PETROPHYSICAL ANALYSIS AND FORMATION EVALUATION OF GAS FIELD

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Certificate

This thesis submitted by **Mr. Faisal Zeb, Mr. Raheel Munawar and Mr. Faheem Amar** is accepted in the present form by Faculty of Earth & Environmental Sciences, Bahria University, Islamabad as satisfying the partial fulfillment of the requirement for the degree of **Master of Sciences** in **Geology.**

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DEDICATION

DEDICATED TO PARENTS WHOSE SUPERVISION AND GUIDANCE ENABLE US TO COMPLETE OUR STUDIES

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ABSTRACT

Petrophysical study has been carried out in Qadirpur Gas Field of well no 16 and 17 for the hydrocarbon exploration. The various techniques applied are mud logging, wireline logging, well testing, core analysis, production testing. In Qadirpur Gas Field Habib Rahi Limestone and Sui Limestone have potential reserves. These two formations were focused for evaluation purposes. The reservoir quality of Sui Limestone is much better as compared to Habib Rahi Limestone.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

In the present time, the economy of the world is being controlled by the energy sector. The energy resources and reserves are being used as indicator of economy and political stability of a country. Petroleum and related energy reserves of a country constitute its most important assets. The role of hydrocarbon availability, exploration and development is directly related to the overall development and prosperity of the human being.

The petroleum exploration and its exploitation have gained special importance over the past few decades to meet the increasing demand of the world energy. Due to its importance this field has developed special interests of the scientists and various hydrocarbon agencies and a number of new geophysical techniques and methods have been developed to explore and exploit the hydrocarbon buried in subsurface geological formations. Geophysical well logging is one of the strong tools which are used to evaluate the formation characteristic features having potential for hydrocarbon development. Well logging, also known as borehole logging is the practice of making a detailed record (*log*) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (*geological* logs) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Well logging is done when drilling boreholes for oil and gas, groundwater, minerals, and for environmental and geotechnical studies.

The oil and gas industry records rock and fluid properties to find hydrocarbon zones in the geological formations within the Earth's crust. A logging procedure consists of lowering a 'logging tool' on the end of a wireline into an oil well (or hole) to measure the rock and fluid properties of the formation. An interpretation of these measurements is then made to locate and quantify potential depth zones containing oil and gas (hydrocarbons). Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, and other properties of the rocks and their contained fluids. Logging is usually performed as the logging tools are pulled out of the hole.

This data is recorded to a printed record called a "Well Log" and is normally transmitted digitally to office locations. Well logging usually refers to downhole measurements made via instrumentation that is lowered into the well at the end of a wireline cable. The wireline consists of an outer wire rope and an inner group of wires. The outer rope provides strength for lowering and lifting the heavy instruments and the inner wiring provides for transmission of power to the downhole equipment and for data telemetry uphole to the recording equipment on the surface.

In recent years, a new technique, Logging While Drilling (LWD), has been introduced which provides similar information about the well. Instead of sensors being lowered into the well at the end of wireline cable, the sensors are integrated into the drill string and the measurements are made while the well is being drilled. While wireline well logging occurs after the drill string is removed from the well, LWD measures geological parameters while the well is being drilled. However, because there is no high bandwidth telemetry path available — no wires to the surface — data is either recorded downhole and retrieved when the drill string is removed from the hole, or the measurement data is transmitted to the surface via pressure pulses in the well's mud fluid column. This mud telemetry method provides a bandwidth of much less than 100 bits per second. Fortunately, drilling through rock is a fairly slow process and data compression techniques mean that this is an ample bandwidth for real-time delivery of critical information.

Although most logs are run to evaluate oil and gas wells, increasing numbers are being run yearly for other purposes, including evaluating geothermal energy and ground water. Well log analysis in petroleum industry for oil and gas emphasis the evaluation of basic petrophysical properties of formations containing hydrocarbons. For the study of hydrocarbon and formation evaluation, a number of well logs have been arranged from Directorate General Petroleum Concession Pakistan, Islamabad. Pakistan occupies a total onshore and offshore sedimentary area of about 828,800 square kilometers. It represents the most extensive active collision region in the world. Its sedimentary exposures and geological structures have attracted geologist for over hundred years.

Petroleum exploration in Pakistan is 120 year old and the first commercial discovery dates back to 1914.The regional tectonics and geology of country have been discussed by Wynne (1975), Oldham (1890), Vredenburg (1906), Gill (1952), Pinfold (1953), Wadia (1957), Williams (1959) Krishnan (1960), Hunting survey corporation (1961), Rahman (1963) Back and Jackson (1964), Shah (1977), White (1979), Ganser (1981), Kazmi and Rana (1982), Raza and Alam (1983) etc.

Qadirpur Block (Sind Province) is the concession area operated by OGDCL. The location of the study area that falls within this block in Central Indus Basin is bounded by Sargodha high in the north, Indian Shield in the east, marginal zone of Indian Plate in the west, and Sukkar Rift in the south (Figure 1.1). The basin is separated from Upper Indus Basin by Sargodha High and Pezu Uplift in the north. Figure 1.1 shows the location of the Qadirpur Well No. 16 and Well No 17. Area falls within the latitude of 27° 55′ to 28° 09′ N and longitude 69° 11′ to 69° 31′ E and it is approximately 820 sq. kilometers. Qadirpur area administratively lies in Ghotki and Jacobabad districts of Sindh Province.

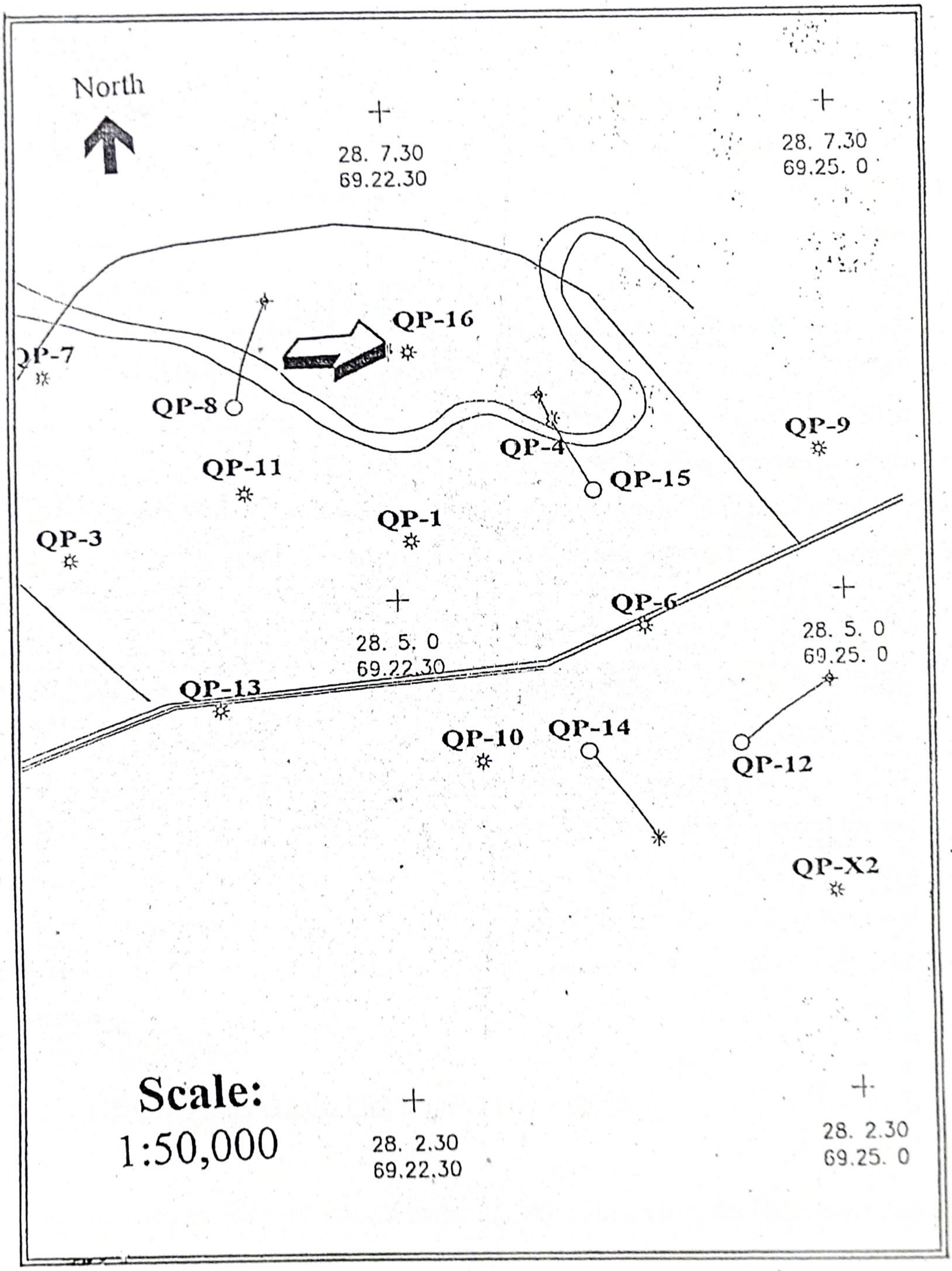


Figure 1.1 Location Map of Qadirpur 16.

1.1 OBJECTIVE

The purpose of study is to find the hydrocarbon potential of well, by evaluating their well logs which include, Porosity calculation, Shale volume calculation, Water saturation calculation , Permeability and to resolve lithology. Geologically Qadirpur is situated with the Mari Kandkot High and Middle Indus Basin of Pakistan. The intended 3D seismic data acquisition and processing programmed of Qadirpur joint venture encompasses an area of 364 sq km previously about 420 lines of 2D seismic survey were carried out by OGDCL in the years of 1990, 1992 and 1998. In 1990, gas was discovered in Eocene Limestone's in Qadirpur area. Until today about 25 wells have been drilled for extensive development of the field. Sui Main Limestone is the main producer of gas in Qadirpur Gas-field area; hence most of the wells were bottomed up to this Formation. On the other hand, Qadirpur-1 and Qadirpur-2 were drilled to Pab/Ranikot (Cretaceous /Paleocene) formations.

The location of 2D seismic lines of Qadirpur area that has been used in this study. This data was acquired and processed by OGDCL in the years of 1990, 1992 and 1998.Composite suite of logs comprising gamma ray, spontaneous potential (SP), resistivity log (i.e., induction electric log, dual induction focused log, , micro spherically focused log, microlatrolog, later log etc.), porosity logs (i.e., sonic log, density log, neutron log, combination of neutron-density log) were run in wells (Qadirpur-1 and Qadirpur -5) are also acquired for log interpretation to estimate the reservoir characteristics.

1.2 REGIONAL GEOLOGY OF THE AREA

Situated on the northwestern margin of the Indian plate, the Sulaiman sub basin displays array of features arising from collision of the Indian and Eurasian plates. The Sulaiman along with other basins located in the Indian plate was affected by the global tectonic events (Powell, 1979). Fragmentation of Gondwanaland resulted in separation of the Indian and African segment during Jurassic period.

Since then Indian plate is moving northward. The present tectonic features of the Sulaiman and its folds and faults came into existence during post cretaceous orogenic events. The pre cretaceous history of the sub basin in marked by non organic movement. The sub basin is bounded on the east by Indian shield and on the west by the marginal zone of the Indian plate. On the north lie Sargodha high and pezu uplift while its southern frontier is marked by Sukkur rift.

The Qadirpur field lies within the Indus basin on the northern flank of Jacobabad high, which separates the Suleiman sub-basin to the north from the kirthar sub-basin to the south. Three reservoir intervals comprise the Qadirpur field, the lower Eocene Sui Main Limestone (SML) and Sui Upper Limestone (SUL) and the Middle Eocene Habib Rahi Limestone. Paleocene and Eocene sediments in the Lower Indus Basin record a period of prolonged and widespread shallow-water platform carbonate deposition. Sediments deposited are generally muddy, foraminifera limestone. The SML and SUL reservoirs comprise decimeter to meter scale, inter bedded muddy limestone, siltstone and shales separated by the Sui Shale interval, developed to a thickness of approximately 45 metres. The SUL is overlain by the Ghazij shale an approximately 200 meter thick shale interval. Above the Ghazij shale lays the Habib Rahi reservoir, a sequence of argillaceous limestone sealed by the overlying Sirki shale.

The Qadirpur structure is an elongate anticline oriented NNW-SSE which plunges gently to south. A northern extension to the structure comprises the kandhkot Field. The Lower Indus Basin is interpreted as a foreland basin to the Kirther-Sulaiman Mountains. The Qadirpur structure is likely to result from phases of plate collision in the late Tertiary to Quaternary. During the lower Eocene transgressive shallow seas covered the lower Indus Basin area depositing thick limestone. Argillaceous content in these limestones is variable reflecting alternating cycles of regression and transgression in Indus Basin. Fluctuations in relative sea level played an important role in the development of Qadirpur reservoirs. Regressions resulted in cleaner limestone and in some instances partial exposure of the sequence resulting in leaching of the exposed sequence and subsequent reservoir enhancement.

Transgressive phases resulted in increased argillaceous content and a series of rapid deepening events resulting in open marine circulation led to abandonment of the three platform margin complexes that comprise the Qadirpur reservoirs. Source rocks in the lower Indus basin are widespread and possible source intervals for the gas at Qadirpur include the Lower Cretaceous Sembar and the Lower Goru shales, also local intra-formational sourcing may be important.

1.3 PETROLEUM PROSPECT

On the surface Qadirpur is covered by Alluvium of floodplain area of the Indus River. It is a NW-SE trending anticline comparatively broad in its Southern half. Potential source rocks include shale of Sembar Formation, but shales of Mughalkot, Ranikot and Ghazij formations are also considered for their source potential. Sui Main Limestone and Sui Upper Limestone is the main producer whereas limestone of Habib Rahi is considered as secondary reservoir.

The Ghazij Shales and shale within Sui Main Limestone and Sui Upper Limestone act as cap rock for Sui Main and Sui Upper Limestone. The Sirki Shales over Habib Rahi Limestone act as a cap rock. The structure surrounding the area include Sui (slightly asymmetrical anticline), Kandkot-Qadirpur structure trend comprising low amplitude domes, Uch (thrust faulted anticline) having compartments formed by cross-cutting wrench faults, and fault-related closures of the Yasin block and block-22. Near the northern portion of the eastern flank of the Jacobabad high, fault-related traps as in Yasin block of the lower Indus trough and Mari-Kandkot high, low amplitude structure flat domal uplifts and combined with draping of the sedimentary cover anticipated to form traps.

CHAPTER 2

STRATIGRAPHY

STRATIGRAPHY

2.1 SWALIKS GROUP

Swalik consists of sand stone with intercalation of clay. The sand stone is off-white to yellowish-white in color, friable to medium hard, fine to medium grain, sub-angular to sub-rounded, moderately sorted and slightly calcareous. Clay is soft and of khaki color. Thickness of the formation is 375m. The environment of deposition is fresh water and the age of the formation early Pleistocene. The lower contact with Nari formation is unconformable (After Raza and Ahmed 1990).

2.2 NARI FORMATION

Nari formation consists of sandstone with streaks of clay. The sand stone is off-white, transparent, quartize, and medium to coarse grained in nature. It is also sub-angular to sub-rounded, loose, moderately sorted, and non-calcareous. The clay in Nari formation is of brown color and soft in nature. Thickness of the formation is 222 m. The environment of deposition is Estuarine and the age is Oligocene. The lower contact with Kirther formation is unconformable.

2.3 KIRTHAR FORMATION

Kirthar formation (Noetling 1903) consists of interbeded series of limestone and shales with minor marl. The limestone is light grey cream color of chalky white weathers in grey, brown or cream color. It is thick bedded to massive in places nodular and occasionally contains algal and coralline structures. The shale is calcareous olive, orange, yellow, grey, soft and earthy. In some parts of the Sulaiman province milky white gypsum beds up to 6 meter thick are present. In most of areas the formation transitionally overlies the Ghazij formation or Laki formation. The formation is richly fossiliferous and represents different ages in various parts of distribution. The Kirthar formation is divisible in to four easily distinguishable members in parts of the eastern Sulaiman province.

2.3.1 DRAZINDA MEMBER

In Drazinda member the main lithology is shale with intercalation of marl. Shale is greenish gray, soft, laminated, moderately indurate. The marl is greenish gray off-white and soft. The thickness of the formation is 58m. The environment of the deposition is shallow marine and the age is Middle Eocene. The lower contact with the Pirkoh limestone is conformable.

2.3.2 PIRKOH LIMESTONE MEMBER

White marl band of (Eames 1952) which has been referred to as Pirkoh limestone in unpublished report of oil companies. This member consist of limestone white, creamy, grey to yellowish grey, hard to very hard, massive to very thick bedded, crystalline, highly foraminifera with calcite veins. Marl grey to greenish grey, soft to medium hard, plastic and shales greenish grey, chocolate brown, slightly indurate, foliated to non foliated, fossiliferous, and calcareous. The thickness of the formation is 109m. The environment of deposition is shallow marine and the age is Middle Eocene. The lower contact with the Sirki member is conformable.

2.3.3 SIRKI MEMBER

Lithology is shale with Alabaster and streaks of limestone and marl. Shale is greenish grey to brownish grey, slightly indurate, fissile, fossiliferous, and pyritic. Alabaster with milky white to dirty white, transfused soft, massive, amorphous to microcrystalline. Limestone is light grey to creamy yellow, medium hard, compact, crystalline, and fossiliferous, and dolomite. Marl is greenish grey, soft, plastic, shallow marine. The thickness of the formation is 48m. The environment of deposition is shallow marine and the age is Middle Eocene. The lower contact with Habib Rahi Member is conformable.

2.3.4 HABIB RAHI LIMESTONE MEMBER

Habib Rahi limestone (SCP) consists of limestone with streaks of marl and shale. Limestone is greenish grey, creamy to yellowish, white to light grey, hard to very hard, compact, crystalline, fossiliferous, slightly argillaceous, cherty some time dolomitic. Marl is light grey, soft to medium hard, plastic. Shales are white, light grey to dark grey, olive green, soft, plastic, calcareous. The thickness of the formation is 85 m. The environment of deposition is shallow marine and the age is Middle Eocene. The lower contact with Ghazij formation is conformable.

2.4 GHAZIJ FORMATION

The Ghazij group of Odham (1890) was redefined as Ghazij formation by Williams (1959). Ghazij formation consists of shale with streaks of limestone and marl. Shales are olive green to light greenish grey, grey moderately indurate, laminated, fossiliferous, splintery fissile, slightly carbonaceous; limestone is whitish grey to grey, brownish grey, hard to very hard, dense, compact, crystalline, fossiliferous, and argillaceous. Marl is light grey, brownish grey, greenish grey, soft to medium hard, plastic, pyritic. The fossil fauna includes foraminifers, gastropods, bivalves, algae (Eames 1952, Hunting survey corporation 1961, Latif 1964, Iqbal 1969). The thickness of the formation is 199 m . The environment of deposition is shallow marine and the age is Lower Eocene. The lower contact with Sui Upper Limestone is conformable.

2.4.1 SUI UPPER LIMESTONE

It consists of 100% limestone. Limestone is white to off-white in color of medium hardness, and is fossil ferrous. The upper contact with Ghazij shale and lower with Sui Shale Member is conformable. The thickness of the formation is 196 m. The environment of deposition is shallow marine and the age is Lower Eocene.

2.4.2 SUI SHALE

Sui Shale contains thin bands of limestone. Shale is of greenish gray in color, pyretic, calcareous, and occasionally fossiliferious. The bands of limestone are 8 to 10 meters thick, having white color and of medium hardness. Upper contact with Sui Upper Limestone and lower contact with Sui Main Limestone is conformable. The age is Lower Eocene.

2.4.3 SUI MAIN LIMESTONE

Sui Main Limestone contains traces of shale. Limestone is off white to creamy in color, medium to hard with calcite veins, marly and highly fossiliferous. Traces of shale are light greenish gray to light gray in color, laminated and fossileferrous. Upper contact with Sui Shale and lower contact with Dunghan Formation is conformable. The age is Lower Eocene.

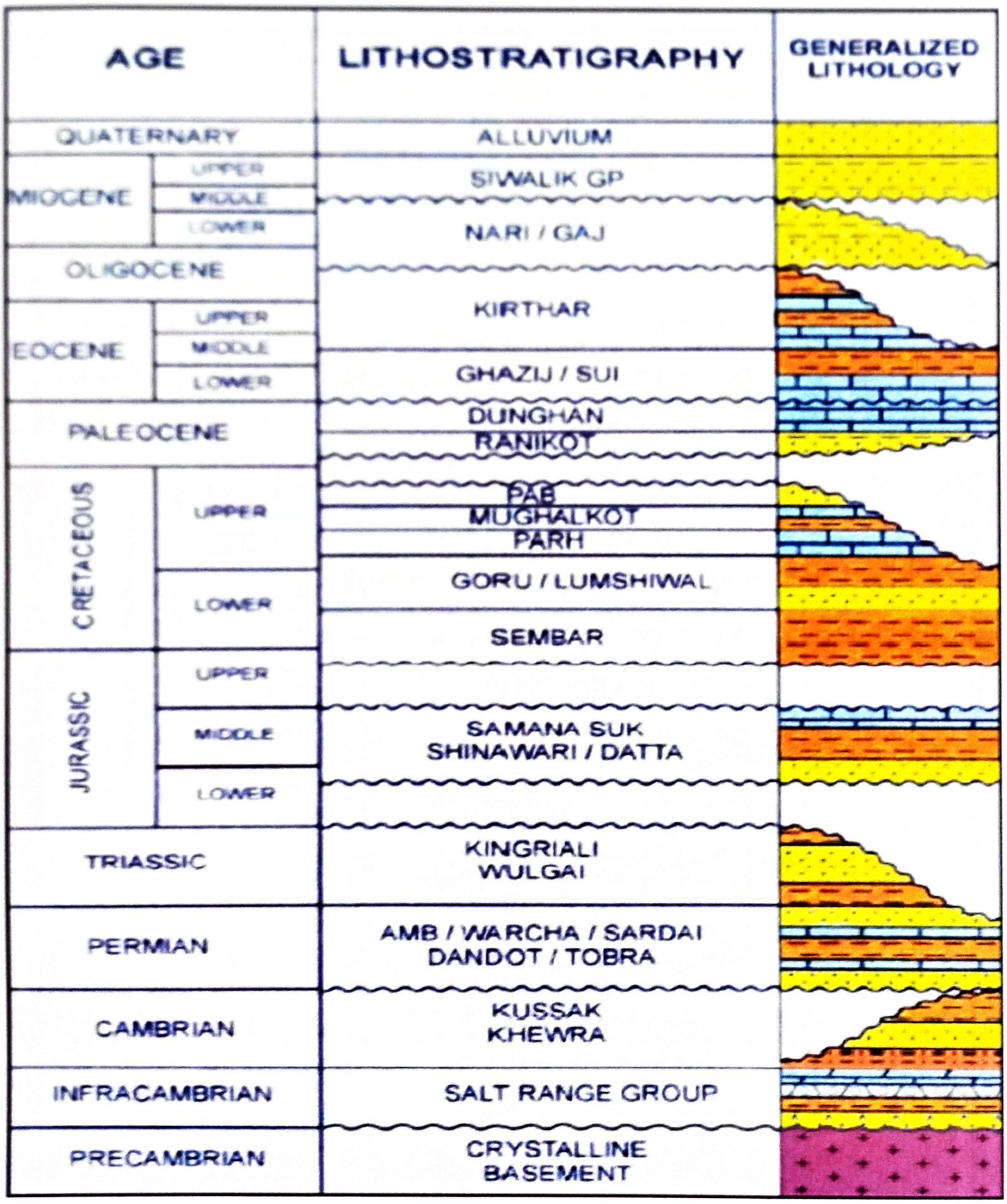


Figure 2.1 General stratigraphy of the Punjab Platform, Central Indus Basin (After Raza and Ahmed 1990)

CHAPTER 3

BOREHOLE ENVIRONMENT

BOREHOLE ENVIRONMENT

When the borehole drilled in a formation, the rock and the fluid in the rock undergoes the alteration in the vicinity of the borehole. All logging measurements are then effected by the borehole and the altered rock around it.

