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Petrophysical characterization of specific Iraqi Oil Field

Graduation research submitted to the Council of the College of Engineering - Petroleum Department as an implementation of the requirements for obtaining a Bachelor's degree

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1446 AH   **2025 AD**

بسم الله الرحمن الرحيم

﴿يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا
الْعِلْمَ دَرَجَاتٍ ۚ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ﴾

[سورة المجادلة، الآية11]

Supervisor Certification

I certify that the preparation of this project entitled **"Petrophysical characterization of specific Iraqi Oil Field"**

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Date: /   / 2025

الاهداء

نهدي عملنا هذا إلى...

حجة الله في أرضه وعينه في خلقه،

إلى صاحب الزمان وخليفة الرحمن، وشريك القرآن وقاطع البرهان،

إلى من تشرق الأرض بنوره وينتشر العدل بظهوره،

المهدي المنتظر صاحب الامر عجل الله فرجه وسهل مخرجه

شكر وتقدير

بسم الله والحمد لله والصلاة والسلام على اشرف الخلق محمد وآله وصحبه ومن والآه اما بعد ، فقد وجب علينا في نهاية بحثنا هذا أن نتقدم بخالص شكرنا وتقديرنا إلى استاذنا و مشرفنا الاستاذ رسول حسين راضي لما ابداه من توجيهات قيمة ولما بذله من جهد طيلة فترة اعداد هذا البحث .

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ولا يفوتنا إن نتقدم بالشكر والامتنان للدكتور احمد خضير عباس والاستاذ علي نور الدين والاستاذ علي ظاهر والمهندس علي احمد والإخ علي قاسم كاظم لما قدموه من دعم علمي ومعنوي.

ويدعونا واجب العرفان والجميل ان نتقدم بالشكر والتقدير الى افراد عائلتنا الذي كان لهم الاثر في دعمنا ومساندتنا لتخطي الصعوبات التي واجهتنا لاكمال مسيرتنا الدراسية.

ومن (العباس اباذر محمد) كما يفرض علي الواجب ان اتقدم بشكري وتقديري الى كل من مد لي يد العون والمساعدة واخص بالذكر الإخوة (مهدي جاسم محمد سعيدان) و (سجاد خماس فرحان جبر) و (حسين كريم حسين بهيدل).

وفي الختام نقدم شكرنا واعتزازنا بمن ساندنا وازرنا طيلة هذه المسيرة العلمية وجميع زملائنا في الدراسة ولا سيما المقربون من دفعتنا في الدراسة الصباحية والمسائية ونعتذر لمن فاتنا ذكرهم سهوا ... لهم منا كل الشكر والامتنان.

Abstract

This study investigates the petrophysical properties within an Iraqi oil field, specifically the Mishrif Formation in the Halfaiya oil field, from well HF-X1 data, known deposited during the Cretaceous period, is one of the economically important formations, was to assess its hydrocarbon production potential. The Mishrif Formation a heterogeneous carbonate reservoir is one of southern Iraq's most important reservoirs.

The assessment of these properties, crucial for evaluating hydrocarbon reservoirs, is conducted using well logs and Techlog software. The research emphasizes the importance of petrophysical parameters such as porosity, shale volume and saturation in determining the reservoir's potential. These parameters are derived from well log data, including Gamma Ray, Sonic, Neutron, Density, and Resistivity logs.

The results of the study revealed that the Mishrif Formation in the HF-X1 well could be divided into several zones with varying reservoir characteristics. Notably, the M5 zone was identified as having the most favorable properties for oil production due to its high effective porosity and low water saturation. The study also confirmed the presence of predominantly limestone lithology within the formation. The findings of this research provide valuable insights for guiding field development strategies and optimizing oil production from the Mishrif Formation in the Halfaya oil field. The study recommends further appraisal, including the use of additional data, core analysis, and geophysical studies, to enhance the understanding of the reservoir and improve production estimates.

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Chapter One

Importance Petrophysical Characteristics in Evaluating Rock

1.1 Introduction

Understanding the petrophysical properties of reservoirs is significance for assessing their characteristics and estimating the potential of oil-bearing formations. Well logs are considered one of the main sources of data for the geological and petrophysical parameters of reservoir formations; well logging plays a crucial role in the determination of the production potential of a hydrocarbon reservoir. This study focuses on the cretaceous reservoir in Iraqi oil field, renowned for its heterogeneous carbonate nature and diverse production formations. Carbonate reservoirs contain more than 60% of the world's oil reserves and contribute to more than 30% of the world's daily oil production. These carbonate reservoirs are more challenging when estimating the petrophysical properties and understanding the fluid flow mechanisms, compared to most sandstone reservoirs in this study refers the most fascinating aspects of carbonate reservoir rocks are their content. Carbonates are usually made of fossils which "range from the very small single cell to the larger shelled animals". Most carbonate rocks are deposited at or in very close neighborhood to their site of creation. The most productive carbonate reservoirs in Iraq are found in the Zubair and West Qurna fields. The carbonates in Iraq are typically of the Jurassic and Cretaceous age and are composed of limestone and dolomite.

The reservoirs rock in Iraq has significant hydrocarbon resources and a diverse range of reservoir rock types, making it an important player in the global oil and gas industry. The Mesopotamian Basin contains several major formations that are important for oil and gas production, including the Upper Jurassic Najmah and Sargelu Formations, the lower Cretaceous Mishirf Formation, and the Upper Cretaceous Tanuma and Zubair Formations. The Mishirf Formation is a major carbonate reservoir rock in Iraq, particularly in the southern part of the country. It is composed mainly of limestone and dolomite, and it is characterized by its high porosity and permeability, which make it an excellent reservoir rock for hydrocarbons. The Mishirf Formation is typically found at depths ranging from 1,000 to 3,000 m, and it is known to contain vast oil reserves. The reservoir rock's porosity and permeability are a result of its depositional environment, which was dominated by shallow marine conditions during the Late Cretaceous period. The formation's sedimentary facies are composed of bioclastic and oolitic grainstones , wackestones , and packstones , which all contribute to the rock's excellent reservoir The main producing formation in several major oil fields, including Rumaila, West Qurna, and Zubair and Halfaya field. The MishirfFormation in the Halfaya field is composed of limestone and dolomite, and is characterized by high porosity and permeability resulting in the development of secondary porosity through processes such as fracturing and dissolution.

1.2 The Study Petrophysical

Petrophysics is a science about the physical property of oil & gas, its formations, and physicochemical phenomena involved in an oil & gas reservoirs and during the exploiting of an oil & gas reservoirs. It primarily includes 3 parts:

(1) The physical properties of the reservoir fluids, including physical properties of oil, water, and gas at high pressure and high temperature, and the law that governs their phase-changing.

(2) The physical properties of the reservoir rocks, including porosity, permeability, saturation, and sensibility of the formation rocks.

(3) The physical properties of multiphase fluids in porous media and their seepage mechanisms.

A petroleum reservoir is geological structure which consists with formation rock, which is a porous medium, and the oil and gas is contained in the porous medium. The reservoir, which is the objectives what we study, is buried thousands of meters below the earth surface, the reservoir fluids are under states of high pressure and high temperature. At this state, the crude oil dissolves large volume of gas therefore, the physical properties of the underground reservoir fluids are vastly different from those of the subaerial ones.

1.3 The Aim Methods for Petrophysics

Petrophysics is a core study for majoring in petroleum engineering, or oil field chemistry and geology. As a science branch, petrophysics is based upon the experiments, so both theories and experiments are important. The primary aim of petrophysics is to understand the physical and chemical properties of rocks and their interactions with fluids. This knowledge is essential for efficient resource exploration and management, particularly in the fields of petroleum engineering, hydrogeology, and geotechnical engineering. Specific objectives include:

1. Characterization of Reservoirs: To identify the composition, distribution, and behavior of subsurface materials that can contain hydrocarbons, water, or other resources.

2. Fluid Movement Understanding: To analyze how fluids flow through rock formations, which is crucial for optimizing extraction methods and predicting reservoir performance.

3. Predicting Reservoir Behavior: To develop models that can forecast how reservoirs will respond under various extraction scenarios.

4. Geological Interpretation: To integrate petrophysical data with geological information, supporting better decision-making related to exploration and development.

Petrophysics plays a central role in the successful development of a hydrocarbon rock reservoir. Its measurements occupy a position of central importance in the life of a well, between two milestones: the surface seismic survey, which has influenced the decision for the well location, and the production testing.

1.4 Petrophysical Evaluation of Mishirf Formation

In the current study the Mishirf Formation, deposited during the Cretaceous period, is one of the economically important formations, the Mishirf Formation a heterogeneous carbonate reservoir is one of southern Iraq's most important reservoirs. The Mishirf Formation which is part of the Wasia Group. During the Cretaceous period, it was deposited in the second sedimentary cycle (Cenomanian-Early Turonian) and is found all throughout the Arabian Gulf (Sadooni and Aqrawi, 2000).

Despite the Khasib Formation being irregularly overlain, the Mishirf Formation is in gradational contact with the underlying Rumaila Formation (Al-Dabbas et al., 2010). The MishirfFormation in central Iraq is the consequence of long-term shallow marine carbonate deposition as the main carbonate reservoirs in central and southeast Iraq throughout the Cretaceous epoch (Al-Dulaimy and Sa’ad, 2013) as shown in Figure 1.1.

1.4.1 Geological Setting

The Mishirf Formation consists of major carbonate reservoirs in southeast Iraq, with 32 structures containing oil (Awadeesian et al., 2019). The oilfields of Rumaila, West Qurna, Zubair fields, Majnoon, and Halfaiya have the largest both oil accumulation and large-scale north-south trending anticline structures. Other commercial oil accumulations in the Mishirf Formation found in Abu Ghirab, Ahdab, Amara, Buzurgan, Dujaila, Gharraf, Hawaiza, and Jabel Fauqi (Aqrawi et al., 2010). Due to its economic hydrocarbon accumulations, several studies have been conducted for the Mishirf Formation in Southern Iraq. These studies involve different disciplines including stratigraphy and petrophysics.

As a result the stratigraphic column was divided into twenty stratigraphic zones: four for the Tanuma Formation, five for the Khasib Formation and eleven for the Mishrif Formation. Although there is controversy over the number of producing units and their stratigraphic intervals, the Mishrif Formation's bottom part is the main reservoir in the geological column (Al-Mimar et al., 2018). The Mishrif Formation is a significant reservoir in the Halfaya Oilfield and one of the most significant carbonate reservoirs in central and southeastern Iraq (Al-Baldawi, 2020), In this study will we using Techlog software for Calculation petrophysical characteristics in Mishrif Formation.

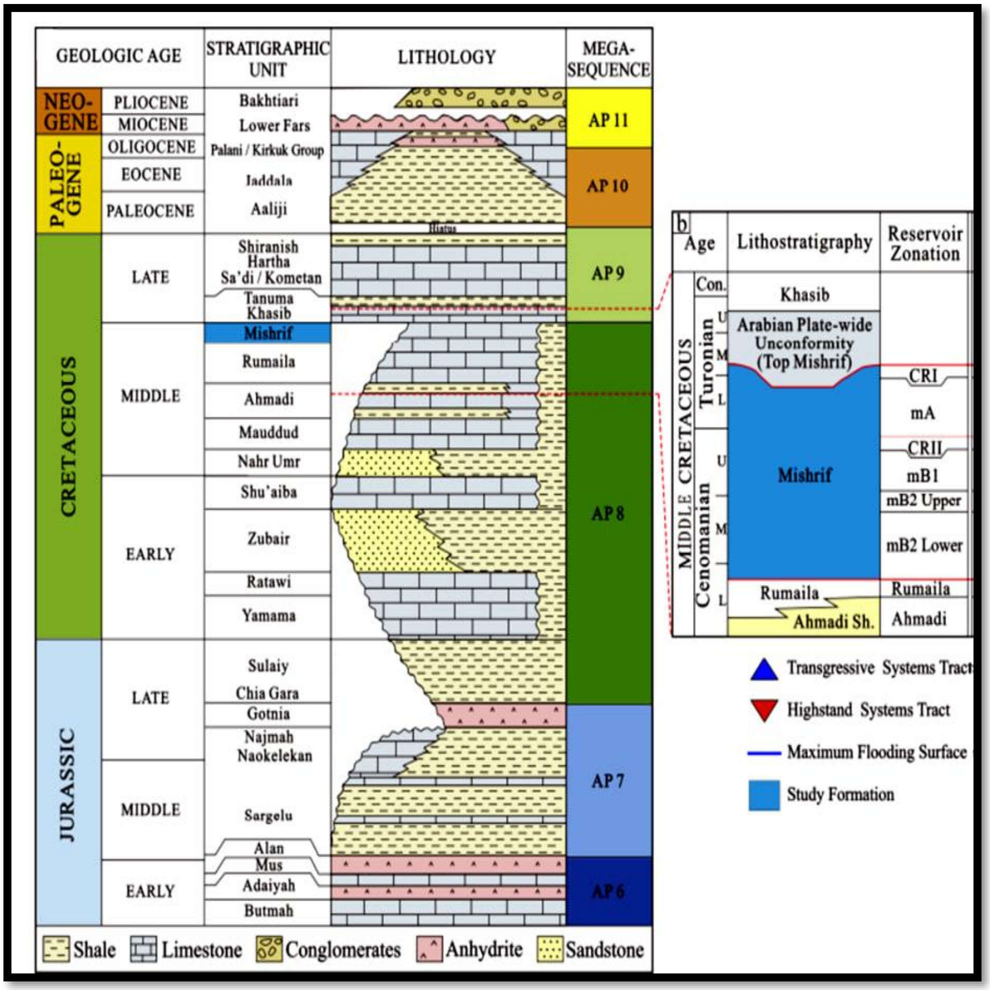


Fig (1.1) Stratigraphic Column of Mishrif Formation (M.O.C, 2013).

This information is a development well in Halfaya oil field. The main interested formations are Tertiary and Cretaceous. Based on the Master-logs and the characteristics of logging response, the formation can be divided as described in Table 1.1.

Table (1.1): Formation Tops.

Formation			Top(m) (Wireline logging)
Tertiary		Jeribe	1910
		Upper Kirkuk	1921
		Middle Kirkuk	2093.9
		Lower Kirkuk	2183.5
		Jaddala	2263
		Aaliji	2453
Cretaceous	Upper	Shiranish	2501.9
		Hartha	2573
		Sadi	2625.2
		Tenuma	2757.6
	Middle	Khasib	2773
		Mishrif	2855.9
		TD in Mishrif	3167

1.4.2 Study Area

In this study we will discuss Halfaiya oil field with bioclastic limestone as the principal producing zone, Halfaiya oilfield is placed in Maysan governorate, 35 km southeast Amara city as shown Figure 1.2. The structure, which is composed of two domes, runs along a northwest–southeast coordinate east (E 726,000 - 739,000) and north (N 3,500,000 - 351,400) and has a gentle elongated anticline of about 38 km long and 12 km wide. Halfaya oilfield is located in the Maysan region, southeast of Iraq, around 400 km from its capital, Baghdad. Tectonically, it is located at the unstable continental shelf in the northern Persian/Arabian Gulf basin at the northern brink of Gondwanaland and at the east side of the unstable continental shelf zone, Mesopotamian main belt, and the south section of the Tigris sub-belt (Zhong et al. 2018; Almalikee and Sen 2021). The Mesopotamian basin has a great deep buried area with thick sediments, somewhat stable tertiary tectonic units, and a well-presented platform environment as shown Figure. 1.2.

