PETROPHYSICAL ANALYSIS OF SAWAN-01 AND SAWAN-02, LOWER INDUS BASIN, PAKISTAN

A thesis submitted to Bahria University, Islamabad in partial fulfillment of the requirement for the degree of BS in Geology

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2022

ABSTRACT

In the current study, the main goal was to identify reservoir zones and to delineate their hydrocarbon potential for Sawan-01 and Sawan-02 wells. Sawan-01 and Sawan-02 wells are located at 68 54’25.17” E, 26 59’30.58” N and 68 56’1.70” E, 27 1’22.70” N respectively, in the Khairpur District of Sindh. Geologically, the research area is located in the extensional regime of Lower Indus Basin, in the southeastern part of the Jacobabad and Khairpur highs, together known as Sukkur rift system. It has Sukkur Rift, Thar Platform, Kithar Foredeep and Indian Shield to the north, south, east and west, respectively.

With previous consent from the Directorate General of Petroleum Concession (DGPC), the well logs of Sawan-01 and Sawan-02 wells were acquired from Landmark Resources (LMKR). Petrophysical evaluation of well Sawan-01 and Sawan-02 was carried out to highlight the reservoir area which included the selection of zone of interest followed by Log interpretation. The zones of interest in our study were marked in Lower Goru Formation in both wells. The petrophysical interpretation showed that there is 56%, 62% 28% and 52% Vsh, 55%, 74%, 59% and 52% Sw and 45%, 26%, 41% and 48% saturation of hydrocarbons in Zones 1, 2, 3 and 4 respectively of Sawan-01. Three zones of interest were marked in Sawan-02 that showed 40%, 72% and 67% Vsh, 54%, 68% and 53% Sw and 46%, 32% and 47% saturation of hydrocarbons in Zones 1, 2 and 3 respectively. The lithological cross plots indicate that the lithology of our zones of interest in Lower Goru Formation is dominated by sandstone.

ACKNOWLEDGEMENTS

Before anything else, we bow to Allah Almighty, who is the Most Merciful and Most Generous. After that, we extend our gratitude to our respected guardians for their prayers, best efforts, and love in order to help us reach our objective. We are grateful to Mr. Saqib Mehmood, Senior Assistant Professor in the Department of Earth and Environmental Sciences at Bahria University, Islamabad, for his leadership, steadfast assistance, and dedication during the completion of our thesis. For his help and consideration, Dr. Said Akbar Khan, head of the Earth and Environmental Sciences department at Bahria University, Islamabad, has our sincere gratitude.

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ABBREVIATIONS

Rt Resistivity of True Zone

Rw Resistivity of Water

Sh Saturation of hydrocarbons

Sw Saturation of water

Vsh Volume of shale

PHIA Average porosity

PHIE Effective porosity

PHIN Neutron porosity

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Petroleum exploration has become an important field of interest in the last few decades as various agencies along with scientists are developing and utilizing efficient geological and geophysical methods for hydrocarbon exploration and exploitation in order to meet the increasing energy requirements of the world.

Borehole geophysics is the science of recording and analyzing measurements of physical properties made in wells or test holes. Probes that measure different properties are lowered into the borehole to collect continuous or point data that is graphically displayed as a geophysical log. Borehole logging, also referred to as "well logging," is the meticulous documentation of the in-situ ground conditions encountered during a borehole. The necessary data are obtained through visual examination of samples that have been taken to the surface or through geophysical measurements made along a borehole's axis using a specialized logging instrument that is lowered into the hole. This method is useful for borehole drilling during petroleum, groundwater, geotechnical and environmental investigation.

1.2 Location of Study Area

The Sawan Gas Field, having about fifteen wells, was discovered in 1998 and has been producing since March, 2003. It is located about 500 km north of Karachi, in the Khairpur District, Sindh, and has coordinates 68 58’ 19.5” E and 27 02’22.7” N. Sawan-01 Well has coordinates of 68 54’25.17” E and 26 59’30.58” N, while the coordinates of Sawan-02 Well are 68 56’1.70” E and 27 1’22.70” N.

Sawan Gas field is located in the southeastern part of the Jacobabad and Khairpur highs, together known as Sukkur rift system.A series of graben and horst features that stretch from the Paleocene to the Cretaceous layers characterise this region. The structural makeup of this area is the result of three post-rifting tectonic episodes: NNW-SSE wrench faults (basement-rooted), uplifting and erosion (late Cretaceous), and uplifting of Khairpur and Jacobabad highs (late Tertiary to recent) (Ahmad et al., 2004).

1.3 Objectives

The objectives are as follows:

1. To delineate hydrocarbon potential and mark suitable reservoir zones in Sawan-01 and Sawan-02 wells.
2. To identify lithology of the marked reservoir zones.

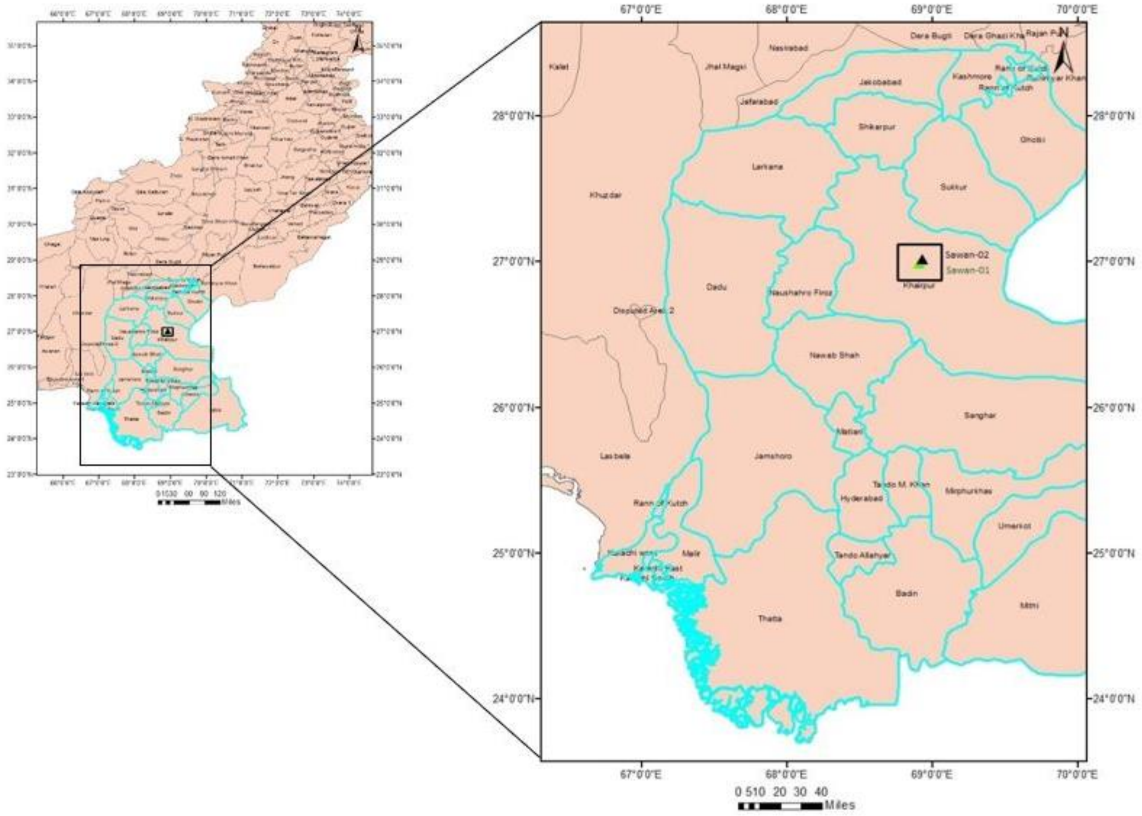

Figure 1.1. Location map of study area (ArcGIS).

1.4 Data Required

The data for this research has been obtained from Land Mark Resources (LMKR) Pakistan, and it includes:

1. Spontaneous Potential Log
2. Caliper Log
3. Gamma Ray Log
4. Resistivity Logs
5. Neutron Log
6. Density Log
7. Sonic (Acoustic Log)

1.5 Methodology

The basic workflow for the petrophysical analysis has been shown in figure 1.2.

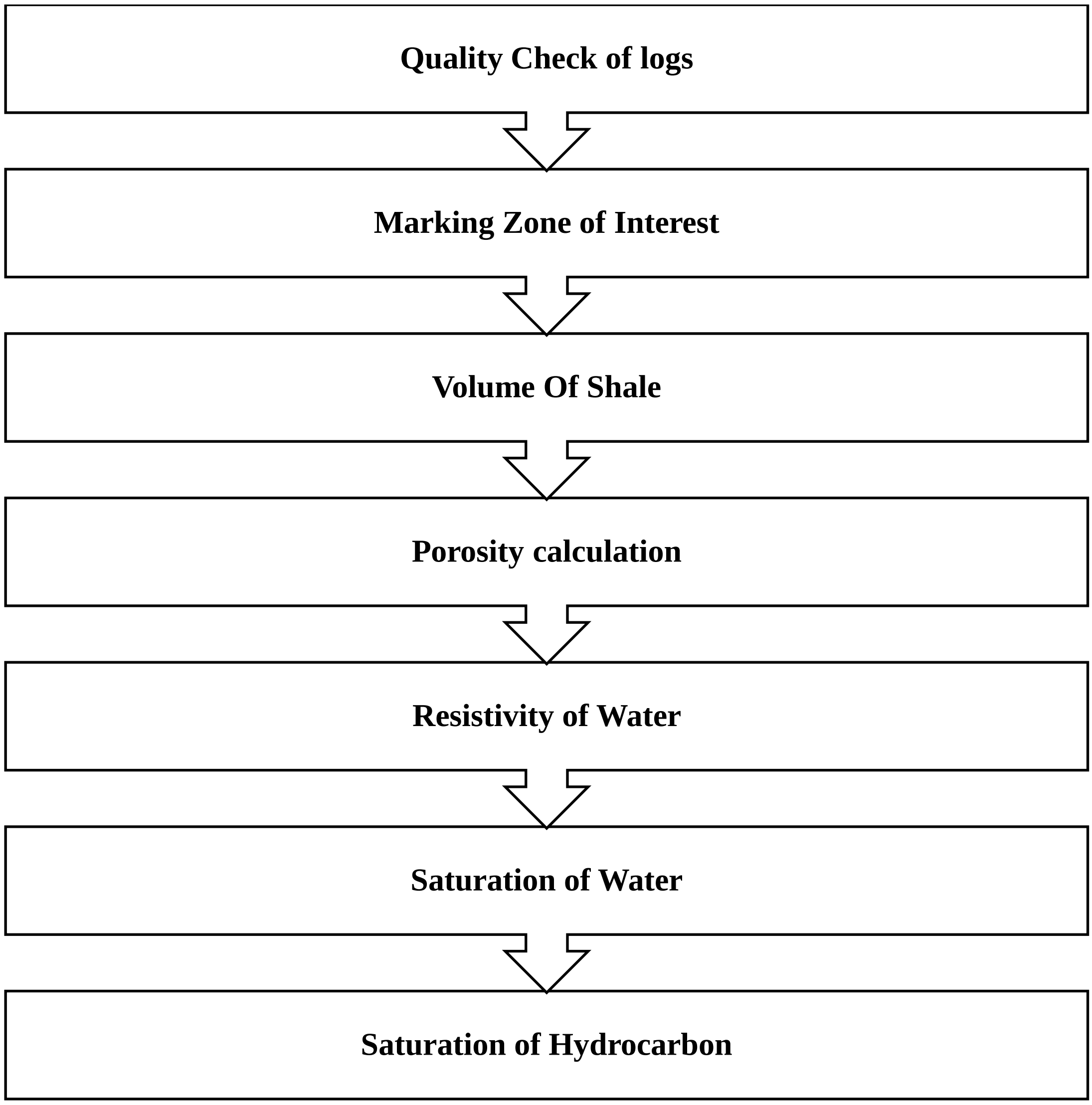

Figure 1.2. Workflow of the current petrophysical analysis.

CHAPTER 2

GENERAL GEOLOGY AND TECTONICS

2.1 Regional Tectonic Setting

The continents used to be a combined mass, forming one super land called Pangea, before the Paleozoic time. They were surrounded by a large ocean called Panthalassa. During Late Paleozoic, two sub-continents were formed as Pangea split into two i.e. Gondwanaland to the south and Laurasia to the north. About 130 million years ago, the great India rifted away from Gondwanaland and travelled towards Eurasia to finally hit it after about 5000 km. This happened near fifty to fifty-five million years ago. The tectonics of Northern Pakistan resulted from this convergence between these two tectonic plates, with Pakistan being at the junction the two. (Kazmi & Jan, 1997)

Pakistan is situated towards the north-west of the Indian plate boundary. The compressional features as a result of thin-skinned tectonics on northern and northwestern margins of the Indo-Pak Plate have been produced because of under-thrusting of Indo-Pak plate under the Eurasian plate since the Eocene. In addition, the Himalayas as well as the thick sediments sheets that thrust over the Indian craton as series of foreland fold-and-thrust belt have been produced because the Indo-Pak plate continuously thrusted under the Eurasian plate.