Borehole conditions effecting the log measurements

a) Bore hole size
b) Drilling mud
c) Mud Cake
d) Mud filtrate

3.1 BORE HOLE CONDITION

3.1.1 BOREHOLE SIZE

The normal size of the hole is taken to be the outside diameter measurement of the drilling or coring bit used to make the hole. Borehole is seldom perfectly circular; it is usually elliptical due to removal of more material in the direction of least subsurface stress.

3.1.2 DRILLING MUD

The main functions of the drilling mud are

- To carry rock cuttings to the surface
- To prevent the uncontrolled escape of the formation fluids
- To cool and lubricate the drill string and the bit
- To suspend cuttings during times when circulation is stopped.

The hydrocarbon static pressure of the drilling fluid must be greater than the formation fluid pressure, this overbalance system allows the entry of the mud fluid into the pore spaces of the permeable rock, and this entry of the mud is called the invasion of the drilling mud that affects the logging tool response.

3.1.3 MUD CAKE

Mud Cake is formed within the few minutes of the formation being penetrated. Clay particles are caked against the size of the borehole and effectively seal off the formation to further invasion. Invasion takes place continuously as the hole is deepened because the mud cake becomes damaged or is removed by drilling, logging or testing tool. Thick mud cake affects the readings of the shallow investigation of the logging tool. The presence of mud cake is usually a good indication of the permeable rock.

3.1.4 MUD FILTRATE

Fluid which enters permeable zone from the mud is called the mud filtrate. The filtrate is usually the water in the normal mud system and its resistivity is dependant on the original salinity of the mud system. All logging tools are affected to some degree by the mud filtrate.

3.2 INVASION

Drilling fluid invasion is a process that occurs in a well being drilled with higher well bore pressure than formation pressure. The liquid component of the drilling fluid (known as the "mud filtrate") continues to "invade" the porous and permeable formation until the solids present in the mud, commonly bentonite, clog enough pores to form a mud cake capable of preventing further invasion. If invasion is severe enough, and reservoir pressures are unable to force the fluid and associated particles out entirely when the well starts producing, the amount of oil and gas a well can produce can be permanently reduced. This is especially true when a process called phase trapping.

This is when a fluid enters a formation that is below its irreducible saturation of that fluid. Once the fluid is present, it is held in place by capillary forces and usually can not be removed. Invasion also has significant implications for well logging. In many cases the "depth of investigation" of a well logging tool is only a few inches (or even less for things like sonic logs), and it is quite possible that drilling fluid has invaded beyond this depth.

3.2.1 DEPTH OF INVASION

The distance from the borehole wall that the mud filtrate has penetrated into the formation. The depth of invasion affects whether a log measures the invaded zone, the undisturbed zone or part of each zone. The term is closely related to the diameter of invasion, the latter being twice the depth of invasion plus the borehole diameter. Depth of invasion is a more appropriate parameter for describing the response of pad and azimuthally focused measurements such as density and microresistivity logs. The term is well-defined in the case of a step profile of invasion. In the case of an annulus or a transition zone, two depths must be defined, corresponding to the inner and outer limits of the annulus or transition zone. When the invasion model is not specified, the term usually refers to the outer limit of invasion. Depth of invasion depends upon several factors during logging like, filtration characteristics of the drilling mud and the differential pressure between the mud and the reservoir.

Invasion of the mud relates to the porosity, once the cake has started to built, its permeability becomes low relative to that of the average formation so that almost the entire pressure differential is across the mud cake and little is applied to the formation. The mud cake therefore controls the filtration rate. Depth of invasion will be minimum at higher porosity where plenty of the pore space available it is approximately inversely proportional to the porosity. Other things being constant. Invasion depth will double as the porosity reduces from 36% to 9% etc.

3.2.2 INVASION PROFILE

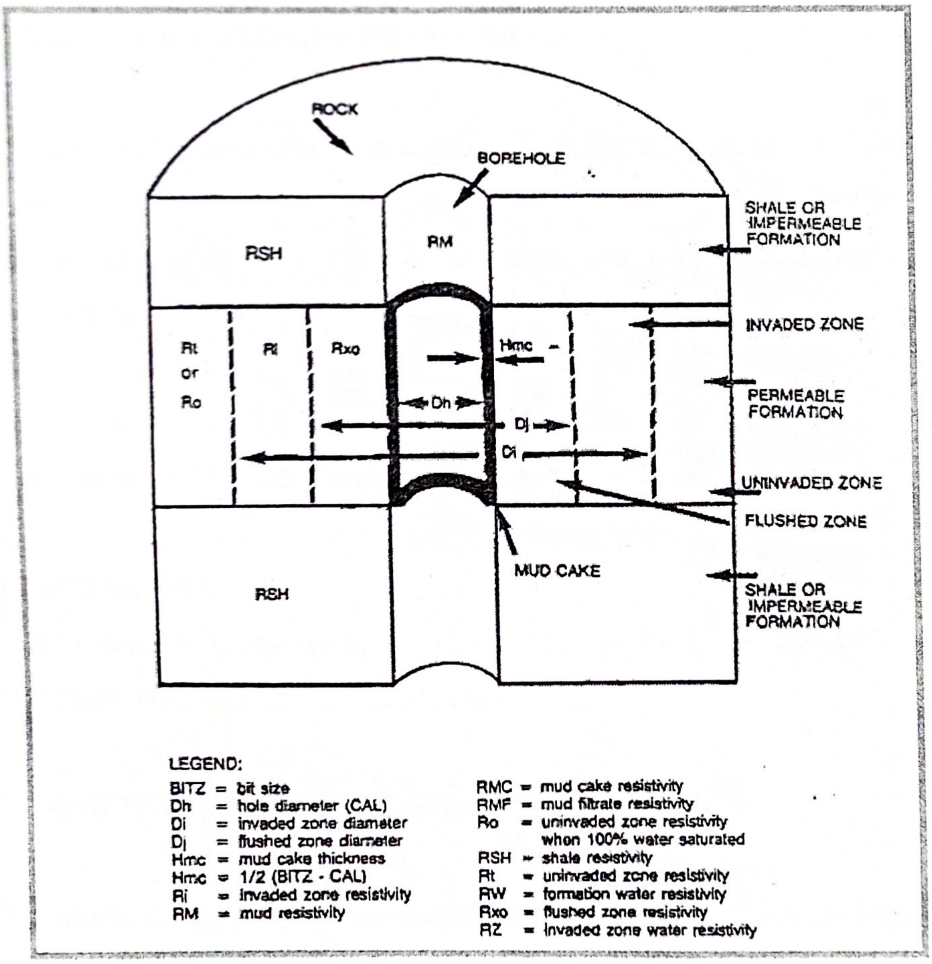
The process of invasion creates an invasion profile extending from the well bore into the formation. Three zones are recognized.

a) Flushed Zone

b) Transition Zone

c) Undisturbed Zone

The invaded zone is that portion of the formation which has been penetrated by the drilling fluids.



- **FLUSHED ZONE**

The volume close to the borehole wall in which all of the moveable fluids have been displaced by mud filtrate. The flushed zone contains filtrate and the remaining hydrocarbons, the percentage of the former being the flushed-zone water saturation, S_{xo}.

- **TRANSITION ZONE**

The volume between the flushed zone and the undisturbed zone in which the mud filtrate has only partially displaced the moveable formation fluids

- **UNDISTURBED ZONE**

The part of the formation that has not been affected by invasion.

3.2.3 INVASION RESISTIVITY PROFILES

The changes in water saturation combine with the changes in the fluid saturation and resistivities within the invaded zone create the invasion resistivity profile. The fluid distribution within the invaded zone of a porous and permeable formation can be represented by three idealized profiles:

a) Step profile
b) Transition profile or Annulus profile

- **STEP PROFILE**

With reference to invasion, an abrupt change from the flushed zone to the undisturbed zone, with no transition zone or annulus

- **TRANSITION PROFILE OR ANNULUS PROFILE**

A realistic profile in which the distribution of fluids in the invaded section beyond the flushed zone varies with increasing distance from the borehole.

CHAPTER 4

WIRELINE LOGGING

WELL LOGGING

Well logging is the process of recording various physical, chemical, electrical, or other properties of the rock/fluid mixtures penetrated by drilling a well into the earth. In its most usual form, an oil well log is a record displayed on a graph with the measured physical property of the rock on one axis and depth (distance from the surface) on the other axis. More than one property may be displayed on the same graph. None of the logs actually measure the physical properties that are of most interest to us, such as how much oil or gas is in the ground, or how much is being produced. Such important knowledge can only be derived, from the measured properties listed above (and others), using a number of assumptions which, if true, will give reasonable estimates of hydrocarbon reserves. Thus, analysis of log data is required. The art and science of log analysis is mainly directed at reducing a large volume of data to more manageable results, and reducing the possible error in the assumptions and in the results based on them. When log analysis is combined with other physical measurements on the rocks, such as core analysis or petrographic data, the work is called petrophysical analysis. The results of the analysis are called mapable reservoir properties. The petrophysical analysis is said to be "calibrated" when the porosity, fluid saturation, and permeability results compare favorably with core analysis data. Further confirmation of petrophysical properties is obtained by production tests of the reservoir intervals.

4.1 CREATING WELL LOGS

To perform a logging operation, the measuring instrument, often called a probe or sonde, is lowered into the borehole on the end of an insulated electrical cable. The cable provides power to the down whole equipment. Additional wires in the cable carry the recorded measurement back to the surface. The cable itself is used as the depth measuring device, so that properties measured by the tools can be related to particular depths in the borehole. A logging tool is made up of a sonde and a cartridge. The sonde is the portion of the tool which gives off energy, receives energy, or both.

The cartridge contains the electrical circuitry or computer components needed to control the down hole equipment, and to transmit data to and from the surface. Combination logging tools consist of more than one sonde and cartridge, so that more than one log can be recorded on a single trip into the well bore. Surface equipment is mounted in a logging truck, van, or skid unit from which all logging operations are controlled. The logging unit (Figure 4.1) contains hoisting equipment for lowering and raising the tools in the hole, and electronic or computer equipment for controlling and recording the down hole measurements.

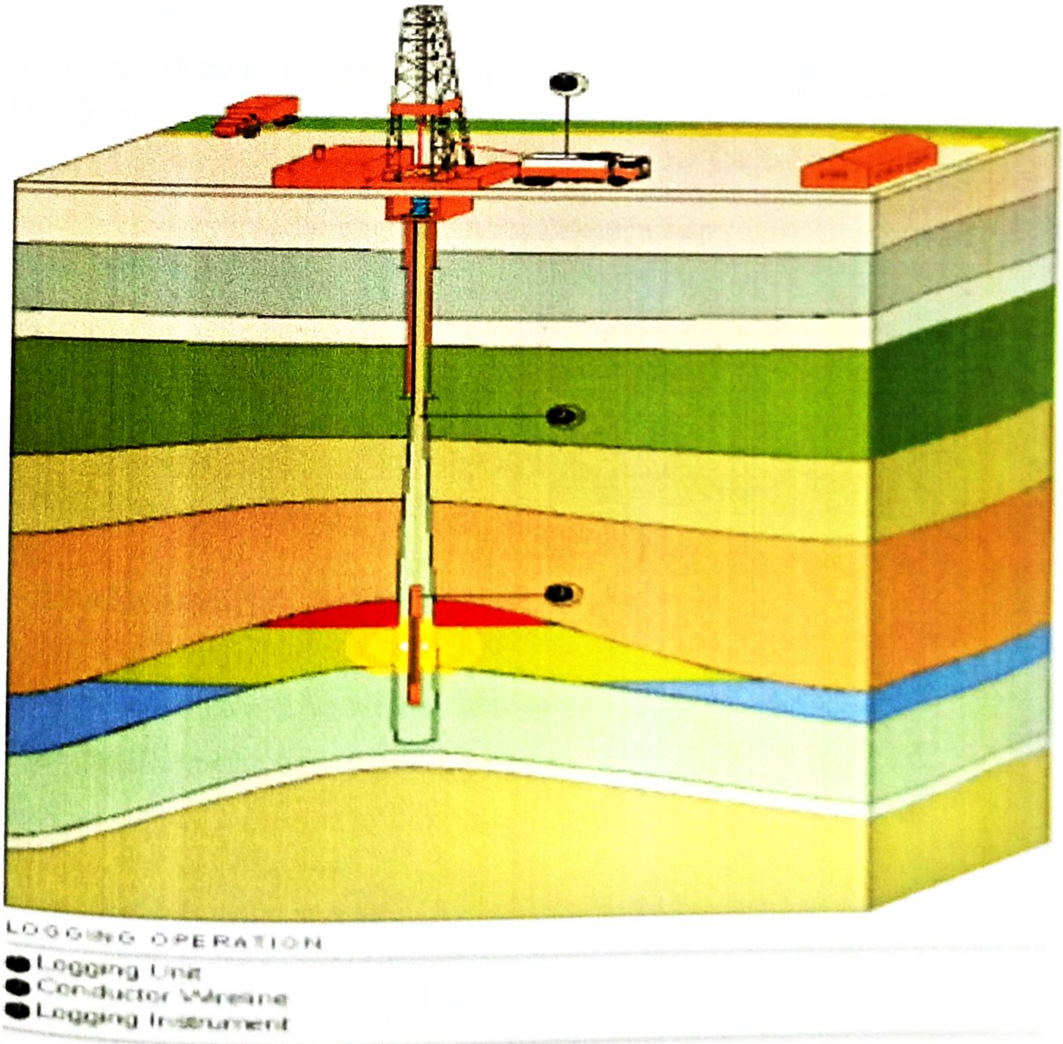


Figure 4.1 Logging Operation (after "Well logging basics" by "Baker Hughes INTEQ" 1992)

4.2 CLASSIFICATION OF LOGGING TOOLS

1. **Lithology Logs** - These logs are designed to
   - Identify permeable formations
   - Determine boundaries between permeable and non-permeable formations
   - Provide lithology data for correlation with other wells
   - Provide a degree of certainty for quantifying the formation lithology

   Examples of lithology logs are
   - Spontaneous Potential
   - Gamma Ray

2. **Porosity Logs** - These logs are designed to
   - Provide accurate lithologic and porosity determination
   - Provide data to distinguish between oil and gas
   - Provide porosity data for water saturation determination

   Examples of porosity logs are
   - Sonic/Acoustic
   - Neutron
   - Formation Density

3. **Saturation (Resistivity) Logs** -These logs are designed to
   - Determine the thickness of a formation
   - Provide an accurate value for true formation resistivity
   - Provide information for correlation purposes
   - Provide a quick indication of formation pressure

   Examples of saturation logs are
   - Normal and Lateral Devices
   - Latero logs
   - Induction Logs

4.3 ELECTRICAL LOGS

4.3.1 NORMAL RESISTIVITY LOG

BASIC CONCEPT

Resistivity logs measure the ability of rocks to conduct electrical current and are scaled in units of ohm-meters. There is a wide variety of resistivity tool designs, but a major difference between them lies in their "depth of investigation" (how far does the measurement extend beyond the borehole wall?) and their "vertical resolution" (what is the thinnest bed that can be seen?). These characteristics become important because of the process of formation "invasion" that occurs at the time of drilling. The replacement of formation water by mud filtrate involves a change of pore water resistivity. Resistivity logs determine what types of fluids are present in the reservoir rocks by measuring how effective these rocks are at conducting electricity. Because fresh water and oil are poor conductors of electricity they have high resistivities. By contrast, most formation waters are salty enough that they conduct electricity with ease. Thus, formation waters generally have low resistivities.

DEFINITION

By definition, resistivity is a function of the dimensions of the material being measured; therefore, it is an intrinsic property of that material. Resistivity is defined by the formula:

$$R = rS/L$$

Where

R = resistivity in ohm-meter

r = resistance in ohm

S = cross sectional area in square meter

L = length in meter

The current is passed between electrodes A and B, and the voltage drop is measured between potential electrodes M and N, which, in the example (Figure 4.2), are located 0.1 m apart, so that 1 V is measured rather than 10V. The current is maintained constant, so that higher the resistivity between M and N, the greater the voltage drop will be. A commutated DC current is used to avoid polarization of the electrodes that would be caused by the use of direct current.

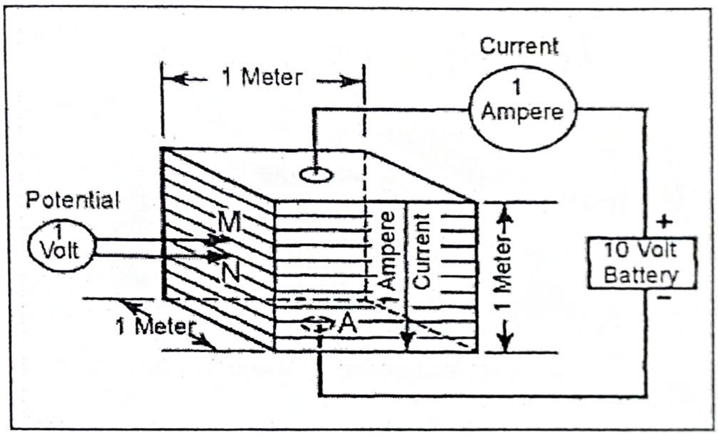


Figure 4.2. Principles of measuring resistivity in Ohm-meter.

DATA ACQUISITION FOR NORMAL RESISTIVITY LOGS

AM spacing for normal-resistivity logging, electrodes A and M are located in the well relatively close together, and electrodes B and N are distant from AM and from each other, as shown in (figure 4.2). Electrode configuration may vary in equipment produced by different manufacturers. The electrode spacing, from which the normal curves derive their name, is the distance between A and M, and the depth reference is at the midpoint of this distance. The most common AM spacings are 40 and 162 cm (16 and 64 in); however, some loggers have other spacing available, such as 10, 20, 40 and 81 cm (4, 8, 16, and 32 in). The distance to the B electrode, which is usually on the cable, is approximately 15 m; it is separated from the AM pair by an insulated section of cable. The N electrode usually is located at the surface, but in some equipment, the locations of the B and N electrodes may be reversed. Constant current is maintained between an electrode at the bottom of the sonde and a remote-current electrode.

The voltage for the long normal (162 cm (64 in)) and the short normal (40 cm (16 in)) is measured between a potential electrode for each, located on the sonde, and a remote potential electrode. The SP electrode is located between the short normal electrodes. The relative difference between the volumes of material investigated by the two normal systems. The volume of investigation of the normal resistivity devices is considered to be a sphere, with a radius approximately twice the AM spacing. This volume changes as a function of the resistivity, so that its size and shape are changing as the well is being logged.

DEPTH OF INVASION

Although the depth of invasion is a factor, short normal (40 cm (16 in or less)) devices are considered to investigate only the invaded zone, and long normal (162 cm (64 in)) devices are considered to investigate both the invaded zone and the zone where native formation water is found (Figure 4.3).

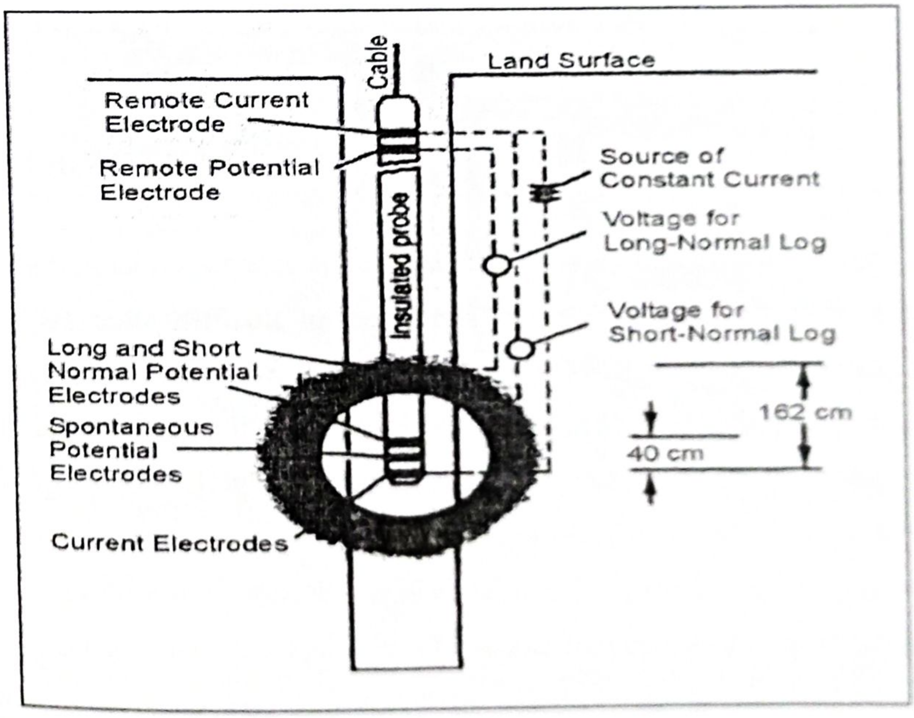
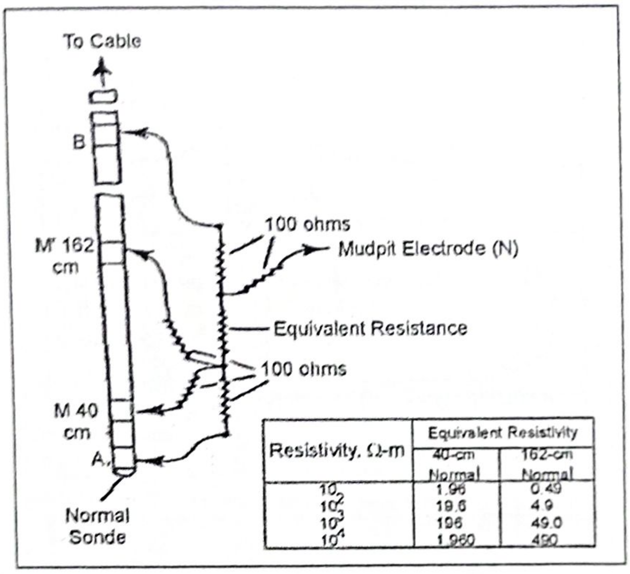


Figure 4.3 System used to make 40- and 162 cm (16- and 64-in) normal resistivity logs. Shaded areas indicate relative size volumes of investigation.

CALIBRATION

Normal-resistivity logging systems (Figure 4.4) may be calibrated at the surface by placing fixed resistors between the electrodes.



Resistivity, Ω-m	Equivalent Resistivity	
	40-cm Normal	162-cm Normal
10	1.96	0.49
10^2	19.6	4.9
10^3	196	49.0
10^4	1,960	490

Figure 4.4 System for calibrating normal resistivity equipment.

DATA INTERPRETATION

Long normal response is affected significantly by bed thickness; this problem can make the logs quite difficult to interpret.The bed thickness effect is a function of electrode spacing. The theoretical resistivity curve (solid line) and the actual log (dashed line) for a resistive bed, with a thickness six times the AM spacing, is shown in the top part of the figure. Resistivity of the limestone is assumed to be six times that of the shale, which is of infinite thickness. With a bed thickness six times AM, the recorded resistivity approaches, but does not reach, the true resistivity (R_t); the bed is logged as being one AM spacing thinner than it actually is. The actual logged curve is a rounded version of the theoretical curve, in part because of the effects of the borehole. The log response when the bed thickness is equal to or less than the AM spacing is illustrated in the lower half of figure (Figure 4.5).

The curve reverses, and the high-resistivity bed actually appears to have a lower value than the surrounding material. The log does not indicate the correct bed thickness, and high-resistivity anomalies occur both above and below the limestone. Although increasing the spacing to achieve a greater volume of investigation would be desirable, bed-thickness effects would reduce the usefulness of the logs except in very thick litho logic units.

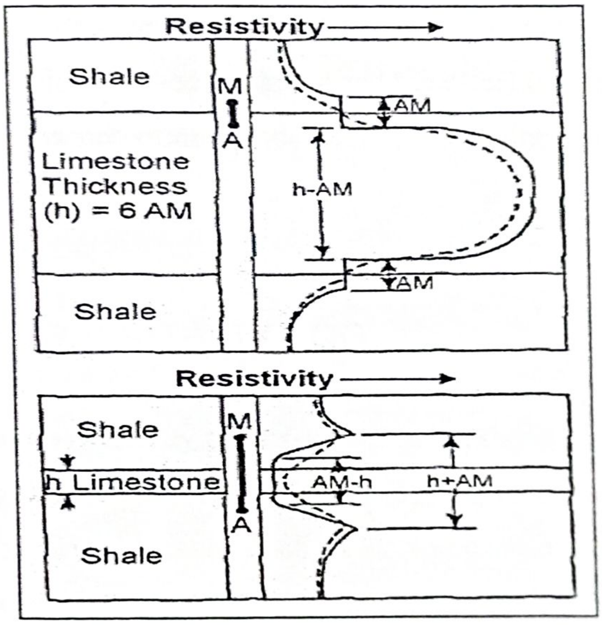


Figure 4.5 Relation of bed thickness to electrode spacing for normal devices at two thicknesses.

