

**2D STRUCTURAL INTERPRETATION AND
PETROPHYSICAL ANALYSIS OF SAWAN AREA LOWER
INDUS BASIN, PAKISTAN**



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JULY 2026

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

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ABSTRACT

The research purpose is to map out the subsurface structure of an area and investigate the fluid properties through well logs to understand and identify hydrocarbon-prone zones and justify the drilling locations. First, our obtained data was matched with the interpretation datum. Structural analysis is carried out by performing horizon interpretation, fault interpretation, and contour mapping on C-Interval of the Lower Goru Formation. The hydrocarbon bearing zones are interpreted using seismic sections and validated through Petrophysical analysis of all available wells. The study revealed normal faults forming a structure, horst and graben systems like negative flower structure, with fault orientations trending northwest to southeast. The contour map indicates the structural inclination and fault-bounded closures near the well locations. Fault seal analysis further confirmed that these faults provide suitable structural closure for hydrocarbon accumulation. Bright spots were identified at the C Interval of the Lower Goru Formation. Petrophysical analysis on available wells showed hydrocarbon saturation exceeding 55% within the C-Interval of the Lower Goru Member. Four potential reservoir zones areas were identified in Sawan-02 well and two zones in Sawan-07 well based on their integrated interpretation of seismic and well-log data. The results indicate that the area of interest possesses favorable reservoir characteristics, including good permeability, effective structural closure, and strong hydrocarbon potential.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

In Khairpur District area of Sindh the Sawan Gas Field is located within the Lower Indus Basin (LIB), represents the most significant hydrocarbon systems of Pakistan. The field lies within a structurally and stratigraphically complex part of the basin where Cretaceous sequences of Lower Goru Formation form principal of reservoir interval. Development and evaluation of this field are strongly dependent on integrated 2D seismic interpretation and petrophysical analysis from key wells including Sawan-02 and Sawan-07, which provide the primary control for subsurface calibration and reservoir characterization within the area. (Ali Et al., 2022)

The reservoir principle units in the Sawan area belong to the Lower Goru Formation (LGF), where stacked sandstone intervals are interbedded with shale, creating strong vertical and lateral heterogeneity. These reservoir sands, particularly within the C-sand interval, show significant variation in quality when analyzed across wells such as Sawan-02 and Sawan-07. The integration of (2D) seismic lines with the well-log data has been essential while mapping the continuity, thickness variation, and structural configuration of these sandstone bodies in the Lower Indus Basin framework. (Khan Et al, 2023)

Accurate reservoir characterization in the Sawan area relies on the integration of 2D seismic interpretation with petrophysical evaluation to define hydrocarbon-bearing zones within the Lower Goru Formation. Seismic interpretation provides structural and stratigraphic control, while the petrophysical analysis from Sawan-02 along with Sawan-07 wells quantifies the key reservoir properties like porosity, water saturation, and also shale volume. This integration enables reliable identification of productive sandstone intervals within the Lower Indus Basin system, particularly where seismic resolution alone is insufficient to resolve fine-scale heterogeneity. (Telford et al., 1990; Chopra & Marfurt, 2007; Khan et al., 2023)

Petrophysical analysis in the Sawan field focuses on transforming wireline log responses from wells such as Sawan-02 and Sawan-07 into quantitative reservoir parameters within the Lower Goru Formation. Gamma ray along with resistivity, density, and neutron logs are primarily use in differentiation of shale-rich intervals from clean

sandstone reservoirs. These interpretations are directly tied to seismic-defined structural frameworks, allowing better correlation between log-derived reservoir properties and seismic response within the Lower Indus Basin. (Asad and Rahimm, 2019)

Seismic interpretation across the Sawan area play a vital role in defining the structural architecture controlling Lower Goru reservoir distribution. 2D seismic profiles are being used to identify faults, stratigraphic boundaries along with horizon continuity, which are then calibrated with well data from Sawan-02 and Sawan-07. This integration helps in understanding lateral variation in reservoir quality and also identifying structural compartments that influence hydrocarbon accumulation in the Lower Indus Basin. (Chopra & Marfurt, 2007)

Within the Sawan field, the linked use of seismic interpretation and petrophysical analysis has been key to improve lower Goru formation reservoir prediction. Seismic derived structural models guide the spatial framework, while petrophysical results from key wells provide ground truth for lithology and fluid distribution. This integrated workflow enhances the reliability of reservoir characterization and supports improved understanding of hydrocarbon-bearing sandstone distribution within the Lower Indus Basin. (Ehsan & Khan et al, 2022)

In present study, Which focuses on integrating 2D seismic interpretation with petrophysical analysis of Sawan-02 and Sawan-07 wells to evaluate reservoir characteristics of the lower Goru Formation of Sawan Gas Field. Main objective is to delineate structural features, identify reservoir intervals, and quantify petrophysical properties in a unified framework. This integrated approach improves the understanding of reservoir heterogeneity and hydrocarbon distribution within the Lower Indus Basin and provides a detailed reliable basis for reservoir evaluation in this study area. (Asad & Rahim, 2019)

1.2 Study Area

Lower Indus Basin consisting of Sawan Gas Field, of Pakistan, a structurally complex sedimentary basin shaped by regional tectonic convergence and extensional deformation. The field lies within Sindh Province, near the Sukkur Rift system, where the subsurface architecture is Pre dominated by the horst and the graben structures are formed by normal faulting. This structural framework directly controls the distribution and compartmentalization of the Lower Goru Formation (LGF) reservoirs, which are primary

focus on 2D seismic interpretation and petrophysical evaluation using well control from Sawan-02 and Sawan-07. (Ehsan et al, 2021)

Regionally, the Sawan is positioned within southeastern segment of the Jacobabad Khairpur structural high system in the Lower Indus Basin. The field is belted by major basement-involved fault trends and structural highs that influence the continuity of Lower Goru sandstone bodies. These structural elements are clearly expressed in 2D seismic profiles as fault blocks and tilted strata, which are later calibrated using petrophysical signatures from key wells such as Sawan-02 and Sawan-07 to confirm its presence of reservoir and quality variations. (Ullah et al., 2022; Khan et al., 2023)

Sawan Gas Field with The basic structural evolution, is composed by the multiple tectonic phases that shaped the present-day configuration of the Lower Goru reservoir system. These phases generated extensional fault networks and reactivated basement faults, producing compartmentalized traps within the Lower Indus Basin. In 2D seismic interpretation, these features appear as fault-bound structural closures and discontinuities, which strongly influence reservoir connectivity and are critical for correlating petrophysical variations observed in Sawan-02 and Sawan-07 wells. (Haris et al, 2022)

The framework of the Sawan field is primarily dominated by the area of Sembar Formation and all the overlaying Lower Goru Formation. The Sembar Formation acts as the primary source rock while the Lower Goru Formation serves us the main reservoir interval within study area. The Upper Goru Formation overlies the reservoir section and functions as a regional sealing unit, which is essential for hydrocarbon trapping identified through seismic interpretation and confirmed by petrophysical analysis of the well log data. (Khan et al.,2012)

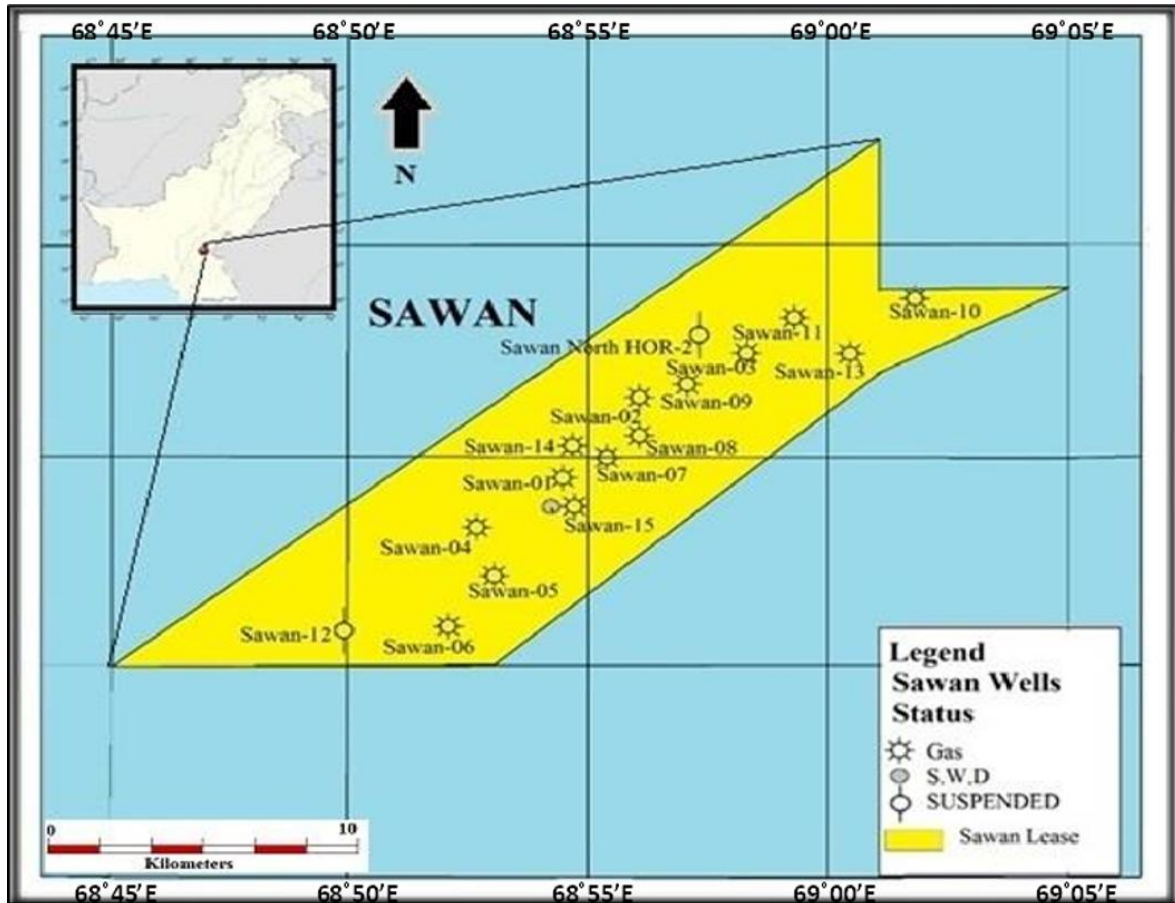


Figure 1. 1 Location map of Sawan Gas Field (after Anwer et al., 2017).

Within Lower Goru Formation, four sandstone intervals form the principal reservoir framework in the Sawan area. These intervals are laterally variable and vertically separated by shale barriers, which create strong heterogeneity in reservoir quality. The C sand interval, which particular, is of primary interest in Sawan-02 and Sawan-07 wells due to its hydrocarbon-bearing potential, which is mapped seismically as laterally discontinuous but structurally controlled sandstone bodies are in the Lower Indus Basin. (Asad & Rahim, 2019)

The Upper Goru Formation comprise predominantly is of very thick shale sequences that act as the main regional seal over Lower Goru reservoir system. In the Sawan area, this sealing unit plays a critical role in trapping hydrocarbons within structurally defined closures identified through 2D seismic interpretation. The integrity of this seal is supported by petrophysical evidence from Sawan-02 and Sawan-07, where pressure and fluid indicators confirm effective containment within the Lower Goru sandstone reservoirs. (Ullah & Khan et al., 2023)

1.3 Climate and Accessibility

In Khairpur District of Sindh is placed Sawan Gas within the Lower Indus Basin, positioned near the Nara region approximately southeast of Sukkur. The area lies within a broad desert belt where surface conditions are directly influenced by subsurface structural deformation expressed in 2D seismic data as faulted blocks controlling the Lower Goru Formation reservoirs. This geographic setting also provides surface access routes that are essential for linking seismic survey operations and well sites such as Sawan-02 and Sawan-07 used in petrophysical evaluation. (Ullah et al., 2012)

The climate condition of the Sawan area is arid to semi-arid, characterized by high seasonal temperature variation, low rainfall, and sparse vegetation cover. These surface conditions directly affect field logistics for seismic acquisition and well operations, particularly during 2D seismic surveys and subsequent reservoir evaluation activities. Despite harsh environmental conditions, continuous production and data acquisition from wells like Sawan-02 and Sawan-07 demonstrate the operational viability of integrated seismic interpretation and petrophysical analysis in the Lower Indus Basin. (Asad & Rahim, 2019; Khan et al., 2023)

Regional accessibility of the Sawan Gas Field is controlled by its structural and geographic setting within the Lower Indus Basin, bounded by major tectonic highs and fold-and-thrust belts. These regional features not only define the subsurface framework of Lower Goru Formation which also influence surface connectivity to industrial hubs such as Sukkur and Karachi, which support field development, seismic data processing, and petroleum operations. (Muhsan et al., 2023)

1.4 Exploration History

Exploration in Sawan Gas Field of the Lower Indus Basin are closely linked to the identification and development of Lower Cretaceous reservoirs, especially within the Lower Goru Formation. The field was discovered in later 1998 and was brought into commercial production in 2003. Development of the field has relied heavily on integrated 2D seismic interpretation and petrophysical analysis, with wells such as Sawan-02 and Sawan-07 providing key subsurface control for reservoir evaluation and production assessment. (Khan et al., 2023; Ali et al., 2020)

The field comprises multiple wells, among which Sawan-02 and Sawan-07 play an important role in defining reservoir properties while validating seismic interpretations.

Production variability across the field which reflects the heterogeneous nature of Lower Goru sandstone reservoirs, where differences in sand-shale distribution directly influence porosity, permeability, and hydrocarbon saturation derived from well-log analysis. This heterogeneity is a critical factor in correlating seismic responses with petrophysical properties. (Asad & Rahim, 2019; Khan et al., 2023)

Exploration within the Lower Indus Basin has historically focused mainly on the Lower Goru Formation due to its Proven reservoir potential, however, identification of productive zones using seismic data alone remains challenging because reservoir thickness often ranges between 2 to 8 meters. Consequently, 2D seismic interpretation is integrated with seismic attribute analysis to enhance resolution and distinguish between reservoir and non-reservoir intervals, particularly in areas constrained by limited vertical seismic resolution. (Azeem et al., 2015; Khan et al., 2023)

Petrophysical analysis further strengthens reservoir characterization by quantifying key bounds including shale volume and porosity, and fluid saturation from well log data. Gamma ray logs are used to distinguish shale from clean sandstone, while resistivity logs help identify hydrocarbon-bearing zones. Effective porosity calculations are particularly important in the Lower Goru Formation because of the presence of interbedded shale, which reduces reservoir quality. These petrophysical results are also integrated with seismic interpretation to improve reservoir mapping and production forecasting. (Ahsan & Rahim, 2019)

Following the discovery related to Sawan Gas Field, extensive extreme seismic data acquisition and reprocessing were carried out to refine subsurface understanding. Approximately 2D seismic data were used to outline the structural features such as faults and closures controlling hydrocarbon accumulation. These interpretations, when tied with well data from Sawan-02 and Sawan-07, enabled improved delineation of reservoir geometry and compartmentalization in the Lower Goru Formation. (Khan et al, 2022)

The expedition and development in the Sawan field demonstrate the importance of integrating 2D seismic interpretation with petrophysical analysis in a structurally complex and heterogeneous reservoir system. The combined use of related seismic attributes, structural mapping, and well-log evaluation has significantly enhanced the understanding of reservoir distribution, fluid content, and production variability consisting in the Lower Goru Formation of Lower Indus Basin. (Ehsan Et al, 2023)

1.5 Objectives

The only main primary objective of the study is to evaluate all possible hydrocarbon potential of the Sawan Gas Field, located in Lower Indus Basin, through the integrated application of 2D seismic interpretation and petrophysical analysis, with specific focus on the Lower Goru Formation using well data from the Sawan-02 and Sawan-07. The integration aims to establish a reliable relationship between subsurface structural configuration and reservoir properties for improved characterization of hydrocarbon-bearing zones. (Khan et al., 2023; Asad & Rahim, 2019)

The first objective is to carry out two-dimensional (2D) seismic structural interpretation of the Sawan area in order to delineate subsurface structural features controlling hydrocarbon accumulation. This involves identification and mapping of normal fault systems and associated horst and graben geometries affecting the Lower Goru Formation. Seismic horizon picking is performed using Sawan-02 and Sawan-07 as control wells, followed by generation of time and depth structural maps. These interpretations provide a framework for understanding trap geometry and structural controls on reservoir distribution within the study area. (Ahsan et al, 2023)

The second objective is to carry out detailed petrophysical analysis of the well log data from Sawan-02 and Sawan-07 to evaluate reservoir attribute of the Lower Goru Formation. This includes the estimation of key framework such as volume of shale, effective porosity, water saturation, and the hydrocarbon saturation using standard log interpretation techniques. The analysis enables differentiation between reservoir-quality sandstones and non-reservoir shale intervals, and also helps in identifying productive zones within the B and C sand intervals of the Lower Goru Formation. (Asad & Rahim, 2019; Ehsan et al., 2023)

1.6 Dataset and software

Following are the selected data include five seismic lines and well log data. Five seismic sections are dip lines and one seismic profile was strike line, among these six lines, all seismic lines are of Sawan Area, all the well is of Sawan area. The tables of 2D seismic profile and acquired well logs are also mentioned below.

