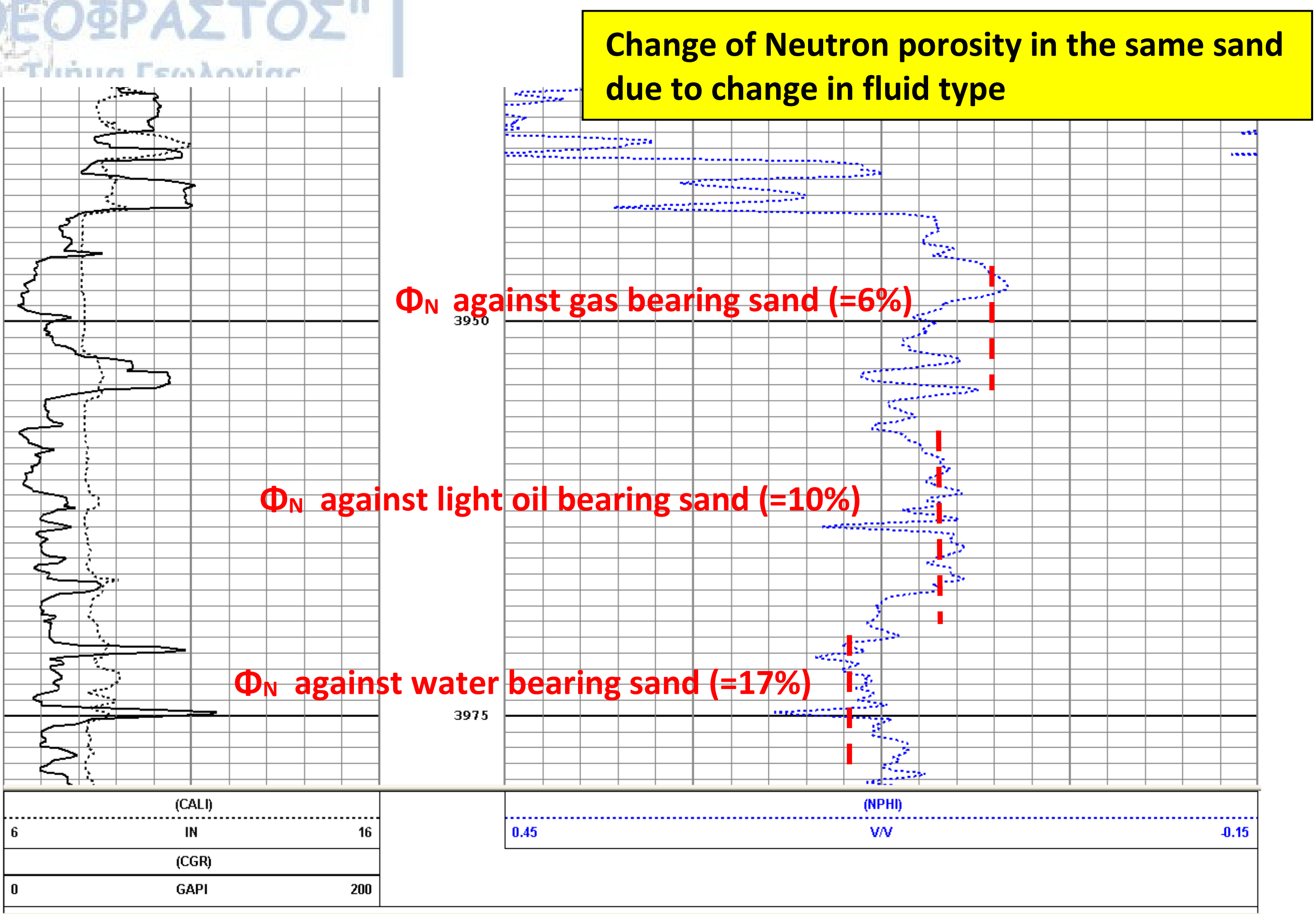


Figure 5.2.4 An example with a Neutron Log ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

Neutron and density porosity are often plotted in the same track. True porosity is frequently close to the average of neutron and density porosity values. Neutron porosity is typically higher than density porosity except when natural gas occupies part of pore space. In this case neutron porosity is less than density porosity. The "crossover" indicates the presence of natural gas and is illustrated below.

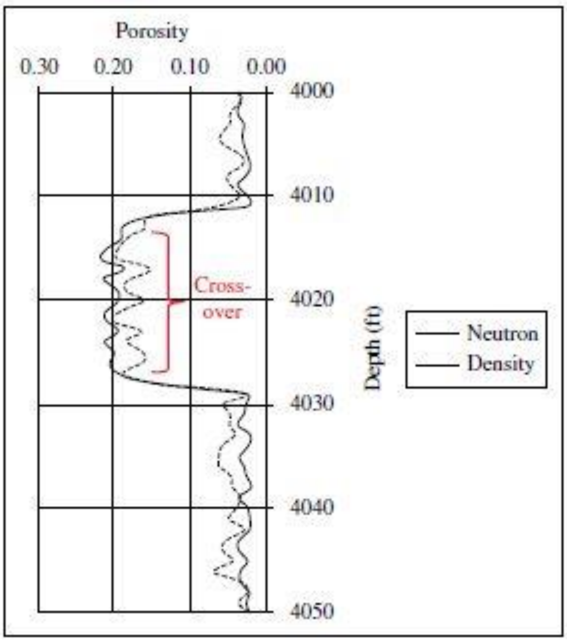


Figure 5.2.5 Illustration of crossover of porosities from Density and Neutron Logs ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering- John Wiley & Sons, Inc. 2017)

Acoustic-Sonic Logs

Acoustic or sonic logs provide another technique for measuring porosity. An acoustic or sonic log is a recording against depth of the travel time of high frequency acoustic pulses through formation close to the borehole. This is done by measuring the pulse arrival time at two receivers spaced at different distances from a piezoelectric acoustic transmitter which emits compressional waves. The time taken to for the elastic sound wave to travel the fixed distance between the two receivers (interval) is recorded as the interval transit time Δt. It is calculated by substacting the transit time to the near receiver from that of the far receiver.

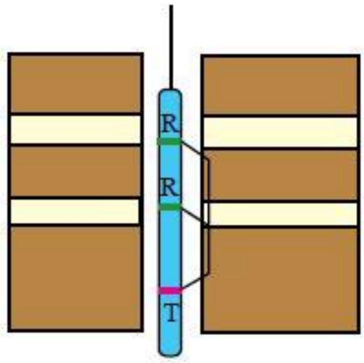


Figure 5.2.6 Acoustic-Sonic Tool (http://www.uio.no/studier/emner/matnat/geofag/GEO4250/v08/Open_Hole_Wireline_logging.pdf)

Sound waves are vibrations in a medium like air or rock. The speed of sound in a medium depends on the density of the medium. In the case of rock, density depends on the density of rock matrix and the density of the fluids occupying the pore space in the rock. In particular, the bulk density ρ_b of the medium is:

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

where ϕ is porosity and ρ_{ma} and ρ_f are rock matrix and fluid densities, respectively. The bulk volume of a formation with large pore space contains more fluid in the bulk volume than a formation with small pore space. Since fluid density is typically several times smaller than matrix density, the bulk density of a system with relatively large pore space is less than the bulk density of a system with relatively small pore space if the fluids in the pore volume are the same in both formations.

An estimate of the speed of sound v in a formation is given by Wyllie's equation. If we write the speed of sound in fluids occupying the pore volume of a rock as v_f and the speed of sound in the rock matrix as v_{ma}, Wyllie's equation is:

$$\frac{1}{v} = \frac{\phi}{v_f} + \frac{(1-\phi)}{v_{ma}}$$

We can write the speed of sound in each medium as the distance traveled divided by the transit time. If we assume the distance traveled is the same in each medium, then the speed of sound is inversely proportional to transit time. Thus Wyllie's equation can be written as:

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

where Δt is transit time in the bulk volume (interval transit time measured by the acoustic-sonic log), Δt_f is transit time in the intersticial fluid and Δt_{ma} is transit time in the rock matrix. A long transit time implies a slow speed of sound propagation. The presence of hydrocarbons increases the interval transit time. Solving the transit time form of Wyllie's equation for porosity gives:

$$\phi = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

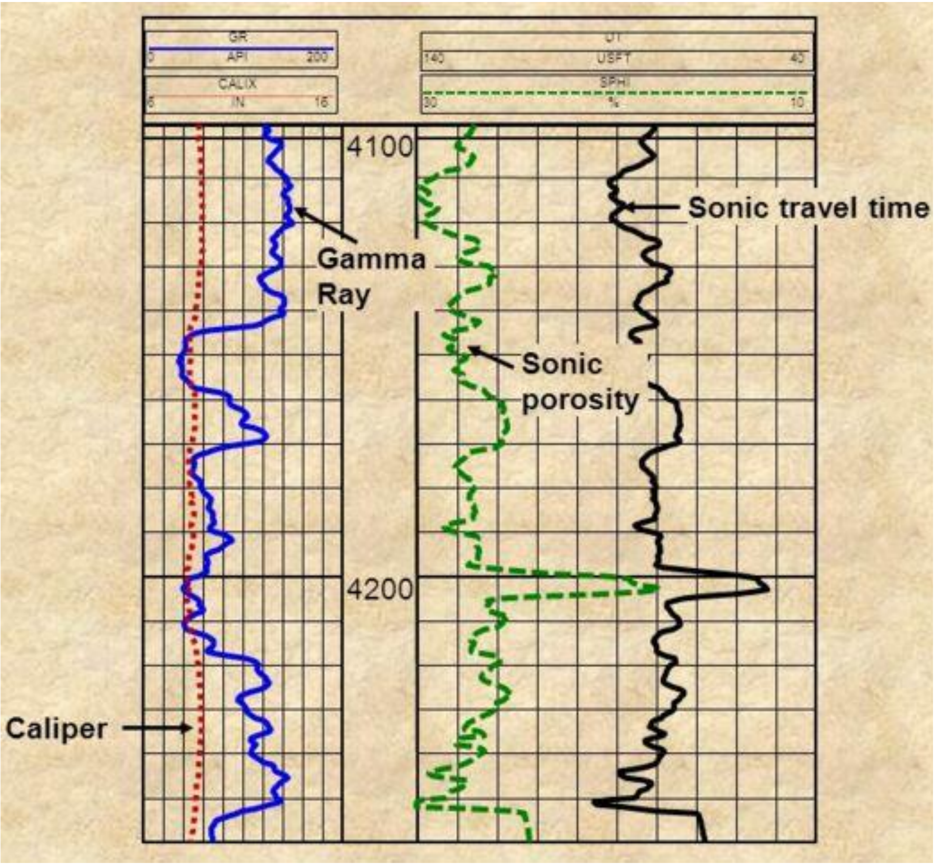


Figure 5.2.7 Example of an Acoustic-Sonic Log
(https://slideplayer.com/slide/8547224/ Porosity Determination from Logs)

The interval transit time Δt is recorded on the acoustic-sonic log DT (illustrated by black in the above figure) in microseconds per foot (ms/ft). Most formations give transit times between 40 ms/ft. and 140 ms/ft., so these values are usually used as the scale. The porosity ϕ is recorded on the acoustic-sonic log SPHI (illustrated by green in the above figure) in %.

Acoustic- sonic logs can also be used to calibrate seismic measurements. The comparison of acoustic and seismic transit time measurements in a formation can improve the accuracy of converting seismic transit times to depths.

5.3 LITHOLOGY LOGS

Lithology logs indicate rock type. Most hydrocarbon accumulations are found in sedimentary rocks. The most important conventional reservoir rocks are sedimentary rocks classified as clastics and carbonates. Clastics include sandstone, conglomerate, shaly sand and shale. Carbonates include limestone, dolomite and evaporite. We consider three types of lithology logs: the gamma ray (GR) logs, the spontaneous potential (SP) logs and the photoelectric (PE) logs.

Gamma Ray (GR) Logs

The Gamma Ray logs are operated by taking down a tool into the borehole and recording the concentration of gamma radiation against depth. Gamma radiation is measured in API units and is a measurement that has its origin from the petroleum industry. Gamma Ray logs are used to detect in situ radioactivity from naturally occurring radioactive materials. They detect gamma ray emissions from radioactive isotopes.

Natural radioactivity includes alpha, beta and gamma rays. Alpha rays are helium nuclei, beta rays are electrons and gamma rays are photons (particles of light). Alpha and beta rays are low energy. Gamma rays emitted by nuclei have energies ranging from 10^3 eV (electron volts) to 10^7 eV and can penetrate several feet of rock. Naturally occurring radioactive materials are minerals that contain radioactive isotopes of the elements uranium, thorium and potassium. The decay of naturally occurring radioactive isotopes produces gamma rays.

Gamma Ray logs are useful for distinguishing between sands and shales in a siliclastic environment. In general, shales contain more radioactive materials than other rock types. This happens for the reason that radioactive potassium dominates the composition of the clay content of shales. Another reason is that the cation exchange capacity of clay causes shales to absorb uranium and thorium. Consequently, the production of gamma rays by radioactive decay is greater in the presence of shale. Thus a high gamma ray response implies the presence of shales, while clean (shale-free) sands or carbonates tend to have a low gamma ray response. For example, sandstones are usually non radioactive quartz and limestones are non radioactive calcite. The distinction between shales and non-shales is succeeded by the gamma ray tool as there is a difference in radioactivity between shales and sandstones/carbonate rocks. But in particular for non-shales, carbonates and sandstones cannot be distinguished because they both have similar deflections on the GR log. To sum up, the absence or presence of gamma rays in a hole indicates the amount of clean sand or shale in the surrounding formation.

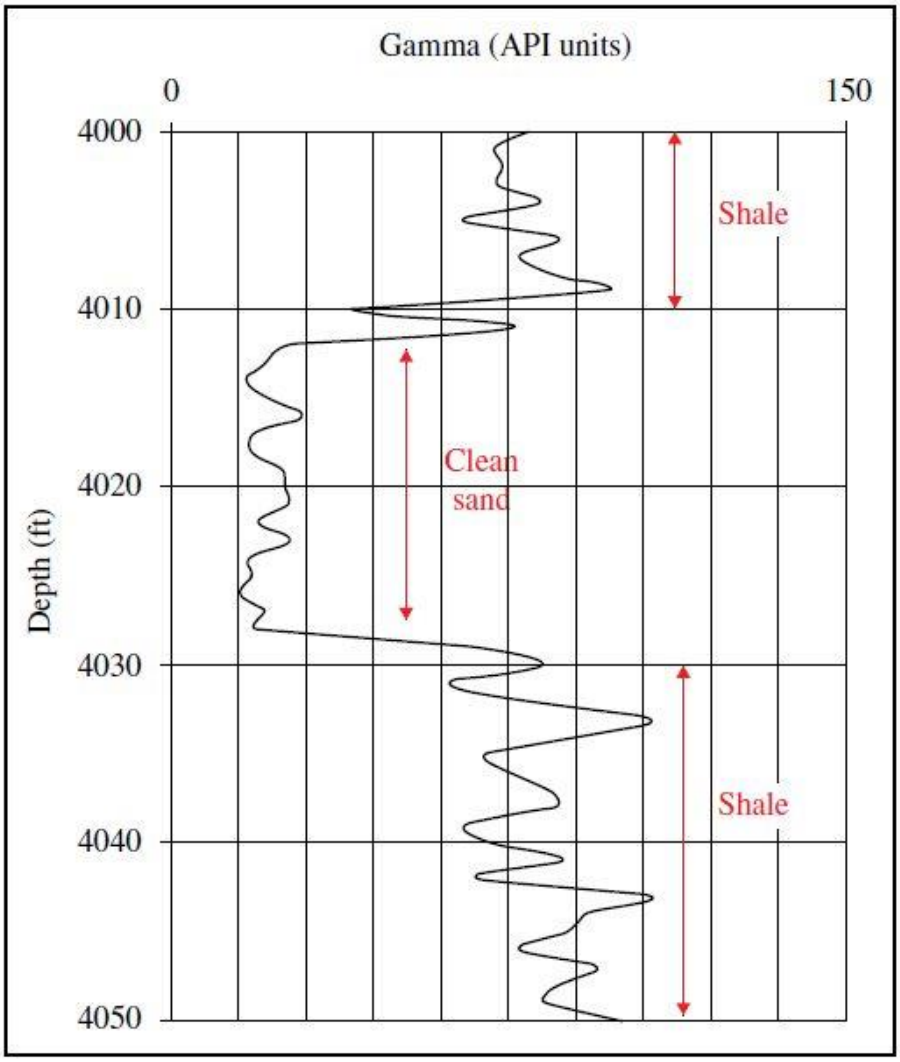


Figure 5.3.1 Illustration of a GR Log response ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering-John Wiley & Sons, Inc. 2017)

The shale content of reservoir rock can be estimated by linear interpolation between the GR log readings across clean rocks (the sand line) and shales (the shale line) such that:

$$V_{Shale} = \frac{GR_{log} - GR_{Clean}}{GR_{Shale} - GR_{Clean}}$$

GR_{log} : gamma ray log reading in zone of interest (API units)
GR_{Clean} : gamma ray log reading in l00% clean zone (API units)
GR_{Shale} : gamma ray log reading in l00% shale (API units)
V_{Shale} : shale volume from gamma ray log (fractional)

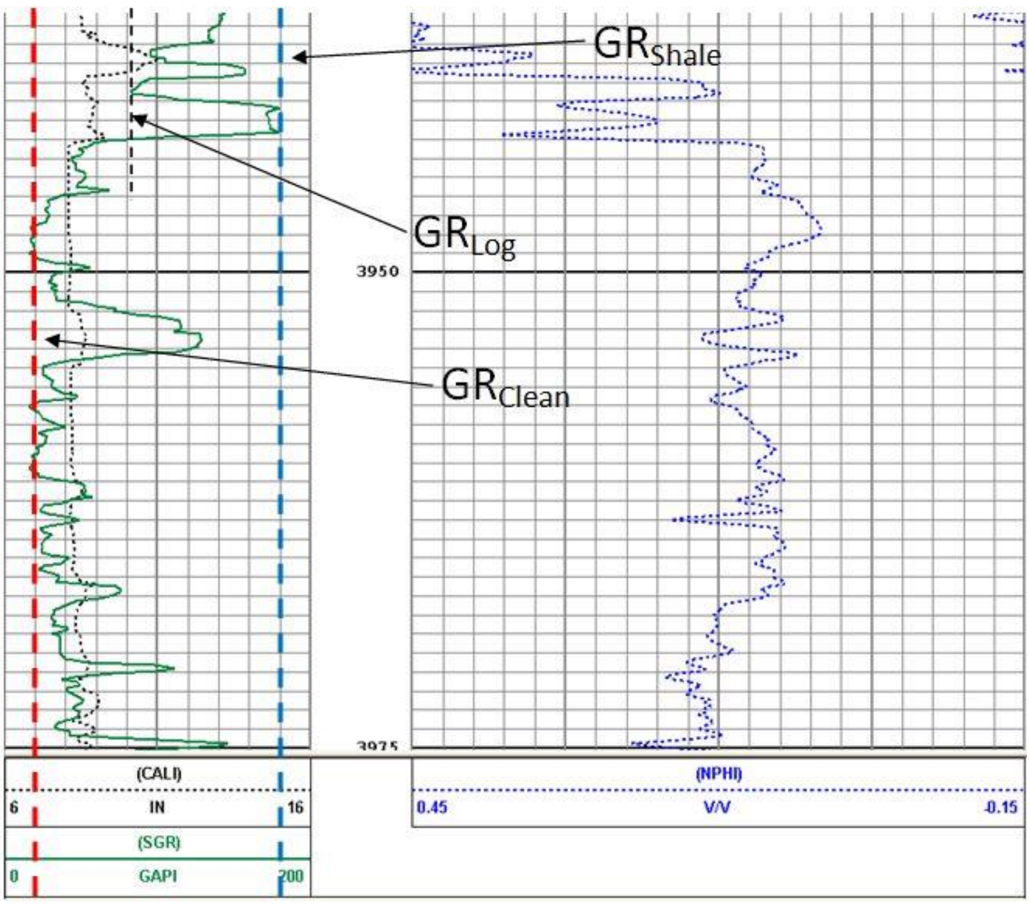


Figure 5.3.2 Example with a Gamma Ray Log (green curve SGR in API units) ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

clean sand line
shale line

$$V_{shale} = \frac{80 - 20}{180 - 20} = 37.5\%$$

Spontaneous Potential (SP) Logs

The SP logs are variously known as "Spontaneous Potential", "Self Potential" or "Shale Potential" logs. The SP log records the direct current voltage difference, or natural (spontaneous) potential difference, between two electrodes, without any applied current. One electrode is grounded at the surface (reference electrode), usually located at the mud pit, and the other electrode on the logging tool moves along the face of formations in the wellbore. SP response is created by electric voltages arising from electrochemical factors in the borehole and adjacent rocks. SP responses are measured in millivolts (mV).

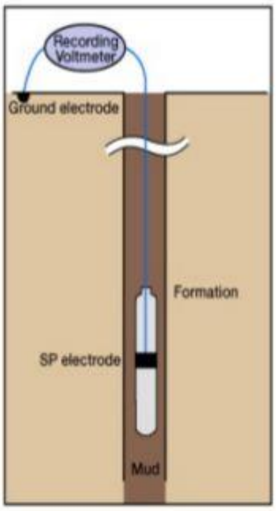


Figure 5.3.3 SP Log operation (https://www.slideshare.net/AmirGhaly/sp-log-well-logging [Amir I. Abdelaziz] Spontaneous Potential Log)

In order to record a potential, the hole must contain conductive mud, as it cannot be recorded in air or oil-based mud. The SP results from diffusion processes in porous rock are driven by differences in the ionic composition (salinity difference) of aqueous mud filtrate (from water-based mud) and in situ formation water. The difference in salinity between the formation water and the drilling mud behaves as a physical battery and causes many voltage effects. Charged ions move between the borehole and the formation water because of this ''battery''. This movement occurs where the rocks are enough permeable. Ion movement is permitted by a permeable formation decreasing the voltage difference between the drilling mud and the formation water (Low SP=permeable beds such as sands). On the other hand, non permeable sections restrict ion movement increasing the voltage difference (High SP=impermeable beds such as shales). An increase or decrease in the SP curve indicates the boundary between one rock type and another.

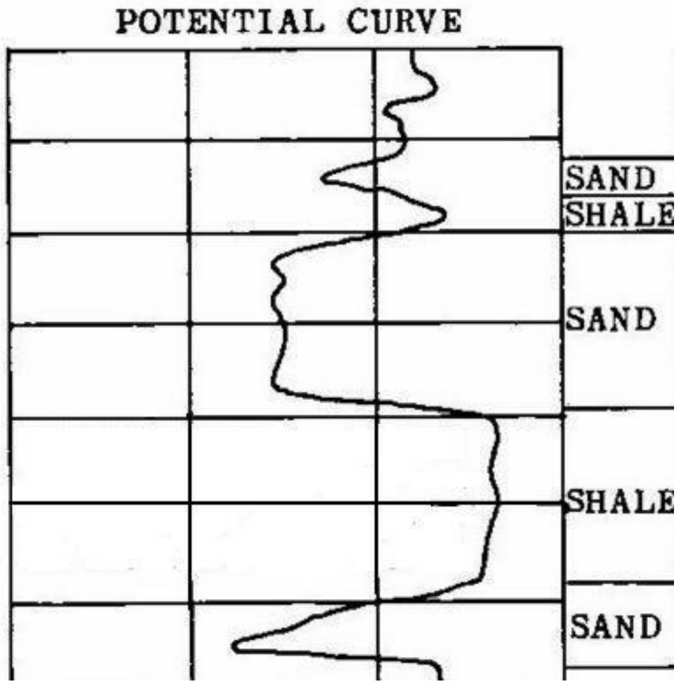


Figure 5.3.4 SP curve showing lithology (rock types and their boundaries)

The direction and magnitude of an SP deflection opposite clean sand permeable zone gives information about formation water salinity and mud filtrate salinity. Salinity of a fluid is inversely proportional to its resistivity, so in practice mud filtrate salinity is indicated by mud filtrate resistivity (R_{mf}) and formation water salinity by formation water resistivity (R_w). If the formation water is more saline than the mud filtrate ($R_{mf}>R_w$), the SP will show a negative deflection to the left and we can assume that fresh water mud has been used there.

The range of the voltage on an SP logging track is typically up to 200 mV. The SP voltage for shales in a particular well is fairly constant and forms a shale baseline for interpretation of the SP log for that well. The SP for clean (shale-free) sands is negative by 50-100 mV relative to the shale baseline and forms a clean sand baseline. These two baselines provide a rule for interpolating the amount of shale in a formation based on its SP.

