RESERVOIR AND SOURCE ROCK EVALUATION OF PANJPIR-01 WELL, CENTRAL INDUS BASIN, PAKISTAN

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

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ABSTRACT

This research presents a comprehensive petrophysical analysis of the Panjpir-01 well located in the district Khanewal area. Focused on the Lumshiwal Formation & Samana Suk as a reservoir and the Chichali Formation as an unconventional source. The analysis revealed crucial information regarding the distribution and characteristics of the Lumshiwal, Samana Suk and Chichali formations. Petrophysical analysis of the Lumshiwal and Samana Suk Formations included assessing porosity, shale volume, resistivity of water and hydrocarbon saturation, yielding significant findings on the reservoir potential. Similarly, the unconventional Chichali Formation was thoroughly investigated to understand its hydrocarbon prospects by using Indonesian's equation and DlogR method to highlight effects and have better understanding. The integration of petrophysical data offers a deeper understanding of the hydrocarbon potential of the Panjpir-01 well, contributing to the broader knowledge of hydrocarbon exploration in the region.

TABLE OF CONTENTS

CHAPTER 3

PETROPHYSICAL ANALYSIS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

OGDCL	=	Oil and gas development corporation
m.y	=	Million Year
m	=	Meter
GR log	=	Gamma ray log
Φ	=	Porosity
API	=	American petroleum institute
µs/ft	=	Microsecond per foot
LLD	=	Deep lateral log
LLS	=	Shallow lateral log
Ri	=	Resistivity of transition zone
MSFL	=	Micro spherical focused log
SP	=	Self-Potential
Rw	=	Resistivity of water
Vsh	=	Volume of shale
Sw	=	Saturation of water
GRmax	=	Gamma ray maximum
GRmi	=	Gamma ray minimum
CNL	=	Compensated neutron log
Φe	=	Effective porosity
Φav	=	Average porosity
a	=	Turtuosity factor
Rt	=	True resistivity
Φ2	=	Effective porosity

CHAPTER 1
INTRODUCTION

The study of petrophysics plays a vital part in our understanding of the physical and chemical attributes of hydrocarbons. Petrophysical analysis yields vital information, including the identification of fluid and mineral types, and the evaluation of porosity. This analysis is pivotal for estimating the volumes of both fluids and minerals in different zones of interest, encompassing both affected and pristine regions. Also, rock physics examinations are accepted to assess the impact of factors similar as porosity, mineral composition, and fluid saturation on the elastic properties of subsurface materials.

1.1 Location of Study Area

The study site is situated in the Kabirwala tehsil and Khanewal district, in close proximity to the renowned city of Multan, inside the Punjab region of Pakistan, as depicted in figure 1. The vicinity of the field consists of a level, alluvial plain that is highly suitable for agricultural purposes, particularly for cultivating citrus and mango crops. The district is intersected by numerous canals, which supply water to the neighbouring fields. This greatly enhances the fertility of the ground. Nevertheless, the land in proximity to the Chenab river is typically inundated during the monsoon period.

1.2 Objective of Research

The objective of the study is to assess the hydrocarbon capacity by identifying the specific area of interest and analyzing the petrophysical properties of the reservoir and source potential in the Panjpir-01 well through the evaluation of wireline logs.

1. Evaluation of the reservoir potential of Lumshiwal and Samana Suk formation in Panjpir area.
2. Evaluation of source rock potential of Chichali Formaiton using Passey method using sonic and resistivity logs.

1.3 Data Acquired for Interpretation

Well logs data which has been acquired for the petrophysical interpretation of Panjpir-1 well including:

1. Resistivity Logs
2. Density Log
3. Neutron Porosity Log
4. Gamma Ray log
5. Sonic log
6. Caliper log

1.4 Methodology

1.4.1 For Reservoir

1. Lithology Identification
2. Porosity Estimation
3. Fluid Saturation

1.4.2 For Source

1. Identification of Prospect Zones
2. TOC Estimation

1.5 Exploration History

Panjpir gas field was discovered by OGDCL in 1985 and is located approximately 100 km northeast of Multan city in the Khanewal and Jhang districts of Punjab province (Fig 1.1). past low permeability gas reservoirs were given less weightage as compared to gas reservoirs with high or moderate permeability. The reason behind this was low well deliverability and low flowing well head pressures of former reservoirs. The producing horizon in this field is Samana Suk Formation of Jurassic age deposited under carbonate dominated depositional environment.

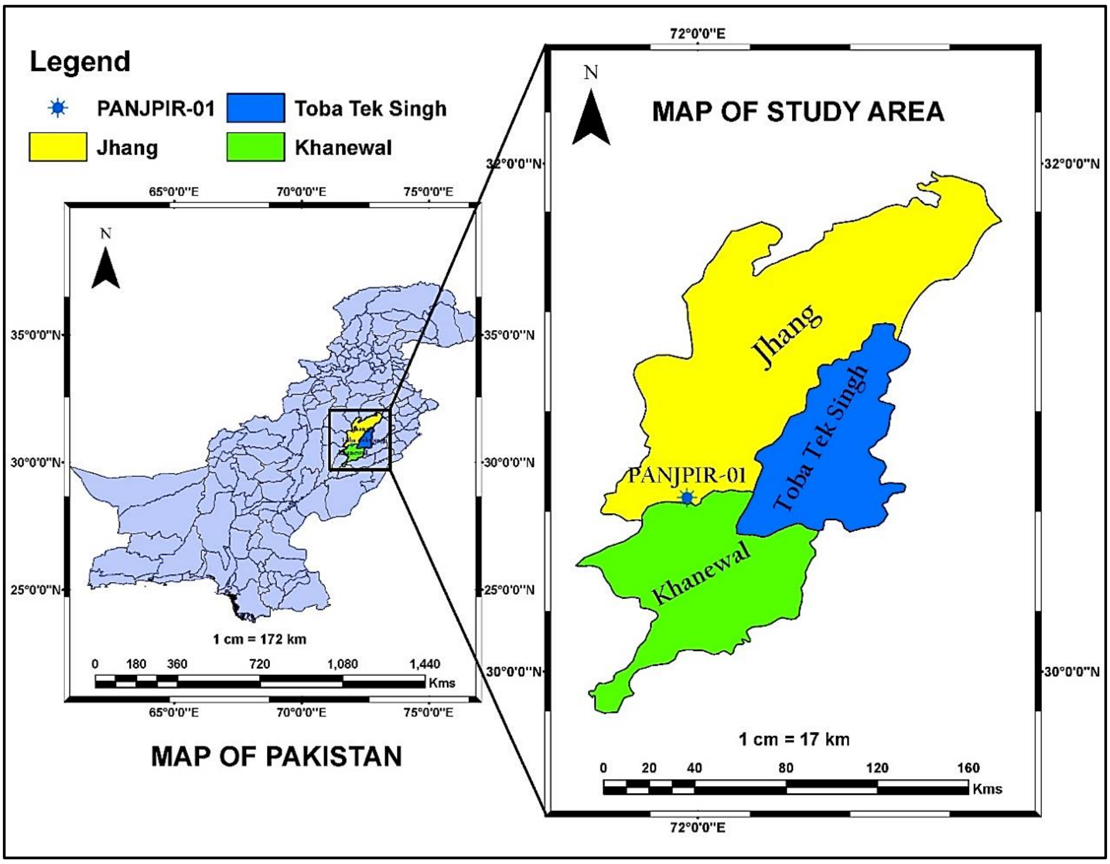

Figure 1.1. Study Area Map of Panjpir-01 Well in Central Indus Basin.

CHAPTER 2
GEOLOGY AND TECTONICS

2.1 Regional Tectonics Settings

The central Indus basin is geographically divided from the upper Indus basin by the Sargodha High and Pezu uplift in the northern region. The region is delimited by the Indian shield to the east and the marginal zone of the Indian plate to the west. In the southern region, the Sukker Rift is composed of the Jacobabad and Mari Kandhkot Highs, which act as barriers separating it from the Lower southern Indus Basin. The Chaman Transform Fault Zone is experiencing oblique subduction in the west, resulting in a wide range of formations with extraordinary size.

The Sulaiman range is characterised by blind thrust fronts, indicating that all frontal folds in the fold belt are underlain by these blind thrusts. The structures have an east-west trend that is almost perpendicular to the path of tectonic motion. In the Punjab platform area, the dips are gradual, and there are many anticlines with salt cores located to the east of the Indus River. The Karampur well (Shell, 1958) contains shallow marine rocks from the Cambrian era. The basin lacks a significant presence of Precambrian rocks, however Precambrian Shield rocks can be observed near the Indian Plate's periphery (Kadri, 1995).

The tectonic activity in the middle or central Indus basin is quite minimal. The basin consists of duplex formations that are defined by prominent anticlines and domes in the passive roof of the Sulaiman fold belt. Moving eastward, these structures are followed by gently dipping strata of the Punjab monocline. The recent identification of oil reserves on a large scale in the Northern Rajasthan Basin of India has led to the assessment of the Punjab Platform. The Punjab Platform is located in the eastern part of the Central Indus Basin, as stated by Kadri in 1995. To the east, the Punjab platform connects with the Bikaner-Nagaur Basin over the Indian border. Geologically, it is a wide, gently sloping monocline that extends towards the Sulaiman depression.

The Pre-Cretaceous orogenic motions caused an eastward tilt of the area throughout the Paleozoic era, which then shifted to a westward tilt from the Mesozoic era onwards. Due to its significant distance from the collision zone, the area experienced comparatively less impact from tertiary orogenic motions. Consequently, there is a scarcity of tectonic folds and faults, with the prevailing structural characteristics being either ancient elevated landforms or salt-induced upwardly curved folds (Raza et al., 1989).

2.2 Structural pattern of Punjab Platform

The Punjab platform is located in the eastern part of the middle Indus basin and is characterised by the absence of exposed sedimentary strata on the surface (Figure 2.1). The Punjab platform is a wide monocline that has a gentle inclination towards the Sulaiman Depression (Kadri, 1995). In the Paleozoic era, the region experienced an eastward and westward tilting due to the collision of the Indian and Eurasian Plates, which occurred since the Mesozoic era. This movement was non-orogenic and occurred before the Cretaceous period.