Table 1. 1 Acquired well-logs of the Sawan field.

Wells Available	Seismic Lines
Sawan - 7	PSM 96-115

Table 1. 2 2D Seismic profiles of study area.

2D Seismic Profiles	Seismic Line Types
PSM 96-114	Strike Line
PSM 96-115	Dip Line
PSM 96-131	Dip Line
PSM 96-129	Dip Line
PSM 96-133	Dip Line
PSM 96-135	Dip Line

The available wells are shown in table 1.1 above do not tie with the given seismic lines.

1.7 Methodology

The methodology choose in this study focuses primarily on integrated the application of 2D seismic interpretation and petrophysical analysis to assess the hydrocarbon potential of the Lower Goru Formation in Sawan Gas Field, Lower Indus Basin, using data from Sawan-02 and Sawan-07 wells. The work begins with the preparation of a base map incorporating seismic lines and well locations, defined in terms of northing and easting coordinates, scale, and spatial distribution of the dataset. This base map provides the fundamental spatial framework for subsequent seismic interpretation and correlation. (Khan et al., 2023)

A well-to-seismic tie is then established to correlate well log data from Sawan-02 and Sawan-07 with seismic reflections. Since our seismic data is recorded in two-way travel time, it is converted to depth using time-depth interrelation derived from well data. Depth correction is applied using seismic reference datum (SRD), accounting for differences between the Kelly Bushing (KB) and seismic datum. The corrected depth is calculated using the relation: $SRD = KB + \text{Formation Top} - \text{Datum}$. This correction ensures

accurate alignment between seismic horizons and formation tops in the Lower Goru Formation. (Kearey et al., 2002)

Seismic interpretation is carried out on 2D seismic sections by identifying and marking key horizons corresponding in the Lower Goru Formation. Horizons are picked based on the reflector continuity, while faults are also interpreted from discontinuities and the offsets in within seismic reflections. The structural style of the Sawan area is characterized by extensional tectonics, where normal faulting produces horst and graben geometries, often associated with wrench-related deformation and negative flower structures. These structural features are mapped across seismic lines using correlation techniques to maintain consistency in interpretation. (Khan et al ., 2022)

We use well log data to conduct the petrophysical analysis in the Sawan-02 and Sawan-07 to quantify reservoir properties of the Lower Goru Formation. The analysis begins with picking out of zones of interest based on log responses, including low gamma ray values indicating clean sand intervals and neutron density crossover suggesting gas presence.

Volume of shale (Vsh) is calculated from the gamma ray index, derived using minimum and also maximum gamma ray values. Sand volume is then obtained as the complement of shale volume, representing the clean reservoir fraction. (Rider, 1996; Asquith et al., 2004)

Porosity are calculated using the density-log data based on the relation between matrix density and bulk density, and fluid density. Neutron porosity are also considered, and average porosity is determined by intermingling the density and neutron porosity values, particularly in gas-bearing formations. Effective porosity is obtained by incorporating the sand fraction, thereby accounting for the pressure of shale content on the reservoir quality. These calculations provide a realistic estimation of pore space obtained for hydrocarbon storage in the Lower Goru sand intervals. (Schlumberger, 1989; Rider, 1996)

Water saturation is estimated using resistivity log data based on Archie's equation, which relates formation resistivity, porosity, and formation water resistivity. The general saturation relationship ensures that the sum of water and hydrocarbon saturation equals unity. These calculations enable differentiation between hydrocarbon bearing and water bearing zones in the reservoir. The integration of porosity and shale volume, and saturation

results provides a comprehensive evaluation of reservoir quality in Sawan-02 and Sawan-07. (Schlumberger, 1989; Archie, 1942)

Finally, the integration of seismic interpretation and petrophysical analysis allows for improved identification of hydrocarbon-bearing zones within the Lower Goru Formation. Seismic analysis support in detection of structural and the stratigraphic features, while petrophysical results validate reservoir presence and fluid content. This combined workflow enhances the reliability of subsurface interpretation and provides a robust basis for evaluating hydrocarbon potential in Sawan Gas Field. (Asad & Rahim, 2019)

1.8 Thesis Workflow

The workflow of this study begins with understanding the structural, stratigraphic, and lithological framework in the Sawan Gas Field within the Lower Indus Basin based on previous studies, with particular stress on the Lower Goru Formation. The initial stage provides the geological context required for subsequent seismic and petrophysical interpretation. (Khan et al., 2023)

Following data acquisition, quality control of both seismic and well-log data are performed. The seismic dataset, being cropped, is conditioned and adjusted prior to interpretation, while well log data from Sawan-02 and Sawan-07 are validated for consistency and completeness to ensure accurate petrophysical evaluation. (Ehsan et al., 2023)

A well-to-seismic tie is then established to correlate seismic reflections with formation depths observed in Sawan-02 and Sawan-07. This step ensures that interpreted seismic horizons correspond accurately to subsurface geological units, particularly within the Lower Goru Formation. (Khan et al., 2023)

Seismic interpretation is carried out by marking key horizons corresponding to the Lower Goru Formation on 2D seismic sections, followed by identification of faults based on discontinuities and disruptions in reflector continuity. These interpretations are used to define the structural framework and understand deformation patterns affecting the reservoir. (Khan et al., 2023)

Structural maps, including both contour maps of time and depth, which are generated using interpreted horizons and faults to visualize subsurface geometry and identify potential hydrocarbon traps. These maps take part in a crucial role in understanding reservoir distribution and compartmentalization within the study area. (Khan et al., 2023)

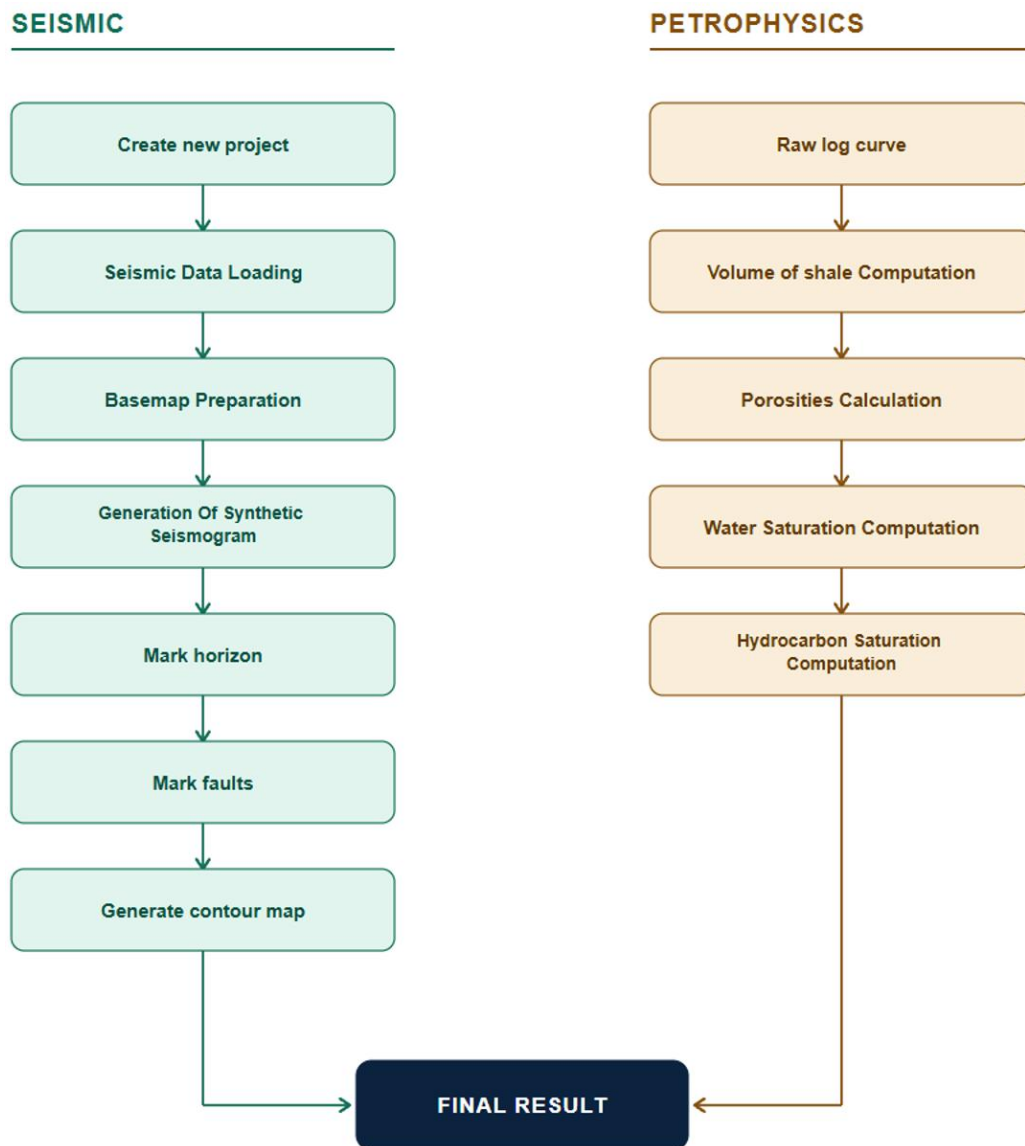


Figure 1. 2 Flow chart of thesis workflow

Petrophysical analysis of Sawan-02 and Sawan-07 is conducted to resolve reservoir properties such as shale content, porosity and fluid saturation consisting within the Lower Goru Formation. These results are integrated with seismic interpretation to prove reservoir presence and quality. (Ehsan et al., 2023)

Finally, the integrated interpretation of seismic and petrophysical data leads to the identification of the hydrocarbon-bearing zones and supports conclusions regarding reservoir potential in the Sawan area. These results form the basis for discussion, recommendations, and overall conclusions of the study. (Khan et al., 2023; Asad & Rahim, 2019)

CHAPTER 2

GEOLOGY OF THE STUDY AREA

2.1 Regional tectonics

The structural evolution of the Lower Indus Platform Basin reflects the Indian Plate's long journey from a rifted fragment of Gondwanaland to its eventual collision with Eurasia. Three tectonic episodes shaped the basin's architecture: Mesozoic rifting, a Late Cretaceous thermal event, and Cenozoic compressional inversion. Over time, the basin transformed from a quiet, passive-margin setting into an actively deforming collision zone. (Herron, 2011)

Rifting began as the Indian Plate broke away from Gondwanaland between the Jurassic and Early Cretaceous, setting the basin's initial structural pattern. Normal faulting oriented N-S to NE-SW produced a classic horst-and-graben fabric across the platform. These fault-bounded blocks later became important both as depocenters for sediment accumulation and as structural traps for hydrocarbons. Throughout this stage, the basin behaved as a passive margin, steadily subsiding while thick Mesozoic clastics and carbonates were laid down. (Herron, 2011)

Conditions changed markedly by the Late Cretaceous, when India's separation from Madagascar coincided with its passage over the Reunion hotspot. Thermal uplift and doming during this period drove widespread erosion, giving rise to the regionally significant Base Tertiary Unconformity. The eruption of the Deccan Traps added a further thermal overprint, contributing to strike-slip movement and NNW-trending normal faults. This episode reworked the earlier rift fabric, generating new fracture systems and shifting the regional stress regime ahead of the main phase of plate convergence.

As the Cenozoic began, the northward-drifting Indian Plate came into contact with the Afghan Block and Eurasia, reshaping the basin's northern and western boundaries. The Bela Ophiolites were emplaced and mildly deformed during the Paleocene-Eocene, though most of the Eocene was tectonically calm, favoring carbonate platform growth. From the Oligocene onward, however, ongoing Himalayan collision subjected the basin to intense sinistral transpression, overprinting older rift fabrics with fold-thrust belts and flower structures along its western margin.

Today, the Lower Indus Platform Basin sits within the Indus Foredeep, characterized by a mix of stable basement highs such as Jacobabad-Khairpur and Mari-Kandhkot and actively deforming fold belts of the Sulaiman and Kirthar ranges. The eastern platform still preserves its original extensional, passive-margin character, while the western and northwestern portions bear the imprint of crustal shortening, expressed as thrust-faulted anticlines and inverted structures. This layered tectonic history rifting, thermal doming, and collisional shortening continues to control the basin's structural and depositional patterns.

2.2 General Geology

General Geology and Tectonics The study area is part of the central Indus basin that has been identified as an extensional basin resulting from an inferred fossil rift crustal feature and is overlain by a thick sedimentary sequence. It is characterized by horst and graben structures, together with a system of transcurrent faults. The sands in Goru are of great importance and are widely distributed from Waziristan to as far south as Cutch in India. Regionally considering the Goru sediments their thickness increases towards the center of Karachi Embayment. The Goru Formation is dominantly shale or mudstone, mainly calcareous. The Lower Goru has been applied to the lower sandy member whereas the shale unit is preferred as Upper Goru Formation.

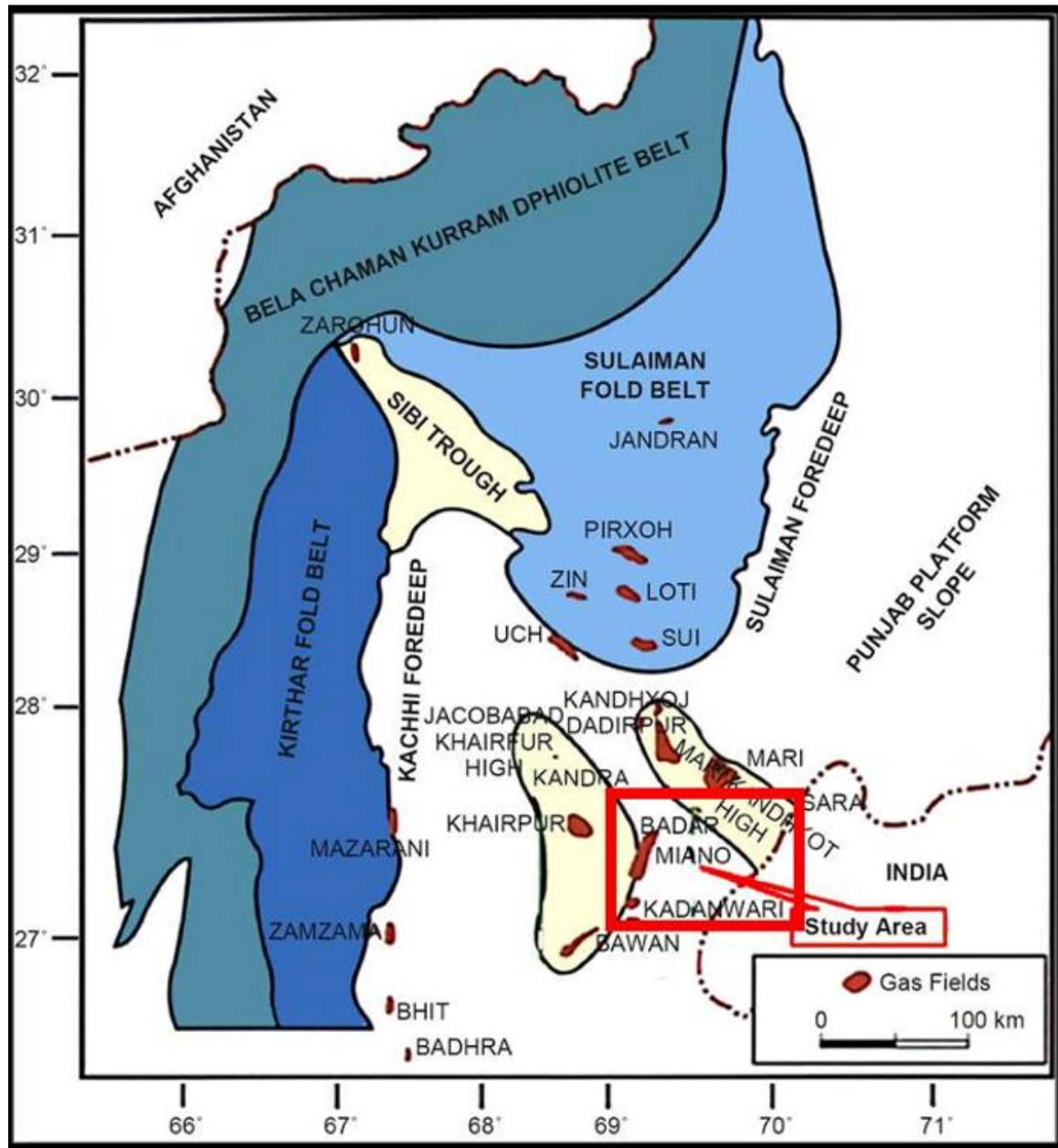


Figure 2. 1 Tectonic map of Central Indus Basin showing the location of Miano block in Pano Aqill Graben. (Saif et al., 2016)