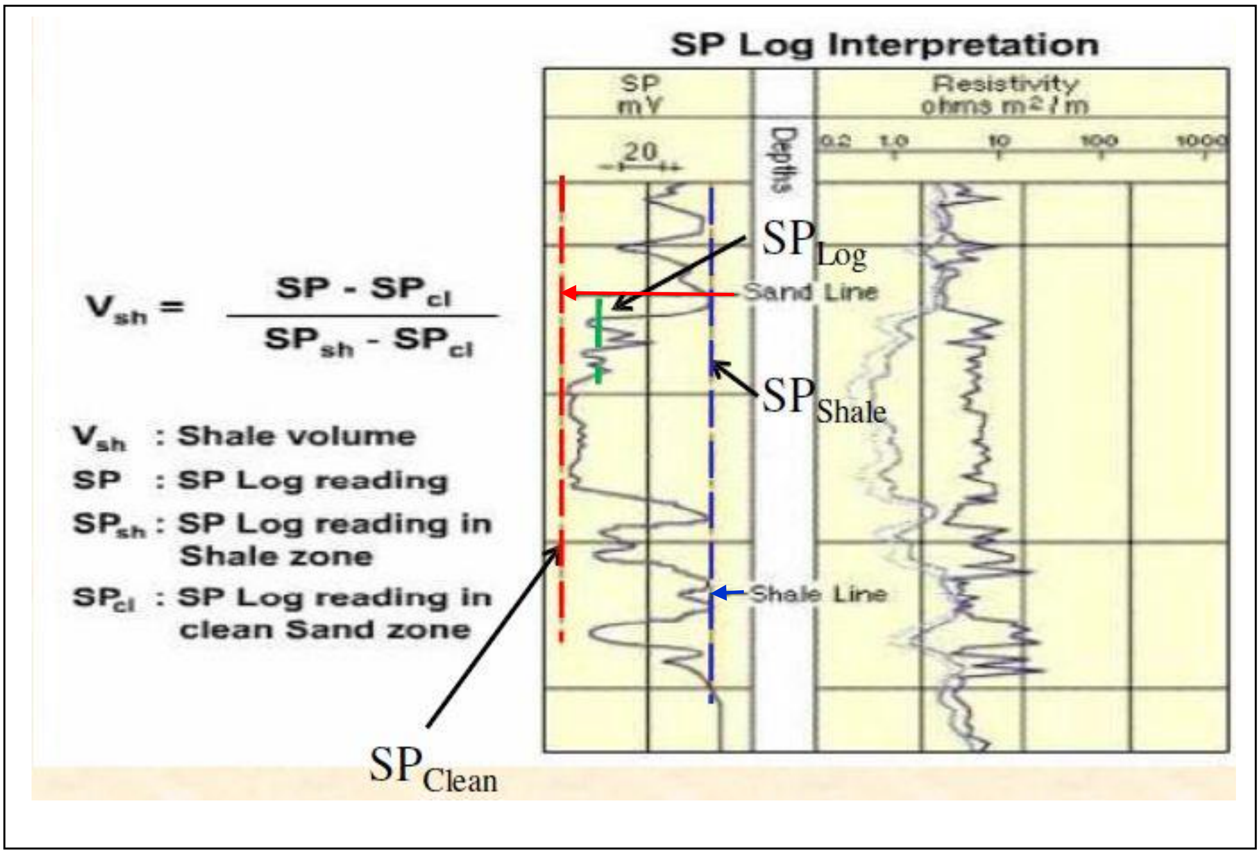


Figure 5.3.5 Example with a Spontaneous Potential Log
([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

Photoelectric (PE) Logs

The PE logging tool is part of the modern density logging tool which monitors the scattered gamma rays in the low energy region. The low energy gamma rays (<0,2 MeV) are those that are undergoing photo-electric absorption. The PE refers to the absorption of a low energy gamma ray by inner orbital atomic electrons. The extent of this absorption varies with atomic number of the atom. In the photoelectric effect, a low energy gamma photon that collides with an atom can transfer all of its energy to an inner orbital electron and cause the ejection of an electron from the atom. The amount of energy required to eject the electron depends on the atomic number.

Photoelectric logs measure the absorption or falloff of low energy gamma photons by atoms in the formation. The absorption or falloff in gamma ray energy is quantified as a PE factor (PEF). The PEF depends primarily on the atomic number of the formation. Hydrocarbon and water contribute very little to the PEF because their atomic numbers are low compared to the rocks in the formation. On the other hand, the atomic numbers of different rock types can be correlated to PEF so that PEF serves as a good indicator of lithology. PEF can be affected by heavy minerals such as barite in the mudcake or mud filtrate. The PE logging track is often scaled from 0 to 10 in units of barns per electron (b/e) since it is proportional to the photoelectric cross section per electron. A barn is a measure of cross sectional area and a barn equals $10^{-28}m^2$. A generalized interpretation guide is given below.

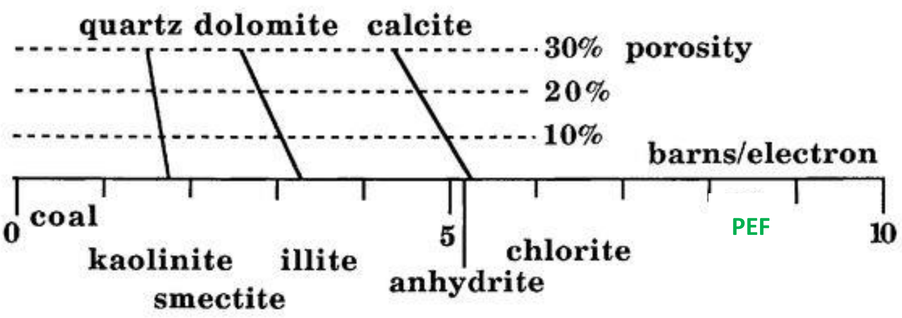


Figure 5.3.6 Photoelectric Factor (PEF) scale indexed with common minerals (http://archives.datapages.com/data/sepm_sp/SC29/The_Photoelectric_Index.htm [The Society for Sedimentary Geology SEPM] The Photoelectric Index 2012)

On this scale, minerals such as calcite, dolomite and quartz have narrowly defined expected values, with a minor downward drift at increasing porosities in their host lithologies. The variable compositions of coals and clay minerals means that their position on the scale should only be taken as a broad indication.

As we have already mentioned, there are two common lithologies, clean sandstones and clean limestones, that cannot be distinguished by GR log. The PE log can distinguish clearly and unambiguously between clean sandstones and clean limestones. Furthermore, limestone and anhydrite cannot be distinguished by the *PE* log. However, anhydrite will always show up with little or no porosity on the neutron log, and will have a bulk density always above 2.9 g/cm^3, which compares with a maximum of 2.71 g/cm^3 possible with a clean limestone. Figure below shows the response of the PE tool to common lithologies.

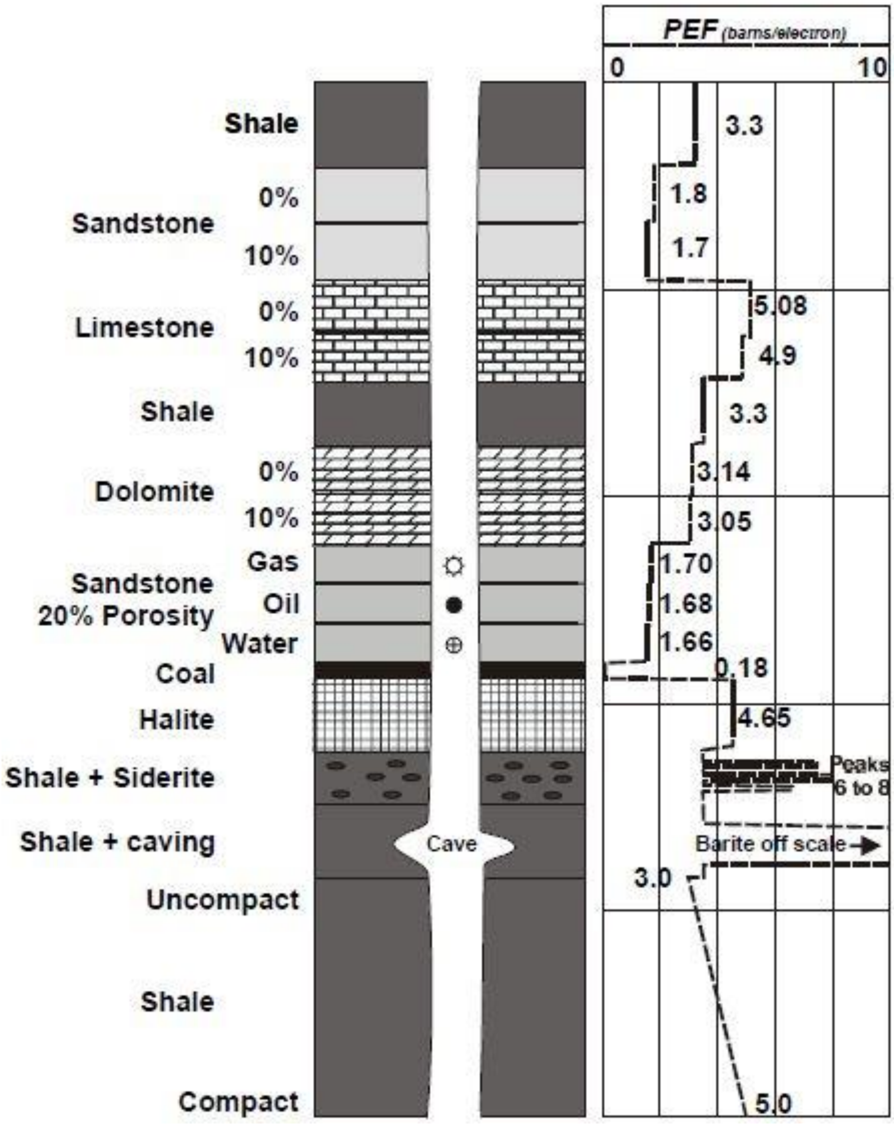


Figure 5.3.7 Measurements of the Photoelectric absorption Log for common lithologies (http://homepages.see.leeds.ac.uk/~earpwjg/PG_EN/CD%20Contents/GGL-66565%20Petrophysics%20English/Chapter%2014.PDF [Dr Paul Glover] Petrophysics MSc Course Notes)

5.4 MISCELLANEOUS LOGS

New logs are being developed as technology evolves and the needs of industry changes. Some of them as caliper logs, nuclear magnetic resonance (NMR) logs, dipmeter logs and borehole imaging logs are introduced here.

Caliper Logs

Caliper logs measure the size and shape (geometry) of the recently drilled borehole. Ideally, the borehole shape will be a uniform cylinder with the diameter of the drill bit used to drill the borehole. In practice, the diameter and the expected cylindrical shape of the borehole may differ substantially from a uniform cylinder with the diameter of the drill bit. The actual borehole shape depends on the type of formation and it can be measured with a caliper log.

The caliper tool measures the diameter of the borehole in inches or cm, using either two or four or six mechanical arms. Variations in hole diameter cause the arms to close or open and the movement is reflected in resistance changes in potentiometers. Caliper log can be used to identify zones where the borehole walls are in possible danger (because of possible fractures or washouts) where the well logs may be less reliable. In this case hole size information by caliper logs is needed in order to correct the other logs and so control logs quality. It is important to point out that washouts are indicative of formation properties. Caliper log (with mnemonics: CAL or CALI) detects washouts so indirectly we can gain lithologic information. It is also obvious that hole volume, estimated by the caliper log measurements, is required in order to proceed with the cementing of the borehole.

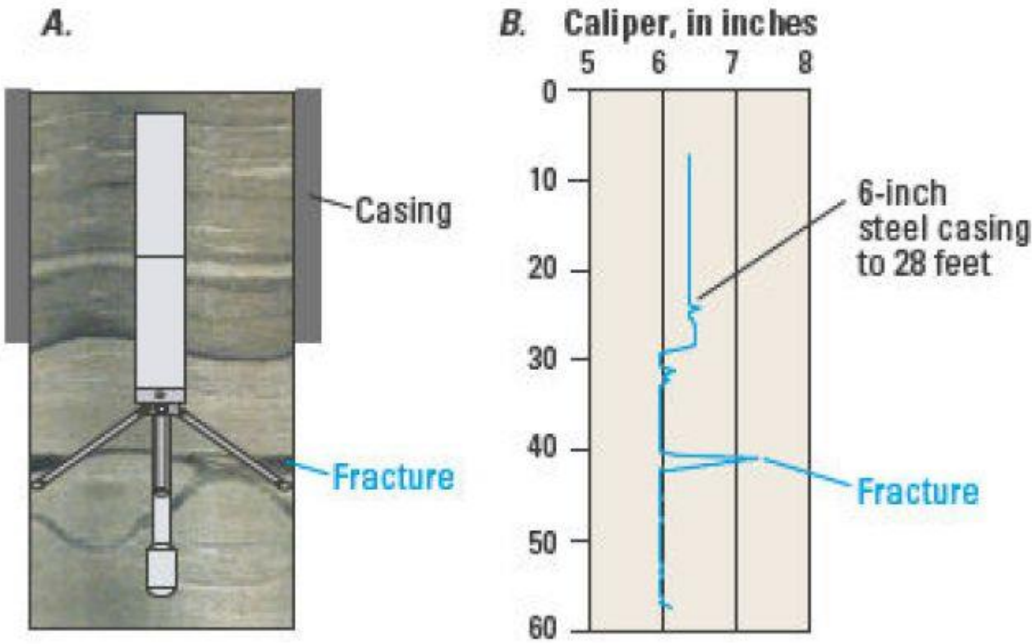


Figure 5.4.1 Example of a Caliper Log ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

As the caliper tool crosses a fracture, the arms open slightly, creating the inflection on the caliper log. This example log shows a fracture at about 42 feet below land surface.

Nuclear Magnetic Resonance (NMR) Logs

Nuclear magnetic resonance (NMR) logging utilizes the NMR response of a rock stratum to estimate its porosity and permeability, giving a full record all along the borehole.

Hydrogen's nuclei have a spin, which corresponds to one macroscopic angular momentum or magnetic moment. In this case the nuclei behave like magnets. NMR log is based on this property of hydrogen in the formation. Resonance condition is needed to detect NMR .This condition can be reached with a static magnetic field and a Radio Frequency magnetic field.

NMR is a response of nuclei in the presence of magnetic field. Nuclei having odd number of proton/neutron are those which respond: in our case it is Hydrogen. Initially, the hydrogen atoms are aligned in the direction of a static magnetic field (B_0). Each proton is like spinning bar magnet. These tiny bar magnets are aligned/polarized along in external magnetic field applied. When external field is switch off, precession starts like gyroscope in gravity field.

NMR log is based on the following principle. The alignment of these protons is called polarization but this does not happen immediately. It grows with a time constant called spin-lattice or longitudinal relaxation time T_1. After T_1 an oscillating magnetic field is applied, sending pulses of radio-frequency energy into the formation. The initial pulse is perpendicular to B_0 and aligns the spins in the transverse direction in phase with one another. As the pulse dies, protons lose their energy/precession by coming to the initial state. This exponential decay is sinusoidal and is called transversal or spin-spin relaxation time T_2. This signal is seen in the receiver coil. Both during build up magnetization and relaxation there is transfer of energy. How this energy is transferred into the surrounding material form the basis for NMR log.

Because the formation contains hydrogen in different forms (in water in large pores, small pores, and bound in clay minerals), there is a distribution of T_2 times. The T_2 distribution is the basic output of NMR measurement. It undergoes a further process that gives the total pore volume (i.e. the total porosity) and pore volumes within variant ranges of T_2, such as the bound and free fluid volumes (BFV and FFV).

NMR logs quantities measured are signal amplitude and decay of the nuclear spin of hydrogen. The response is essentially only that of the protons in fluids as the nuclei in solids have little direct effect on the NMR measurements. Signal amplitude is proportional to hydrogen nuclei present and calibrated to give porosity. Uniquely, a petrophysicist analyses the rate of decay of NMR signal during each cycle and gives information about pore size (porosity) and then makes an empirical estimation of permeability. Small pores have short decay time which means that hydrogen nuclei are bound to the clay, whereas large pores have large decay time which means that producible fluid exists.

The main application of the NMR instrument is to estimate moveable fluid volume (BVM) of a rock. This is the pore space not including clay bound water (CBW) and irreducible water (BVI). Both of them do not move in the NMR sense, so older logs do not observe these volumes. On modern instruments, CBW and BVI can in many cases be observed in the signal response after the transformation of the relaxation curve to the porosity domain. With stronger magnets and better processing, modern tools can usually give the irreducible water volume (BVI) and clay bound water (CBW).

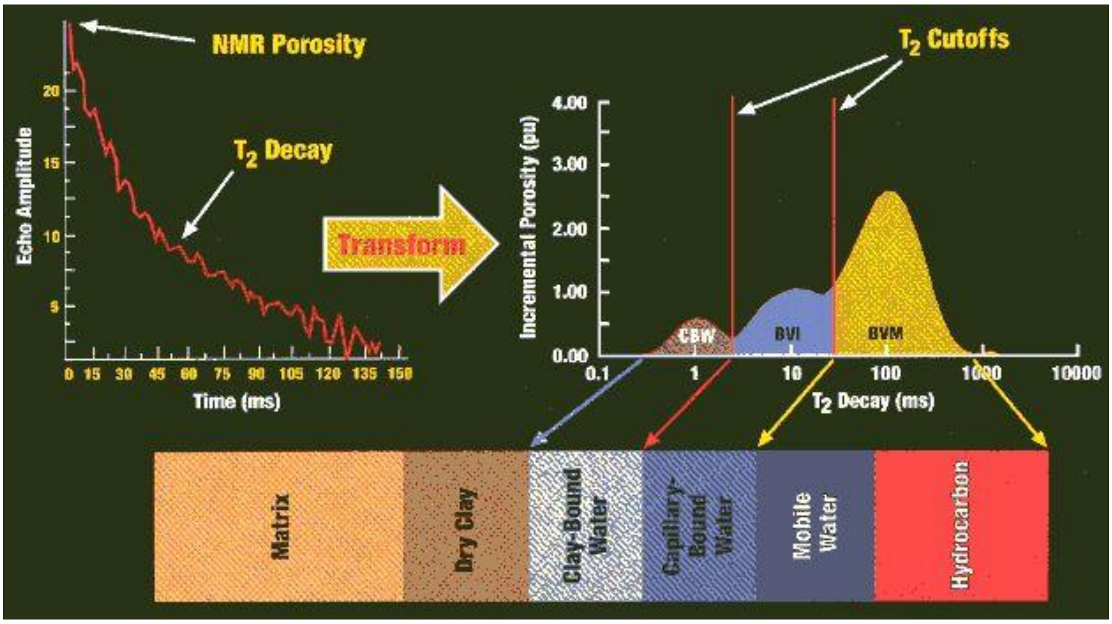


Figure 5.4.2 Transforming the precession decay time curve into the porosity domain, showing breakdown of CBW, BVI, and BVM. The T_2 cutoff for the boundary between CBW and BVI is often chosen at 3 ms. In sandstones, the boundary between BVI and BVM is usually chosen at 32 or 33 ms, but in carbonates the cutoff could be much higher (80 to 120 ms) and varies with lithology. The cutoffs can be determined on rock samples in the lab. (https://www.spec2000.net/07-nmrlog.htm Crain's Petrophysical Handbook, Nuclear Magnetic Resonance Logs)

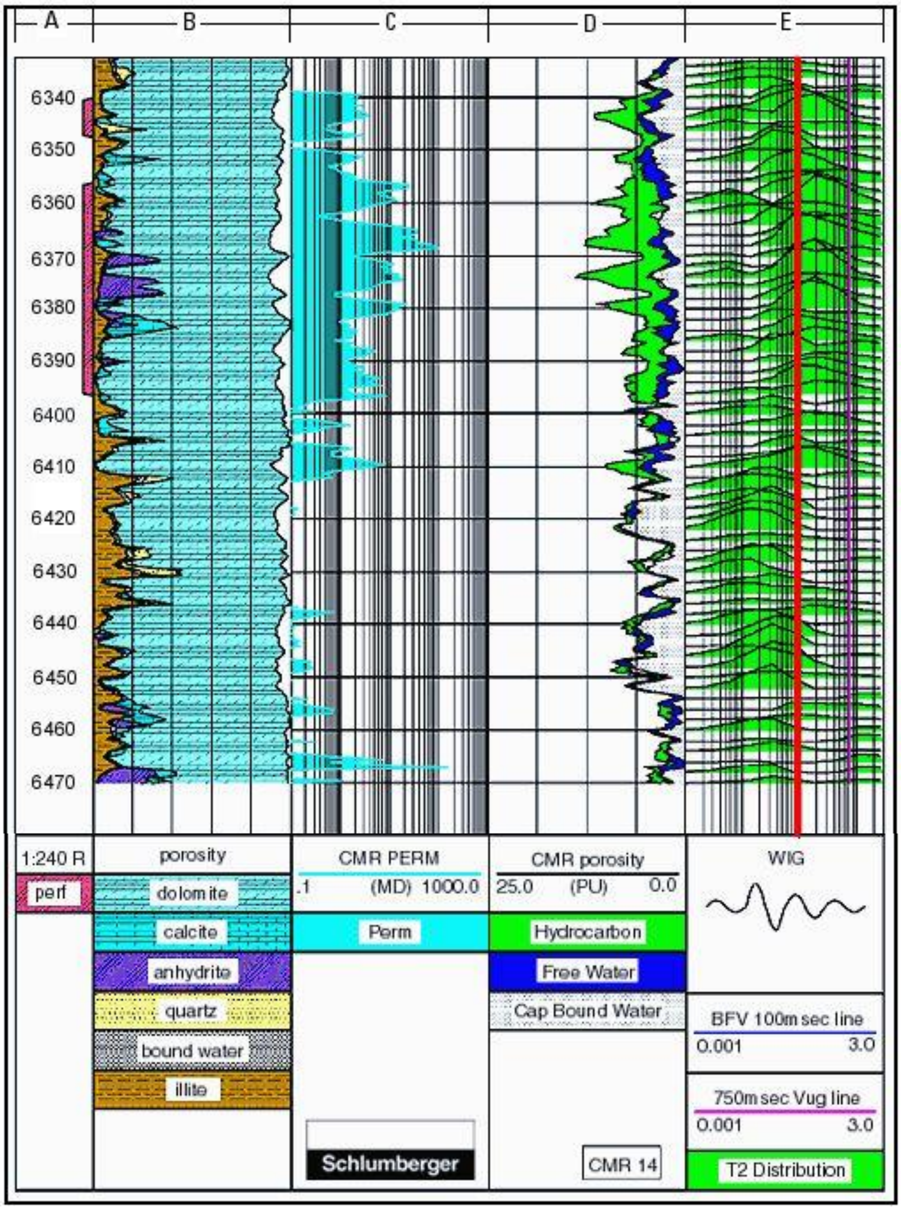


Figure 5.4.3 NMR sample log: Lithology analysis (Track 1), NMR permeability (Track 2), NMR porosity (Track 3 - white area = irreducible water volume BVI), NMR pore size distribution (Track 4) (https://www.spec2000.net/07-nmrlog.htm Crain's Petrophysical Handbook, Nuclear Magnetic Resonance Logs)

A sample of a modern NMR log is shown above. The depth scale (in feet) is at the extreme left in column A. In the right hand track – column E – there is a small graph at each depth illustrating the distribution of pore sizes as deduced from the NMR measurements. Below 6410 feet almost all the weight in the distributions is in small pores, as shown by a green peak to the left of the red line. Above 6410 feet the weight is predominantly in large pores, shown by a green peak to the right, indicating a coarse-grained formation. Thus a geologist can look at the NMR data and immediately recognize a change in rock texture at an unconformity in a formation more than a mile underground. A log of NMR-derived fluid permeability is shown in Track 2 (column C). The permeability changes by orders of magnitude in this section. In the fine-grained formation, the permeability is negligible, while in the upper coarse-grained section it is substantial. These results were used by petroleum engineers to institute an efficient production program for this well.

Finally it is important to mention the advantages and disadvantages of the NMR logging. The advantages are: •Only fluids are visible to NMR technology so porosity measurement can be independent of the lithology •Producible zones with high percentage of clay-bound water can identified •In-situ measurement of oil viscosity as it is related to the polarization time constant T_1. On the other hand, the disadvantages are: •Any diamagnetic or paramagnetic ions present in the formation can affect the tool response (reduce relaxation times) •Expensive •Slower logging speeds •Permeability measurement is actually empirical and should only be used to compare with core permeabilities (calibration with core data).

Dipmeter Logs

As long as oil migrates updip, it would seem there is nothing more fundamental in oil exploration than determining which way is up. It is for this basic purpose that the electric wireline technique known as the dipmeter was designed. From these primitive beginnings, however, the dipmeter log has evolved to become a device capable of providing a major input into a complete geological description of the formations crossed by a borehole.

The aim of dipmeter log so is to determine the angle to the horizontal and the azimuth referenced to magnetic north and geographical north of the dip of the planes cut by the well. These planes can be: -bed boundaries -an open or closed fracture -an erosional surface -a stylolitic joint. The planes can be planar, or can correspond to a convex or concave surface intersecting the well.

Most of the surfaces intersected by a well can be described as a plane at the scale of the hole diameter. A plane is defined by a minimum of three points not lying in a straight line. It should be sufficient, therefore, to know the coordinates (X,Y,Z) of three points in space to define the plane. In logging, these points correspond to the intersection of three generatrices of the borehole wall (cylinder) with this plane.