The study region is a gentle northwest–southeast anticline, influenced by the Alpine movement. The Mishrif formation was formed during the middle Cretaceous period, with a sedimentary thickness of 350–400 m that gradually thins to 150 m as it moves southwest. In the Iraq–Iran borders and Basra area, it is striped in a southeast–northwest direction (Alkersan 1975; Aqrawi 1998; Buday and Jassim 1987; Dunnington 1958; Ghalib 2014; Owen and Nasr 1958). It is part of the Qamchuqa group, and its reservoir rocks are carbonate with rudist deposited in a shallow marine platform. The most common are intergranular, intragranular (dissolved), and frame pores (Gao et al. 2013). Mishrif Formation (Cenomanian-Early Turonian) in the field of Halfaiya consists of permeable limestone, chalky limestone, compact calcareous, and chert shale at the base of the formation.

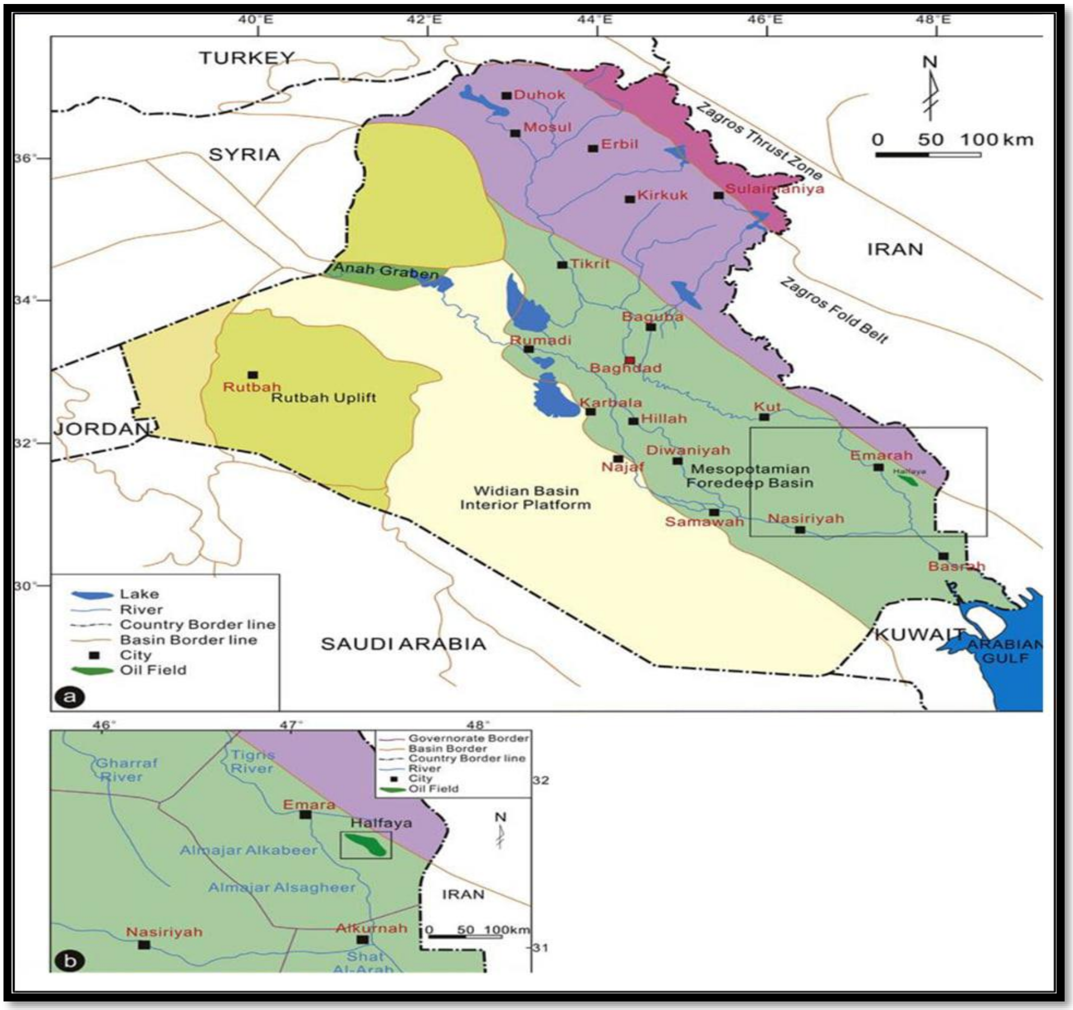


Fig (1.2) (a) Location and regional structure of the study area in Iraq (Al-Ameri et al., 2015); (b) Enlarged of the study area.

1.5 Wireline Process to Calculate Petrophysical Properties

In this study, we using in calcuation petrophysical characterization well logging proces that means different things to different people. For a geologist, it is primarily a mapping technique for exploring the subsurface. For a petrophysicist, it is a means to evaluate the hydrocarbon production potential of a reservoir. For a geophysicist, it is a source of complementary data for surface seismic analysis. For a reservoir engineer, it may simply supply values for use in a simulator. The initial uses of well logging were for correlating similar patterns of electrical conductivity from one well to another, sometimes over large distances. As the measuring techniques improved and multiplied, applications began to be directed to the quantitative evaluation of hydrocarbon-bearing formations.

The process of logging involves a number of elements, which are schematically illustrated in Figure 1.3. Our primary interest is the measurement device, or sonde. Currently, over fifty different types of these logging tools exist in order to meet various information needs and functions. Some of them are passive measurement devices; others exert some influence on the formation being traversed. Their measurements are transmitted to the surface by means of the wire line. Much of what follows in succeeding chapters is devoted to the basic principles exploited by the measurement sondes, without much regard to details of the actual devices. It is worthwhile to mention a few general points regarding the construction of the measurement sondes. Superficially, they all resemble one another. They are generally cylindrical devices with an outside diameter on the order of 4 in. or less; this is to accommodate operation in boreholes as small as 6 in. in diameter. Their length varies depending on the sensor array used and the complexity of associated electronics required. It is possible to connect a number of devices concurrently, forming tool strings as long as 100 ft.

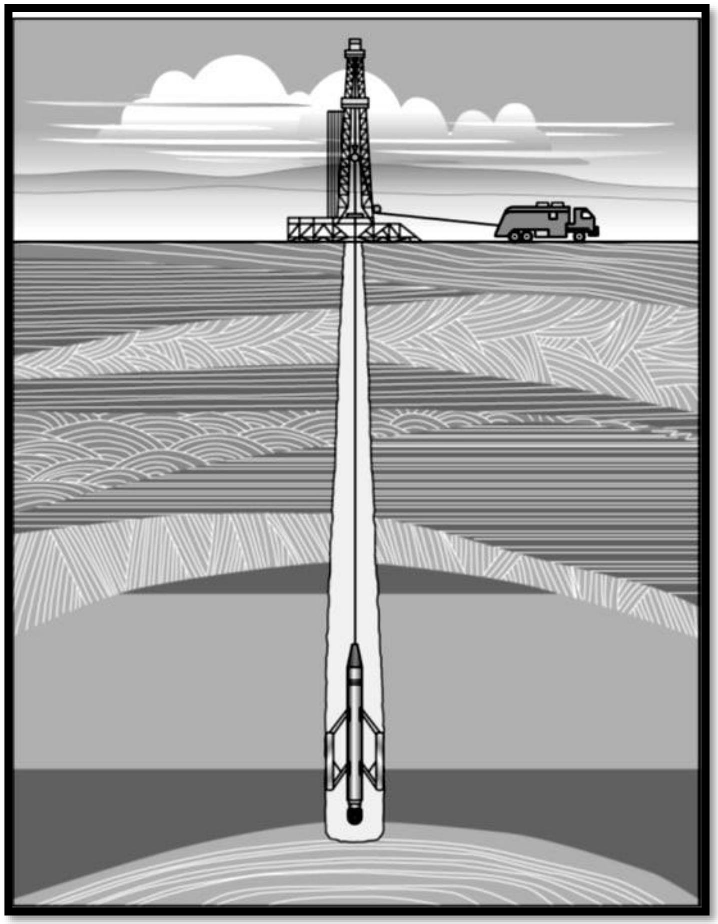


Fig (1.3) The elements of well logging: a measurement sonde in a borehole, the wireline, and a mobile laboratory. Courtesy of Schlumberg

Chapter Two

An Overview of Well Logging Tools

This chapter discusses all required steps and introduces methodology to complete this study.

2.1 Description

This chapter presents a general overview of the problem of log interpretation and examines the basic questions concerning a formation's potential hydrocarbon production that are addressed by well logs. The borehole environment is described in terms of its impact on the electrical logging measurements, and all of the qualitative concepts necessary for simple log interpretation are presented.

With going into the specifics of the logging measurements, the log format conventions are presented, and an example is given that indicates the process of locating possible hydrocarbon zones from log measurements. Although the interpretation example is an exercise in the qualitative art of well log analysis, it raises a number of issues. These relate to the extraction of quantitative petrophysical parameters from the logging measurements.

2.2 Measurement Techniques

Well logging measures rock and fluid properties (electrical, nuclear, acoustic) to estimate hydrocarbon volume in porous formations. Electrical conductivity indicates fluid type (brine vs. hydrocarbon) and is affected by porosity. Nuclear methods estimate porosity using neutron interaction with hydrogen or gamma ray attenuation for bulk density. Neutron capture also enables chemical analysis. Acoustic measurements relate velocity to porosity and lithology, and can assess borehole shape, casing integrity, and permeability. Logging tools measure related parameters, requiring interpretation to determine key petrophysical properties by integrating tool response with geological knowledge.

2.3 Logging Tools

Wireline logging is performed by lowering a 'logging tool' or a string of one or more instruments on the end of a wireline into an oil well and recording petrophysical properties using a variety of sensors Logging tools developed over the years measure the natural gamma ray, electrical, acoustic, stimulated radioactive responses, electromagnetic, nuclear magnetic resonance, pressure and other properties of the rocks and their contained fluids. In first equipment is unloaded "Logging tolls" into the well, where this equipment transmits information from inside the well to the surface, and the data appears on "a logging truck" in the form of charts that are later interpreted by the probe "interpretation engineers". Common log tools are divided as in the Table 2.1.

Table (2.1): Classification Of Well Log Types

<table>
<tr><th colspan="3">Type of well logging operations</th></tr>
<tr><th colspan="2">Open Hole logging</th><th rowspan="2">Cased Hole loggong</th></tr>
<tr><th>Conventional log</th><th>High tech log</th></tr>
<tr><td>1. Lithology logs:
➢ SP
➢ GR</td><td>1. Nuclear magnetic resonance log (NMR)</td><td>1. Cement Bond log.</td></tr>
<tr><td>2. Porosity logs:
➢ Density
➢ Neutron
➢ Sonic</td><td>2. Modular dynamic formation tester (MDT)</td><td>2. Casing inspection log</td></tr>
<tr><td>3. Resistivity logs</td><td>3. Micro resistivity imaging.</td><td>3. Saturation log</td></tr>
<tr><td rowspan="2">4. Caliper log</td><td>4. Sidewall core.</td><td>4. Production logging tools (PLT)</td></tr>
<tr><td>5. Vertical seismic profile (VSP)</td><td>5. Spectral Noise log (SNL)</td></tr>
</table>

Common logging tools that used to extract petrophysical properties are introduced briefly below

2.3.1 Gamma Ray Log (GR)

The radioactivity of the formations measured or evaluated through utilizing Gamma ray log, because there is the presence of radioactive elements in shale formations. Thus, the Gamma-Ray typically identifies shale formation or presence of shale in the formation. The Gamma-Ray log (GR) is usually illustrated in the first track on a linear grid and is scaled in American Petroleum Institute (API) unit from (0 to 100 or 0 to 150). Radioactivity with high readings causes a deflection of the curve to the right and low radioactivity causes a deflection to the left; thus high readings indicate shale and lower readings indicate less shale or shale free formations called clean sandstone, clean limestone or clean dolomite. However, when there is mica, uranium feldspar, glauconite presence in the clean sandstone formations, Gamma ray may show high readings (Asquith et al., 2004).

So, with having Potassium (K), Thorium (Th) and Uranium (U) content in sandstone formation, Spectral Gamma Ray should be run to separate each radioactive elements with different readings as seen in Figure 3.1. Other three common simple uses of Gamma-ray are the correlation of stratigraphic units, mineral analysis and shale volume calculation which is important for calculating water saturation in shale bearing formations (Dewan, 1983).

This leads to complications in the presence of clay-bearing formations, since the hydrogen associated with the clay minerals is seen by the tool in the same way as the hydrogen in the pore space. As an alternative, gamma ray attenuation is used to determine the bulk density of the formation. With a knowledge of the rock type, more specifically the grain density, it is simple to convert this measurement to a fluid-filled porosity value. The capture of low-energy neutrons by elements in the formation produces gamma rays of characteristic energies. By analyzing the energy of these gamma rays, a selective chemical analysis of the formation can be made. This is especially useful for identifying the minerals present in the rock. Interaction of higher energy neutrons with the formation permit a direct determination of the presence of hydrocarbons through the ratio of C to O atoms.

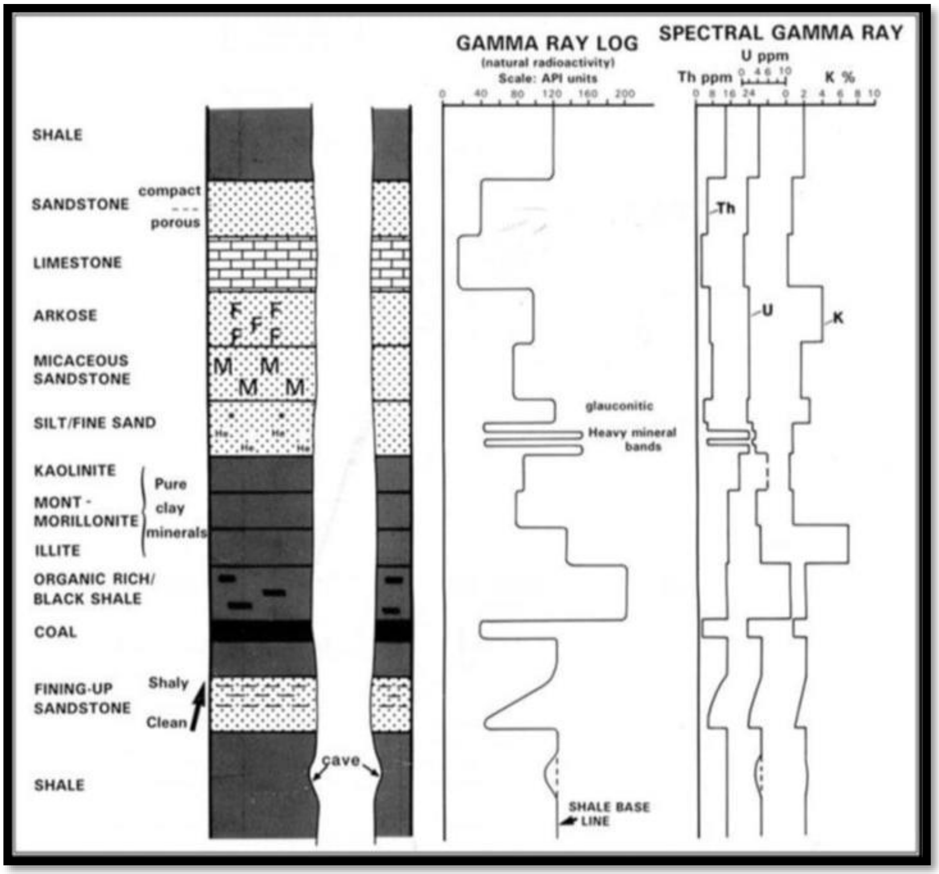


Fig (2.1) Comparison of total Gamma Ray and Spectral Gamma Ray curves opposite different lithologies (After Rider, 1986).