2.3 Tectonic Framework

The basin is structurally bounded by major tectonic elements that define its evolution and hydrocarbon potential. The Sargodha High forms the northern boundary, while Mari-Kandkot and Jacobabad Highs both lie to the south. The Indian Shield that marks the eastern margin, whereas Kirthar and Sulaiman fold and the thrust belts define the western boundary. These structural features have played a key role in controlling sediment deposition, fault development, and the formation of hydrocarbon traps, which are

interpreted through 2D seismic data in the Sawan area. (Asad & Rahim, 2019; Ullah et al., 2022)

Within this tectonic structure the Sawan Gas Field is located in structurally complex zone associated with the Sukkur Rift System. The area is characterized by extensional tectonics resulting in the horst, graben geometries that directly influence reservoir compartmentalization within the Lower Goru Formation. These fault systems, depicted through seismic sections and validated using Sawan-02 and Sawan-07 well data, are critical for understanding reservoir continuity, thickness variation, and hydrocarbon accumulation. (Khan et al., 2023)\

The tectonic evolution of the basin, including uplift and wrench faulting events, has significantly influenced the structural configuration of the Lower Goru reservoirs. NW–SE trending extensional faults and associated deformation patterns control the distribution and trapping of hydrocarbons in the Sawan area. These structural elements are essential targets in 2D seismic interpretation and are further constrained through petrophysical analysis to confirm reservoir presence and fluid characteristics within the study wells. (Khan et al., 2023; Asad & Rahim, 2019)

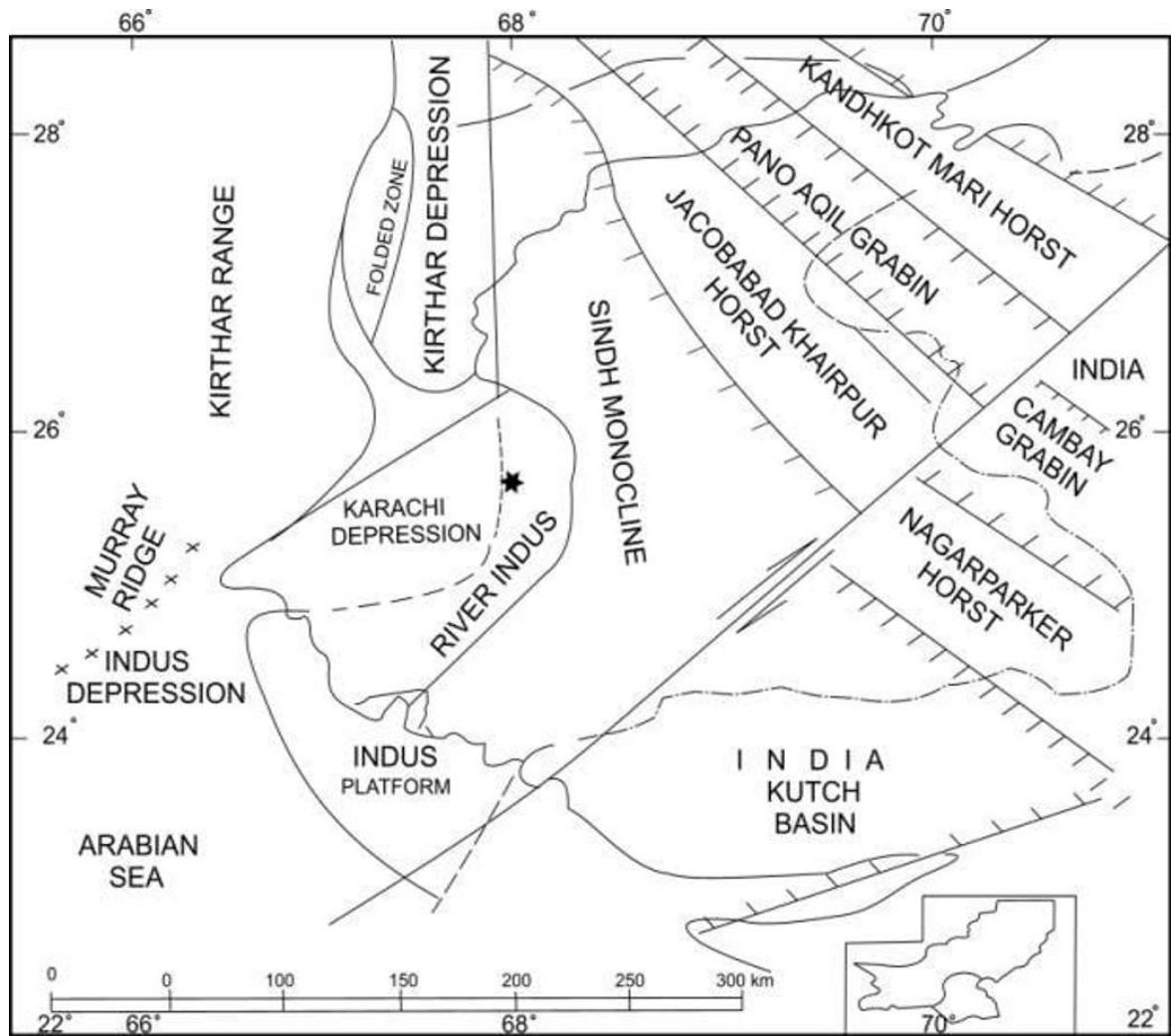


Figure 2. 2 Tectonic map of Lower Indus Basin showing the studied area (after Raza et al. 1990)

2.4 General Stratigraphy

In Lower Indus Basin is stratigraphic framework of Sawan Gas Field ,it is the primarily significant because the presence of Cretaceous reservoir along with seal units, particularly the Lower Goru and Upper Goru formations. Although with basin consist of a wide geological succession parameters from Jurassic to the recent deposits, the hydrocarbon potential in the Sawan

domain is mainly associated within Lower Goru Formation, which also serves as principal reservoir, while Upper Goru formation acts as an effective regional seal. This stratigraphic configuration is fundamental for integrated 2D seismic interpretation and petrophysical analysis carried out using Sawan-02 and Sawan-07 well data. (Khan et al., 2023)

In the base of penetrated stratigraphic sequence which lies the Early Cretaceous Eras Sembar Formation, which underlies in the Lower Goru Formation and plays a critical role the primary source rock in the Sawan field. They consists of predominantly of marine shale within the minor interbeds of sandstones and siltstone. The organic-rich nature of this formation, dominated by Type III kerogen, makes it gas-prone and responsible for hydrocarbon generation within the Lower Goru reservoirs. The stratigraphic relationship between the Lower Goru formation and Sembar is essential in understanding the petroleum system and is indirectly interpreted through seismic data and validated using petrophysical parameters from Sawan-02 and Sawan-07. (Khan & Rahim et al, 2023)

AGE	STRATIGRAPHY		LITHOLOGY	RESERVOIR POTENTIAL			OIL / GAS SHOWS	FIELDS		
				SOURCE	CAPROCK	RESERVOIR				
RECENT / PLOICENE	ALLUVIUM / SIWALIKS									
E O C E N E	KIRTHAR FM.	DRAZINDA MB.			C					
		PIRKOH MB.				R				
		SIRKI MB.			C					
		HABIB RAHI MB.				R	*	Mari		
	LAKI FM.	GHAZIJ MB.			C					
		SUI MAIN LST. MB.				R	*	Kandhkot, Sui Qadirpur, Pirkoh		
PALEOCENE	DUNGHAN FM.				C		R	*	Zarghun	
	RANIKOT FM.				C			*	Pirkoh	
						R				
	PARH FM.									
UPPER CRETACEOUS	GORU FM.	UPPER GORU MB.								
		LOWER GORU MB.	SHALE INTERVAL	S	C					
			"D" INTERVAL			C				
			"C" INTERVAL	S	C		R	*	Sawan, Mari Latif	
			"B" INTERVAL	S	C		R	*	Miano, Rehmat, Kadanwari	
			"A" INTERVAL				R	*		
LOWER CRETACEOUS		SEMBAR			S					
	CHILTAN									
JURASSIC										

Figure 2. 3 Generalized Stratigraphic Column of Central Indus Basin (Azeem et al., 2016).

The Lower Goru Formation displays main reservoir unit in the Sawan Gas Field and are the primary focus of both seismic interpretation and petrophysical evaluation. It

consists of alternating sandstone and shale sequences deposited under mixed fluvial, tidal, and shallow marine conditions. The sandstone units are also subdivided into distinct intervals, among which the B and C sands are almost significant in terms of hydrocarbon accumulation in the Sawan field. These reservoir sands exhibit variable porosity and permeability due to heterogeneity in grain size, shale content, and diagenetic effects such as pore-lining chlorite, which helps preserve porosity. These variations are quantitatively evaluated using well log analysis from Sawan-02 and Sawan-07 and correlated with seismic responses for reservoir characterization. (Khan et al., 2023; Asad & Rahim, 2019)

Overlying the Lower Goru Formation is the Upper Goru Formation, which consists predominantly of thick marine shale deposits. This unit acts as regional seal which also acts as preventing the upward migration of hydrocarbons and make sure their entrapment within the underlying Lower Goru sandstone reservoirs. The effectiveness of this seal is critical for hydrocarbon preservation and is an important consideration during seismic interpretation, where the contrast between sandstone reservoirs and overlying shale enhances reflector continuity and aids in horizon identification. (Khan & Ullah et al, 2022)

The stratigraphic configuration in Sawan field, characterized by the source rock of Sembar Formation , the reservoir unit Lower Goru Formation, and sealing unit (Upper Goru Formation), forms a complete petroleum system. This system is effectively analyzed through integration of the 2D seismic data and also the petrophysical evaluation from Sawan-02 and Sawan-07, allowing for accurate identification of reservoir intervals, fluid content, and structural controls on the hydrocarbon accumulation of the Lower Goru Formation. (Asad & Rahim, 2019)

2.5 Borehole Stratigraphy

Overview

Well	Field	Basin	Main Reservoir
Sawan-2	Sawan Gas Field	Middle Indus Basin, Pakistan	Lower Goru Formation (Cretaceous)
Sawan-7	Sawan Gas Field	Middle Indus Basin, Pakistan	Lower Goru Formation (Cretaceous)

Both wells penetrate a thick sedimentary succession ranging from recent alluvium to Cretaceous rocks.

Borehole Stratigraphy — Sawan-2 Well

Formation	Age	Lithology	Reservoir Significance
Alluvium	Recent	Sand, silt, clay	Surface deposits
Siwalik Group	Miocene–Pliocene	Sandstone, claystone, conglomerate	Non-reservoir
Laki Formation	Eocene	Limestone, shale	Seal
Ghazij Formation	Eocene	Shale with sandstone	Source/Seal
Ranikot Group	Paleocene	Limestone, shale	Regional seal
Pab Formation	Late Cretaceous	Sandstone	Minor reservoir
Upper Goru Formation	Early Cretaceous	Shale	Regional cap rock
Lower Goru Formation	Early Cretaceous	Sandstone interbedded with shale	Main gas reservoir
Sembar Formation	Early Cretaceous	Organic-rich shale	Major source rock

Borehole Stratigraphy — Sawan-7 Well

Formation	Age	Lithology	Reservoir Significance
Alluvium	Recent	Sand, silt, clay	Surface deposits
Siwalik Group	Miocene–Pliocene	Sandstone and claystone	Non-reservoir
Laki Formation	Eocene	Limestone	Seal
Ghazij Formation	Eocene	Shale	Source/Seal
Ranikot Group	Paleocene	Limestone and shale	Seal
Pab Formation	Late Cretaceous	Sandstone	Secondary reservoir
Upper Goru Formation	Early Cretaceous	Shale	Regional cap rock

Formation	Age	Lithology	Reservoir Significance
Lower Goru Formation	Early Cretaceous	Fine- to medium-grained sandstone with shale	Principal gas-producing reservoir
Sembar Formation	Early Cretaceous	Dark marine shale	Hydrocarbon source rock

Sawan-2 vs Sawan-7 Comparison (Lower Goru & Sembar Formations)

Formation	Sawan-2 Lithology	Sawan-7 Lithology	Common Significance
Lower Goru	Sandstone interbedded with shale	Fine- to medium-grained sandstone with shale	Main/Principal gas-producing reservoir
Sembar	Organic-rich shale	Dark marine shale	Major hydrocarbon source rock

2.6 Petroleum Prospect

The hydrocarbon expedition history of the Lower Indus Basin ages back several decades, with the region gradually emerging as the most prolific hydrocarbon-producing area in Pakistan. The basin has been the focus of sustained exploration efforts owing to its favorable geological setting, well-developed petroleum system, and the presence of multiple productive formations. The earliest significant hydrocarbon discoveries in the broader Indus Basin region sets the foundation for the understanding of the petroleum potential of an field, and subsequent exploration campaigns progressively unlocked the gas-bearing potential of the Lower Cretaceous reservoirs, particularly the interval of sandstone of Lower Goru Formation. (Ullah Et al, 2022)

In the petroleum system Sawan area along with the broader Lower Indus Basin was established during the Cretaceous period. Drilling and the logging results have confirmed us that a complete petroleum system is being deposited during this time, with the Lower Goru and Sembar Formations serving as the vital reservoir along with the source rocks respectively in both the Lower and Middle Indus basins. The Sembar Formation, being gas-prone and predominantly containing Type III kerogen are widely recognized as the

principal part of source rock that charged the Lower Goru sandstone reservoirs. The thick transgressive shales in the Upper Goru Formation act mainly as the regional seal, completing the essential elements of the petroleum system in this part of the basin. (Khan et al., 2023; Ullah et al., 2022; Asad & Rahim, 2019)

Building on the success of the Miano discovery, OMV subsequently mark the Sawan-gas field in the Khairpur field, leading to its discovery in 1996 with an estimated reserve of 1.12 TCF of gas. This made the Sawan field fourth-largest gas producer in Pakistan at the time of its discovery and one of the most significant hydrocarbon accumulations consisting of Lower Indus Basin. The discovery of the Sawan field area was a landmark event in Pakistan's petroleum history, as it demonstrated the commercial productivity of the Lower Goru sand interval at considerable depths and the encouraged further appraisal and development drilling in the area. (Khan et al., 2023; Asad & Rahim, 2019; Ullah et al., 2022)

The explorations and development in the Sawan gas area has been conducted under a Joint Venture arrangement involving ENI, Pakistan Petroleum Limited, Morose Dolly, GHPL, and OMV Pakistan. The exploration block of Sawan was recognized as lying in the prospective zone II of Pakistan by Pakistan Petroleum Limited. Following the initial discovery well, appraisal drilling confirmed the lateral continuity and commercial viability of the gas-bearing Lower Goru sand interval across the field, within the wells Sawan-01, Sawan-02, all intersecting productive reservoir zones at depths ranging from approximately 3,220 to 3,587 meters. Numerous areas in the Lower Indus Basin have been developed and are still actively producing hydrocarbons from this reservoir, underscoring the long-term productivity and economic importance of Lower Goru Formation in the hydrocarbon-bearing unit. (Asad & Rahim, 2019)

The petroleum history of the Sawan field and the more Lower Indus Basin reflects in a progressive evolution from early exploration and initial discovery to sustained production and ongoing field development. The seismic interpretation integrates the petrophysical analysis, and advanced reservoir characterization techniques has been central to the unlocking the full hydrocarbon potential in this basin, and the Sawan gas area continues to serve as a type example for the exploration and development of Cretaceous clastic reservoirs in Pakistan. (Khan et al., 2023; Ullah et al., 2022; Asad & Rahim, 2019).