The dipmeter tool consists of at least three electrodes mounted on pads in a plane perpendicular to the axis of the tool and situated at angles of 120 degrees (3-pad tool) or 90 degrees (4-pad tool) to each other. The three electrodes (sensors) each make a micro resistivity measurement of the borehole wall. Because of the size of the electrode and the current focusing that occurs on each pad, the micro resistivity measurement is assumed to be a point measurement at the electrode. When the tool crosses the boundary between two formations, the corresponding response change is recorded (as an abrupt change in reading of the curve) for each pad at different depths according to the apparent dip (dip angle to the horizontal plane). The relative depth differences for the three individual log curves give the necessary information to evaluate the dip and the azimuth.

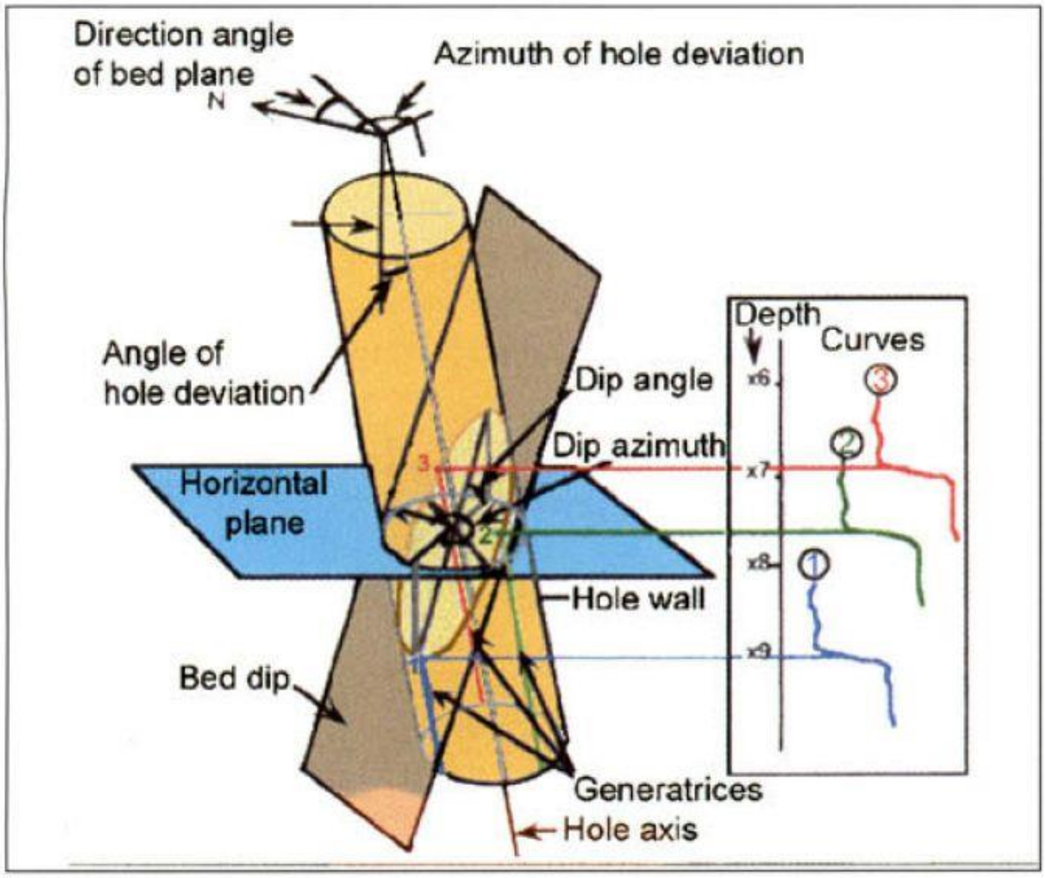


Figure 5.4.4 Definition of a formation plane by dipmeter (3-pad tool) correlation curve activity ([Serra O., Serra L.] Well Logging, Data Acquisition and Applications)

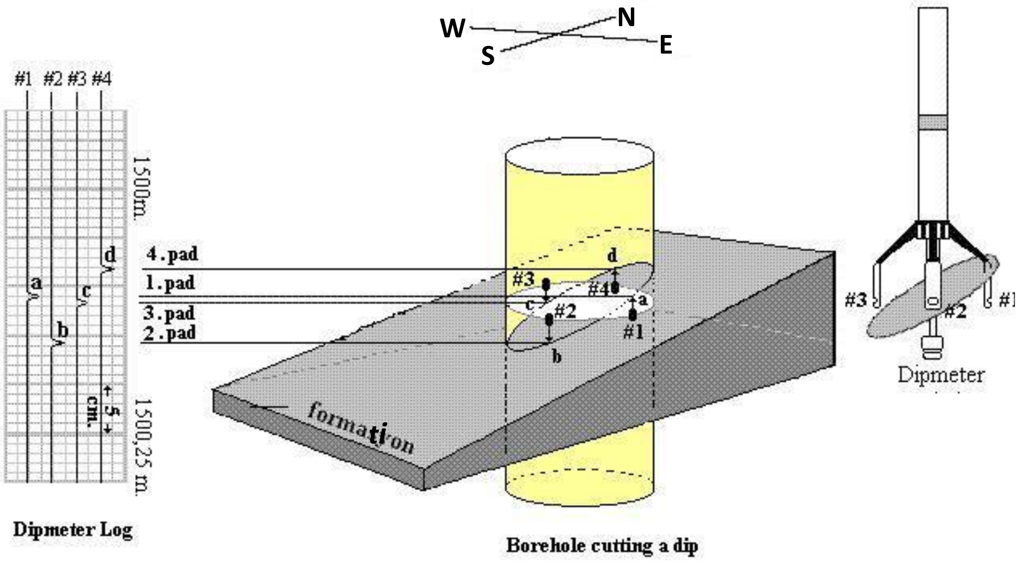


Figure 5.4.5 Definition of a formation plane by dipmeter (4-pad tool) correlation curve activity (micro resistivity device used with 5cm vertical resolution) (http://www.bridge7.com/grand/log/gen/dipmeter/dip1.htm [Yalcin Pekiner] Well Logging Course)

Early dipmeters in the 1940s had three pads which is the minimum number needed to define a plane. These evolved to the four-arm dipmeter in the 1960's and the modern dipmeter which has six arms to help in the distinction of real bedding features from artefacts.

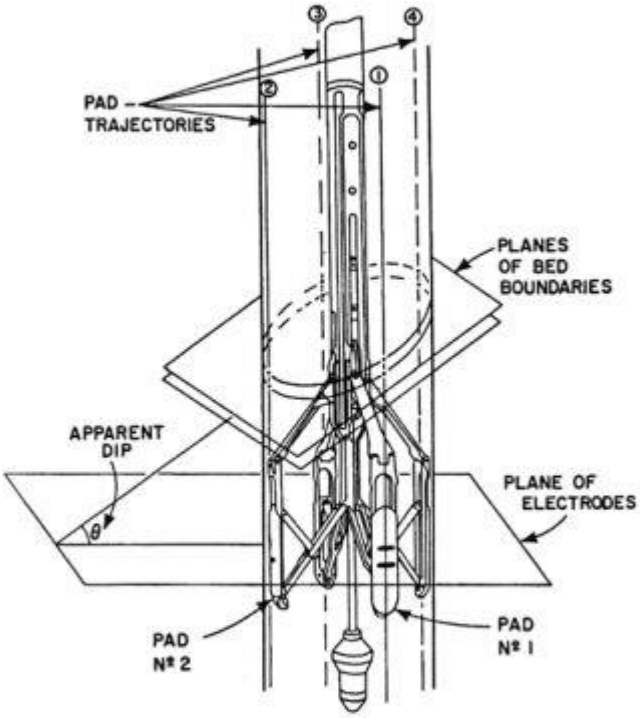


Figure 5.4.6 Sketch of a four-arm high resolution dipmeter tool (HDT) with the trajectories (generatrices) the pads take when the tool is pulled uphole (https://link.springer.com/chapter/10.1007%2F978-3-662-04627-2_4 [Stefan M. Luthi] Geological Well Logs, Their Use in Reservoir Modelling)

Correlation process has already fit a plane and then dip/dip-azimuth can be computed. Computer processing of the data yields a tadpole plot of dips and dip directions in the well. Dip results are presented graphically in arrow or tadpole plots. This is the most widely known presentation and can be produced at depth scales of 1/1000, 1/500, 1/200. Each calculated point is plotted in abscissa according to the dip angle and in ordinate with depth. The point (tadpole=circle with an arrow) •⟋ is extended by a short straight line in the dip direction, with geographical north towards the top of the plot (or log). Different symbols are used to represent points: a black circle indicates a good quality result whereas an open or wide circle indicates a point which the quality is undefined.

The dipmeter measurements provide information related to tectonics or structural geology, sedimentology and stratigraphy. Dip measurements are fundamentally used to define regional or structural dip, but also to detect structural dip anomalies associated with structural deformation such as faults, folding, etc. Additionally, a dipmeter gives an indication of sedimentary features present in the interval and consequently an idea of the depositional processes. Furthermore, analysis of the dipmeter may bring out information on stratigraphic phenomenon such as discontinuities or angular unconformities.

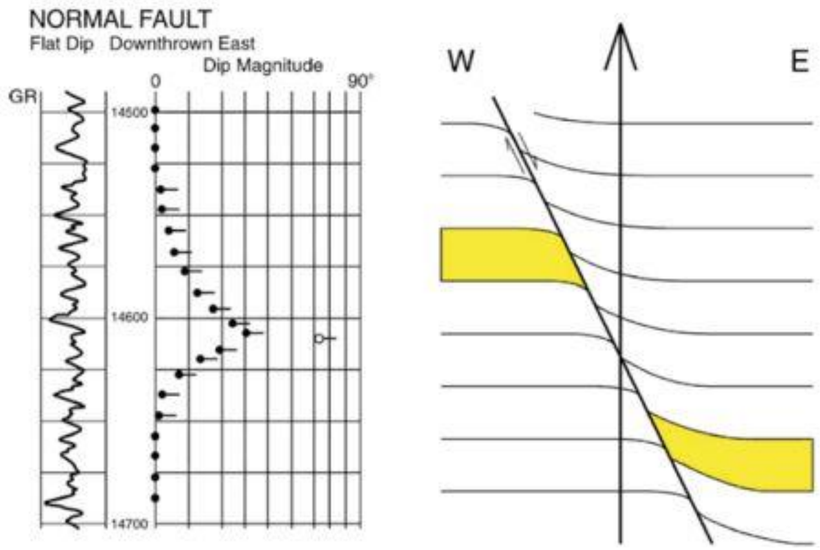


Figure 5.4.7 Simple dip model for the description of a normal fault with drag (https://books.google.gr/books?id=uwlIqGxpfLEC&pg=PA75&lpg=PA75&dq=the+practise+of+reservoir+engineering+revised+edition+dipmeter+logs&source=bl&ots=DFhZeKj7GZ&sig=Ke-qZc4jSGzX-9HH0itfxqyc4Hk&hl=el&sa=X&ved=2ahUKEwi-nZDm74LdAhXLAewKHZENASQQ6AEwAXoECAkQAQ#v=onepage&q=the%20practise%20of%20reservoir%20engineering%20revised%20edition%20dipmeter%20logs&f=false [L.P. Dake] The Practice of Reservoir Engineering (Revised Edition))

The above figure shows gamma ray and dipmeter log from a well that penetrated a normal fault. Each tadpole denotes the strike and dip of strata at that particular footage in the well. The black dot or ”head” of the tadpole provides the dip magnitude (see horizontal axis) from 0-90^o, and the straight line or ”tail” of the tadpole represents the orientation of the plane of bedding of 0-360^o, with 0^o being oriented to the north. The dip magnitude increases as the fault is approached. The orientation of the beds does not change from a 90^o azimuth.

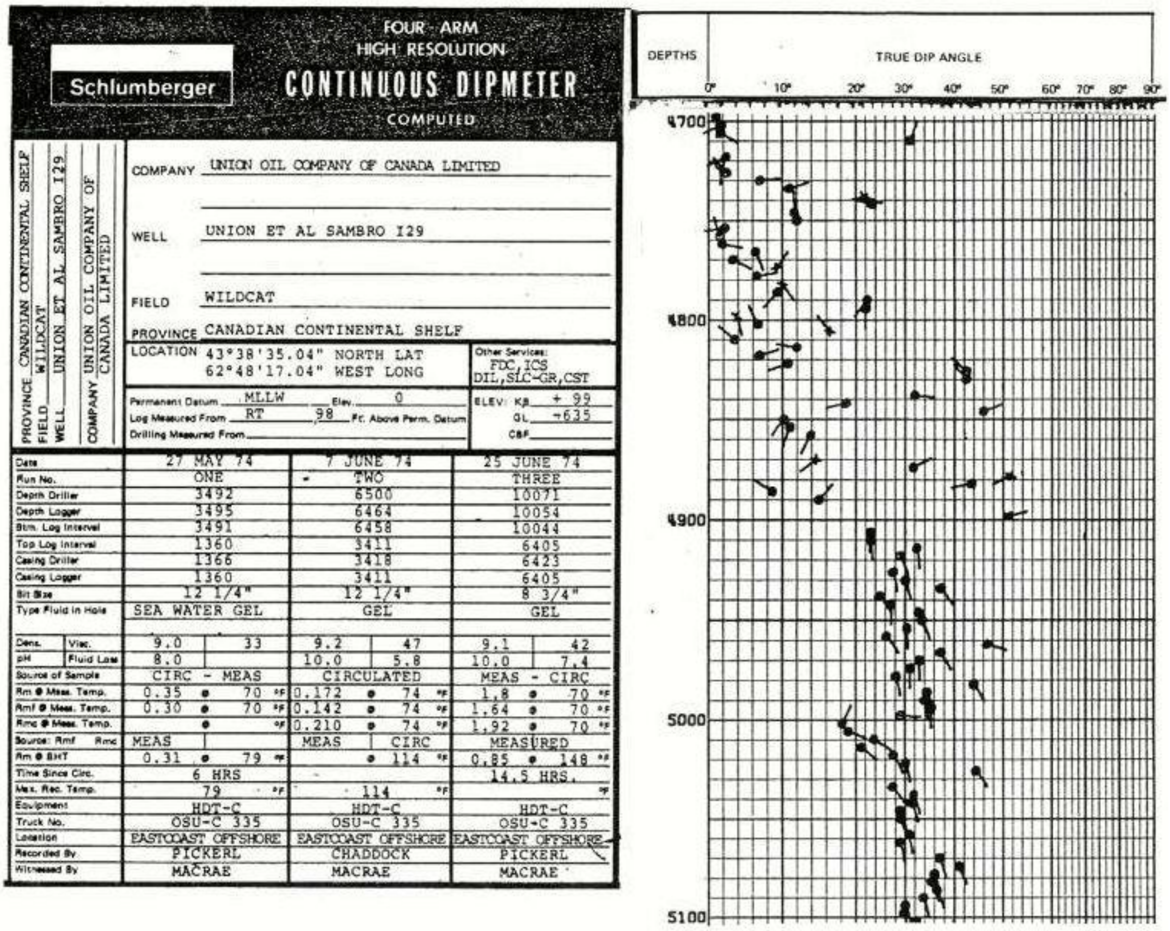


Figure 5.4.8 Dipmeter example in an offshore well on the east coast Canadian continental shelf
(http://www.kgs.ku.edu/Publications/Bulletins/LA/13_dipmeter.html KGS Geology, Geological Log Analysis, The Dipmeter Tool)

A major unconformity occurs at a depth of 4900 feet with rather erratic dips in the Cretaceous section above the unconformity, and an abrupt change to a systematic dip of about 30 degrees to the south-southeast in the Jurassic section below the unconformity.

This stratigraphic pattern is corroborated by a seismic section shot near the well, as shown next.

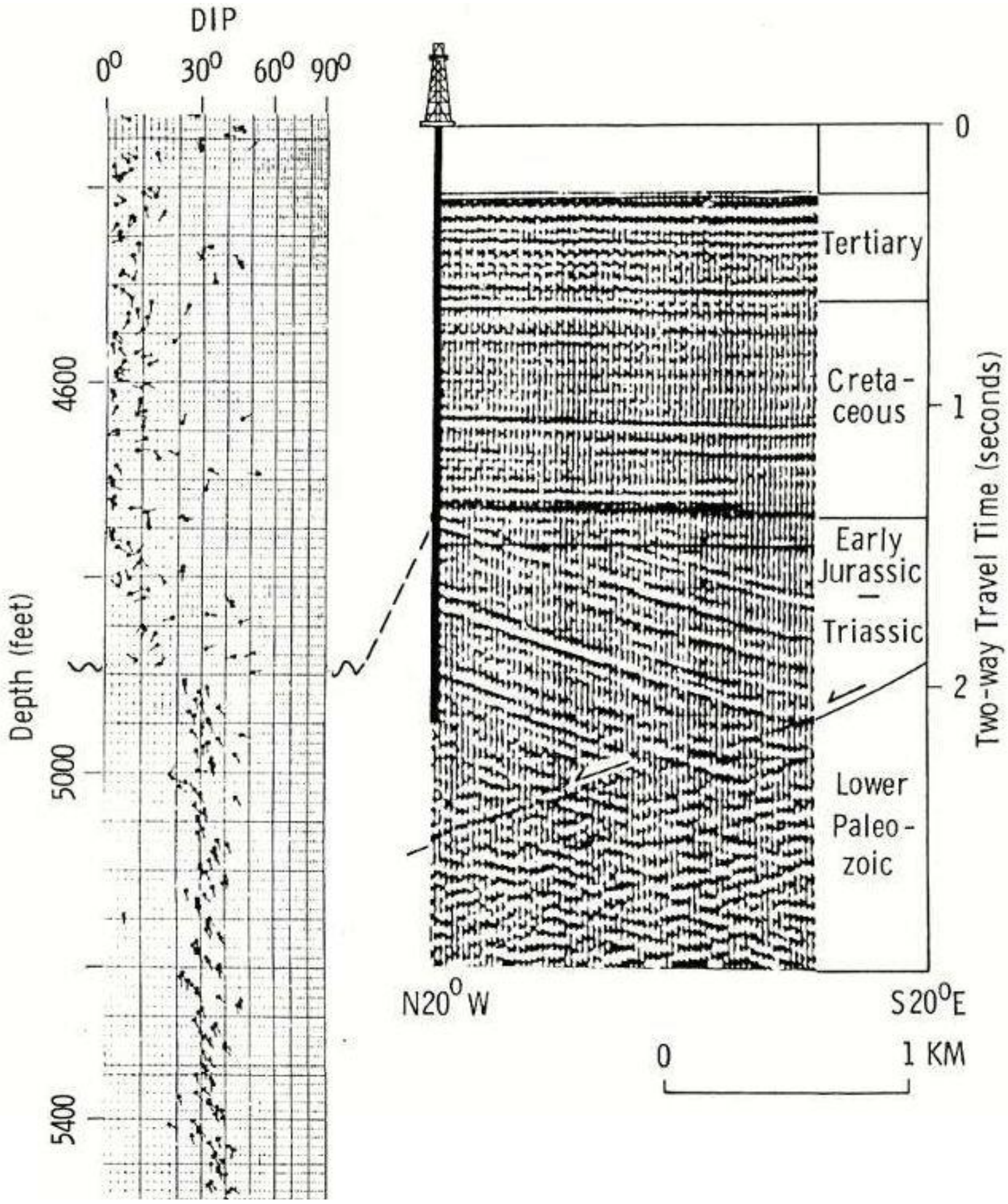


Figure 5.4.9 A match of a dipmeter log with a seismic section (http://www.kgs.ku.edu/Publications/Bulletins/LA/13_dipmeter.html KGS Geology, Geological Log Analysis, The Dipmeter Tool)

On the left of the graphic, we see an expanded section of the dipmeter log shown on the previous page. On the right is the seismic section, with the location of the well to the left. The seismic section has a N20W-S20E orientation, so that the dipping reflections in the Jurassic section match those indicated by the dips of the dipmeter log. The relationship between dip in degrees shown on a dipmeter and stratigraphic correlation expressed in terms of depth difference should be considered carefully.

Borehole Image Logs

A picture is worth a thousand words because visualizing an object or concept is a powerful means of assimilating large amounts of information. Geologists and petrophysicists may use imaging tools to visualize downhole formations. These tools provide information that can be crucial for determining rock and formation properties, especially when physical core samples are not available.

When we speak about ''borehole imaging'' we refer to those logging and data-processing procedures which are familiar with producing centimeter-scale images of the hole wall and the rocks that compose it. They include optical, acoustic and electrical imaging techniques. Today, borehole imaging is a largely progressing technology in wireline logging. Borehole image logs have specific applications such as: identifying fractures, analyzing small-scale sedimentological features, evaluating net pay in formations with thin beds, observating of structural and stratigraphic dip and detecting of breakouts (enlargements in the wellbore which are aligned with the minimum horizontal stress and occur where stresses around the borehole wall go over the compressive strength of the rock).

Borehole imaging tools are categorized, according to the technique used, into the following types.

Optical imaging	video (optical scanning)	**OPTV** (Optical Televiewer)
Acoustic imaging	ultrasonic energy (ultrasonic reflection)	**UBI** (Ultrasonic Borehole Imager) **CBIL** (Circumferential Borehole Imaging Log) **HiRAT** (High-Resolution Acoustic Televiewer) that replaced today the oldest **BHTV** (Borehole Televiewer)
Electrical imaging	electrical resistivity (electrical scanning)	**FMS** (Formation MicroScanner) **FMI** (Formation MicroImager) **HD-FMI** (High Definition FMI) **OBMI** (Oil Based MicroImager) **ARI** (Azimuthal Resistivity Imager) **RAB** (Resistivity-At-Bit) *used only in Logging-While-Drilling (LWD)*
Both acoustic and electrical imaging	combination of acoustic and resistivity measurements	**STAR** (Simultaneous Acoustic/Resistivity Imager)

Optical (video) imaging: Downhole cameras were the first borehole imaging devices. The principal drawback is that they require a transparent fluid in liquid-filled holes. Unless transparent fluid can be injected ahead of the lens, the method of optical imaging fails. This requirement has limited the application of downhole cameras. Today the Optical Televiewer (OPTV) probe, using visible light optics, provides a continuous, detailed and orientated 360° true color image of the borehole walls using a unique optical imaging system. This system is equipped with a high resolution digital color camera with a light source. The resulting data offers the unique ability to present the core either as a wrapped image, showing an external view of the core or as an unwrapped image, looking out from the center of the borehole. The image can be rapidly interpreted, using data from the internal orientation module, to obtain a complete feature analysis that includes dip, strike, frequency and fracture aperture. Downhole video applications generally cover visual characterization of the open hole and visual inspection of fluids.

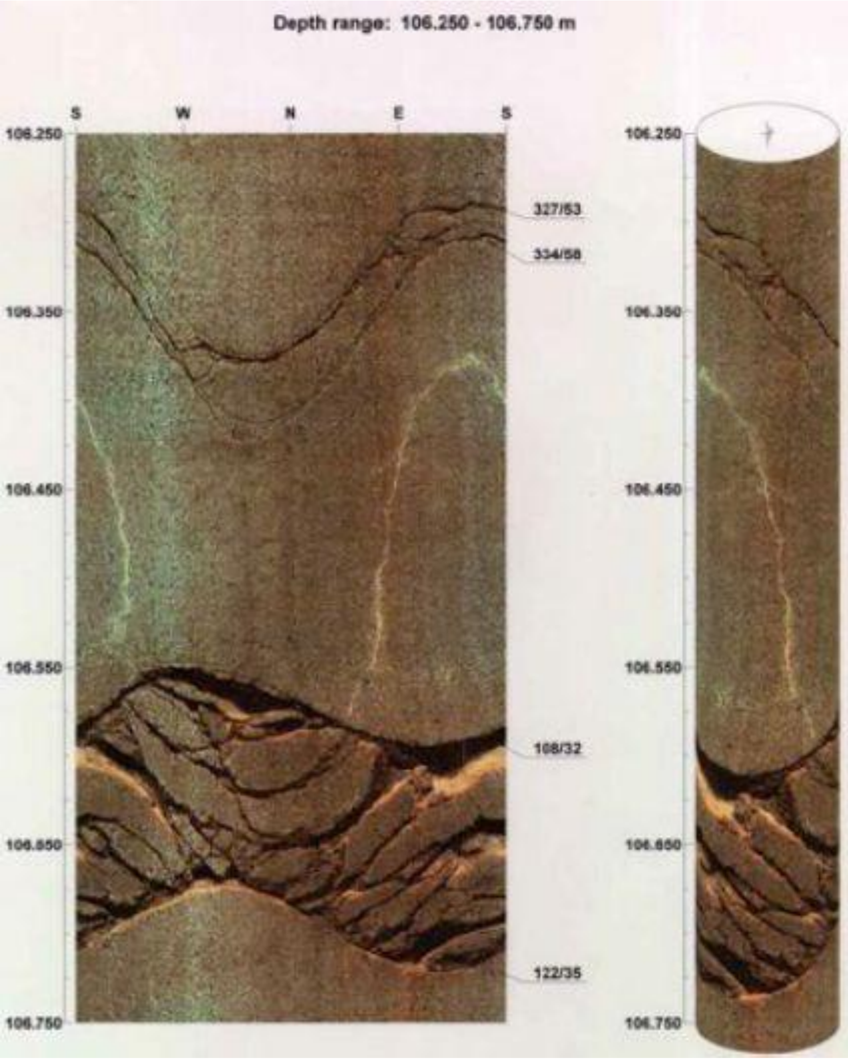


Figure 5.4.10 Downhole video image
(https://www.ldeo.columbia.edu/res/div/mgg/lodos/Education/Logging/slides/Image_fracture.pdf [Trevor Williams, Lamont Doherty Borehole Research Group] Well Logging Principles and Applications: Borehole Image Analysis 2008)

Industry-standard wireline image tools measure either the electrical conductivity of the borehole wall or the sonic travel time and amplitude of the reflected acoustic signal. The wireline resistivity image tools are pad tools that measure the formation micro conductivity directly through an array of resistivity buttons mounted on pads that are pressed against the borehole wall. Such tools normally provide the best high-resolution borehole images in conductive (water-based) muds. The wireline acoustic tools (or Acoustic TeleViewers ATVs) send sound pulses out to the formation and measure both the amplitude and the travel time of the returning signals. Because ATVs rely on sound pulses, they can work in resistive (oil based) muds, where electrical conductivity is very poor. Their disadvantages when compared to electrical images are a heightened sensitivity to borehole roughness or washouts and a generally poorer quality image overall in part or all of some holes.