The Indian plate drifted northwards and entered warmer latitudes during Early Cretaceous and shales of marine environment, limestones and sandstones of near-shore environment were deposited on the western shelf (Sembar and Goru Formations). These were deposited above a surface of erosion on the ‘Sulaiman Limestone Group’.

The visible features of convergent plate boundaries and recent tectonic movements are present along Foreland Fold-and-Thrust belts. As Pakistan is present at the junction of two converging plates, A number of active faults are present along the North Western Himalayan Fold-and-Thrust belt. Along the western oblique margin of this collision, there is a left-lateral transform fault i.e Chaman Fault, linked in the south to Ornach Nal Fault zone.

2.2 General Geology

The Lower Indus Basin and the Middle Indus Basin are separated by the Jacobabad and Mari Kandhkot Highs (Sukkur Rift). Pakistan's 533,500 km2 Indus basin, which is composed of sediments with ages ranging from the Precambrian to the Recent, has a sizeable quantity of oil and gas potential. The Karachi depression, the Sulaiman-Kirthar depression, and the inner folded zones of the Kirthar mountains and Sulaiman have all seen oil and gas discoveries (foredeep). The Indus Basin's divisions are depicted in Figure 2.1.

Figure 2.1. Divisions of the Indus Basin showing location of study area in the Lower Indus Basin (modified after Awan et al., 2021).

The Indus basin is further broken down into:

1. Upper Indus Basin

2. Lower Indus Basin (Central and Southern Indus Basin)

2.2.1 Sub-divisions of the Southern Indus Basin

The Sukkur rift, which separates the central and Lower Indus Basins, is located directly south of the Lower Indus Basin. The Indian shield to the east and the Indian plate's marginal zone to the west define the boundaries of the Lower Indus Basin. By the offshore Murray ridge Owen fracture plate limit, it cannot extend southward (Kadri, 1995).

The following five primary units make up the Lower Indus Basin:

1) Thar platforms

The Thar platform is a subterranean monocline that slopes gently, similar to the Punjab platform in the central Indus basin (Map 2:3). In the direction of the Indian shield, which is visible at Nagar Parkar high, the sedimentary cover pinches out. In contrast to the Punjab platform, the Thar platform exhibits buried structures created by extensional tectonics as a result of the Indian plate's most recent anticlockwise movement. The platform represents exceptionally successful development of the Goru Cretaceous Sands, which serve as reservoirs for oil and gas fields (Kadri, 1995).

2) Karachi Trough

The thick early Cretaceous sediments that make up the trough classify it as the final stages of marine sedimentation. The trough is made up of several long, narrow anticlines that resemble chains, some of which include oil and gas fields (Kothar, Sari & Hundi). Throughout the course of geological history, it has been a trough. The region has well-preserved rocks from the early, middle, and late Cretaceous periods. The Cretaceous/Tertiary (K/T) boundary's ongoing deposition is the most intriguing aspect (Kadri, 1995).

3) Kirthar Foredeep

With a north-south orientation, the Kirthar foredeep has accumulated sediments with a combined thickness of more than 15,000 metres. Its eastern border with Thar platform is faulted. While the Upper Cretaceous is absent, the Paleocene is well preserved. Kirthar Foredeep offers excellent potential for source rock maturation (Kadri, 1995).

4) Kirthar Fold Belt

The Sulaiman fold belt and the Kirthar fold belt are structurally similar and stratigraphically equivalent tectonic features with a north-south trend. Here, wrecks from the Triassic to the Recent periods were deposited. The Oligocene-Miocene oceans closed due to the Kirthar fold belt's structure (Kadri, 1995).

5) Offshore Indus

This region is a passive continental edge that appears to have undergone two independent geological eras (Cretaceous-Eocene and Oligocene-Recent). In the offshore Indus region, sedimentation began in the Cretaceous period (Kadri, 1995).

2.3 Generalized Stratigraphy

The research area's stratigraphy includes rocks from the Sembar Formation to the Siwaliks (Wandrey et al, 2004). Figure 2.2 depicts the generalised stratigraphic column of the Lower Indus Basin. Figures 2.3 depicts the stratigraphy found in wells Sawan-01 and Sawan-02.

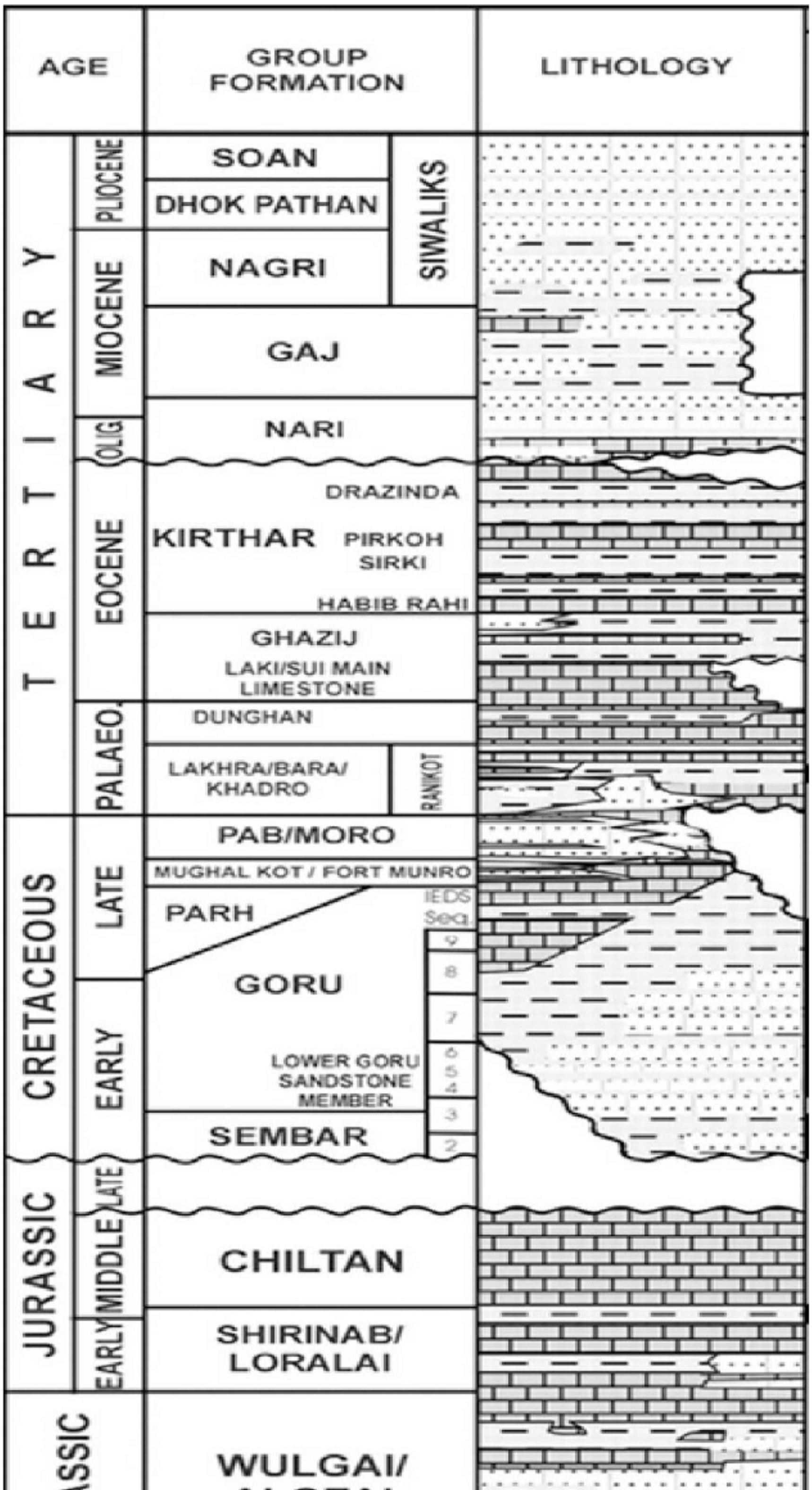

Figure 2.2. Generalised stratigraphy of Lower Indus Basin (Zaigham and Mallick, 2000).

2.3.1 Cretaceous

The actual breakup of Gondwanaland occured in the Early Cretaceous (Africa-South America). Approximately 120 Ma (Aptian), when Sembar/Goru were being deposited, Eastern Gondwanaland broke up to form what is now known as the Greater India. Thus, shallow seas were present during the whole Cretaceous period.

Early Cretaceous is a transgression period, whereas end of Cretaceous (Mesozoic Era) is a global regression, characterised by continuous sedimentation. As a result, it is easy to see the contact in the outcrops, ditch cuttings, and on wireline logs. Early Cretaceous sediments are known for their shaly response on logs.

An interesting phenomenon can be seen at the upper Cretaceous–Paleocene contact in Pakistan. It is significant economically because laterite, bauxite, coal, and iron reserves are found along the contact in various regions of Pakistan. Since the Basal Tertiary is often characterised by transgressive seas and the Top Cretaceous by regressive phase, their contact is very clearly visible on ditch cuttings and wireline logs. (Kadri, 1995)

In the Lower Cretaceous rocks, black shale, siltstone, and argillaceous of the Sembar Formation extend up to 250 metres, and limestone with shale (interbedded), and sandstone (Lower Goru) extend up to 500 metres. In the Southern and Middle Indus Basins, and Sulaiman-Kirthar region, the Sembar is regarded as the principal petroleum source rock. Most of the reservoirs that are producing the Composite TPS of Sembar-Goru and Ghazij are found in Lower Goru sandstone reservoirs. The Parh carbonates, the Moghal Kot shales, sandstones, and limestones, and the Fort Munro limestones and shales are evidence of the shelf to shallow-marine environment that existed throughout the majority of the Late Cretaceous period. (Wandrey et al, 2004)

i. Sembar Formation

Silty shale (black) and interbedded siltstone (black), and rusty, weathering, argillaceous limestone (nodular) layers or concretions make up the Sembar Formation. Glauconitic has a greenish tint as a result of weathering. The depositional environment is deep marine and Ammonites, Belemnites, and Forums are among the fauna (Fatmi, 1977).

It is believed that the Sembar Formation is where the hydrocarbons from the the Badin Platform fields and the enormous gas accumulation in Suleiman Province come from. It is considered that the Sembar was deposited on a broad shelf that gently sloped away from the Indian Sheild in the direction of the west.

The Sembar acts as a good source rock and has shown oil and gas shows. These are consistent with other such signs and point to the existence of reducing conditions. Within the formation's sandstones are potential reservoirs. The likelihood of oil migration from Sembar into the underlying Jurassic Formation against faults also seems to be rather good.

ii. Goru Formation

The Goru Formation is made up of sandstone, interbedded limestone, shale, and siltstone, according to Fatmi (1977). The limestone shows colors of light-medium grey/olive grey, and it consists of fine grains and thin beds. In both the formation’s lower and upper parts, limestone predominates. The Goru Formation is 536m thick near the type locality. Belemnites and Forams are among the fauna. The upper contact is with the Parh Formation and the lower contact is with the Sembar Formation, and both are conformable. There are two members of Goru Formation, that are:

1. Lower Goru
2. Upper Goru

a) Upper Goru Member

Upper Goru Member is Upper Cretaceous in age. The transition from sandstone and claystone to marl and limestone marks the upper boundary of the Upper Goru. Marl is hard, subblocky, light to medium gray in colour and is also silty while the upper portion’s sand becomes argillaceous or marly at places. The siltstone present there is subblocky, calcareous and the color is light gray. Dark gray in color, moderately hard, subfissile, and grading to calcareous claystone is shale (Kadri, 1995).

Since shale dominates the Upper Goru, it has no potential as a reservoir (Quadri and Shuaib, 1986).

b) Lower Goru Member

Lower Goru is Lower to Upper Cretaceous in age. A shift from marl to claystone lithology indicates the upper boundary of Lower Goru Member. Shale has a dark grey colour, firm to moderately hard, sub platy, sub fissile, moderately calcareous, carbonaceous at parts, silty, and locally grades to siltstone. A light grey color, friable, calcareous, glauconitic, and locally grading to very fine sandstone are all characteristics of the siltstone. The characteristics of sandstone include a medium grey colour, friability, very fine grained, well cemented with calcareous cementation, argillaceous matrix, common lithic pieces, and mica traces. Due to the fact that it contains all of the hydrocarbons in the Sindh Monocline, the Lower Goru Sand has very good petroleum potential (Kadri, 1995).

Basal, middle, and upper sands are the primary components of the Lower Goru Formation, underlain and overlain by lower and upper shales, respectively. The upper sands contain the main hydrocarbon-producing zones. This zone is split into four subzones, A, B, C, and D, by Turk, Badin, and Jhol shale, respectively (Quadri and Shuaib, 1986).