4.3.2 LATERAL RESISTIVITY LOG

Lateral resistivity measurements are used when it is necessary to obtain deep formation resistivity measurements. Deep formation resistivity is a close approximation of true resistivity where invasion is small. In cases of deep invasion, interpretation must include a correction for the invading borehole fluid. Due to the larger spacing of electrodes used in this method, thin formations are less noticeable on the log. Lateral logs are made with four electrodes like the normal logs but with a different configuration of the electrodes.

The potential electrodes M and N are located 0.8 m apart; the current electrode A is located 5.7m above the center (0) of the MN spacing in the most common petroleum tool, and 1.8m in tools used in groundwater. Lateral logs are designed to measure resistivity beyond the invaded zone, which is achieved by using a long electrode spacing. They have several limitations that have restricted their use in environmental and engineering applications. Best results are obtained when bed thickness is greater than twice AO, or more than 12 m for the standard spacing. Although correction are available, the logs are difficult to interpret. Anomalies are asymmetrical about a bed, and the amount of distortion is related to bed thickness and the effect of adjacent beds. For these reasons, the lateral log is not recommended for most engineering and environmental applications.

4.3.3 FOCUSED RESISTIVITY LOG

Focused electrode resistivity tools are used in boreholes that have low resistivity mud or other drilling fluids. Normal and lateral logging tools tend to conduct current through the borehole fluid in this case. Focused electrode systems are designed to reduce or eliminate borehole fluid conduction. The current emanating from the tool therefore flows into the surrounding formation and provides a more accurate measurement of formation resistivity.

Focused resistivity systems were designed to measure the resistivity of thin beds or high-resistivity rocks in wells containing highly conductive fluids. A number of different types of focused resistivity systems are used commercially such as "guard" or "laterolog." Focused or guard logs can provide high resolution and great penetration under conditions where other resistivity systems may fail. Focused-resistivity devices use guard electrodes above and below the current electrode to force the current to flow out into the rocks surrounding the well. The depth of investigation is considered to be about three times the length of one guard, so a 1.8 m guard should investigate material as far as 5.5 m from the borehole.

The sheet like current pattern of the focused devices increases the resolution and decreases the effect of adjacent beds in comparison with the normal devices. Micro focused devices include all the focusing and measuring electrodes on a small pad; they have a depth of investigation of only several centimeters. Because the geometric factor, which is related to the electrode spacing, is difficult to calculate for focused devices, calibration usually is carried out in a test well or pit where resistivities are known. When this is done, the voltage recorded can he calibrated directly in terms of resistivity. Zero resistivity can be checked when the entire electrode assembly is within a steel-cased interval of a well that is filled with water.

Correction for bed thickness (h) is only required if h is less than the length of M, which is 6 in. on some common tools. Resistivities on guard logs will approach Rt and corrections usually will not be required if the following conditions are me. $Rm/Rw < 5$, $Rt/Rm > 50$, and invasion is shallow. If these conditions are not met, correction and empirical equations are available for obtaining R, (Pirson, 1963).

4.3.4 MICRORESISTIVITY LOG

Micro electrode resistivity tools have small electrodes attached to a non conductive pad that is pressed against the borehole while logging. These tools are designed to measure the resistivity of the combined mud filtrate (Rmf) and resistivity of the flushed zone (Rxo). The objective is to obtain information about formation porosity and permeability. The small spacing used in the electrodes make this tool very accurate in establishing bed boundaries.

A large number of microresistivity devices exist, but all employ short electrode spacing so that they have a shallow depth of investigation. They can be divided into two general groups: focused and non-focused. Both groups employ pads or some kind of contact electrodes to reduce the effect of the borehole fluid. Non-focused sondes are designed mainly to determine the presence or absence of mud cake, but they also can provide very high-resolution lithologic detail.

Names used for these logs include micro log, minilog, contact log, and micro-survey log. Focused microresistivily devices also use small electrodes mounted on a rubber-covered pad forced to contact the wall of the hole hydraulically or with heavy spring pressure. The electrodes are a series of concentric rings less than 2.5 cm apart that function in a manner analogous to a laterolog system. The radius of investigation is from 76 to 127 mm, which provides excellent lithologic detail beyond the mud cake, but probably is still within the invaded zone.

4.3.5 INDUCTION LOGGING

BASIC CONCEPT

Induction logging devices originally were designed to make resistivity measurements in oil-based drilling mud, where no conductive medium occurred between the tool and the formation. The basic induction logging system is shown in (Figure 4.6) . A simple version of an induction probe contains two coils: one for transmitting an AC current, typically 20 to 40 kHz, into the surrounding rocks, and a second for receiving the returning signal. The transmitted AC generates a time-varying primary magnetic field, which induces a flow of eddy currents in conductive rocks penetrated by the drill hole. These eddy currents set up secondary magnetic fields, which induce a voltage in the receiving coil. That signal is amplified and converted to DC before being transmitted up the cable. Magnitude of the received current is proportional to the electrical conductivity of the rocks. Induction logs measure conductivity, which is the reciprocal of resistivity. Additional coils usually arc included to focus the current in a manner similar to that used in guard systems. Induction devices provide resistivity measurements regardless of whether the fluid in the well is air, mud, or water, and excellent results are obtained through plastic casing. The measurement of conductivity usually is inverted to provide curves of both resistivity and conductivity. The unit of measurement for conductivity is usually MilliSiemens per meter (mS/m), but milliohms per meter and micromhos per centimeter are also used. One S/m is equal to 1,000 ohm-m.

Calibration is checked by suspending the sonde in air, where the humidity is low, in order to obtain zero conductivity. A copper hoop is suspended around the sonde while it is in the air to simulate known resistivity values. The volume of investigation is a function of coil spacing, which varies among the sondes provided by different service companies. For most tools, the diameter of material investigated is 1.0 to 1.5 m; for some tools, the signal produced by material closer to the probe is minimized. It shows the relative response of a small-diameter, high-frequency induction tool as a function of distance from the borehole axis. These smaller diameter tools, used for monitoring in the environmental field, can measure resistivities up to 1,000 ohm-m

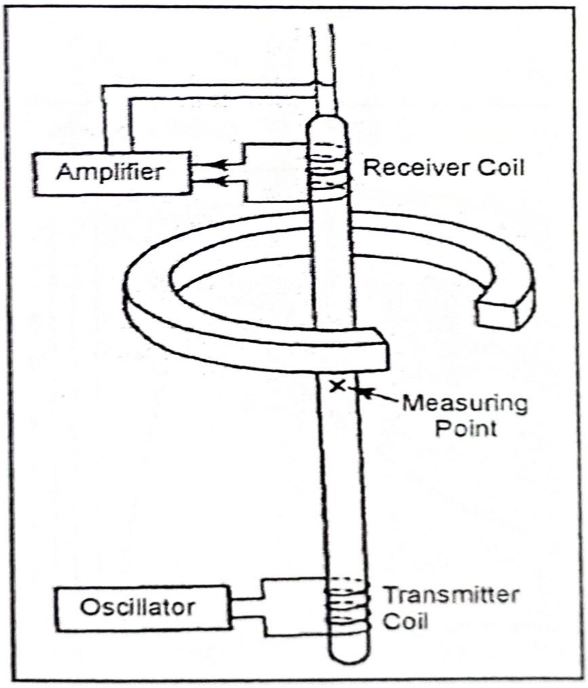


Figure 4.6 System used to make induction logs

DATA INTERPRETATION

Induction logs are becoming widely used on environmental projects for monitoring saline contaminant plumes by logging small-diameter, PVC or fiberglass-cased wells. They also provide high-resolution information on lithology through casing and are excellent for this purpose when combined with gamma logs. The response curve (Figure 4.7) is for a tool that can be used in 5-cm dia (2-in) casing. There is a comparison of induction resistivity logs in an open and cased well (Figure 4.8) with a 40-cm (16-in) normal resistivity log. The open hole was 23 cm (9 in) and drilled with a mud rotary system. The well was completed to a depth of 56 m with 20-cm (4-m) Schedule 80 PVC casing and neat cement, bentonite seal, and gravel pack. Even in such a large-diameter well with varying completion materials, the differences in resistivity are not significant.

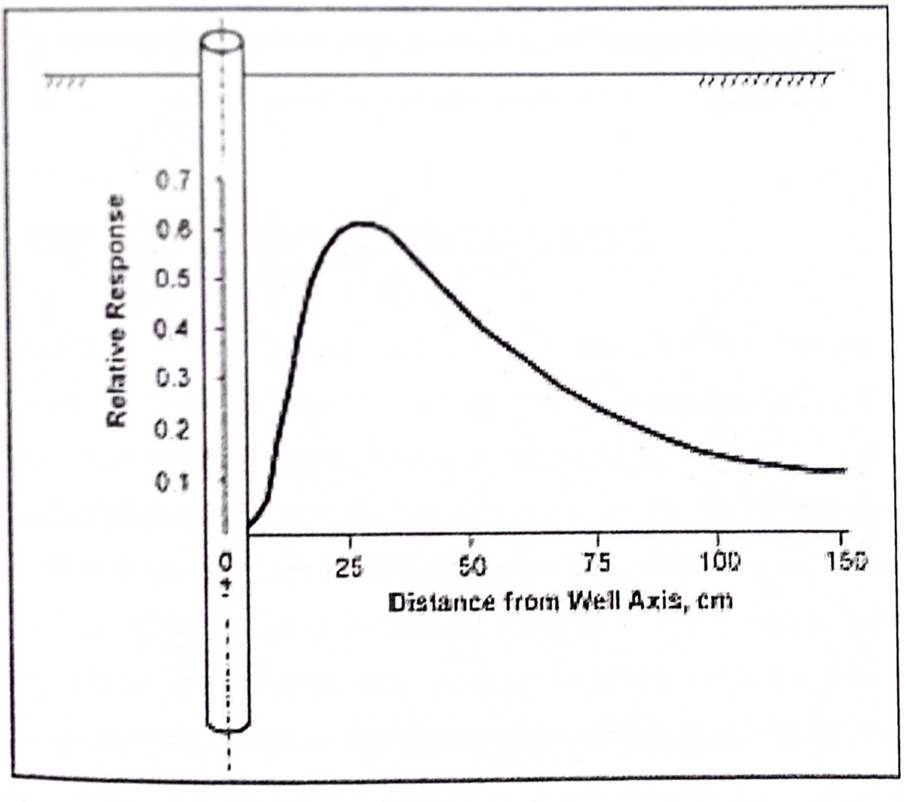


Figure 4.7 Relative response of an induction probe with radial distance from borehole axis

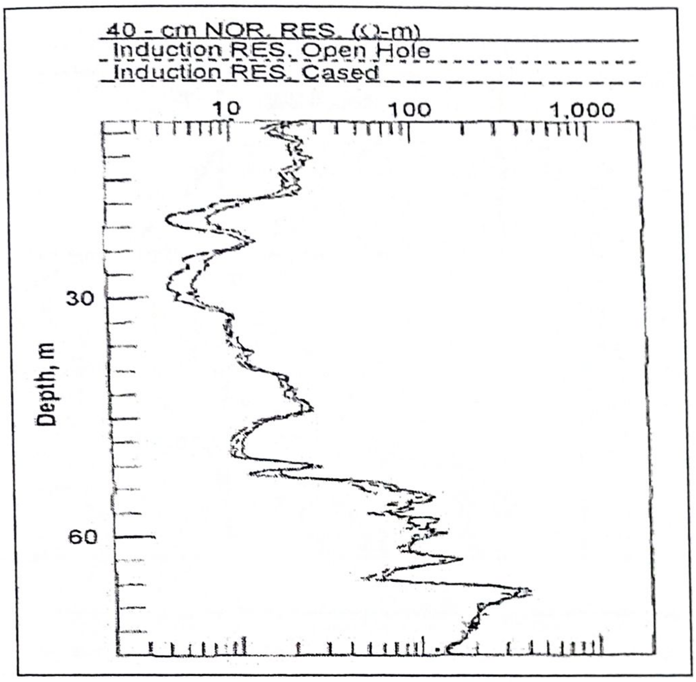


Figure 4.8 Comparison of open hole induction log with normal log and induction log made after casing was installed.

4.4 SPONTANEOUS POTENTIAL LOG

SP (spontaneous potential) logs indicate the permemabilities of rocks in the well by measuring the amount of electrical current generated between the drilling fluid and the formation water that is held in pore spaces of the reservoir rock (Figure 4.9). Porous sandstones with high permeabilities tend to generate more electricity than impermeable shales. Thus, SP logs are often used to tell sandstones from shales. Spontaneous potential (SP) is one of the oldest logging techniques. It employs very simple equipment to produce a log whose interpretation may be quite complex, particularly in freshwater aquifers. The spontaneous potential log (incorrectly called self potential) is a record of potentials or voltages (Figure 4.10) that develop at the contacts between shale or clay beds and a sand aquifer, where they are penetrated by a drill hole.

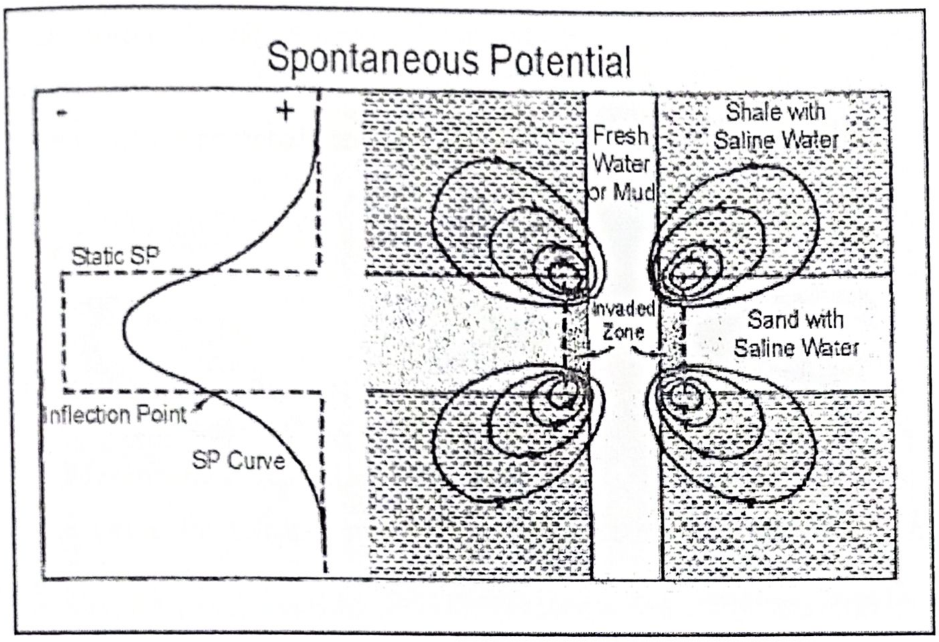


Figure 4.9 Flow of current at typical bed contacts and the resulting spontaneous potential curve and static values.

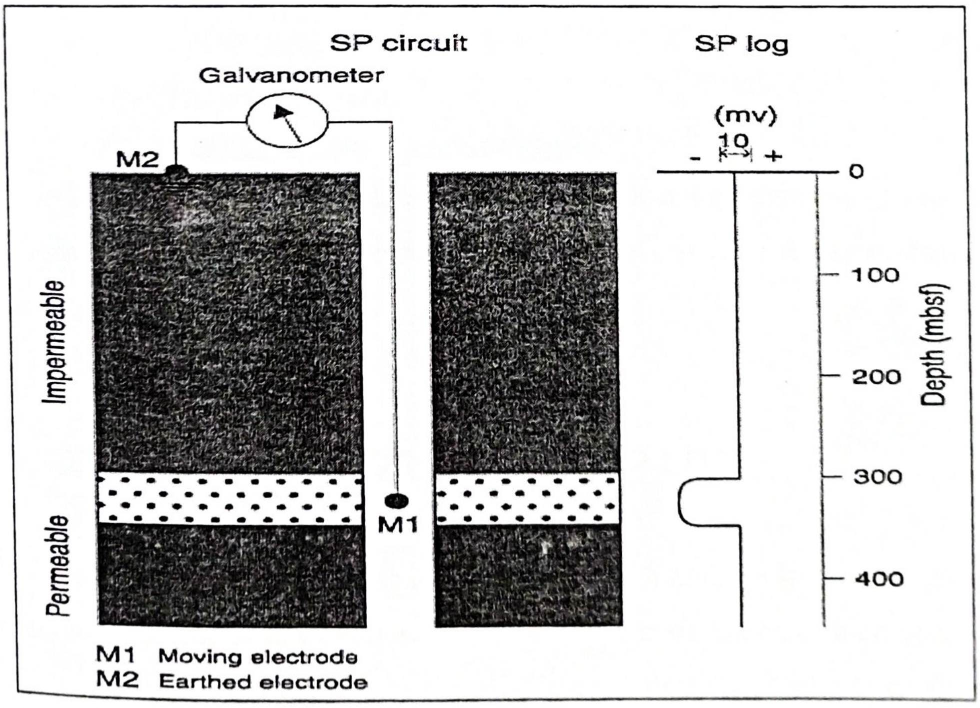


Figure 4.10 Illustration of the principle of the spontaneous potential (SP) log

4.4.1 ORIGIN OF SP

There are two types of potentials present in the earth,

1- Electochemical
2- Electrokinetic

ELECTROCHEM1CAL POTENTIAL

a) Shale or Membrane Potential

Shale acts as ion selective membrane. It allows the cations only due to movement of ions the electromotive force is generated.

b) Liquid Junction Potential

The current flowing across the junction between the solutions of different salinity is produced by an electromagnetic force called liquid Junction Potential. The magnitude of the liquid junction potential is only about the membrane potential.

ELECTROKINETIC POTENTIAL

In the borehole, an electrokinetic's emf is produced by the flow of mud into the formations due to difference in pressure, when mud cake is formed than no more electro kinetic potential is produced.

4.4.2 DETERMINATION OF SP FROM SP LOG

Total track of potential on sp log is 200 mv. Each division is of 20 mv. Sometimes it depends on the borehole conditions. First of all we mark the shale base line on the sp log. Then we draw the sand line at the maximum deflection of sp curve. The interval between the shale base line and sand base line is determined.

FACTORS AFFECTING THE SHAPE AND AMPLITUDE OF SP CURVE

A number of factors affect the shape and amplitude of the sp including

- Rmf/Rw
- bed thickness
- bed resistivity
- bore hole diameter
- invasion
- shaliness of porous and permeable bed

APPLICATION OF SP LOG

- Differentiate shaly from non shaly formations
- Detect permeable beds
- Locate bed boundaries for correlation
- Determine the value of formation water resistivity (R_w)

4.5 THE GAMMA RAY LOG

GR (gamma ray) logs measure radioactivity to determine what types of rocks are present in the well. Because shales contain radioactive elements, they emit lots of gamma rays. On the other hand, clean sandstones emit very few gamma rays. The GR Log measures the natural radioactivity of the formations. GR Log gives the response about the shale content of the formations in the sedimentary rocks. Because the radioactive elements are present in the clays and shales.

PROPERTIES OF GR LOG

Gamma Rays are bursts of high energy electromagnetic waves that are emitted spontaneously by some radioactive elements. Sources of Gamma Rays: Potassium, Uranium, Thorium

COMPTON SCATTERING COLLISIONS

Where a gamma ray collides with an electron orbiting some nucleus. In this case, the electron is ejected from its orbit and the incident gamma ray loses energy.

PHOTO-ELECTRIC EFFECT

Where a gamma ray collides with an electron, is absorbed, and transfers all of its energy to that electron. In this case, the electron is ejected from the Gamma Rays experience Compton Scattering collisions with atoms of the formation material, losing energy after each strike. After losing energy, it is absorbed by means of the photo electric effect. The rate of absorption varies with formation density. The Gamma Ray log response after appropriate corrections for borehole etc. is proportional to the weight concentrations of the radioactive material in the formation.

$$GR = \Sigma \rho_i V_i A_i / \rho_b$$

Where,

ρ_i = Densities of the radioactive material

V_i = Bulk Volume Factors of the minerals

A_i = Proportionality factors corresponding to the radioactive of the minerals

ρ_b = Bulk Density of the Formation

DEPTH OF THE INVESTIGATION

The depth of the investigation of the GR Log is about 1 feet.

EQUIPMENT

A sonde contains a scintillation counter detector for measuring the radiations from the nearby formation. Scintillation counters are used for their high efficiency. Gamma Rays from the formation produce tiny flashes of light on the NaI Crystal. These flashes are then converted to an electrical] pulses. Pulse size depends on the amount of energy absorbed from the gamma rays.

CALIBRATION

The primary calibration standard for GR tool is the API Test. A field calibration standard is used to normalize each tool to the API standard & the logs are calibrated in the API units .The radioactivities in sedimentary formations generally ranges from a few API units in anhydrite or salt to 200 or more in shales.

BORE- HOLE CORRECTIONS CURVES

The GR deflection is a function not only of the radioactivity & density but also of the hole conditions, since the material interposed between the counter & the formation absorbs the GR .The following is used to make the borehole corrections.

APPLICATIONS

- Gamma Ray Log is used for defining the shale beds.
- Gamma Ray Log is used in non conductive muds, empty or air drilled holes, cased holes.
- Gamma Ray Log is the quantitative indicator of the shale.
- It is used for the detection & evaluation of the radioactive minerals (K, U)
- It is also used for the detection of coal, halite, anhydrite and gypsum.
- Gamma ray Log is applicable when Rmf = Rw

4.5.1 THE NATURAL GAMMA RAY SPECTROMETERY LOG

The NGS Log measures the natural radioactivity of the formations. The GR Log measures the total radioactivity, but the NGS Log measures both the number of the gamma rays, the energy level of each & also the concentrations of radioactive elements like;

- Potassium
- Thorium
- Uranium

MEASUREMENT PRINCIPLE

The NGS Tool use a NaI scintillation Detector contained in the pressure housing & it is in the skid mounted shape. Because of the interaction & the response of the NaI scintillation detector. The original spectrum is degraded to smeared spectra. The high energy part of the detected spectrum is divided into three energy windows Wl, W2, W3. Each covering a characteristic peak of the three radioactive series.

LOG PRESENTATION

This Log provides a recording of the concentrations of the radioactive elements in the formation. The thorium & uranium concentrations are presented in ppm while the potassium is in the percentage. A standard gamma ray curve is recorded & presented in track 1, it is in the API units.

BORE HOLE CORRECTION CURVE

The NGS tool response is a function not only of the concentration of the

- Potassium
- Thorium
- Uranium

But also of the Hole conditions (hole size, mud wt. etc) & the interaction of the three radioactive elements themselves.

APPLICATIONS

It can be used to detect & evaluate the radioactive minerals. It can be used to identify types of clay & to calculate clay volumes which further tell us the depositional environment, digenetic history, the petrophysical characteristics of the rocks. In less complex mixtures it is used to identify minerals with greater certainty and volume to be calculated with greater accuracy.

4.6 POROSITY LOGS

4.6.1 NEUTRON LOG

Neutron logs, determine porosity by assuming that the reservoir pore spaces are filled with either water or oil and then measuring the amount of hydrogen atoms (neutrons) in the pores. The neutron log records counts of the collisions between neutrons that radiate from a tool source and hydrogen atoms within the rock of the borehole wall. So, the log is mainly a measure of hydrogen concentration (mostly contained by the pore fluids of the formation).