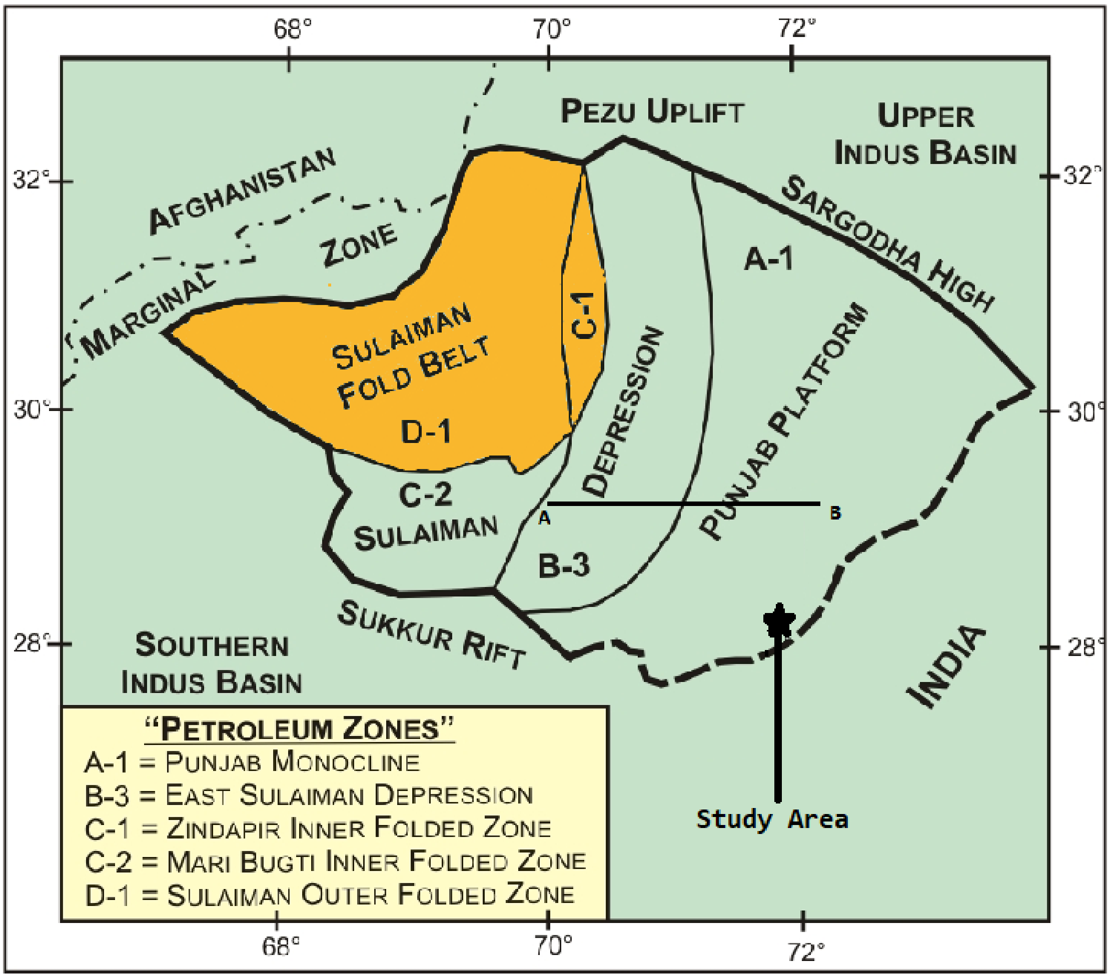

Figure 2.1. Tectonic map showing the location of study area (Ali, 2010; Ahmad etal.,2013).

2.3 Tectonics of Punjab Platform

The Punjab Platform in Pakistan is less impacted by tectonic activity compared to other parts of the Indus basin. It is characterized by a wide, gently sloping monocline that extends towards the Sulaiman depression. The Punjab platform stretches towards the east into India and is referred to as the Bikaner-Nagaur Basin. The Bikaner-Nagaur Basin is located on the western side of the Indian platform and is the southwestern boundary of a large sedimentary basin that extended from the Aravalli range to the Salt Range (Indus Basin) during the Paleozoic era.

The basin in question is located in the northwest and is a component of the Indus Basin. This basin is separate from the Aravalli Range and consists of many horst and graben blocks. The horse and graben structures generally have a north-south orientation, while the shelf-slope-basin formations extend from east to west. The tectonic history of the Indian Plate mostly revolves around two significant events. Mesozoic rifting of Gondwanaland and Cretaceous-Tertiary Indian Plate collision with Eurasian Plate.

These two events have been the primary factors contributing to the development of the petroleum industry in Pakistan, and assessing their impact is crucial for understanding the country's petroleum system. The Punjab platform, located far from the site of significant tectonic events, was tectonically stable over most of the Mesozoic to Cenozoic era, indicating a period of peace in the area. Nevertheless, small-scale tectonic activities seem to have altered the pre-existing formations.

2.4 Geology of Punjab platform

The drilling results at the Punjab platform indicate the presence of Paleozoic to Cenozoic rocks above the basement. The Punjab platform in the subsurface consists of Mesozoic, Paleozoic, and Neogene sediments, as well as Paleogene sediments covered by Neogene River deposits. The area is distinguished by regional unconformities.

The sedimentary rocks of the Punjab platform are not visible on the surface due to being buried by extensive deposits of alluvium, which consist of layers of clay, silt, and sand. The Punjab platform has been the focus of petroleum explorations, with over twenty onshore exploration wells drilled in recent years. This region is also being focused on because of a recent finding along the boundary with neighboring India.

The Punjab region is characterised d by unconsolidated Quaternary sediments, which can reach a maximum thickness of approximately 500 meters. They form an extensive aquifer. The deposits that occurred after the Eocene period are mostly related to rivers and deltas, as stated by Kazmi and Jan in 1997.

The reservoir rocks in India are part of the Infra Cambrian sedimentary sequence, specifically the Marwar super group. This group is correlated with the group found in the Kirana complex of Pakistan basement. During the Infra-cambrian period, there was a marine transgression that led to the deposition of shallow marine siliciclastic on the shallow shelf. This deposition was caused by the influx of fluvial activity. Carbonates were deposited in a shallow and extensive shelf. Evaporites, such as large deposits of rock salt, were formed during periods of periodic sea level change. The thickness of Infra-cambrian sediments has increased on both sides of foundation ridges that stretch from India to Pakistan.

2.5 Generalized stratigraphy of Punjab platform

The Sulaiman fold belt contains exposed early Pliocene continental sandstone, conglomerates, and clays. However, in the northern region, there are rocks from the Cretaceous period, including the Sembar, Goru, Parh, Mughal Kot, and Pab Formations. The Pre-Cambrian salt range in the Punjab is only accessed by wells drilled in an easterly direction. During the Permian period, sedimentary rocks consisting of continental clastics and a mixture of marine clastics and carbonates were deposited in the eastern region, along the coastline that existed during that time. During the Neogene period, the regression resulted in the accumulation of sediments from continental rivers and alluvial fans (Kadri, 1995).

The subsurface geological data reveals that the Precambrian basement rocks consist of granites, meta sediments devoid of fossils, and meta volcanics. The earliest rocks found in the Punjab platform after drilling are the Infra-Cambrian Salt Range Formation. Prior to the formation of the Himalayas, tectonic movements occurred, leading to long-lasting upward movements of the Earth's crust and subsequent lowering of sea levels, resulting in the formation of unconformities. Consequently, the southern part of this monocline is anticipated to contain many salt cored anticline formations, as indicated by Kadri (1995) and Humayun et al. (1991). The Sargodha, Kirana, Shahkot, and Sangla hill area only has isolated occurrences of Precambrian shield rocks (Shabih et al., 2005). The stratigraphic sequence of the area is given below.

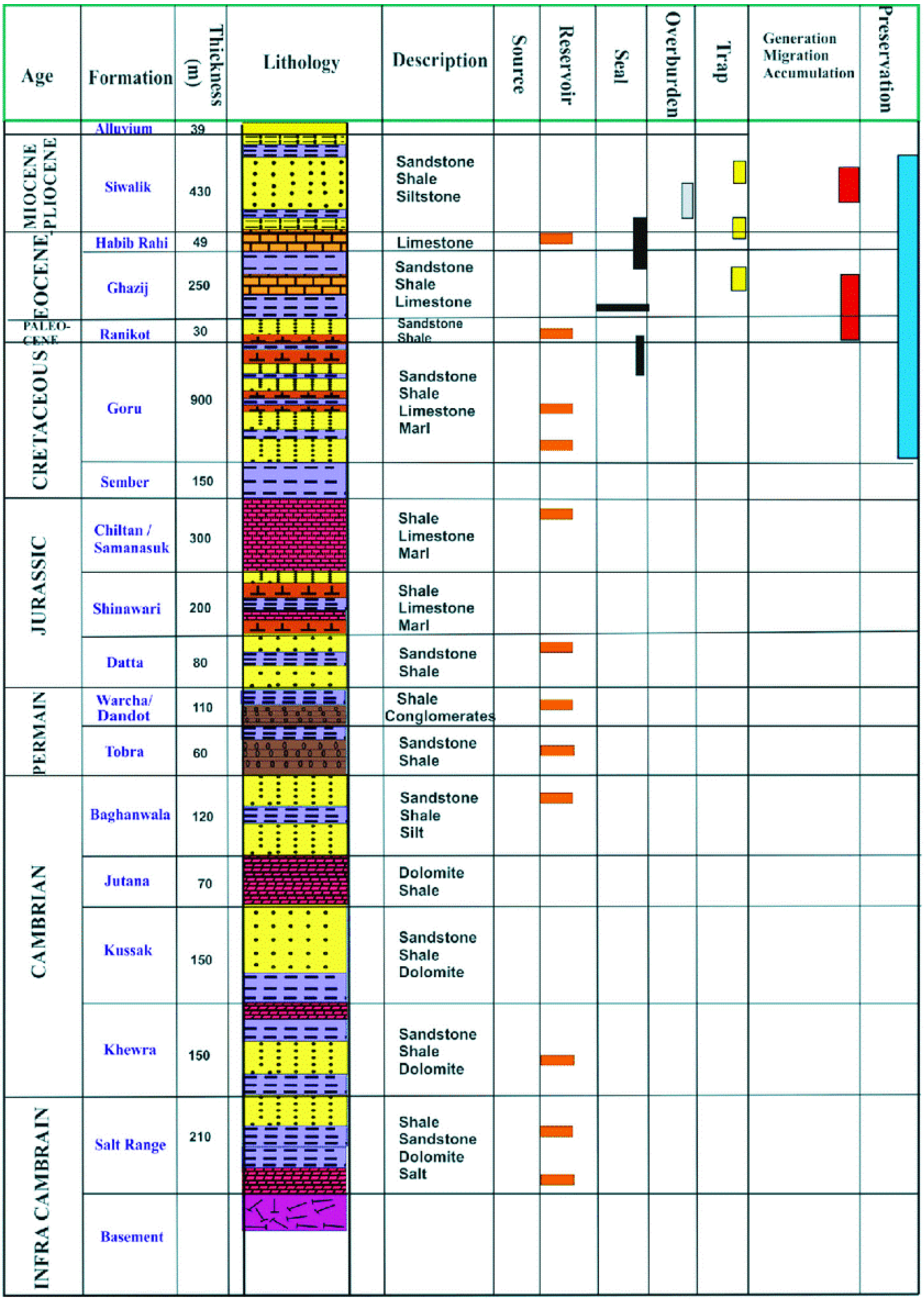

Figure 2.2. Generalized stratigraphy column of the Middle Indus Basin (Azeem et al., 2016).