Acoustic imaging: The acoustic imaging method relies upon the generation of ultrasonic pulses from a rotating transducer. The same transducer/receiver then measures the reflected echoes from the surface of the borehole wall. The transducer records two measurements:

- two-way travel time of the ultrasonic pulse.

The travel time of the sound from the transducer to the wellbore wall and back to the same transducer/receiver is measured. This provides a complete image of wellbore diameter (black colour indicates large diameter, white colour is "near" bit size) and also fractures and wellbore breakouts are seen.

- amplitude of the reflected signal.

The amplitude of the sound signal reflected from the borehole wall is a measure of the acoustic impedance of the rock. Low values represent shale or soft sandstone (shaded black on the log) and high values represent competent rock such as cemented sandstones or carbonates (shaded white on the log). Fracture and wellbore breakouts are easily seen here.

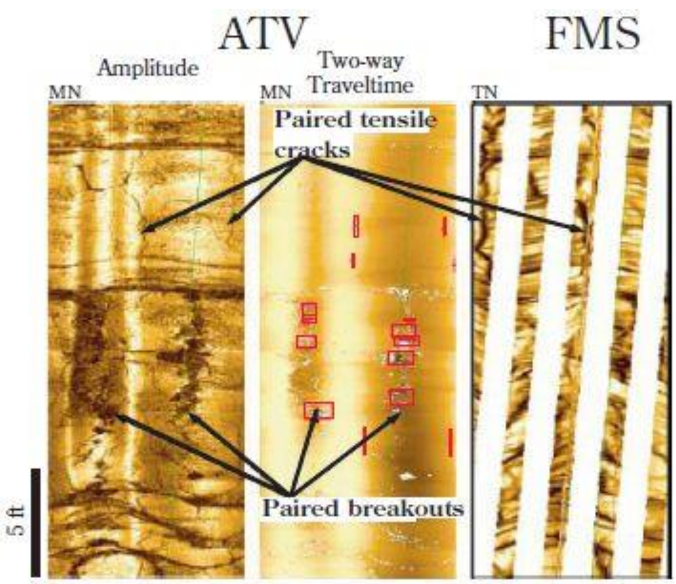


Figure 5.4.11 Borehole wall tensile fracture and breakouts in acoustic televiewer (ATV). [A] amplitude, [B] travel time images, and [C] Formation MicroScanner (FMS) electrical images. The ATV and FMS logs are oriented with respect to magnetic North (MN) and true North (TN) respectively (Modified from Zoback et al., 1985). (http://publications.iodp.org/sd/05/suppl/borehole_imaging_tools.pdf [Philippe Gaillot et al.] Technical Developments, Borehole Imaging Tools – Principles and Applications 2007)

Acoustic imaging devices work in all types of drilling fluids, including: fresh water-based muds, salt water-based muds, oil-based muds and polymer muds.

An early acoustic imaging tool, called the Borehole Televiewer (BHTV), perhaps an unfortunate abbreviation since it is often confused with the downhole video camera, was developed in the 1960s. This acoustic device employed a rotating piezoelectric transducer that transmitted sonic pulses to the borehole wall, and then measured the reflection times of these pulses. Differences in the travel time and amplitude of the reflected signals indicated the presence of fractures and other formation irregularities, while a flux-gate magnetometer provided a means of determining the orientation of these features. Modern-day acoustic imaging tools represent improvements to the original Borehole Televiewer.

An example of a modern ultrasonic imaging tool is Schlumberger's Ultrasonic Borehole Imager (UBI). The tool incorporates a rotating transducer within a subassembly. The size of the subassembly is selected on the basis of the diameter of the hole that is to be logged. The direction of rotation of the subassembly governs the orientation of the transducer. There are two positional modes: -the standard measurement mode with the transducer facing the borehole wall, and -the fluid-property mode with the transducer facing a target within the tool. In standard mode, the tool measures both amplitude and transit time at one of two frequencies, 250 or 500 kHz, with recommended logging speeds of 800 ft/hr (244 m/hr) and 400 ft/hr (122 m/hr) respectively. The higher frequency allows a sharper image resolution of 0.2 in. (5 mm), but it is less effective in highly dispersive muds where the lower frequency should be used. The tool is rated for 350 F (177°C) and 20000 psi (138 MPa).

Baker Atlas' Circumferential Borehole Imaging Log (CBIL) has a similar range of capability but is rated to 20000 psi (138 MPa) and 400°F (204°C). The CBIL operates at a frequency of 250 kHz for enhanced performance in larger holes and heavier muds. The signals are processed to create a photograph-like image that covers the entire 360-degree circumference of the wellbore.

The High Resolution Acoustic Televiewer (HiRAT) is the latest Robertson Geologging development in acoustic borehole imaging and replaces the old Borehole Televiewer probe (BHTV). It provides high-resolution, oriented images of the borehole walls presented in "pseudo-color". The probe uses a fixed acoustic transducer and a rotating acoustic mirror to scan the borehole walls with a focused ultrasound beam. The amplitude and travel time of the reflected acoustic signal are recorded simultaneously as separate image logs. Features such as fractures reduce the reflected amplitude and often appear as dark sinusoidal traces on the log. The travel-time log is equivalent to a high-precision 360-arm caliper and shows diameter changes within open fractures and 'break-outs'. Directional information is also recorded and used to orient the images in real time. The HiRAT includes many new features such as automatic optimization of head rotation speed according to borehole diameter, cable speed and desired resolution. A new design of acoustic

transducer provides improved image focus and resolution compared to the previous BHTV probe.
(http://www.geovision.com/PDF/App%20Note%20-20Borehole%20Televiewer.pdf [Geovision geophysical services] Borehole Televiewer Logging Methods)

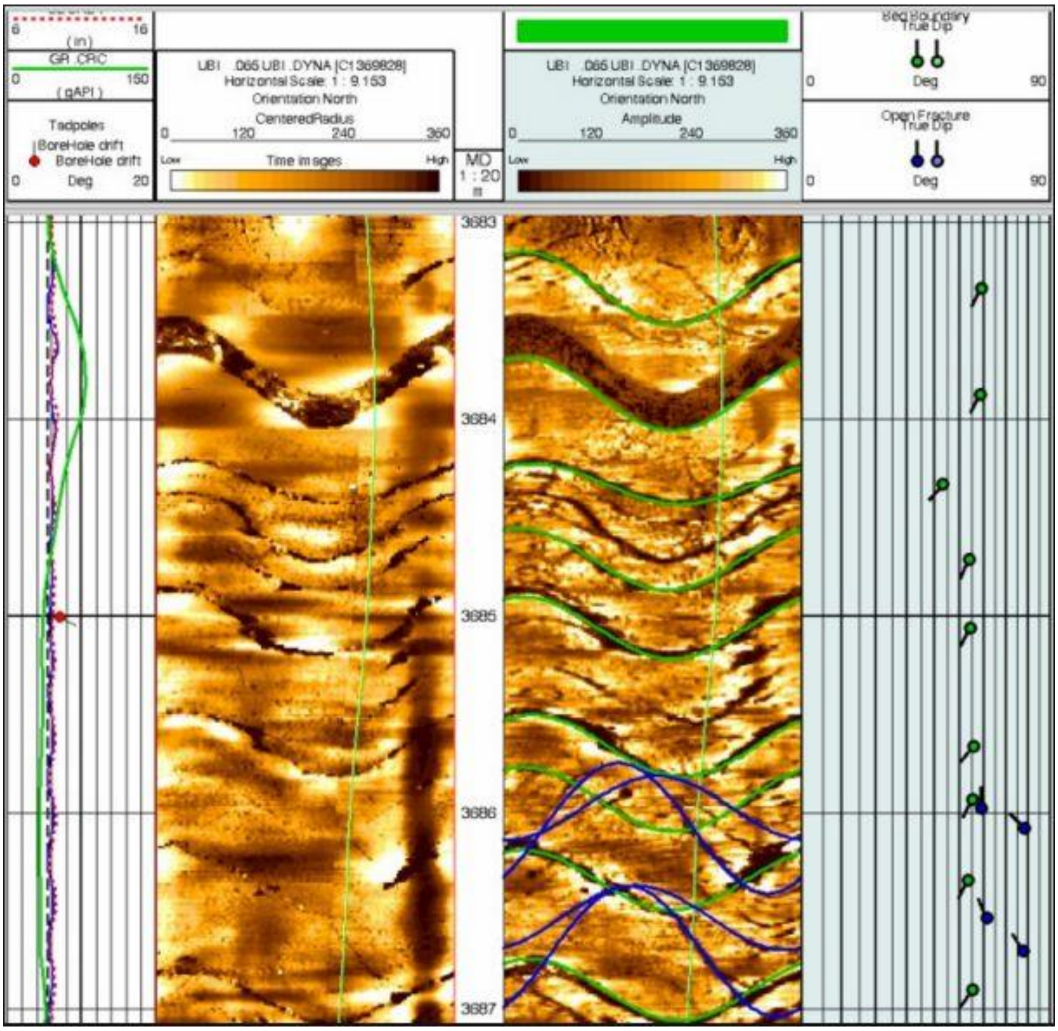


Figure 5.4.12 **Ultrasonic Borehole Image Log:** travel time image (left) indicates borehole diameter, amplitude image (right) shows acoustic impedance, dips calculated from image show both bedding (green) and fracture (blue) dips*. The dark areas on the travel time image show borehole elongation in the NW-SE direction, with maximum stress direction at right angles to this axis. On real logs, check heading carefully, as travel time and amplitude images can be interchanged in position, and North may be on the right or the middle of the track. (https://www.spec2000.net/07-acousticimagelog.htm Crain's Petrophysical Handbook, Acoustic Image Logs)

**Fractures show up as black sinusoid shapes on both images. The strike direction (azimuth) of the fracture can be picked at the trough on the sinusoid and converted to a compass orientation using the scale at the top of the log. Dip angle of the fracture can be found by comparing the peak to peak amplitude of the sine wave (in borehole depth units) to the borehole diameter (measured in the same units). DIP = arctan (Y/D) where Y = peak to peak distance and D = borehole diameter.*

Electrical imaging: Electrical resistivity imaging methods were introduced during the mid-1980s, as an outgrowth of dipmeter technology. These tools relied upon a series of electrodes mounted on a single pad that measured the formation micro conductivity or micro resistivity at the borehole wall, from which a graphic of the borehole wall was generated. A single electrode pad provided only limited coverage of the borehole. Modern tools utilize four to six independent arms, each with articulating pads containing multiple electrodes. Individual articulating sensors conform to the borehole wall to provide high-resolution measurements of formation resistivity, and can cover as much as 80 percent of an 8-inch borehole.

A typical tool emits an electrical "survey" current into the formation, while another current focuses and maintains a high-resolution measurement. The currents measured by each electrode vary according to formation conductivity, which reflects changes in fluid properties, permeability, porosity, rock composition, and grain texture. These variations are processed and converted into synthetic color or gray-scale images, which are interpreted according to the following convention:

- Light colours: reflect low micro conductivity zones i.e. low porosity, low permeability and high resistivity (detecting healed fractures, and tight streaks: thin layers in sedimentary rock with extremely low or no permeability)
- Dark colours: reflect high micro conductivity zones i.e. high porosity, high permeability and low resistivity (detecting open fractures and shales)

Borehole imagers use a fixed-contrast (static) presentation for gross correlations, and a dynamic averaging display to enhance local features. The fixed, or absolute contrast allows the viewer to correlate color values between different zones of interest within the well, or between images from different wells. The dynamic averaging display is applied to local events, to allow the viewer to distinguish features on a smaller scale (see Figure 5.4.16)

In 1986, Schlumberger developed a tool called the Formation MicroScanner (FMS) with four pads, 16 buttons each pad, covering 25%-40% of hole diameter. Later version of this tool was called Sclumberger's Fullbore Formation MicroImager (FMI) with four pads and four hinged flap and 24 buttons on each pad and flap. The hinged flap is able to increase coverage of up to 80%. The individual buttons are aligned in two rows; processes for depth corrections shift the recorded resistivity to one row. Each button consists of an electrode surrounded by an insulation.

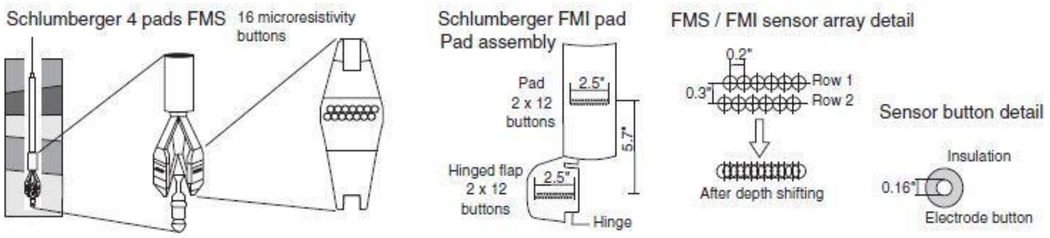


Figure 5.4.13 FMS and FMI function
(http://publications.iodp.org/sd/05/suppl/borehole_imaging_tools.pdf [Philippe Gaillot et al.] Technical Developments, Borehole Imaging Tools – Principles and Applications 2007)

Electrical borehole scanning is an extension of the dipmeter technique. In this method, a large number of closely spaced electrodes of 0.2-in. diameter are mounted on a conductive pad and pressed against the borehole wall. The amount of current emitted from each electrode is recorded as a function of azimuth and depth. The tool thus produces a micro resistivity map. The resulting image stripes are about 2.5 in. wide and are oriented azimuthally by a downhole magnetometer unit. In a 8.5-in. borehole, the four-pad Formation MicroScanner, which needs exclusively water based drilling fluid, provides a 45% circumferential coverage. Repeat logging passes can often increase this percentage. FMS images record changes in rock resistivity caused by variations in porosity and clay content of a small rock volume in the vicinity of the borehole wall. Increased pad stand-off due to mudcake buildup on the borehole wall may decrease the spatial resolution, while abrupt changes in tool movement may produce a local misalignment or sawtooth effect in the layers. Important bedding types and surfaces can be identified and measured for their dip and azimuth, as are fractures and stylolites. Faults are often readily recognized on Formation MicroScanner images because of the offset of rock types across the fault plane.
(http://wiki.aapg.org/Borehole_imaging_devices)

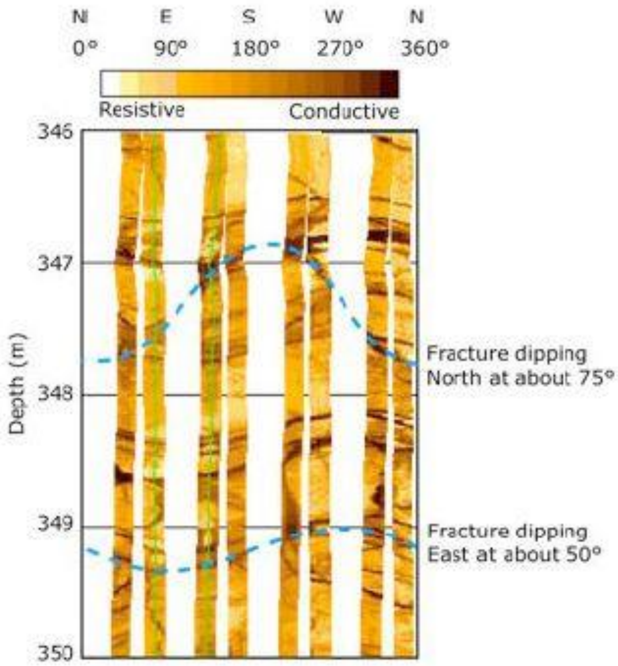


Figure 5.4.14 FMS resistivity image (https://www.ldeo.columbia.edu/res/div/mgg/lodos/Education/Logging/slides/Image_fracture.pdf [Trevor Williams, Lamont Doherty Borehole Research Group] Well Logging Principles and Applications: Borehole Image Analysis 2008)

The Fullbore Formation MicroImager (FMI) provides real-time micro resistivity formation images and dip data, in water-based mud, with 80% borehole coverage in 8-in boreholes and 0.2-in. image resolution in the vertical and azimuthal directions. It is used for determining net pay in laminated sediments of fluvial and turbidite depositional environments, visualizes sedimentary features to understand structure specially in not cored intervals and provides high quality of bedding dip data in highly deviated wells which improves the structural interpretation of seismic sections and computation of the true stratigraphic thickness.

Today the Sclumberger's High-Definition Formation MicroImager (HD-FMI) takes high definition to a new level of clarity. The visibility and interpretability of small features is significantly increased for all environmental conditions—even across extreme variations in formation resistivity or resistivity anisotropy between the formation and mud (R_t/R_m). This means that water-base mud environments that cannot be clearly imaged with conventional micro resistivity imaging technology can now be seen in great detail, including wells drilled with salt-saturated muds or high-resistivity reservoirs. Wellsite operations are streamlined as the entire range of formation resistivity is imaged in one run.
(https://www.slb.com/services/characterization/geology/wireline/fullbore_formation_microimager_hd.aspx)

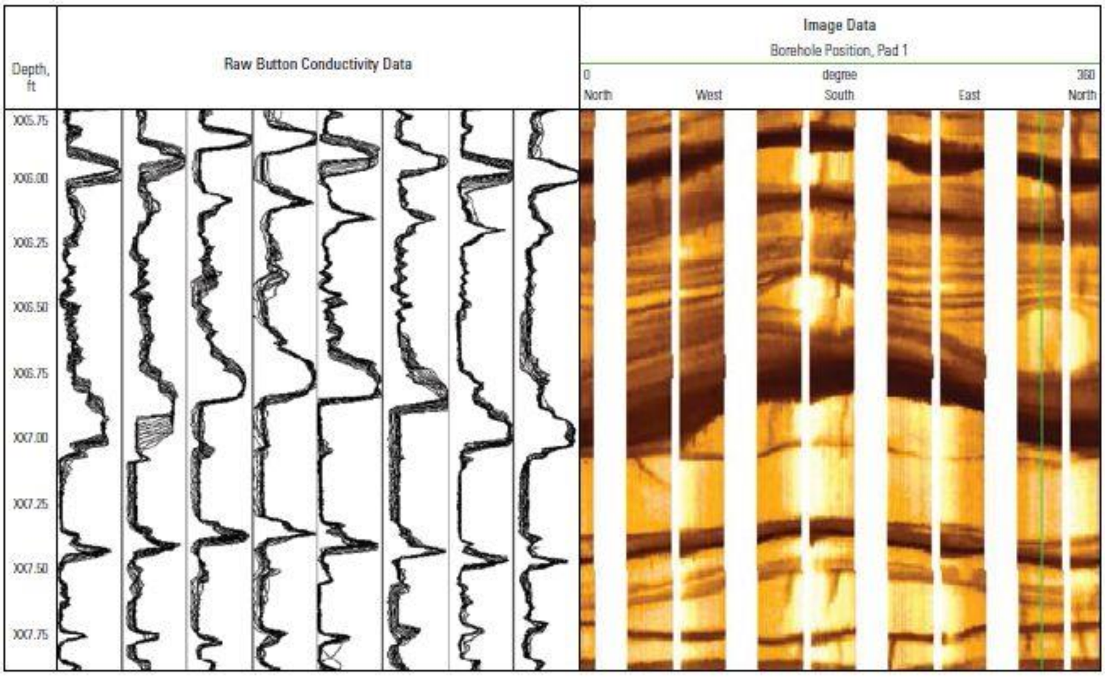


Figure 5.4.15 Data from the HD-FMI tool converted to an image log. The 192 buttons located on the tool's four pads and four flaps generate a stream of conductivity data (left). These data are processed, the values are assigned a scaled colour, and an image is produced (right). The geologist analyzing the images can modify the colour scale and range to enhance features. The cardinal location of Pad 1 can be indentified from the green curve at the far right. (https://www.slb.com/~/media/Files/resources/oilfield_review/ors15/sept15/01_imaging.pdf [Janice Brown et al.] Imaging: Getting the Picture Downhole 2015)

Schlumberger introduced a new type of oil-based mud imaging log (Oil Based MicroImager-OBMI) for use in nonconductive mud systems in 1988. It uses micro induction resistivity measurements instead of the usual electrical resistivity pads. It had 4 pads with 2 rows of 4 electrodes on each pad, operating in the 10 to 20 kiloHertz range. A second tool could be added at 45 degree offset to increase borehole coverage. Resolution vertically and horizontally was about 1 cm, much coarser than the conventional tools (FMS, FMI). It was not very effective in fractures and there were other artifacts that caused shadow events, making the image difficult to interpret in some cases.

The micro-induction technique of older oil based mud imagers and scratchers of even older dipmeters have been replaced by Schlumberger's OBMI Quanta Geo tool. It makes a capacitive measurement at two frequencies in the megaHertz range (instead of the kiloHertz range used in conventional tools) and then derives the best image from the optimal frequency. The tool has 8 pads so the coverage is good compared to other OBM tools. The electrodes are surrounded by guard electrodes that focus current through the mud and mudcake into the formation.

The capacitive measurement allows the processing to determine the amplitude of the current / voltage ratio and the phase shift between the two measurements. The ratio gives the electrical impedance of the rocks. At the frequencies used, the impedance is not directly proportional to resistivity, but the images produced have the same general appearance as conventional image logs. Vertical resolution is 6 mm and horizontal resolution is 3 mm, comparable to the FMI-HD in water based mud. Both open and healed fractures are quite evident on the Quanta Geo output as high resistivity (white) sinusoids. An acoustic image log could be used to distinguish open from healed.

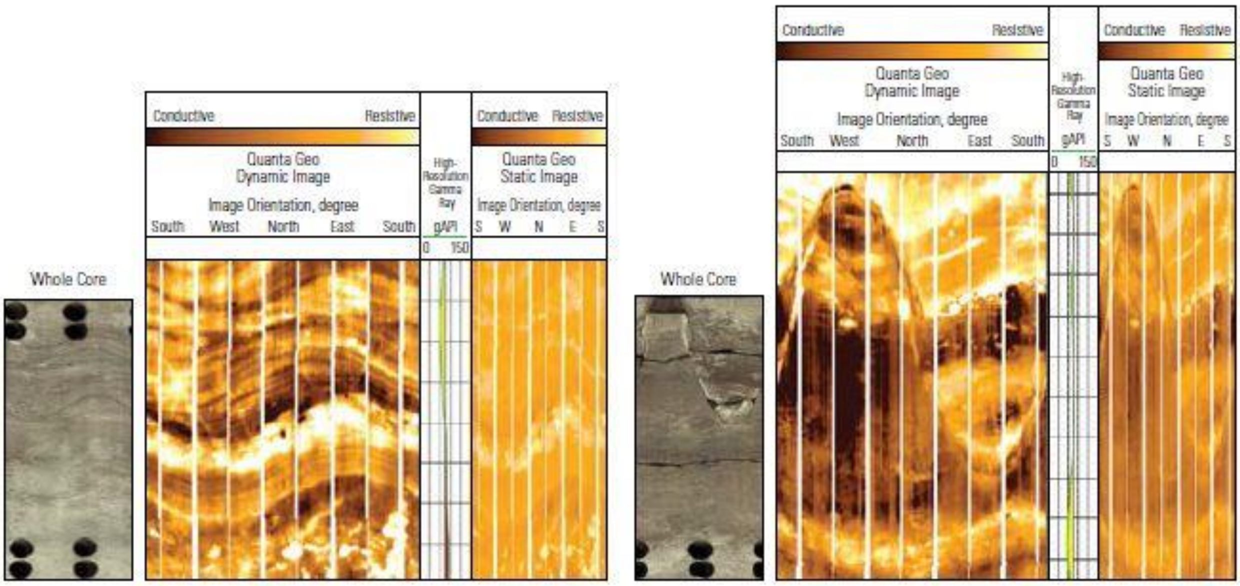


Figure 5.4.16 High quality images from OBMI Quanta Geo. Visible bedding planes in a whole core (left) can be easily seen in the dynamic image (Track 1) but not so clearly seen in the static image (Track 3). A fault crossed by the wellbore (right) is visible in both the dynamic image and the whole core taken across this section.
(https://www.slb.com/~/media/Files/resources/oilfield_review/ors15/sept15/01_imaging.pdf [Janice Brown et al.] Imaging Getting the Picture Downhole 2015)

The Schlumberger's Azimuthal Resistivity Imager (ARI) is not a pad-contact tool. It uses an array of 12 electrodes, spaced 30 degrees apart. This array of electrodes measures deep resistivity readings with a vertical resolution of eight inches. The ARI tool is less sensitive to borehole rugosity than the other electrical imaging tools and is able to provide coarse structural dip measurements. This tool is rated to 350 F (177°C), and 20000 psi (138 MPa).Using azimuthal electrodes incorporated in a dual laterolog array, the ARI imager provides deep oriented resistivity measurements in addition to standard deep and shallow resistivities. The depth of investigation of the deep oriented measurement can access the virgin formation, beyond the invaded zone, and the sensitivity of the ARI imager's measurements to azimuthal heterogeneities identifies anomalous resistivity conditions and discriminates between shallow and deep features. A very shallow auxiliary measurement provides data to fully correct the azimuthal resistivities for borehole effects.