BASIC CONCEPTS

This log is a member of the porosity log family .Neutron Porosity tool use a radioactive source, such as Plutonium, Beryllium or Americium, to bombard the formation with high energy neutrally charged particles called neutrons (Figure 4.11). When these high energy neutrons collide with the various atoms of both formation material and fluids, they begin to lose their energy, the amount of loss can be stated as

$$FEloss=4m/\ (1+m)^2$$

Where,

FE = Represents the fractional energy loss

m=Mass of the struck nucleus in atomic mass unit

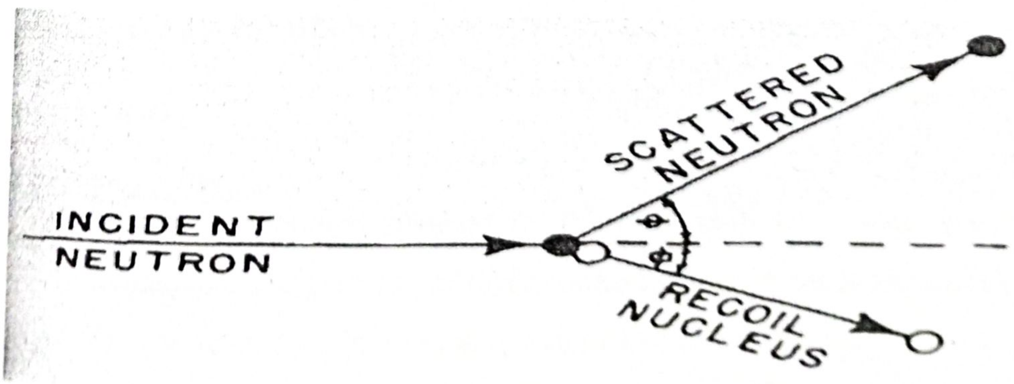


Figure 4.11 Collision of neutron

If the atom is small, the more energy the neutron will loss on collision. Collision depends on angle and mass. Energy is lost by neutrons due to collision. Hydrogen Index plays a vital role. Neutron have the same size as the Hydrogen atoms if there are more no of hydrogen atoms in the pore space, more neutrons collide, thereby losing their energy and become captured. The count rate is consequently reduces. The pore space is usually filled with water, oil, gas. Water and oil have the same amount of hydrogen while gas has the lower hydrogen density. The neutron tool can not differentiate between oil and water, but gas can be detected.

CNL TOOL

The CNL Compensated Neutron Log tool contains a radioactive source that bombards the formation with fast neutrons. These neutrons are slowed and then captured, primarily by hydrogen atoms in the formation. The slowed neutrons deflected back to the tool are counted by detectors. Since the tool responds primarily to the hydrogen content of the formation, the measurements are scaled in porosity units. Both epithermal (intermediate) neutrons and thermal (slow) neutrons can be measured depending on the detector design.

The CNT-H tool uses two thermal detectors for a borehole-compensated thermal neutron measurement. The CNT-G Dual-Energy Neutron Log (DNL) tool has two thermal and two epithermal detectors and provides separate energy measurements for gas detection and improved reservoir descriptions. The epithermal measurement can be made in air or gas-filled holes.

CALIBRATION

The primary calibration standard for the CNL tools is a series of water filled laboratory formations. The porosity of these controlled formations is known within ±0.5 porosity units. The secondary calibration is water filled calibrating tank.

API NEUTRON UNIT

One API unit is defined as 1/1000 of the difference between the instrument zero (tool response to zero radiation) and log deflection opposite a 6 ft. zone of Indiana Limestone in the neutron calibration pit. This limestone has 19 % porosity.

LOG PRESENTATION

- It is recorded in tracks 2 and 3 with a linear scale
- The unit used is Neutron API unit
- The caliper is recorded in track 1
- An optional gamma ray log can also be recorded in track 1

FACTORS AFFECTING THE MEASUREMENTS

- Neutron absorbers
- Hydrocarbons
- Mud density
- Mud salinity
- Hole diameter
- Casing and cement

APPLICATIONS

- Evaluation of porosity.
- Detection of gas or light hydrocarbons.
- Evaluation of hydrocarbon density (in conjunction with other logs).
- Identification of Lithology (in conjunction with other logs).

4.6.2 DENSITY LOG

It is a continuous record of the variation in the density of the lithological column cut by the borehole. The density log is a measure of apparent density of the rock and is computed from the absorption of gamma rays emitted from a tool radioactive source by the formation. A Density Log when properly calibrated will provide reliable information about matrix bulk density. When density is known and a specific matrix is assumed then porosity of the matrix may be determined.

BULK DENSITY

The term bulk density is applied to the overall or gross density of the unit volume of the rock. In the case of porous rock it includes the fluid density in the pore spaces as well as the grain density of the rock..

NEUTRON – BULK DENSITY CROSS-PLOT

Combination of data from a Neutron Porosity Log and Bulk Density log can be helpful in identification of lithology. A chart is used that has the known relationship between Neutron Porosity and Bulk Density for three matrices; Sandstone, Limestone, and Dolomite. It is possible to determine ratio of Sandstone/Limestone and obtain a more accurate porosity using the cross-plot chart. Results from the cross-plot chart should be correlated with known lithological information.

PRINCIPLE

A radioactive source, applied to the borehole wall in a shielded side wall skid, emits medium energy gamma rays into the formations. These gamma rays may be thought of high velocity particles that collide with the electrons of the formation. At each collision a gamma ray losses some, but not all of its energy to the electrons, and then continues with the diminished energy. This type of interaction is called Compton scattering.

EQUIPMENT

To minimize the effect of mud cake, a shield is used around the radioactive source to focus the gamma radiations into formations. Another shield is used to prevent the rays from reaching the detector directly, and in certain instruments (Figure 4.12), to receive the preferential electrons.

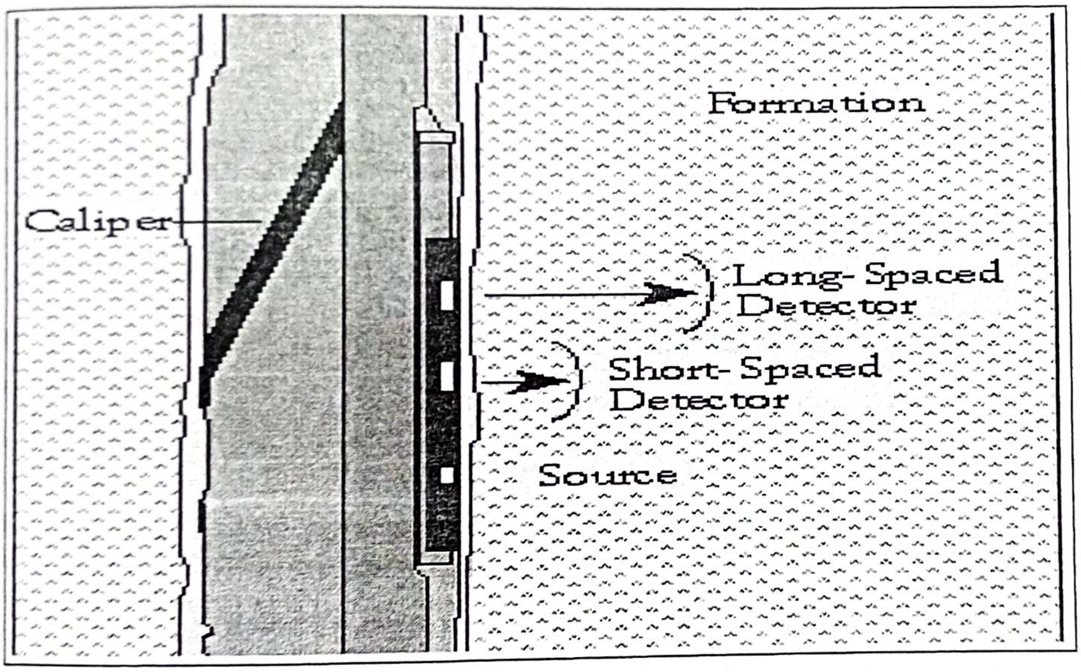


Figure 4.12 Density tool

PRINCIPLE & THEORY

Gamma rays are "electromagnetic" waves; so indeed are x-rays and visible light. The only difference between gamma ray and x-rays of the same wave length is their mode of origin. Gamma rays are emitted from within nuclei excited by radioactive or other high energy processes; x-rays are produced outside the nucleus. Radiation is not a smooth continuous flow of energy; rather it is emitted in discontinuous bursts or "bundles", are called "quanta". The more common term applied to a quantum of electromagnetic radiation is the "photon".

At energies above 0.51 Mev, photons may be treated as if they were particles having "mass". The shorter the wave length of the photon, the greater it's "mass". Density logging devices utilize gamma ray sources which produce photons in the energy range of 0.66 Mev to 1.33 Mev. If the source is Cesium 137, the energy level is constant at 0.66 Mev, if the source is Cobalt 60, two photons are emitted having energies of 1.17 Mev. and 1.33JMev.

There are three modes of gamma ray interaction that contribute to the response measured by density logging instruments. The energy of the "incident" photon determines which one of the following interactions with occurs:

(1) Compton Scattering
(2) Photoelectric Effect
(3) Pair Production

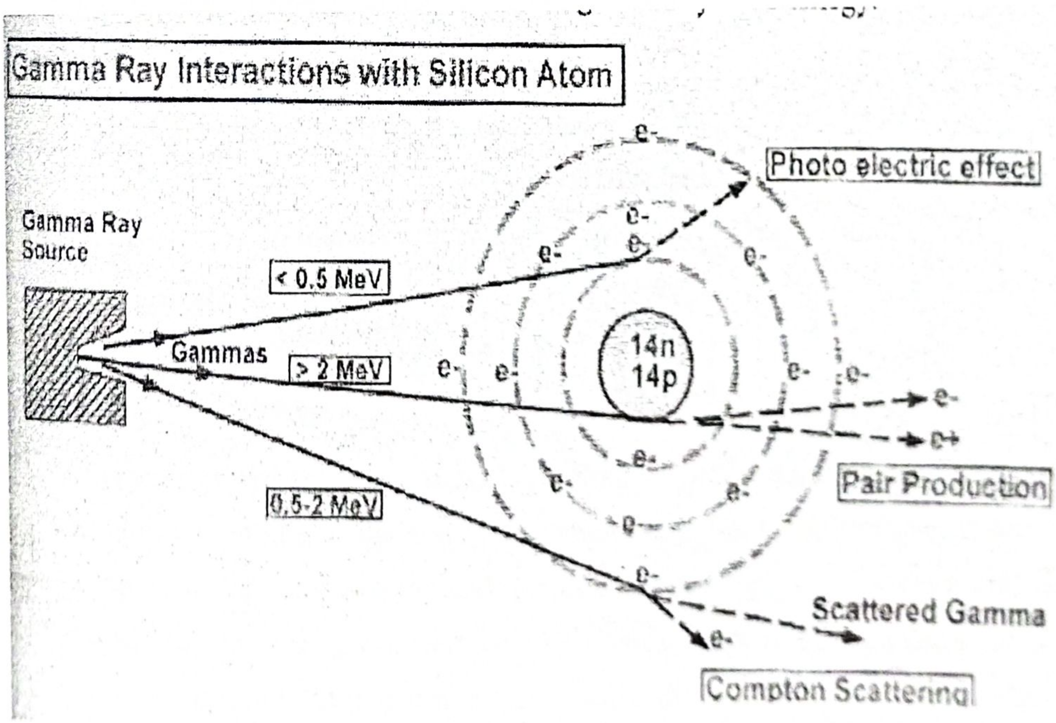


Figure 4.13 Gamma Ray interactions with silicon atom

COMPTON SCATTERING

Where a gamma ray collides with an electron orbiting some nucleus. In this case, the electron is ejected from its orbit and the incident gamma ray loses energy.

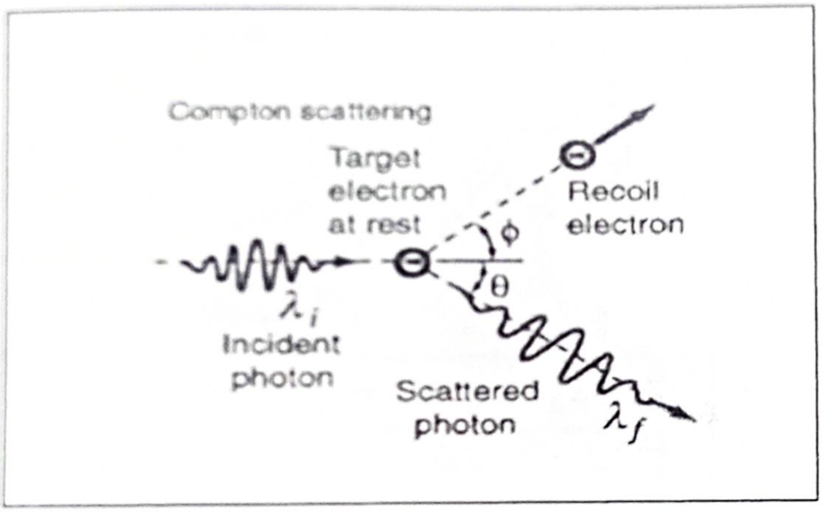


PHOTO ELECTRIC EFFECT

Where a gamma ray collides with an electron, is absorbed, and transfers all of its energy to that electron. In this case, the electron is ejected from the atom.

PAIR PRODUCTION

Where a gamma ray interacts with an atom to produce an electron and positron. These will later recombine to form another gamma ray. Photoelectric interaction can be monitored to find the lithology-related parameter, Pe. For the conventional density measurement, only the Compton scattering of gamma rays is of interest. Conventional logging sources do not emit gamma rays with sufficient energies to induce pair production; therefore pair production will not be a topic of this discussion. Since the density of a mixture of components is a linear function of the densities of its individual constituents, it is a simple matter to calculate the porosity of a porous rock.

Let the bulk volume model of a clean formation with water-filled pore space Unit volume of porous rock consists of a fraction made up of water and a fraction (1- Φ) of solid matrix in (Figure 4.14).

Simple rearrangement of the terms leads to an expression for porosity given by:

$$\Phi = (\rho_{ma} - \rho_b) / (\rho_{ma} - \rho_f)$$

Where;

ρ_{ma} = assumed matrix density

ρ_f = fluid density

ρ_b = measured bulk density

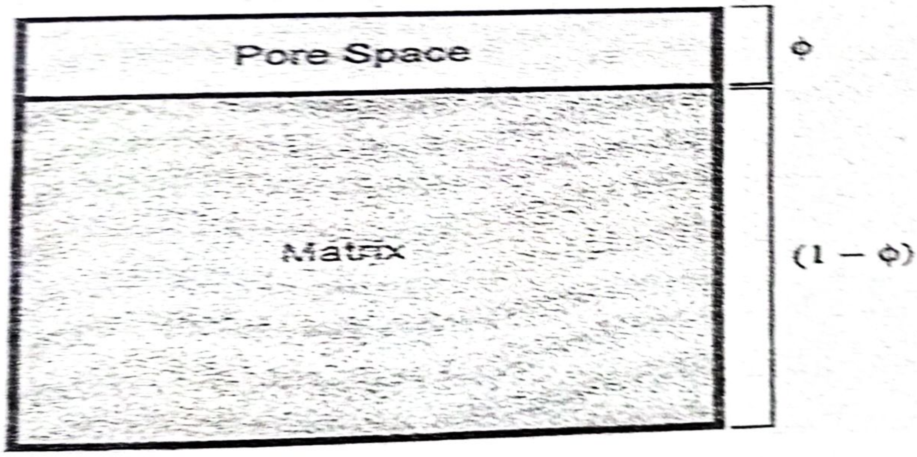


Figure 4.14 Matrix and pore space

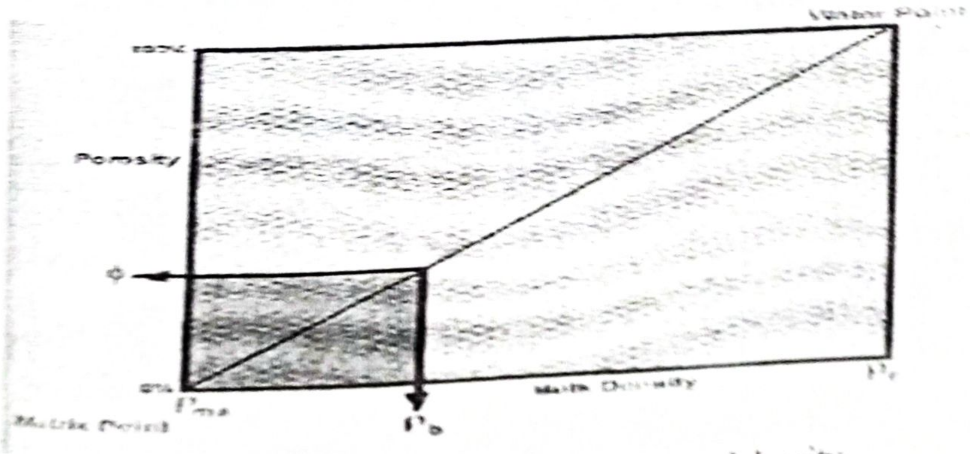


Figure 4.15 Graph between porosity and density

Where bulk density ρb is plotted against porosity Φ (Figure 4.15). Note that points falling on the line meeting the matrix point (ma, 0= 0%) and the water point (ρf, Φ =1 100%) represent possible cases extending from a zero-porosity rock matrix to 100% porosity. Any intermediate value of ρb corresponds to some porosity Φ. The matrix density in normal reservoir rocks varies between 2.87 gm/cc (dolomite) and 2.65 gm/cc (sandstone). The fluid density of normal brines ranges from 1 to 1.1 gm/cc and is controlled by the properties of the invading mud filtrate in permeable zones. Porosity derived from a density log is denoted as Φd. The density log gives reliable porosity values, provided the borehole is smooth, the formation is shale-free, and the pore space does not contain gas. In shaly formations and/or gas-bearing zones, it is necessary to refine the interpretative model to make allowances for these additions or substitutions to the rock system.

APPLICATIONS

The Formation Density log has a number of applications:

- Measuring density of the formation
- Calculation of porosity
- When combined with sonic travel times, the density data gives the acoustic impedance, which is important for calibration of seismic data
- Identification of evaporites
- Gas detection in reservoirs when used in combination with the neutron log
- The Pe curve is a good lithology indicator. The influence of reservoir porosity and fluid content (including gas) on the Pe is minor.

LITHOLOGIC DENSITY TOOL

The Pe, or litho density log, run with the litho density tool (LDT), is another version of the standard formation density log. In addition to the bulk density (rb), the tool also measures the photoelectric absorption index (Pe) of the formation. This new parameter enables a lithological interpretation to be made without prior knowledge of porosity.

The photoelectric effect occurs when a gamma ray collides with an electron and is absorbed in the process; so that all of its energy is transferred to the electron. The probability of this reaction taking place depends upon the energy of the incident gamma rays and the type of atom. The photoelectric absorption index of an atom increases as its atomic number, Z increases. The litho density tool is similar to a conventional density logging device, and uses a skid containing a gamma ray source and two gamma ray detectors held against the borehole wall. Gamma rays are emitted from the tool and are scattered by the formation, losing energy until they are absorbed via the photoelectric effect. Variation in Gamma Ray Spectrum for formations of different densities. This Figure also shows that an increase in the formation density results in a decrease in the number of gamma rays detected over the whole spectrum.

4.6.3 SONIC LOG

The acoustic or sonic log is a continuous record versus depth of the specific time required for a compressed wave to traverse a given distance of formation adjacent to the borehole. The acoustic tool (Figure 4.16) contains a transmitter and two receivers. When the transmitter is energized, at a rate of 10 to 20 pulses per second, the sound wave enters the formation from the mud column, travels through the formation and back to the receivers through the mud column. Formation velocity (travel time or t) is determined using the difference in arrival times at the two receivers. The system has circuits to compensate for hole size changes or any tilting of the tool. The basic measurement recorded on the log is interval travel time, which is the reciprocal of interval velocity. This parameter is recorded on the log in microseconds/foot. To convert velocity to acoustic travel time. Acoustic travel time will normally fall between 40 and 200, which corresponds to velocity readings of 25,000 to 5,000 ft/s.

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

Where: v = velocity (ft/s)

Log tracer

The acoustic curve is recorded in Tracks 2 and 3 on a linear scale. The acoustic log is usually run with Caliper and Gamma Ray curves, which are recorded in Track 1.

Attenuation of Sound Waves

All waves continue to propagate until they are completely attenuated. Attenuation is caused by several factors.

1. Some energy is reflected back into the well bore due to the change in acoustic impedance between the mud and the rock. The impedance of any material is equal to the product of its density and velocity. The greater the change in acoustic impedance the larger the amount of reflected energy. Thus, not all energy is transmitted into the formation. In large or rough holes, the energy may be so low as to cause difficulty with the sonic log readings.
2. Some energy is lost due to internal reflection inside the formation when the sound wave strikes a fracture plane or a bedding plane.
3. Spherical divergence, which reduces energy by the square of the distance from the source, takes place only on body waves.
4. Absorption occurs on all waves, which converts the mechanical energy into heat.
5. Phase interference of one wave mode with another due to varying frequency components can attenuate portions of the wave train in a variable fashion.
6. Multiple ray paths through rough borehole or altered rock usually reduce sonic amplitude, but more rarely may cause additive interference.
7. Poorly maintained logging sondes, especially earlier generations of tools, can attenuate the transmitted or received signal, by causing poor acoustic coupling with the borehole fluid.
8. Gas entrained in the mud column, and gas in the formation, can also attenuate the sonic signal, sometimes causing poor logs (cycle skipping on older logs, missing or interpolated lo curves on newer tools.

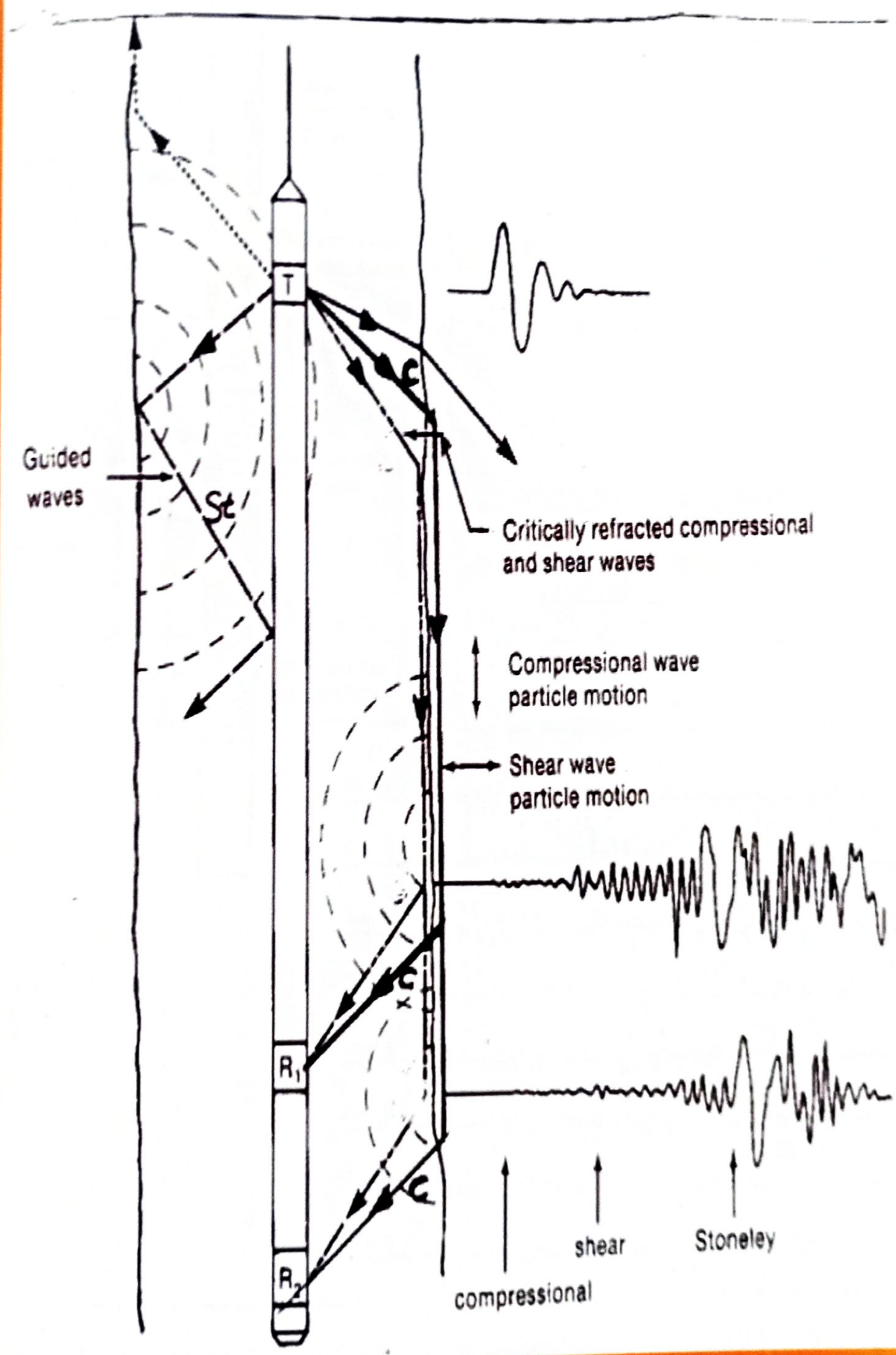


Figure 4.16 Sonic log ray paths and recorded wave forms (After "Open Hole Well logging" by "SPE reprint series" 1997).