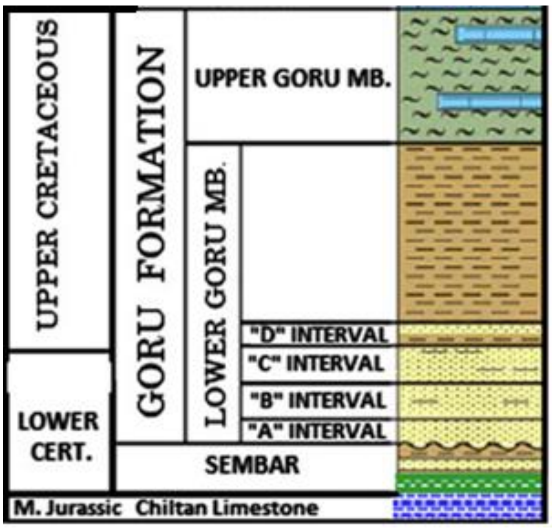

Figure 2.3. The stratigraphic column showing the subdivisions of Lower Goru Formation into Sand intervals A, B, C and D (Ahmad et al. 2004).

2.3.2 Tertiary

2.3.2.1 Paleocene

With the exception of a few sandstones and some limestone with high energy, the environment of Paleocene is anoxic and of low energy. The quantity of hydrocarbons and their preservation is favored by it. The northward movement of the

Indian Plate, which intensified (16 cm/year) throughout the Paleocene, marks the end of the Cretaceous and the beginning of the Tertiary (Powell 1988).

The Central Sulaiman Basin and a portion of the Kirthar Basin include Paleocene (Danian) strata; the remaining Paleocene is present throughout Pakistan with some local unconformities.

Throughout the Tertiary in the Lower Indus Basin, various local areas emerged as a result of the collision of the Indian and Eurasian Plates. Different transgression and regression periods can be seen in this basin. While other places did not acquire Danian sediments, the Central Sulaiman (Tangi Sar/Drug Lahar, Rakhi Nallah parts) and Kirthar (Bara Nallah section) basins received the Khadro Formation during the early Paleocene (Danian) incursion. The Paleocene sediments were dispersed significantly by Jacobabad High. Before the major Paleocene (Ranikot) sea transgressed and inundated the whole Indus Basin, this transgression was followed by a swift, brief return.

The Paleocene rocks in the Central and Lower Indus Basin are virtually exclusively marine in origin. Limestone predominates in the lithology, with marls, shale, sandstone, and conglomerate all present in variable amounts. However, in parts of the Sulaiman Basin, these are distinguished by a predominance of shale lithology, which points to a significant rise in sea level in some areas (Kadri, 1995).

i. Ranikot Formation

Vredenburg separated Blanford's renamed "Ranikot Group" into Lower Ranikot and Upper Ranikot consisting of sandstone and limestone respectively. The current report upholds the validity of this subdivision. As a result, the Ranikot Group consists of 3 formations, in ascending stratigraphic order:

- Khadro Formation i.e., beds of Cardita beaumonti
- Bara Formation i.e., sandstone of Lower Ranikot
- Lakhra Formation i.e., limestone of Upper Ranikot

The Khadro Formation, which makes up the group's bottom portion, is composed of sandstone and shale of yellow brown/olive color and has limestone that is interbedded. This is followed by sandstone (variegated) and shale of Bara Formation (fluviatile). The higher portion is made up of sandstone (weathering brown/ grey to brown) and eustarine shale of Lakhra Formation. The Kirthar Province has the most exposures.

The Pab Sandstone and the Moro Formation appear to be overlain by the group apparently irregularly. It is covered in a uniform manner by various units in various locations. The group was deposited during Paleocene time, based on the fossils found in the Khadro Formation and Lakhra Formation. The group shares similarities with Pakistan's western and southern Dungan Formation and Rakhshani Formation.

2.3.2.2 Eocene

i. Kirthar Formation

In a conformably transitional position, the Ghazij Formation is overlain by Middle Eocene Kirthar Formation. The upper contact of Kirthar Formation is disconformable with the Nari Formation of Oligocene time. The primarily constituents of the formation are fossiliferous limestone and minor amounts of marl and shale. There is thick-bedded limestone that is massive and nodular in certain places, and the deposition environment was a shallow sea. The Kirthar Formation consists of four distinct individuals: Habib Rahi, Drazinda, Pirkoh, and Sirki are the members (Kadri, 1995).

a. Drazinda Member

The Drazinda Formation, which is more than 380 and 300 m thick in Rakhi Nala and Zinda Pir, respectively, is made up of secondary marl and limestone strata and dark brown/greenish gray shale.

b. Pirkoh Member

The Pirkoh Formation is composed of fine-grained, typically thin and consistently bedded, light grey to chalky white, buff to brown, and frequently argillaceous limestone. The formation is followed by the Drazinda Formation and the Domanda Formation. The two contacts are temporary. The middle and top portions of the Pirkoh Formation are exceptionally rich in fossils. Foraminifera, gastropods, bivalves, and echinoids are some of the fossils. Age-wise, it is Middle Eocene.

c. Sirki Member

Eocene is the member's age in Sirki. The transition from limestone to claystone marked the upper border of the Sirki component. Claystone is soft to hard, dark bluish green in hue, and mildly calcareous. Limestone is a reasonably hard rock with a light yellowish grey tint with foramina traces (Kadri., 1995).

d. Habib Rahi Member

The Habib Rahi Formation is a firm, buff and greyish brown limestone that weathers white. It is predominantly argillaceous, thin-bedded, fine-grained, and slopes into marl in a few spots. The formation's few thin cherty beds are only found in the top layers, where Assilina-rich marl predominates. The Habib Rahi Formation is composed of a big upper portion, a thick bedded middle, and a massive bottom portion at Shinki Post (North Waziristan). The formation at the Sirki Paila in the Kohat District is made up of five higher metres of marl that is brown to plum in color and also has pure limestone.

The Habib Rahi Formation is present in North and South Waziristan, towards the eastern part of the Sulaiman Range. The Domanda Formation and Baska Formation are both uniformly overlaid and underlain over the Habib Rahi Formation in the Sulaiman Province. The Baska Formation, a transitional formation in Waziristan, is where the Habib Rahi Formation makes its lower contact. The bottom portion of the formation is characterised by an abundance of assilina. The formation dates from the Early to Middle Eocene.

ii. Ghazij Formation

Shale, with subordinate claystone, sandstone, conglomerates, and alabaster, as well as coal seams, make up the Early Eocene Ghazij Formation. The Ghazij Formation is 590 metres thick and was deposited in a depp marine environment. Its contacts are both conformable. Its lower contact with Laki Formation and Dungan Formation, as well as its upper contact with Kirthar Formation, are both conformable. There are fossilised forams, bivalves, gastropods, echinoids, and algae within its three-meter thickness range. Laki Formation and Ghazij Formation are related (Vredenburg, 1908).

iii. Laki Formation

The Laki Formation's limestone (Early Eocene) is primarily creamy grey in colour, with minor amounts of calcareous shale, marl, some sandstone and laterite. There is one hundred metres thickness of the shallow marine deposition environment. There are 2 members of the formation, i.e., the Meting limestone and shale (upper) and Sohnari (lower) containing the base Laki laterite (Shah, 1977). Forums, bivalves, gastropods, echinoids, and algae fossils have been discovered. While the bottom contact is inconformable with the Ranikot Formation, the top contact conforms to the Ghazij Formation (Vredenburg, 1908).

iv. Sui Main Limestone

The most prevalent lithology type in the Khairpur/Kandra region is planktonic, benthonic foraminiferal lime mudstone with some argillaceous content. Wackestone composed of foraminifera is the other typical lithology. Also seen are ellipsoidal calcite nodules encased in a lime mud matrix.

The Sui Main Limestone is Eocene in age. The transition from shale to limestone lithology marks the upper border of the Sui Main limestone component. The colour of limestone is a pale yellow-gray, and it occasionally contains chert and crystalline calcite remnants. Shale is subplaty, subfissile, firm to moderately hard, and somewhat calcareous. The colour of marl ranges from light to greenish grey. Subblocky in places and showing signs of forams This area's argillaceous limestone is hard, subblocky, chalky to microcrystalline, light grey to whitish in colour, and contains traces of forams (Kadri, 1995).

2.4 Borehole Stratigraphy

	SAWAN-01			SAWAN-02		
Age	**Formation**	**Tops**	**Thickness (m)**	**Formation**	**Tops**	**Thickness (m)**
Eocene	**ALLUVIUM**	**0**	**34**	**ALLUVIUM**	**0**	**58**
	DRAZINDA	**34**	**134**	**DRAZINDA**	**58**	**120**
	PIRKOH	**168**	**94**	**PIRKOH**	**178**	**85**
	SIRKI	**262**	**12**	**SIRKI**	**263**	**10**
	HABIB RAHI	**274**	**27**	**HABIB RAHI**	**273**	**28**
Paleocene	**GHAZIJ**	**301**	**816**	**GHAZIJ**	**301**	**808**
	SUI MAIN LIMESTONE	**1117**	**142**	**SUI MAIN LIMESTONE**	**1109**	**142**
	RANIKOT	**1259**	**1189**	**RANIKOT**	**1251**	**1161**
Cretaceous	**UPPER GORU**	**2448**	**248**	**UPPER GORU**	**2412**	**271**
	LOWER GORU	**2696**	**891**	**LOWER GORU**	**2683**	**806**

Figure 2.4. Borehole stratigraphy of Sawan-01 and Sawan-02.

2.5 Petroleum System

70% of Pakistan's known gas reserves are in the Lower Indus Basin, a gas province. Upper Cretaceous and Tertiary deposits contain the majority of proven reserves. The Central Indus Basin's prospective role for Lower Cretaceous sandstone in the future has been reinforced by the finds of Kadanwari, Miano, Mari Deep, and Sawan. The primary producer of Lower Goru Sand is these fields.

2.5.1 Source Rock

The reservoir sands received hydrocarbons from Sembar Formation (Lower Cretaceous), a locally documented organic-rich shale, and from the Lower Goru Member, an organic-rich shale. Since the Late Cretaceous-Early Tertiary, these shales have been in the gas generation phase and have organic matter (terrestrial) with 0.5-1.7% TOC and kerogen of Type III (Fatmi, 1977). The global sea level rose at the start of the Cretaceous period, causing an abundance of organic life. Additionally, the preservation of organic matter was a result of basin-wide anoxia. This stored organic matter was converted into hydrocarbons under ideal time and temperature circumstances.

The Sembar Formation, Goru Formation, and Moghal Kot Formation all contain thick and widely distributed Cretaceous shale. They have a lot of organic content and typically have favourable source rock qualities. Additionally, the majority of the Cretaceous subcrops are located within the oil window. Some of the samples from Cretaceous shale, according to source rock analyses, are at a reasonably advanced stage of hydrocarbon energization. In the potential and producing reservoirs, this shale is thick enough to create enormous hydrocarbon reserves (Wandrey et al 2004).

2.5.2 Reservoir Rock

The Indus Basin has numerous excellent reservoirs thanks to the thick Cretaceous deposits. The gas and oil fields located in the area of Badin Platform or Sindh Monocline have the Lower Goru sands as reservoirs, which have a porosity range of 5 to 30%. They include the Khaskeli, Dhabi, Laghari, Mazari, Nari, Makhdumpur, South Mazari, Tando Alam, Bobi and other oil fields and Sawan, Miano and Kadanwari gas fields.

Pab Sandstone serves as the reservoir of the Pirkoh Gas Field and the Dhodak/Rodho gas condensate fields in the Central Indus Basin (Sulaiman sub-Basin).

The Mogal Kot Formation displays favourable reservoir properties in Jandran. Limestone from the Moghal Kot Formation and elsewhere exhibits significant potential for secondary porosity development. Primary (intergranular) porosity and the possibility for secondary porosity growth are both well-represented by the texture of Pab sandstones. In the found fields (Pirkoh, Dhodak, and Rodho), the porosity of the Pab Sandstone ranges from 5-15%.

The well-known Moghal Kot oil seepage, which takes place in the basal outcrops of Pab Sandstone, is another indicator of hydrocarbon production and its transit through permeable Pab Sandstone. Additional Cretaceous rocks with reservoir potential include possible reef and fore reef facies in the Parh Limestone and delta and submarine fan facies in the Moghal Kot Formation (Wandrey et al 2004)

2.5.3 Seals

Shale that is interspersed makes up the system's recognised seals. Thin strata of varying thicknesses of shale act as efficient seals in producing areas. Impermeable seals over truncation traps and flaws are other seals that could be useful.

2.6 Petroleum play

2.6.1 Source

Sembar Formation of the Lower Indus Basin is the source rock. Shale makes up the majority of the Lower Cretaceous Sembar Formation; the remainder is made up of siltstone and sandstone.

2.6.2 Reservoir

Sands from the Lower Goru act as a reservoir. Shale, siltstone, and thin layers of shaly sand make up the majority of the formation's upper portion, whilst reservoir-quality sandstones with interlayering of shale and limestone make up most of the lower portion.