2.3.2 Sonic Log

The whole process of sonic log could be mentioned as the operation of sending and receiving sound pulses by the end of the tool. The simplest one comprises of one transmitter and a pair of receivers. Usually sonic curve is plotted in Track 2 or 3 ranging from 40 – 140 µsec/ft. The time that need for cross the sound wave on the formation recorded by sonic log, called as slowness and obtainable in microseconds per foot (µsec/ft) and it rely on the formation lithology and its porosity value (Figure 2.2). In addition, increasing porosity lead to increase interval transit time (Oghenekohwo, 2010).

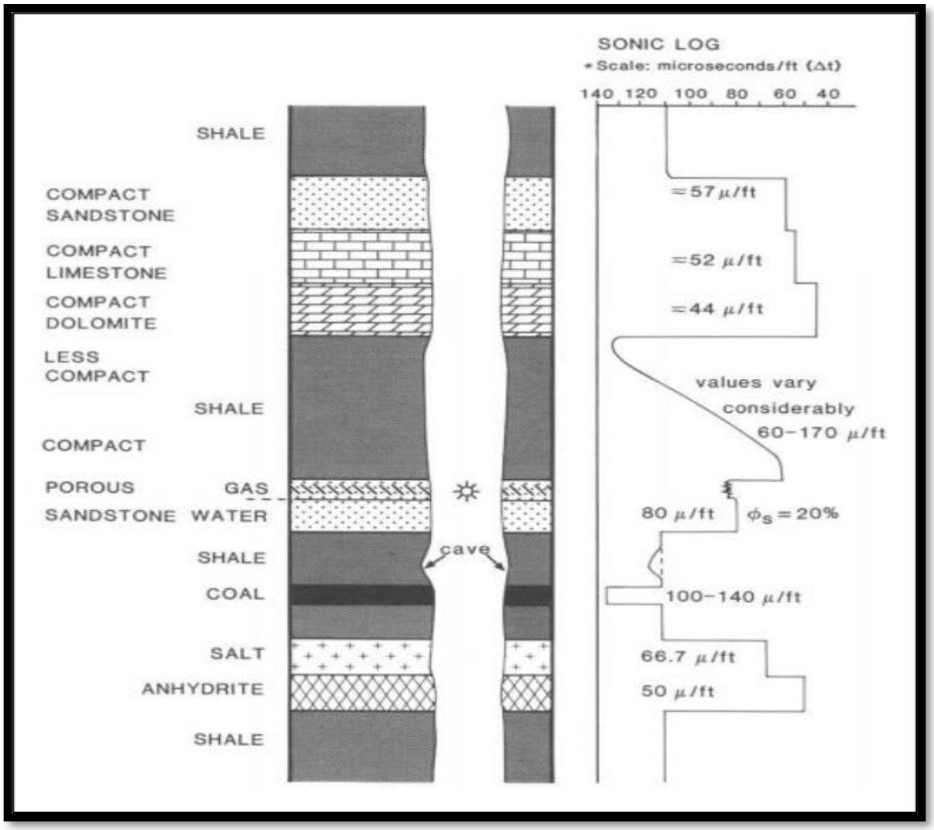


Fig (2.2) Sonic log records in various lithologies (After Rider, 1986).

2.3.3 Neutron Log

The Neutron log responds primarily to hydrogen atoms in the formation. The two substones in the formation with the greatest concentration of hydrogen atoms are water and liquid hydrocarbons that occupy the pore spaces. In clean formations the tool reflects the amount of liquid filled porosity. Neutron porosity readings are computed automatically and displayed as a curve scaled in linear porosity units similar to the density porosity display. Neutron readings are affected to some extent by the lithology of the rock matrix, therefore a matrix setting must be chosen prior to logging the well. Neutron logs, however, usually calibrated for a limestone matrix and if actual lithology coincides with the chosen matrix setting porosity may be read directly from the log. Porosity for the lithology other than limestone may be determined from a chart if the lithology is known (Asquith et al., 2004).

2.3.4 Density Log

The Formation density tool radiates gamma rays into the formation from the source and measures gamma rays returning at the detectors. By introducing the known amount of radioactive energy into the formation and monitoring its loss while transit, a good approximation of rock density can be obtained. Gamma rays are emitted continuously from the source and the passed through the mud cake into the rock, where they are scattered or absorbed some are returned back through the mud cake to the detectors and counted. In the formation density tool source and receiver detectors spacing is so close, so the device evaluates invaded zone close to the bore wall. The loss of gamma ray energy that occurs during transit from source to detector is used to interpret porosity of the formation (Asquith et al., 2004).

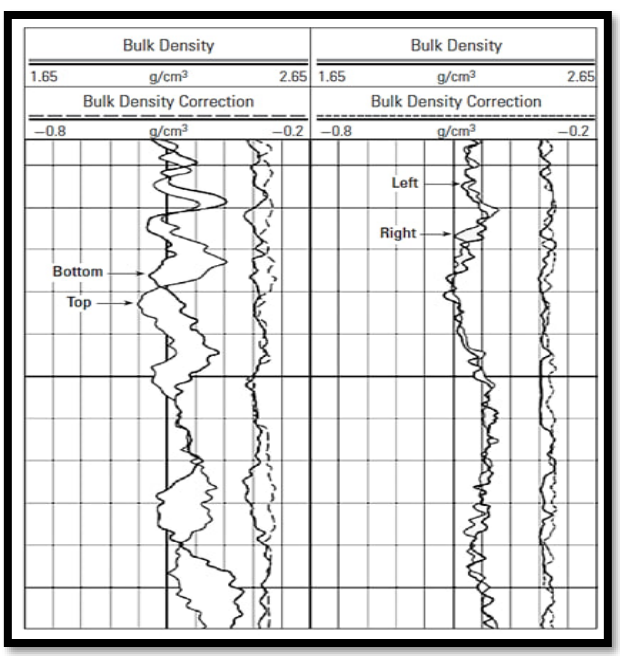


Fig (2.3) An example of a LWD density log where the data has been collected in oriented quadrants. From Bourgois et al. 1998.

2.3.5 Resistivity Log

Formation resistivity is very important because it is inversely related to water saturation (Sw). In a reservoir rock as water saturation increase electrical resistivity of the formation decreases. Consequently, from resistivity measurements water saturation and therefore hydrocarbon saturation could be determined. The simple measuring system has a pair of current electrodes and a pair of voltage electrodes. The resistivity logs could be used in differentiating hydrocarbon bearing zone from water-bearing zone. When porosity logs are not available it could be used for porosity determination and could be used to indicate permeable zones. Resistivity is measured in ohm-meters (Asquith et al., 2004).

The resistivity logs are normally illustrated on a logarithmic scale ranging from 0.2 - 2000 ohm-meters in Tracks 2 or 3, the values increase from left to right. In electrical logging several factors control the measure of electrical response. These are: water saturation, salinity, porosity and pore interconnections sometimes referred to as tortuosity. The first two of these factors are fluid dependent while the third one is rock dependent. As the salinity of the sample is changed you can observe a change in the voltage reading. As salinity increases current flows between the current electrodes and there is a potential or voltage drop measured in logging terms the resistivity of the formation decreases, resistivity also decreases as water saturation increases and as porosity increases (Krygowski, 2003).

2.3.6 Caliper Log

A caliper is an auxiliary tool which is used for measuring borehole diameter. This tool usually consists of (2, 4 up to 30) extendable arms. The caliper curve generally schemed in Track 1 with the bit size for reference scaled range (6 – 16) based on the bit size. If the caliper log reads a constant hole size, this phenomenon is called on gauge. This happens if has non-permeable Formation or well consolidated formation like massive sandstones, metamorphic rock and igneous rock. If caliper read more than bit size its mean we have caving, weak formation or soluble formation like (unconsolidated sand or salt formation) in this case called over gauge, inversely if caliper read less than bit size its means there is swelling or mudcake development, where swilling happens in shale layers and mudcake develops in pours and permeable sandstone layers. This is called under gaue (Figure 2.4). The caliper logs have more applications as follows (Parsons, 1943):

Caliper information is useful in lithological identifications, indicate porous permeable zones, computing thickness of the mudcake, calculation volume of borehole, calculation of cement volume and hole characteristics.

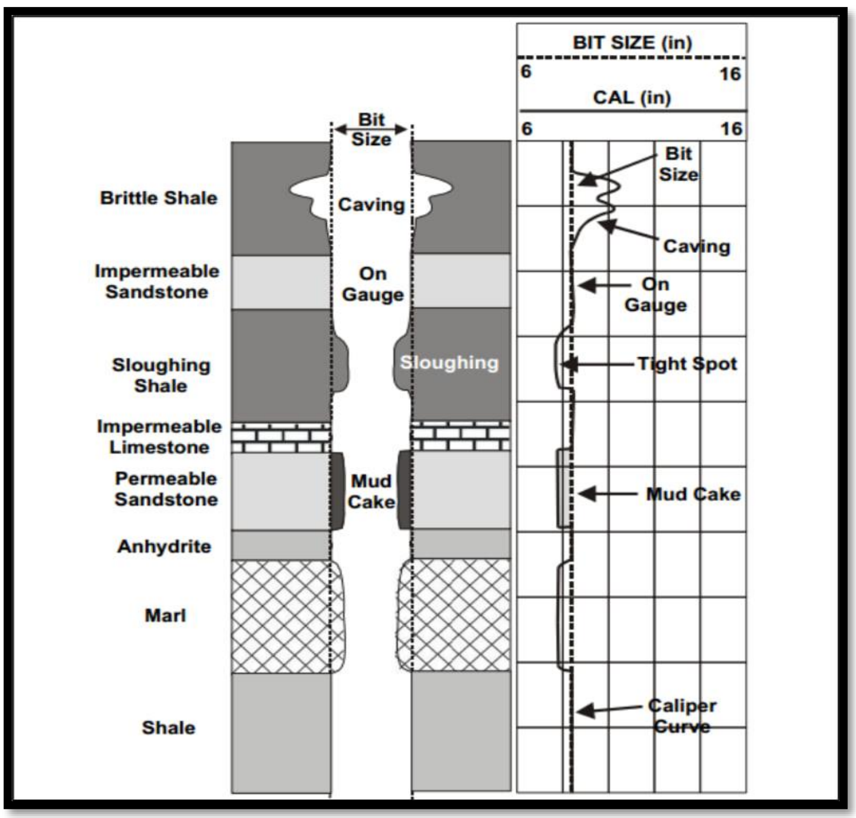


Fig (2.4) Caliper log readings in numerous lithologies (After Ahammod et al., 2014).

2.4 Typical Log Presentation

Figure 2.5 displays the "standard presentation." Perhaps it should be called a traditional presentation: with the computing and graphics capabilities within reach of most logging engineers and petrophysicists, there may no longer be a "standard." Why is the porosity curve, NPHI, labeled "sand" and why does the scale for NPHI seem to be presented backwards?

In Figure 2.5, the neutron and density traces are found in track 3 in a compatible scale overlay. The particular scheme shown assumes that the lithology is expected to be predominantly sandstone. The idea behind the overlay is to adjust the gain and offset of the two traces so that they agree, or overlay, when the formation is water-filled sandstone. For this reason, the neutron curve is denoted "sand." It will be seen that there are two other common lithology outputs, "lime" and "dolomite". Presumably, when the tool measurement is presented in the selected units, the readings will agree with the porosity of the water-filled rock of the type selected.

Returning to the gain and offset, it has been traditional to present a dynamic range of 1 g/cm3 on the density trace across the full track (or sometimes two tracks). It is easy to show that a change in bulk density of 1 g/cm3 in a water-filled formation corresponds to a porosity change of about 60 units (p.u.). Consequently, the neutron trace is usually shown with a dynamic range of 60 p.u. across the density track.

The offset simply shifts the zero point on the neutron track to the density of the matrix; in this case of quartz sandstone, 2.65 g/cm3. The density is also shifted so that the scale runs from 1.9 to 2.9 g/cm3. In this scheme, the 0 p.u. point is two and a half divisions from the right hand of the track. The consequence of accommodating the 60 p.u. swing of the neutron makes it range from −15 p.u. on the right edge to 45 p.u on the left hand of the track.

The limestone compatible scale (which may be a standard, or may depend on locale) will be seen in another example. For that case, the density scale generally runs from 1.95 to 2.95 g/cm3. The matrix density of limestone is 2.71 g/cm3 so the neutron scale (but it is in limestone units – more about that later) remains at 45 to −15 p.u. for an approximate match at 0 p.u. Another scale, common in the Gulf of Mexico, where the apparent neutron porosity generally is high, has the neutron running from 60 to 0 p.u. and the density from 1.65 to 2.65 g/cm3.

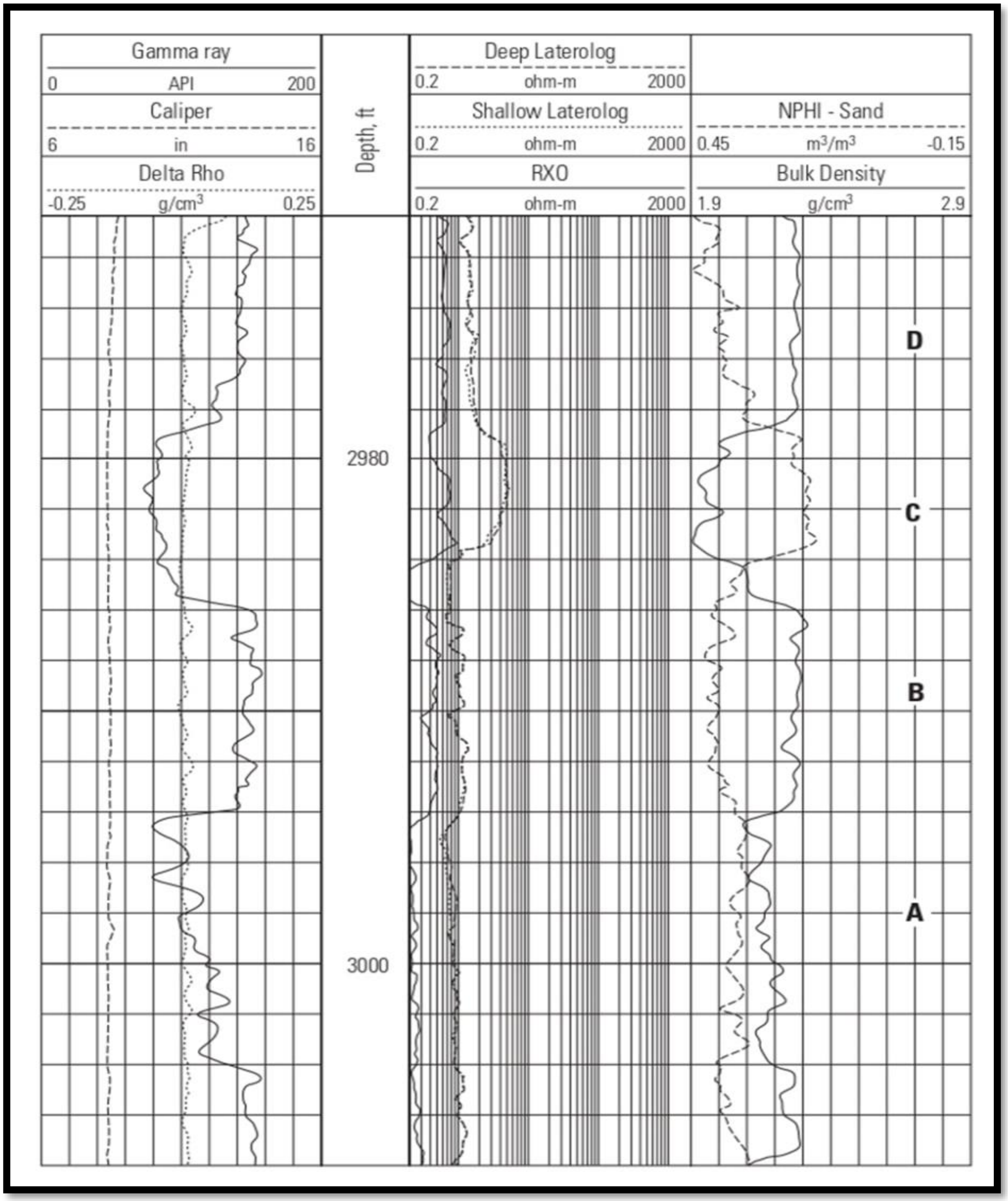


Fig (2.5) A "typical" neutron-density presentation is shown in track 3. The neutron porosity, indicated to be in "sand" units, is scaled from 0.45 to −0.15 v/v, increasing to the left. The density scale is from 1.9 to 2.9 g/cm3, increasing to the right. From Ellis et al. [1]. Used with permission.