2.5.1 Tredian Formation

This Formation consists of two components. The lower layer is composed of sandstone and shale and is part of the Landa formation. The upper layer is composed of the Khatkiara member, a substantial and thickly layered white sandstone that transitions into the Kingriali Formation above it. The age corresponds to the Middle Triassic period.

2.5.2 Kingriali Formation

The specific location where it was first discovered is the Kingriali peak in the Kishore range. The thickness of this specimen is measured to be between 76 and 106 meters. The lithology of the formation consists of dolomite and dolomitic limestone, ranging in thickness from thin to thick. Additionally, the top section of the formation contains dolomitic shale and marl. The fossils found include brachiopods, bivalves, and crinoids. The age of the object is classified as the late Triassic. The deposition of this material occurred in a shallow maritime environment.

2.5.2 Datta Formation

The specific location where it was first discovered is Data nala in Surghar range, and its thickness is measured at 212 meters. The lithology of the Formation consists of sandstone, siltstone, shale, and mudstone, with sporadically dispersed glass sand and fine clay layers. It lacks any fossils. The age of the object is classified as early Jurassic. The deposition of this substance occurred in a deltaic environment.

2.5.3 Shinawari Formation

The formation comprises grey, thinly to moderately bedded sandy limestone and calcareous sandstone, with occasional shale layers. The Shinawari Formation is believed to have been formed in a shallow marine environment with a mixture of clastic and carbonate sediments The Shinawari Formation has transitional interfaces with the underlying Datta Formation and the topping Samana Suk Formation. Fossils such as ammonites, bivalves, brachiopods, and others that suggest an almost Jurassic era have been gathered from the bottom section of the formation. However, it is possible that the upper section could also belong to the Middle Jurassic period (Fatmi and Cheema, 1972).

2.5.4 Samana Suk Formation

The formal designation for this formation is Samana Suk , as established by Davies in 1930. The Formation consists of grey to dark grey limestone, which is medium to thick bedded. It also contains smaller amounts of marl and calcareous shale layers. The Formation's age is Jurassic. The lower contact of the formation is characterised by a transitional relationship with the Shinawri Formation, while the upper contact with the Chichali Formation is disconformable. The Formation varies in thickness, measuring 129 to 136 metres in Baroch nala and 242 meters in the Shaikh Budin Hill.

2.5.6 Chichali Formation

The Chichali Formation is a geological formation in Pakistan that dates back to the Early to Middle Cretaceous period. Plesiosaur remains have been excavated from the geological layers in which they are found. The formation consists of laterites, glauconitic sandstones, and carbonaceous green shales that were formed on an outside ramp in the Nizampur Basin.

2.5.7 Lumshiwal Formation

The type locality of this geological formation is located one km north of Lumshiwal Nala in the Samana Suk mountains. The thickness of the formation ranges from 80 to 120 metre's. The lithology of the formation consists of sandstone, siltstone, and gluconitic shale. The fossils found include brachiopods, bivalves, ammonoids, and other specimens. The age of the object is classified as early Jurassic. The deposition of this substance occurred in a deltaic environment.

2.5.8 Ranikot Formation

The Ranikot Formation, which dates back to the Early Paleocene period, consists primarily of grey limestone. The top section also contains some brown sandstone and shale, while the bottom section is characterised d by sandstone with shale and limestone interbeds. The upper boundary of the rock layer is in agreement with the Laki Formation, whereas the lower boundary is not in agreement with the Khadro Formation. The fauna of this area consists of gastropods, bivalves, forams, corals, and echinoids. The deposition environment is characterised sed as a shallow maritime setting. The Ranikot Formation is considered to be equivalent to the Khadro Formation, as stated by Vredenburg in 1908.

2.5.9 Ghazij Formation

The Ghazij Formation, which dates back to the Early Eocene period, primarily comprises shale with smaller amounts of claystone, sandstone, conglomerates, and alabaster. Additionally, there are coal seams present within this formation. The Ghazij Formation has a thickness of 590 metre's and was deposited in a deep marine environment. Both of its contacts are compliant. The upper boundary of the formation with the Kirthar Formation and the lower boundary with the Laki Formation can both be verified. The thickness varies between 160 and 300 meters. Fossilised remains of Foraminifera, Bivalves, Gastropods, Echinoids, and Algae are present. The Ghazij Formation is considered to be equivalent to the Laki Formation, as stated by Vredenburg in 1908.

2.5.10 Nammal Formation

The Nammal Formation, which dates back to the Ypresian era, is extensively visible across the Salt Range. Analysed in depth were the sedimentological and palaeontological aspects of the Nammal Formation, utilising six significant measured sections in the Salt Range. The formation is mostly formed of alternating layers of nodular limestone, marl, and shale. The Nammal Formation is mostly composed of wackestone, packstone, wackestone to packstone, dolomitic limestone, and grainstone facies. These facies are found in a fine-grained bioclastic matrix that contains several larger benthic foraminifera grains.

2.5.11 Chinji Formation

The Chinji Formation in the Potwar Plateau yields numerous prominent Siwalik fossils from widely recognised ed layers (Colbert 1935). According to our research (Barry et al. 1995), the Chinji Formation is mainly made up of reddish mudstones. In the middle section of this formation, there is a high concentration of fossils, but as we move towards the upper part, the number of fossils decreases.

2.5.12 Nagri Formation

The Nagri Formation, which is the focus of this investigation, is located in the northeastern region of the Kashmir basin in Pakistan, spanning an area of approximately 250 square kilometres. The Nagri Formation consists of alternating layers of sandstone, claystone, and/or mudstone. These molasse deposits were created during the Himalayan orogeny and are from the early Pliocene period. The Nagri Formation, which is the focus of this research, is located in the northeastern region of the Kashmir basin in Pakistan, spanning an area of approximately 250 square kilometres. The Nagri Formation consists of alternating layers of sandstone, claystone, and/or mudstone. The molasse deposits were created during the Himalayan orogeny and date back to the early Pliocene period.

2.6 Petroleum Geology of the Area

2.6.1 Hydrocarbon Potential

Significant oil and gas reserves have been found in the Infracambrian deposits of the Siberian platform and Oman. This highlights the appropriateness of conducting further hydrocarbon exploration in the Infra-cambrian of the Punjab platform.The region we are studying is situated in the Central Indus Basin, which is associated with the Bikaner-Nagaur basin in India. In this location, there are exposed Infracambrian reservoir rocks, specifically the jodhpur sandstone and Bilara dolomite, located to the west of the Aravalli Range. The geological formations in question stretch northward and northwestward into the Salt Range, encompassing the Kirana area (Sargodha Hills). They have been identified in the Bijnot-1 well in Pakistan and the Baghanwala-1 well in India. Nevertheless, the exact presence and distribution of these reservoir rocks in the subsurface of the Punjab Platform (located in the center Indus basin) is currently not well comprehended or defined. Hence, we may establish a correlation between the infra-Cambrian strata on the Punjab platform and the Bikaner-Nagaur Basin of India.

2.6.3 Source rock

The Panjpir field in the southern region offers evidence of a viable petroleum system in the area (Ppisonline, 2011). The Cretaceous shale has been widely regarded as a highly productive source rock by numerous authors.

2.6.4 Reservoir rock

The anticipated reservoir objectives include Lumshiwal Formation's Cretaceous sandstone and the Samana Suk limestone from the Jurassic era, which possesses favourable reservoir properties and is regarded as a promising reservoir.

Table 2.1. Borehole stratigraphy showing the well tops of Panjpir-01 well.

AGE	FORMATION	LITHOLOGY	FORMATION TOPS
PLIOCENE	NAGRI	Sandstone Claystone	ON SURFACE
MIOCENE	CHINJI	Claystone Siltstone	620
EOCENE	SAKESAR	Limestone	1326
	NAMMAL	Shales Limestone	1326.1
	GHAZIJ SUI MEMBER	Shales Sandstone	1360
PALEOCENE	DUNGHAN	Limestone	1521
	RANIKOT	Limestone Shale	1542
CRETACEOUS	LUMSHIWAL	Sandstone	1602
	CHICHALI	Sandstone	1672
	SAMANA SUK	Limestone Shale	1727
JURASSIC	SHINAWARI	Limestone Sandstone	1854
	DATTA	Sandstone Mudstone	1931
TRIASSIC	KINGRIALI	Sandstone Shale	1949
	TREDIIAN	Sandstone	2077

2.6.5 Seal rock

There are rocks with an intraformational seal. The shale found in the Datta Formation and Ranikot shale are effective barriers for the reservoir below (Ppisonline, 2011).

2.6.6 Hydrocarbon Traps

The configuration of the hanging-wall in the central Indus platform basin is influenced by the strain exerted around faults. According to Ppisonline (2011), structures associated with normal faults are the most frequently observed potential traps related to faults.

CHAPTER 3
PETROPHYSICAL ANALYSIS

3.1 Interpretation Workflow

The reservoir potential evaluation of Lumshiwal and Samansuk formations have been performed in the Panjpir area using the wireline log data of Panjpir-01 well. The petrophysical properties computed for the this reservoir evaluation includes the volume of shale, porosities and fluid saturation. Figure 3.1 shows the adapted methodology workflow for the evaluation of petrophysical properties of Lumshiwal and Samansuk formations in Panjpir-01 well.