2.6.3 Seal

In this petroleum play, the interbedded Lower Goru Formation shales serve as a seal. In the upper portion of the Lower Goru Formation, there are thin strata of shaly sand, siltstone, and shale.

CHAPTER 3

PETROPHYSICAL INTERPRETATION

Petrophysical investigation helps us identify the fluid that is occupying the rock pores while also determining the qualities of the reservoir rock. Petrophysical analysis is crucial to the petroleum industry since it is a crucial tool for both hydrocarbon exploration and reserve assessment of any reservoir zone. The main petrophysical characteristics of shale are its volume, its density porosity, the neutron porosity, as well as the average porosity and effective porosity, and lastly, calculation of saturation of water and hydrocarbon. The lithology of the encountered rock unit can also be roughly estimated by professionals using the petrophysical analysis.

3.1 Quality check of logs

The calliper log is likewise on-gauged for the most of the depths, and the logging data for the Sawan-01 and Sawan-02 wells is of good quality as we noted low GR values. The logs are of decent quality and may be read as well.

3.2 Log trends

Track-01 represents lithology logs i.e., Gamma Ray and Spontaneous Potential logs, along with caliper log and bit size. Fig 3.1 and Fig 3.2 show that the caliper log remained on-gauged for most of the depths. However, the GR log showed both high and low peaks (undulations and gradual peaks).

Track-02 shows resistivity logs i.e., MSFL, LLS and LLD. The resistivity logs have been represented on the logarithmic scale and deviations could be observed in them throughout the borehole depth. Also, at some depths there was no significant separation between MSFL and LLD. However, the potential hydrocarbon zones (irrespective of other logs) showed a clear separation between MSFL and LLD, in the following order:

$$MSFL < LLS < LLD$$

Track-03 shows porosity logs i.e., Neutron, Density and Sonic logs. The neutron and density logs have been used to compute average porosity whereas the sonic log has been used to compute sonic porosity.

We added another track i.e., track 7, and n order to check the reliability of the bulk density i.e., RHOB, a curve for density correction i.e., DRHO has been added in this track. This means that the data from RHOB is reliable if DRHO is less than 0.15.

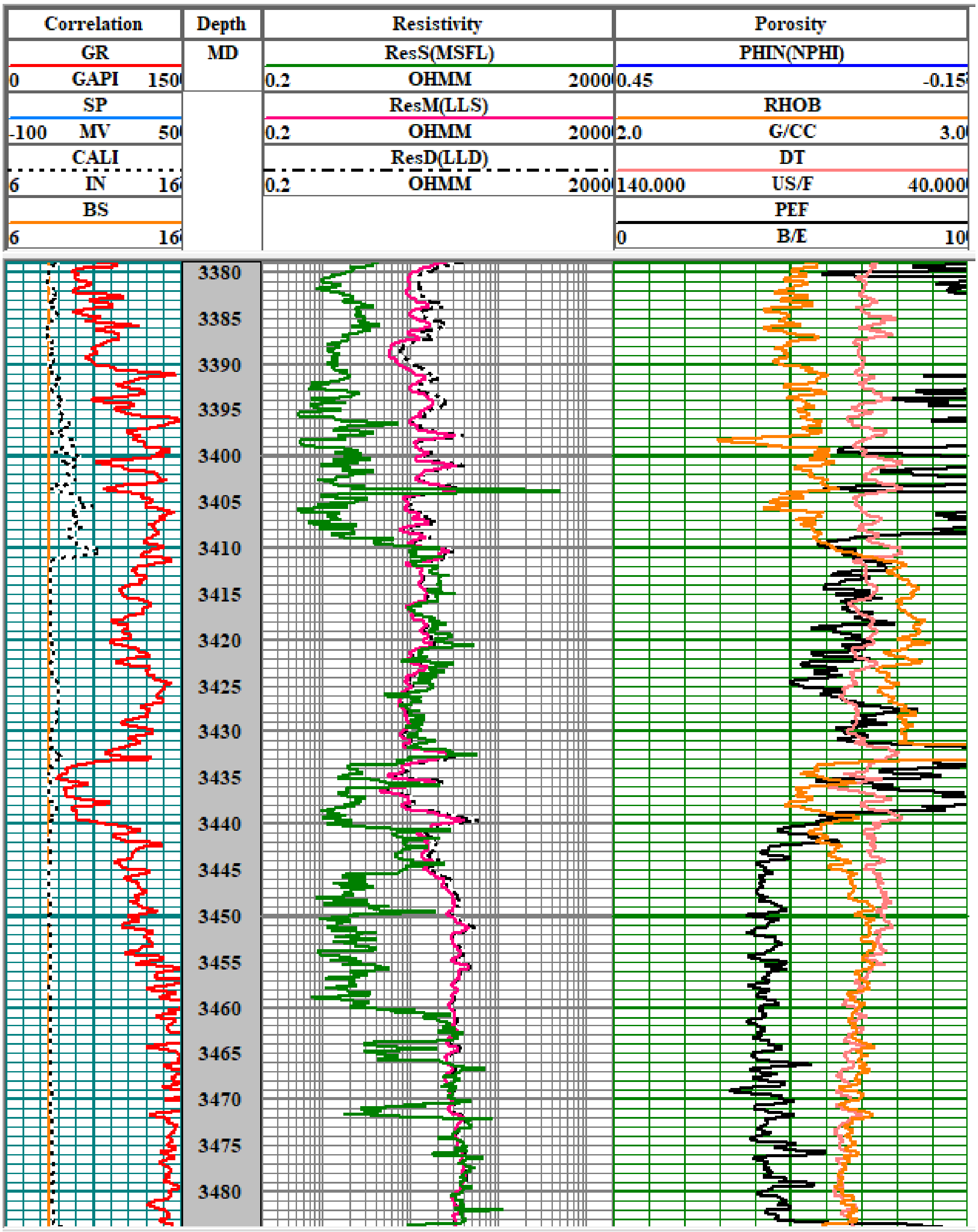

Figure 3.1. Uninterpreted raw log curves of Sawan-01.

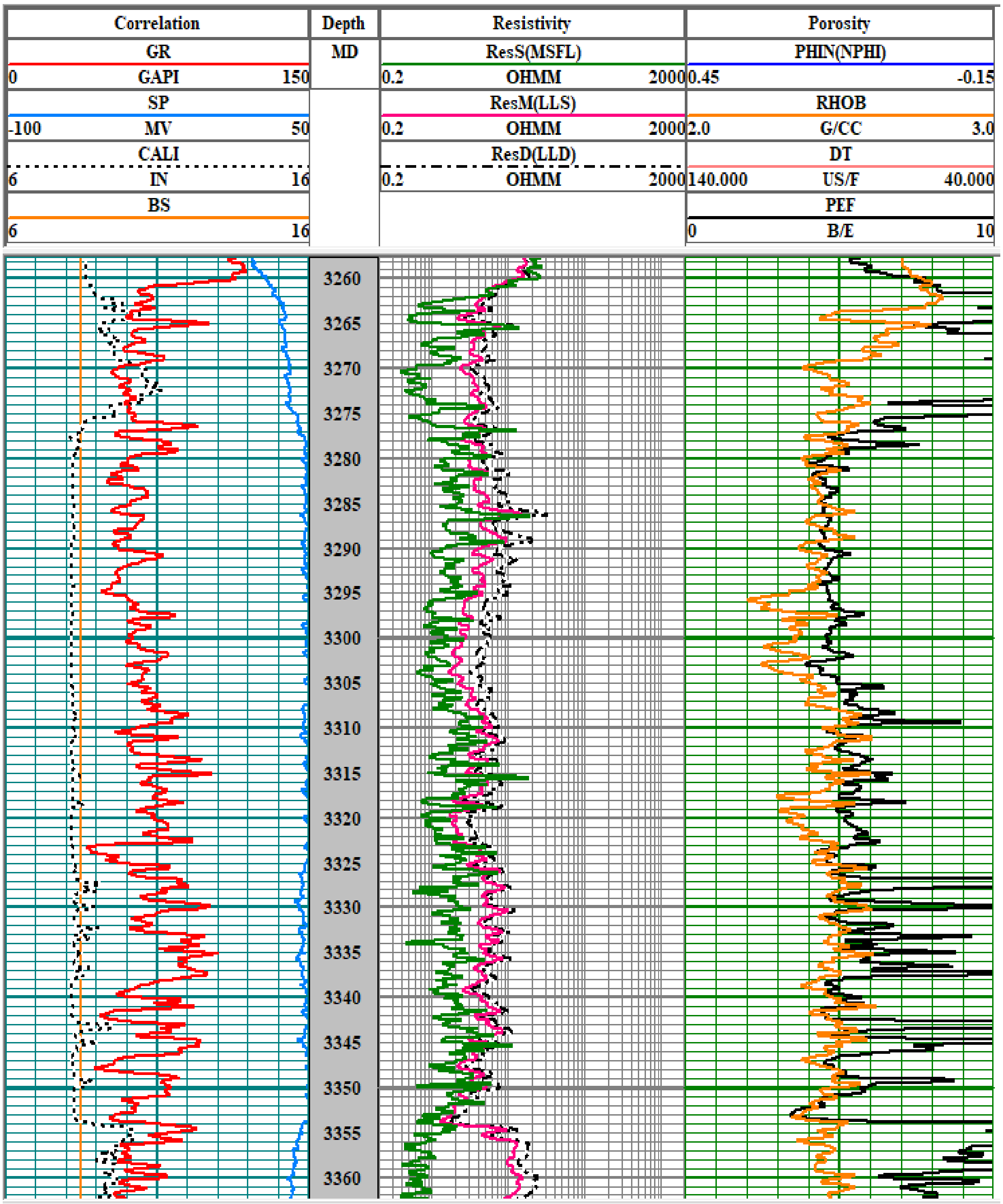

Figure 3.2. Uninterpreted raw log curves of Sawan-02.

3.3 Marking zone of interest

It is the first and most important step of petrophysical analysis. This is because if the zone of interest is not correctly identified, then all calculations are of no use. So, zone should be marked very carefully by using well log data. Reservoir zones can be identified by observing the following parameters on log data:

1. According to the calliper log, the zone of interest is primarily inside the area of stable borehole geometry. The calliper log displays on gauged or slightly in gauged response since the reservoir zone is located in a consolidated and porous formation.
2. A low gamma ray value implies a clean lithological zone, and reservoir zones always sit in clean lithological zones because they allow for fluid circulation.
3. Another way to tell if the mud being utilised is water-based is by looking at the low value of shallow resistivity logs and the high value of deep resistivity logs. because hydrocarbons have high resistance values while saline water has low resistivity values.
4. A cross-over formed between neutron and density log curves, resulting from low values of both. The low value of neutron log marks the reservoir zone because low value of neutron log indicates that the formation has high number of hydrogen atoms within it which is an indication of good porosity. In addition, low value of density log gives the clue about the reservoir zone because it indicates the formation is highly porous.

Sawan 1

Table 3.1. Zones of interest of Sawan-01 well.

Zone of Interest	Reservoir zone	Starting depth (m)	Ending depth (m)	Total thickness (m)
Zone 1	Lower Goru	3250	3260	10
Zone 2	Lower Goru	3284	3308	24
Zone 3	Lower Goru	3313	3318	5
Zone 4	Lower Goru	3369	3382	13

Sawan 2

Table 3.2. Zones of interest of Sawan-02 well.

Zone of Interest	Reservoir zone	Starting depth (m)	Ending depth (m)	Total thickness (m)
Zone 1	Lower Goru	3279	3308	29
Zone 2	Lower Goru	3323	3343	20
Zone 3	Lower Goru	3352	3367	15

Among these zones of interest, our target zones will be the ones with maximum thickness i.e., Zone 1, 2 and 5 in Sawan-01 well and Zone 1, 2 and 4 in Sawan-02 well. However, lateral extent of the zones also plays an important role in quantity of hydrocarbon production. In some cases, we also target less thick zones that have good quality hydrocarbons.

3.4 Volume of shale (Vsh)

The identification of shale beds during examination and the determination of the volume of shale in the formation are both aided by gamma ray logs. Depending on the amount of clay minerals present in the formation, gamma ray log detects radioactivity. The absence of radioactive materials in clean rocks is considered throughout the quantitative study of shale volume.

Shale volume can be calculated using both GR log and SP log. Our estimation of shale volume is based on gamma ray log and its volume is then used further for the estimation of other reservoir properties. The formula generally used for the calculation of volume of shale is as follows:

$$IGR = \frac{GR\ log - GR\ min}{GR\ max - GR\ min}$$

Here,

IGR = volume of shale

GR log = gamma ray formation reading

GR min = minimum gamma ray reading (sandstone)

GR max = maximum gamma ray reading (shale)

3.5 Calculation of porosity

The porosity of a rock is the proportion of its volume that is made up of pore spaces. There are two types of porosity: primary porosity, which develops during deposition, and secondary porosity, which develops during or after the alteration process.