2.5 Studies Conducted in Relation to Petrophysical Characterization

Qadir (2008) used two methods for studying Formation evaluation in the upper Qamchuqa reservoir in the Khabbaz oil field (Kirkuk area), which was wire-line logs data, and core data. Lithology was classified into three lithological units, A, B and C. Furthermore, among these three, Unit A was defined as the best reservoir unit.

Harrison and Jing (2001) reconsidered the most common saturation height methods and their effect on volumetric hydrocarbons in place approximations. This paper reconsidered some of the most common saturation-height methods such as Leverett, Johnson, Cuddy (1941) and Skelt (1995) methods which are commonly used by the oil and gas industry. A comparison between all these methods has been determined to select the most representative method. Therefore, for this aim two wells which have predictable core data, SCAL and a full set of electric logs were used. The research concluded that Cuddy's technique was the humblest to appliance. Leverett's SCAL-based J-Function, whereas Johnson's and Skelt's SCAL-based methods were extremely inconvenient for the analysis. To observe the effect on the estimated oil in place, the considered methods were compared on a well basis, through which the resultant saturation height applied as a relationship to the reservoir structure.

Sahib (2003) evaluated the permeability of sandstone rock in southern Iraqi oil fields using well logs focusing on the geological factors such as, nature of the porosity and grain properties. He used different methods to calculate permeability by integrating core and log data. He also compared his result with porosity permeability direct correlations, the irreducible water saturation method, improved log derived permeability by pore throat radius and cementation exponent parameters, the resistivity ratio method, and the transform approaches method. Finally, it was concluded that each Formation has its own character to apply a method in order to calculate permeability in the un-cored wells with approximate results. He concluded that only porosity was insufficient to clarify the permeability variations.

Obeida et al. (2005) applied various techniques to calculate fluid saturation which was a case study on a huge complex carbonate reservoir in the Middle East. This study was adjusted using MIPCs and J Functions obtained from core tests. The reasons behind using the J Function model were that in one area the results for matching irreducible water saturation were not good, and a capillary pressure curve for each reservoir rock type was used. Again, the results of this method were not satisfactory, especially when picking up an average from a single capillary pressure test. Eventually log derived J-function and the results were used.

Abdulkareem (2011) studied petrophysical properties of the Jribe, Dihban, Euphrates, and Bajwan Formations in an Iraqi gas field. In his study, Archie parameters were determined from well logs analysis. It was concluded that the lithologies of these Formations were mostly limestone while it was partially dolomitized and contained some shale. Moreover, clay volume was calculated using combination of gamma ray log method, resistivity log method, neutron log method, density neutron cross-plot method, density - acoustic crossplot method and neutron - acoustic cross-plot method.

Furthermore, porosity was determined from sonic log, density log and neutron logs, and also secondary porosity index which occur due to diagenetic process was determined. Crystallization, dolomitization, and recrystallization are the diapenetic processes determined. In addition, the following formation related parameters were determined:

- Formation water resistivity was determined from the apparent water resistivity method using spontaneous potential log.
- Fluid saturation was determined by using Archie equation, Dual water model and Indonesian model.
- Irreducible water saturation was calculated through plotting water saturation versus porosity in a linear scale.
- From empirical equations permeability was estimated.
- Distribution of porosity and permeability were mapped using the SURFER software.

Tixier (1949) studied evaluation of permeability through electric-log resistivity gradients in oil/water transition zones with regards a deep investigation resistivity tool. Although the investigations were the existing empirical relationships between resistivity and water saturation, water saturation and capillary pressure were employed for that purpose. Therefore, using the resistivity gradient from the corresponding layers resulted in the calculation of the average permeability.

Chapter Three

An Overview Petrophysical Characterization

3.1 Description

Petrophysical characterization is like taking measurements of a rock deep underground to understand what fluids (like oil, gas, or water) it holds and how easily those fluids can flow through it. This helps us figure out if it's a good place to get oil and gas. The material of which a petroleum reservoir rock may be composed can range from very loose and unconsolidated sand to a very hard and dense sandstone, limestone, or dolomite. The grains may be bonded together with a number of materials, the most common of which are silica, calcite, or clay. Knowledge of the physical properties of the rock and the existing interaction between the hydrocarbon system and the formation is essential in understanding and evaluating the performance of a given reservoir. Rock properties are determined by performing laboratory analyses on cores from the reservoir to be evaluated. The cores are removed from the reservoir environment, with subsequent changes in the core bulk volume, pore volume, reservoir fluid saturations, and, sometimes, formation wettability. The effect of these changes on rock properties may range from negligible to substantial, depending on characteristics of the formation and property of interest, and should be evaluated in the testing program. Once these relationships are established, more quantitative procedures of interpretation will be described.

3.2 Techlog Software

TECHLOG software is a Schlumberger software platform to identify and collect all well bore information. In addition, through using this software we will be able to interpret logs and core data. In this research study, TECHLOG software has been used in order to find and identify porosity, water saturation and hydrocarbon and gas zones.

But before entering into the use of the Techlog software, we must review the petrophysical properties more accurately for oil reservoirs in general, which we will need to understand the theoretical basis for interpreting well logs accurately, as well as knowing the nature of the program's work, which includes theoretical equations and calculations. It can solve all the properties easily and very quickly.

3.3 Porosity of Reservoir Rocks

The total volume V_b of a rock, also called bulk volume or bulk volume, is composed of the pore volume V_p and the volume of the solid grains (the volume of the matrix) V_s:

$$V_b = V_p + V_s \qquad \dots (3.1)$$

Porosity ($\emptyset$) is defined as the ratio of the pore volume V_p in a rock to the bulk volume V_b of that rock in percentage. Expressed mathematically as:

$$\emptyset = \frac{V_p}{V_b} * 100\% \quad \dots (3.2)$$

Substitute Eq. (2.1) into the equation above, we can get:

$$\emptyset = \frac{V_b - V_s}{V_b} * 100\% = \left(1 - \frac{V_s}{V_b}\right) * 100\% \quad \dots (3.3)$$

1. Absolute Porosity of Reservoir Rocks:

The total pore volume (V_a) in rock can be divided into:

(1) Interconnected pore volume (also called effective pore volume); mobile pore volume and immobile pore volume.

(2) Unconnected pore volume.

Absolute porosity $\emptyset_a$ is the ratio of the total void space in the rock to the bulk volume of the rock, expressed in percentage:

$$\emptyset_a = \frac{V_a}{V_b} * 100\% \quad \dots (3.4)$$

2. Effective Porosity of Reservoir Rocks:

Effective porosity $\emptyset_e$ is the ratio of the interconnected void space in the rock to the bulk volume of the rock, expressed in percentage:

$$\emptyset_e = \frac{V_e}{V_b} * 100\% \quad \dots (3.5)$$

The effective porosity is more frequently used in reserve calculation and reservoir evaluation.

3. Mobile Porosity of Reservoir Rocks:

Not all the interconnected microcapillary pores let the fluid through. Normally, for the pores with throats of extremely small diameter, it is almost impossible for usual production pressure differential to enable the fluids to flow through them. Besides, this problem also exist in hydrophilic rocks where there are water films absorbed on the rock surfaces and consequently the channels present in the pores are reduced in volume. The so-called mobile porosity is the ratio of the volume of the space V_f that is occupied by mobile fluids to the bulk volume of the rock:

$$\emptyset_f = \frac{V_f}{V_b} * 100\% \quad \dots (3.6)$$

Since neither the volume of the dead pores nor that of the microcapillary pores are included in the calculation of mobile porosity, it is different from effective porosity. The former one, the mobile porosity, is not a fixed value but changing with the changes of the pressure gradient and physical or chemical properties of the liquids present in reservoirs. In reservoir developments, the parameter of mobile porosity is practically valuable to some extent.

Seeing from the definitions given above, we can know that: absolute porosity $\emptyset_a$ > effective porosity $\emptyset_e$ > mobile porosity $\emptyset_f$.

Porosity is an important index in reserve calculation and reservoir evaluation. Effective porosity is adopted by engineers to evaluate formations in the petroleum industry, so generally speaking, the mentioned "porosity" in relevant context specially refers to the "effective porosity." The porosity of sandstone formations usually ranges between 5 and 25 %, while that of carbonate rock matrix is apt to be smaller than 5 %. Normally, a sandstone formation with porosity lower than 5 % is not valuable for development. The ranking of sandstone formations according to porosity is shown in **Table 3.1**.

Table (3.1): Ranking of sandstone formations according to porosity.

Porosity %	Evaluation
25–20	Extremely good
20–15	Good
15–10	Moderate
10–5	Bad
5–0	No value

Divided into two types for convenience: the initial porosity or matrix porosity which reflects the intergranular pores present among rock grains and the induced porosity (also referred to as cavity porosity and fracture porosity) which reflects the space formed in the cavity and fracture systems. Therefore, the total porosity of this kind of medium should be described with the term "dual-porosity." **Figure 3.1** shows it. For fractured reservoirs: bulk volume of rock = fracture volume + matrix volume, and total pore volume = fracture volume + initial pore volume. The correlation among the total porosity $\emptyset_t$, the fracture porosity $\emptyset_f$, and the initial porosity $\emptyset_p$ is written below:

$$\emptyset_t = \emptyset_p + \emptyset_f \quad \dots (3.7)$$

Where

$\emptyset_p$: Initial pore volume present in matrix/bulk volume of rock;

$\emptyset_f$: Fracture volume/bulk volume of rock.

The determination of rock porosity can be accomplished via two approaches:

(1) Direct measurement through experiments in laboratory;

(2) Indirect measurement.

Based on a variety of logging methods. Of the two methods, the indirect measurement is usually subjected to so many influencing factors that great error is produced during its usage.

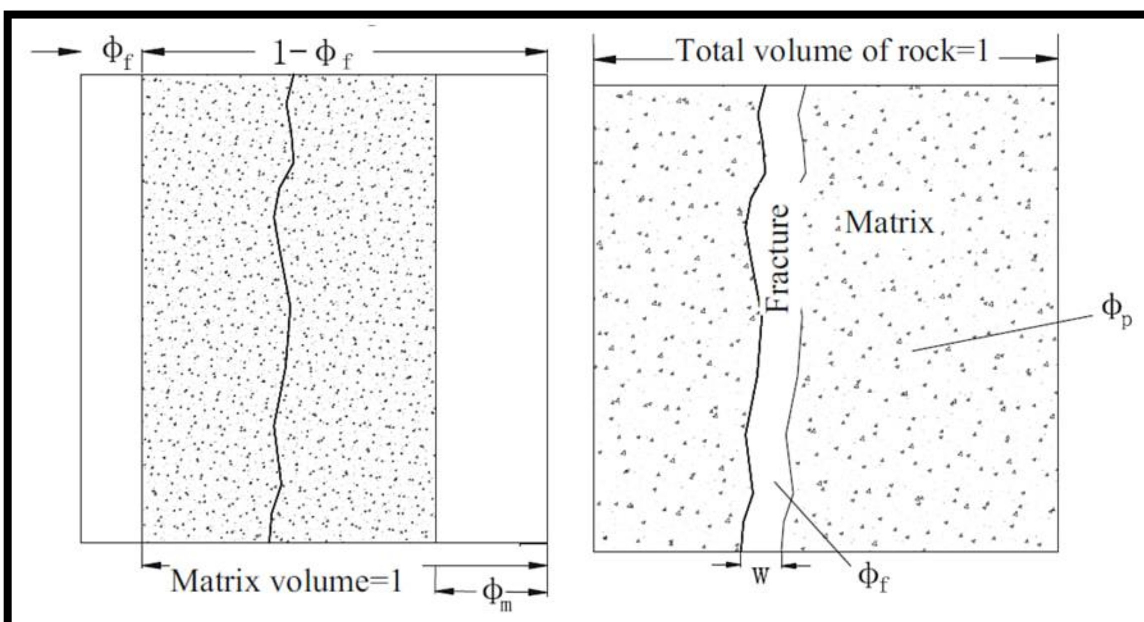


Fig (3.1) Porosity of dual-porosity medium rock.

3.4 Saturation

Generally, fluid saturation is defined as the ratio of the volume of a fluid phase in a given reservoir rock sample to the pore volume of the sample. In other words, fluid saturation is defined as that fraction or percent of the pore volume occupied by a particular fluid phase (gas, oil, or water) expressed by a generalized mathematical expression:

$$fluid\ saturation = \frac{total\ volume\ of\ the\ fluid\ phase}{pore\ volume} \quad \ldots (3.8)$$

It should be noted that the fluid saturation may be reported either as a fraction of the total pore volume or as the effective (interconnected as well as dead-end- or cul-de-sac-type pores) pore volume.

However, fluid saturation is generally reported as a fraction of the effective pore volume rather than the total pore volume because it is more meaningful as fluids present in the completely isolated pore space cannot be produced. Therefore, Equation 3.8 assumes that the pore volume is effective pore volume.

Equation 2.8 can now be applied to the specific fluid phases:

$$S_o = \frac{volume\ of\ oil}{pore\ volume} \quad \ldots (3.9)$$

$$S_w = \frac{volume\ of\ water}{pore\ volume} \quad \ldots (3.10)$$

$$S_g = \frac{volume\ of\ gas}{pore\ volume} \quad \ldots (3.11)$$

Where S_o, S_w, and S_g are the gas, oil, and water saturations, respectively.