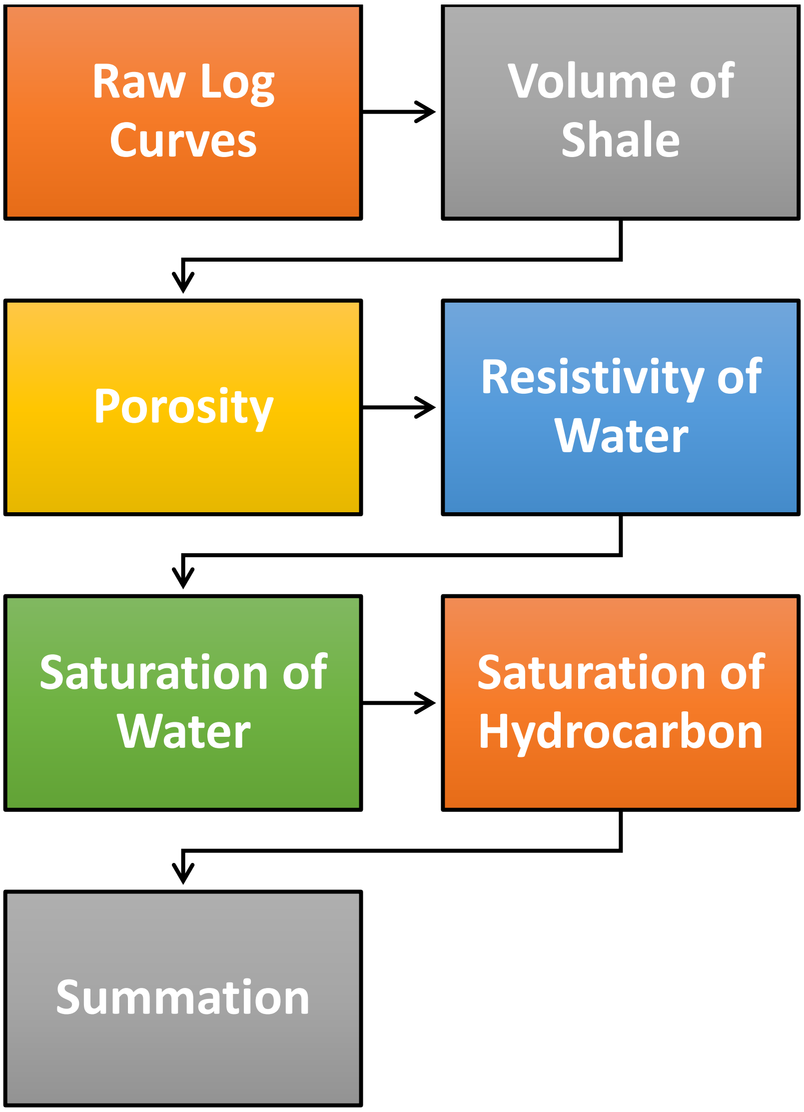

Figure 3.1. Methodology workflow adapted for petrophysical properties.

3.2 Petrophysical Parameters and Interpretation Techniques

3.2.1 Raw log curves

Raw log curves refer to the unprocessed or uninterpreted measurements obtained from well logging tools. These raw log curves provide direct measurements of various physical properties of subsurface formations.

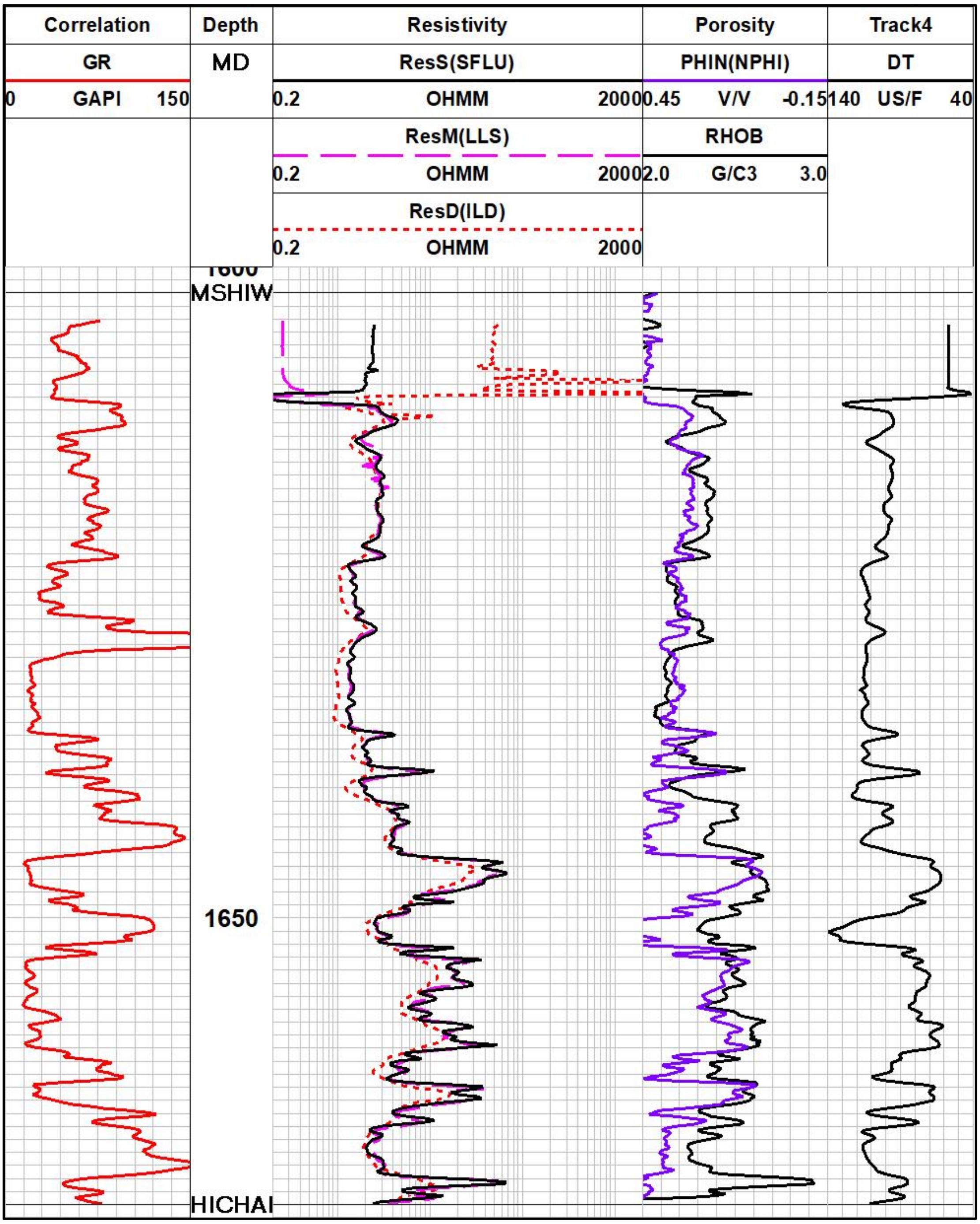

Figure 3.2. Raw Log curve of Lumshiwal Formation as a Reservoir.

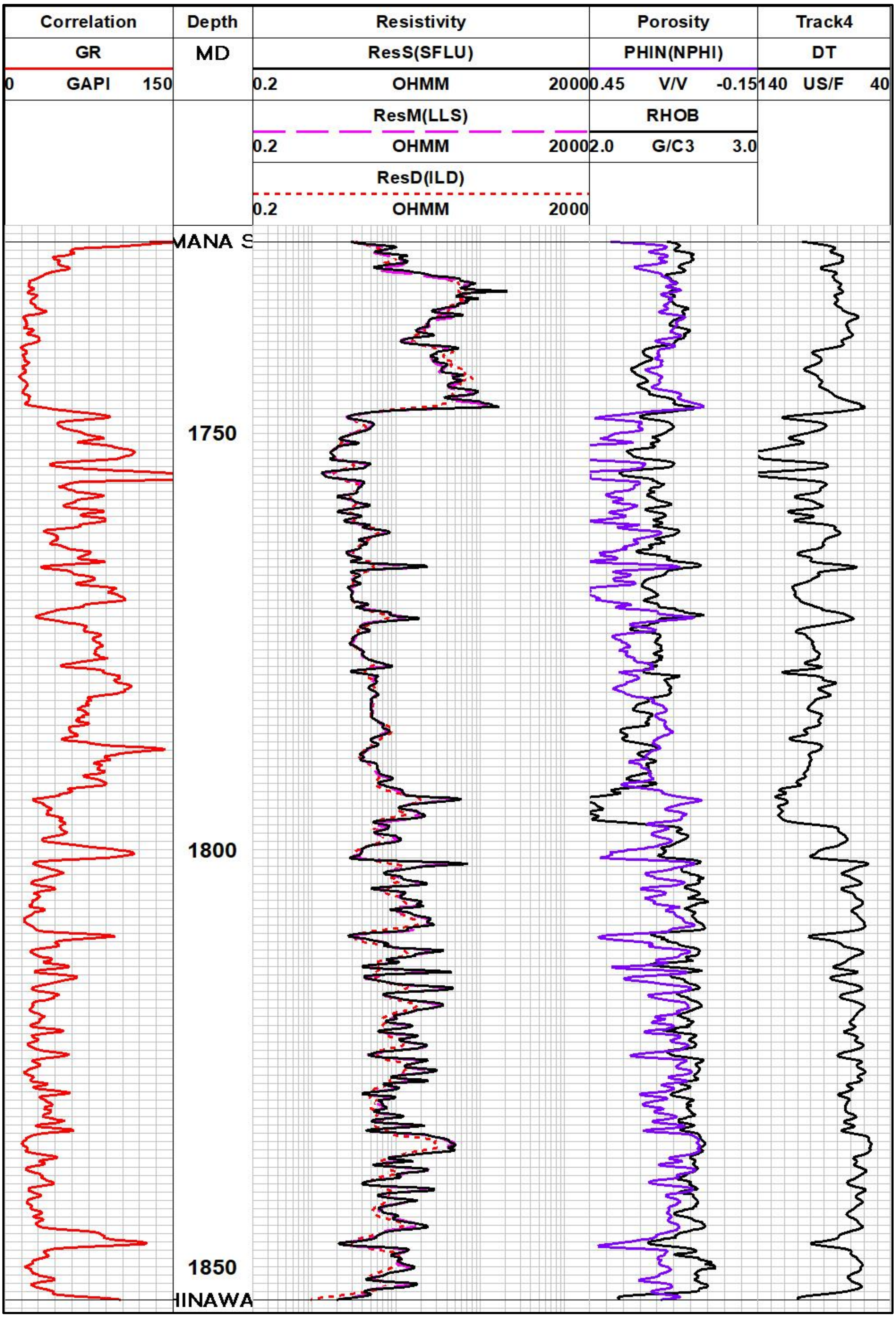

Figure 3.3. Raw Log curve of Samana Suk Formation as a Reservoir.