3.5.1 Neutron Porosity

The concentration of hydrogen ions in the formation affects the porosity log known as the neutron log. The liquid-filled porosity of a clean deposit, when the spaces are filled with water or oil, is measured by the neutron log.

Depending on the type of detector used and the lithology (such as sandstone, dolomite, and carbonate), the reactions of the neutron log vary. Neutron porosity values typically range from 20 to 40%. The hydrogen index (HI) in the formation is determined by neutron log. Since hydrogen is a component of all three fluids, i.e., water, oil, and gas, the neutron curve can give us an idea of the fluid's presence and concentration.

3.5.2 Density porosity

The formation density log is a porosity log that uses electron density to calculate the formation's bulk density. The professionals analyse complex lithology, hydrocarbon density, minerals, gas-bearing zones, evaporates, and minerals using this log. Washouts are present when high density porosity values between 60 and 80% are present.The formula used for calculation of density porosity is as follows:

$$\Phi d = \frac{\rho ma - \rho b}{\rho ma - \rho f}$$

Here,

ρma = Density of the rock matrix

ρb = Bulk density of the formation

ρf = Density of the fluid occupying the pores

Φd = Density porosity of the rock

3.5.3 Average Porosity

Total porosity is another name for the average porosity. It provides information about the formation's total pore volume and is calculated by averaging neutron porosity and density porosity. It is calculated by using the following formula:

$$\Phi A = \sqrt{(\Phi^2 N + \Phi^2 D)/2}$$

ΦA = Average porosity

$\Phi^2 N$ = square of NPHI

$\Phi^2 D$ = square of DPHI

3.5.4 Effective Porosity

The term "effective porosity" refers to the total number of interconnected voids in a rock. Effective porosity, which indicates the presence of linked pores, is negatively correlated with shale content. It is determined utilising the relationship between the volume of shale's average porosity and effective porosity. Its formula is:

$$\Phi E = \Phi A * (1 - Vsh)$$

ΦE = Effective Porosity

ΦA = Average Porosity

Vsh = Volume of Shale

3.6 Resistivity of water

It is the most important and sensitive parameter used to determine water saturation. Resistivity of water (Rw) is essential to be computed in order to know the saturation of the fluid present. Three methods are used to calculate it, i.e.,

- Quick look method i.e., by directly using the equation.
- Pickett plot method i.e., on standard graphs.
- SP method, delivering the most reliable and accurate results.

We used Pickett plots to calculate Rw for Sawan-01 and Sawan-02, which have been shown below:

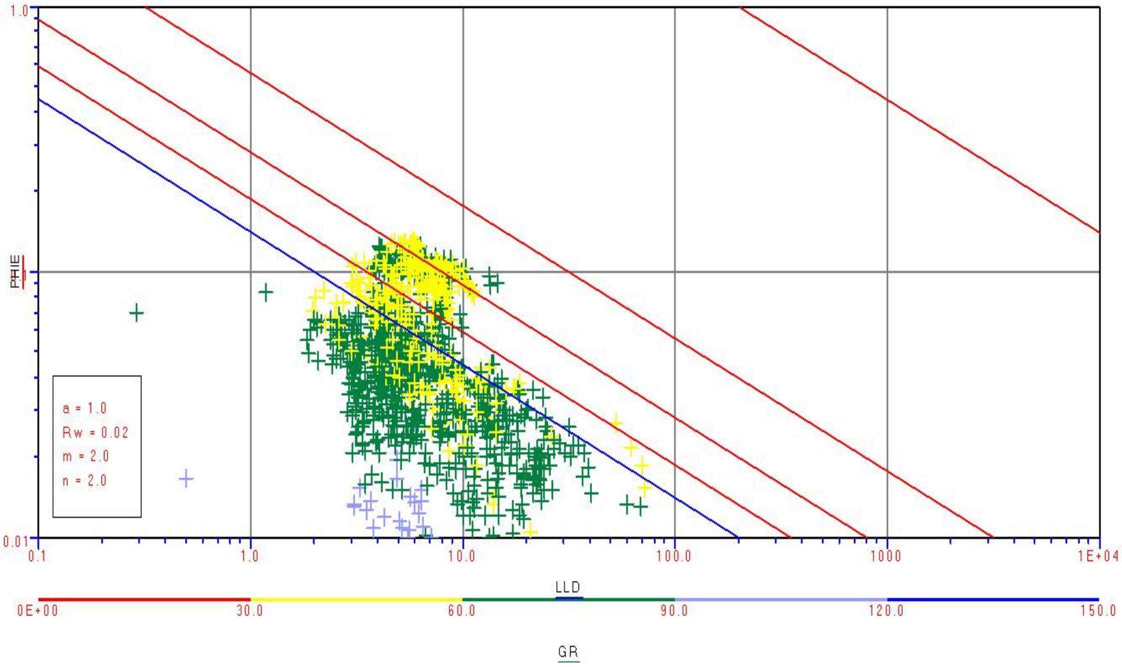

Figure 3.3. Pickett plot of Lower Goru in Sawan-01.

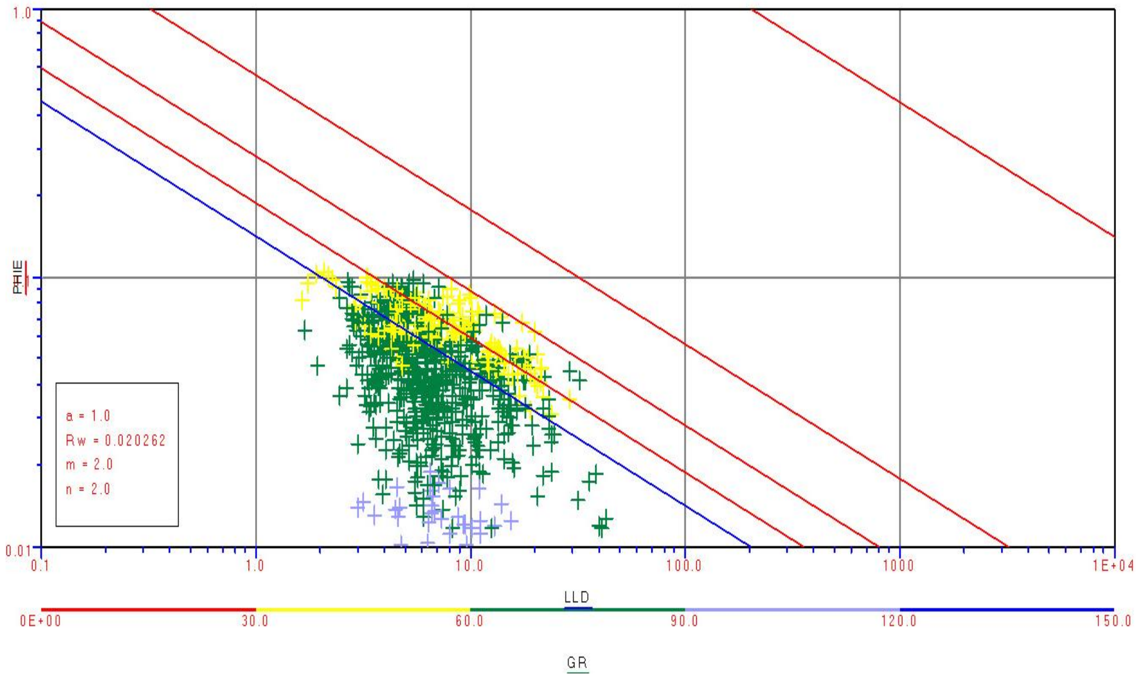

Figure 3.4. Pickett plot of Goru Formation in Sawan-02.

3.7 Saturation of water

Saturation of water refers to the volume of water found in the pore spaces of rock. Sw is a representative of it. It provides details regarding the presence of hydrocarbons. Sw values below zero indicate excessive hydrocarbon saturation. If a formation exhibits 100% water saturation, there are no hydrocarbons present, and the zone is not commercially viable. Indonesian equation is used to determine the water's saturation in lithology that is not clean. Its formula is:

$$\mathrm{Sw} = \left\{ \sqrt{\frac{1}{\mathrm{Rt}}} \Big/ \left(\frac{\mathrm{Vsh}^{(1-0.5\mathrm{Vsh})}}{\sqrt{\mathrm{Rsh}}} \right) + \sqrt{\frac{\Phi \mathrm{e}^{\mathrm{m}}}{\alpha.\mathrm{Rw}}} \right\}^{(2/n)}$$

Where,

Sw = Water saturation of the uninvaded zone

Rw = Resistivity of the formation water

Φe = Effective porosity at water zone

Rt = True resistivity of formation

Rsh = Shale resistivity from LLD

Vsh = Volume of shale

m = Cementation exponent (usually around 2)

n = Saturation exponent (usually around 2)

α = Empirical constant (usually around 1)

3.8 Saturation of hydrocarbon

Knowing the saturation of water is necessary to calculate the hydrocarbon saturation. Water saturation and hydrocarbon saturation have an inverse relationship. Conversely, a zone with low hydrocarbon saturation will have a high water saturation. It is calculated using the following formula:

$$\mathrm{Sh} = 1 - \mathrm{Sw}$$

Sh = Hydrocarbon saturation

Sw = Water saturation of the uninvaded zone

3.9 Results

The results for porosities, volume of shale and volume of clean, saturation of water and saturation of hydrocarbon have been obtained after observing the log trends in Sawan-01 and Sawan-02 wells. The log curves were available only for Lower Goru Formation and hence, it was studied in both wells.

3.9.1 Results of Sawan-01

As discussed before, the reservoir zones in Sawan-01 have been marked in Lower Goru Formation. Given below are the average values of the important parameters for the zones marked.

Zone 1

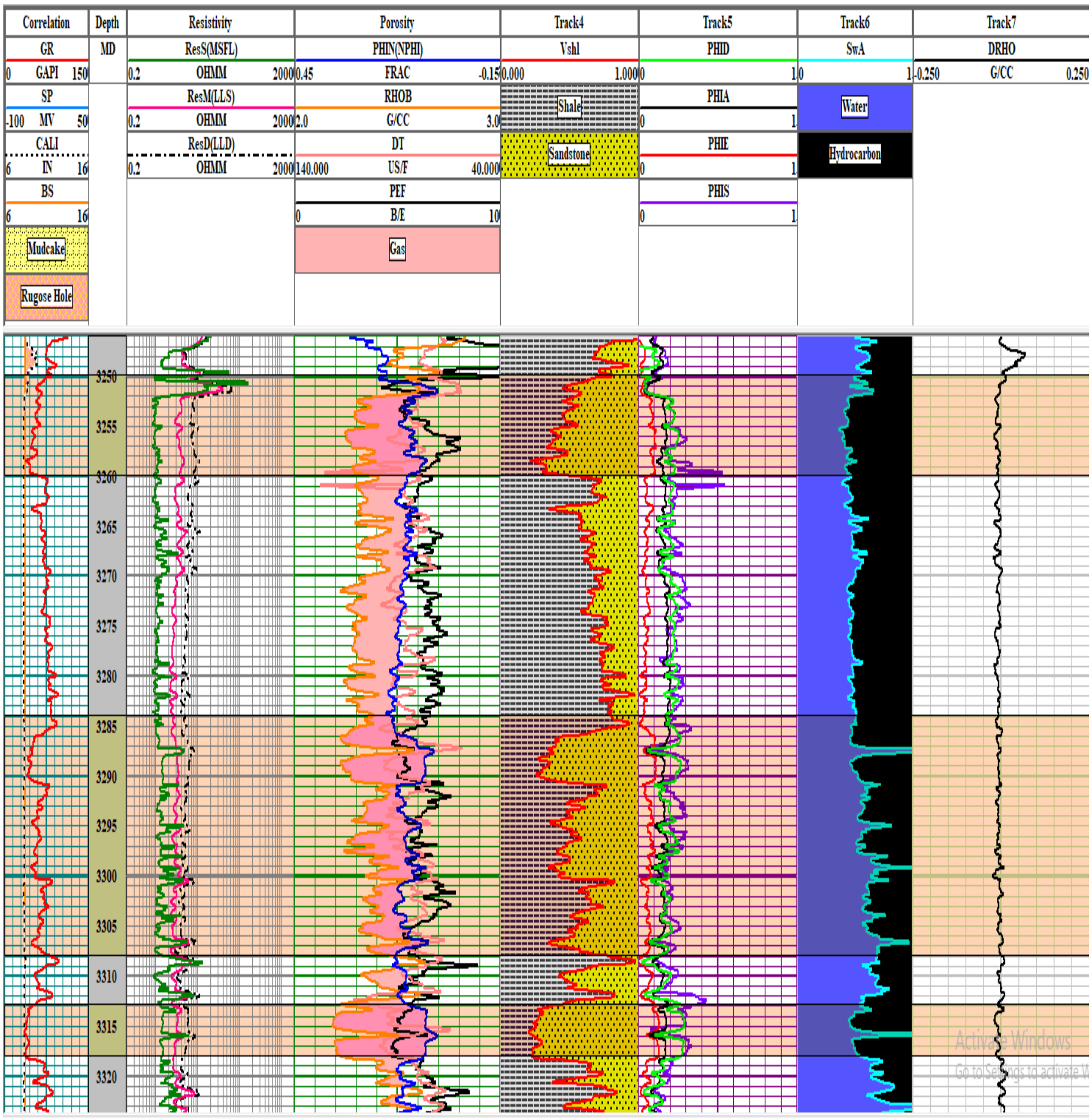

Figure 3.5. Zones 1, 2 and 3 of Sawan-01.