CHAPTER 3

SEISMIC INTERPRETATION OF SAWAN FIELD

3.1 Introduction

For the best interpretation good processing and , good acquisition is mandatory. The real and precise picture of subsurface lithology must be shown by reflectors. The final picture should taken into account for best fit of both geophysical and geological data as the information is near to accurate rather than any source alone. The processing must justify the acquisition and lithology and must give a better result by applying parameters that can be reliable.

The dataset used in this study comprises six seismic sections along with two well logs, as introduced above in Chapter 1. The seismic survey was acquired using a sweep frequency ranging from 8 to 80 Hz, with a sweep duration of 10 seconds and six sweeps per vibration point (6 SWPS/VP). The source point interval was maintained at 50 m, while 120 receiver groups were deployed. A receiver array configuration of 3×12 was used, with a horizontal array length of 5.76 m and a geophone spacing of 1.39 m. During acquisition, frequencies below 3 Hz and above 136 Hz were filtered out. Each record had a duration of 5 seconds and was sampled at an interval of 2 Ms.

The acquired seismic data was processed through a standard workflow. The processing sequence included setting a 5-second record length with a 4 ms sampling interval, geometry assignment, editing of noisy or bad traces, field static correction, spherical divergence correction, application of a symmetric filter (100–2100 ms), first break-Muting, band Pass filtering, normal moveout correction, dip moveout correction, stacking of 60-fold data, noise suppression, static corrections and final dynamic equalization.

3.2 Data Loading

The Seismic dataset is provided in SEG-y format along with the corresponding navigation files. The navigation files contain essential survey information, including longitude and latitude coordinates, X–Y coordinates, shot point locations, line orientation, and other positional details required for correctly loading and interpreting the seismic data. Without these navigation files, the SEG-Y data cannot be properly imported or processed.

In this study, both the SEG-Y files and their associated navigation files were available; however, the SEG-Y data had been cropped before being provided.

Approximately 10% of the seismic data had been trimmed from both the beginning and the end of the SEG-Y files. As a result, difficulties arose when positioning the seismic lines at their correct survey locations. While the navigation files identified the first shot point as the starting location, the corresponding SEG-Y files effectively began at the eleventh shot point because the initial traces had been removed. Likewise, several shot points at the end of the seismic lines were also absent, as illustrated in Figure 3.1. This mismatch between the navigation and seismic data led to inaccurate spatial alignment, which adversely affected seismic line correlation, well-to-seismic ties, structural interpretation, and the accurate placement of well locations on the interpreted structures.

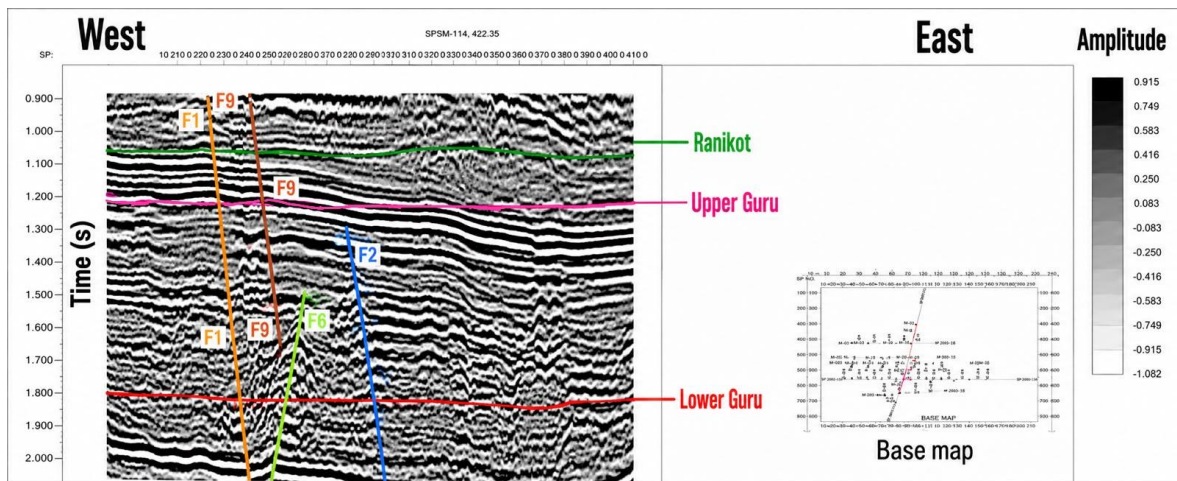


Figure 3. 1 Image showing cropped seismic section (PSM 96-131).

This issue was addressed using several approaches, with the most straightforward method being the modification of the navigation files to match the cropped SEG-Y data. Although some seismic interpretation software can automatically handle such inconsistencies, these automated corrections may alter the original coordinates, positions, or other spatial information, potentially affecting the accuracy of the dataset

3.3 Basemap of Area

Figure 3.2 presents base map which shows the acquired seismic dataset for the Sawan area. Unlike conventional maps that use geographic coordinates (latitude and longitude), this base map is referenced using X–Y coordinate values. A detailed description of study area and the base map is provided in Chapter 1.

X/Y Meters

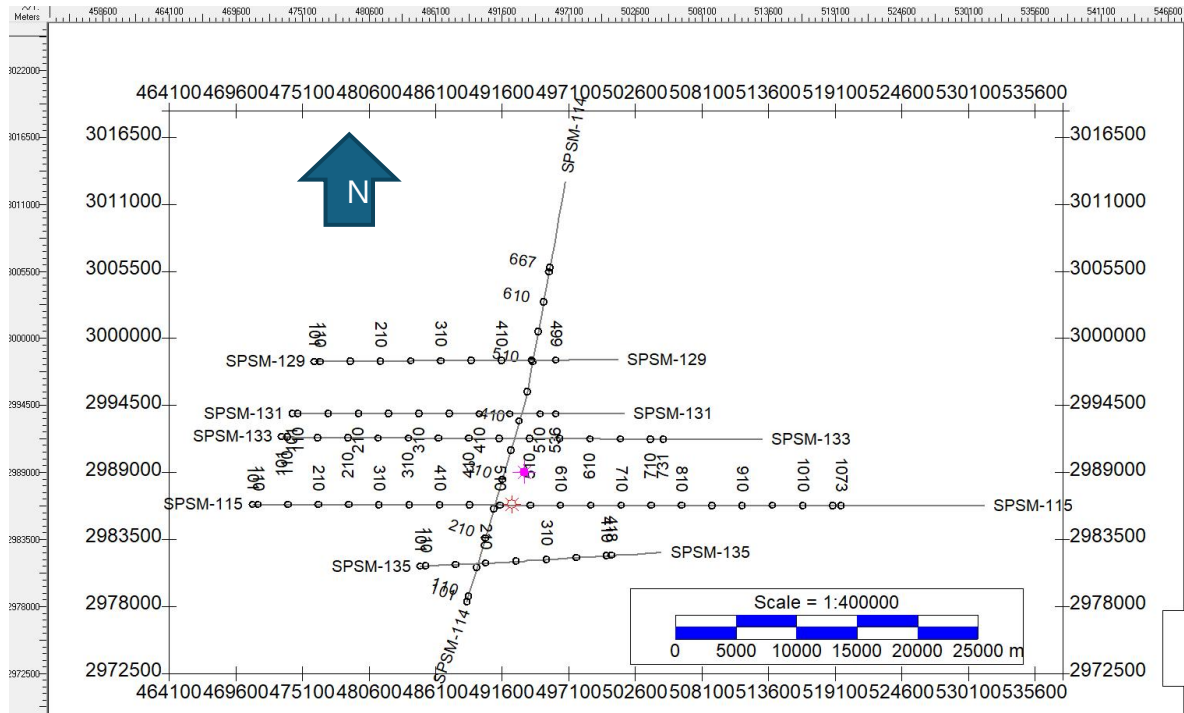


Figure 3. 2 Basemap showing acquired seismic lines spread and wells.

3.4 Seismic-Well Datum Correlation

Accurate interpretation of Seismic sections requires proper datum correlation because formation tops and depth information obtained from well logs are referenced to a different datum than the seismic data. Well data are referenced to the Kelly Bushing (KB) datum, whereas seismic data use the Seismic Reference Datum (SRD). Therefore, a datum conversion is necessary before integrating well and seismic information.

The relationship between these reference datums can be expressed as:

- Seismic Reference Datum (SRD) = Formation Top (Well) – Kelly Bushing (KB)The true vertical depth (TVD) is then calculated using the following equation:
- True Vertical Depth (TVD) = Formation Top – (Kelly Bushing + Seismic Reference Datum)

For example, the True vertical depth of the Lower Goru Formation is determined:

- $TVD = 2683.0 - (55.14 + 50.0) \text{ m}$
- $TVD = 2577.86 \text{ m}$

3.5 Synthetic seismogram

The a synthetic seismogram generation is an essential step before initiating seismic interpretation because it facilitates the accurate seismic horizons identification and the correlation of seismic reflections are in terms of travel amplitude and time. Synthetic seismograms also provide a direct link between geological information, seismic data and well log measurements, thereby improving the reliability of well to seismic correlation (Naeem et al., 2015).

In the present study, Synthetic seismograms were generated for the available wells, including Sawan-7 and Sawan-2. For each well, density and sonic logs were used to compute the acoustic impedance, while the gamma-ray log served as a reference for lithological correlation. Several wavelet types were evaluated during the synthetic generation process; however, the most reliable correlation was achieved using a wavelet extracted directly from the seismic data rather than theoretical wavelets.

Wavelet generation can be performed either by employing theoretical wavelets, such as Ricker, Ormsby, minimum-phase, and Butterworth wavelets, or by extracting a representative wavelet from the seismic traces through frequency matching. In this research, the latter approach was adopted. The extraction process utilized seismic traces located within a 500 m radius of each borehole. A total of 40 traces were included, and the wavelet was computed over the full trace length using a sampling interval of 2 ms, a time window of 0.4 s, and a zero-degree phase angle.

The surface seismic was subsequently correlated by extracted wavelet data using five neighboring seismic traces to obtain the best possible match. The Synthetic seismogram generated for well Sawan-2 (Figure 3.6) demonstrates the correlation between the Synthetic response and also recorded seismic trace. Initially, only a static time shift was applied to align the synthetic and seismic events. Dynamic adjustments, such as stretch-and-squeeze operations, were intentionally avoided because they can distort the original seismic signal and reduce the reliability of the well-to-seismic tie. 33.81 percent with minimal squeeze and stretch, resemblance was raised to 62.40 percent.

A similar workflow was followed for generating the Synthetic seismogram of the Sawan-7 well. This well is situated close to the seismic Dip line (PSM 96-115). The generated synthetic seismogram showed an overall correlation of approximately 40% with the corresponding seismic data. A limited stretch-and-squeeze adjustment was used or

applied within the Goru Formation interval to improve the alignment between the seismic reflections. After correcting the Mistie, a Synthetic seismogram was generated, as described in Section 3.6.1. Horizon interpretation was then carried out using the available well data. The interpreted formation tops, together with their corresponding depths, were used to establish an accurate well-to-seismic tie, providing a reliable basis for subsequent seismic interpretation.

Following the well-to-seismic tie, the interpreted well tops were projected onto the seismic section to guide horizon picking. Because the available dataset consisted of only 2D seismic lines, none of the wells were located directly on the seismic profiles. Therefore, the nearest well to each seismic line was selected for interpretation. In this study, Sawan-2 was chosen because it is located approximately 120 m from seismic line PSM 98-201, making it the most suitable well for correlating formation tops with the seismic data.

After completing the horizon interpretation, faults were identified and mapped by recognizing discontinuities in seismic reflectors, including abrupt changes in reflector continuity, transitions between wave crests and troughs, and vertical displacement (throw) of interpreted horizons. Seismic amplitude and variance attributes were also utilized to improve fault detection and enhance the reliability of the structural interpretation.

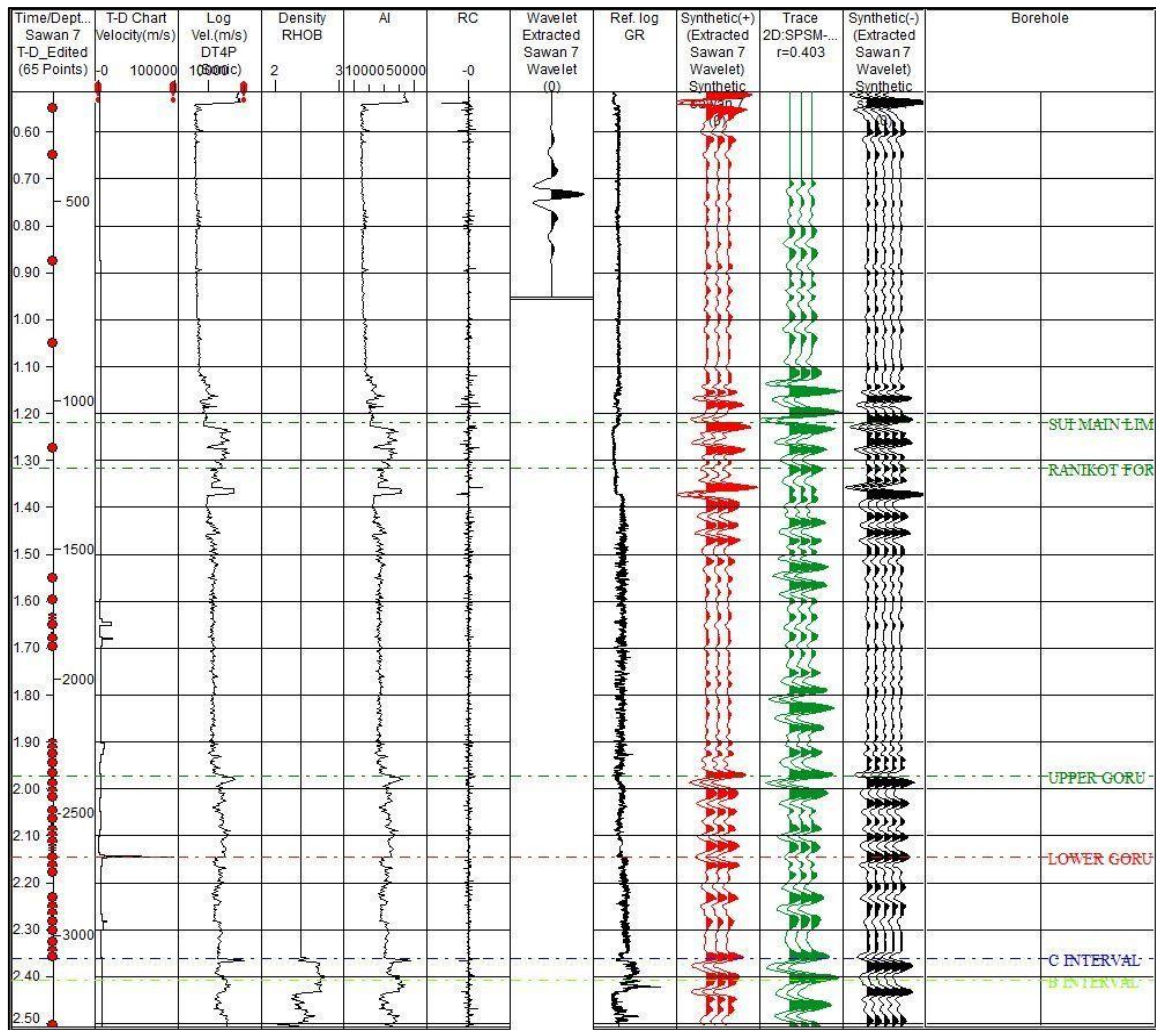


Figure 3. 3 Image of synthetic seismogram

PSM -96-114

The seismic profile PSM-96-114 represents the strike line selected for the study. As observed from the base map, most of the dip lines intersect this strike line, including the available cross-lines, allowing direct cross-correlation between seismic events.