3.2.2 Gamma ray log

Gamma ray logging is a method of measuring naturally occurring gamma radiation to characterize the rock or sediment in a borehole or drill hole. It is a wireline logging method used in mining, mineral exploration, water-well drilling, for formation evaluation in oil and gas well drilling and for other related purposes. Gamma Ray Log is used for defining the shale beds. Gamma Ray Log is the quantitative indicator of the shale. The measurement of Gamma ray values is expressed in API units, as explained in the book "Introduction to Wireline Log Interpretation" by OGTI.

$$GRn = \frac{GR - GRmin}{GRmax - GRmin}$$

- *GR*n is the normalized gamma ray,
- *GR* is the raw gamma ray log reading,
- *GR*min is the minimum expected gamma ray value for the specific formation, and
- *GR*max is the maximum expected gamma ray value for the specific formation**.**

3.2.3 Neutron log

The neutron instrument primarily detects the presence of hydrogen atoms. If the pore space within the Formation is saturated with liquid, the resulting reaction is mostly a measurement of porosity. The log is often calibrated in units of porosity based on a matrix of limestone or sandstone. Adjustments to the porosity measurements are necessary when the lithology of the formation deviates from the calibration of the tool. The presence of shale and gas has an impact on the porosity measurements, as explained in the book "Introduction to Wireline Log Interpretation" by OGTI

$$\varphi = \frac{\varphi ma - \varphi b}{\varphi ma - \varphi f}$$

- φ is the porosity of the formation
- φ_{ma} is the matrix porosity (the porosity of the rock matrix when it is fully mineral),
- φ_b is the apparent porosity observed from the neutron log, and
- φ_f is the fluid porosity (the porosity of the rock when it is fully filled with fluid).

3.2.4 Density log

The density log provides a continuous record of density variations in the lithologic column extracted from the borehole. Bulk density refers to the total or gross density of a given volume of rock. For porous rocks, the density calculation takes into account both the density of the fluid in the pore spaces and the density of the rock grains (Introduction to Wireline Log Interpretation, OGTI). The measurement of bulk density is expressed in grammes per cubic centimetre (g/cm³). The density tool can differentiate between oil and gas in the pore space based on their distinct densities. the density can be utilised to ascertain V clay and to compute reflection coefficients for synthesising purposes.

$$\rho_b = \left(\frac{\varphi}{\varphi ma}\right) * \rho_{ma} + \left(\frac{1-\varphi}{\varphi n}\right) * \rho_{fl}$$

- ρb is the bulk density of the formation,
- ϕ is the porosity of the formation,
- ϕma is the matrix porosity (porosity when the formation is fully mineral),
- ρma is the matrix density (density of the mineral matrix),
- ϕfl is the fluid porosity (porosity when the formation is fully filled with fluid),
- $p$fl is the fluid density (density of the formation fluid).

3.2.5 Resistivity Measurement

The resistivity of the formation is the primary indicator of hydrocarbons in log evaluation, so the accurate estimation of resistivity has been prioritised . The resistivity of a formation is contingent upon the quantity of water present and the geometric structure of its pores (Introduction to Wireline Log Interpretation, OGTI).

The resistivity tools employed for this objective include:

- Deep Resistivity Tool (measures Rt, in undisturbed zone).
- Medium/Shallow Resistivity Tool (measures Ri, transition zone).
- Micro Resistivity Tool (measures Rxo, flushed zone).

3.2.5.1 Later log deep (LLD)

Laterolog tools are generally used for High resistivity Formation and Saline muds. Later logs utilise concentrating currents to precisely control the direction of the measured current. This current is directed through the mud and the invaded zone, ultimately reaching the uninvaded Formation. They mitigate the impacts of the borehole adjacent formations and slender layers, however they are still influenced by the diameter of the hole, the resistivity of the drilling mud, and extremely thin formations with significant resistivity differences across layers. The LLD is a tool used to quantify the resistivity (Rt) in an undisturbed zone (Introduction to Wireline Log Interpretation, OGTI).

3.2.5.2 Laterolog shallow (LLS)

The dual Laterolog (DLL) comprises two sophisticated laterolog devices that utilise the same electrodes on the principal sonde. One laterolog is employed to conduct a thorough examination of the undisturbed zone (Rt), while the other is utilised to investigate the transition zone (Ri) at shallower depths (Introduction to Wireline Log Interpretation, OGTI).

3.2.5.3 Microspherically Focused Log (MSFL)

The Microspherically Focused Tool (MSFL) is an optional secondary sonde that is used to evaluate the resistivity of the flushed zone. It also allows for the correction of invasion in the deep laterolog. The tools can also record Gamma Ray, SP, and Calliper curves. (Introduction to Wireline Log Interpretation, OGTI).

3.2.6 Volume of Shale

The resistivity of the Formation is used to quantify the volume of clays present in the rock's lithology. The conductivity of clays often increases as the current flows through their layered structure, allowing them to locate and conduct water and ions.

$$\mathbf{V_{Shale}} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}}$$

Where:

- GR_{log} is the gamma ray log value at a specific depth.
- GR_{min} and GR_{max} are the minimum and maximum values of the gamma ray log curve, respectively.

3.2.7 Porosity Calculation

The porosity of a rock determines its capacity to hold fluid.

3.2.7.1 Density Porosity (PHID)

Density porosity is derived from density log readings and is a critical measure of a rock's porosity. It is calculated using the formula:

$$\varphi_D = \frac{\rho_m - \rho_b}{\rho_m - \rho_f}$$

Where:

- ρf is the fluid density.
- ρm is the matrix density.
- ρlog is the log density.
- φd is the density

3.2.7.2 Neutron Porosity (PHIN)

Neutron porosity is directly measured using neutron logs and is a key indicator of a formation's porosity. It is particularly useful for identifying the presence of fluids within the rock matrix.

3.2.7.3 Average Porosity (PHIA)

Average porosity is given by:

$$PHIA = \left(\frac{PHID + PHIN}{2}\right)$$

PHID and PHIN are density porosity and neutron porosity respectively.

3.2.7.4 Effective Porosity (PHIE)

The pores that can release liquid as the pressure is released in their surroundings are a measure of effective porosity.

$$\varphi_E = \varphi_A * (1 - V_{Shale})$$

3.2.7.5 Resistivity of Water

The resistivity of water is calculated using the Rwa method.

$$Rwa = Ø^m \times Rt$$

Where;

m = 2

Ø = Porosity

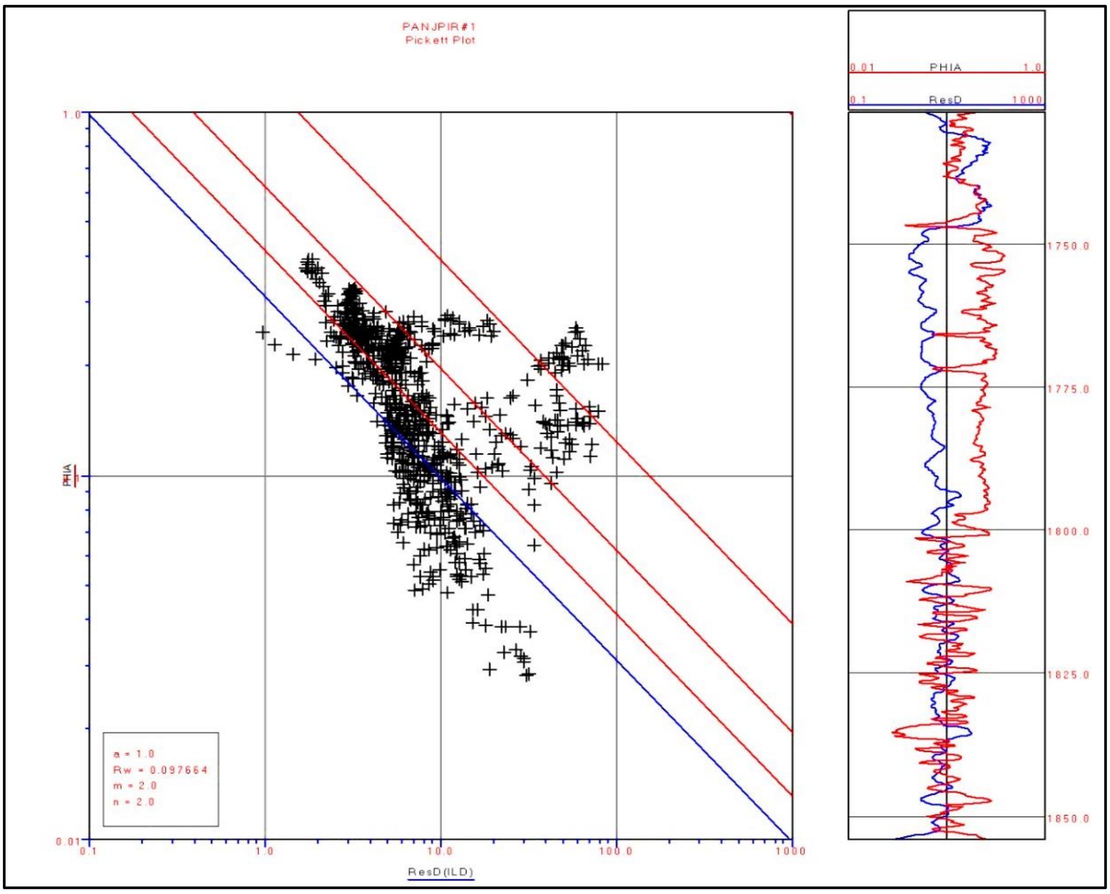

Figure 3.4. Picket Plot of Samana Suk Formation.