Table 3.3. Petrophysical results (%) of Zone 1 of Sawan-01 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3250	13.4	3.3	75.6	60.8	39.2
3252.5	16.3	9	44.8	52.1	47.9
3255	14.9	7.2	51.3	50.3	49.7
3257.5	14.7	7.2	49.3	54.4	45.6
3260	14.3	5.9	58.8	56.5	43.5
Average	**14.72**	**6.52**	**55.96**	**54.82**	**45.18**

Zone 2

Table 3.4. Petrophysical results (%) of Zone 2 of Sawan-01 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3284	17	3.2	81.2	79	21
3290	15.6	11	29.3	59	41
3296	17.7	7.7	56.7	74.2	25.8
3302	16.2	6.1	62.1	73.2	26.8
3308	12.8	2.5	80.2	86.9	13.1
Average	**15.86**	**6.1**	**61.9**	**74.48**	**25.54**

Zone 3

Table 3.5. Petrophysical results (%) of Zone 3 of Sawan-01 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3313	15.8	10.2	35.5	65.2	34.8
3314.25	17.6	12.6	28	52.3	47.7
3315.5	14.7	11.6	21.2	59.1	40.9
3316.75	17.6	12.2	30.5	55.7	44.3
3318	16.5	12.4	24.6	63.3	36.7
Average	**16.44**	**11.8**	**27.96**	**59.12**	**40.88**

Zone 4

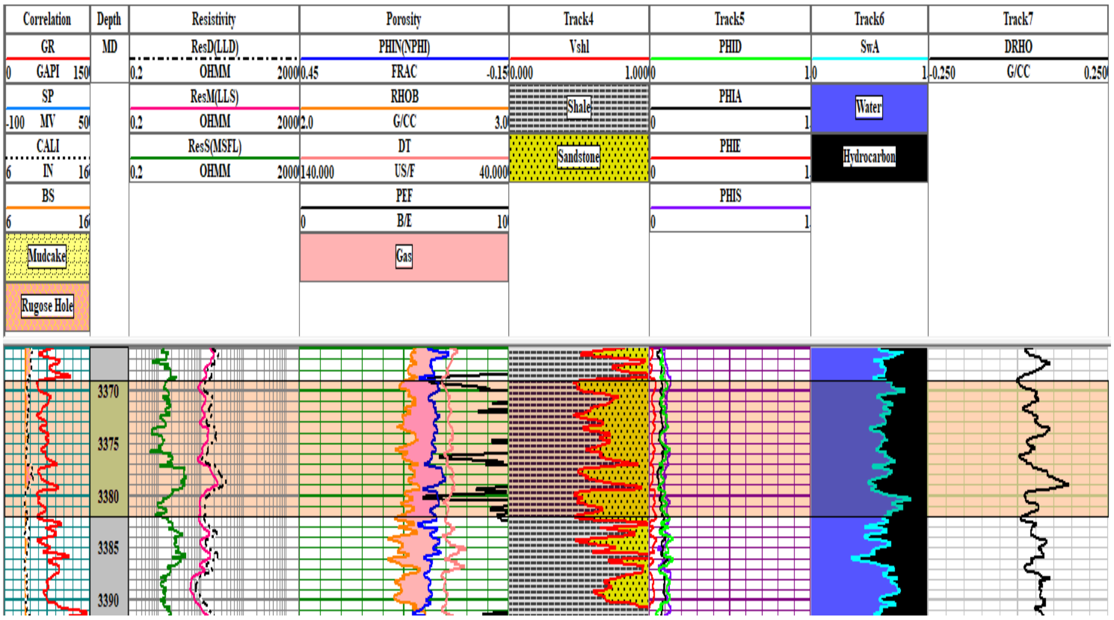

Figure 3.6. Zone 4 of Sawan-01.

Table 3.6. Petrophysical results (%) of Zone 4 of Sawan-01 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3369	8.2	4.1	50.4	56.3	43.7
3372.25	7.5	3.9	48	51.7	48.3
3375.5	9.3	4.2	55.2	52.4	47.6
3378.75	5.6	2.4	57.3	42	58
3382	9	4.8	47.1	58	42
Average	**7.92**	**3.88**	**51.6**	**52.12**	**47.92**

3.9.2 Results of Sawan 2

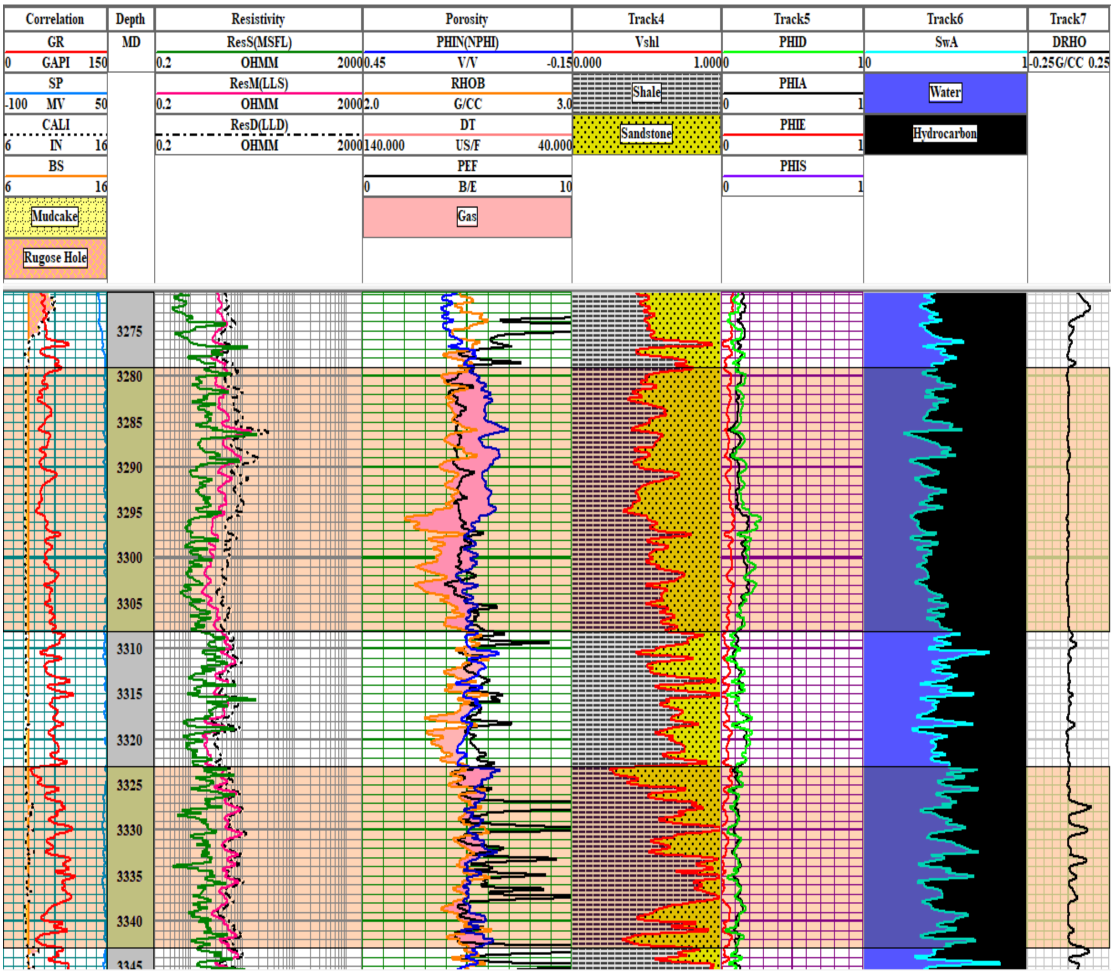

Figure 3.7. Zones 1 and 2 of Sawan-02.

Zone 1

Table 3.7. Petrophysical results (%) of Zone 1 of Sawan-02 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3279	12.6	2.3	44	69.9	30.1
3286.25	10.6	4.4	24.9	30.1	69.9
3293.5	11.4	6.1	42.5	50.2	49.8
3300.75	18	7.8	33.9	50.7	49.3
3308	11.2	3.9	54.5	70.4	29.6
Average	**12.76**	**7.66**	**39.96**	**54.26**	**45.74**

Zone 2

Table 3.8. Petrophysical results (%) of Zone 2 of Sawan-02 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3323	11.6	8	31	59.7	40.3
3328	11.7	3.3	72.1	58.7	41.3
3333	11.2	0.5	95.3	83.3	16.7
3338	14.4	3.7	74.3	65	35
3343	12.2	1.7	86.1	72.8	27.2
Average	**12.22**	**3.44**	**71.76**	**67.9**	**32.1**

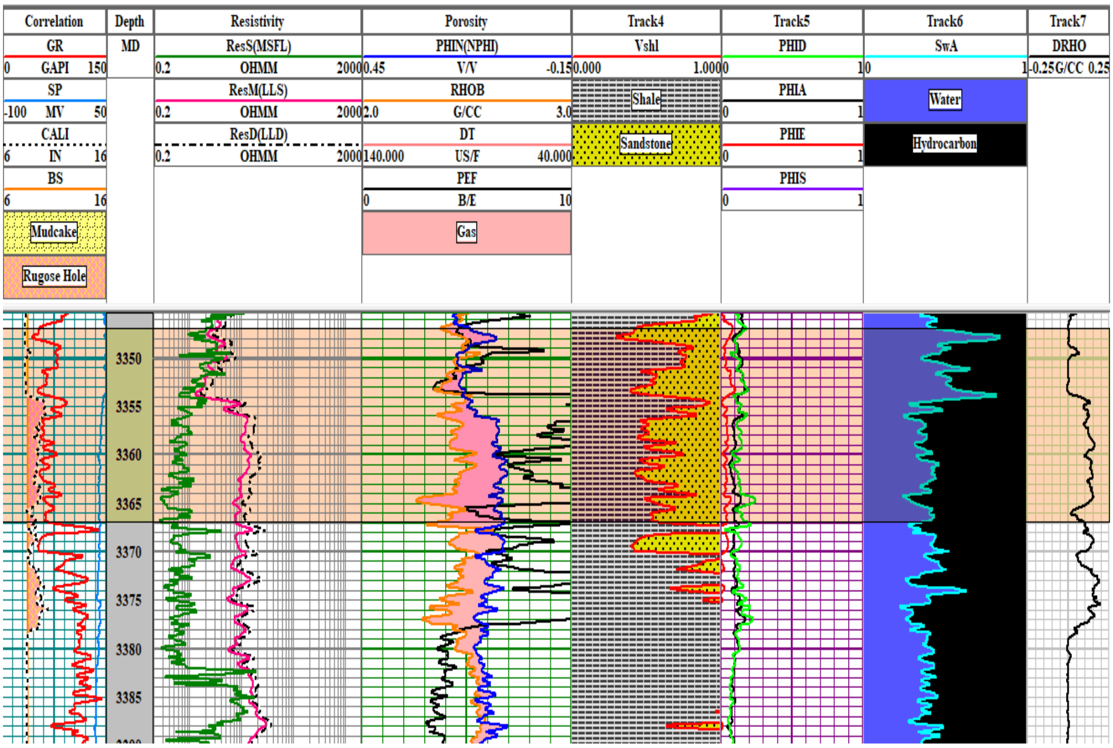

Figure 3.8. Zone 3 of Sawan-02.

Zone 3

Table 3.9. Petrophysical results (%) of Zone 3 of Sawan-02 well.

Depth (m)	PHIA (%)	PHIE (%)	Vsh (%)	Sw (%)	Sh (%)
3352	15.6	6.8	56.5	75.9	24.1
3355.75	14.2	3.1	78	56.8	43.2
3359.5	8.7	3.4	61.2	42.5	57.5
3363.25	10.2	2.8	72.3	45	55
3367	12.8	4.1	68.2	44.6	55.4
Average	**12.3**	**4.04**	**67.24**	**52.96**	**47.04**

3.10 Lithology identification

To identify lithology, two cross plots were constructed.