Fluid saturation can be expressed as a fraction or percentage (by multiplying the values in Equations 3.9 through 3.11 by 100) of the pore volume. Equations 3.9 through 3.11 clearly indicate that saturations can range from 0% to 100% or 0 to 1, and since all saturations are scaled down to the pore volume, their summation should always equal 100% or 1, leading to

$$S_o + S_w + S_g = 1.0 \quad \ldots (3.12)$$

Equation 3.12 is probably the most simple yet fundamental equation in reservoir engineering and is used almost everywhere in reservoir engineering calculations. Moreover, many important reservoir rock properties, such as capillary pressure and relative permeability, are actually related or linked with individual fluid-phase saturations. The definition of properties such as relative permeabilities or capillary pressures without relating them to fluid-phase saturations is basically meaningless.

It can also be seen from Equations 3.9 through 3.12 that

Volume of gas + volume of oil + volume of water = pore volume …(3.13)

So if fluid saturations are accurately measured on a reservoir rock sample, the summation of volumes of individual fluid phases can also be used to determine the pore volume (or porosity if the bulk volume is also known) of that particular sample because fluid phases originated from the pore spaces of that very sample. In order to illustrate the significance of Equation 3.12, the fluid saturation distribution for a hypothetical core plug sample is shown in **Figure 3.2**.

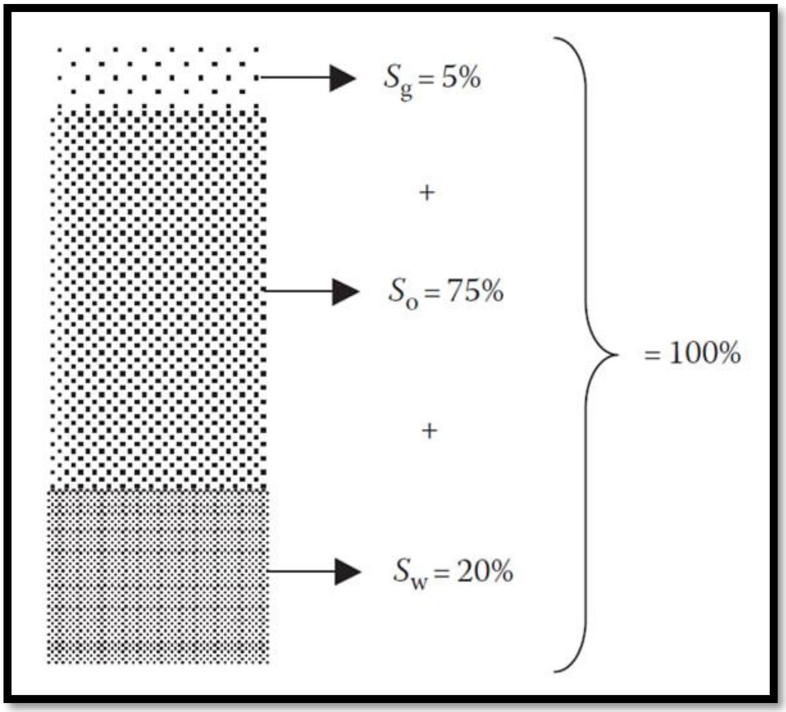


Fig (3.2) Fluid saturation distribution in a hypothetical reservoir rock sample.

The fluids in most reservoirs are believed to have reached a state of equilibrium and, therefore, will have become separated according to their density, i.e., oil overlain by gas and underlain by water. In addition to the bottom (or edge) water, there will be connate water distributed throughout the oil and gas zones. The water in these zones will have been reduced to some irreducible minimum. The forces retaining the water in the oil and gas zones are referred to as capillary forces because they are important only in pore spaces of capillary size.

Connate (interstitial) water saturation Swc is important primarily because it reduces the amount of space available between oil and gas. It is generally not uniformly distributed throughout the reservoir but varies with permeability, lithology, and height above the free water table. Another particular phase saturation of interest is called the critical saturation, and it is associated with each reservoir fluid. The definition and the significance of the critical saturation for each phase are described below.

1. **Critical oil saturation, S_{oc} :**

   For the oil phase to flow, the saturation of the oil must exceed a certain value, which is termed critical oil saturation. At this particular saturation, the oil remains in the pores and, for all practical purposes, will not flow.

2. **Residual oil saturation, S_{or} :**

   During the displacing process of the crude oil system from the porous media by water or gas injection (or encroachment), there will be some remaining oil left that is quantitatively characterized by a saturation value that is larger than the critical oil saturation. This saturation value is called the residual oil saturation, S_{or}. The term residual saturation is usually associated with the non-wetting phase when it is being displaced by a wetting phase.

3. **Movable oil saturation, S_{om} :**

   Movable oil saturation S_{om} is another saturation of interest and is defined as the fraction of pore volume occupied by movable oil as expressed by the following equation:

$$S_{om} = 1.0 - \ S_{wc} + \ S_{oc} \quad \ldots (3.14)$$

Where

S_{wc} = connate water saturation.

S_{oc} = critical oil saturation.

4. **Critical gas saturation, S_{gc} :**

   As the reservoir pressure declines below the bubble-point pressure, gas evolves from the oil phase and consequently the saturation of the gas increases as the reservoir pressure declines. The gas phase remains immobile until its saturation exceeds a certain saturation, called critical gas saturation, above which gas begins to move.

5. **Critical water saturation, S_{wc} :**

The critical water saturation, connate water saturation, and irreducible water saturation are extensively used interchangeably to define the maximum water saturation at which the water phase will remain immobile.

6. **Average Saturation :**

Proper averaging of saturation data requires that the saturation values be weighted by both the interval thickness $\boldsymbol{h_i}$ and interval porosity $\boldsymbol{\emptyset_i}$. The average saturation of each reservoir fluid is calculated from the following equations:

$$S_o = \frac{\sum_{i=1}^{n} \emptyset_i \, h_i \, So_i}{\sum_{i=1}^{n} \emptyset_i \, h_i} \quad \ldots (3.15)$$

$$S_w = \frac{\sum_{i=1}^{n} \emptyset_i \, h_i \, Sw_i}{\sum_{i=1}^{n} \emptyset_i \, h_i} \quad \ldots (3.16)$$

$$S_g = \frac{\sum_{i=1}^{n} \emptyset_i \, h_i \, Sg_i}{\sum_{i=1}^{n} \emptyset_i \, h_i} \quad \ldots (3.17)$$

Where the subscript $\boldsymbol{i}$ refers to any individual measurement and $\boldsymbol{h_i}$ represents the depth interval to which $\boldsymbol{\emptyset_i}$, $\boldsymbol{S_{oi}}$, $\boldsymbol{S_{gi}}$, and $\boldsymbol{S_{wi}}$ apply.

3.5 Shale Volume

Determination of shale type in shale formation has long been a difficult task. Presence of shales in some of the Iraq reservoir formations are one of the most important subject. Shale types have to be considered, because existence of shale type reduces, effective porosity and permeability of the reservoir to some extent. Allogenic Shale is distributed in formations in three basic types, Dispersed, Laminar and structural. Each of these shale types has different effect on porosity, permeability and water saturation. Dispersed shale type reduces effective porosity and permeability to a great extent, but, laminar and structural have less effect on petrophysical parameters.

Shale is a fine-grained sedimentary rock usually composed of 50% silt (3.9-62.5μm), 35% clay (0.98-3.9μm) and 15% other fine clastic particles (feldspars, quartz, carbonates, zircon, etc.). Shale is distributed in reservoir formations in three basic types, structural, laminar, dispersed or combination of these three types. Each type of shale is described as given in below.

1. **Structural shale:**

Exists in the form of fragments or crystals which are an integral part of the rock framework. In other words, is considered as a portion of rock matrix. This mode of shale distribution has no effect on porosity or permeability.

2. **Laminar shale:**

Exists as layer of clay minerals within clean formations (i.e. sandstone, carbonate, etc). The effect of this type on porosity and permeability is sometimes severe and should be investigated.

3. **Dispersed shale**

Dispersed shale is composed of clay minerals, fragments or crystals which usually found on grain surface, occupying pore spaces between particles. Dispersed shale will include both detritus and diagenetic clay minerals. One or both of these forms may be present in this type shale. This type of shale reduces effective porosity and permeability to a great extent.

Considerable portion of shale consists of clay minerals such as illite, kaolinite, chlorite, montmorillonite, and etc. Clay minerals in reservoir formation have severe effects on petrophysical properties and reduce the effective and total porosities as well as permeability of the reservoir. Also, shale causes serious problems in formation evaluation and drilling operations.

Well logs measure the total porosity ($\emptyset_t$), while the effective porosity ($\emptyset_e$) is computed through an empirical relationship concerning $\emptyset_t$, $\emptyset_e$ and V_{sh} (shale volume). Accordingly, given V_{sh} and $\emptyset_t$, we estimate $\emptyset_e$:

- Clean sand: $\emptyset_e = \emptyset_t$.
- Laminar shale: $\emptyset_e = \emptyset_t * (1 - V_{lam})$.
- Structural shale: $\emptyset_e = \emptyset_t$.
- Dispersed shale: $\emptyset_e = \emptyset_t - V_{dis}$.

3.6 Permeability

The porosity and the permeability are important parameters of particularly interesting to petroleum engineers. The porosity governs the storage capacity of rock or, in other words, the oil and gas contained in unit volume of rock. The permeability, which is a measure of the capacity of the medium to transmit fluids (oil, water, and gas) under some specified pressure differential, imposes a direct and great effect on the production of oil and gas. As most of the pores present in sandstones are interconnected, the fluids are able to flow through the porous medium, which is named “seepage flow.” The laws governing seepage flow are quite different from that governing the flow in circular tubes which are usually discussed in hydromechanics. The flowing laws in porous medium and the permeability of reservoir rocks will be discussed in this chapter.

This rock characterization was first defined mathematically by Henry Darcy in 1856. In fact, the equation that defines permeability in terms of measurable quantities is called Darcy’s Law. Darcy developed a fluid flow equation that has since become one of the standard mathematical tools of the petroleum engineer.

Figure 3.3 shows the apparatus used in the famous Darcy’s Experiment. In 1856, Henry Darcy investigated the flow of water downwards through a sand filter, a cylindrical sand column packed by uncemented uniformly sized grains. He found out some rules from his experiments: As the water flows through the sand column, the volume flow rate of it is directly proportional to the cross-sectional area of the column (A), directly proportional to the pressure differential between the inflow and outflow faces of the column (ΔH or ΔP), while reciprocally proportional to the length of he column (L). Besides, it was also found that the flow rate did vary with the particle size packed in the sand filter when the other conditions such as A, L, μ, and ΔP are given identically. Darcy interpreted his observations so as to yield a result in the form of equation, the famous Darcy's Law:

$$K = \frac{Q}{A} * \frac{\mu L}{\Delta P} \quad \ldots (3.18)$$

Where

Q : Flow rate of the fluid through the sand column, bbl/day;

A : Cross-sectional area of the sand column, ft^2;

L: Length of the sand column, ft;

μ : Viscosity of the fluid flowing through the sand column, cp.;

ΔP: Pressure differential between the two ends of the sand column, Psi;

K: A constant of proportionality, named the absolute permeability of this porous medium, D.

Under most circulations, the unit millidarcy (mD) is more often used in petroleum industry, because that 1 darcy is too large a measure to use with the permeability of the oil and gas bearing reservoir rocks.

$$1D = 1000\ mD = 1.02 \times 10^{-8}\ cm^2 \approx 10^{-8}\ cm^2 = 1\ \mu m^2;\ 1\ mD = 10^{-3}\ \mu m^2$$

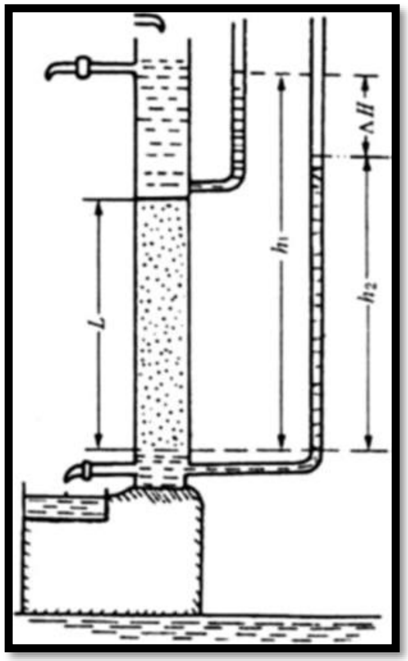


Fig (3.3) Schematic drawing of Henry Darcy's experiment

on flow of water through sand.

The discussion in above on permeability referred to absolute permeability of a porous medium that was fully saturated with a single fluid phase. The experiments that Darcy conducted included 100% water-saturated sands, and later developments of Darcy's law that is commonly used in the petroleum industry extended it to include a generalized case of the flow of any single-phase fluid, for example, oil or water. However, petroleum reservoirs having such simple single-phase fluid systems seldom exist because reservoir rocks are saturated with at least two immiscible fluid phases, for example, the pore space is shared by gas and oil or oil and water or by gas, oil, and water. Therefore, it becomes necessary to further extend or modify Darcy's law to include the simultaneous fluid flow of two or more fluid phases present in a porous medium. This is achieved by including the concept of effective permeability of each fluid phase instead of absolute permeability. The concept of effective permeability plays an important role in the reservoir flow processes when petroleum reservoirs are produced by primary recovery mechanism or immiscible displacement methods involving the injection of gas or water. It is under these circumstances that more than one fluid phase is flowing or is mobile through a porous medium; thus, the flow of one fluid phase interferes with the other.

Permeability and permeability distribution are important to efficient reservoir characterization, because of these parameters used for planning and employment of completion strategies for building of representative simulation models for effective reservoir management. Estimation of permeability by two methods as shown below:

1. Core Analysis:

- Provides direct measurements of permeability.
- Offers accurate data for specific intervals in the well.
- Calculation Methods: (Classical method and Flow Zone indicator).

2. Log Data:

- Permits estimation of permeability in intervals without core data.
- Calculation Methods in Techlog Software: Common models include:

(a) Coates Model: Utilizes NMR logs and porosity data.

(b) Timur Model: Relates porosity and irreducible water saturation to permeability.

(c) Wyllie-Rose.

3.7 Petrophysical Properties Calculations from Well Logs

3.7.1 Determination of Lithology

Determination of the lithology is one of the important components for formation evaluation of a reservoir. There are many techniques used to accomplish this task. In this study Density versus Neutron cross plot technique was used for lithology determination; this method consists of plotting corrected neutron porosity ($\emptyset_N$) versus corrected bulk density (ρ_b) on a standard plot.

3.7.2 Porosity Determination

Porosity can be calculated from sonic log through the following equation;

$$\boxed{\emptyset_s = \underbrace{\frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}}_{\text{For clean formation}} * \frac{1}{B_{cp}}} \quad \ldots (3.19)$$

Where:

$\emptyset_s$ = prosity from sonic log.

Δt = is the transit time from sonic log, *µsec/ft*

Δt_{ma} = is the matrix transit time, *µsec/ft*

Δt_f = is fluid travel time (freshwater or saltwater mud filtrate).

B_{cp} = is compaction correction, where

$$B_{cp} = \frac{\Delta t_{shale}}{100} \geq 1.0 \quad \ldots (3.20)$$

Porosity also can be calculated from density log through the following equation;

$$\emptyset_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{mf}} \quad \ldots (3.21)$$

Where:

$\emptyset_D$ = porosity from density.

ρ_b = is the bulk density, gm/cc

ρ_{ma} = is the matrix density, *gm/cc*

ρ_{mf} = is the density of mud filtrale, *gm/cc* (freshwater or saltwater mud filtrate).