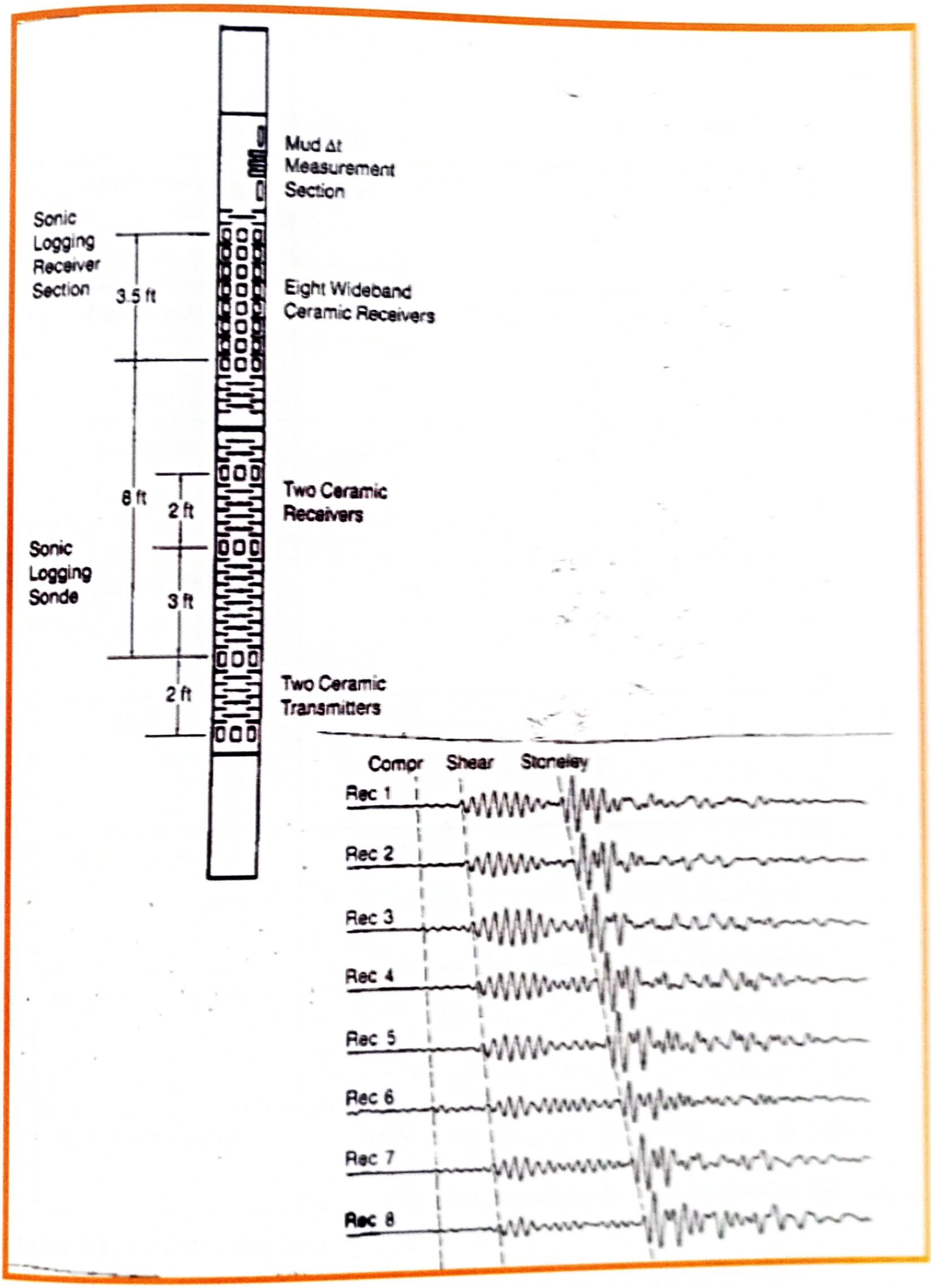


Figure 4.17 Array sonic tool and waveforms (After "Open Hole Well logging" by "SPE reprint series" 1997).

Material	Velocity (ft/sec)	t (sec/ft)
Sandstones	18,000 - 19,000	55.5 - 51.0
Limestones	21,000 - 23,000	47.5
Dolomites	23,000	43.5
Anhydrite	20,000	50.0
Halite	15,000	67.0
Casing (Iron)	17,500	57.0
Fresh Water Muds	5300	189
Salt Water Muds	5400	185

Table 4.1 Velocities and Interval Transit Times for Common Oilfield materials.

4.7 LOG SELECTION

This chapter deals with the types of logs run over reservoir sections of a well and discusses the good and bad points of each tool in the various logging environments. A "normal" logging suite involves:

Run #1: Induction - Acoustic - Gamma Ray – SP

This should always be the first tool suite run in the open hole because it does not contain radioactive sources or pad devices and has the minimum risk of sticking. This string will give a good indication of hole conditions, which should be the basis of decisions concerning other tool runs. In addition, resistivity and porosity tools on this first run will allow a quick evaluation of suspected pay zones, so that RFT and sidewall core points can be picked, and other tools cancelled, if they are not necessary.

Run #2: Density - Neutron - Spectral Gamma Ray

This should be the second tool suite run because, assuming hole conditions are good, it is best to run the logs with radioactive sources as soon as possible before hole conditions deteriorate. These tools will also give improved porosity and lithology information for evaluation.

Run #3: Dual Later log - Micro-Resistivity Log – SP

This suite is usually optional, depending on the presence of hydrocarbons. The micro-resistivity will be necessary to compute the hydrocarbon corrections to the neutron and density logs. The later log will give a better estimate of Rt in hydrocarbon (high resistivity) zones.

Run #4: Dipmeter

This should be run after the other open hole logs and before the RFT. It will give time for the other logs to be analyzed and identify depths for the RFT to be set.

Run #5: Formation Tester

If hole conditions are deteriorating, a wiper trip should be considered to condition the hole. The formation tester allows the formation pressures to be measured in the open hole and a sample of the formation fluids to be taken.

Run #6: Well Seismic Tool

This tool is either run as "check shots" to calibrate the sonic log or as a "Vertical Seismic Profile (VSP)" to give improved seismic control ahead of the bit.

Run #7: Side Wall Core Guns

These guns obtain small diameter formation samples. They must be the last tools run on the logging job because lost bullets and their connecting wires can easily stick other logging tools.

4.8 SELECTION OF TOOLS

FOR RESESTIVITY OF UNINVADED ZONE

The induction log usually gives the best value for Rt. In some cases these other logs may be as good or better.

- In thick uniform formation a standard IES may be best Rt tool.

- The responses of the 6FF40 and LL7 indicates the LL7 reads closer to Rt only when invasion is greater than 0" and Ri/Rt is less than 1/5.

- In very thin formations with shallow invasion a later log or Guard Log may be used to give bed definition and Rt.

FOR POROSITY

- If cores are available, a plot of core porosity versus log porosity will aid in selecting the best tools in future wells in a field.

- If information related to lithology is desired, more than one porosity tool should be run.

- If two porosity tools are to be run, the density and the neutron may be the best combination in most wells, but local experience is the best guide.

- The neutron along with the density or sonic can be used to detect gas.

- The neutron log and sonic log are influenced by shale and give porosities that are too high when shale is present. The density is normally influenced less by shale than the sonic or neutron.

- In areas where the Movable Oil Plot is useful, a Microlaterolog may be run along with the density, neutron or sonic. This may be the only logging technique available in deeply invaded formations where Rt cannot be obtained.

- In low porosity, regular formations, the neutron is probably the best, the density second and the sonic third. The Microlaterolog is not recommended for porosities less than 5%

4.9 TYPES OF LOGS FOR VARIOUS BORE HOLE CONDITIONS

FRESH MUD (Salinity less than 20,000 ppm Cl or Rmf/Rw >4)

Data Desired	Soft Formations	Hard Formations
Resistivity and Lithology	Induction IES Gamma Ray	Induction Laterolog IES Gamma Ray
Porosity	Formation Density Sonic/Acoustic Neutron	Formation Density Sonic/Acoustic Neutron Microlaterolog
Permeability Indication	Microlog Caliper	Microlog Microlaterolog Caliper

Table 4.2 Logs used in borehole filled with fresh mud both for soft as well as hard formations.

SALT MUD (Salinity greater than 20,000 ppm Cl or Rmf/Rw <4)

Data Desired	Soft Formations	Hard Formations
Resistivity and Lithology	Induction IES Laterolog Gamma Ray	Induction Laterolog Gamma Ray
Porosity	Formation Density Sonic/Acoustic Microlaterolog Microlog Neutron Caliper	Formation Density Sonic/Acoustic Neutron Microlaterolog Caliper
Permeability Indication	Microlog Microlaterolog Caliper	Microlog Microlaterolog Caliper

Table 4.3 Logs used in borehole filled with saline mud both for soft as well as hard formations.

OIL BASE MUD (NON CONDUCTING)

Data Desired	Soft Formations	Hard Formations
Resistivity	Induction	Induction
Lithology	Gamma Ray Formation Density Neutron Sonic/Acoustic	Formation Density Neutron Gamma Ray
Porosity	Formation Density Sonic/Acoustic Neutron	Formation Density Sonic/Acoustic Neutron
Permeability Indication	Formation Tester	Formation Tester

Table 4.4 Logs used in borehole filled with oil base mud both for soft as well as hard formations.

AIR OR GAS DRILLED HOLE

Data Desired	Soft Formations	Hard Formations
Resistivity and Lithology	As with oil-Based, no sonic	As with oil-based, no sonic
Porosity	Formation Density Neutron	Formation Density Neutron
Permeability Indication	Temperature	Temperature

Table 4.5 Logs used in borehole filled with air or gas both for soft as well as hard formations.

4.10 LOG PRESENTATION

Gamma Ray/SP/Induction/Sonic			
	Track 1:	Gamma Ray/SP	On suitable scales
		(Linear)	SP 15 mV or 10 mV per division
		Preferably	GR 0-100 API or 0-150 API
	Track 2:	Induction	0.2 to 20 Ohms m^2/m with
		(Logarithmic)	20 to 2000 Ohms m^2/m Back-up
	Track 3:	Sonic	140 to 40 MicroSecs Per Foot
		(Linear)	single spaced transit times should be
			Presented in the depth track)
	Gamma Ray/Density/Neutron		
	Track 1:	GR/Caliper	GR 0-100 API or 0-150 API
		(Linear)	CAL 6 - 16 inches (or suitable)
	Track 2+3:	FDC/CNL	CNL: +45 to -15 p.u.
		(Linear)	FDC: 1.95 to 2.95 g/cc
	Track 3:	DELTA RHO/Pe	DELTA RHO: -.25 to +.25
		(Linear)	Pe: -4.0 to +6.0
	Gamma Ray/Dual Laterolog		
	Track 1:	GR/Caliper	As Above (Linear)
	Track 2+3:	DLL/MSFL	0.2 TO 2000 Ohm m^2/m
		(Logarithmic)	

Table 4.6 Different log presentation with tracks and with suitable scales.

DETERMINATION OF BASIC RESERVOIR CHARCTERISTICS FROM LOGS

POROSOTY DETERMINATION

1. Density Logs measure effective porosity and are less affected by shale. Porosity values will be high with gas in pore spaces and with shallow invasion. Corrections will be necessary.
2. Acoustic Logs show good porosity in intergranular and inter crystalline porosity. They do not indicate all secondary porosity (vugs and fractures). Porosity values will be high in shaly zones.
3. Neutron Logs are frequently recorded with density or acoustic logs. Porosity values are high in shaly zones and low in gas zones.
4. Positive separation on Contact or Micro logs indicate porosity values which are dependent on knowledge of residual hydrocarbon saturation and are more accurate in moderate to low resistivity formations.

PERMEABLE BED LOCATION

1. SP Curve Deflection

The SP current depends primarily on formation water being in contact with mud filtrate, so there must be some permeability. There is, however, no direct relationship for a qualitative evaluation. Shaliness or hydrocarbon saturation will reduce the magnitude of the deflection.

2. Resistivity Separation

For a formation to be invaded by a drilling filtrate, it must be permeable. The resistivity differences between shallow and deep investigation curves will indicate this invasion when Rmf is greater than Rw. In hydrocarbon zones the resistivity difference will be less depending on the amount of flushing (Residual Hydrocarbon Saturations), but will usually still be evident. Contact logs are useful for this purpose.

HYDROCARBON SATURATION INDICATIONS

1. Where porosity values are assumed to be fairly constant, permeable zones having higher resistivity than adjacent sands indicate hydrocarbon saturation. The resistivity index may be estimated by the ratio (Rt/Ro).
2. When the deep reading resistivity curves have higher values than the shallow resistivity curves (Rt greater than Rxo), hydrocarbons are indicated.
3. A comparison of the deep investigation resistivity curve and a porosity log indicates hydrocarbons where resistivity values and porosities increase in the same zone.
4. Gas is indicated by lower porosity values on the neutron log. It is better than either the density or acoustic logs.

BED BOUNDRY DETERMINATION

1. The SP curve is very good for picking bed boundaries in fresh drilling muds and sand-shale sequences. Much of the SP character is lost in salt muds or in highly resistive and carbonate rocks.
2. The shallow investigation resistivity curves may be used for bed boundary determination. Normal curves will be distorted by one-half the spacing distance at each boundary. Focused current logs are excellent for this purpose. Induction logs have poor vertical resolution in thin beds.
3. The Gamma Ray log is very useful for determination bed boundaries both in open hole and cased holes. With normal logging speeds and correct time constants the vertical resolution is very good.

OTHER INFORMATIONS FROM LOGS

- Data to establish a lithology column
- The ability to correlate with other wells
- Variables to determine reserve characteristics
- Data to aid in the solution of production problems
- Data to evaluate secondary or tertiary recovery projects

EFFECTS OF CIRCULATING FLUID

- Water-base fluids, including oil emulsions, serve as an electrical bridge to a formation. Filtrate will usually displace all formation water from the invaded zone. In zones containing hydrocarbons, a residual oil or gas saturation will remain in the invaded zone. The depth of invasion is usually deeper in low porosity, low permeability zones.
- In a few wells drilled with an oil emulsion mud, the filter cake resistivity has been very high.
- Traces of oil may invade the formation when oil emulsion fluid is used.
- Any of the logs can be run in water-base muds.
- In oil-base fluids the induction, radioactivity, and acoustic logs may be used. The SP is not used.
- If oil is the continuous phase and invades the formation displacing formation, it will leave a residual saturation of formation water and gas if present.
- Oil-based "Black Magic" has blown asphalt, surfactants, ground oyster shells and little water. Barrio's "Invermul" and other inverted emulsion mud's contain about fifty percent water, but oil is the continuous phase.
- In wells drilled with air or gas, the induction and radio log may be used.

4.11 COMPANY TOOLS

This included the following kinds of tools:

- Nuclear Tools
- Resistivity Tools
- Acoustic Tools
- Electromagnetic Propagation Tools
- Magnetic Resonance Tools

THE 36 BAKER HUGHES TOOLS

Tool Code / Model	Tool Description
AC	BHC acoustilog
CDL	Compensated sensilog
CN	Compensated neutron log
DAC	Digital array acoustilog
DAL	Digital acoustilog
DEL2	Dielectric log – 200 Mhz
DEL4	Dielectric log – 400 Mhz
DIFL	Dual induction focused log
DLL	Dual laterlog
DPIL	Dual phase induction log
DPR	Dual propogation resistivity
FMT	Formation multi-tester
GR	Gamma ray log

HDIL	High-definition induction log
HDLL	High-definition lateral log
IEL	Induction electrolog
ISSB	Isolation sub - spontaneous Potential
MAC	Multipole array acoustilog
MAC2	Multipole array acoustilog
MDL	Modular density lithology
ML	Minilog
MLL	Micro Laterolog
MNP	Modular neutron porosity
MPR	Multiple propogation resistivity
MRIL	Magnetic resonance imaging log
MSL	Micro spherical laterolog
PROX	Proximity Log
RCI	Reservoir characterization instrument
SL	Spectralog
SP	Spontaneous potential
SYST	Surface system
TBRT	Thin-bed resistivity
TTRM	Temperature/tension/mud resistivity sub
WTS	ECLIPS WTS downhole common remote
XMAC	Cross-multipole array acoustilog
ZDL	Compensated Z-Densilog

Table 4.7 List of Baker Hughes wire line logging tools with models and tool description.

THE 6 HALLIBURTON TOOLS

Tool Code / Model	Tool Description
CSNG	Compensated spectral natural gamma tool
CTN	Compensated thermal neutron
DSN	Dual spaced neutron tool
NGRT	Gamma ray tool
SDL	Spectral density logging tool
SLD	Stabilized litho density

Table 4.8 List of Halliburton wire line logging tools with models and tool description.

THE 54 SCHLUMBERGER TOOLS

Tool Code / Model	Tool Description
AND	Azimuthal density neutron tool
AITB or AITC	Array induction imager tool – B or C
AITH	Array induction imager tool – H
ALATA or ALATB	Azimuthal Laterolog – A or B
AMS	Auxiliary measurement sonde
APS	Accelerator □pectrom sonde
ARC	Array compensated resistivity tool
BSP or SPAA or SPEA	Bridle spontaneous potential
CDN	Compensated density neutron

CDR	Compensated dual resistivity tool
CMRT or CMR-A or CMR-B	Combinable magnetic resonance
CNTA	Compensated neutron tool – A
CNTD	Compensated neutron tool – D
CNTG	Compensated neutron tool – G
CNTH	Compensated neutron tool – H
CNTS	Compensated neutron tool – S
SLT-BA, DSLT-BB, DSLT-BC, DSLT-H	Digitizing sonic loggin tool – BA, BB, BC, or H
DSSTA, DSSTB, DSSTC	Dipole shear sonic imager tool – A, B, or C
EPTD, EPTG	Electromagnetic Propagation Tool
HILTB, HILTC, HILTD	(with AIT) High resolution integrated logging tool – B, C, or D
HNGS-AA, HNGS-BA	Hostile natural gamma ray sonde – AA or AB
HRLT	High-resolution laterolog array tool
LDS	Litho density sonde (for IPLT)
LDTD	Litho density tool – D
NGTC, NGTD	Natural gamma ray □pectrometry tool – C or D
RFTB	Repeat formation tester – B
SDTC	Sonic digital tool – C
SGTL, SGTN	Scintillation gamma ray tool – L or N
TJ, SLTL, SLTM, SLTN, SLTQ, SLTT	Sonic logging tool – J, L, M, N, Q, or T
SON675, SON825	LWD sonic tool – 6.75 inch or 8.25 inch
SRTC	High-resolution laterolog array tool

Table 4.9 List of Schlumberger wire line logging tools with models and tool description.

CHAPTER 5

PETROPHYSICAL ANALYSIS

PETROPHYSICAL ANALYSIS

5.1 INTERPRETATION WORK FLOW

The parameters are calculated for the saturation of hydrocarbons according to work flow.

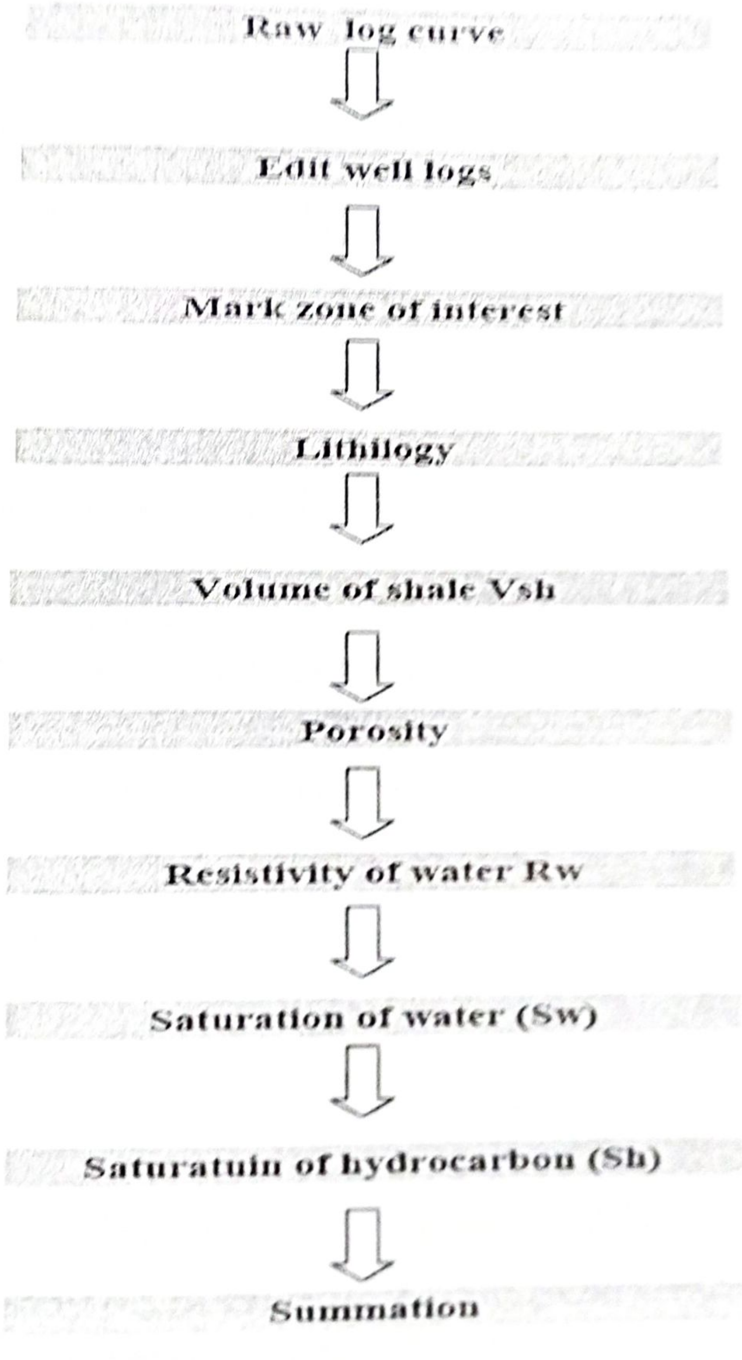


Figure 5. 1 Work flow chart

5.2 PETROPHYSICAL TECHNIQUES

In general terms the petrophysical techniques that are used to study the parameters a, m, n and R. The techniques all use the relationships defined by the Archie equation:

$$S_W^N = \frac{a}{\Phi n} \times \frac{Rw}{Rt}$$

$$= F \times \frac{Rw}{Rt}$$

$$= \frac{Ro}{Rt}$$

Where:

Where:	S_w	is the water saturation
	R_t	is the deep resistively
	R_w	is the resistivity of the formation water
	n	is the saturation exponent
	m	is the cementation exponent
	a	is the tortuosity factor
	F	is the formation resistivity factor
	R_0	is the wet resistivity

5.3 PICKETT PLOTS

A Pickett plot is a cross plot of porosity versus resistivity on log-log graph paper. This represents a rearrangement of the Archie equation into the following form:

$$\text{Log } R_t = -m \log \Phi + \log (aR_w) - n \log S_w$$

When log data is plotted on such a plot the "wet" points ($S_w = 1$) define a line with a slope equal to "-m" and an intercept equal to the product "aR_w".

The way in which Pickett plots can be used depends on which of the parameters "a", "m", "n", R_w and S_w, are known. A typical procedure is to assume that S_w is known to be 1.0 for some plotted points. A line drawn through these points results in values for "m" and "aR_w". If R_w is known then "a" can be calculated. Now, with values for "m", "a" and R_w, and using an assumed value for "n", lines can be drawn on the plot for varying values of S_w. With these new lines the plot assigns water saturation values to each of the plotted log points. An example of an alternative application of Pickett plots is in determining R_w when "m" and "a" are known and some plotted points are "wet" points.