3.2.7.6 Water Saturation

The water saturation can be determined by measuring the amount of water that fills the pores in the rock. An electric current is applied to the Formation, and the resistivity of the Formation is used to determine the level of water saturation. If the water saturation level surpasses 50%, the formation often generates water. The Archie equation was employed to compute the saturation of formation water.

The parameters "a, m, n, and R" are examined in order to assess Petrophysical analysis. The Archie equation is formulated using these variables:

$$\mathbf{S_{w_{Indonesian}}} = \left[\frac{\sqrt{\frac{1}{R_t}}}{\left(\frac{V_{sh}^{(1-0.5*V_{sh})}}{\sqrt{R_{sh}}} \right) + \sqrt{\frac{\varphi_E{}^{m}}{a * R_w}}} \right]$$

Where:

S_w is the water saturation.

R_t is the deep resistively

R_w is the resistivity of the Formation water n is the saturation exponent m is the cementation exponent a is the tortuosity factor Ø is Porosity.

3.2.7.7 Saturation of Hydrocarbons

Hydrocarbon saturation can be calculated from the following formula:

$$\mathbf{S_H = 1 - S_W}$$

Where;

S_h= Saturation of hydrocarbon

S_w = Saturation of water

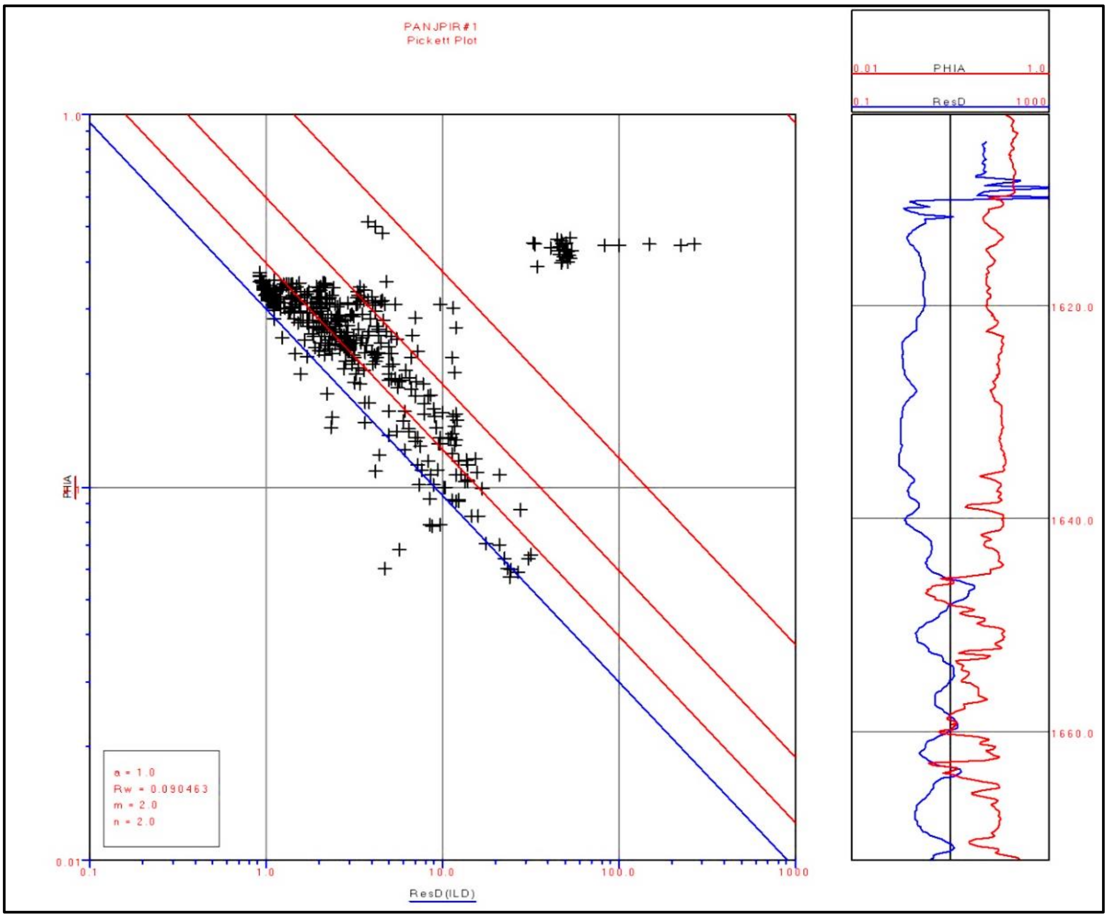

Figure 3.5. Picket Plot of Lumshiwal Formation.

3.3 Petrophysical Interpretation

3.3.1 Interpreted Curves

The petrophysical analysis of well Panjpir-1 involved the determination of key petrophysical characteristics, including the calculation of shale volume, effective porosity, and estimates of water and hydrocarbon saturation.

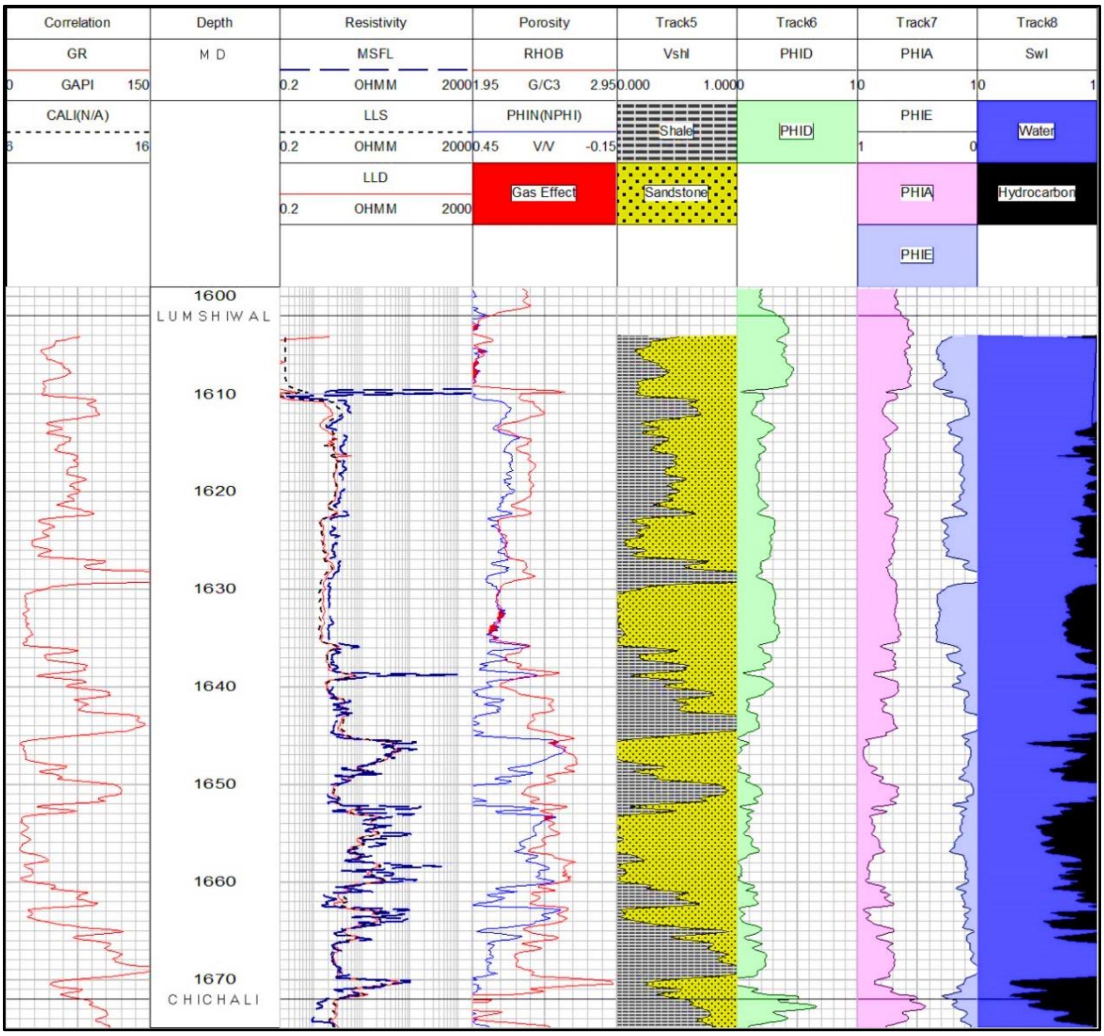

Figure 3.6. Interpreted Results of Lumshiwal Formation.

The entire formation is considered a reservoir because not all criteria for the zone of interest are met. The average shale volume in the entire formation is 0.412, which is crucial for determining porosity where the average porosity is 0.272 and effective porosity is about 0.149. The graphs clearly show the porosity curves along with water saturation and hydrocarbon saturations which is 0.918 and 0.082. The average parameters of the entire formation are presented in the table below.

Table 3.1. Reservoir Interval Zone and parameters of Lumshiwal Formation.