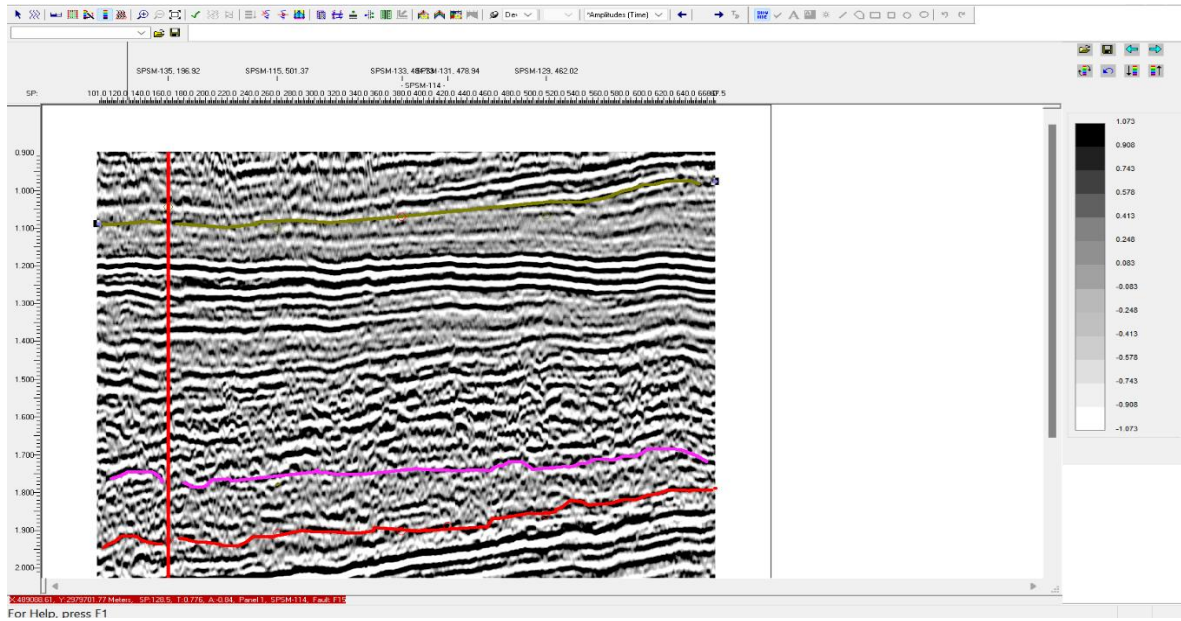


Figure 3. 4 Seismic section of strike line PSM 96-114

PSM-96-115

The dip line PSM-96-115 is also the longest seismic profile within the available dataset. It reveals lateral variations in seismic facies, with facies changes becoming more prominent toward the Eastern side of the study area. The eastern region also exhibits diverse fault patterns, including wrench faulting and the development of horst and graben features. In contrast, seismic lines located toward the western part of the area display comparatively more continuous reflectors and fewer structural variations.

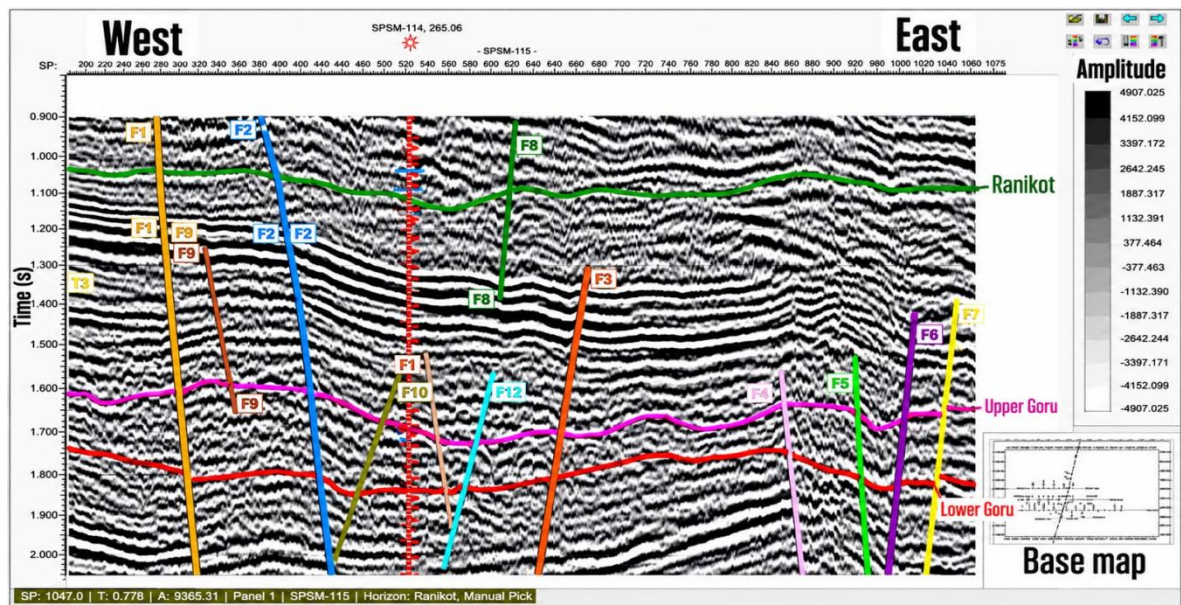


Figure 3. 5 Seismic section of dip line PSM-96-115

PSM 96-131

The Dip line represents the northernmost seismic profile in the available seismic lines. A observed structure is negative flower structure in the central part of the seismic section, indicating the presence of a transgressional or transtensional structural feature. The interpreted horizons show a progressive increase in depth toward the south, which supports the occurrence of a structural depression. This observation is consistent with the presence of the Lundo Low, as discussed in the previous sections.

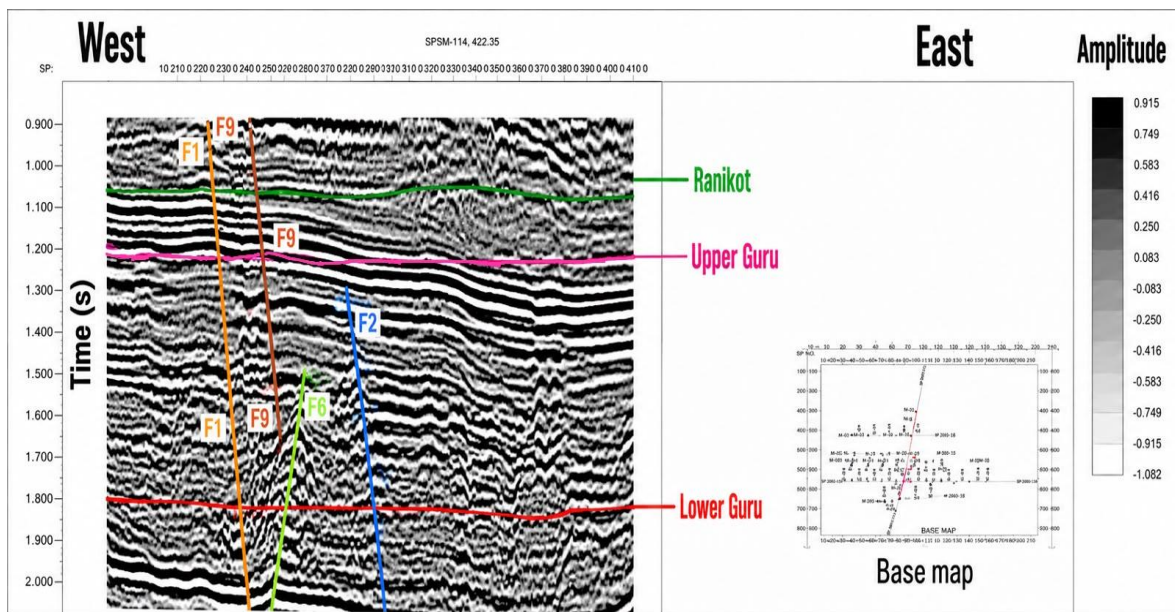


Figure 3. 6 Seismic section of dip line PSM 96-131

PSM-96-133

The presence of a negative flower structure is also observed along this seismic line, and the same structural trend extends toward PSM-96-115. PSM 96-135 (Figure 3.13), indicating that the structure is not consistently developed across all seismic profiles.

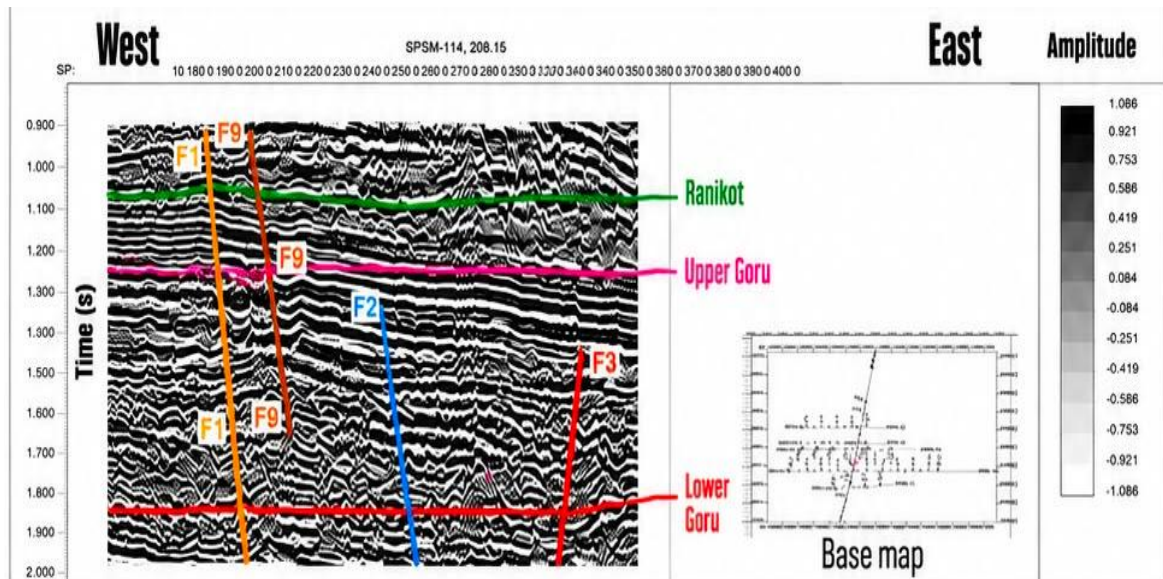


Figure 3. 7 Seismic section of dip line PSM-96-133

PSM-96-135

The Seismic dip line PSM-96-135 represents the southernmost profile within the acquired seismic dataset. Since this line does not intersect with any other available seismic profile, horizon interpretation was performed using the correlation method. Only these fault segments are interpreted on this section that could be correlated with faults identified on adjacent seismic lines, as these were subsequently incorporated into fault polygon construction. The overall structural pattern observed along this seismic line is consistent with the trends identified on the other interpreted seismic profiles.

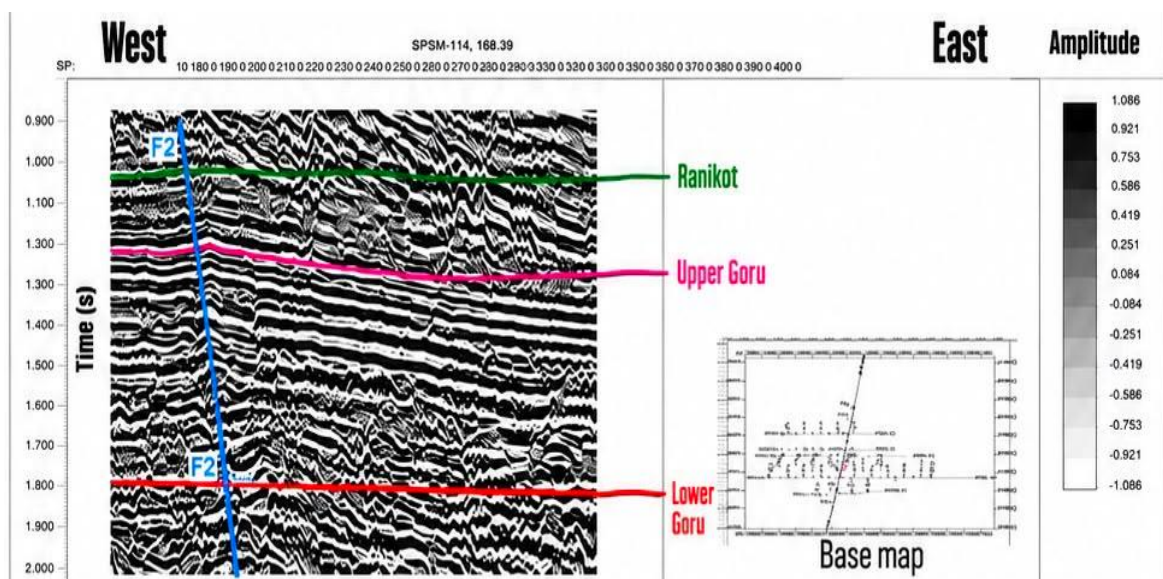


Figure 3. 8 Seismic section of dip line PSM 96-135

The dip line PSM96 -129 and it is the longest seismic profile with the available dataset. It also reveals significant lateral variations in seismic facies, with the facies changes becoming increasingly prominent toward this eastern part of the study field. This eastern region also displays complex structural deformation along with including wrench faulting and the development of horst and graben structures. In comparison, the western portion of the profile is characterized by relatively continuous seismic reflectors and fewer structural disruption, indicating a little more stable geological setting.

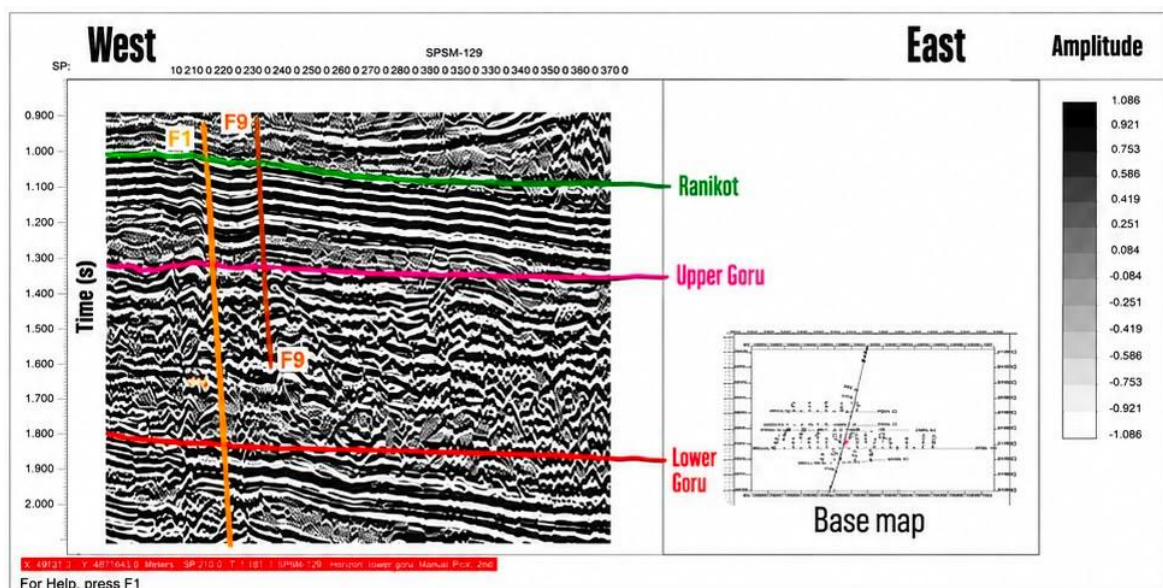


Figure 3. 9 Seismic section of dip line PSM 96-129

3.6 Conclusion of seismic interpretation

Seismic interpretation demonstrates that the subsurface horizons are inclined toward the east, as indicated by the west–east trending dip profiles. An anticlinal feature is observed in the western sector of the Sawan area. According to previous geological studies, the southeastern portion of the area is associated with the Lundo Low, whereas the northwestern part represents the Jacobabad High.

The seismic sections also indicate greater facies complexity toward the eastern part of the study area compared with the western region, particularly along the profiles PSM 96-115. The interpreted structural elements include normal faulting, wrench fault systems, and horst–graben configurations, which collectively suggest an extensional tectonic setting. A more detailed evaluation of these structural features is provided through the generated time–depth structure maps.