5.3.1 Determination of Cementation Exponent "m" from Core

The cementation factor can be determined from the results of special core analysis. Core samples of varying porosity are saturated with a brine of known resistivity. The resistivity of each saturated sample is measured. In this situation S_w is known to be 1.0 and "a" is typically assumed to be 1.0.

Archie's equation reduces to

$$\textbf{Log}\ \frac{Rt}{Rw} = \textbf{-m log}\ \Phi$$

A plot on log-log paper of the ratio of the core resistivity to the brine resistivity versus the porosity of each core sample defines a line with a slope equal to "-m". This technique is usually repeated with the core sample subjected to successive simulated overburden pressures to detect any mechanical changes that may be attributed to the applied pressure. Studies have shown that "m" is related to the degree of cementation, and to changes in applied pressure. In some areas "m" is referred to by the name "lithology" exponent.

5.3.2 Determination of Saturation Exponent "n" from Core

The saturation exponent is also derived from special core analysis. A dry core sample is weighed. It is then saturated with brine and its resistivity (R_0) is measured. Through the use of a semi permeable membrane and/or a centrifuge the sample is gradually desaturated. At different stages during the desaturation the sample is weighed to determine the brine remaining in the core. This is converted to a water saturation using the previously measured core porosity. The resistivity (R_t) is also measured at the time of each weighing. The resistivity is usually expressed as the resistivity index R_t/R_O. This situation is described by Archie's equation in the following form.

$$\text{Log}\ \frac{Rt}{Ro} = -n \log S_w$$

A plot of resistivity index versus brine saturation on log-log paper defines a line with a slope of "-n".

5.4 PETROPHYSICAL PARAMETERS

5.4.1 POROSITY

It is a measure of the amount of internal space that is capable of holding fluids; a porosity of 1% is equivalent of volume of 77.58 bbl/acre-ft. Quantitatively, the porosity of the rock is the ratio of the void space to the bulk volume. The porosity depends on the shape, surface, texture, angularity, orientation, and degree of cementation and size distribution of the grains, which make up the rock.

- **Primary Porosity**

The spaces between the fragments of the solid material deposited as sediment are the primary porosity.

- **Secondary Porosity**

Secondary porosity is the contribution from vugs fractures, pits and other discontinuities in the bulk volumes of matrix. The contribution of the secondary to the overall bulk porosity is generally small yet it can lead to dramatic increases in bulk permeability.

- **Effective Porosity**

Effective porosity is the only capacity, which can make contribution to the flow. Pores initially present but subsequently seals off by cementation or recrystallization effects are of no interest.

5.4.2 PERMEABILITY

The ability, or measurement of a rock's ability, to transmit fluids, typically measured in darcies or millidarcies. Formations that transmit fluids readily, such as sandstones, are described as permeable and tend to have many large, well-connected pores. It is a measure of the capacity of rock for its specific flow and can be determined only from flow measurements. Permeability depends upon the continuity of the pore space. There is no any unique relationship exists between the porosity and permeability.

- **Absolute Permeability**

The measurement of the permeability, or ability to flow or transmit fluids through a rock, conducted when a single fluid, or phase, is present in the rock. The symbol most commonly used for permeability is k, which is measured in units of Darcies or millidarcies. This is the property of the rock and not of the fluid flowing through it. Absolute permeability is measured with the fluid which saturates 100% of the pore space.

- **Effective Permeability**

The ability to preferentially flow or transmit a particular fluid when other immiscible fluids are present in the reservoir (e.g. effective permeability of gas in a gas-water reservoir). The relative saturations of the fluids as well as the nature of the reservoir affect the effective permeability. In contrast, absolute permeability is the measurement of the permeability conducted when a single fluid or phase is present in the rock. It is the permeability of a flowing phase which does not saturate 100% of the rock such as the oil in the presence of water. The effective permeability is always less than the absolute permeability for the rock.

- **Relative Permeability**

It is the ratio of the effective permeability to the absolute permeability. If a single fluid is present in a rock, its relative permeability is 1.0. Calculation of relative permeability allows comparison of the different abilities of fluids to flow in the presence of each other, since the presence of more than one fluid generally inhibits flow.

5.5 WATER SATURATION

The fluid saturation of a rock is the ratio of the volume of the fluid within the pores of the rock to the total pore volume. 30% of saturation means that three-tenths of the pore space is filled with water.

$$S_h = 1 - S_w$$

Where,

S_w = Water saturation

S_h = Hydrocarbon saturation

Available porosity or vugs in rocks are filled with water, which provide apart to electric current to pass through it. These values of resistivity are used to determine water saturation. The water saturation of formation is the fraction of pore volume occupied by water. If water saturation exceeds 50% then formation produces water, in most of cases. There are many methods and formulae can be used to calculate water saturation, these formulae are

- Archie method
- R_{wa} method (Apparent water resistivity)
- S_w method

We follow Archie equation in this project for the calculation of formation water saturation.

$$S_w = (FR_w/R_t)^{1/2}$$

Where

F = Formation resistivity factor

R_w = Resistivity of formation water at formation temperature

R_t = True deep resistivity of the formation

5.6 VOLUME OF SHALE

Clay's shale contributes to formation conductivity. Shale exhibits conductivity because of the electrolyte that it contains and because of an ion-exchange process where by ions move under the influence of impressed electric field between the exchange sites on surface of clay particles. So there will be effect of shale on the other rocks. This effect depends on the amount, type and distribution of shale. The shale influences all logging measurements, and the corrections of shale contents are required.

5.6.1 DETERMINATION OF VOLUME OF SHALE

Volume of shale can be computed by different methods using i.e.

- Gamma rays
- SP NGS tool
- φ_n vs. φ_d cross plot
- φ_n vs. φ_s cross plot

We used two methods to compute the volume of shale, which are given below.

5.6.2 VOLUME OF SHALE BY GAMMA RAY LOG

The gamma ray log has been used as one of the important shale indicator in the evaluation of shaly formations. In the quantitative evaluation of shale content, it is assumed that radioactive minerals other than shale are absent.

A gamma ray "shale index" I_{GR}, has been defined as

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

Where

GR_{log} = log response in the zone of interest, API units

GR_{min} = log response in the clean beds, API units

GR_{max} = log response in the shale beds, API units

The gamma ray shale index has been empirically related with the fractional volume of the shale information by the curve such as curve 1 for linear relationship and curve 2, used for formations and it is defined by the formula.

5.6.3 VOLUME OF SHALE FROM SP LOG

Volume of shale can also be estimated either directly from SP curve or by using following formula;

$$V_{SH} = \frac{SP_{log} - SP_{min}}{SP_{max} - SP_{min}}$$

Where

SP_{log} = SP log reading at each interval depth

SP_{min} = Minimum value of SP log

SP_{max} = Maximum value of SP log

5.6.4 CUT OFF

This process is similar to filtering of seismic data. First we define criteria for reservoir and non reservoir, which possess following factors.

For Non Reservoir following criteria is followed

- **Porosity** $\varphi < 6\%$
- **Volume of shale** $V_{sh} > 30\%$
- **Water saturation** $S_w > 40\%$

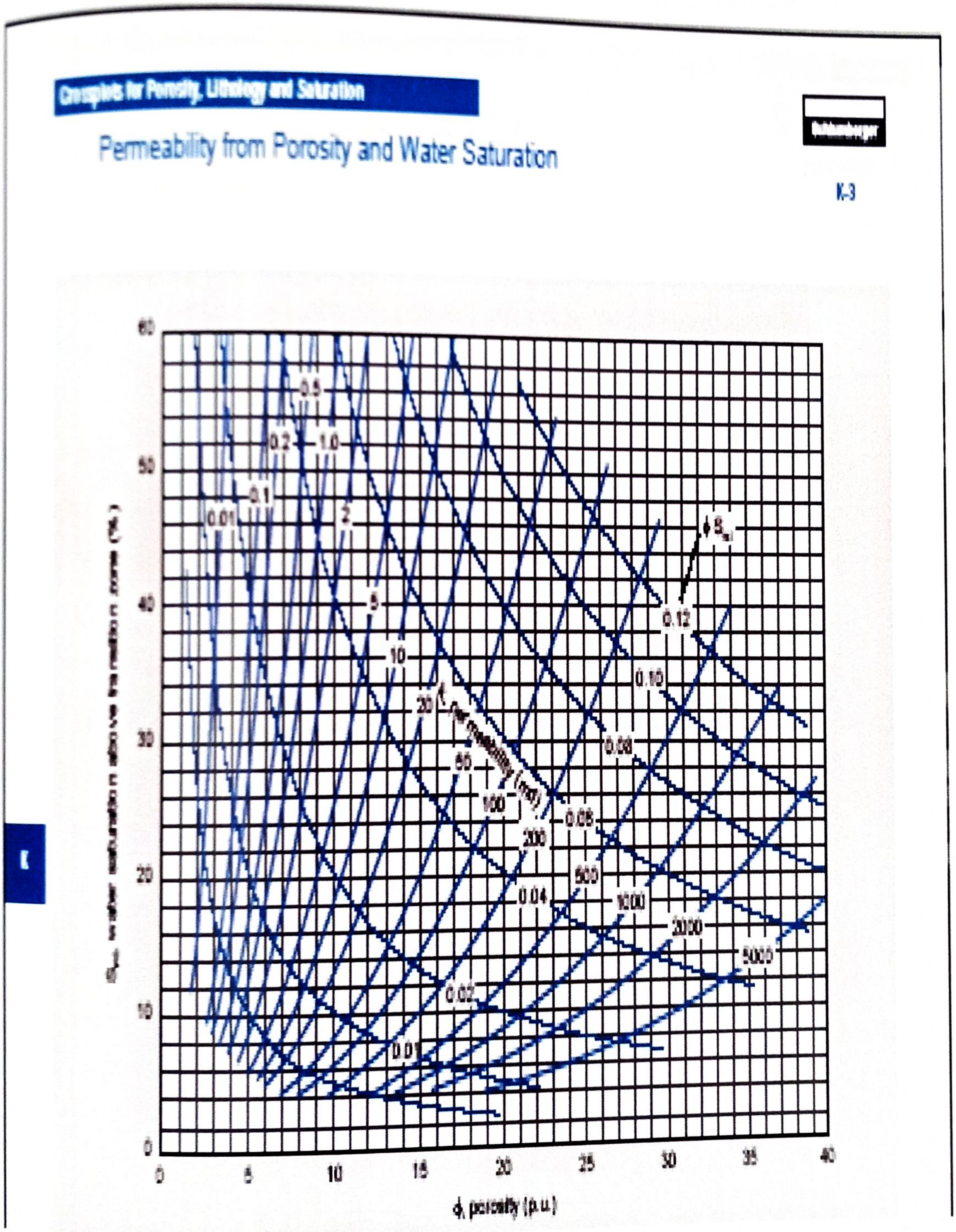


Figure 5.2 Permeability from porosity and water saturation

Determination of Apparent Matrix Parameters from Bulk Density or Interval Transit Time and Apparent Total Porosity

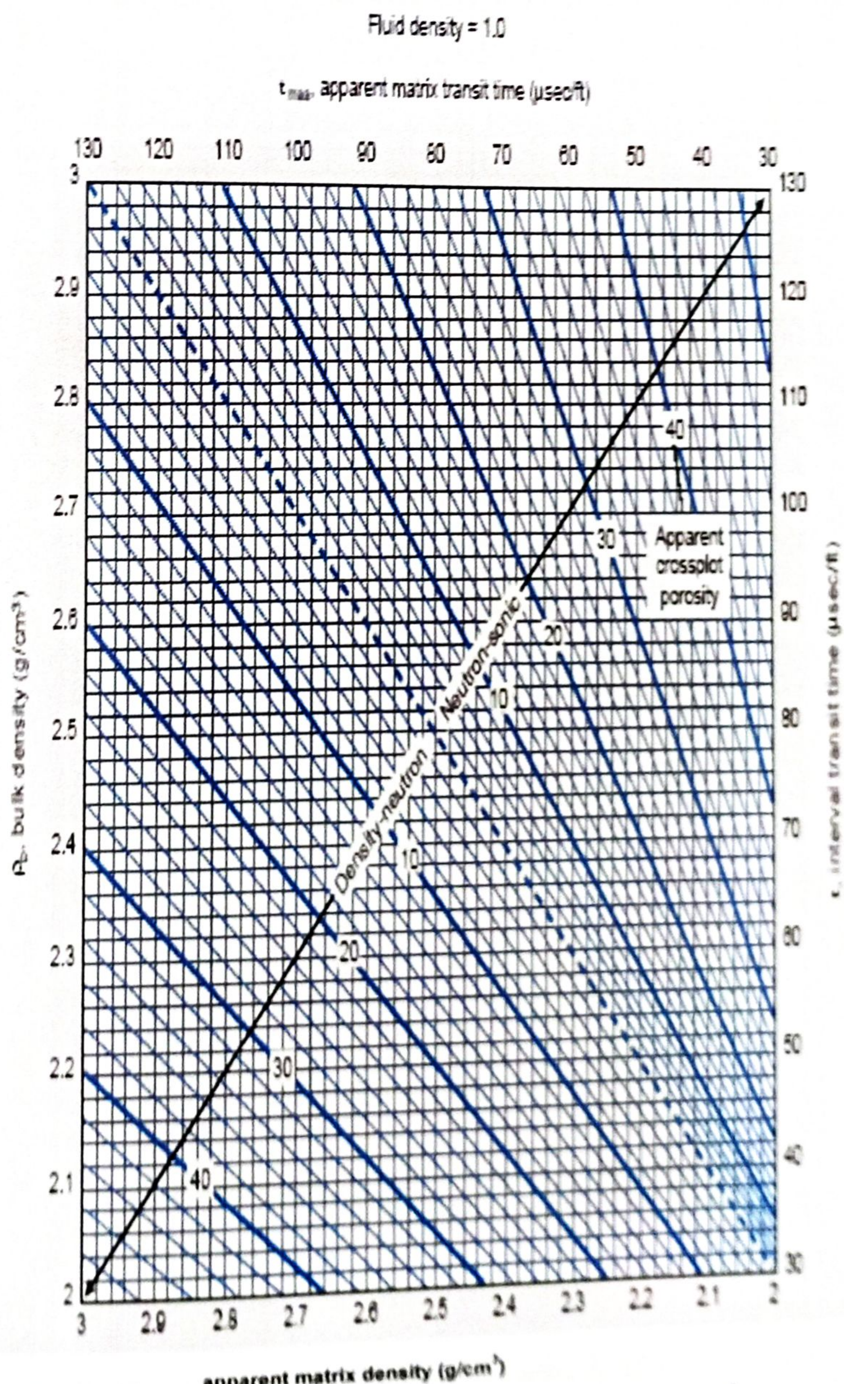


Figure 5.3 Apparent matrix parameter from bulk density & total porosity

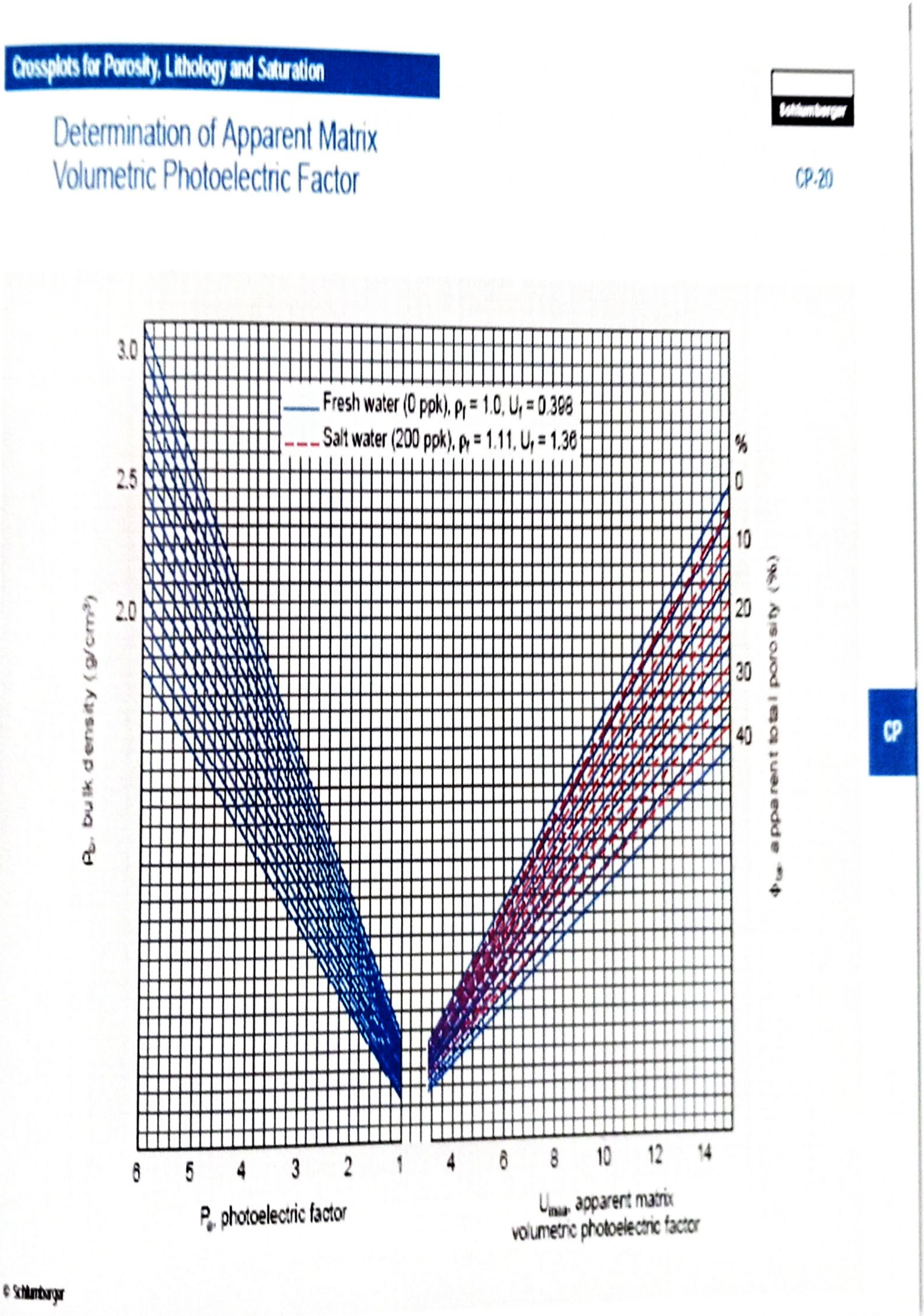


Figure 5.4 Determination of apparent matrix volumetric photoelectric factor

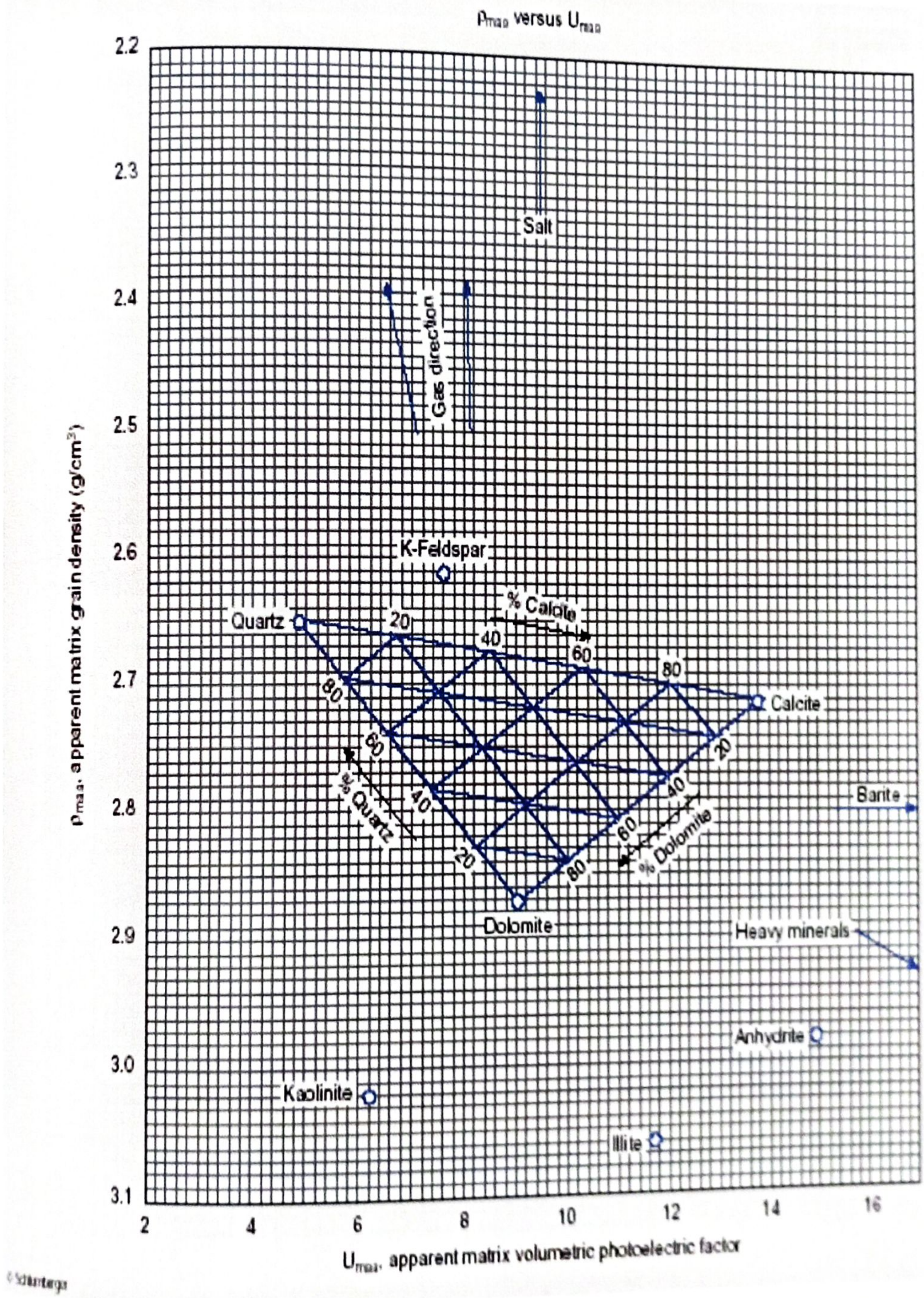


Figure 5.5 RHOMA versus UMAA Chart used for lithology identification (after Schlumberger chart book 2000)

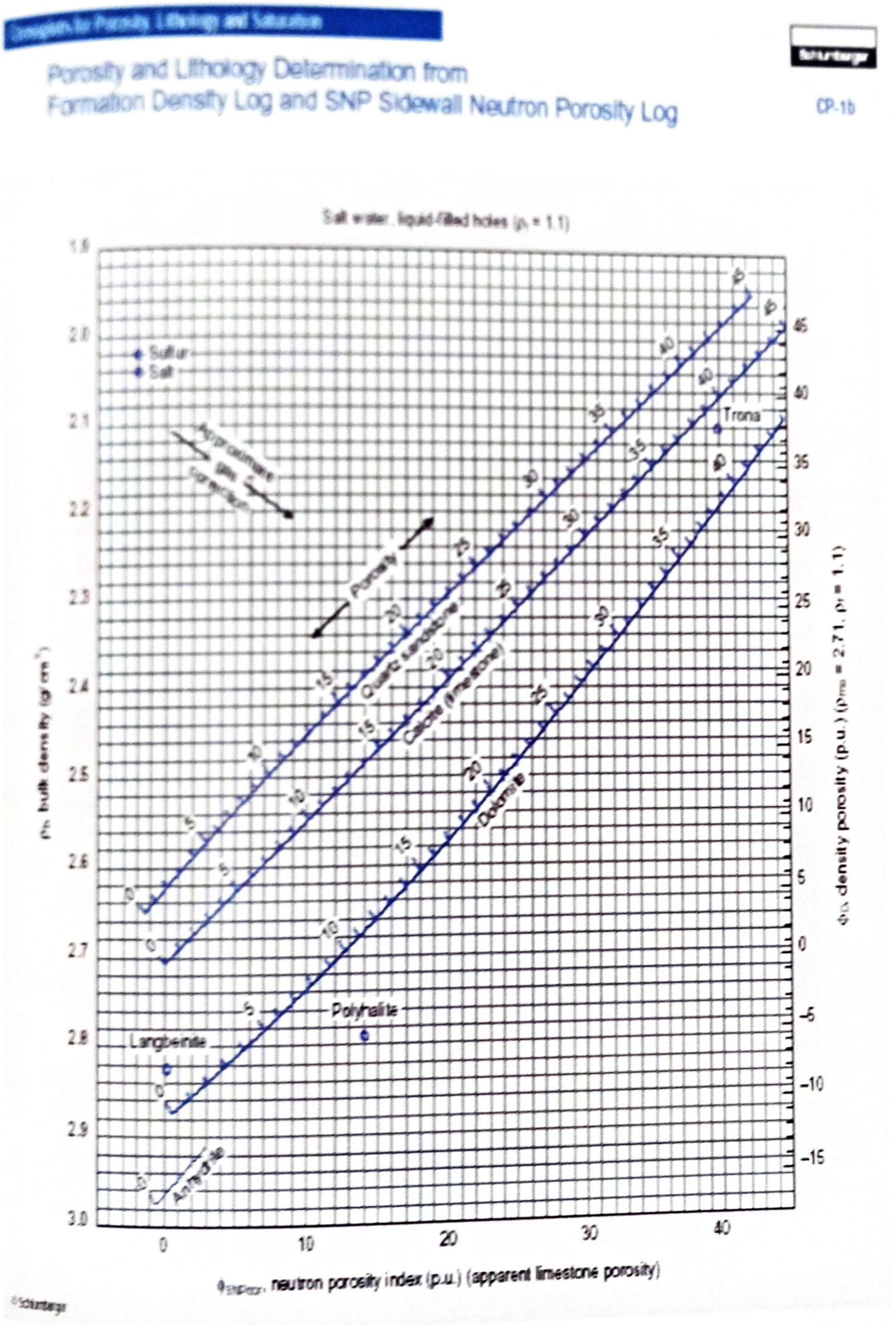


Figure 5.6 CP-1b Chart used for the porosity and lithology determination from density and neutron porosity (after Schlumberger chart book 2000).