Depth (1602-1672)	Vsh	PHIA	PHIE	Sw	Sh
Average	0.412	0.272	0.149	0.918	0.082
Average %	41.23	27.21	14.89	91.84	8.16

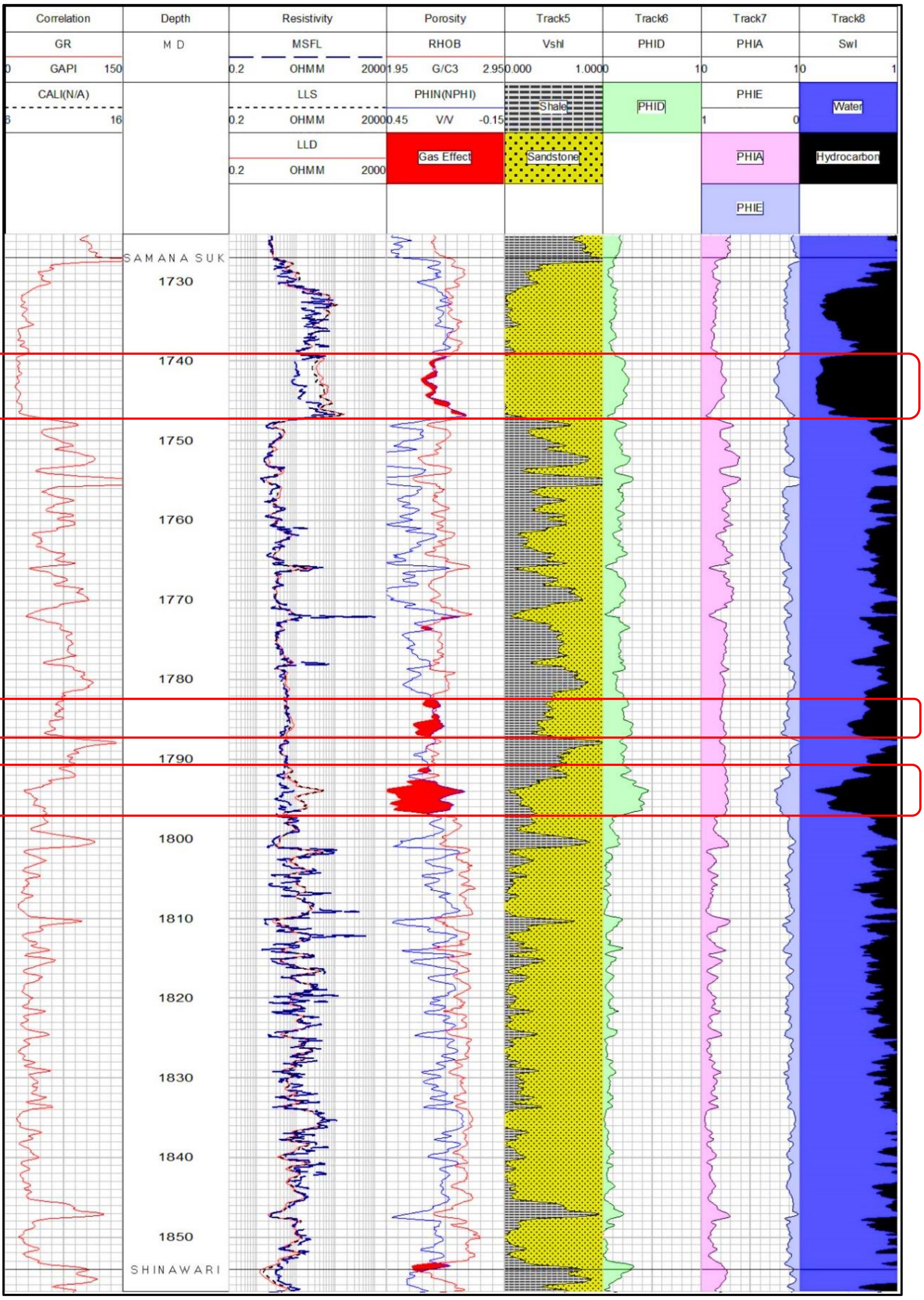

Figure 3.7. Interpreted Results of Samana Suk Formation.

Three zone have been marked in the Samana Suk Formation based on the gamma ray, resistivity and porosity logs. Low gamma ray values are considered as it shows the clean lithology. Shallow and deep resistivity log curves show a separation where deep resistivity log curve values show relatively higher values. Whereas the third criteria based on the porosity curve trend, neutron and density log curves show a cross over having both the curves showing a decreasing trend in hydrocarbon bearing zone. Zone 1 and zone 3 meets all the three criteria however, resistivity separation in zone 2 is minimal. The average shale volume in the entire formation is 0.309, which is crucial for determining porosity where the average porosity is 0.17 and effective porosity is about 0.103. The graphs clearly show the porosity curves along with water saturation and hydrocarbon saturations which is 0.67 and 0.33. The average parameters of the entire formation are presented in the table below.

Table 3.2. Reservoir Interval zone and parameters of Samana Suk Formation.

Zone 1 (1727-1854)	**Vsh**	**PHIA**	**PHIE**	**Sw**	**Sh**
Average	0.018	0.181	0.177	0.317	0.683
Average %	1.8	18.1	17.7	31.7	68.3
Zone 2 (1727-1854)	**Vsh**	**PHIA**	**PHIE**	**Sw**	**Sh**
Average	0.311	0.188	0.103	0.637	0.363
Average %	31.1	18.8	10.3	63.7	36.3
Zone 3 (1727-1854)	Vsh	PHIA	PHIE	Sw	Sh
Average	0.161	0.192	0.153	0.377	0.623
Average %	16.1	19.2	15.3	37.7	62.3

3.4 Source Rock Analysis

The primary aim of the investigation was to assess the Chichali Formation as a source rock. The primary objective is to evaluate the hydrocarbon potential and other characteristics of the Chichali Formation shales using wireline log data, namely the electric, radioactive, and acoustic logs.

The initial parameters for identifying lithological characteristics are the shale volume, density porosity, and other relevant parameters. These data can be used to determine the characteristics of the Chichali Formation. By analysing the total organic carbon content of the formation, one can assess the potential of the Chichali Formation to produce hydrocarbons as a source rock.

3.4.6 Shale Gas Characteristics

Shale is a type of sedimentary rock that possesses porosity, yet its permeability is quite low. This is a result of the pressure, which allows for the storage and maturation of the hydrocarbon. Currently, shale gas is emerging as a significant hydrocarbon resource. Due to its extremely low permeability, shale gas is naturally occurring and can serve as a profitable gas reserve. The shale rock must possess a precise volume and organic matter content, along with specific heat conditions, in order to produce hydrocarbons in a gaseous state. During the assessment of possible shale gas reservoirs, a haim express log of shale gas is observed to be present above the standard shale layer. The 10g ips possess notable characteristics such as exceptionally strong gamma ray activity, bit resist, and low bulk density (Lewis, 2004).

Additionally, the presence of kerogen can enhance the precipitation of uranium, leading to elevated values in the gamma ray log. Due to the low water saturations, the resistivity log typically exhibits a high response, leading to the evacuation of gas.

3.4.7 Chichali Formation as a Shale Gas Reservoir

In order to determine the source rock, a limited study is conducted that includes assessing the total organic carbon content, which serves to confirm the presence of hydrocarbon potential. The Chichali Formation is recognised as a promising reservoir for hydrocarbons, particularly natural gas. Based on the van Reven diagram for the Chichali Formation, the Chichali shales are classified as belonging to the type 3 kerogen zone. Consequently, the Chichali shale serves as the gas reservoir due to its composition of shale rock, thereby classifying it as a shale gas reservoir. The Chichali Formation has a shale gas resource, which has the potential to produce hydrocarbons in the form of gas (Gakkhar et al., 2012).

The Chichali Formation has been identified as having a potential for hydrocarbon production based on earlier literature, which utilised total organic carbon and Rock-Eval analysis. The presence of type 3 kerogen indicates that the hydrocarbon exists in the form of a source gas. Furthermore, the Chichali Formation serves as the unconventional reservoir. The reference is from Gakkhar et al. (2012). Hence, in order to determine the precise proportion of potential, it is necessary to compute the total organic carbon content based on the provided log data of the Panjpir-01.

Table 3.3. Source Quality according to TOC Percentage.

Total Organic Carbon content weight %	Kerogen Quality
<0.5	Very Poor
0.5-1	Poor
1-2	Fair
2-4	Good
4-12	Very Good
>12	Excellent

3.5 Total Organic Carbon

TOC stands for the total organic carbon. It is the measure of the quantity of the hydrocarbons in the specific strata. The TOC is the key factor of finding out the potential of the hydrocarbon in any source rock that can yield enough hydrocarbons to leed the reservoir, which is Lumshiwal Formation in this case. Chichali Formation consisting mainly of shale is acting as the source rock as well as the seal rock to prevent the hydrocarbon migration for the Samana Suk Formation, which is aso a (sevot rock. For the specific quality of the shale as a source rock, the percentage of TOC can help to make an analysis over the hydrocarbon content available.

3.4.1 Shale Identification on the Log Data

The log data indicates that the high gamma log values, along with high resistivity and low density, are indicative of the presence of the Chichali Formation, which primarily consists of shales. In addition to the well log readings, the well tops also indicate the depth of the Chichali Formation shales.

3.4.2 Gamma Ray Log

Source rocks generally exhibit elevated values in gamma ray logs. Spectral gamma ray logging yields data pertaining to the presence of uranium, potassium, and thorium. The presence of uranium can serve as an indicator of total organic carbon (TOC), particularly in rocks that have been deposited under specific conditions such as weathered granitic.

3.4.3 Sonic Log

The presence of organic content in the source rock leads to an increase in transit time, resulting in a decrease in velocity. The presence of organic content also decreases density, which in turn impacts travel time.

3.4.4 Passey's "DlogR" Method

This technique employs acoustic, neutron, and density logs. Shales exhibiting lower resistivity are considered non-source rocks, whereas potential source rocks display a crossover point between sonic and resistivity curves. The calculation of the "DlogR" is as follows:

$$\text{DlogR} = \log\left(\frac{ILD}{ILDBASE}\right) + 0.02 \times (\text{DTC} - \text{DTCbase})$$

Where:

- ILD = Deep resistivity in any zone.
- ILSDbase = Deep resistivity baseline in non-source rock.
- DTC = Compressional sonic log reading in any zone.
- DTCbase = Sonic baseline in non-source rock.
- DlogR = Passey's number from sonic.