3.7 Contour maps

Primary target interval investigated in this study is the C Interval of the Lower Goru Formation. Based on the available literature and the findings of this research, no other interval, member, or formation has been identified as a potential reservoir or zone of interest within the study area. Therefore, the interpreted time and depth contour maps were generated specifically for the C-Interval of the Lower Goru Formation.

3.8 Time contour map

The Time contour map was created by creating a grid of the interpreted horizon across the complete seismic base map, while fault polygons were derived from the interpreted fault surfaces. A total of nine fault polygons were recognized, which intersect the interpreted horizon at different locations, as illustrated in Figure 3.14. The contour Interval used for the map is 0.02 seconds (20 ms) with a map scale of 1:60,000. A more precise representation of the contour variations is provided in Figure 3.15, where the contour interval is reduced to 0.005 seconds (5 ms).

The contour map consists of the gridded horizon surface, contour lines of the C-Interval, nine fault polygons showing a consistent northwest–southeast orientation, a color scale representing structural variations, and the seismic base map. The interpreted structure shows increasing depth toward the southeast in the direction of the Lundo Low, whereas shallower values are observed toward the northwest near the Jacobabad High. The area between these major tectonic features represents the prospective petroleum play region. All three wells are located within fault-bounded zones, while the Sawan-7 well is positioned on a relatively shallow structural closure. Integration of Petrophysical evaluation, Seismic attribute analysis, and fault-seal analysis indicates that these wells are situated within favorable reservoir settings.

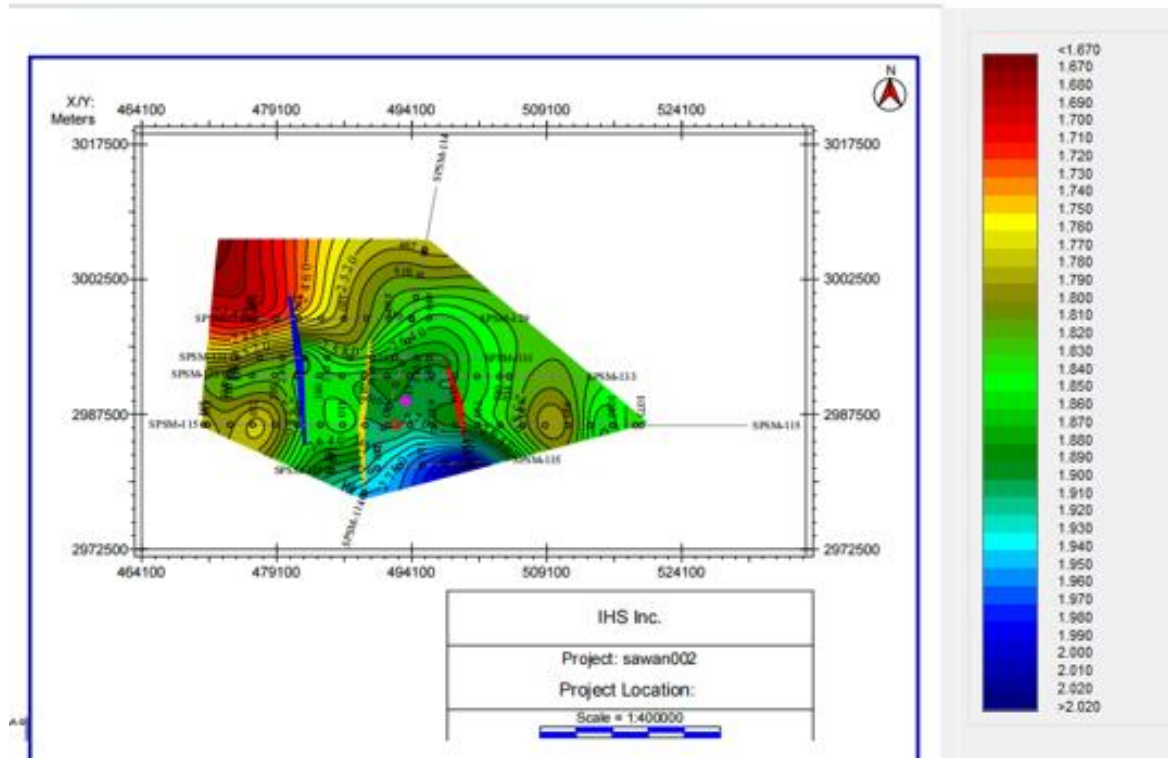


Figure 3. 10 .Time contour map of C-Interval, Lower Goru Formation.

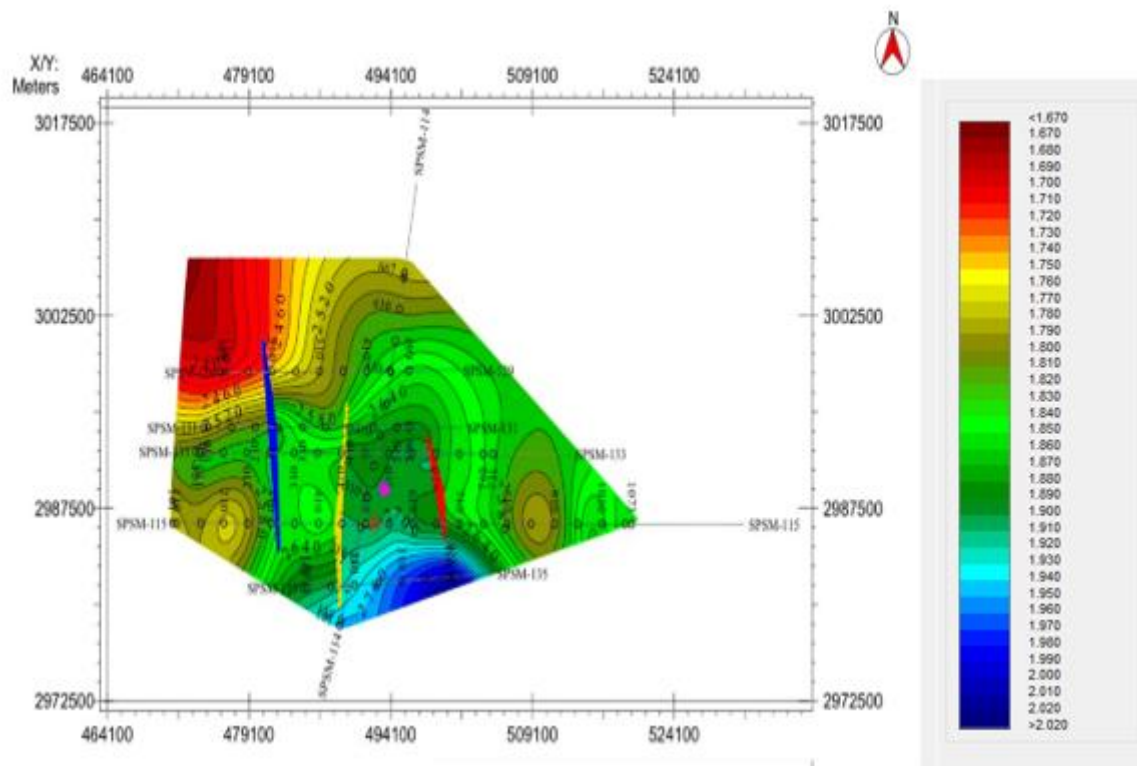


Figure 3. 11 Depth contour map of C-Interval, Lower Goru Formation with contour lines.

3.9 Depth contour map

Depth Conversion and Depth Contour Map Generation

The methodology adopted for generating the depth map in this study is described below:

i. Calculation of Velocity

The velocity of the C Interval were determined using the Velocity windows available within the seismic sections, as well check-shot data were not available for calibration. Two types of velocity information were provided in the seismic dataset: Root Mean Square velocity and migrated velocity NMO. Additionally, both velocity types were evaluated; however, the RMS velocity produced inconsistent depth results, showing variations of approximately 50–200 m when compared with the migrated velocity. Therefore, the final depth conversion was performed using the migrated values of velocity.

ii. Depth Conversion

The seismic velocity values in well locations were manually extracted and compiled in Microsoft Excel. The processed velocity data were then applied to the time grid to generate the depth grid using the standard time-depth relationship:

$$\text{Depth} = (\text{Velocity} \times \text{Time}) / 2$$

For the depth Contour-map, depth grids were made by combining the interpreted time grid with the corresponding velocity grid over the same survey area. Fault polygons were subsequently created from the interpreted fault surfaces. A total of nine fault polygons were identified, intersecting the depth surface at different locations, as shown in Figure 3.16. The contour interval used in Figure 3.16 is approximately 50 m, while a more detailed contour representation with an interval of 10 m is presented in Figure 3.17.

The depth contour-map includes the gridded surface of the C Interval, nine fault polygons oriented predominantly in a northwest–southeast direction, a color scale representing structural variations, and the seismic base map. The depth structure displays a similar overall trend to the time contour map; however, it provides a clearer representation of structural relief and fault displacement. The Sawan-2 well is located within a relatively shallow structural trend, indicating a possible structural closure favorable for hydrocarbon accumulation.

CHAPTER 4

PETROPHYSICAL ANALYSIS OF THE STUDY AREA

4.1 Introduction

Well-logging is one of the most fundamental techniques used in subsurface evaluation, involving the continuous recording of physical, chemical, and electrical properties of geological formations penetrated by a borehole. These measurements, referred to as well logs, provide critical information that enables geoscientists to identify lithology, detect hydrocarbon bearing zones with a high degree of accuracy and evaluate reservoir characteristics. Through the interpretation of log responses, different rock types such as sandstones, shales, and carbonates can be distinguished, while key reservoir properties including porosity and permeability can be quantitatively estimated. Additionally, well logs play a crucial role in fluid identification by differentiating between water, oil, and gas, as well as in determining fluid saturation levels within the pore spaces of the rock. They are also extensively used for reservoir zonation and correlation between wells, allowing for a better understanding of subsurface continuity and heterogeneity. In this study, well log data is utilized to perform petrophysical analysis, which focuses on evaluating the fundamental rock and fluid properties of the reservoir, forming the basis for further reservoir characterization and hydrocarbon assessment (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

4.2 Well Logs Used in This Study

The petrophysical evaluation in this study is based on a comprehensive set of well logs, each providing specific information about subsurface formations and reservoir characteristics. The Gamma Ray (GR) log is primarily used for lithological identification, particularly for distinguishing shale from clean sand formations, and is measured in API units with a typical range of 0 to 150 API. The caliper log records the borehole diameter in inches, generally ranging

from 6 to 16 inches, and is essential for identifying borehole irregularities that may affect log quality. The Spontaneous Potential (SP) log, measured in millivolts (mV) within a range of approximately -100 to +100 mV, serves as an indicator of permeability and helps in correlating permeable zones. Resistivity logs, Later log Shallow (LLS), , including Micro Spherically Focused and Later log Deep (LLD), are crucial for determining fluid type and estimating water saturation, with values typically ranging from 0.2 to 2000 ohm-

m. The Density log (RHOB), measured in grams per cubic centimeter (g/cc), provides bulk density information and is widely used to calculate porosity, with values commonly between 1.95 and 2.95 g/cc. Similarly, the Neutron log (NPHI) estimates porosity based on hydrogen content and is expressed in volume fraction (v/v) or percentage, generally ranging from 0 to 45%. The Sonic log (DT), measured in microseconds per foot ($\mu\text{s}/\text{ft}$), provides information about acoustic velocity and is also used to derive porosity, with typical values between 40 and 140 $\mu\text{s}/\text{ft}$.

These logs are conventionally displayed in multiple tracks within the raw log presentation to facilitate interpretation. Track 1 typically represents depth, serving as the reference scale for all other logs. Track 2 usually contains the Gamma ray and Spontaneous potential logs for lithological and permeability indication. Track 3 is dedicated to resistivity logs (MSFL, LLS, LLD), which are essential for fluid analysis and saturation estimation. Track 4 commonly presents a Density–Neutron overlay, allowing for effective porosity evaluation and gas detection through crossover effects. Additional tracks (Track 5 and beyond) are often used to display computed petrophysical properties such as porosity, water saturation, and shale volume, providing a more integrated interpretation of reservoir characteristics (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

4.3 Petrophysical Analysis

Petrophysical analysis is the quantitative evaluation of reservoir properties using well log data. The key properties evaluated include:

- Volume of shale (Vsh)
- Porosity (Φ)
- Water resistivity (Rw)
- Water saturation (Sw)
- Hydrocarbon saturation (Sh)
- Lithology

4.4 Zone of Interest (ZOI)

A ZOI refers to a specific interval within a well that exhibits characteristics suggesting the presence of hydrocarbons and is therefore selected for detailed petrophysical evaluation. Identification of such zones is based on a combination of log responses that collectively indicate good reservoir quality and favorable fluid conditions. A stable caliper log is first considered, as it reflects a good borehole condition with minimal washouts,

ensuring that the recorded log data is reliable and not distorted by hole enlargement or instability. Low gamma ray values are another key indicator, typically below 80 API, suggesting clean sandstone with low shale content and thus higher reservoir quality. Resistivity log behavior is also critical, where elevated resistivity values indicate potential hydrocarbon presence, and a characteristic separation trend is expected such that MSFL values are lower than LLS, which are in turn lower than LLD, reflecting increasing investigation depth and possible hydrocarbon saturation. In addition, neutron-density crossover is used as a strong gas indicator, where the neutron porosity curve shifts left while the density curve shifts right due to the addition of gas in the pore spaces. Spontaneous potential (SP) deflection further supports zone identification by highlighting permeable formations where fluid movement between formation water and mud filtrate occurs. Only those intervals that satisfy the combined response of these criteria are selected as zones of interest for subsequent petrophysical analysis and reservoir characterization (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

1. Stable Caliper Response

A stable caliper response indicates that the borehole remains close to its drilled diameter and that significant washout is absent. Stable borehole conditions increase confidence in the density, neutron, and other formation-sensitive log responses. Therefore, intervals with a relatively stable caliper response are preferred during reservoir identification because the recorded log data are less likely to be affected by borehole enlargement.

2. Low Gamma Ray Response

The gamma ray log is used to distinguish clean reservoir sandstone from shale-rich intervals. Lower gamma ray values generally indicate cleaner sandstone with a lower shale content, whereas higher gamma ray values indicate increased shale content. In the present study, low GR intervals were therefore considered favorable for identifying potential reservoir sands. The Sawan thesis specifically uses low GR as one of the principal ZOI criteria.

3. High Resistivity and Separation of Resistivity Curves

Resistivity logs are important for identifying the type of fluid occupying the pore spaces. Hydrocarbon-bearing formations generally exhibit higher resistivity than water-

bearing formations. In the present study, the separation between the shallow and deep resistivity curves, particularly the relationship $MSFL < LLS < LLD$, was considered an important indicator of possible hydrocarbon saturation and invasion effects.

4. Neutron-Density Crossover

The neutron and density logs were interpreted together to identify porosity and possible gas-bearing intervals. A pronounced neutron-density crossover is considered a strong indicator of gas because gas in the pore spaces affects the neutron and density responses differently. Therefore, intervals showing a clear crossover along with favorable lithology and resistivity were considered prospective hydrocarbon-bearing zones.

5. Effective Porosity

Effective porosity represents the interconnected pore space that can contribute to fluid storage and movement. Higher effective porosity is therefore considered favorable for reservoir quality. In this study, the selected intervals generally show effective porosity in the range of approximately 15–22%, with the highest values associated with the cleaner and gas-indicated intervals.

6. Low Water Saturation

Water saturation indicates the proportion of pore space occupied by formation water. Lower water saturation generally corresponds to a greater proportion of hydrocarbon-filled pore space when the other reservoir indicators are favorable. In the Sawan study, the lowest water saturation occurs in the cleaner sandstone intervals, supporting their interpretation as the more prospective reservoir zones.