Because the resistivity measurement is directional instead of azimuthally averaged, it is not by default primarily influenced by the beds that are parallel and close to the borehole. To address this typical logging concern in horizontal wells, the most representative reading can be selected from the deep azimuthal resistivity measurements.

Images from the ARI imager complement image logs from the UBI ultrasonic borehole imager and the FMI fullbore formation microimager because of the tool's sensitivity to features beyond the borehole wall and its lower sensitivity to shallow features. By flagging the azimuthal heterogeneities, the resistivity images from the ARI imager avoid misinterpretation that could occur with an azimuthally averaged resistivity log.
(https://www.slb.com/services/characterization/petrophysics/wireline/legacy_services/azimuthal_resistivity.aspx)

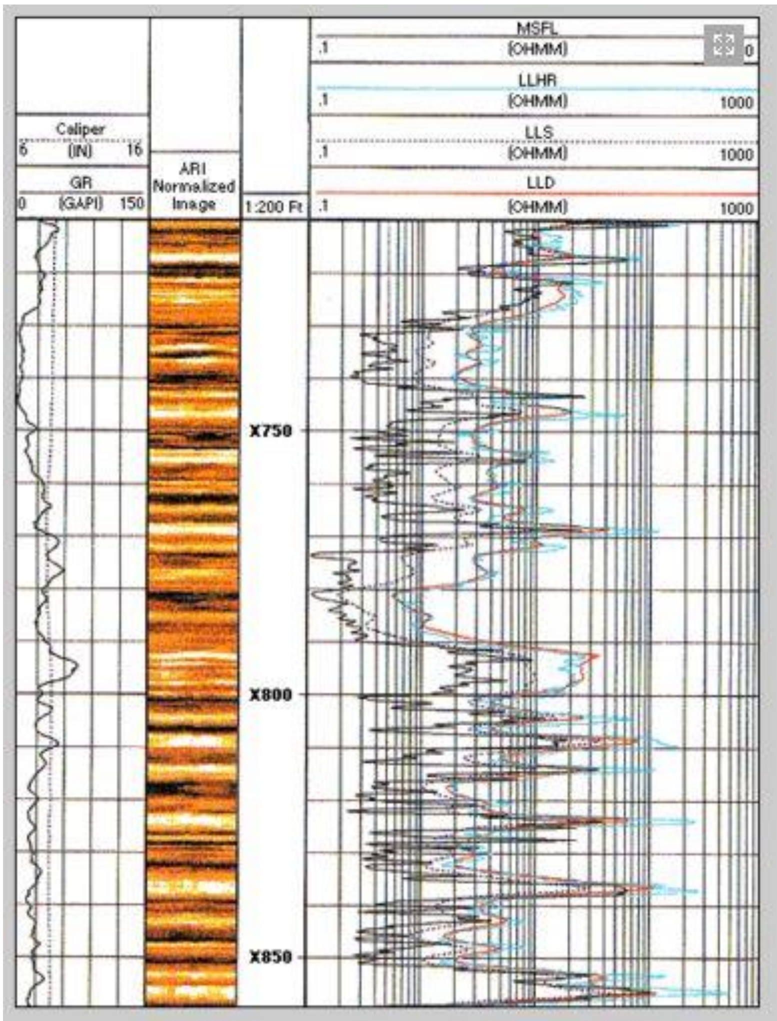


Figure 5.4.17 Example with ARI image and its curve.
In this example of deep conductive invasion, the high-resolution deep resisitivity (LLHR) curve of the ARI azimuthal resistivity imager has a depth of investigation similar to that of the deep laterolog (LLD) curve but provides greater detail through improved vertical resolution that approaches that of the MicroSFL spherically focused resistivity tool.
(https://www.slb.com/services/characterization/petrophysics/wireline/legacy_services/azimuthal_resistivity.aspx)

Back to oil-business industry standards, a major step in downhole geology includes logging while drilling, or LWD, where the formation properties are measured just after they have been drilled. Electrodes on a rotating LWD collar produce 360° images of the formation resistivity. These images can be analyzed in real time by geologists and the driller to make timely decisions about difficult drilling operations (unstable hole conditions). The common LWD resistivity image tools are the GVR and RAB. Essentially they are the same tool, though the GVR is slightly more advanced in terms of measurement resolution and recording speed. Commonly, the RAB only refers to the larger 8-1/4 inch collar. These tools are analogous to the wireline FMS and FMI tools. The Resistivity at Bit (Schlumberger RAB) tool is a LWD tool that can provide azimuthal oriented images of the borehole. Connected directly to the drilling bit, this tool uses its lower portion and the bit as a measuring electrode. Button electrodes provide shallow, medium, and deep resistivity measurements as well as azimuthally oriented images acquired as the RAB rotates, with a ~6° resolution. RAB tool may either be placed in the open hole section during the leak off test or logged over the open hole section before and after the leak off test to determine the extent of invasion and detect fractures, as the movement of drilling fluid into the formation during pressure buildup and leakoff results in a measurable change in resistivity.

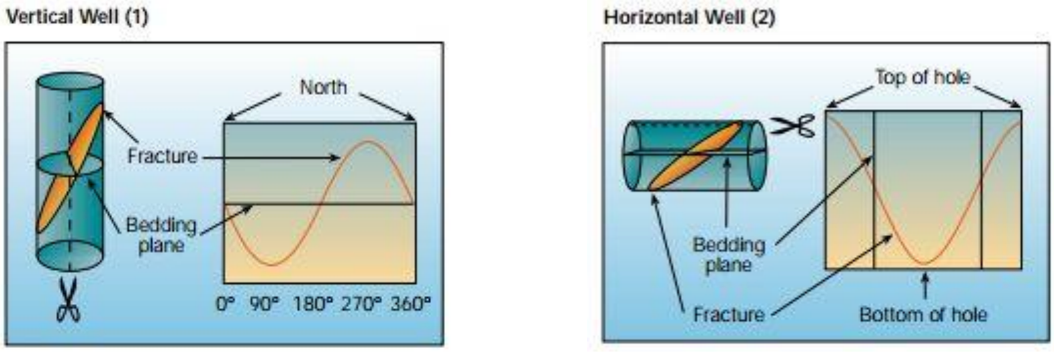


Figure 5.4.18 Vertical and Horizontal wells interpretation of images: resistivity images show the surface of the borehole-cut along the northerly direction for a vertical well (1) or the top of the hole for a horizontal well (2)-laid out flat. (https://www.slb.com/~/media/Files/resources/oilfield_review/ors96/spr96/ors96_rwd_p4_19.pdf [Steve Bonner et al.] Resistivity While Drilling – Images from the String 1996)

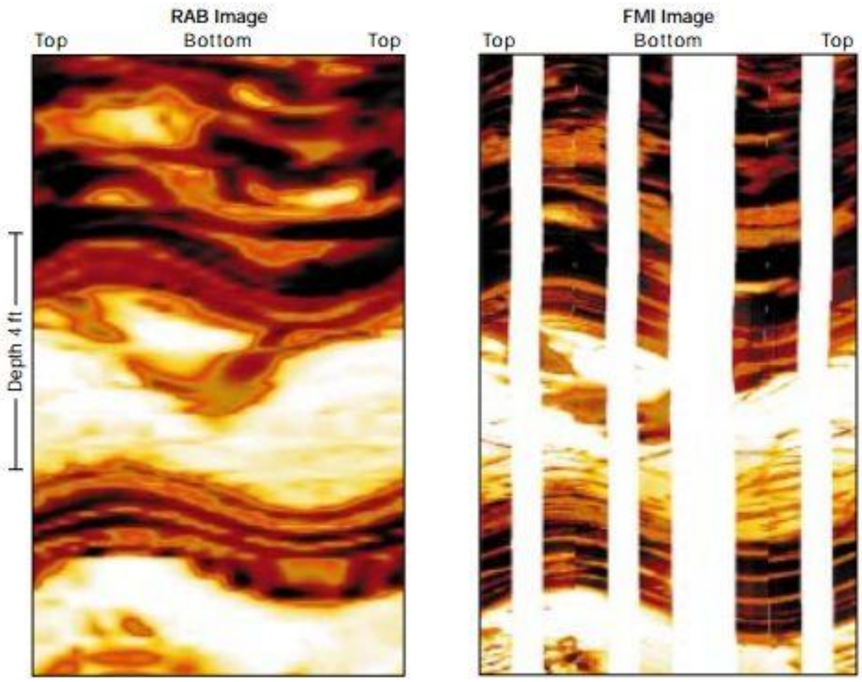


Figure 5.4.19 Fractures imaged by RAB and FMI tools in a horizontal well. Fractures with large apertures or close spacing that appear on the FMI image (right) are seen on the RAB image (left). (https://www.slb.com/~/media/Files/resources/oilfield_review/ors96/spr96/ors96_rwd_p4_19.pdf [Steve Bonner et al.] Resistivity While Drilling – Images from the String 1996)

A resistivity image log has about 10 times the spatial resolution of an acoustic image log and 500 times the amplitude resolution, due to the difference in contrast between the resistivity and acoustic impedance ranges measured by the respective tools. Because of the large dynamic range and high resolution micro resistivity images are very detailed. However, the coverage tends to degrade when borehole size increases. Acoustic image provides 360-degree borehole coverage, but acoustic reflectivity limits the dynamic range so images are less detailed than micro resistivity images.

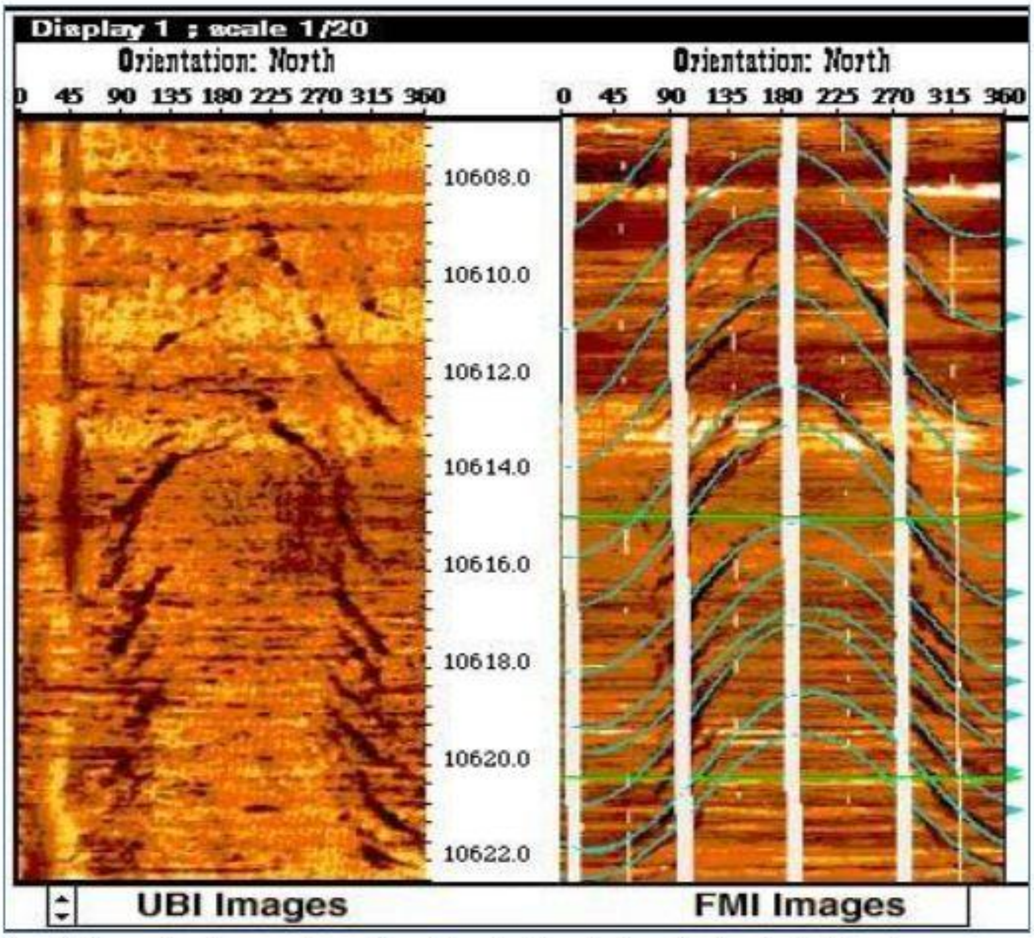


Figure 5.4.20 Comparison between ultrasonic and electrical image logs, showing the significantly greater detail with electrical imaging. ([Atefeh Shahinpour] Borehole image log analysis for sedimentary environment and clay volume interpretation 2013, Norwegian University of Science and Technology)

Both acoustic and electrical imaging: To some extent, the ultrasonic and electrical images are complementary because the ultrasonic measurements are influenced more by rock properties, whereas the electrical measurements respond primarily to fluid properties. All the differences between them (including coverage and drilling mud environment) can be accommodated through the combined use of electrical and acoustic imaging.

There are methods that draw on both acoustic and electrical imaging techniques using the same logging tool such as STAR tool. The Baker Atlas' Simultaneous Acoustic and Resistivity Imager tool (STAR) simultaneously acquires high-resolution images of borehole features (in conductive water based mud systems) that have resistivity contrast or acoustic impedance. It uses a combination of a CBIL and a six-pad resistivity imager with 24 electrodes per pad, giving a total of 144 micro resistivity measurements with a vertical and azimuthal resolution of 0.2 in. (~5 mm). The tool delivers a more complete data set than is achievable using either of the components separately. The combination of acoustic and resistivity measurements partially compensates for any shortcomings inherent in either of the individual measurements. This six-arm tool uses a powered standoff to improve pad contact with the borehole, providing resistivity coverage of 60 percent in an 8-inch hole, and 100 percent acoustic coverage. The combined tool is 86 ft (26.2 m) in length with a diameter of 5.70 in. (145 mm). It is rated to 20000 psi (138 MPa) and 350°F (177°C).

6. COMBINATIONS OF LOGS

Modern logging techniques combine logging tools to obtain a more reliable representation of formation properties. An analysis of a combination of well logs (suite of well logs) makes it more likely that the characterization of the reservoir is correct. Here are some examples of combinations of well logs (well log suites).

The neutron density logging tool combines a neutron logging tool and a density logging tool. Both tools provide information about formation porosity but respond differently to the presence of hydrocarbon gas. The presence of hydrocarbon gas in the pore space increases the density log porosity and decreases neutron log porosity. The gamma ray logging tool can be included in a suite of logging tools because it measures natural radioactivity. The gamma ray logging tool can indicate shale content, identify lithology and correlate stratigraphic zones. One more log, an electrical log measuring resistivity, is usually added to the suite of logs, because an extensive zone filled with hydrocarbon is apparent on an electrical log typically as more resistive than an adjacent water filled zone.

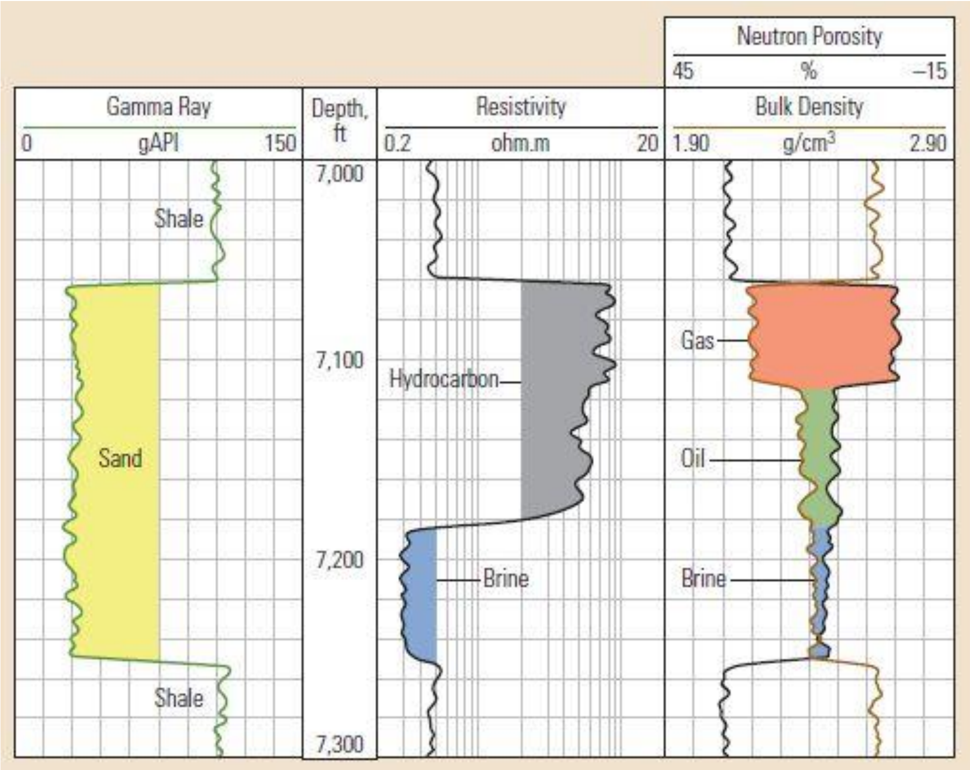


Figure 6.1 Combination of GR, resistivity, density and neutron logs
A common combination of logging measurements includes gamma ray, resistivity, density and neutron porosity combined on one tool string. The gamma ray response (Track 1) distinguishes the low gamma ray value of sand from the high value of shale. The next column, called the depth track indicates the location of the sonde in feet (or meters) below a surface marker. Within the sand formation, the resistivity (Track 2) is high where hydrocarbons are present and low where brines are present. Both neutron porosity and bulk density (Track 3) provide measures of porosity, when properly scaled. Within a hydrocarbon zone, wide separation of the two curves in the way shown here indicates the presence of gas. ([Mark Andersen] Discovering the Secrets of the Earth, Oilfield Review 2011, From Schlumberger Defining Logging)

The next figure 6.2 shows a combination of synthetic well logs for three wells in Valley Fill reservoir: Wells 7, 3 and 9. Well 7 and 9 are dry holes and Well 3 is an oil producer. Well 3 is in the center of a line that extends from Well 7 to Well 9. Figure 6.2 shows the spontaneous potential (SP) log, seismic reflection coefficients (RC) and the resistivity (Res) log. The SP log and resistivity log are in arbitrary units. Depth is measured in feet. Regional dip from Well 7 to Well 9 can be estimated by correlating the SP log and seismic RC at the top of the productive interval (at a depth of ~8450ft). The SP trace indicates for the Well 3 a permeable formation from 8450 to 8570. The resistivity log shows that the upper part of the productive interval in Well 3 has a higher resistivity than the other wells because the Well 3 is an oil producer, while Well 7 and 9 are not. Furthermore, the depth at which a change in resistivity takes place in Well 3 from a higher to a lower value (decrease of resistivity from 8540 ft to 8550 ft) within the productive interval, denoted by the SP log, is an indication of the depth interval of the oil-water contact. The decrease in resistivity in the lower part of the productive interval in Well 3 suggests that there is an increase in conductivity, which can be interpreted as an increase in water saturation. This indicates the presence of an oil-water contact (OWC). This combination of wells logs supports the Valley Fill interpretation.

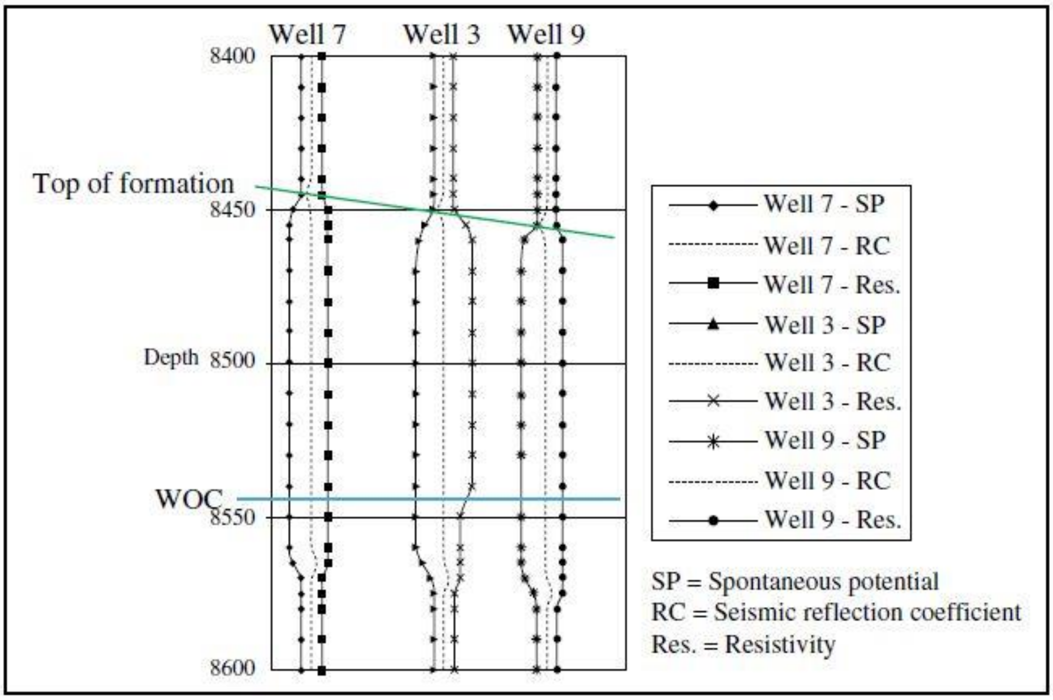


Figure 6.2 Combination of well logs for Valley Fill reservoir ([John R. Fanchi, Richard L. Christiansen] Introduction to Petroleum Engineering-John Wiley & Sons, Inc. 2017)

Another example of a well log suite is illustrated in the following figure.