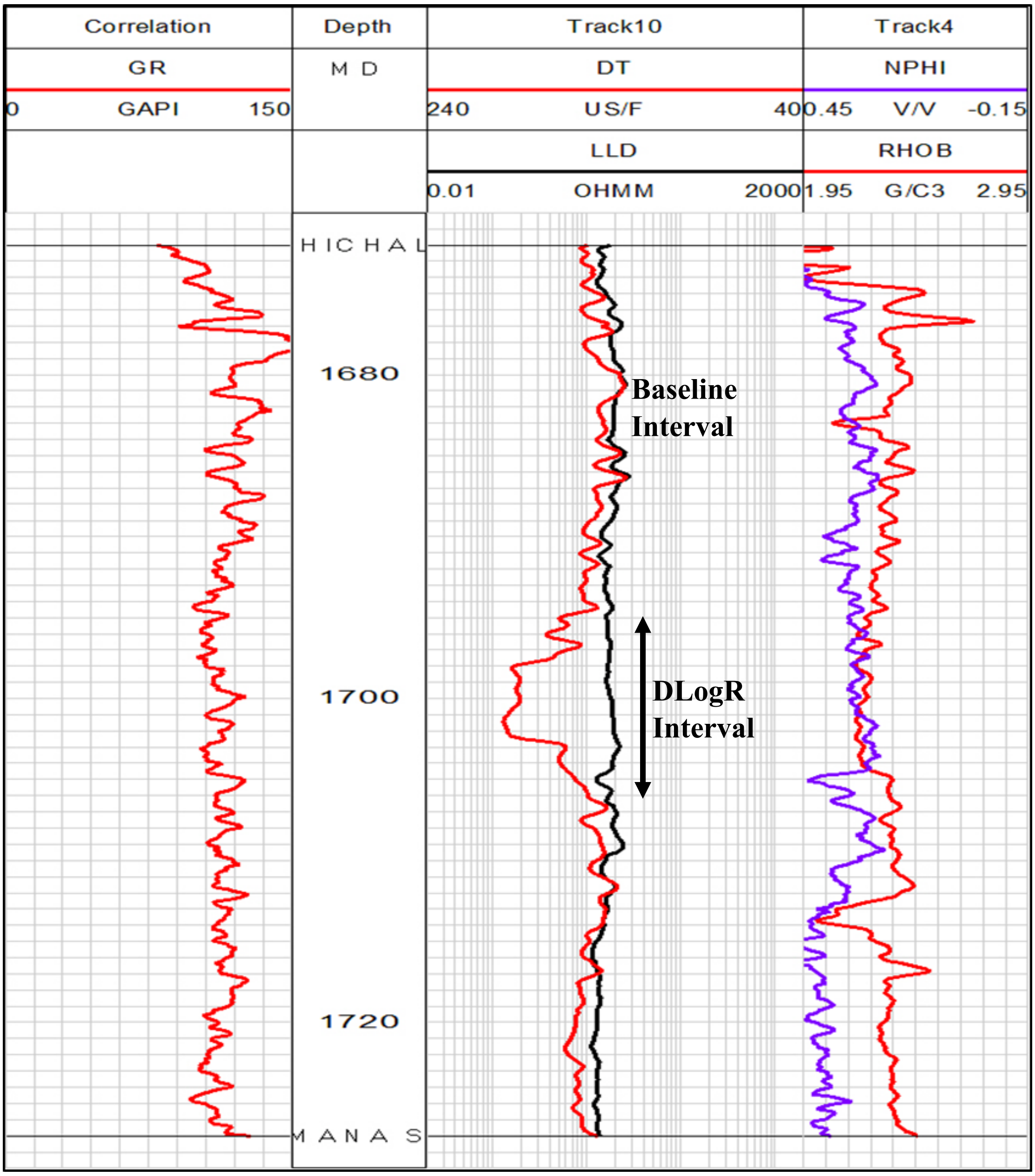

Figure 3.8. Raw log curve of Chichali Formation as source rock.

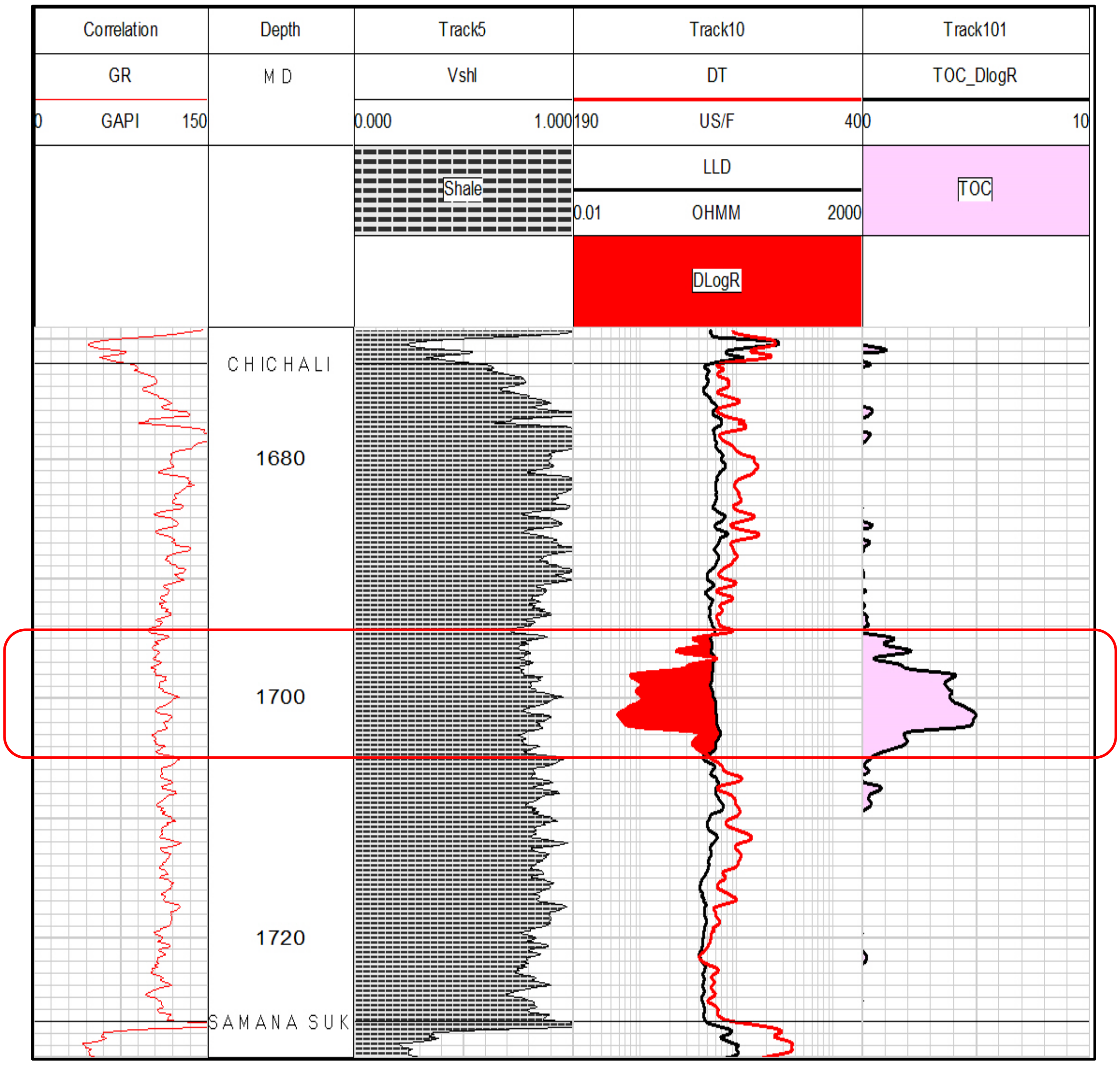

Figure 3.9: TOC Calculations of Chichali Formation by DlogR.

The figure above illustrates the zone where the Total Organic Carbon (TOC) indicates the good source rock potential in the Chichali Formation. Based on the DLogR method, the potential source rock interval is marked from 1694 to 1705 m depth. This interval show a clear separation between sonic and deep resistivity log curve value. The parameters that is in the below table is indicating the minimum and maximum values of the TOC curve which is highlighting a specific TOC zone. These parameters were evaluated across depths ranging from 1694 to 1705 m.

Table 3.4. TOC Evaluation Parameters.

TOC Zone Depth	Minimum Value	Maximum Value	Average
1694-1705	1	5.0484	3.67

CONCLUSIONS

1. Petrophysical analysis of the Lumshiwal Formation revealed that the formation bears good effective porosities and is mostly water wet. However, on the other hand, three zones have been identified in the Samana Suk Formation where zone 1 and zone 3 shows good effective porosities with higher values of hydrocarbons saturation averaging about 68 and 62 % respectively.
2. Source rock potential evaluation for the Chichali Formation shows a potential zone from 1694 to 1705 m having average TOC values of 3.67%. However, the top and lower part of the formation shows very low TOC values.

REFERENCES

Awan, A., 1999.Environment of Deposition and Sedimentological study report.

Doveton, J. H., & Prensky, S. E. (1992). Geological applications of wireline logs: a synopsis of developments and trends. *The Log Analyst*, *33*(3), 286-303.

Exploration performance in sedimentary zones of Pakistan. *Pakistan Journal of Hydrocarbon Research*, *1*(1), 1-7.

Humayon, M., Lillie, R. J., & Lawrence, R. D. (1991). Structural interpretation of the eastern Sulaiman foldbelt and foredeep, Pakistan. *Tectonics*, *10*(2), 299-324.

Kazmi, A. H., & Jan, M. Q. (1997). Geology and tectonics of Pakistan.

Kazmi, H. A., & Abbasi, I. A. (2008). Stratigraphy and Historical Geology of Pakistan: National Centre of Excellence in Geology. *University of Peshawar: Peshawar, Pakistan*, 210.

Mahmud, S. A., & Sheikh, S. A. (2009, November). Reservoir potential of lower nari sandstones (Early Oligocene) in southern Indus basin and Indus offshore. In *Annual Technical Conference (ATC)* (pp. 7-8).

Mujtaba, M. (2006). Petroleum prospects of Punjab Platform. *Middle Indus Basin, Pakistan, through personnel communication*.

Nasir, K. and John G. P., 1989.Introduction to Wireline Log Interpretation, Published by Oil and Gas Training Institute (OGTI).

Raza, H. A., & Ahmed, R. (1990). Hydrocarbon potential of Pakistan. *Journal of Canada Pakistan Cooperation*, *4*(1), 9-27.

Raza, H. A., Ahmed, R., Ali, S. M., Sheikh, A. M., & Shafique, N. A. (1989).

Serra, O. E. (1983). Fundamentals of well-log interpretation.

Sheikh, R. A., Jamil, M. A., McCann, J., & Saqi, M. I. (2003, October). Distribution of Infracambrian reservoirs on Punjab Platform in Central Indus Basin of Pakistan. In *Proc. ATC 2003 Conf. and Oil Show, Islamabad* (pp. 1-17).

Wandrey, C.J., Law, B.E. and Shah, H.A., 2004. Goru/Ghazij Composite Total Petroleum System, Indus and Sulaiman-Kirthar Geologic Provinces, Pakistan and India, U.S Geological Survey Bulletin 2208-C.

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