Finally effective porosity can be calculated directly from neutron porosity log and denoted as $\emptyset_N$.

$$\emptyset_e = \emptyset_t - (\emptyset_{shale} * V_{shale}) \quad \ldots (3.22)$$

Where:

$\emptyset_e$ = effective porosity.

$\emptyset_t$ = is total porosity.

$\emptyset_{shale}$ = value of the porosity measurement in a nearby shale.

V_{shale} = shale volume.

V_{shale} estimated from cross-plot method is validated with V_{shale} calculated from Gamma ray spectrum (CGR). CGR is the best and most accurate method for determining shale volume.

3.7.3 Water and Hydrocarbon Saturation Determination

After calculating porosity, it is possible to calculate water saturation. The Archie equation is adopted to achieve this task as in the following equation for non-invaded zone:

$$S_w{}^n = \frac{a\,R_w}{\emptyset^m\,R_t} \quad \ldots (3.23)$$

Where:

S_w = water saturation.

$\emptyset =$ is total porosity.

R_w = formation water resistivity

R_t = formation true resistivity.

$a =$ tortuosity factor.

m = cementation factor.

n = saturation factor.

For flushed zone this equation is used;

$$S_{xo}{}^{n} = \frac{a\,R_{mf}}{\emptyset^{m}\,R_{xo}} \quad \dots (3.24)$$

Where:

S_{xo} = water saturation of the flushed zone.

R_{mf} = resistivity of mud filtrate at formation temperature.

R_{xo} = shallow resistivity from Micro Spherically Focused Log (MSFL).

$$movable\ hydrocarbon = \emptyset_e\,(S_{xo} - S_w) \quad \dots (3.25)$$

The volume of residual hydrocarbon can be calculated as:

$$residual\ hydrocarbon = \emptyset_e\,(1 - S_{xo}) \quad \dots (3.26)$$

3.7.4 Cut-off Determination

Identification of petrophysical property of the formation units could be proposed or intended through using cut-off determination, when the formation contains poor reservoir zones. Because, formation volume accumulations should not contain poor reservoir zones during assessing formation recovery (Worthington, 2008).

More clearly, cut-off determination process begun with identifying the reference parameter which become a factor to evaluate or differentiate between intervals that do not contain reservoir potential and intervals that contain reservoir potential. Based on the researches, there is no any reliable method to cut-off evaluation (Worthington and Cosentino, 2005). Cut- off identification is require to determine volume of hydrocarbon in reservoir. Due to that, net pay that identified by cut-off determination hold hydrocarbon in the reservoir.

Flow rate utilized to define net pay and recovered fluids; formations with having proper permeability that allow good hydrocarbon movement are categorized as net reservoir or net sandstone. So that, net pay zones means ability to produce fluids or hydrocarbons with acceptable water and hydrocarbon ratio (Suzanne and Robert, 2004).

1. Porosity Cut Off Determination:

A plot of porosity on the linear scale versus permeability on the log scale was used for determination of cut off porosity. The intersection of a straight line drawn from 0.1md with the best fit line between core permeability and core porosity determines the cut off core porosity. Conventionally, a permeability of 0.1md is the accepted minimum value for conventional oil production.

2. Water Saturation Cut-Off Determination:

As previously has be.en mentioned porosity cut-off is selected based on core permeability and core porosity, then water saturation cut-off was achieved through plotting the porosity against water saturation in linear scale and drawing the hyperbolic best fit line through the data to determine water saturation cut off corresponding the porosity cut-off. Ringrose and Bentley (2014) advocate the use of a total property approach to modelling, whereby no cut-offs are applied; rather, a facies or rock-type classification can be used to exclude non-reservoir.

3. Shale Volume Cut-Off Determination:

Shale volume cut-off of is a reasonable starting point to exclude shale-dominant intervals; this can be extended or reduced as required to determine net sand. When we start with a **V_{sh}-cutoff = 100%**, we accept all rocks with **$V_{sh} \leq 100\%$**. Since **$V_{sh} \leq 100\%$** is always true, we are accepting all rocks, both sealing rocks and pay rocks. No rock is discarded and the total hydrocarbon column reaches its maximum possible value. When the **V_{sh}-cutoff** is decreased slightly, we start to reject very shaly sealing rocks that don't bear much oil, so the total hydrocarbon column is almost the same (the plateau). As **V_{sh}-cutoff** is decreased more and more, most of the shaly rocks non bearing oil are rejected and the elbow point is reached (the end of the plateau). This is the **V_{sh}** value for which the oil succeed to migrate and accumulate. As **V_{sh}-cutoff** approaches 0, even the cleaner pay rocks are discarded and the total hydrocarbon column approaches 0.

Chapter Four

Petrophysical Evaluation of Mishrif Formation

4.1 Description

The Mishrif Formation is a significant, thick layer of carbonate rock in Iraq, particularly in the southern region, and holds substantial petroleum reserves. It was deposited in various shallow marine environments. The formation is primarily composed of limestone, dolomite, and shale, and its reservoir quality tends to improve towards the north. While it's a major oil reservoir and exploration target, its quality and properties can vary due to its depositional history. The formation is underlain by the Rumelia Formation and overlain unconformably by the Khasib Formation. Petrophysical analysis has divided the Mishrif Formation into six units with varying potential. This chapter focus on showing the calculation of petrophysical properties of Mishrif Formation to evaluating the oil reservoir by evaluating the geological formation containing hydrocarbons. Also Identify areas with good hydrocarbon productivity for the purpose of start oil production from them and attempting to improve petrophysical properties in areas with low levels through various oil operations.

4.2 Method of Study

The Mishrif Formation was analyzed using advanced techniques in the Schlumberger Techlog software. The porosity calculated based on the liquid volume and water saturation using Archie's equation. The software facilitated the estimation of petrophysical characteristics using wireline log measurements such as Caliper, Gamma Ray, Density, Neutron, Resistivity Deep, and Resistivity Shallow Logs. The calculation of the volume of shale (Vsh) was based on gamma-ray reading logs (Asquith et al., 2004), while the lithology was determined by neutron and density logs using visual separation of curves or by indicating the two values on special neutron and density cross-identified graphics. Density logs are commonly utilized to determine porosity and, in combination with neutron logs, lithology identification.

Density-neutron cross plots allow lithologic analysis through either multi-well comparisons or tailored single-well interpretations to constrain lithologic variations and porosity for individual wells. In these cross plots, the intersection of the two parameters defines the likely porosity and lithology at any given depth. This targeted approach facilitates assessment of the specific stratigraphic intervals and lithologic assemblages penetrated by each borehole across the field (Gimbe, 2015). Porosity analysis involves total porosity (PHIT) and effective porosity (PHIE) calculations using neutron and density porosity logs (Schlumberger, 1989). Water and hydrocarbon saturation were determined using Archie's equation, whereas the bulk volume of water (BVW) was obtained by multiplying the water saturation (Sw) by the porosity (ø). Water saturation (Sw) and water saturation of the flushed zone (Sxo) were used to calculate the amounts of oil and moveable oil (Asquith et al., 2004). However, there is no standard industry definition or quantification method for hydrocarbon-impregnated reservoir intervals (Worthington, 2010). By default, the shale volume, porosity, and water saturation were considered. (Ellis & Singer, 2007).

4.3 Data Available for Work

In this work interactive Petrophysics software (Tech. log) has been used for correction and interpretation. HF-X1 well data from the Halfaiya oil field have been used in this study. The data were used from available well log records in form of LAS-files; such as potential spontaneous records (SP), gamma rays, density, sonic, neutrons and resistivity as shown in Figure 4.1. Also the log service includes GR/SP/CALS/LLD/LLS/MSFL/NPHI/RHOB/DT, and service was run using Techlog software System. Before petrophysical analysis the data was properly checked. All logging curves are in accord with Log Quality Control standards, and conform to the rule of local area.

1. Data Preprocessing: Before processing, all data had to be preprocessed very well. The main procedure of preprocessing includes depth matching and environmental correction.

2. Depth Matching: As all logs used for petrophysical analysis were logged in one combination run: LLD – LLS – MSFL – NPHI – DT – RHOB – SP – GR – CAL – PEF – HDRA, the depth of each curve is matched very well at each measuring point. Normally, the depth of curve GR is used for reference of depth matching to all curves, and the final depth is checked and corrected by the depth of casing shoe.

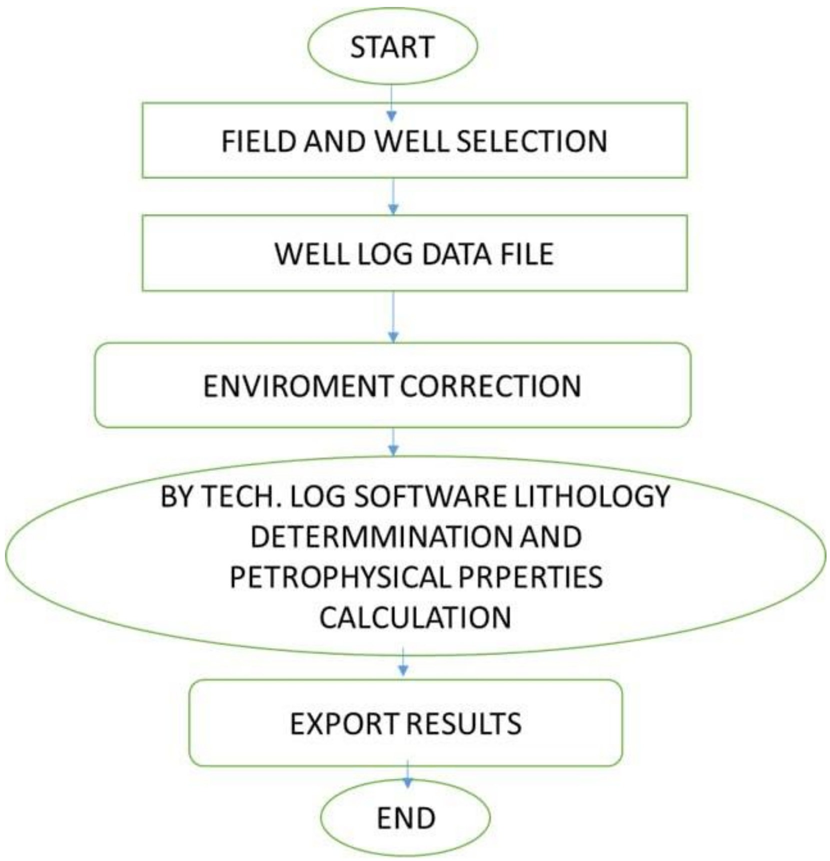


Fig (4.1) Work Flow Chart.

From the laboratory tests carried out for this well, we were able to obtain some of the following parameters as shown in the Table 4.1 (a) and (b).

Table (4.1): (a): Parameters of mud property.

Mud Type	Density	Viscosity	Resistivity / Temperature	Maximum Temperature
BH-WEI	**1.26 g/cm^3**	**48.0 s**	**Rm: 0.13 Ω m/25 ˚C** **Rmf: 0.08 Ω m/25 ˚C** **Rmc: 0.25 Ω m/25 ˚C**	**89.5˚C**

Table (4.1): (b): Processing parameters.

	a	m	n	R_w (ohm)
Mishrif	**1**	**1.8**	**2**	**0.02**

Rmf: 0.08 Ω m/25 ˚C

Temperature Maximum = 89.5 ˚C

Determine the R_{mf} values By converting surface temperature to formation temperature using the formula:

$$R_2 = R_1 \left(\frac{T_1 + 6.77}{T_2 + 6.77}\right) \ldots..(4.1)$$

$$T = 1.8\,°C + 32 \ \ldots..(4.2)$$

$T_1 = 1.8 * 25 + 32 = 77$ °F $\qquad T_2 = 1.8 * 89 + 32 = 192.2$ °F

$$R_2 = R_{mf} = 0.08 \left(\frac{77 + 6.77}{192.2 + 6.77}\right) = 0.034\,\Omega.m\ @Tem.Max.$$

Using equations mentioned in the **paragraph 3.7.3** and laboratory information, we will calculate the following through the **Techlog software**:

1. Water saturation (Sw) from "Archie Equation" to calculate BVW.
2. Mud filtrate Saturation in flushed zone (Sxo) to calculate BVWXO.

4.4 Data Processing

Petrophysical characteristics must be determined and assessed in order to infer reservoir properties of the Mishrif formation to the Halfaya field for **HF-X1** well by as following using Techlog software:

1. We does the following steps through Techlog program (Project New) by input las file **HF-X1** well data then by Log View windo for prsentation (caliper, bit size, GR, Rt, Rxo, DT, N, D) logs.
2. By the behavior of the logs the layers are divided in the Techlog software in **Table 4.2** shows the Top and Bottom of the Mishrif Formation in the HF-X1 well of this study.

Table (4.2): Distribution Top and Bottom of the Mishrif Formation.

Well Name	Top (m)	Bottom (m)	Zone Name
HF-X1	2868.7	2884	M1
HF-X1	2884.001	2891.6	M2
HF-X1	2891.601	2905.22	M3
HF-X1	2905.221	3038.46	M4
HF-X1	3038.461	3084.21	M5
HF-X1	3084.211	3093.38	M6
HF-X1	3093.381	3107.21	M7
HF-X1	3107.211	3130.05	M8
HF-X1	3130.051	3147.93	M9

3. Calculation Shale volume (V_{sh}) from gamma ray log: Techlog works instead of the previously mentioned mathematical equations.

4. Calculation Porosity (∅):

- The total porosity of the Mishrif formation was calculated by using of the Neutron-Density logs.

- The effective porosity of the Mishrif formation was calculated by using of the Neutron-Density logs.

The total porosity of the Mishrif formation was calculated of the Mishrif formation by using of the Density log and Neutron-Density logs idicator to measures primary porosity and secondary porosity is caused by some geologic process subsequent to formation. The effective porosity of the Mishrif formation was calculated by using of the Neutron-Density because Neutron and density logs are used as reliable tools for measuring effective porosity because they provide vital information about the water condition and stress handling in soils and rocks.

1. Calculation of water Saturation: After level by level porosity determination, water saturations are calculated. The Archie equation is adopted to achieve this task. Water saturation of both limestone and dolomite determined through using Archie equation inserting number of real data including n, m and a. shown in the **Table 4.1 (b)**.

2. Calculation of Flushed Saturation: using Archie equation inserting (Micro Restivity) and (Effective porosity) at $Rmf = 0.034\ \Omega.m$ as shown in **Figure 4.2**.

Group	Well	Dataset	Zone	Top	Bottom	a	m	n	RMF@FT (ohm.m)
	HF-X1	HF-X1	1	2868.7	2884	1	1.8	2	0.034
	HF-X1	HF-X1	2	2884.001	2891.6	1	1.8	2	0.034
	HF-X1	HF-X1	3	2891.601	2905.22	1	1.8	2	0.034
	HF-X1	HF-X1	4	2905.221	3038.46	1	1.8	2	0.034
	HF-X1	HF-X1	5	3038.461	3084.21	1	1.8	2	0.034
	HF-X1	HF-X1	6	3084.211	3093.38	1	1.8	2	0.034
	HF-X1	HF-X1	7	3093.381	3107.21	1	1.8	2	0.034
	HF-X1	HF-X1	8	3107.211	3130.05	1	1.8	2	0.034
	HF-X1	HF-X1	9	3130.051	3147.93	1	1.8	2	0.034

Fig (4.2) Calculation of Flushed Saturation at Rmf = 0.034 Ω.m.