1. A crossplot between NPHI and RHOB.

2. A crossplot between NPHI and DT.

3.10.1 Sawan-01

Zone 1

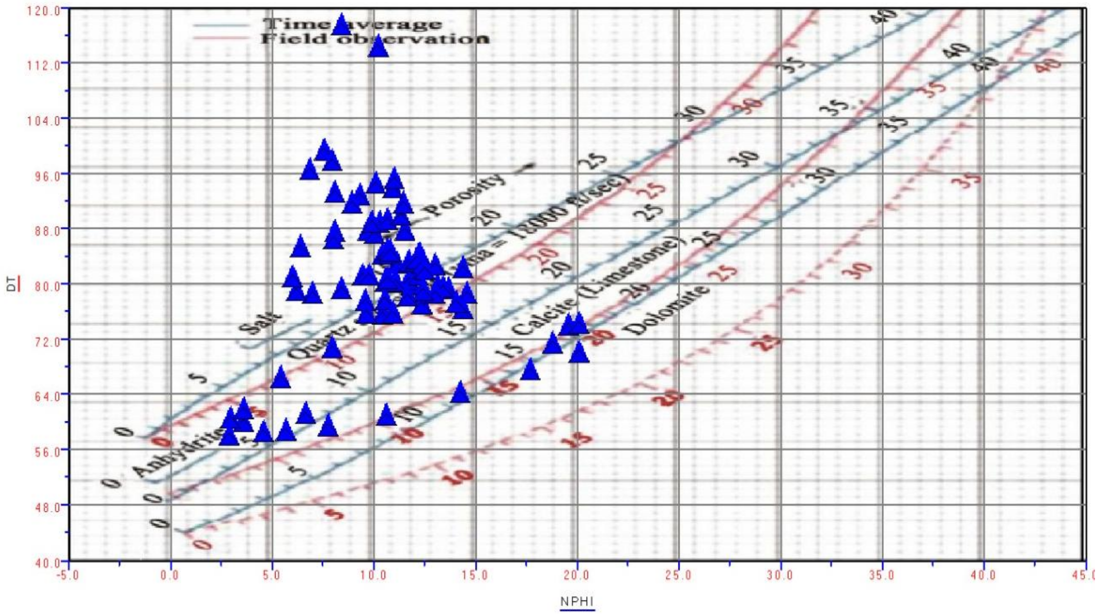

Figure 3.9. Cross plot between NPHI and DT for Zone 1 of Sawan-01.

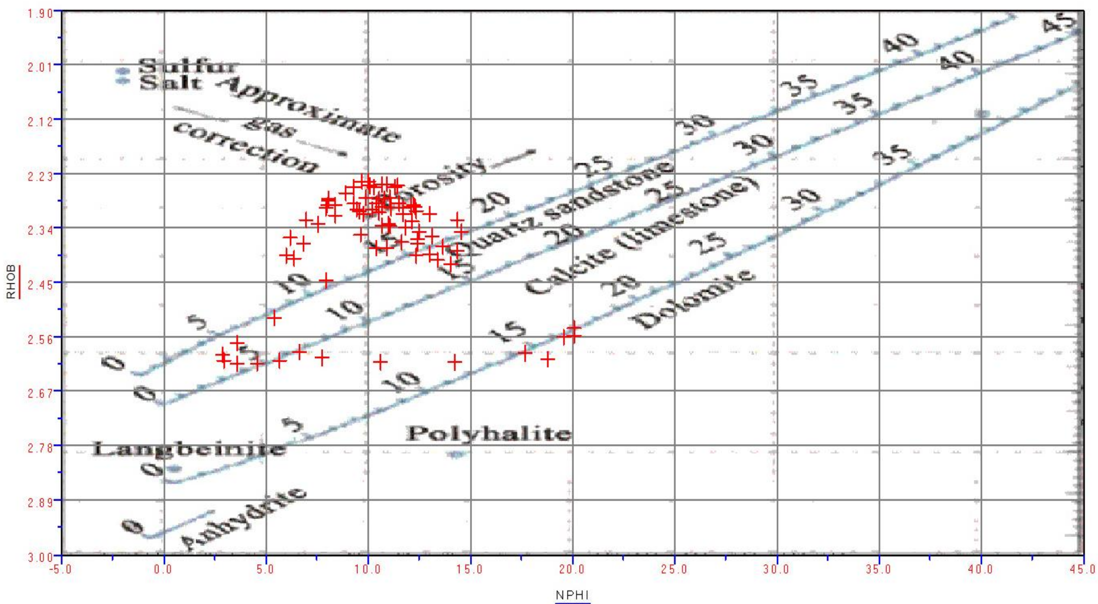

Figure 3.10. Cross plot between NPHI and RHOB for Zone 1 of Sawan-01.

Zone 2

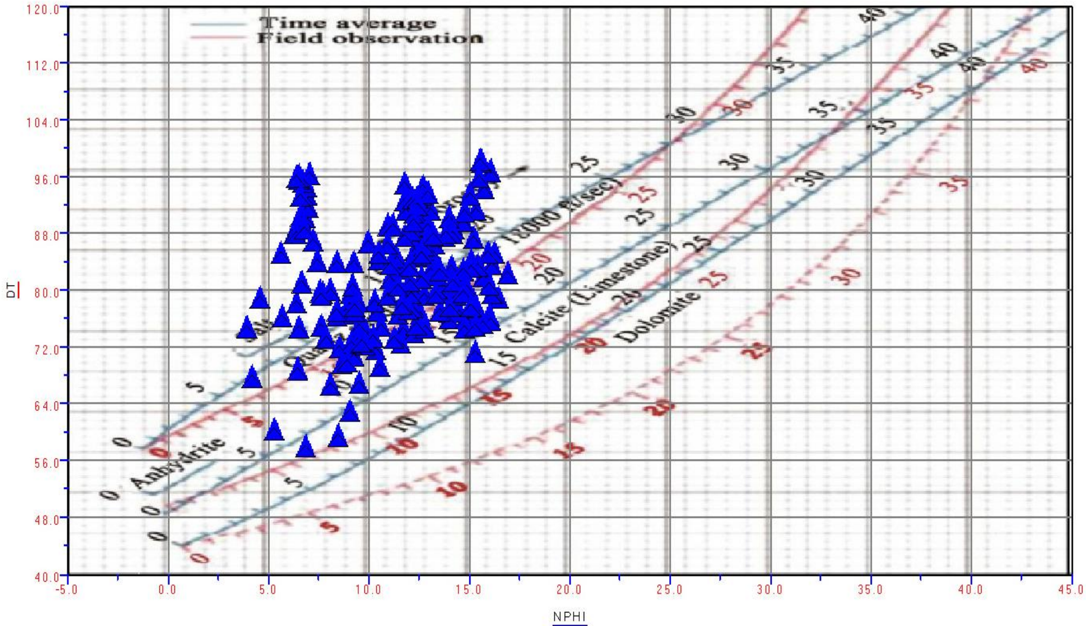

Figure 3.11. Cross plot between NPHI and DT for Zone 2 of Sawan-01.

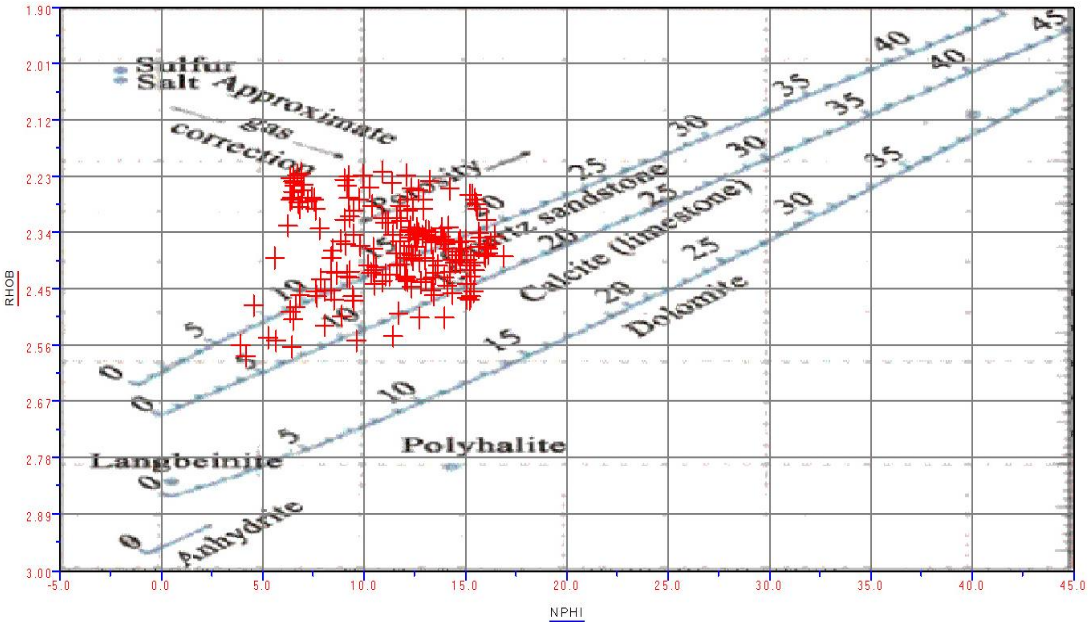

Figure 3.12 Cross plot between NPHI and RHOB for Zone 2 of Sawan-01.

Zone 3

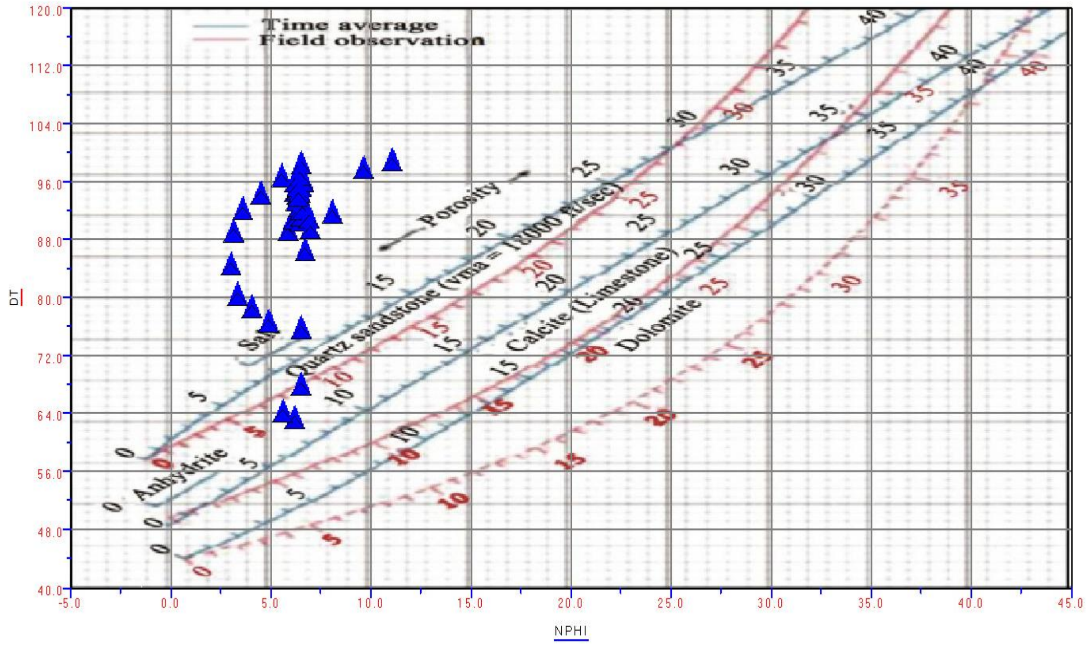

Figure 3.13. Cross plot between NPHI and DT for Zone 3 of Sawan-01.

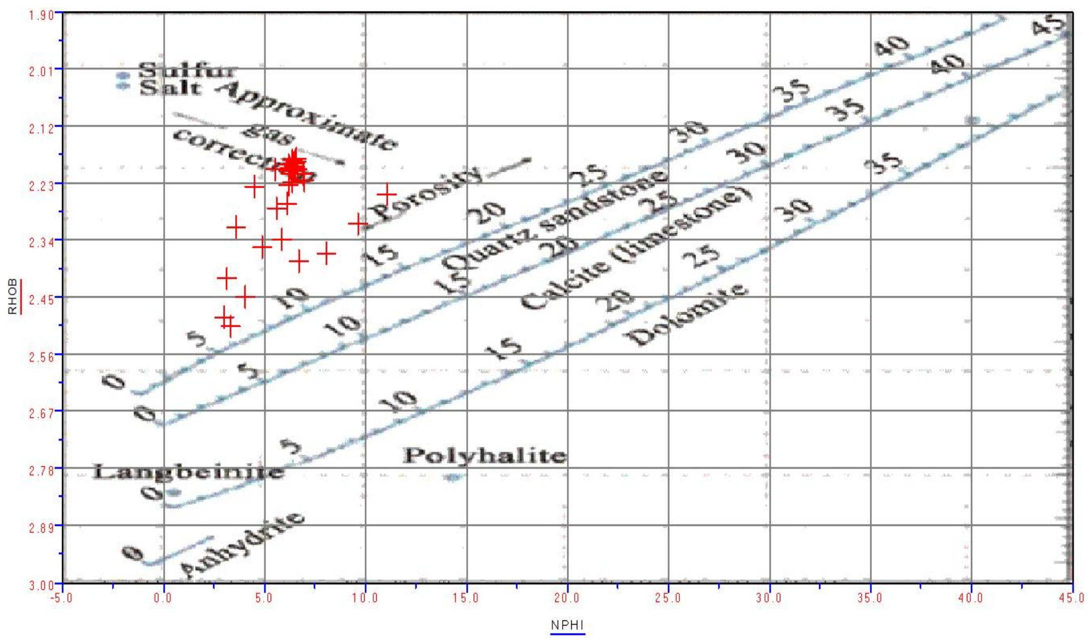

Figure 3.14 Cross plot between NPHI and RHOB for Zone 3 of Sawan-01.