4.5 Formulas

Gamma Ray Index	$IGR = (GR_{max} - GR_{min}) / (GR_{log} - GR_{min})$
Volume of Shale — V_{sh}	$V_{sh} = Igr / 3 - 2Igr$
Density Porosity — ϕ_D	$\phi_D = (\rho_{ma} - \rho_f) / (\rho_{ma} - \rho_b)$
Sonic Porosity — ϕ_S	$\phi_A = 2\phi_D + \phi_N$
Effective Porosity	$V_{sand} = 1 - V_{sh}$
Water Saturation — S_w	$S_w = R_t / (R_w \times \phi_e) - 1$
Depth from Seismic Time	$S = V \times T$

Acoustic Impedance	$Z=\rho V_p$
Reflection Coefficient	$R=\frac{Z_2 - Z_1}{Z_2 + Z_1}$
Synthetic Seismogram	$S(t)=W(t)* R(t)$

4.6 Log Interpretation Summary

Log Type	Observation
Gamma Ray (GR)	Generally low throughout highlighted intervals, indicating predominantly sandstone; local increases correspond to thin shale streaks
Resistivity	Deep resistivity consistently higher than shallow in main reservoirs (hydrocarbon invasion effect); highest at 3278–3300 m and 3356–3378 m
Neutron–Density Porosity	Clear crossover in upper and middle reservoir intervals — classic gas indicator
Sonic Log	Relatively stable through clean sandstone; slight transit-time increases coincide with porous sections
Shale Volume (Vsh)	Most productive intervals show Vsh below 30%; increases below ~3410 m, reducing reservoir quality
Effective Porosity (PHIE)	Ranges ~15–22% (good for sandstone); highest porosity aligns with gas-effect intervals
Water Saturation (Sw)	Lowest (~20–35%) in clean sandstone intervals; increases downward with shale content

4.7 Best Reservoir Zones

Zone	Interval (m)	Lithology	PHIE (%)	Vsh (%)	Sw (%)	Key Feature	Rating
Zone 1	3278–3300	Clean sandstone	21	17.5	25	Strong gas effect	Excellent gas reservoir
Zone 2	3356–3378	Clean	20	20	25	Strong neutron-	Very good gas-

Zone	Interval (m)	Lithology	PHIE (%)	Vsh (%)	Sw (%)	Key Feature	Rating
		sandstone				density crossover	bearing reservoir
Zone 3	3378–3408	Slightlyshaly sandstone	18	—	32.5	Moderate hydrocarbon indication	Good hydrocarbon reservoir

4.8 Overall Interpretation

The logged interval is dominated by clean to slightly shaly sandstone reservoirs with good effective porosity (≈ 17 – 19%) and moderately low water saturation (≈ 30 – 40%). Multiple intervals exhibit a pronounced neutron-density crossover, confirming the presence of gas. The most prospective reservoir intervals occur at 3278–3300 m and 3356–3378 m, where low shale volume, high resistivity, favorable porosity, and low water saturation collectively indicate excellent gas-bearing sandstone reservoirs. Reservoir quality decreases below approximately 3410 m due to increasing shale content and higher water saturation.

4.9 Formation Under Study

The petrophysical analysis in this study was conducted on the Lower Goru Formation, which represents a major reservoir unit within the Lower Indus Basin. This formation is of significant interest due to its proven hydrocarbon potential and favorable lithological characteristics, particularly its dominance of sandstone with interbedded shale layers, which together create suitable conditions for reservoir development and fluid accumulation. The interval selected for analysis is defined by an initial depth of (add your exact value) and a final depth of (add your value), and the net thickness of the formation is determined by subtracting the initial depth from the final depth. This stratigraphic interval was chosen based on log responses indicating reservoir quality and hydrocarbon presence, making it suitable for detailed petrophysical evaluation and interpretation of subsurface properties (Shah, 2009; Asquith and Krygowski, 2004).

4.10 Petrophysical Parameters and Equations

4.10.1 Volume of Shale (Vsh)

First, Gamma Ray Index is calculated:

Equation (4.1): Gamma Ray Index

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

Where:

- (GR_{log}) = observed gamma ray
- (GR_{min}) = clean sand value
- (GR_{max}) = shale value Then using Steiber equation:

Equation (4.2): Volume of Shale

$$[V_{sh} = \frac{I_{GR}^3 - 2I_{GR}}{3 - 2I_{GR}}] \quad 4.1$$

4.10.2 Porosity (Φ)

From density log: Equation (4.3): Density Porosity

where

ϕ_D = Density Porosity of the formation

ρ_{ma} = matrix density of the rock (commonly 2.65 g/cm³ for sandstone) ρ_b = Bulk density of the formation obtained from the log

ρ_f = Density of the pore fluid (approximately 1.1 g/cm³)

Neutron log gives direct porosity.

Average Porosity:

Equation (4.4):

- $\Phi_T = \Phi_D + \Phi_N/2$ 4.2
- ϕ_A = Average Porosity.
- ϕ_D = Density Porosity.
- ϕ_N = Neutron Porosity.

4.10.3 Water Resistivity (Rw)

Rw is calculated using Pickett Plot or Archie method.

4.11 Pickett Plot Concept:

- Plot R_t vs Φ on log-log scale
- Slope gives cementation factor
- Intercept gives R_w

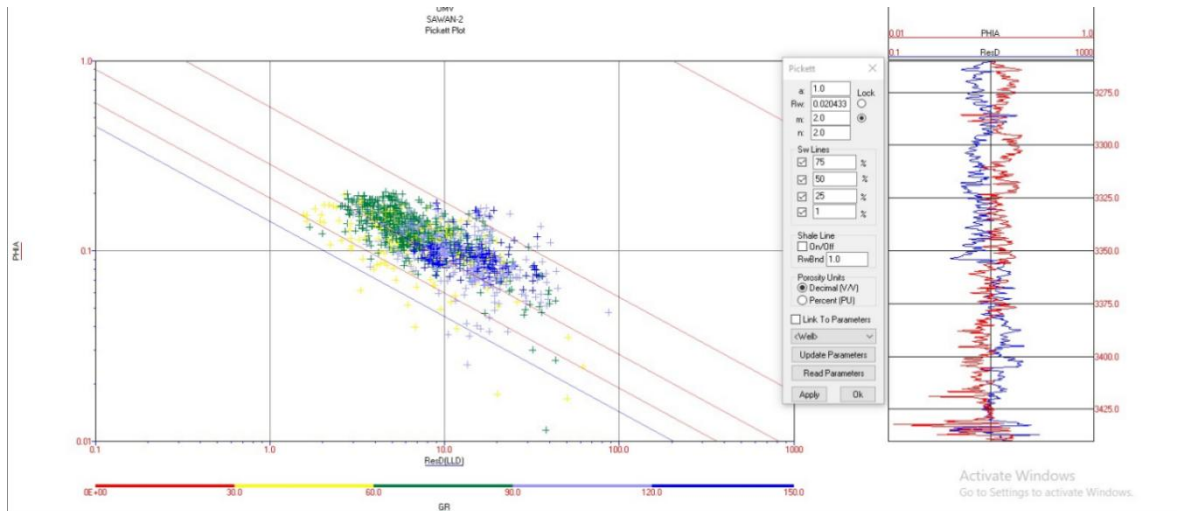


Figure 4. 1 Pickett plot of Sawan 02Well in Lower Goru Formation

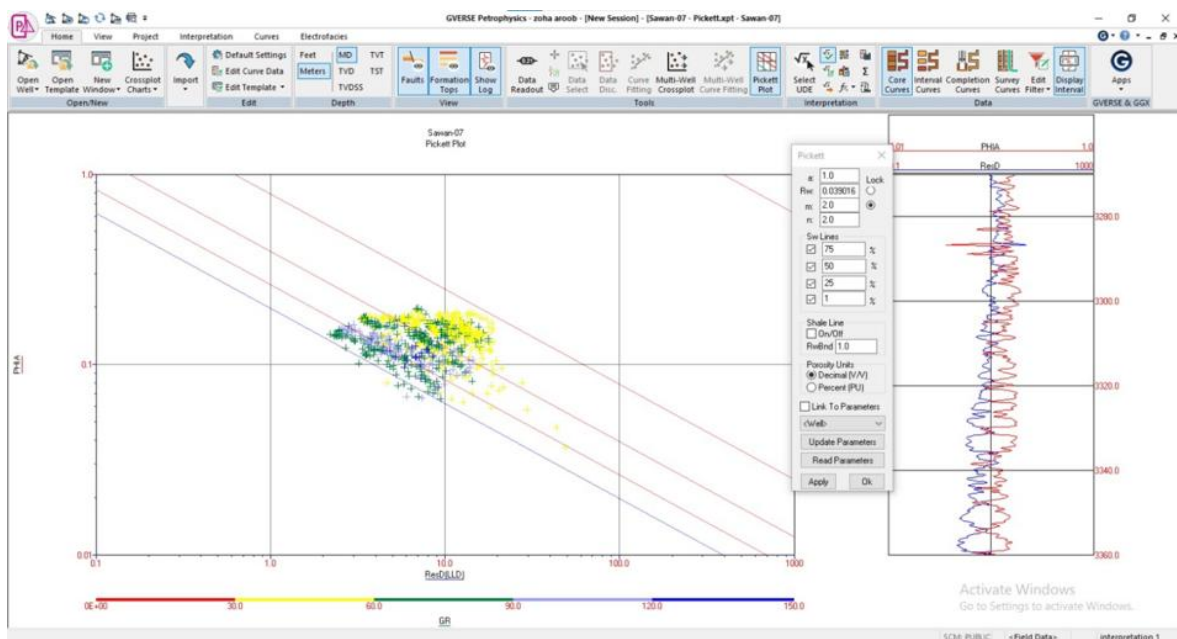


Figure 4. 2 Pickett plot of Sawan 07 Well in Lower Goru Formation

Water Saturation (Sw)

Using Archie's Equation:

Equation (4.5): Archie Equation

$$[S_w^n = \frac{a R_w}{\Phi^m R_t}] \quad 4.3$$

Where:

- (S_w) = water saturation 4.4
- (R_w) = water resistivity
- (R_t) = true resistivity (LLD)
- (Φ) = porosity
- (a) = tortuosity factor
- (m) = cementation exponent
- (n) = saturation exponent

4.11.1 Hydrocarbon Saturation (Sh) Equation (4.6):

$$S_h = 1 - S_w \quad 4.5$$

4.12 Interpretation Logs

After applying the established cutoffs and performing the required petrophysical calculations, a set of interpretation logs is generated to visually represent the subsurface reservoir characteristics. These results are typically displayed in the final tracks of the well log presentation, where different petrophysical parameters are distinguished using color-coded outputs for clearer interpretation. The volume of shale (Vsh) is represented in gray and highlights shale content within the formation, which directly impacts reservoir quality and fluid flow potential. The volume of sand is shown in yellow and indicates the cleaner, more reservoir-prone intervals with higher storage capacity. Water saturation (Sw), displayed in blue, displays the proportion of pore space reserved by formation water and is critical for evaluating hydrocarbon productivity. Hydrocarbon saturation (Sh), shown in green, reflects the proportion of pore space filled with hydrocarbons and is a direct indicator of reservoir potential. Together, these interpretation tracks provide an integrated visual summary of reservoir quality, allowing for efficient evaluation of productive zones and aiding in the final assessment of hydrocarbon-bearing intervals.