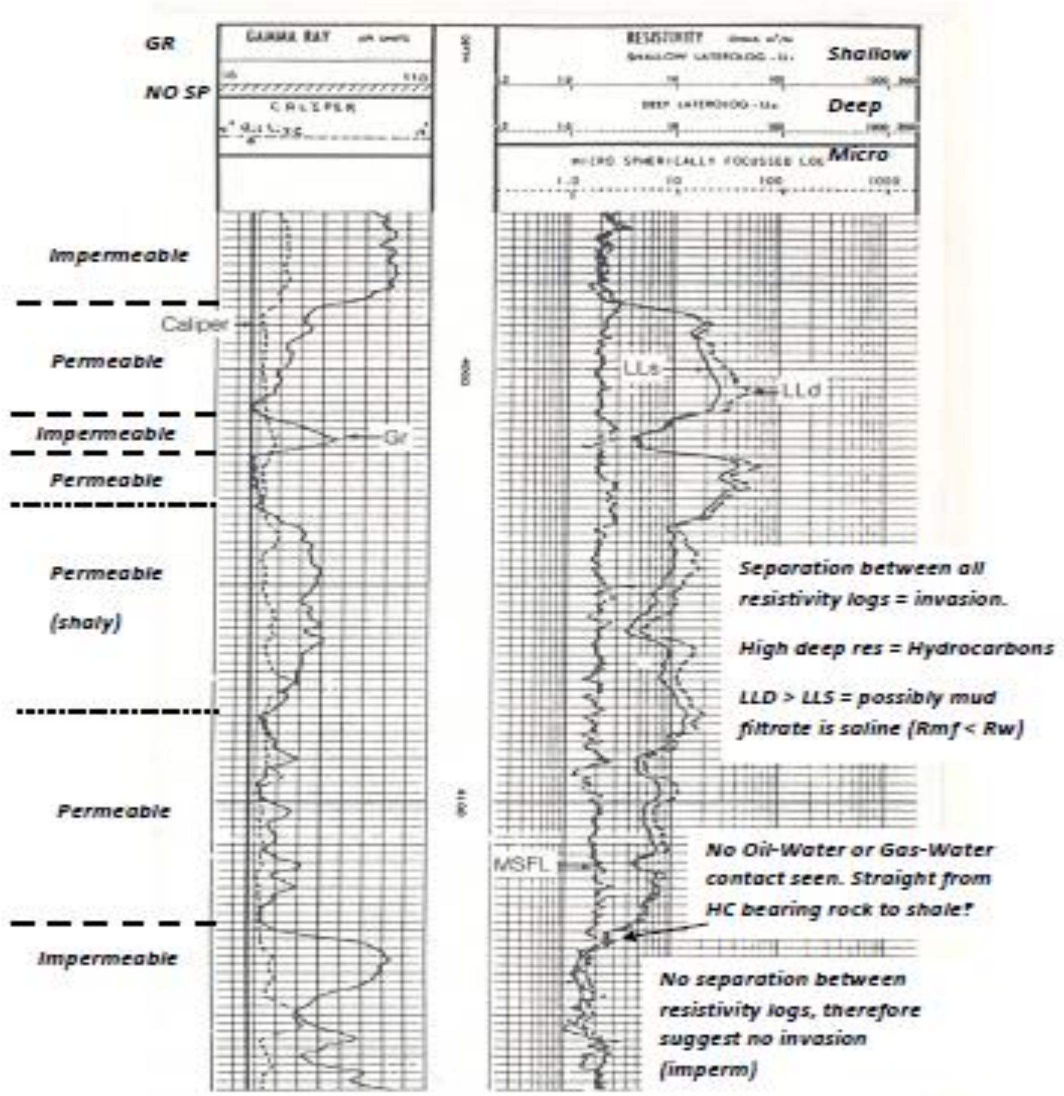


Figure 6.3 A well log suite of gamma ray, caliper, shallow laterolog, deep laterolog and micro spherically focused log, along with an indicative interpretation. ([A.Georgakopoulos,V.Kosmidou] MSc Hydrocarbon Exploration and Exploitation, Aristotle University of Thessaloniki, Course Notes, 2017)

The combination of the density log with neutron log and photoelectric log is very powerful in lithological assessment. In our example gamma ray and caliper logs are also combined. The gamma ray log is very important because it is run to aid depth matching with the other logs. Figure 6.4 show the typical layout of density (photoelectric tool is part of the modern density tool), neutron, caliper and GR tool combination.

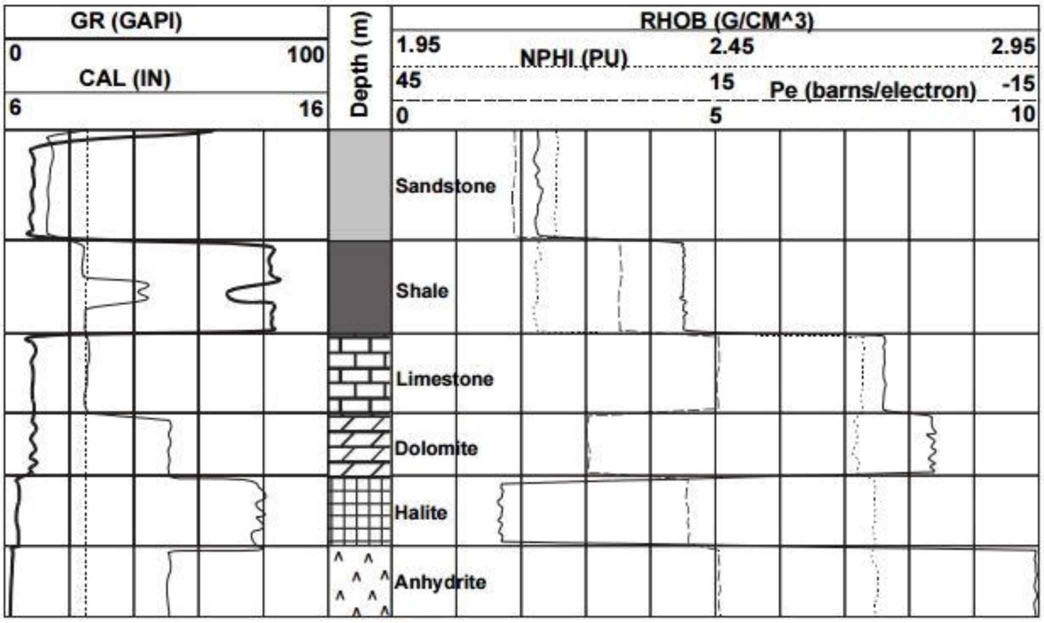


Figure 6.4 Layout of a typical density RHOB (including photoelectric PE tool), neutron NPHI, caliper CAL and gamma ray GR tool run. (http://homepages.see.leeds.ac.uk/~earpwjg/PG_EN/CD%20Contents/GGL-66565%20Petrophysics%20English/Chapter%2014.PDF [Dr Paul Glover] Petrophysics MSc Course Notes)

The Figure 6.5 below shows a combination of logs used as tool and technique for characterizing oil and gas reservoirs.

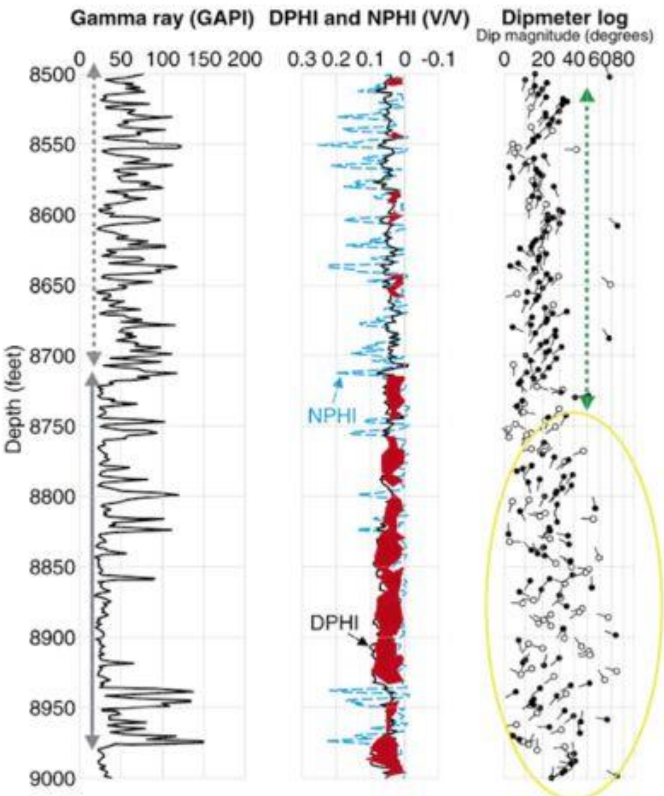


Figure 6.5 Combination of GR, DPHI, NPHI and Dipmeter logs (https://books.google.gr/books?id=uwlIqGxpfLEC&pg=PA75&lpg=PA75&dq=the+practise+of+reservoir+engineering+revised+edition+dipmeter+logs&source=bl&ots=DFhZeKj7GZ&sig=Ke-qZc4jSGzX-9HH0itfxqyc4Hk&hl=el&sa=X&ved=2ahUKEwi-nZDm74LdAhXLAewKHZENASQQ6AEwAXoECAkQAQ#v=onepage&q=the%20practise%20of%20reservoir%20engineering%20revised%20edition%20dipmeter%20logs&f=false [L.P. Dake] The Practice of Reservoir Engineering (Revised Edition))

Gamma ray (GR) log on the left track, density-porosity (DPHI) and neutron-porosity (NPHI) logs in the middle track, and dipmeter log on the right track. The red/dark gray areas in the middle track the gas-bearing interval in the formation (density-neutron porosity crossover). The dipmeter log shows two patterns. The upper half of the well has a relatively consistent dip pattern, suggestive of a deepwater sheet-sandstone interval. The lower (circled) interval exhibits more diversity in its dip pattern, suggestive of a deepwater channel-sandstone interval. After Romero (2004).(https://books.google.gr/books?id=uwlIqGxpfLEC&pg=PA75&lpg=PA75&dq=the+practise+of+reservoir+engineering+revised+edition+dipmeter+logs&source=bl&ots=DFhZeKj7GZ&sig=Ke-qZc4jSGzX-9HH0itfxqyc4Hk&hl=el&sa=X&ved=2ahUKEwi-nZDm74LdAhXLAewKHZENASQQ6AEwAXoECAkQAQ#v=onepage&q=the%20practise%20of%20reservoir%20engineering%20revised%20edition%20dipmeter%20logs&f=false
[L.P. Dake] The Practice of Reservoir Engineering (Revised Edition))

Finally, log suites from two case studies are represented and interpreted. The first suite is from the case study of ''Laja'' Oil Field located in Niger Delta. The other is from member 5 (Ma 5) of the Majiagou Formation in the Ordos Basin of West China.

According to J.O Amigun, B. Olisa and O.O. Fadeyi, in their full length research paper ''Petrophysical analysis of well logs for reservoir evaluation: A case study of “Laja“ Oil Field, Niger Delta'', the objectives of using the gamma ray, resistivity, neutron and density logs include the determination of lithologic units and the differentiation between hydrocarbon bearing and non-hydrocarbon bearing zones identifying reservoirs.

“Laja“ Oil Field is an onshore field located within latitude 5.3° and 5.4°N and longitude 6.0° and 6.2°E in the Niger Delta as shown below (Figure 6.6). Six wells have been drilled in the field. We focus on logs from three wells: Well Laja 1, Well Laja 2, Well Laja 3.

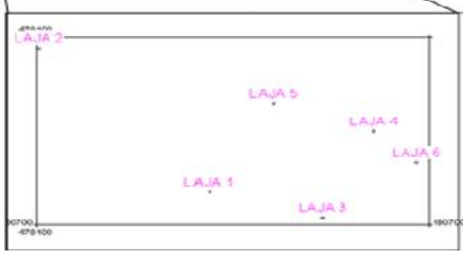


Figure 6.6 The Map of Niger delta showing location of Laja field and insert is the Base map indicating Well Locations. ([J.O Amigun, B. Olisa and O.O. Fadeyi] Petrophysical analysis of well logs for reservoir evaluation: A case study of ‘Laja’ Oil Field, Niger Delta 2012)

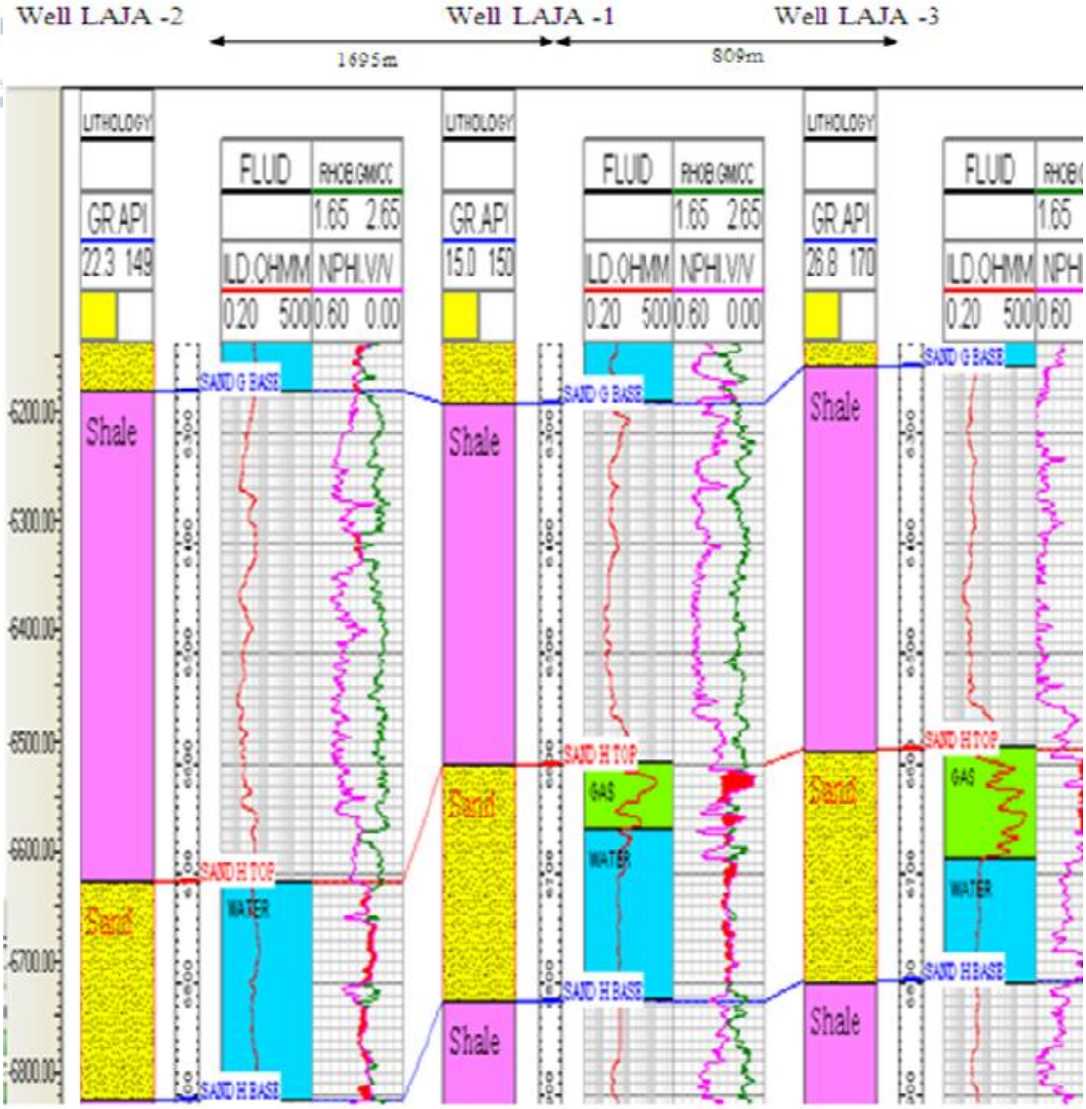


Figure 6.7 Lithologic Correlation Panel of Hydrocarbon Bearing Reservoir of "Laja" field, Niger Delta. ([J.O Amigun, B. Olisa and O.O. Fadeyi] Petrophysical analysis of well logs for reservoir evaluation: A case study of 'Laja' Oil Field, Niger Delta 2012)

The above Figure 6.7 shows a composition of alternating sand and shale layers delineated in each of the three wells of "Laya" Field. The main goal is to identify the zones of interest i.e. clean sand with hydrocarbon. Gamma ray (GR) log (track 1 in Figure 6.7) has already been used to identify sand/shale lithology. The deep laterolog (LLD) (track 2) is used to differentiate between hydrocarbon and water bearing zones (the water zones correspond to very low resistivities, whereas the hydrocarbon zones to high resistivities). The formation density (RHOB) and neutron (NPHI) logs are used for the differentiation of the various fluid types. Especially, the gas zones are interpreted from crossover of these two porosity logs.

Lithologic correlation of equivalent strata across the three wells was done using the gamma ray log. Equally, identified potential hydrocarbon reservoirs in the wells were correlated using the gamma ray and resistivity logs to know their lateral and vertical extent. Their results are presented as correlation panels in Figure 6.7.

In Well 2 there is a sand zone from the depth of 6130m (as seen in the record) to 6180m (sand G base). The next zone is a shale zone ranging from 6180m to 6630m. From this point another sand zone (with the depth of 6630m as sand H top) follows up to the end of the record at the depth of about 6825m (sand H base).

In Well 1 the sand G zone is also seen from the depth of 6130m but it extends up to the depth of 6200m. The next zone is a shale zone ranging from 6200m to 6520m. The sand H zone in this well ranges from 6520m (sand H top) to 6740m (sand H base). From this point another shale zone occurs up to the end of the record.

In Well 3 the sand G zone is as before seen from the depth of 6130m but it extends up to the depth of 6160m. The next zone is a shale zone ranging from 6160m to 6510m. The sand H zone in this well ranges from 6510m (sand H top) to 6720m (sand H base). From this point another shale zone occurs up to the end of the record.

Sand zone H in Figure 6.7 is a possible reservoir for all the wells. It is hydrocarbon bearing in Well 1 and Well 3 with hydrocarbon type detected from density-neutron crossover as gas. It is obvious that water is found below the gas as expected from the abrupt reduction of resistivity. The GWC (gas water contact) is found at the point of the beginning of this reduction (at 6580m for Well 1 and at 6610m for Well 3). On the other hand, in Well 2 the reservoir sand zone H is wet i.e. containing only water as indicated from the constant low values of resistivity.

Shale zone between sand zones G and H in Well 1 and Well 3 acts as a possible source rock for these reservoir sands.

The other log suite is from member 5 (Ma 5) of the Majiagou Formation, which is an important gas-bearing stratigraphic unit in the Ordos Basin of West China.

According to Jin Lai, Xiaojiao Pang, Qiyao Xiao, Yujiang Shi, Haitao Zhang, Taiping Zhao, Jing Chen, Guiwen Wang, Ziqiang Qin in their article ''Prediction of reservoir quality in carbonates via porosity spectrum from image logs'' an aim is to recognize and describe the lithology of the Ma 5 carbonate reservoirs in Ordos basin, and investigate the well log (conventional and image) responses of the typical reservoir types.

A combination of conventional and image logs illustrated in the following Figure 6.8 can be used to recognize fractures zones.

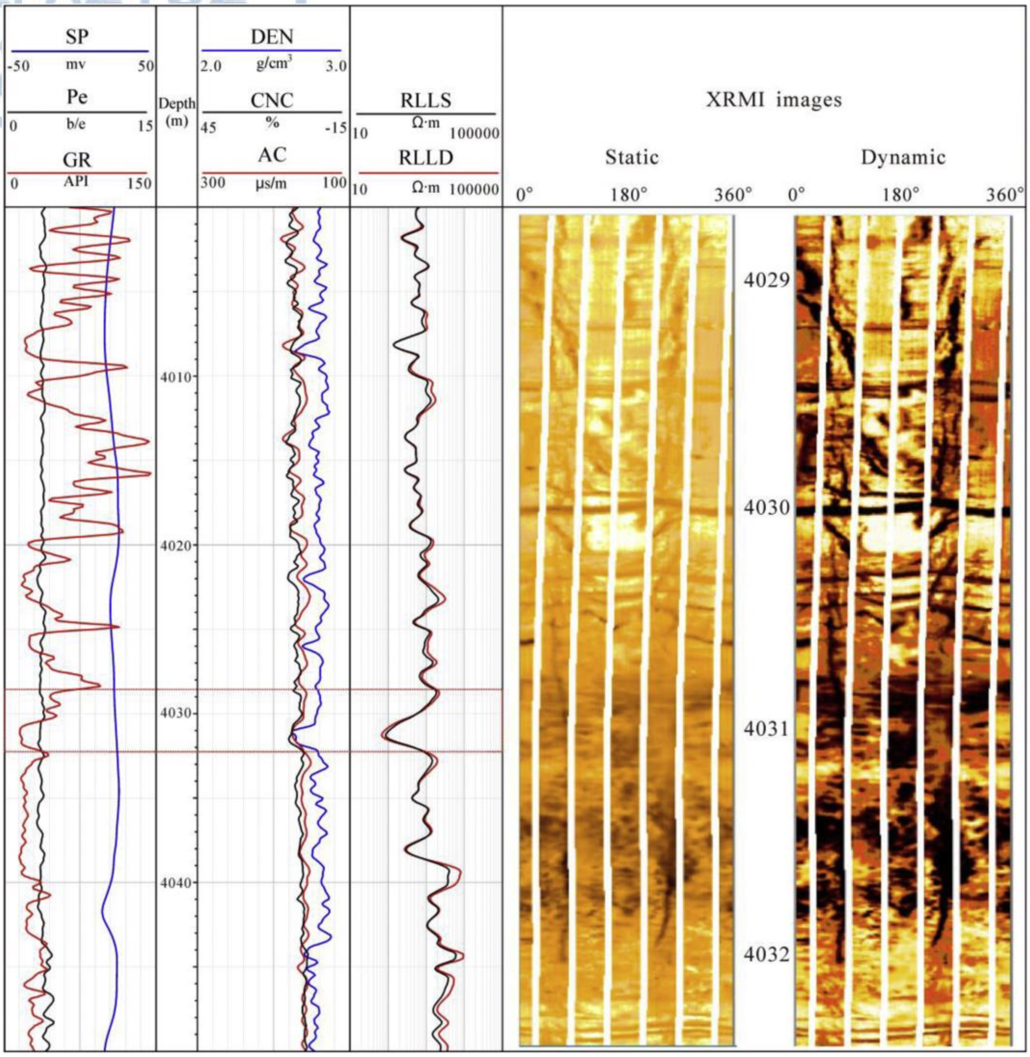


Figure 6.8 Combination of conventional and image logs from the Ma5 Member in the Ordos Basin ([Jin Lai et al.] Prediction of reservoir quality in carbonates via porosity spectrum from image logs 2018)

The values of photoelectric log (Pe) in the whole record are constant at about 3.5 barns per electrode, which means that there is a whole carbonate zone of dolomites shown in this figure. Open fractured zones are recognized as dark continuous or discontinuous sinusoidal waves on the image log of Halliburton's XRMI (Extended Range Micro Imager), especially on the dynamic image which is more detailed. Furthermore, it should be noted that there are also vertical induced fractures observed on this image log. In our case we observe that where there are natural fractures, the corresponding resistivity is low (for example at the depth of 4031,5 m). According to Nie et al. 2013 that occurs because the fractures are filled with low resistivity drilling mud. Apart from the dark sinusoidal waves on the image log and the reduction of resistivity log readings, the reduction in the bulk density (DEN) as well as the increase of sonic transit time (AC) also implies the development of natural fractures e.g. at the depths of 4008m and 4031,5 m. It is important to mention that at the depth of 4008m the reduction of resistivity along with the reduction of bulk density and increase of sonic transit time indicate an open fracture, even without image log to compare with at this depth. According to Khoshbakht et al. 2019 and Lai et al. 2017b zones with natural fractures often have high permeability and gas productivity.

7. LOGGING WHILE DRILLING (LWD)

Logging While Drilling or LWD is the general term used to describe the systems and techniques for gathering downhole data while drilling a well. These techniques provide almost the same well information as conventional wireline logging. The difference is that sensors are incorporated into the drill string and not taken down into the wellbore by means of wireline cable. The first commercial LWD services appeared in the late 1970's and early 1980's.

LWD is an advanced logging operation allowing acquisition of log data via tools placed in the actual drilling assembly (they are integrated into the rotating bottom hole assembly). Some basic data are transmitted to the surface in real time (”real-time data”) via pressure pulses through the well's mud fluid column (known as mud pulses of mud telemetry). The other data are recorded in the tool memory (”memory data”) and then retrieved on the surface when the tools are pulled out of hole.

Logs that can be run during drilling include resistivity, gamma ray, density, photoelectric, neutron, caliper, sonic, borehole image and NMR logs. The ''real-time data'' lets geologists and drilling engineers to immediately get information like resistivity, porosity, weight on bit and direction of the hole. This information can be used from them in order to decide without delay about the well's future and the drilling's direction.

A LWD type, Measurement While Drilling (MWD) particularly refers to data used to assist in the drill's steering. These data can be for example direction, orientation and drill bit information. Measurement while drilling (MWD) refers to real-time measurements of drilling progress with sensors in the bottom hole assembly (BHA). MWD allows better control of the drilling operation for reaching targets efficiently. Originally, MWD sensors measured drilling direction only, but currently they can also measure weight on the drill bit, torque on the drill bit in lb-ft, rotation speed of the drill string in RPM, and other drilling-related parameters along with inclination (deviation of the wellbore from vertical, in degrees) and azimuth (orientation of the wellbore to north, in degrees). Natural gamma-ray logging sensors are included in some MWD assemblies. All of this information is communicated to the surface with pressure pulses in the drilling mud. Opening and closing a valve in the BHA generates the pulses. Rates of 1–3 bits per second are common. A battery pack or a small turbine driven by drilling mud provides electrical power for the MWD equipment.

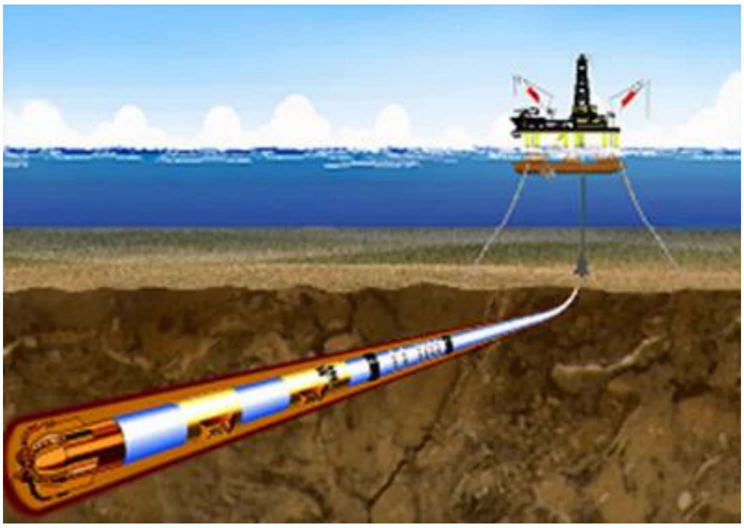


Figure 7.1 Illustration of an offshore horizontal oil well from a drilling platform. Mud motor and MWD equipment is used to drill the horizontal hole. Source: Accu Tech The MWD Company (https://www.rigzone.com/training/insight.asp?insight_id=296&c_id= How does Measurement-While-Drilling (MWD) work)

By the time that directional drilling was applied, well logging had to be improved so as to log a well which was not anymore vertical. Once a wellbore deviates beyond 60^{o} traditional wireline instruments can no longer be pushed through the drill string, so MWD technologies are used despite their increased cost. It is obvious that Logging While Drilling (LWD) tools are particularly valuable in deviated, offshore, or horizontally drilled wells. They are especially useful in long, directionally drilled wells for providing real-time information on borehole environment during the drilling operation.