CHAPTER 6

PETROPHYSICAL INTERPRETATION

PETROPHYSICAL INTERPRETATION

6.1 CORE

There are four cores taken from Qadirpur well No 16.

6.1.1 CORE NO 1

The interval cored is 905 to 914 meters. Recovery of core is 8.94 meter (99.33%), formation is Habib Rahi Limestone and maximum gas is 2.4%.

905 to 906.15 meter

Pack stone, gray, soft to medium hard, argillaceous, highly foraminiferal, and conchoidal in nature.

906.15 to 906.71 meter

Wackstone to pack stone, yellowish gray, medium hard, micro crystalline, argillaceous, highly fossiliferous.

906.71 to 913.94 meter

Wackstone, white to off-white, medium hard to hard, calcite veins present, argillaceous, and moderately fossiliferous having poor porosity.

6.1.2 CORE NO 2

The interval cored is 914 to 923 meter. Recovery of core is 8.84 meters (98.22%), Formation is Habib Rahi Limestone and maximum gas is 2.3%.

914 to 922.84 meter

Wackstone to packstone, yellowish to gray, off-white, medium hard to hard, microcrystalline, calcitic, argillaceous, moderately fossiliferous.

6.1.3 CORE NO 3

The interval cored is 1186 to 1195 meters. Recovery of core is 5.85 meter (65%); formations are Ghazij and Sui Upper Limestone.

1186 to 1187.14 meter

Wackstone, gray, medium hard to hard, argillaceous, highly foraminiferal. Primary porosity is poor.

1187.14 to 1188.04 meter

Shale: Greenish gray, light gray soft to medium hard, fissile, pyretic shale to non-calcareous.

1188.04 to 1189.42 meter

Wackstone, light gray, medium hard, highly fossiliferous, with poor porosity.

1189.42 to 1189.95 meter

Shale: Greenish gray, light gray soft to medium hard, fissile, pyretic shale to non-calcareous.

1189.95 to 1190.42 meter

Wackstone, light gray, medium hard, highly fossiliferous, with poor porosity.

1190.42 to 1191.85 meter

Limestone: wackstone, off-white, creamy white, hard compact, at places argillaceous but clean limestone intervals are highly fossiliferous. The primary porosity is poor while secondary porosity 3 to 5 %.

6.1.4 CORE NO 4

The interval cored is 1195 to 1200 meters. The recovery of core is 3.37 meters (67.40%), formation is Sui Upper Limestone and the maximum gas is 1.2 %.

1195 to 1195.79 meter

Limestone: wackstone, gray, whitish gray, medium hard to hard, compact, crystalline rarely fossiliferous with thin lamination of shale. Hairline fractures are filled with pyrite or calcite.

1195.79 to 1197.32 meter

Limestone: wackstone to packstone, whitish gray, creamy, medium hard to hard, compact, argillaceous, rarely fossiliferous.

1197.32 to 1198.37meter

Limestone: wackstone, gray, whitish gray, medium hard to hard, compact, crystalline rarely fossiliferous with thin lamination of shale. Hairline fractures are filled with pyrite or calcite.

6.2 HYDROCARBON PRODUCTION

Only the gas shows were recorded during the drilling of Habib Rahi Limestone, Sui Upper Limestone and Sui Main Limestone. A considerable amount of hydrocarbon gases were detected in Habib Rahi Limestone, Sui Upper Limestone and Sui Main Limestone.

Maximum gas percentage recorded in different formation is given below.

Formation	Gas Percentage
Habib Rahi Limestone	4.0
Ghazij Formation	5.60
Sui Upper Limestone	4.0
Shale Unit	1.25
Sui Main Limestone	30.00

Table no 6.1 Showing the gas % in different formations

6.3 INTERPRETATION

The following parameters are used in interpretation of well logs LDL-CNL-GR, DLL-MSFL-SP-GR, BHC-GR.

1. Volume of Shale
2. Porosity
3. Saturation of Water
4. Hydrocarbon Saturation
5. Permeability
6. Lithology

6.4 INTERPRETATION DATA OF WELL LOGS

(a) INTERPRETATION OF ZONE -A WELL # 16 AT DEPTH OF (903-981)

No.	Depth (m)	Shale Volume (Vsh) (%)	Porosity (Φ) (%)	Water Resistivity (Rw) (Ωm)	Water Saturation (Sw) (%)	Saturation of HC (Shc) (%)	Lithology
1	903	11.1	14	0.17	53	47	Calcite
2	906	88.8	17	0.17	62	38	Calcite
3	909	33.3	17	0.17	50	50	Calcite
4	912	44.4	20	0.17	41	59	Dolomite
5	915	33.3	18.5	0.17	49	51	Dolomite
6	918	77.7	21	0.17	35	65	Dolomite
7	921	44.4	20.5	0.17	40	60	Dolomite
8	924	27.7	16	0.17	40	60	Calcite
9	927	61.1	12.5	0.17	66	34	Quartz
10	930	11.1	11.5	0.17	56	44	Feldspar
11	933	33.3	11.5	0.17	56	44	Feldspar
12	936	44.4	33.5	0.17	62	38	Feldspar
13	939	55.5	27.5	0.17	65	35	Calcite
14	942	16.6	14.5	0.17	73	27	Calcite
15	945	33.3	19	0.17	82	18	Calcite
16	948	11.1	18	0.17	76	24	Calcite
17	951	5.5	19.5	0.17	82	18	Calcite
18	954	44.4	22.5	0.17	71	29	Calcite
19	957	50.0	26.5	0.17	63	37	Calcite
20	960	44.4	26.5	0.17	83	17	Calcite
21	963	38.8	33	0.17	62	38	Calcite
22	966	33.3	33.5	0.17	68	32	Calcite
23	969	44.4	29	0.17	71	29	Dolomite
24	972	27.7	15	0.17	61	39	Calcite
25	975	61.6	18	0.17	63	37	Calcite
26	978	44.4	14	0.17	85	15	Calcite
27	981	66.6	10.5	0.17	84	16	Calcite

Table No 6.2 Showing the different parameters of Zone A.

(b) INTERPRETATION OF ZONE- B OF WELL # 16 AT DEPTH (1321-1375)

No.	Depth (m)	Shale Volume (Vsh) (%)	Porosity (Φ) (%)	Water Resistivity (Rw) (Ωm)	Water Saturation (Sw) (%)	Saturation of HC (Shc) (%)	Lithology
1	1321	8.4	14	0.17	0.81	19	Calcite
2	1324	15	11	0.17	0.44	54	Calcite
3	1327	9.4	16	0.17	0.30	70	Calcite
4	1330	5.6	15	0.17	0.22	78	Calcite
5	1333	28	23	0.17	0.32	68	Calcite
6	1336	15	19	0.17	0.30	70	Calcite
7	1339	37	17	0.17	0.34	66	Calcite
8	1342	28	18	0.17	0.41	59	Dolomite
9	1345	28	28	0.17	0.23	67	Dolomite
10	1348	29	9	0.17	0.27	73	Dolomite
11	1351	15	16	0.17	0.21	79	Calcite
12	1354	18.8	23	0.17	0.15	85	Calcite
13	1357	15	22	0.17	0.22	78	Calcite
14	1360	33	28	0.17	0.26	74	Quartz
15	1363	24.5	22	0.17	0.26	74	Calcite
16	1366	24.5	22.5	0.17	0.27	73	Calcite
17	1369	18.8	21	0.17	0.39	61	Calcite
18	1372	17	22	0.17	0.36	64	Calcite
19	1375	17	18	0.17	0.47	53	Calcite

Table No 6.3 Showing the different parameters of Zone B.

(c) INTERPRETATION OF ZONE –A OF WELL # 17 (1314-1392)

No.	Depth (m)	Shale Volume (Vsh) (%)	Porosity (φ) (%)	Water Resistivity (Rw) (Ωm)	Water Saturation (Sw) (%)	Saturation of H.C (Shc) (%)	Lithology
1	1314	0	15	0.17	54	46	Calcite
2	1317	27.6	18	0.17	86	14	Calcite
3	1320	8.8	7	0.17	100	0	Dolomite
4	1323	28	16	0.17	37	63	Calcite
5	1326	33	22	0.17	66	34	Dolomite
6	1329	25.3	11	0.17	100	0	Calcite
7	1332	8.8	18	0.17	25	75	Calcite
8	1335	0	20	0.17	21	79	Calcite
9	1338	0	17.5	0.17	24	76	Calcite
10	1341	9.9	27	0.17	19	81	Calcite
11	1344	26.6	13	0.17	57	43	Quartz
12	1347	17.6	21	0.17	35	65	Feldspar
13	1350	16.5	13	0.17	70	30	Calcite
14	1353	12.5	25	0.17	42	58	Dolomite
15	1356	8.8	18	0.17	27	63	Dolomite
16	1359	6.6	26	0.17	22	78	Dolomite
17	1362	11	25	0.17	10	90	Calcite
18	1365	12.5	24	0.17	40	60	Quartz
19	1368	9.9	14	0.17	65	35	Calcite
20	1371	11.1	27	0.17	35	65	Calcite
21	1374	6.6	25	0.17	42	58	Feldspar
22	1377	8.8	26	0.17	50	50	Quartz
23	1380	5.5	27	0.17	48	52	Heavy mineral
24	1383	7.7	26	0.17	52	48	Heavy mineral
25	1386	8.8	25	0.17	62	38	Calcite
26	1389	7.7	24	0.17	85	15	Calcite
27	1392	8.8	26	0.17	91	9	Calcite

Table No 6.4 Showing the different parameters of Zone C.

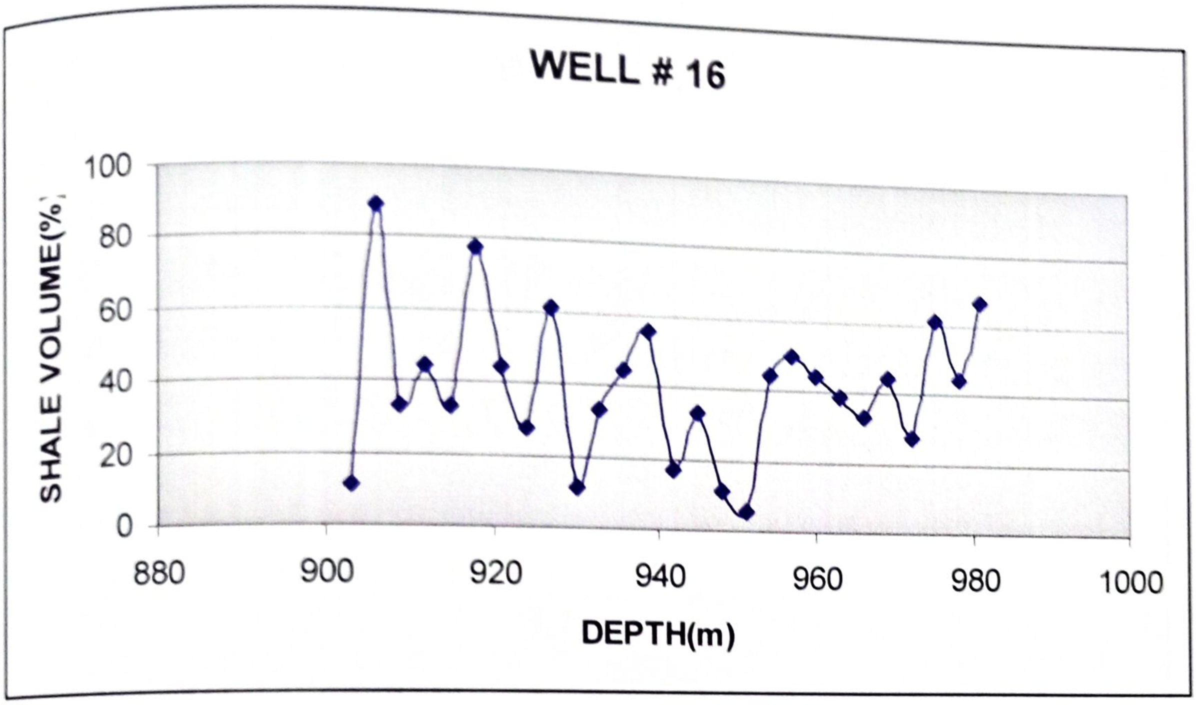


Figure 6.1 Graphical representation of depth vs shale volume of Zone A.

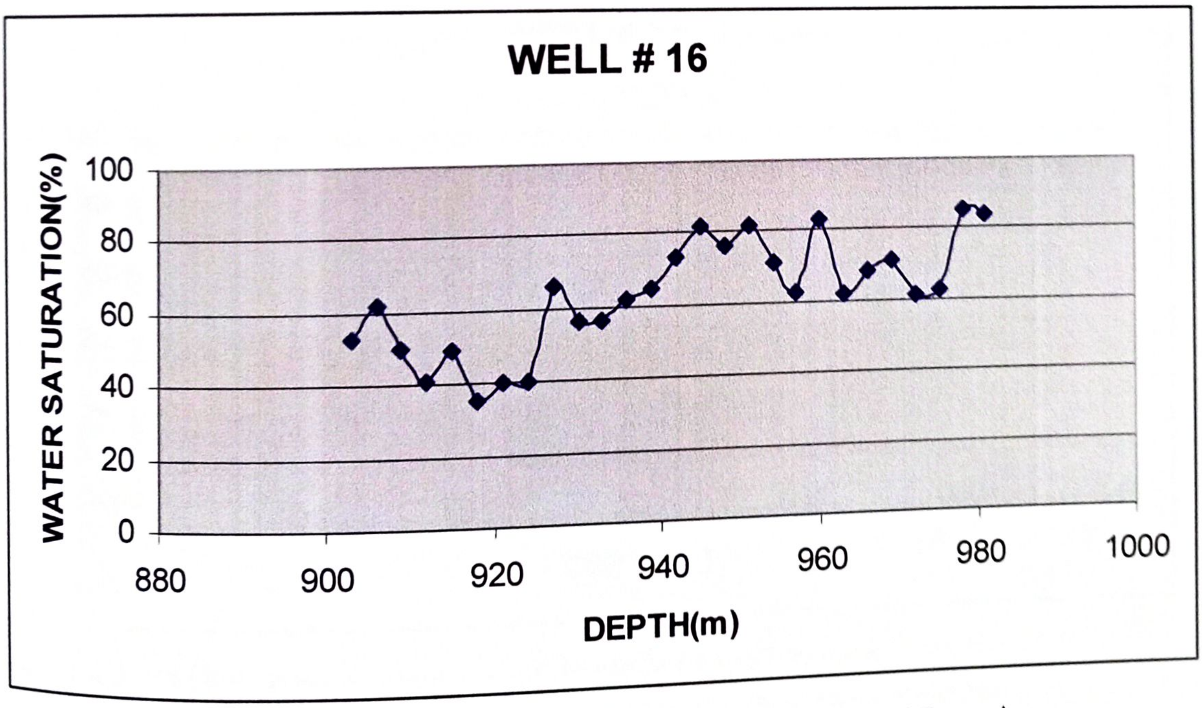


Figure 6.2 Graphical representation of depth vs water saturation of Zone A.

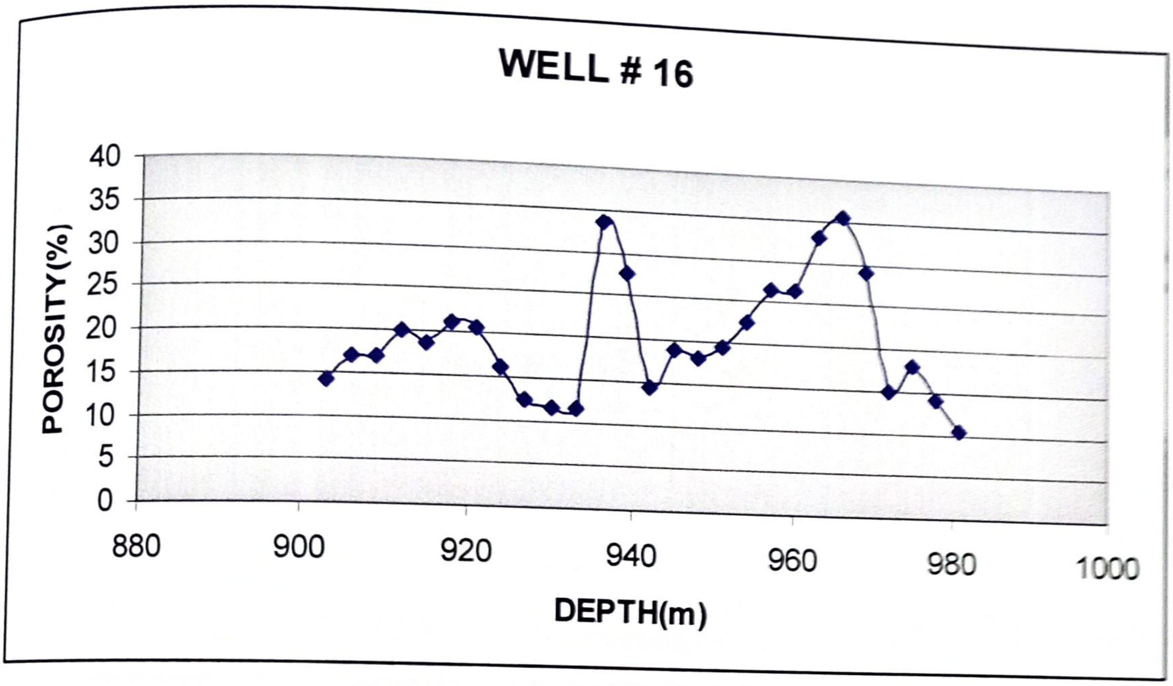


Figure 6.3 Graphical representation of depth vs porosity of Zone A.

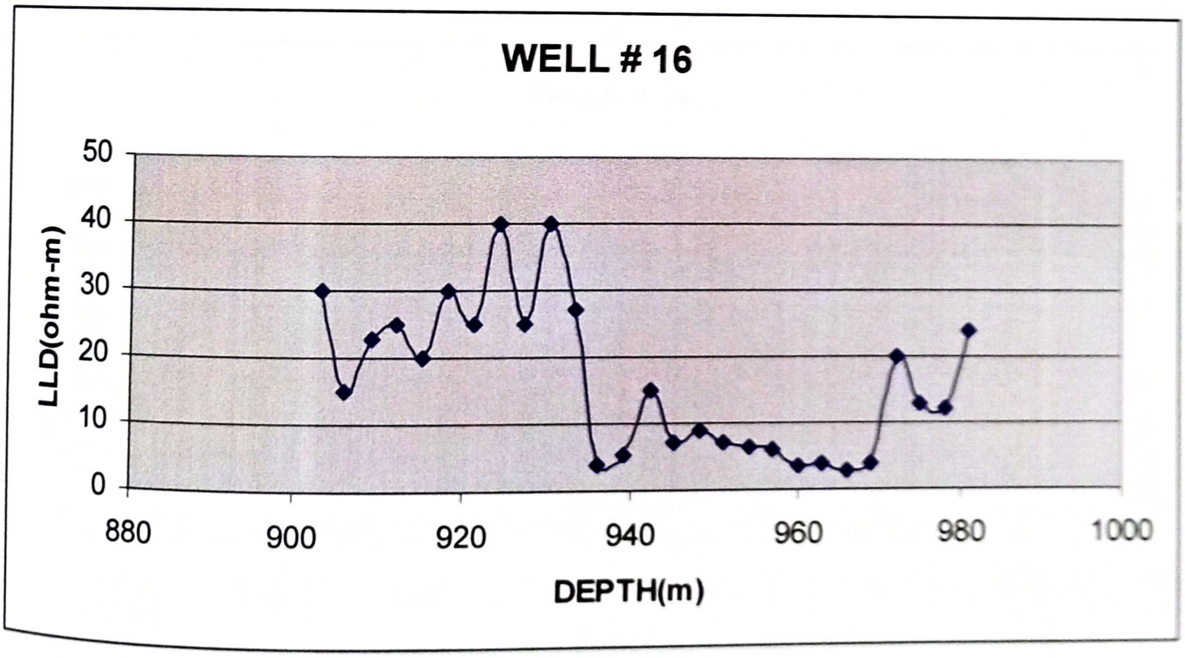


Figure 6.4 Graphical representations of depth vs LLD of Zone A.

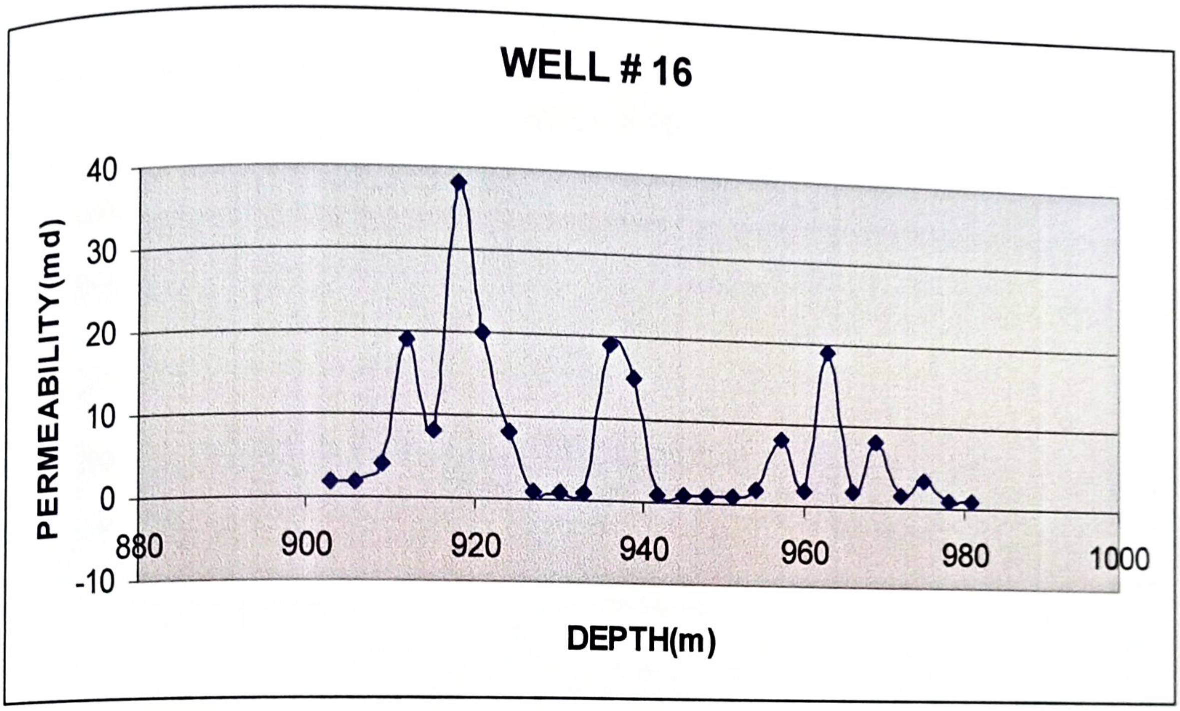


Figure 6.5 Graphical representation of depth vs permeability of Zone A.