Determination lithology formation: from inferred from cross plot responses using standard petrophysical cross-sections as shown in Figure 4.3. That is a neutron density cross-sectional plot across the Mishrif formations where cross plot calculation lithology beetween x-axis/Neutron Log and y- axis/Density logs.

4.5 Results and Discussion

The resultant petrophysical appraisal of the Mishrif Formation provides illuminating revelations regarding the heterogeneity and hydrocarbon production potential in the analyzed oil field. Lithological characterization revealed predominantly interlaminated limestones, dolomites, and subsidiary shale beds, corroborating previous studies by Al-Dabbas et al. (2010) and Alghafour et al. (2022) to validate the efficacy of the implemented analytical techniques.

The neutron-density cross-plots for well HF-X1 depict the predominant lithologies intersecting the reservoir units. The data points were clustered mainly within the limestone and subordinate dolomite fields, with minor signatures of calcareous shale. When plotting only the reservoir interval data, the cross-sections clearly revealed a predominance of limestone facies interbedded with dolomite and shale intercalations (Figure 4.3). The distribution patterns were notably consistent between the sampled wells, with the highest density of data points concentrated in the limestone fields. This clustering reflects the dominant carbonate lithology within the Mushrif Formation. The consistent cross plot signatures confirm the broadly homogeneous carbonate mineralogical composition within the Mishrif Formation across the study area, although minor constituents of the shale and sandstone facies were also discernible. The neutron-density overlay demonstrates the effectiveness of these logs in delineating the lithologic characteristics and associated petrophysical properties of the reservoir intervals penetrated by the wells.

To Interpretation the records for Appendix 1 and Appendix 2:

***M1 zones* (2868.7m – 2884 m).**

Lithology mostly limestone, Low gamma ray (V_{sh} < 25 %), medium effective porosity (0.12-0.14), water saturation approximation (25-60%), medium hydrocarbon saturation (40%) the separation between LLD and MSFL maybe indicate to permeable zone, it is consider good hydrocarbon interval indicator.

***M2 zones* (2884.001m- 2891.6 m).**

By looking at this layer, it is considered a reservoir with good effective porosity, low gamma ray ($V_{sh} < 25$ %), medium effective porosity (0.12-0.14), very little shale volume (almost non-existent), and medium water saturation, but the oil volume was not of a high value compared to looking at the resistivity logs.

M3 zone (2891.601m - 2905.22m).

By looking at this layer, it is not considered a reservoir as its high gamma ray ($V_{sh} > 25$ %), very low effective porosity (0.06), so the water saturation readings are very high (90-95%), low hydrocarbon saturation (5%) and the resistivity logs are low and this indicate the presence remaining water in rock.

M4 zone (2905.221m - 3038.46m).

Considering this layer, it is considered an oil reservoir with average properties, as effective porosity is moderate, saturation values are also moderate, shale volume is present at a moderate rate, and resistivity logs are good.

M5 zone (3038.461m - 3084.21m).

Lithology mostly limestone , Low gamma ray ($V_{sh} < 25\%$) ,High effective porosity (0.25-0.30), low water saturation (10-25%), medium hydrocarbon saturation approximation (75%), the separation between LLD and MSFL maybe indicate to permeable zone, it is consider good oil interval indicator.

M6 zone (3084.211m- 3093.38m).

Considering this layer, it is considered an reservoir as the low gamma ray ($V_{sh} < 25$ %), medium effective porosity (0.12-0.14), the water saturation is medium (35%), and the resistivity logs are medium it is considering good hydrocarbon indicator.

M7 zone (3093.381m- 3107.21m).

Considering this layer, it is considered a good reservoir, as the effective porosity is high, the shale volume is low, and the water saturation is also low, but compared to the resistivity logs, it is average (an oil reservoir with medium properties).

M8 zone (3107.211m- 3130.05m).

By looking at this layer, it is not considered a reservoir as the porosity is low and the shale volume is higher (V_{sh} > 25 %), so the water saturation is high and compared to the resistivity logs it is very low.

M9 zone (3130.051m- 3147.93m).

Looking at this layer, it is considered an reservoir because the porosity is high with low shale volume (V_{sh} < 25 %), and high water saturation, but the resistivity logs are low and this indicator transition zone, so the reservoir is more saturated with water than oil.

All the results of the calculations for the Mishrif reservoir are shown in **Appendix 1** and **Appendix 2**. The Petrophysical properties of the available logs where were calculated and their results were given in a simplified manner. Through the descriptive interpretation, the best layers indicating the oil area are **M5-layers.** (Note; the layers were divided according to the behavior of the logs in the Techlog software).

OWC (3147 m) depth because the resistivity logs are low, so the reservoir is more saturated with water than oil in bottom. Oil Water Contact (**OWC**) is the lowest level of producible oil, where water and oil are co-produced above this level up to the water relative permeability becomes exceedingly low and oil will move only.

The procedures of final interpretation mainly include effective reservoir discrimination, fluid type determination and oil and gas bearing zone identification by cutoffs.

1. **Criterion of Effective Reservoir Discrimination:** According to the local experience, the cutoffs for discriminating the effective zones are:

- Effective porosity < 5%
- Vsh > 25%

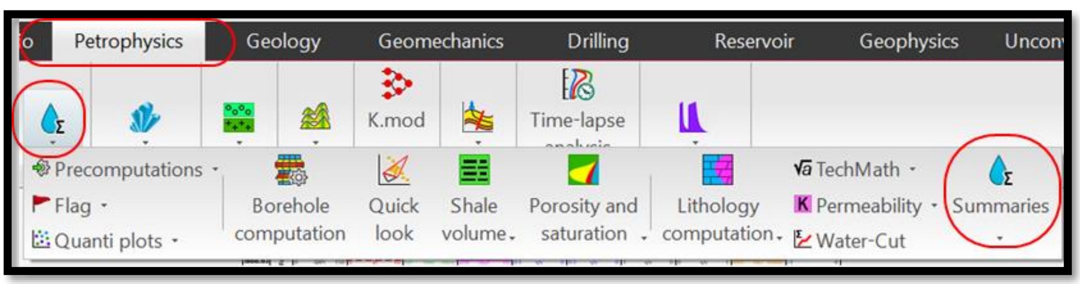
2. **Criterion of Fluid Type Determination:** Due to the effects of shale content and bound water, the resistivity in most pay zones is lower than that of usual clean carbonate rocks oil/gas zone, and even there is no difference from the shale zone. The criteria for fluid type discrimination are:

Oil zone —— Oil saturation ≥ 50 % (Sw ≤ 50 %)

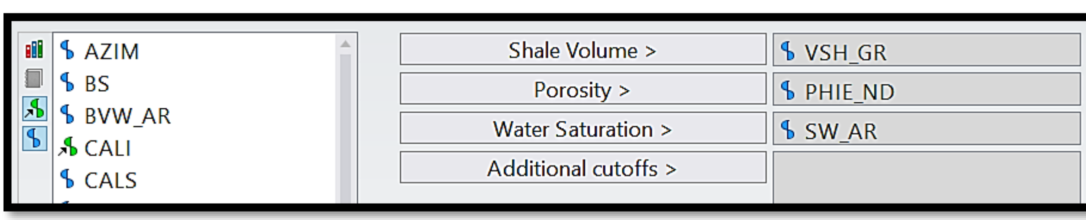
Water zone —— Oil saturation < 50 % (Sw > 50 %)

Simplified Interpretation in cutoff, can be made through a Techlog software.

1. **From Petrophysics window, as shown in Figure below;**



2. Input Data, as shown in Figure below;



3. To interpretation the well by determine the limits of the response in software, which is known as the cutoff, as shown in Figure below;

Inputs | Zonation | Parameters | Flags | Result MD | Result TVD | Result TVDSS | Result TST

	Flag Name	Flag shading colour	Shale Volume cutoff	Porosity cutoff	Water Saturation cutoff
1	ROCK		yes	no	no
2	RES		yes	yes	no
3	PAY		yes	yes	yes

4. The limits are distributed to the constraints above as in Table 4.3

Table (4.3): The limits Cutoff Parameters

Shale Volume-Min	Shale Volume-Max	Porosity-Min	Porosity-Max
0	**0.25**	**0**	**0.5**
Water Saturation-Min		**Water Saturation-Max**	
0		**0.5**	

As the results appear in **Appendix 3** and **Appendix 4**.

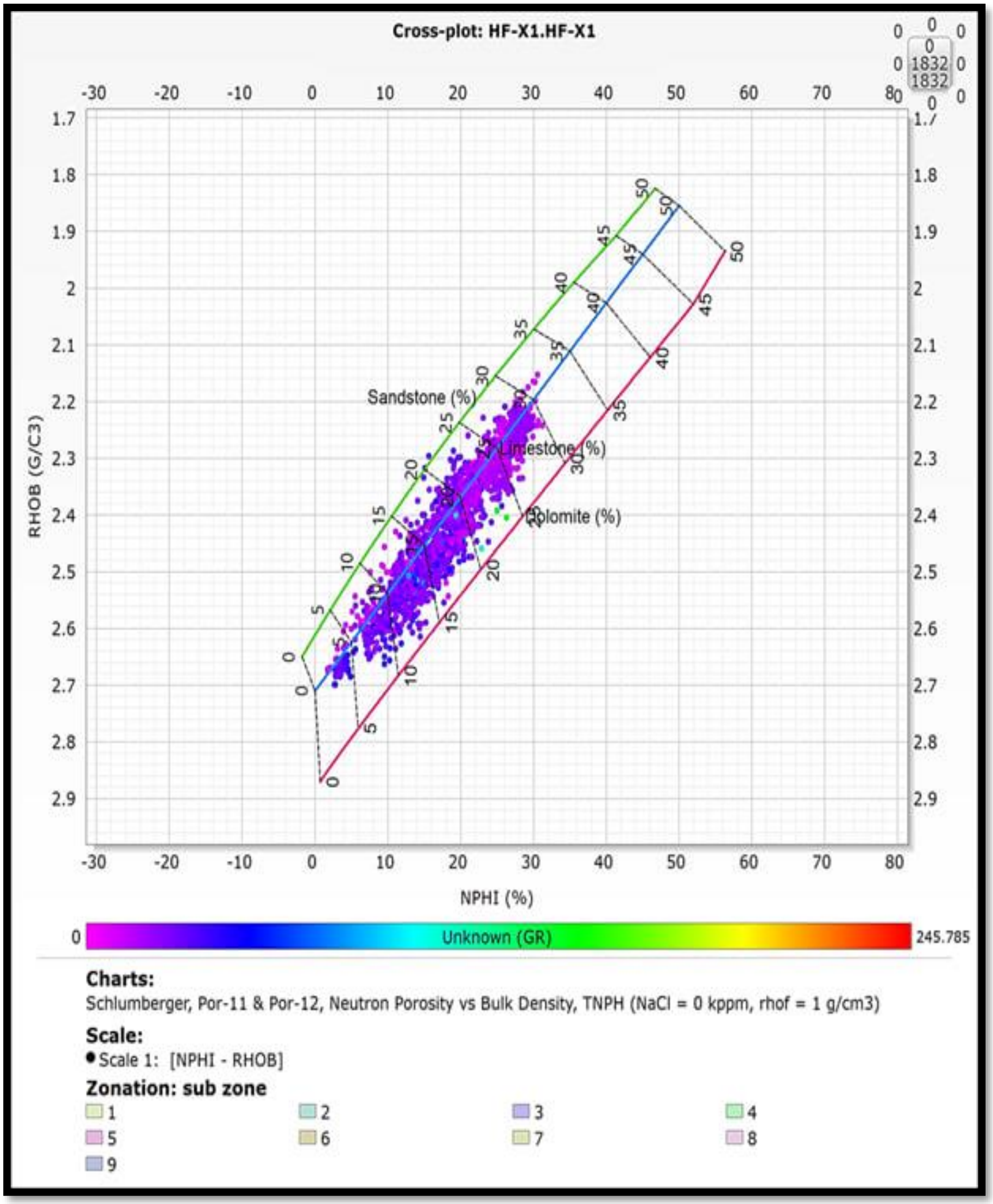


Fig (4.3) Cross plot Density-Neutron for Mishrif formation.

Chapter Five

Conclusions and Recommendations

5.1 Conclusions

Through this study, we demonstrated the Mishrif reservoir evaluation using data from the Halfaya oil field, well HF-X1. Using the Techlog software, we predicted and identified areas good for perforation and oil production. In this work, petrophysical properties of the Mishrif Formation and the study is based on well logs. Through performing this study following conclusions are reached.

1. The Mishrif Formation in the HF-X1 well could be divided into several zonations of reservoir that differ in terms of a reservoir characteristics, depending on the results of the well logs analysis. M5 is considered the most important due to the high effective porosity values and the decreasing water saturation. Other units show lower quality reservoir properties due to increased water saturation as in units M3 and M8.

2. It was shown through the cross-plots of the neutron and density logs that the rock in the study well is limestone rocks.

3. The results confirm the presence of zones that are amenable to ample hydrocarbon production. These findings illuminate the variability in reservoir characteristics that is fundamental for guiding appropriate field developmental strategies. Reservoir properties directly impact field development plans, mandating further appraisal to fully characterize lateral reservoir continuity.

4. No free gas indicators were found in this formation within the study area.

5.2 Recommendations

1. Recommended to use data others for this well for study of an accurate OOIP estimation and producible reserve estimation.

2. The necessity of providing a complete rock core for the purpose of conducting routine laboratory tests (horizontal air permeability, porosity, and grain density) and

special tests (relative permeability, capillary pressure tests, wettability, and homogeneity) to be used in reservoir geological studies, particularly in determining flow units.

3. Conduct geophysical studies of the study area and link them with available petrophysical information and modern technologies to conduct a comprehensive study.

4. Recommended to study gas reserves in the field and recommended to construct all necessary subsurface maps.

5. Master mud log data should be obtained to identify lithology along with cutting data and cores data for the well. Data is also taken from several wells for the Mishrif reservoir to create correlation for accurate characterization and other purposes. It is also recommended to use image log to identify the presence of fracture, as well as well test data or NMR to identify permeability and MDT pressure data to identify contact points if any (OWC or GOC).

6. Further appraisal is imperative to fully delineate reservoir continuity and barriers.

7. The necessity of joint cooperation between universities and oil companies to facilitate the process of obtaining information in a broader and better manner.

8. Drilling appraisal wells in the Mishrif Formation, as it has good petrophysical properties and a number of good reservoir units. It is preferable to drill at the top of the fold, due to the improvement of its petrophysical specifications.

9. Providing a specialized laboratory for petroleum studies within the University of Misan to facilitate research analysis in order to reduce costs.