Nowadays well logs use computer-generated logs to straightly interpret data obtained while drilling. Besides saving measurements, these sophisticated logs can also inform drillers of possible hazards and transfer information via satellite to computers away from the field. As a result, engineers and drillers can use LWD information immediately for definition of well placement and prediction of drilling hazards. The term '' intelligent drilling'' refers to the utilization of real time logging info provided by LWD to enable more successful offshore and onshore wells.

LWD's use is justified when: -real time information is required for operational reason e.g. steering a well (see figure 7.2), -acquiring data prior to the hole washing out or invasion occurring, -safeguarding information if there is a risk of losing the hole, and -following a trajectory where wireline acquisition is difficult (also see figure 7.2).

Figure 7.2 Ideal configuration for effective geosteering in complex reservoirs ([Papakonstantinou K.] Formation Evaluation & Well Logging ΔΠΜΣ 2016)

Logging while drilling is basically the operations of acquiring data in real time while drilling. On the other hand, the wireline service is the operation of acquiring data, but after finishing drilling an interval, a section, or a well. Both of them can provide advantages and disadvantages:

Wireline Logging	
Advantages	***Disadvantages***
Smaller, lighter and delicate tools	The whole operation takes time
Accurate depth	Measurements are taken after long time of finished drilling
High data speeds due to wire usage	Specific coverage (as the tools do not rotate)
Good borehole contact	Problem at high deviation
Communication and powered using cable	Susceptible to hole condition
Cased hole logging	

Logging While Drilling (LWD)	
Advantages	***Disadvantages***
Acquiring data after less time after drilled passed which means less affected by mud invasion	Big, heavy, tough and more expensive tools
Critical for geological decisions while drilling	Data variety depends on speed telemetry
More capable in tough environment (deviated wells, horizontal wells, unstable borehole)	Limited control (programmed before run in hole, unlike wireline where you can make two ways communications with the tools)
Guides well placement so that the wellbore remains within the zone of interest or in the most productive reservoir	Powered using batteries and/or mud turbine
	Vibrations, stick and slip phenomenon (stick-slip motion is the most common form of torsional vibrations of drill string while drilling)

(https://www.linkedin.com/pulse/logging-while-drilling-vs-wireline-ahmed-al-ali [Ahmed Al Ali] Logging While Drilling VS Wireline Logging)

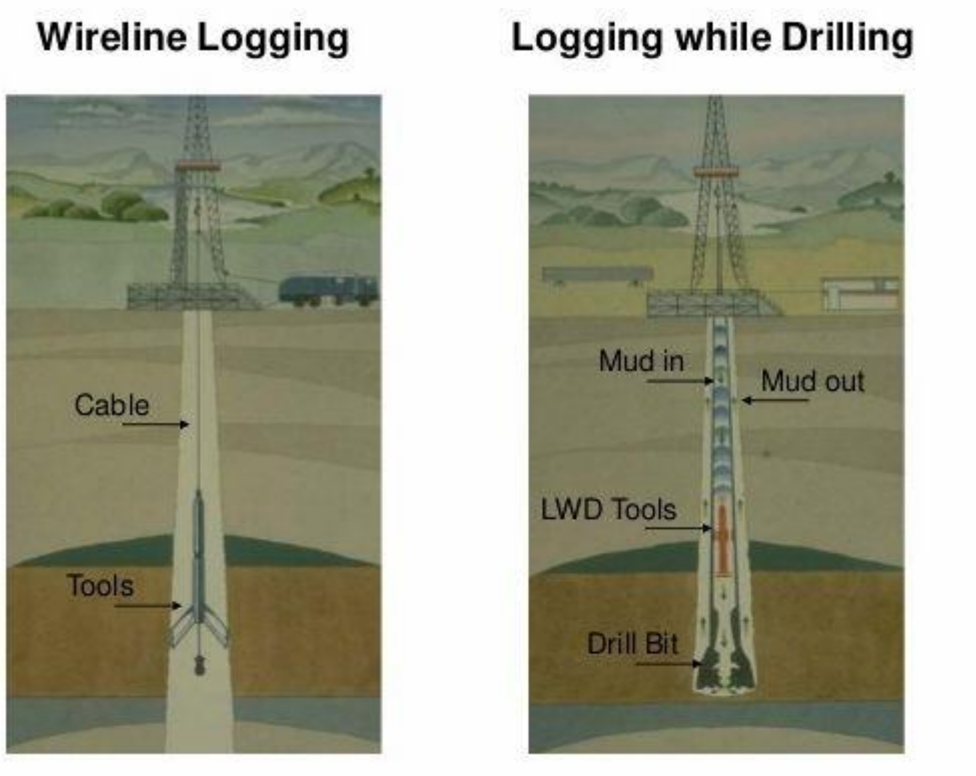


Figure 7.3 Wireline Logging versus Logging While Drilling (https://www.slideshare.net/VahidEhmedov/basic-well-logging-design [Sigit Sutiyono] Basic Well Logging Design)

8. EQUIPMENT

Oil and gas reservoirs lie deep beneath the Earth's surface. Geologists and engineers cannot examine the rock formations in situ, so tools called usually sondes go there for them. It is important to mention that sonde is the section of a logging tool that contains the measurement sensors, as distinct from the cartridge, which contains the electronics and power supplies. Specialists lower these tools into a wellbore and obtain measurements of subsurface properties. The data are displayed as a series of measurements covering a depth range in a display called a well log. Often, several tools are run simultaneously as a logging string, and the combination of the results is more informative than its individual measurement.

The main components of a wireline logging system from the borehole to the surface are: • logging tool which generally contains a sensor that is able to measure the value of some physical quantity • armoured cable by which the measuring devices are lowered and retrieved from the borehole • data acquisition system which is generally mounted on a logging truck and collects the measured data transmitted along the shielded insulated wires in the interior of the cable.

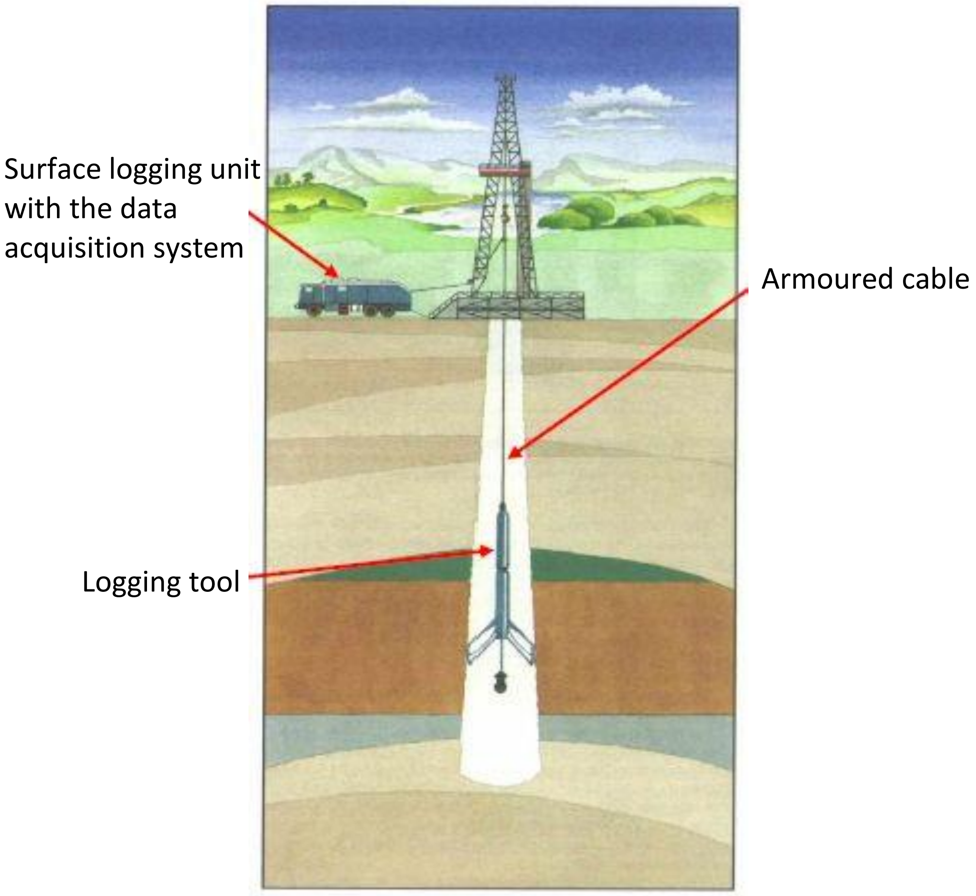


Figure 8.1 Wireline logging system (https://docplayer.net/85015426-Well-logging-equipment-and-operation-edited-by-g-petho-p-vass-for-petroleum-engineer-geoengineer-msc-students.html
[G.Pethő and P.Vass] Well logging equipment and operation)

A ***logging tool*** is actually a measurement device applied in borehole environments. Several types of logging tools are used in the practice of wireline logging in order to obtain various information about the subsurface rock formations and the interior of wells. Some of them are passive measurement devices (SP, GR and caliper tools), which means that they can only measure the effects of natural physical or physicochemical processes (e.g. spontaneous phenomena, in situ radioactivity from naturally occurring radioactive materials) taking place under the surface. Other of them are active measurement devices (laterolog, induction, density, neutron and sonic tools), because they exert some influence on the borehole environment by generating some kind of physical phenomena (e.g. electric current, electromagnetic field, gamma radiation, neutron radiation, elastic waves) and measure the response of the subsurface medium to the induced effect.

A typical part of a logging tool is a sensor which is able to detect some physical effect and convert it into electric voltage signal. The relation between the value of electric voltage and the magnitude of the detected quantity is determined by the calibration of the logging tool and it is the characteristic function of the sensor. Different terms are used for the sensor depending on the measurement method. Beside the sensors the active measurement devices contain one or more exiting units by which some physical influence can be exerted on the environment of the logging tool in a controlled way. The type of influence depends on the applied measurement method.

Method	Designation of the sensor	Influence	Designation of the exiting unit
electric	measure electrode	electric current	current electrode
electromagnetic	receiver coil	electromagnetic field	transmitter coil
nuclear	detector	gamma radiation neutron radiation	gamma ray source neutron source
sonic or acoustic	receiver	elastic waves	transmitter

All the internal parts of a logging tool (sensor, exiting units, electric circuits and other electro-mechanical parts) are encapsulated in an antimagnetic stainless steel case called ***housing***. It is generally cylindriform with an outside diameter of 1.5 to 5in (3.8 to 12.7cm). Due to this size range, the minimum hole size is the consequence of maximum tool diameter, so logging tools can pass through boreholes generally as small as 6in. in diameter. Maximum hole size is established by signal strengths and arms lengths and varies generally from 14 to 22in. Some logging devices are modified by service companies for larger and smaller holes. The length of logging tools varies depending on the number of sensors and exiting units, the spacing between them and the complexity of required electronics. Since the total length is more than can be conveniently handled in one piece, the logging tool is divided into different sections that are assembled at the wellsite. These sections consist of cartridges and sondes.

Figure 8.2 Assembling a logging tool on a rig floor. One logging operator holds a logging tool in place (left) while another assembles a connection (right). The upper part of the tool is suspended from the rig derrick (not shown, above the men). The operators will connect that to the lower section of the tool, seen protruding above the rig floor between the men. That part of the tool is suspended in the wellbore, held in place at the rig floor by the flat metal C-clamp. Most logging tools have a small diameter but can be the height of an average one-story building. ([Mark Andersen] Discovering the Secrets of the Earth, Oilfield Review 2011, From Schlumberger Defining Logging)

Bow spring ***centralizers*** are attached also to the housing of a logging tool when this tool is required to operate in a centralized position in the borehole. Furthermore, a ***pad*** (sensor package) ***or pads*** are added in the tool when some measurements require the direct contact of pads with the formation through the borehole wall. This is done by two, four or six mechanically actuated steel arms or a single back-up arm. While the tool is being lowered, its arms are in closed positions (so as not to stick in the borehole). When the tool has reached the bottom of the depth interval to be logged, the operator extends the arms by means of direct current electric motors from a remote control system (control signals are transmitted along the logging cable).

Each type of a logging tool has a ***measure point***. It is a point on the housing and its position depends on the arrangement of the sensor(s) and exiting unit(s). The measured value is always assigned to the actual position of the measure point in the borehole. As a result, as the tool moves, the depth level of the measure point changes, so that the values measured in different positions are assigned to different depth levels.
(https://docplayer.net/85015426-Well-logging-equipment-and-operation-edited-by-g-petho-p-vass-for-petroleum-engineer-geoengineer-msc-students.html
[G.Pethő and P.Vass] Well logging equipment and operation)

Figure 8.3 WDSC Micro-resistivity scanning imaging logging tool.
Diameter 5 in. (12.7cm)
Min hole 6,25 in. (15.88cm)
Max hole 21 in. (53.34 cm)
Length 24.18 ft (7.37m)
Weight 496 lbs (225kg)
Max logging speed 30 ft/min (9.1 m/min)
Producer: Huanding Energy Services
(http://www.huanding.com/en/Products_Mes.aspx?type=16&Id=36)

Both tools are specified for:
Max temperature 350 F (175° C) and
Max pressure 20000 psi (140 MPa)

Figure 8.4 Gowell's Six-arm caliper logging tool.
Diameter 3-5/8 in. (9.2cm)
Min hole 4.5 in. (11.4cm)
Max hole 22 in. (56cm)
Length 10,5 ft (3.2m)
Weight 192 lbs (87kg)
Max logging speed 120 ft/min (36 m/min)
Producer: Gowell International
(http://www.gowellpetro.com/product_profiles/ancillary_sac_1qcz.pdf)

In practice, logging tools are generally not used alone. They are usually connected in suitable combinations. Each tool has a male threaded end by which it can be driven into the female end of another one. This connected combination of logging tools is called ***logging tool string***. The total length of a logging tool string varies from 40 to 140 ft, depending on the logging plan.

The most significant advantages of using logging tool strings are the following:
➢ saving the rig time, because more characteristics of the rock formations can be measured simultaneously.
➢ improved depth correlation of all measured quantities, because there is a common depth reference for all the recorded logging curves.
➢ facilitation of decision-making at wellsite, when a quick decision is needed to make on the further operation.

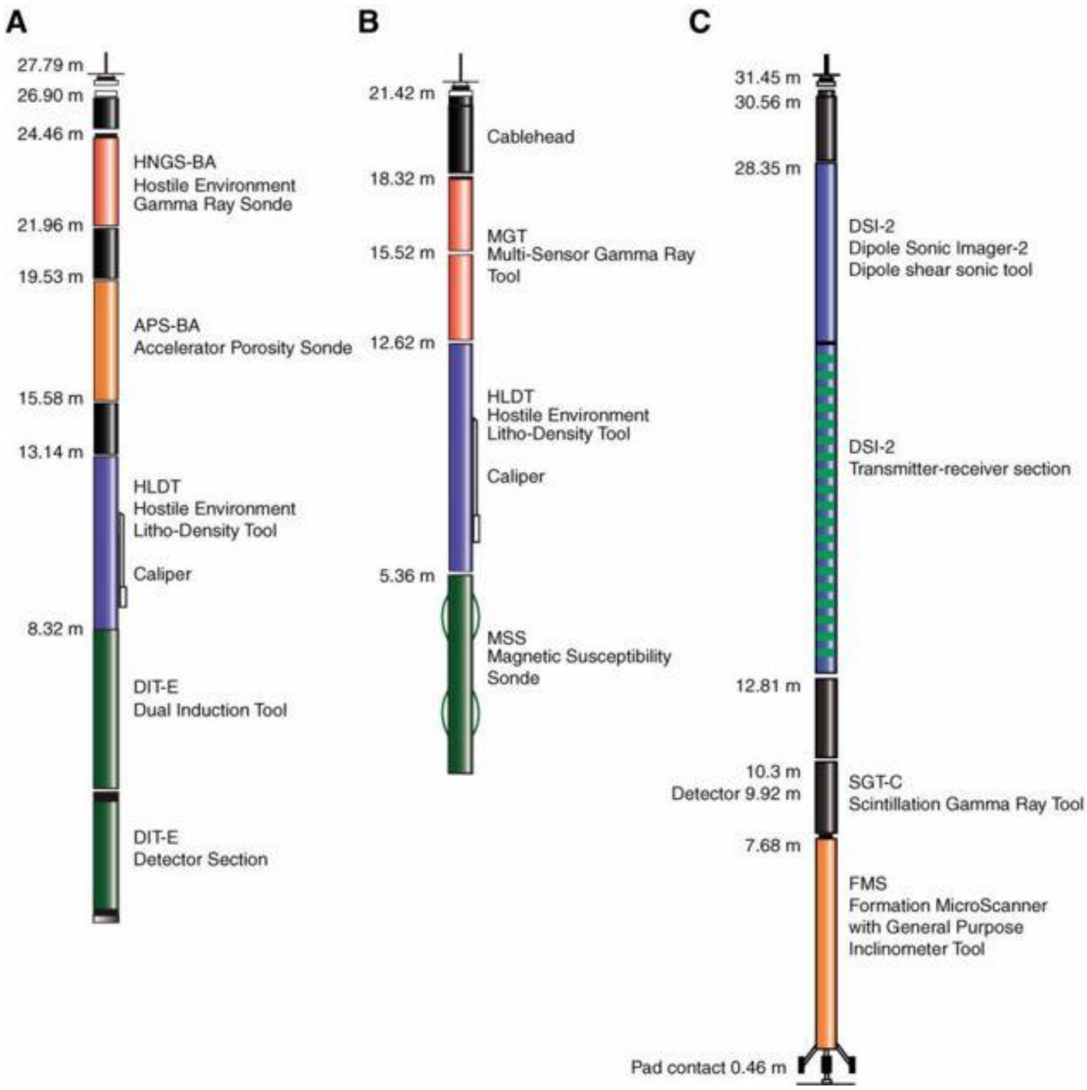


Figure 8.5 Three different wireline logging tool strings with their components from IODP (Integrated Ocean Drilling Program) Expedition 320/321 (Honolulu, Hawaii, USA 2009) scientific prospectus.
(http://publications.iodp.org/scientific_prospectus/320_321/320_f36.htm)

The above Figure 8.5 shows: **A** LDEO-BRG* **"Triple Combo"** wireline tool string. It is always run first and acquires most of the basic logs (gamma ray, neutron porosity, density, caliper and resistivity) all in a single logging pass. The term "Triple Combo" is derived from the three principle measurements collected by the tool string: density, porosity and resistivity. **B** LDEO-BRG* **"Paleo Combo"** wireline tool string. It is a modified **"**triple combo**"** and is a combination of high-resolution tools that can be used to enhance the potential for decimeter-scale core-log integration using natural gamma radiation, density, and magnetic susceptibility (amount of magnetic material). **C FMS-Sonic** tool string. It consists of the Formation MicroScanner and Dipole Sonic Imager-2 for FMS resistivity images of the borehole and sonic-acoustic velocity data (elastic wave velocities), respectively.
*Throughout wireline logging, logs are generated from an assortment of Schlumberger and Lamont-Doherty Earth Observatory Borehole Research Group (LDEO-BRG) logging tools united into tool strings, which are lowered into the borehole when coring operations are finished.

A long and solid tool string can easily get stuck in a wellbore which is not vertical or full of caverns or wash-outs. In order to reduce the risk of getting stuck, flexible joints (such as ***knuckle joints*** and ***swivel***) are added in the tool string to ease passage in the borehole.

Each logging tool string has its own ***reference point***, which acts as a zero point. For a wireline tool string the reference point is normally its bottom, which is aligned with the level of the drill floor (rig floor), before the tool string is being lowered into the hole. Since the distance between the reference point of a logging tool string and the measured point of each build-in logging tool is a known constant, the measured values of the different tools can be assigned to their own depth values by means of depth shifting. For MWD/LWD the reference point is the bit. Generally, the term of reference point is sometimes used to mean the depth reference. The depth measured from that point is the Measured Depth (MD) for the well and is different from the True Vertical Depth (TVD), since a borehole is not necessary vertical.

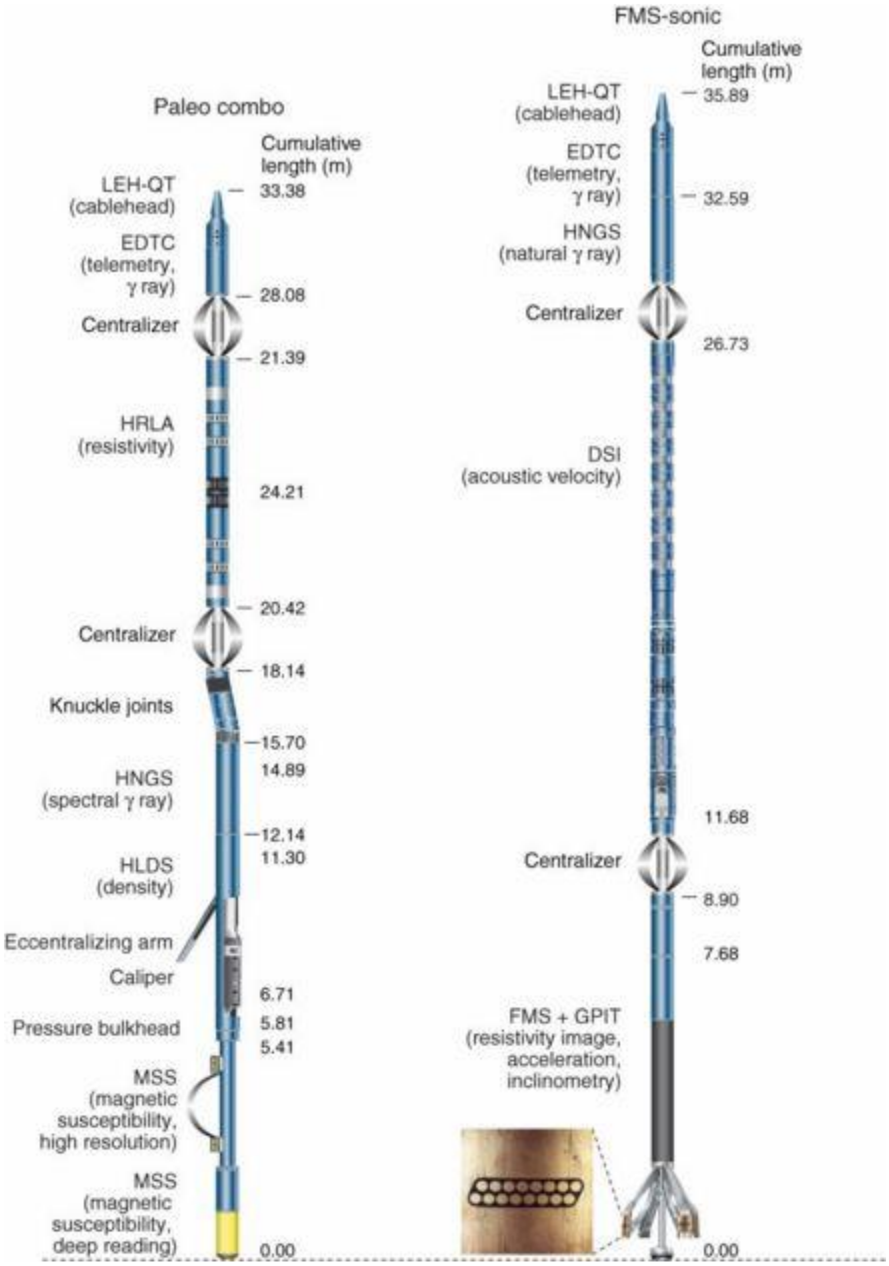


Figure 8.6 Two main wireline logging tool strings used during IODP Expedition 346 (Valdez, Alaska, USA 2013) proceedings. (http://publications.iodp.org/proceedings/346/102/102_f15.htm)

Definitions of tool acronyms in the above Figure 8.6:
"Paleo Combo" LEH-QT = logging equipment head (model QT), EDTC = enhanced digital telemetry cartridge (for communication through the wireline), HRLA = High-Resolution Laterolog Array, HNGS = Hostile Environment Natural Gamma Ray Sonde, HLDS = Hostile Environment Litho-Density Sonde, MSS = Magnetic Susceptibility Sonde
FMS-Sonic LEH-QT = logging equipment head (model QT), EDTC = enhanced digital telemetry cartridge, HNGS = Hostile Environment Natural Gamma Ray Sonde, DSI = Dipole Shear Sonic Imager, FMS = Formation MicroScanner, GPIT = General Purpose Inclinometry Tool.
All tool names except the MSS, are trademarks of Schlumberger.