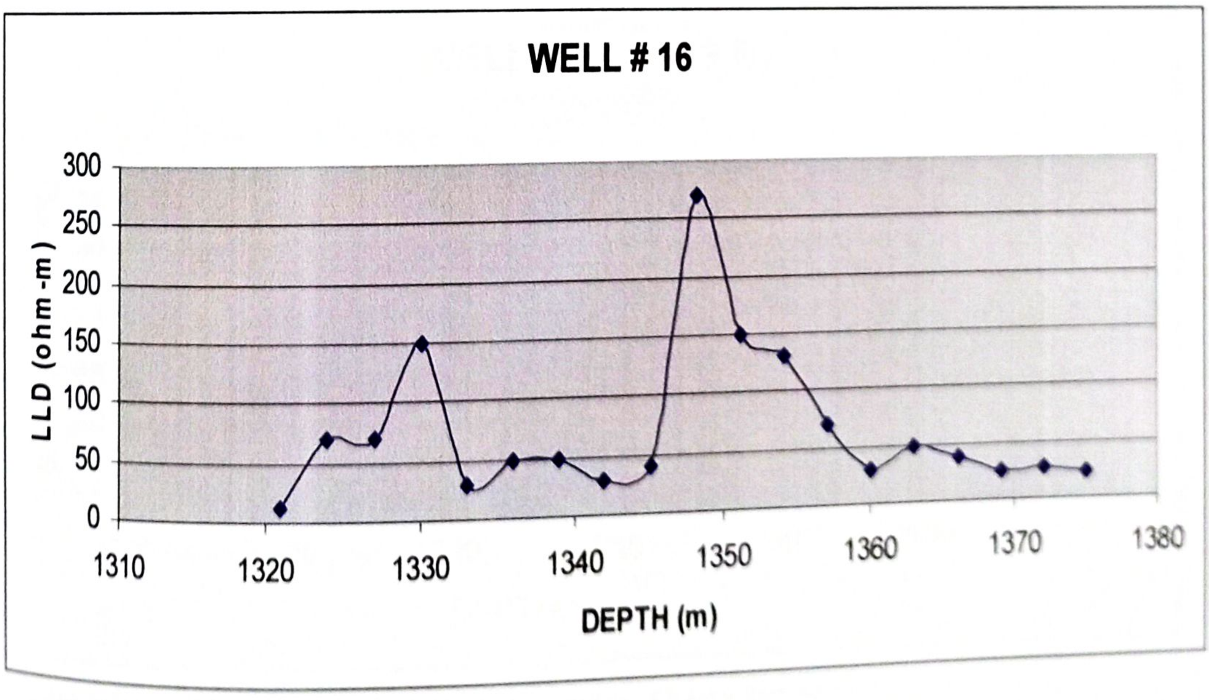


Figure 6.6 Graphical representation of depth vs LLD of Zone B.

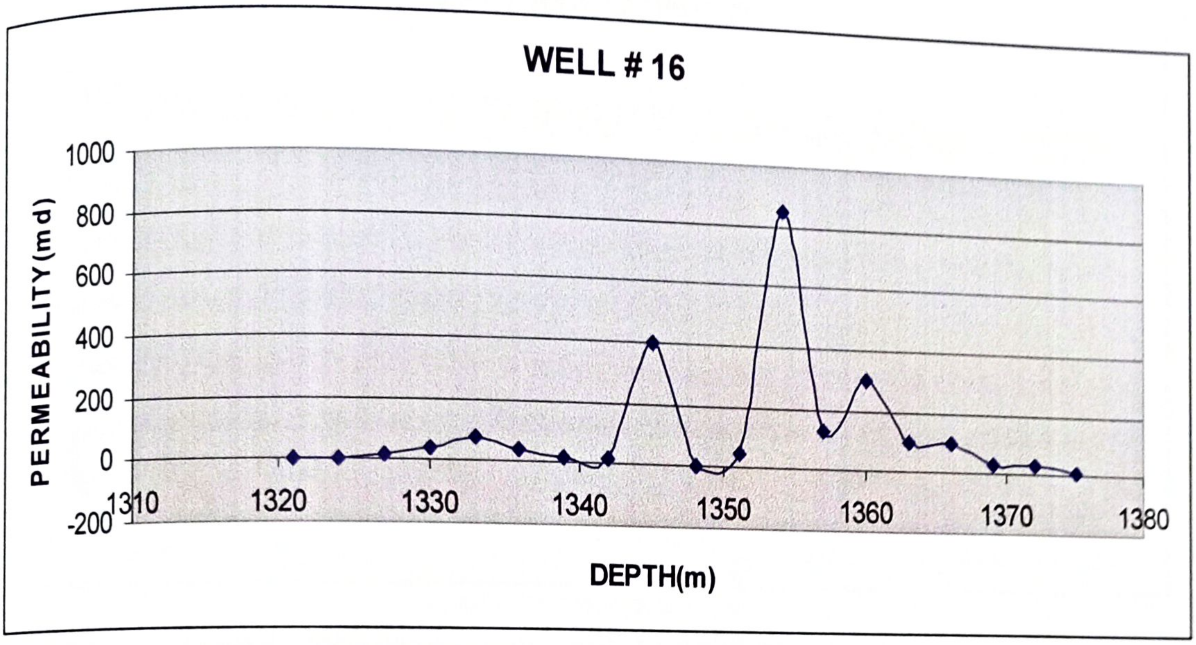


Figure 6.7 Graphical representation of depth vs permeability of Zone B.

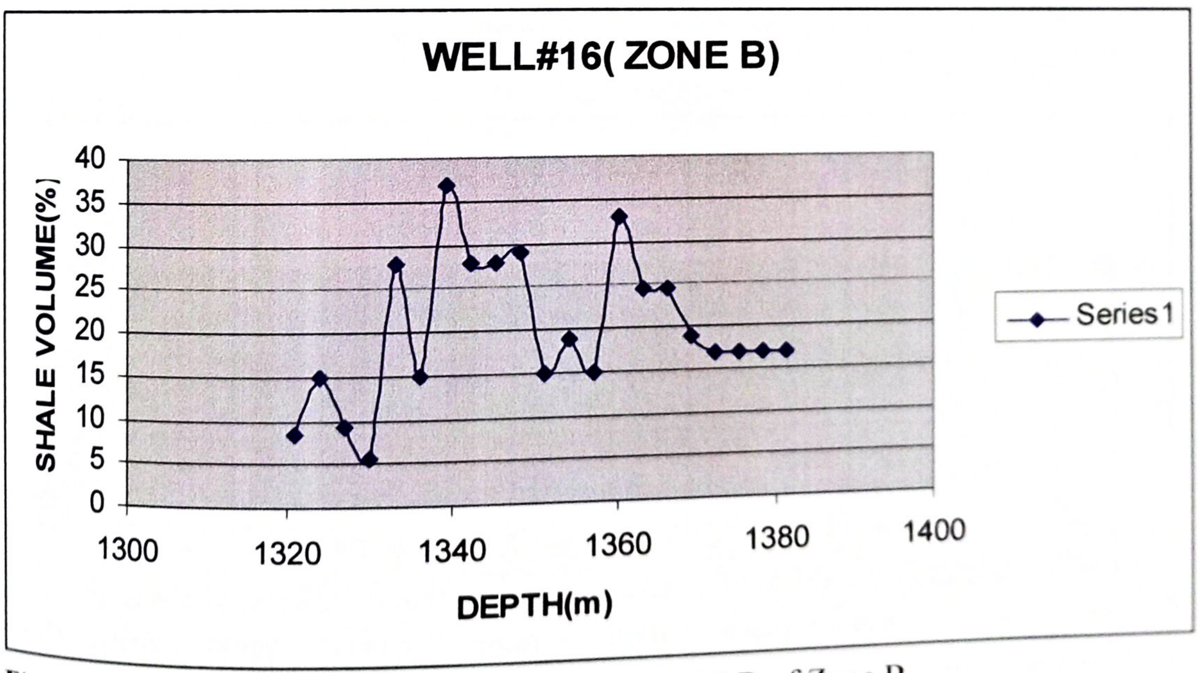


Figure 6.8 Graphical representation of depth vs LLD of Zone B.

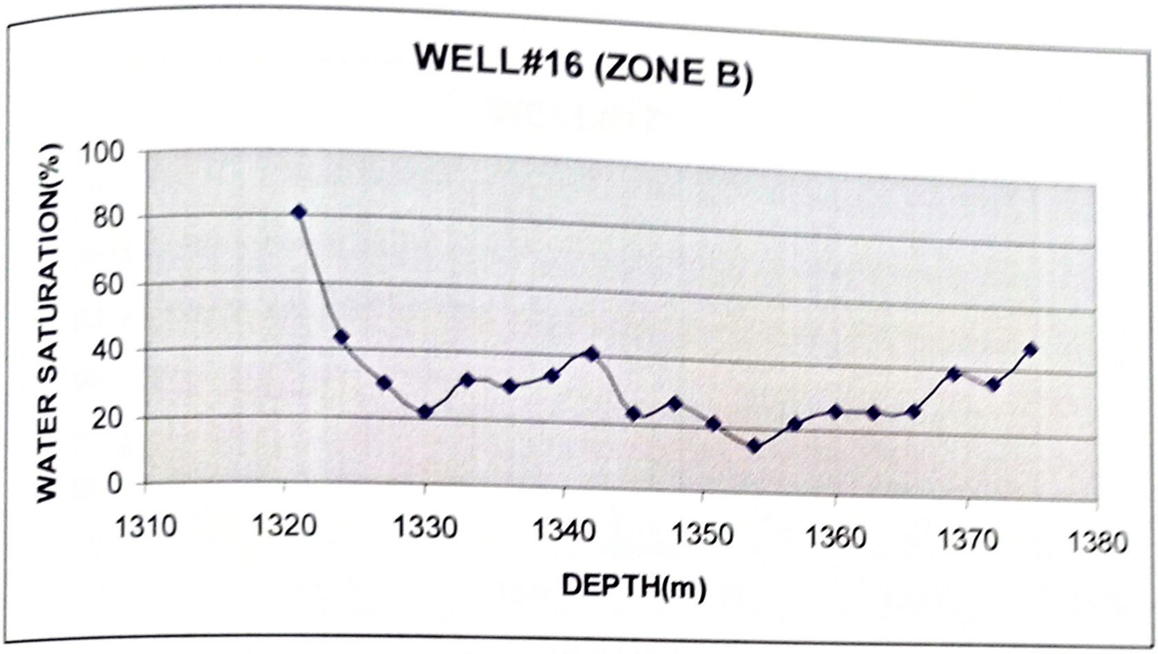


Figure 6.9 Graphical representation of depth vs water saturation of Zone B.

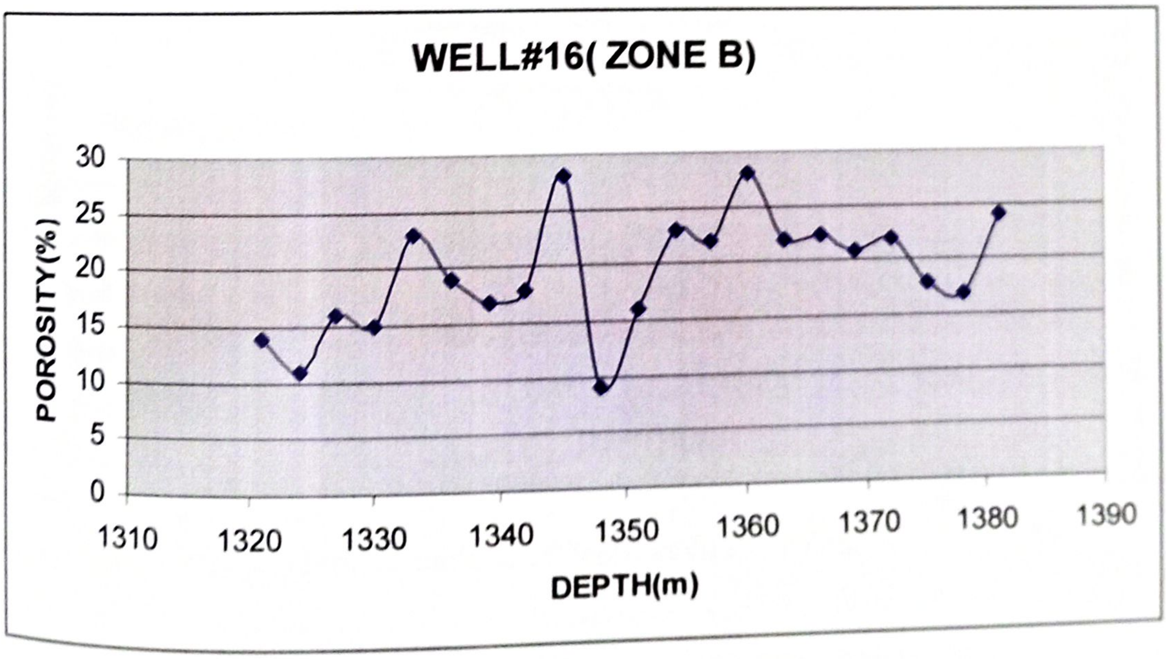


Figure 6.10 Graphical representation of depth vs Porosity of Zone B.

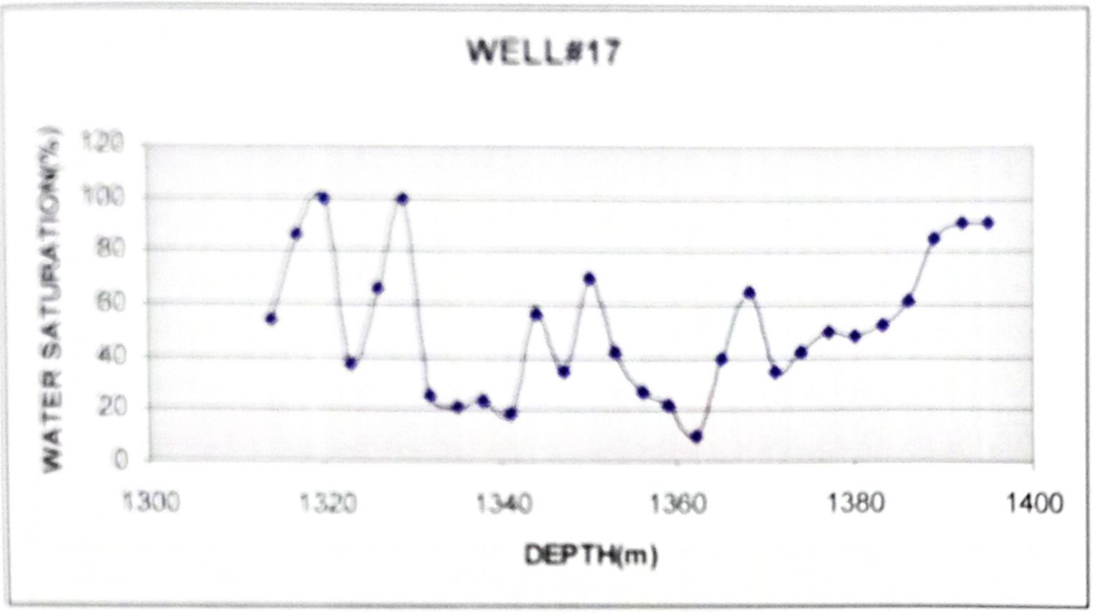


Figure 6.11 Graphical representation of depth vs water saturation of Zone A.

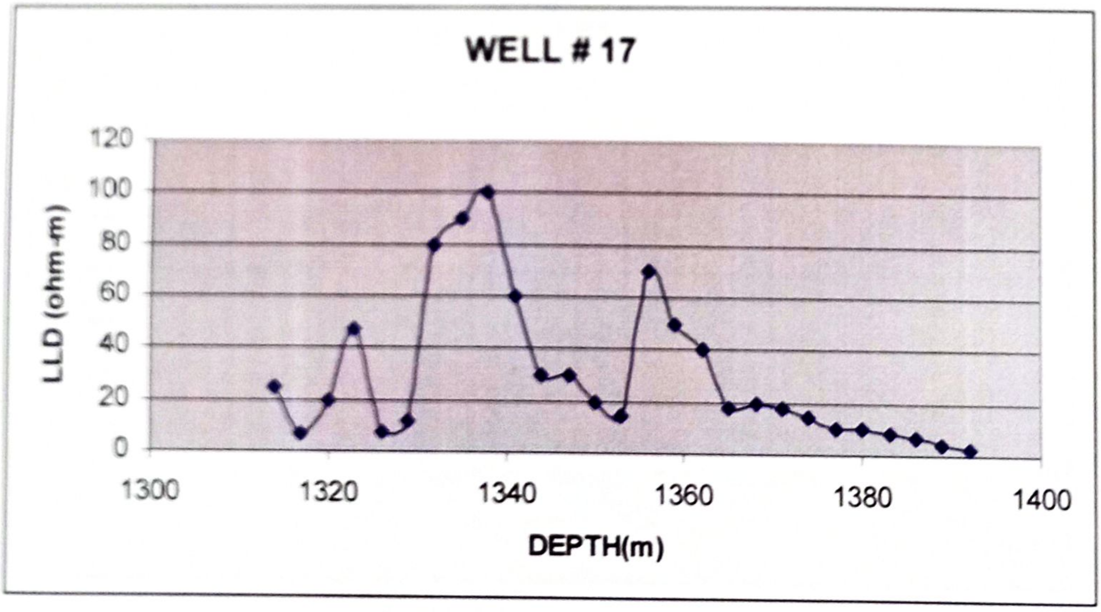


Figure 6.12 Graphical representations of depth vs LLD of Zone A.

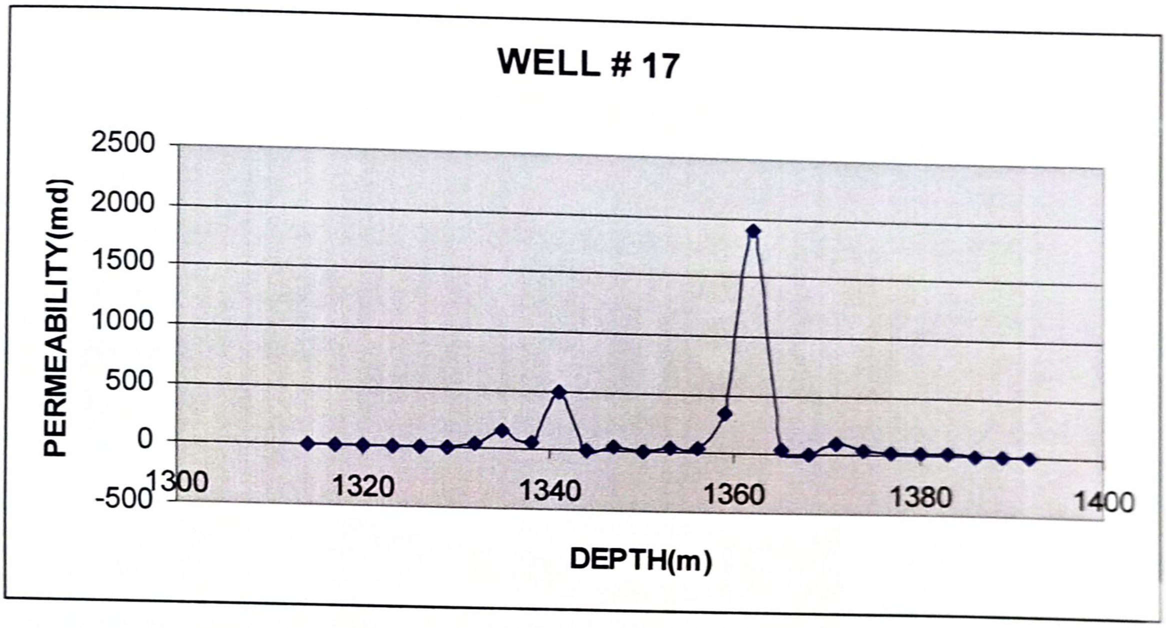


Figure 6.13 Graphical representation of depth vs permeability of Zone A.

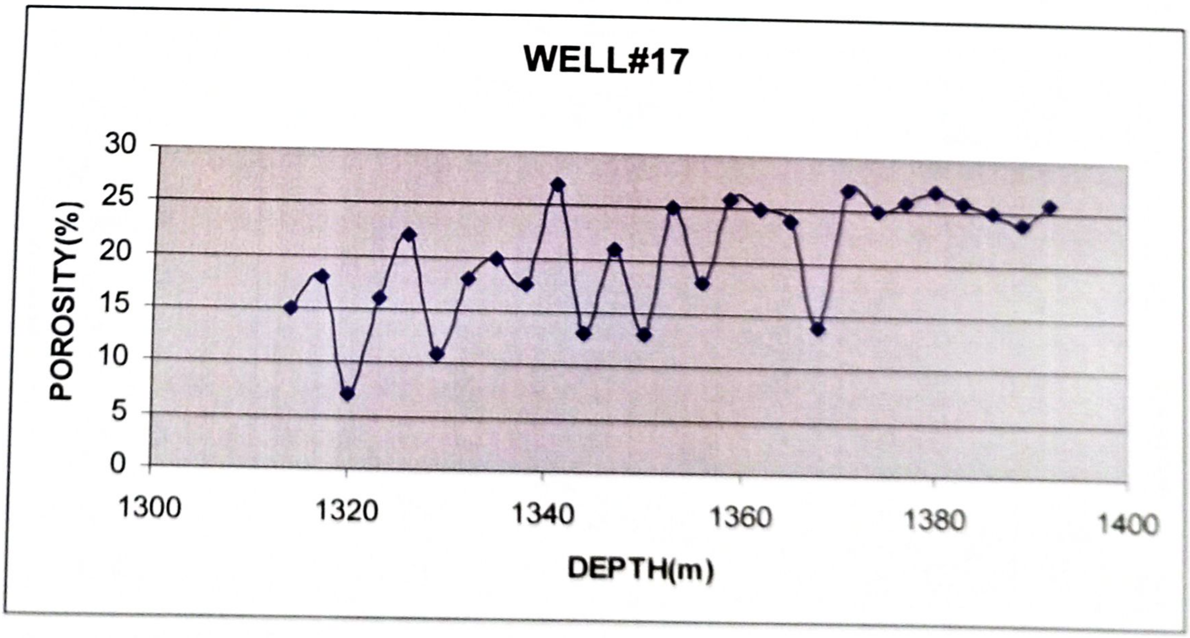


Figure 6.14 Graphical representation of depth vs porosity of Zone A.

CHAPTER 7

CONCLUSION

CONCLUSION

QadirPur is a part of Lower Indus Basin and is characterized by the extensional regimes and gas window. QadirPur Gas was discovered in Early Eocene, Sui Main Limestone, Sui Upper Limestone, and Middle Eocene Habib Rahi Limestone. On the basis of well log curves there are three Zones of interest, which are from 903-981m, 1314 -1392m, 1321-1375m. Porosity calculated from Neutron Density ranges from 7% to 25%. The Qadirpur Gas Field has great potential to serve the future gas requirements of Pakistan.

7.1 RECOMMENDATIONS

1. Drilling practices should be modified so that the whole enlargement is minimized. Even slight washing out of the bore wall can cause deterioration of the quality of density and PEF measurement.
2. Present logging suite is adequate for logging for the future, as a good understanding of the electrical properties and capillary pressure is critical to evaluate reserve.
3. More logs should be acquired
4. MDT/RFT, Production log should be run
5. Stimulation should be done for more hydrocarbon production

CHAPTER 8

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8. REFERENCES

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