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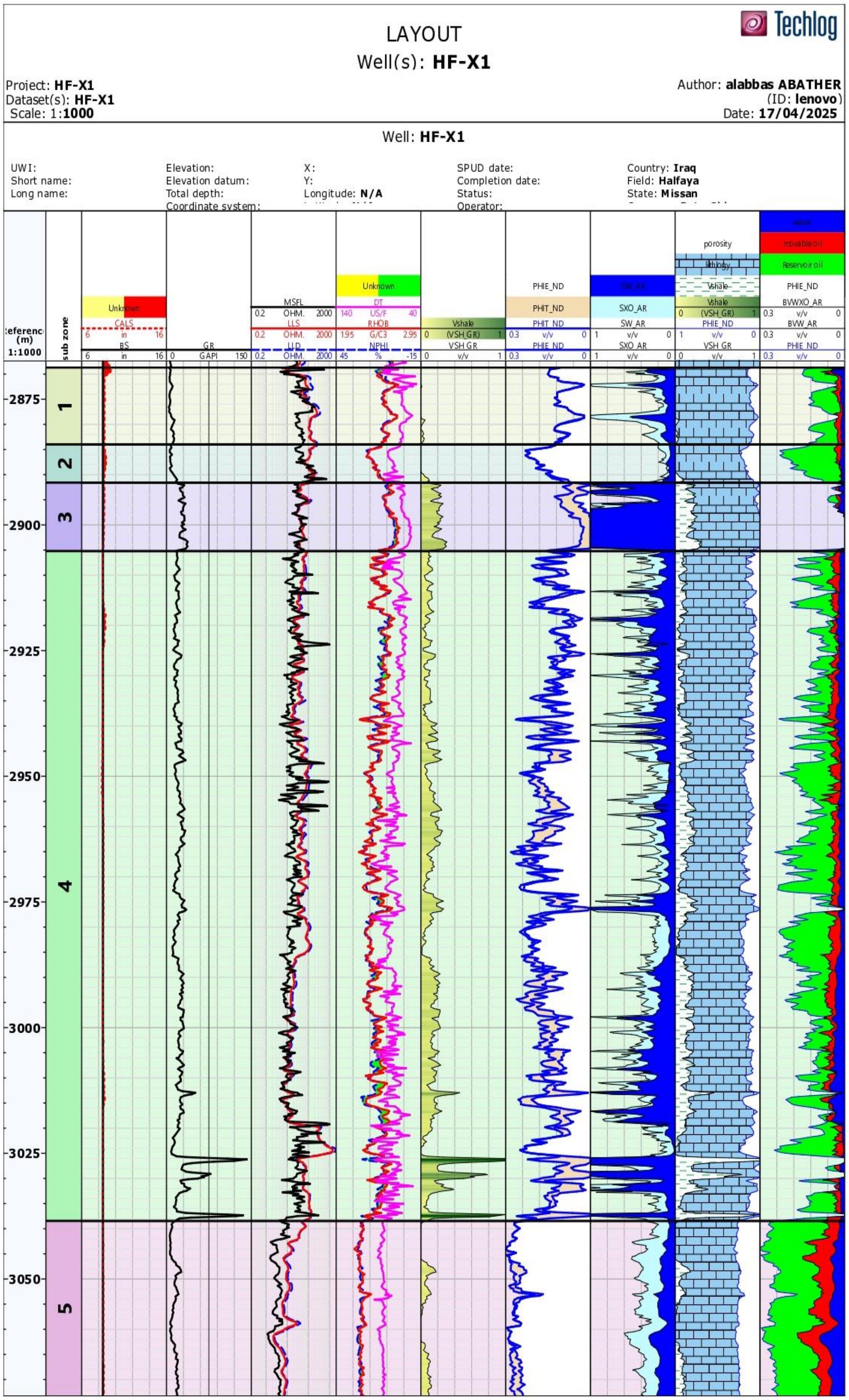
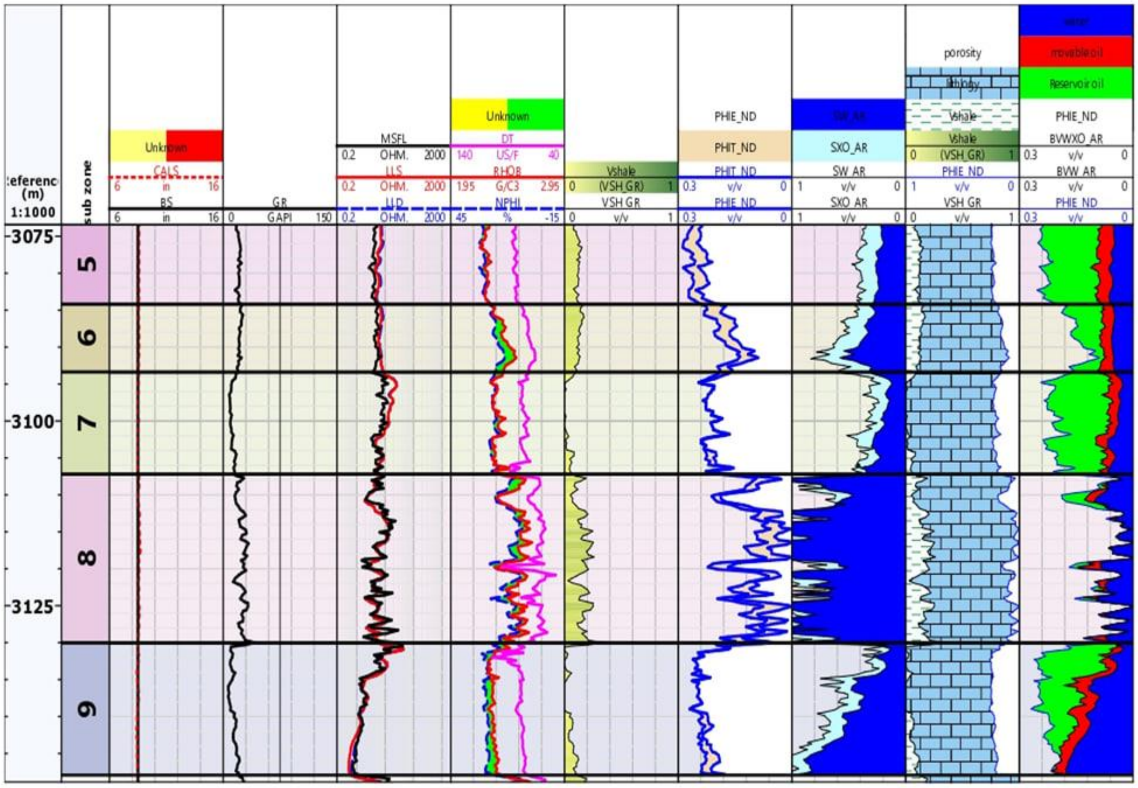
Appendix

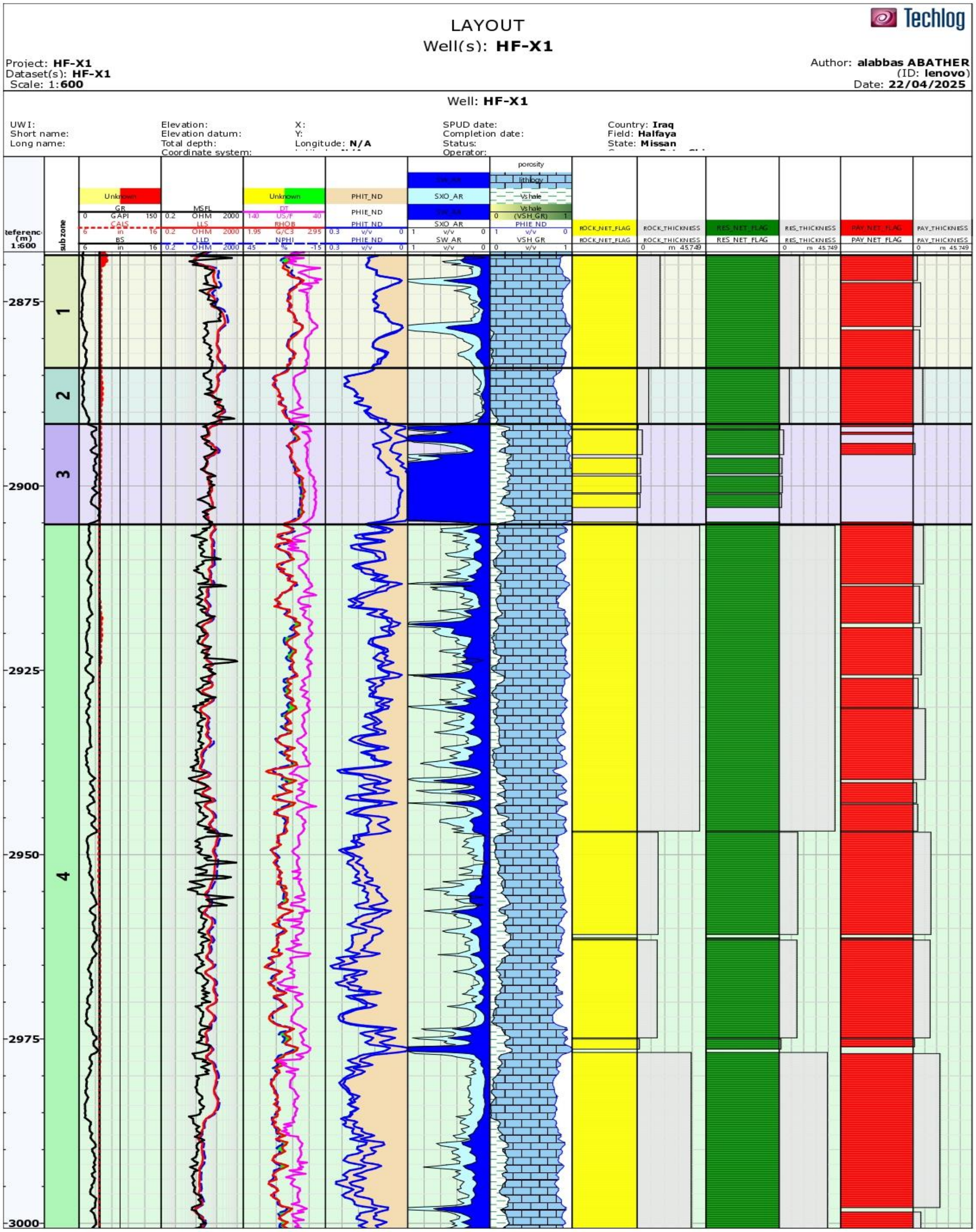
Appendix 1


LAYOUT
Well(s): HF-X1
Techlog
Project: HF-X1
Dataset(s): HF-X1
Scale: 1:1000
Author: alabbas ABATHER
(ID: lenovo)
Date: 17/04/2025
Well: HF-X1
UWI:
Short name:
Long name:
Elevation:
Elevation datum:
Total depth:
Coordinate system:
X:
Y:
Longitude: N/A
SPUD date:
Completion date:
Status:
Operator:
Country: Iraq
Field: Halfaya
State: Missan
sub zone
CALS
BS
GR
MSFL
LLS
LLD
DT
RHOB
NPHI
Vshale
VSH_GR
PHIE_ND
PHIT_ND
SXO_AR
SW_AR
porosity
lithology
Vshale
PHIE_ND
VSH GR
Reservoir oil
movable oil
BVWXO_AR
BVW_AR
2875
2900
2925
2950
2975
3000
3025
3050
1
2
3
4
5

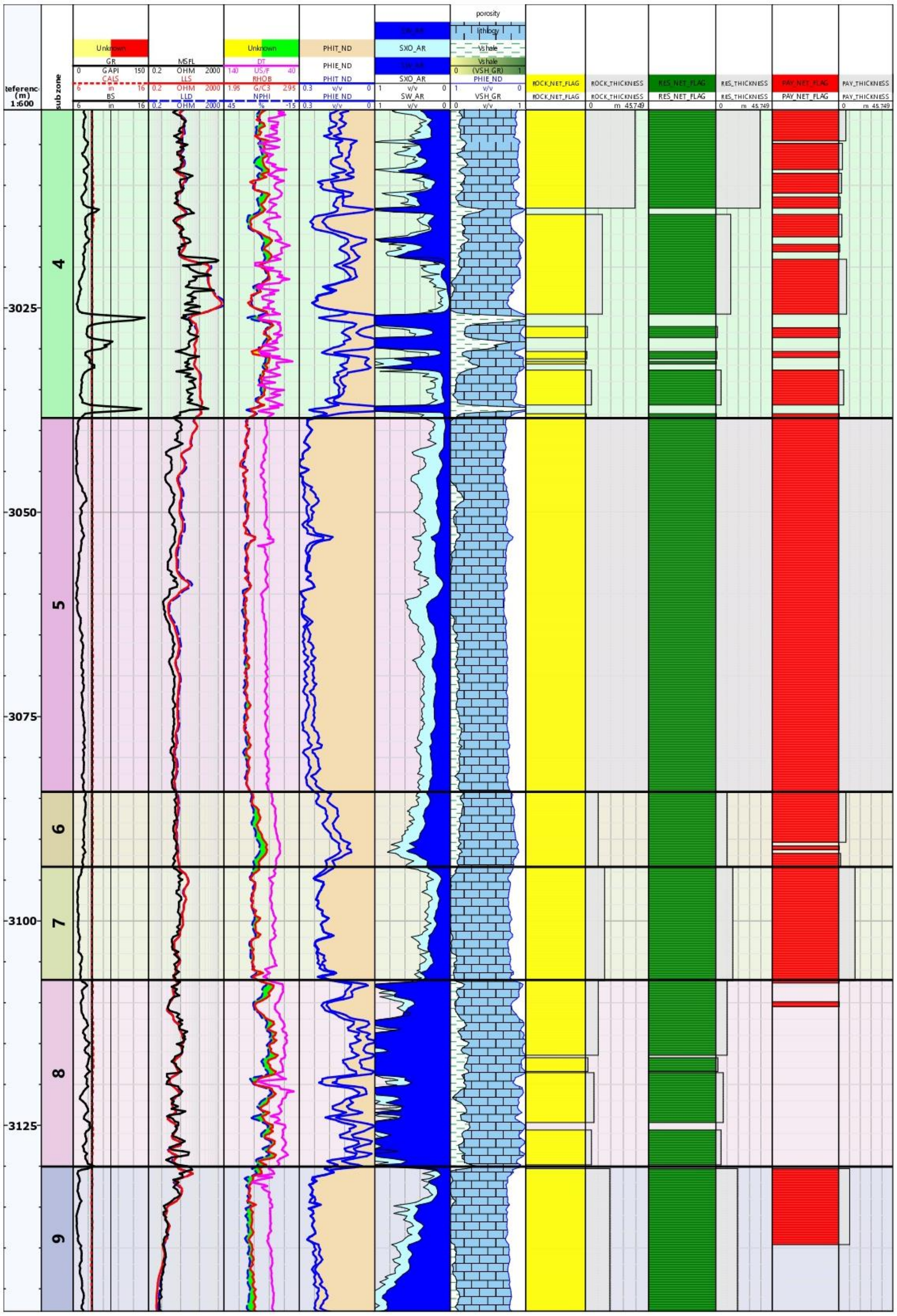
Appendix 2



Appendix 3


LAYOUT
Well(s): HF-X1
Techlog
Project: HF-X1
Dataset(s): HF-X1
Scale: 1:600
Author: alabbas ABATHER
(ID: lenovo)
Date: 22/04/2025
Well: HF-X1
Country: Iraq
Field: Halfaya
State: Missan
ROCK_NET_FLAG
ROCK_THICKNESS
RES_NET_FLAG
RES_THICKNESS
PAY_NET_FLAG
PAY_THICKNESS
2875
2900
2925
2950
2975
3000

Appendix 4



sub zone
4
5
6
7
8
9
3025
3050
3075
3100
3125
GR
MSFL
DT
PHIT_ND
SXO_AR
porosity
lithology
Vshale
ROCK_NET_FLAG
ROCK_THICKNESS
RES_NET_FLAG
RES_THICKNESS
PAY_NET_FLAG
PAY_THICKNESS