The term wireline refers to the armoured ***logging cable*** which is primarily used for lowering and pulling up the measurement devices in the borehole or well. The logging cable provides a mechanical support for the tool and a communication channel for data transmission. The cable is wrapped with a two-layered galvanized (protection from corrosion) steel armour. Both of these layers are formed by twisted (in opposite directions) steel wires wound around the core of the cable. The interior of the cable contains shielded (for electrical noise reduction) insulated (with teflon) wires. These copper conductors provide electrical connection between the downhole logging tools and the computerized data acquisition system located at the surface. They also transfer the measured electric signals from the tool to the surface elements. The core of the logging cable may also contain an optical fiber cable, which provides much higher rate of data transmission. For open hole logging operation, seven-conductor cables (hepta-cables) are generally used as well as three- and four-conductor cables.
(https://docplayer.net/85015426-Well-logging-equipment-and-operation-edited-by-g-petho-p-vass-for-petroleum-engineer-geoengineer-msc-students.html
[G.Pethő and P.Vass] Well logging equipment and operation)

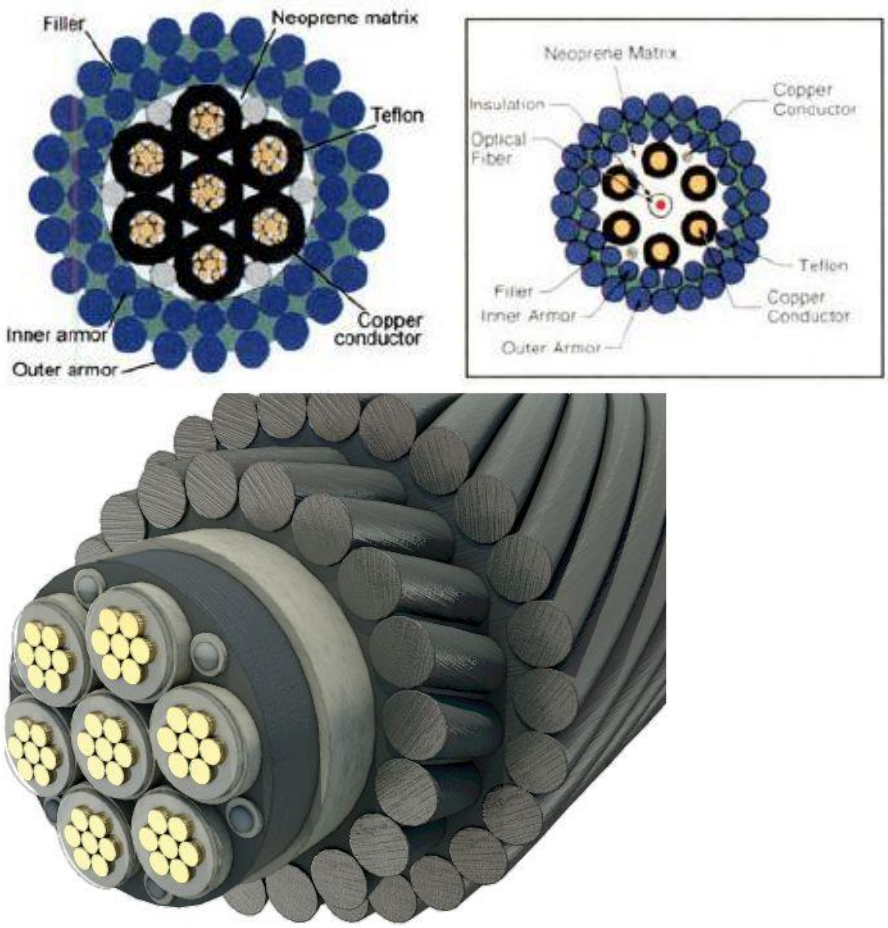


Figure 8.7 High-strength logging cable
Top left: section of the hepta-cable.
Top right: section of the fiber optic cable.
([Serra O., Serra L.] Well Logging, Data Acquisition and Applications 2004)
(https://www.slb.com/services/technical_challenges/high_pressure_high_temperature/hpht_reservoir_characterization.aspx)

The communication between the surface equipment and the downhole devices is duplex. The voltage signals of measured data are transmitted from the tools to the surface and electrical power as well as control signals are transmitted from the surface logging unit to the measurement devices.

The cable is attached to the upper element of the tool string by the so-called ***cable head***. The cable head provides mechanical and electrical connection between the wireline cable and the tool string. A weak point is build into the cable head, that holds the weight of the tool string and enables the wireline cable to be released from the cable head (to be pulled free) when the tool string become stuck in the wellbore.

The motorized ***winch unit*** (winch and drum) is needed for the running in and out of the hole of both the wireline cable and the logging tool string. A winch-man operates the winch by means of a control panel. The winch unit is driven generally by a hydraulic motor.

Two ***sheaves*** (upper and lower) are fixed to the drilling rig in order to achieve the change of the logging cable's direction at two points, between the winch and the borehole.

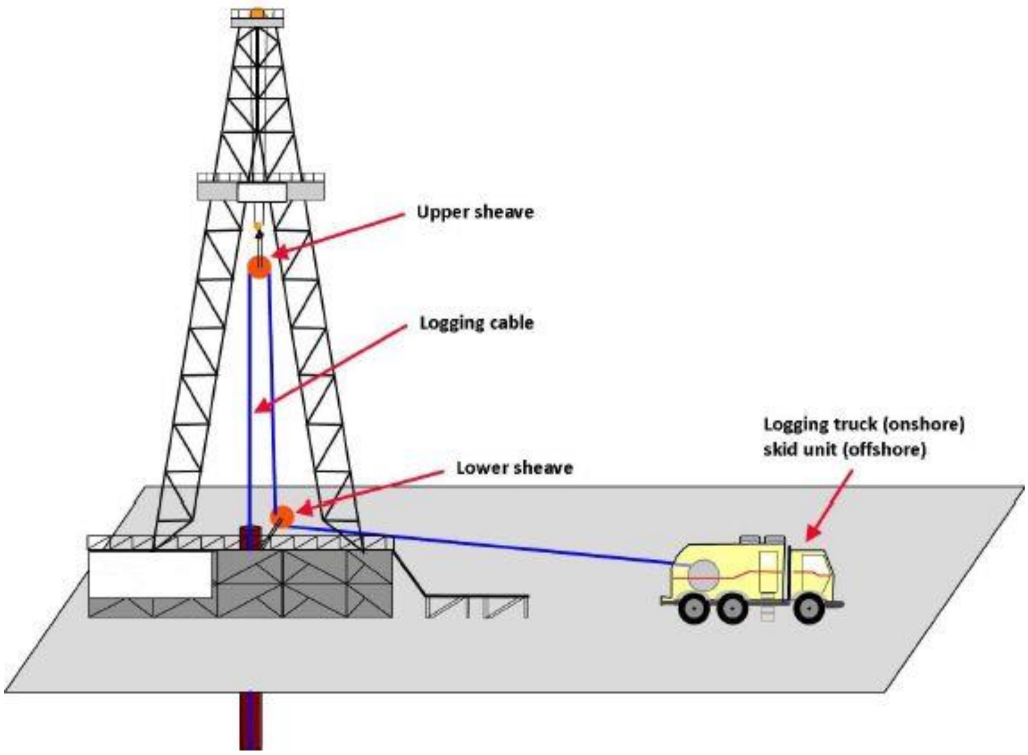


Figure 8.8 A logging system set up to a drilling rig (https://docplayer.net/85015426-Well-logging-equipment-and-operation-edited-by-g-petho-p-vass-for-petroleum-engineer-geoengineer-msc-students.html [G.Pethő and P.Vass] Well logging equipment and operation)

The surface equipment of a wireline logging system is the so-called ***surface logging unit***. It is enclosed into a rugged and transportable cabin. The cabin is separated into two parts: • the *drawworks area* which contains the winch assembly, and • the *operator's cab or logging cab* which houses control panels of the winch and other downhole instruments, as well as the computerized data acquisition and processing system. The surface logging unit is mounted on a heavy-duty truck for logging onshore wells or on a skid for logging offshore wells. The logging truck carries the logging tools in its storage bay during the transportation.

A logging truck also provides alternative current power for the surface instruments, computers and auxiliary devices. The surface logging unit provides direct current power for the downhole tools. The computerized data acquisition system receives, preprocesses and stores the raw measured data coming from the logging tools. By means of its interactive software environment, the whole logging operation can be controlled. According to data transmission, the maximum data rate of conventional logging cables is about 80 Kbits/second in the case of analogue transmission. The change from analogue to digital telemetry in the 90s increased the data rate of conventional 7-conductor wireline from 80 to 660 Kbits/second.

Modern wireline logging systems use digital signal transmission. Specifically, the measured voltage signals of a sensor are digitized inside the logging tool. Then, the digitized signals are transmitted to the telemetry unit in the upper part of the tool string and are collected there. Next, telemetry unit transmits them to the surface equipment. Finally, the measured data are displayed and quality controlled immediately, by means of the monitors connected to the computerized system. The well log, which is the continuous recording of measured data, is printed on a roll of logging paper by a field printer inside the logging cab.

Furthermore, monitoring the cable tension is continuously required during the logging operation so as to control the movement of the logging tool string. Cable tension suddenly changes in case of stucking of the tool string. For this reason, two types of ***cable tension measurement devices*** are used. The cable tension device with the load cell can be inserted between one of the sheave and the drilling rig (the rotary hook or the drill floor). The other type, which is combined with a depth indicator, is placed before the cable is reeled up onto the drum, and the cable is threaded through it.

Most of the logging tool measurements are performed as the tool string is being pulled up slowly towards the surface. The advantages of logging in the upward direction are a taut cable and better depth control. ***Logging speed*** is the speed of cable movement during the logging operation. Different logging tools and different applied methods require different maximal logging speed.

Recommended maximum logging speeds ([O.Serra] Well Logging Handbook 2008)		
Measurement	Maximum logging speed	
	ft/min	**m/min**
Spontaneous Potential	100	30
Induction	83	25
Sonic-acoustic transit time	60	18
Laterolog	50	15
Gamma Ray	20	6
Density	15	4,5
Neutron	30	9
Imagery	15	4.5
Dipmeter	50	15

At the end, it is important to mention that maintenance check and repair of tools and equipment is necessary. The complete logging operation requires a proper care and control all the time. Loggers, drillers and operator company's representatives have to cooperate continuously for the best and safe result.

9. FORMATION EVALUATION - LOG CALIBRATION WITH FORMATION SAMPLES

Formation evaluation is the process of interpreting various measurements that are taken inside a borehole for detecting and quantifying oil and gas reserves in the rocks around the well. This is done mainly to ascertain whether or not economic reserves of hydrocarbons are present and, if they are, to determine the most economical and efficient way to extract them. Formation evaluation data in petroleum exploration can be gathered from open-hole logging, logging while drilling (LWD), mud logging and coring. Specialists, called petrophysicists, study the physical properties of the rocks and the fluids contained within them. They are engineers or geologists that specialize in the profession of formation evaluation.

The primary objective of formation evaluation is to determine the size of a reservoir, the quantity of hydrocarbons in place, and the reservoir's producing capabilities. The initial discovery of a reservoir lies squarely in the hands of the exploration geologist using seismic, gravity and magnetics studies. Formation evaluation presupposes that a reservoir has been located and is to be defined by drilling as few wells as possible. Enough data should be gathered from those wells to extrapolate reservoir parameters field wide (in an entire field, rather than simply in a specific area of the field) and arrive at realistic figures for both the economic evaluation of the reservoir and the planning of the optimum recovery method. Formation evaluation offers a way of gathering the data needed for both economic analysis and production planning.

The geophysicist needs to know the time-depth relationship in order to calibrate conventional seismic and vertical seismic profile surveys. The geologist needs to know the stratigraphy, the structural and sedimentary features, and the mineralogy of the formations through which the well was drilled. The reservoir engineer needs to know the vertical and lateral extent of the reservoir, its porosity (the nature of the porosity) and permeability, fluid content, and recoverability. The manager needs to know the vital inputs to an economic study which are: the original petroleum hydrocarbons in place, recoverability, cost of development and, based on those factors, the profitability of producing the reservoir.

Log measurements, when properly calibrated, can give the majority of the parameters required by all these professionals. Specifically, logs can provide either a direct measurement or a good indication of:

- porosity, both primary and secondary (fractures and vugs)
- permeability
- water saturation and hydrocarbon movability
- hydrocarbon type (oil, gas, or condensate)
- lithology
- formation (bed) dip and strike
- sedimentary environment
- travel times of elastic waves in a formation
- rock mechanical properties

From this data, good estimates may be made of the reservoir size and the petroleum hydrocarbons in place.

In practice, the order in which formation evaluation methods are used tends to follow the order: from the macroscopic to the microscopic. Thus a prospective structure will first be defined by seismic, gravity, and/or magnetics studies. Most wellbores drilled through such a structure are mud-logged and/or measured while drilled, from which cores may be cut or sidewall samples taken. Once the well has reached a prescribed depth, logs are run.

Conclusions derived from logging data are subject to varying levels of error. To reduce that error and build confidence in interpretations of logs, it is useful to compare the logs to samples from the formation. The cuttings collected during the mud logging process provide one set of samples. Other samples can be collected with coring operations.

The mud log is obtained during the drilling operation of a wildcat well. It includes several tracks: rate of penetration, depth, composition of gas liberated at the surface from the drilling mud, plus word and strip chart descriptions of cutting samples. The samples of cuttings are collected from the shale shakers, washed and sieved by the mud loggers in order to take out any drilling mud and too large cavings (rock fragments from above the bit). Afterwards, these expert geologists examine the washed samples with a microscope to classify the lithology and express it as percentages, and under ultraviolet light to indicate oil shows. They usually do this analysis quite quickly depending on their experience, knowledge and skill with the examination of the sample. The samples are the first direct evidence of lithology obtained from the borehole and are routinely compared to open-hole logs. The rate of penetration track shows the amount of time it takes to drill through a foot of rock and indicates the hardness of the formation. Rock hardness inferred from the rate of penetration gives information about the rock type, which can be compared to the lithology logs. Oil and gas shows in the mud log can be compared to indications of hydrocarbon in the porosity and resistivity logs.

Figure 9.1 Analyzing rock cuttings and hydrocarbons carried to the surface inside the mud logging unit. (https://www.weatherford.com/en/products-and-services/drilling/surface-logging-systems/)

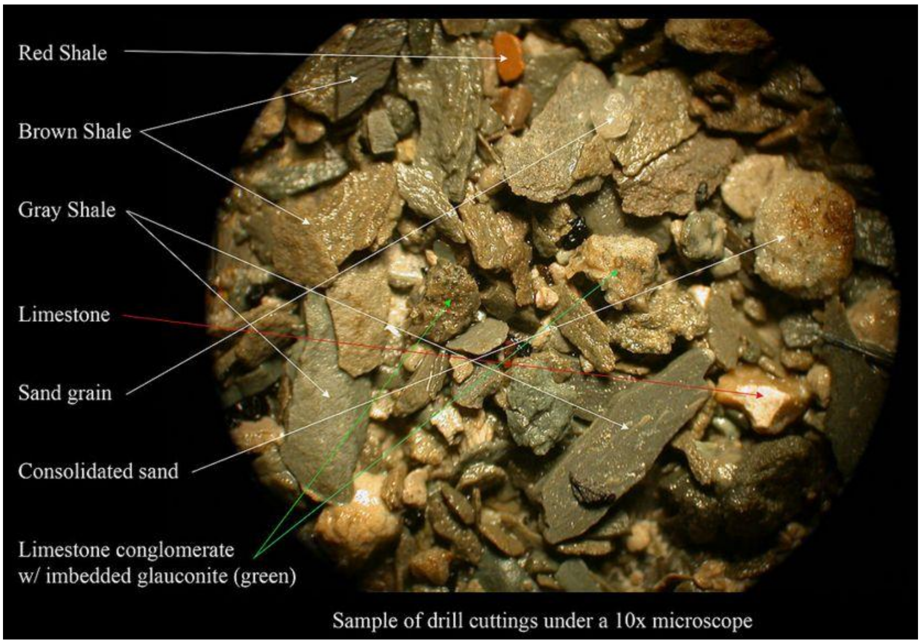


Figure 9.2 Sample of drill cuttings of shale while drilling an oil well in Louisiana. (https://en.wikipedia.org/wiki/Mud_logging)

Another way to obtain more detailed samples of a formation is by coring, where formation sample is drilled out by means of special drill bit. Two techniques are commonly used: the whole core and the sidewall core.

The whole cores, also called conventional cores, are continuous pieces of rock taken out from the formation. Core samples are obtained by replacing the drill bit with a ring-shaped coring bit. The coring bit is hollow. Thus, a solid cylinder of rock can be cut and captured as the coring bit gets into the formation. This cylinder is brought to the surface as a united piece (core).The rock sample is collected in a core barrel in the lower portion of the bottom-hole assembly (BHA). At the surface, the core is retrieved from the core barrel and placed in transport boxes, which are transported to a laboratory for study. The need to replace the drill bit with a coring bit, obtain a core, and then replace the coring bit with a drill bit to resume drilling means that coring is a time-consuming and expensive process, so few wells are cored and especially in limited sections of the well, which provide the most useful information.

Figure 9.3 An illustration of the Intelligent Coring System (ICS) which uses a suite of sensors to analyze reservoir cores samples as they are being acquired and a communication system that sends this data to the rig in real-time. Source: CoreAll. The company, founded in 2012, says its ICS is the first technology of its kind to collect formation evaluation data of the core and transmit it to the surface in real-time through mud-pulse telemetry. (https://www.spe.org/en/jpt/jpt-article-detail/?art=4171 [Trent Jacobs, Journal of Petroleum Technology (JPT) Digital Editor] Norwegian Firm Adds Smarts to Offshore Coring 2018)

Sidewall cores refer to plugs of rock cut from the borehole wall. Wireline-conveyed tools usually capture these cores. Sidewall coring activities are cheaper and not so time-consuming compared to those of conventional coring. Furthermore, in this technique, cores from multiple zones of interest can be recovered in a single run.

Some of these devices use percussive means to drive a sampling cup into the formation. Other devices use rotary saws for cutting samples. While percussive sampling is faster, rotary cutting provides better samples. Because sidewall cores are typically obtained after logging tools have been run, geologists can use log measurements (GR or SP logs as guides) to pick the depths at which the sidewall cores should be taken.

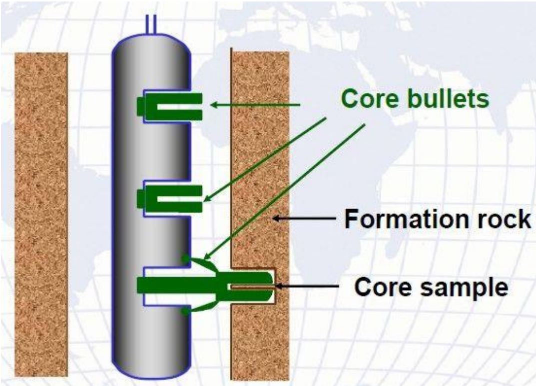


Figure 9.4
Percussion sidewall core gun with steel bullets.

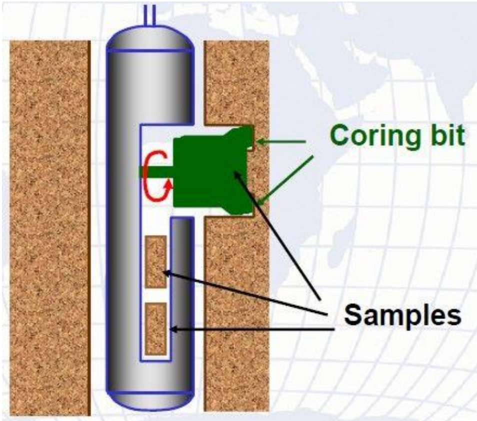


Fig 9.5
Rotary core drill on wireline.

(https://www.spec2000.net/09-corepore.htm
Crain's Petrophysical Handbook, Coring and Core Porosity)

The cores can be used to determine important reservoir properties such as lithology, porosity and permeability. Core properties can be detrimentally modified during the coring process because reduction in temperature and pressure as the core is lifted to the surface alters core fluid content. For this reason, core samples may be obtained using a process known as native-state coring that is designed to keep core samples at original in situ conditions. Cores and any results of core analysis support the open-hole logs as a way to calibrate their response and improve their interpretation.

Figure 9.6 Marcellus Shale cores. These four cores, acquired in the Marcellus Shale (a Middle Devonian age unit of marine sedimentary rock found in eastern North America) are examples of the high quality rock samples taken during rotary coring operations.(Photos courtesy Larissa Walker) (https://www.slb.com/~/media/Files/resources/oilfield_review/ors13/win13/03_rotary_side.pdf [Abhishek Agarwal, Robert Laronga, Larissa Walker] Rotary Sidewall Coring – Size Matters, Schlumberger 2014)

10.PLACE AND ROLE OF LOGGING IN PETROLEUM EXPLORATION

Logging is a continuous recording of the physical properties of rocks in the well with respect to depth. Logs, having become the geologist's eye and an instrument for the reservoir engineer, occupy a special place and play an important role in petroleum research by the economies that they bring and the amount of information they contain. It is the cheapest method of collecting and assessing the data related to geophysical properties of a well. The information that logs provide represent approximately 90% of the information that can be extracted from the drilling of a well.

Instead of drilling wells with dedicated coring tools, it is much more cost-effective to obtain wireline logs using high-tech logging equipment. This is a significant investment made by oil and gas companies as logging activities can represent between 5% and 15% of total well costs. The amount of money that is saved is difficult to determine but we can estimate that continuous coring would triple the drilling costs.

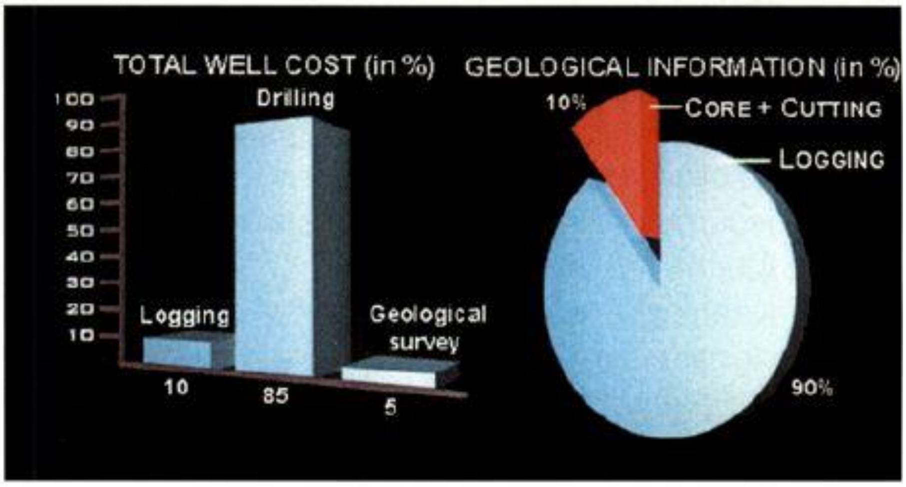


Figure 10.1 A recent evaluation made on wells drilled in USA.
([Serra O., Serra L.] Well Logging, Data Acquisition and Applications 2004)

The process of coring is not only expensive but also sometimes non-effective because the pressure in the well can damage softer sediments in the core. In this regard, logging data offers better insights about the natural characteristics of sediments or rocks without causing any damage to them. Logs are easily transported, easily compared and are a relatively indestructible form of information. Furthermore, logs take lesser space for storage than core samples, which need climate-controlled facilities for their storage.

Well logging provides real-time evaluation of the formation characteristics. This information can be effectively used for correcting the borehole drilling schedules. For example, if the depth of target formation is different from the expected depth, well logs can be used for assessing this flaw and take corrective measures in the real time. Log data, once captured, can be evaluated again for further exploration of the same site for more natural resources.

To more precisely evaluate the volume of hydrocarbons both in place and extractible from a field, the reservoir must be put back in its precise geological setting. The latter requires the determination of its depositional environment, the nature of its surrounding facies, its diagenetic environment, and a detailed and accurate description of the tectonic structure. Seismics has not the resolution to achieve this description. In any case, surface seismic data need a model for their interpretation. Only image data, associated to other log data, allow this precise geological description.

In the end, well logging plays an essential role in petroleum exploration and exploitation. It is used to identify the pay zones of gas or oil in the reservoir formations. It gives continuous downhole record and detailed picture of both gradual and abrupt changes in physical properties of subsurface lithology. It has a central role in the successful development of a hydrocarbon reservoir. Logging is able to adequately reveal the whole of the drilled sequence and has the added advantage that it measures, in situ, rock properties which cannot be measured in a laboratory from either core samples or cuttings. From this data, it is possible to obtain good estimates of the reservoir size and the hydrocarbons in place. Thus no hydrocarbon can be produced without the intervention of logs.

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