Zone 4

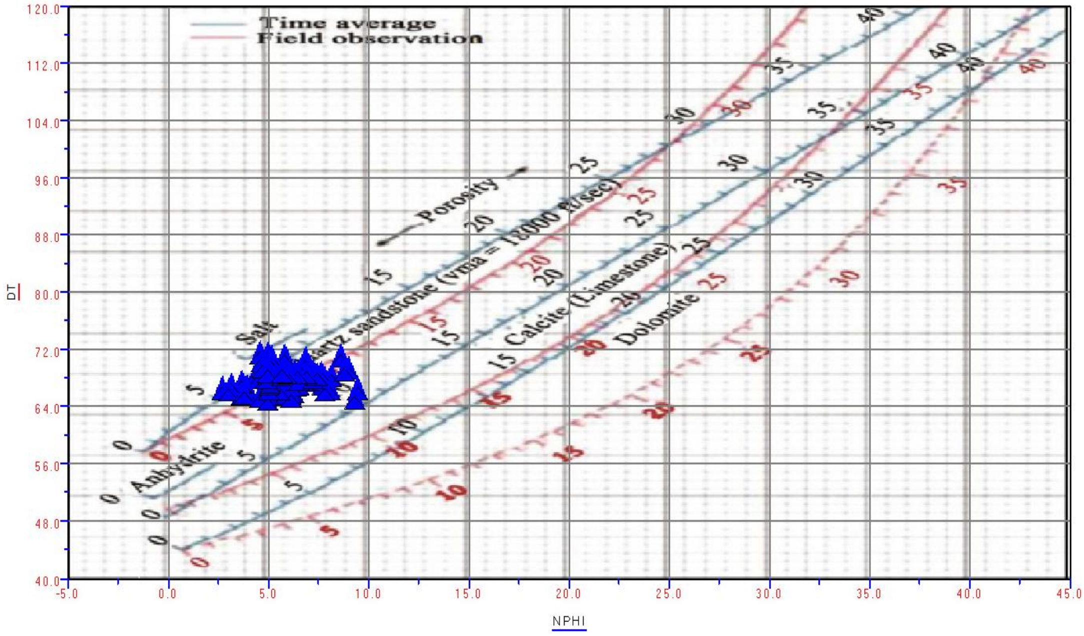

Figure 3.15. Cross plot between NPHI and DT for Zone 4 of Sawan-01.

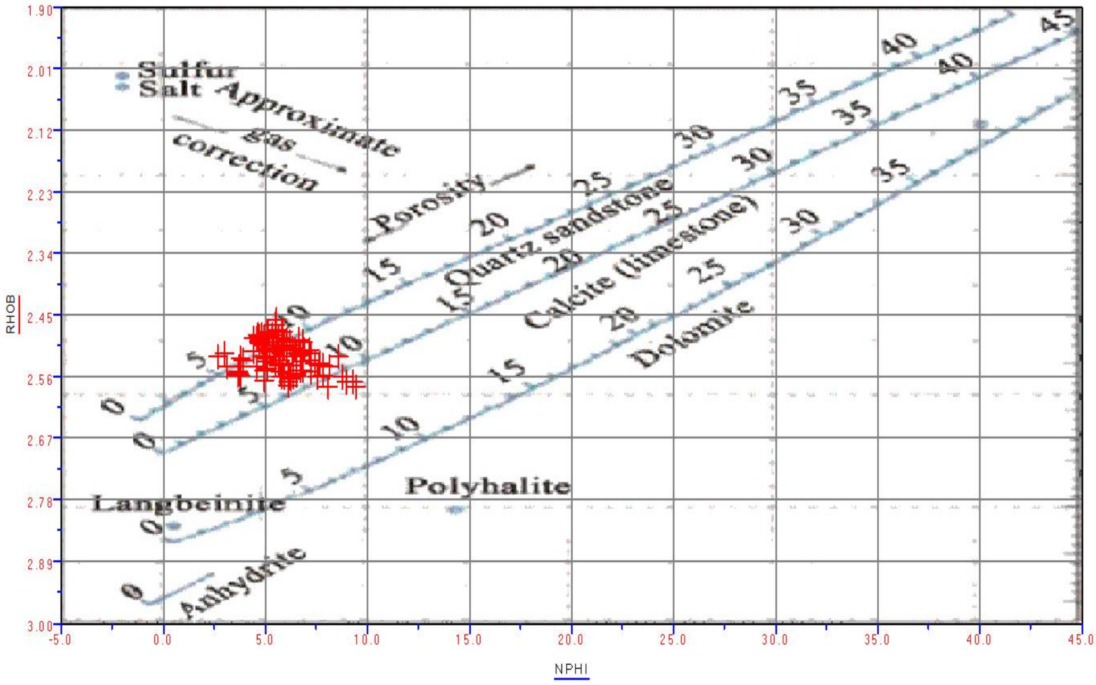

Figure 3.16 Cross plot between NPHI and RHOB for Zone 4 of Sawan-01.

3.10.2 Sawan-02

Zone 1

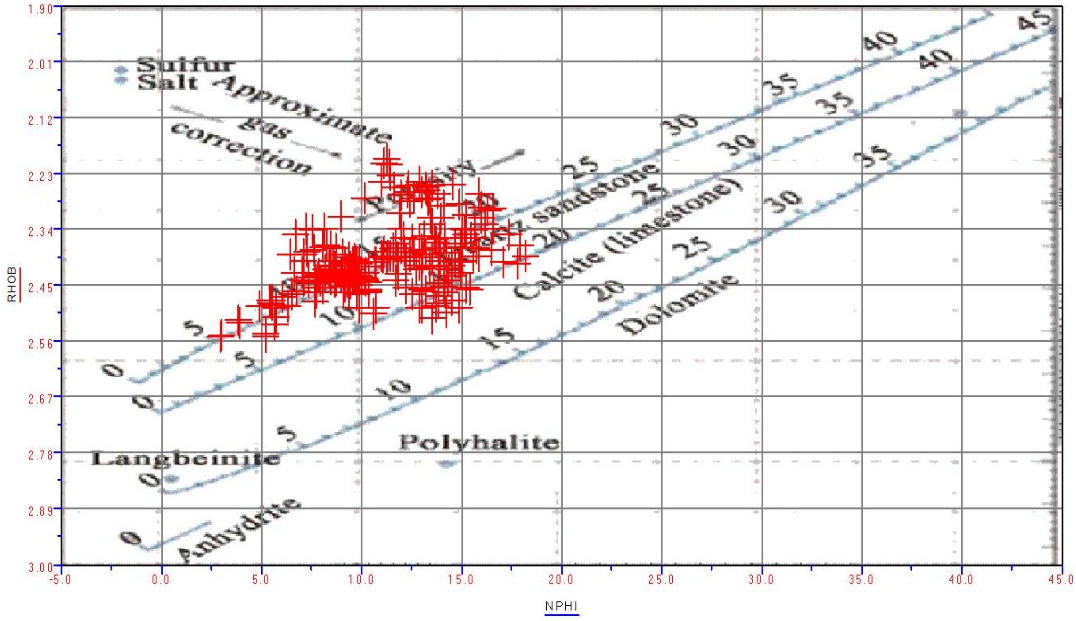

Figure 3.17 Cross plot between NPHI and RHOB for Zone 1 of Sawan-02.

Zone 2

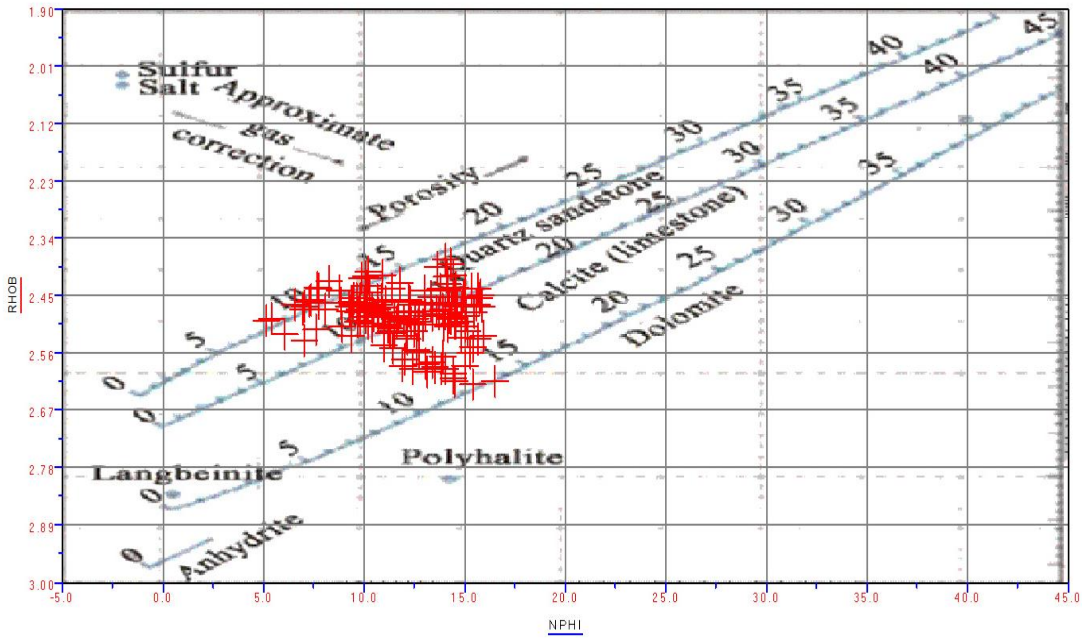

Figure 3.18 Cross plot between NPHI and RHOB for Zone 2 of Sawan-02.

Zone 3

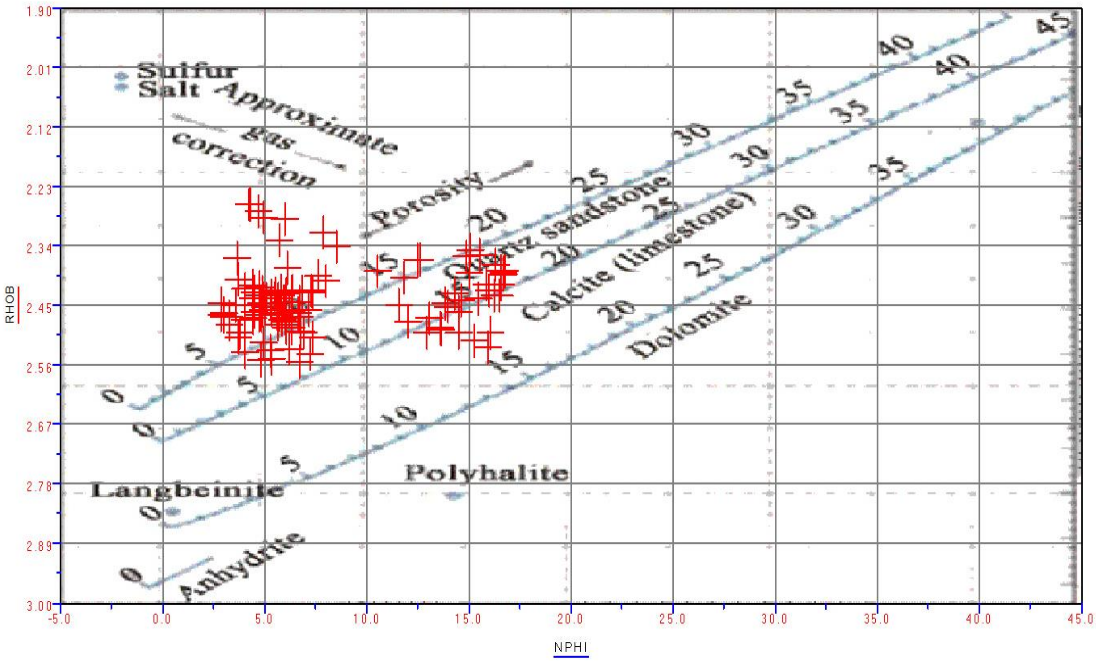

Figure 3.19 Cross plot between NPHI and RHOB for Zone 3 of Sawan-02.

CONCLUSION

Lower Goru acts as a reservoir in Sawan-01 and Sawan-02 wells. Four target reservoir zones have been marked in Sawan-01 and three in Sawan-02. Zone 3 in Sawan-01 and Zone 1 in Sawan-02 wells are showing the least volume of shale and maximum potential for hydrocarbon concentration. The results of PHIN-RHOB and PHIN-DT cross plots confirm the lithology of Lower Goru and sandstone.

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