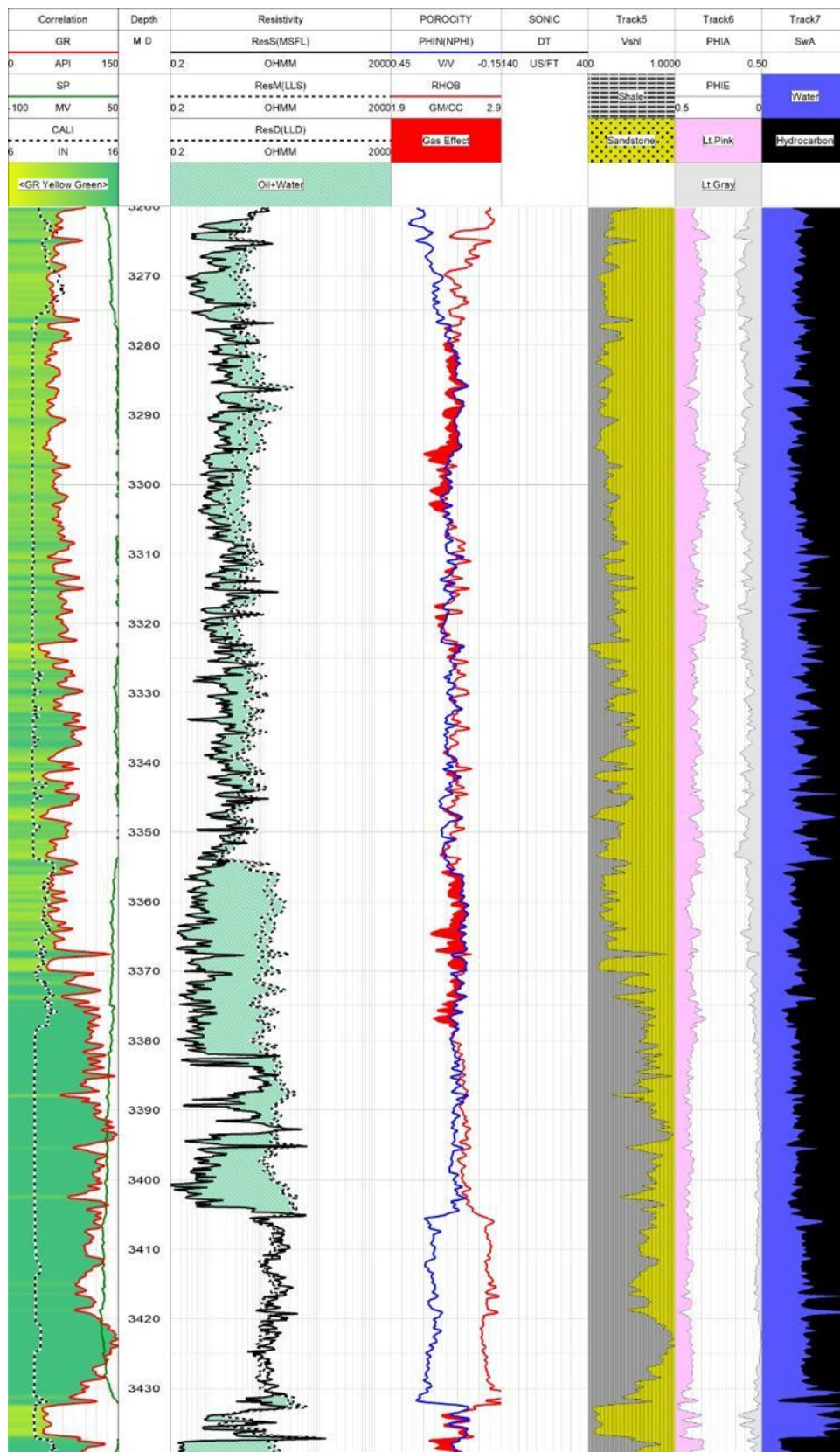


Figure 4. 3 Uninterpreted Sawan 02 Well in Lower Goru Formation

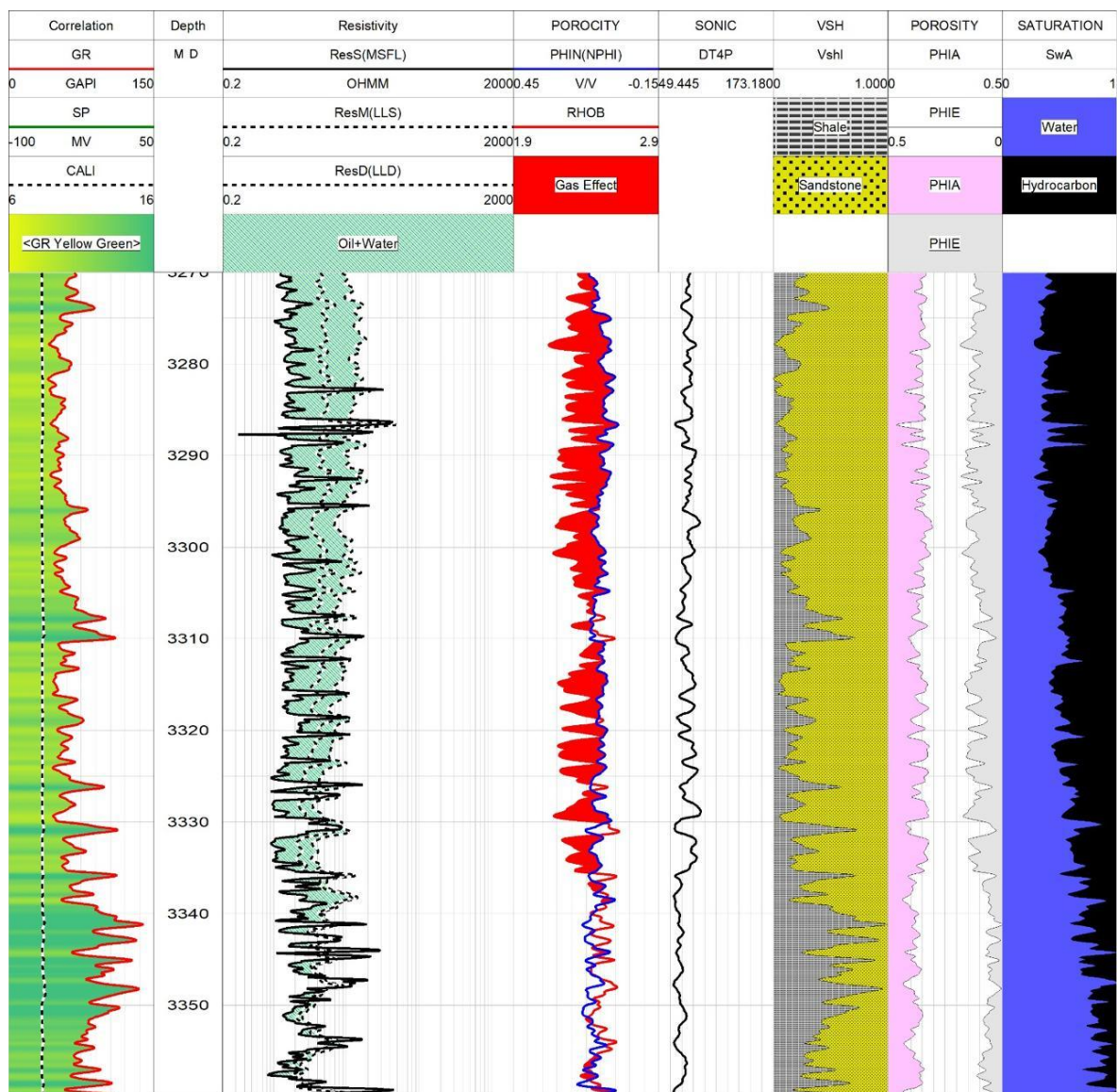


Figure 4. 4 Uninterpreted Sawan 07 Well in Lower Goru Formation

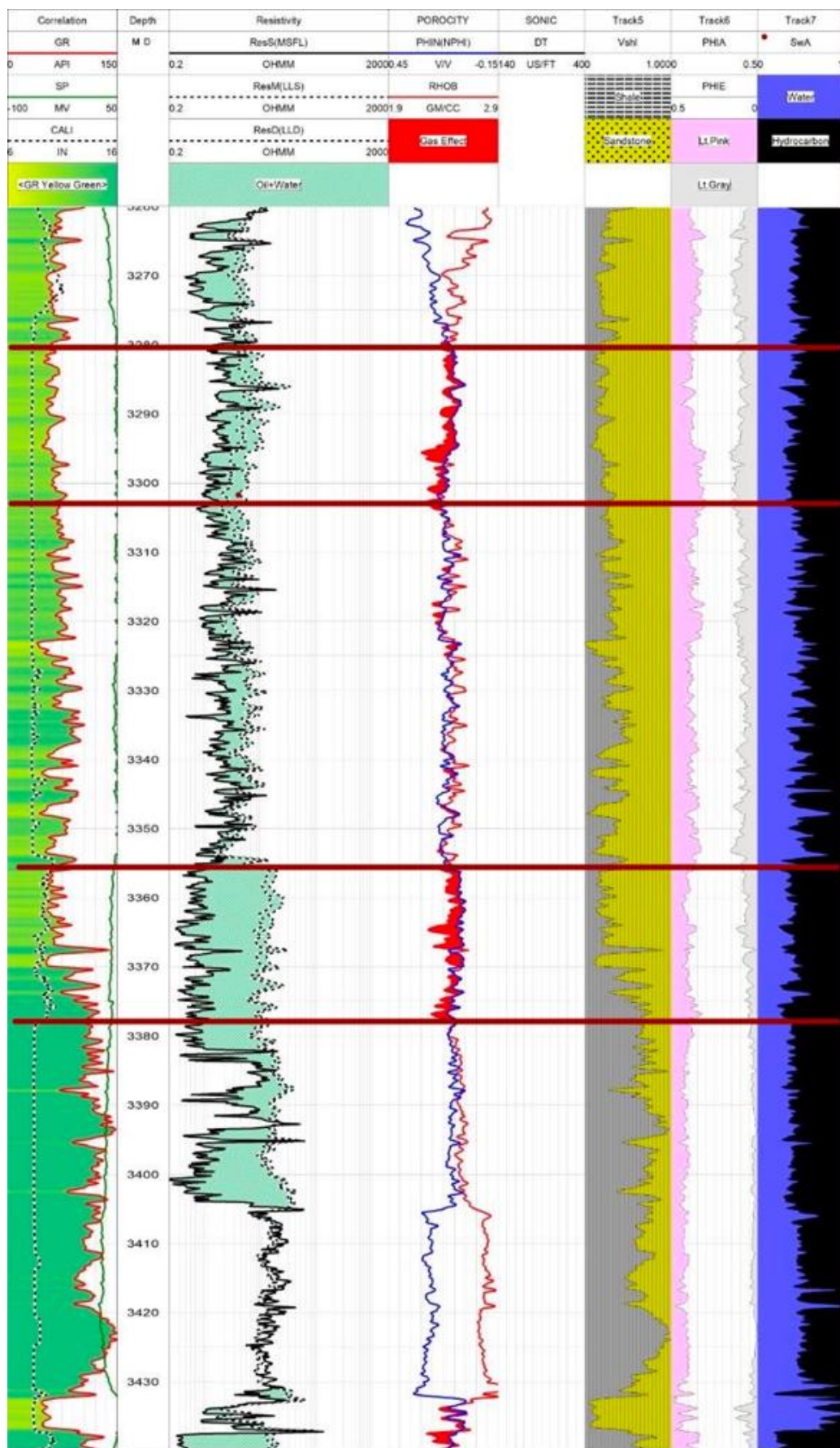


Figure 4. 5 Interpreted Zones of Sawan 02 Well in Lower Goru Formation

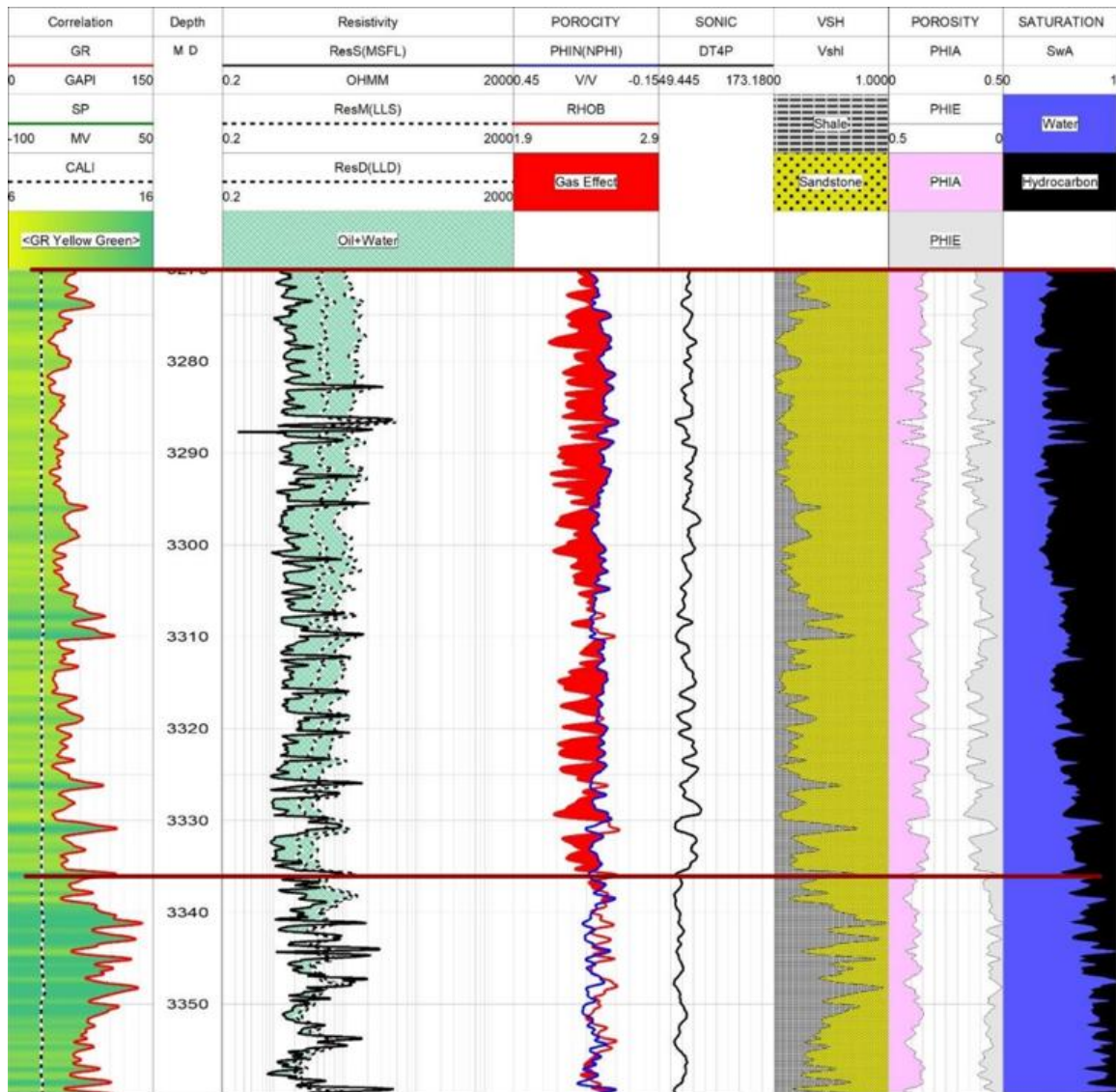


Figure 4. 6 Interpreted Zones of Sawan 07 Well in Lower Goru Formation

4.13 Interpretation of the Interpreted Well Log

The interpreted well-log response provides an integrated view of lithology, reservoir quality, porosity, and fluid saturation within the investigated interval of the Lower Goru Formation. The gamma ray response is generally low across the principal reservoir intervals, indicating predominantly clean sandstone, although local increases in gamma ray correspond to shale-rich streaks. The resistivity response shows higher deep resistivity compared with shallow resistivity within the main reservoir intervals, particularly at 3278–3300 m and 3356–3378 m, indicating favorable hydrocarbon saturation and invasion effects. The neutron and density logs display clear crossover behavior in the upper and middle reservoir intervals, which provides a strong indication of gas. The sonic response

remains relatively stable through the clean sandstone intervals, with slight increases in transit time corresponding to more porous sections.

The calculated petrophysical parameters further support the interpretation of these intervals. The most productive intervals generally have V_{sh} values below 30%, while effective porosity ranges approximately from 15–22%. Water saturation is lowest within the cleaner sandstone intervals, generally ranging from approximately 20–35%, indicating a comparatively greater hydrocarbon-filled pore volume. In contrast, increasing shale content and water saturation below approximately 3410 m result in poorer reservoir quality.

Based on the integrated interpretation of gamma ray, resistivity, neutron-density, shale volume, effective porosity, and water saturation, the 3278–3300 m interval (Zone 1) is interpreted as the best reservoir zone in the studied interval. This zone consists of clean sandstone and exhibits relatively low shale volume of approximately 15–20%, effective porosity of approximately 20–22%, and low water saturation of approximately 20–30%. The interval also shows a strong neutron-density crossover and high resistivity response, providing strong evidence for gas saturation. The combination of clean lithology, favorable porosity, low water saturation, high resistivity, and strong gas indication makes Zone 1 an excellent gas-bearing reservoir interval.

The 3356–3378 m interval (Zone 2) is interpreted as the second-best reservoir interval. It is characterized by clean sandstone, shale volume of approximately 15–25%, effective porosity of 18–22%, and water saturation of approximately 20–30%. A strong neutron-density crossover and relatively high resistivity further support the presence of gas. Therefore, this interval is classified as a very good gas-bearing reservoir.

The 3378–3408 m interval also represents a good reservoir zone, but its slightly shaly nature and somewhat higher water saturation reduce its quality compared with Zones 1 and 2. Its effective porosity remains favorable at approximately 16–20%, while water saturation increases to approximately 25–40%. It is therefore interpreted as a good hydrocarbon-bearing reservoir rather than an excellent one.

4.14 Hydrocarbon Bearing Zones

Hydrocarbon Bearing zones are identified through the integration of multiple log-based criteria that collectively indicate favorable reservoir conditions and fluid presence. Low gamma ray values are used as the primary indicator of clean sandstone, reflecting

minimal shale content and thus improved reservoir quality. High resistivity responses further support hydrocarbon presence, as hydrocarbons resist electrical current more strongly than formation water, resulting in elevated resistivity readings. The neutron–density crossover is also a key diagnostic feature, particularly for gas-bearing zones, where the neutron porosity curve shifts left while the density curve shifts right due to the lower hydrogen index of gas compared to liquids. In addition, proper resistivity separation among shallow and deep resistivity tools reinforces fluid interpretation, where a consistent trend such as $MSFL < LLS < LLD$ often suggests invasion effects and hydrocarbon saturation in the uninvaded zone. When these indicators occur together, they provide a reliable basis for delineating hydrocarbon-bearing intervals within the reservoir (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

4.15 Sawan-2 Well

Four hydrocarbon zones identified

- Zone 1: 3280-3303 (MD)
- Zone 2: 3356-33779(MD)

4.16 Sawan-7 Well

Two hydrocarbon zones identified:

- Zone 1: 3268-3338 (MD)

4.17 Lithology Analysis

Lithology interpretation in this study is carried out using neutron–density cross plots, which provide a reliable method for identifying formation composition based on the combined response of porosity-sensitive logs. The results indicate that sandstone is the dominant lithology within the reservoir interval, suggesting favorable reservoir quality and good storage capacity for hydrocarbons. In addition to sandstone, minor shale and calcite are also present, reflecting heterogeneity within the formation that may influence reservoir continuity and fluid flow behavior. The interpreted porosity values from the neutron–density relationship range between 10% and 25%, indicating moderate to good porosity conditions suitable for hydrocarbon accumulation and production potential. This lithological and petrophysical interpretation provides an essential framework for reservoir characterization and further evaluation of the Lower Goru Formation (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

4.18 Summary

The Petrophysical analysis of the Lower Goru Formation indicates the presence of multiple hydrocarbon-bearing zones, confirming its significance as a productive reservoir interval within the Lower Indus Basin. The formation is predominantly composed of sandstone, which provides favorable conditions for hydrocarbon storage and flow due to its relatively higher porosity and permeability compared to finer-grained lithologies. The evaluated porosity is generally moderate to good, suggesting sufficient pore space for hydrocarbon accumulation and potential economic recovery. Clear and consistent log signatures further support the presence of hydrocarbons, as evidenced by characteristic responses in gamma ray, resistivity, and neutron–density logs, which collectively validate the interpreted fluid content and reservoir quality. Overall, the integration of well log data, established petrophysical equations, and systematic interpretation techniques enables a reliable and comprehensive evaluation of the reservoir characteristics and hydrocarbon potential within the study interval (Asquith and Krygowski, 2004; Rider and Kennedy, 2011).

CONCLUSIONS

1. A comprehensive study was undertaken in the Sawan Area which identified several normal faults indicating active extensional tectonics in the region. These faults categorized as F1 till F10 are interpreted in seismic sections which is leading to the creation of multiples horst and graben structures favorable for hydrocarbon accumulation.
2. Petrophysical analysis showed two zones within the Lower Goru Formation showing below par reservoir potential. Zone 1 exhibited 33.9% shale volume, 27.6% hydrocarbon saturation and 8.9% effective porosity indicating a moderate potential for hydrocarbon content. In contrast Zone 2 showed 42% shale volume, 33.5% hydrocarbon saturation and 5.7% effective porosity suggesting a higher hydrocarbon saturation, but lower effective porosity as compared to Zone 1. These findings highlight the heterogeneous nature of hydrocarbon distribution within the Lower Goru Formation where zone 2 having relatively more values of hydrocarbon saturation but depict high volume of shale with less effective porosities.

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