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The geophysical approach to interpret reservoir characterization of the Middle Jurassic Shinawari Formation, Upper Indus Basin, Pakistan

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Abstract

The Shinawari Formation of Middle Jurassic age is represented by the stratigraphy of mixed carbonate and clastic rocks. The present study attempts to incorporate data from subsurface wells CDW 01 and MW 01 and seismic lines, covering the area of the Upper Indus Basin, Pakistan. In the CDW 01 well, the Shinawari Formation reaches a total thickness of about 71 m, between 4579 and 4650 m. Zone 1, the principal zone of interest, is developed between 4580 and 4635 m, having 39% Ω·m water resistivity (Rw), 4.2% average porosity (PHIE), 58 µs/ft Delta-T (DT) value, and 8% effective porosity. At the CDW 01 well, the reservoir shows approximately 68% water saturation (SWA) and 32% hydrocarbon saturation. While the MW 01 well is characterized by 116 meters of thickness, having a zone of interest designated as zone 1 with 32% average shale value, 49 % Ω·m water resistivity (Rw), 64% average porosity (PHIE), 50.64 µs/ft Delta-T (DT) value, and 20.0 % effective porosity. At the MW 01 well, the reservoir shows approximately 42% water saturation (SWA) and 58% hydrocarbon saturation. Furthermore, depth contour and two-way time (TWT) maps are generated and interpreted from the seismic data. Furthermore, an integrated approach from seismic and well logs (Bulk density vs Neutron porosity cross plot) data portrays that the Middle Jurassic, Shinawari Formation has good potential for the indigenous hydrocarbons and heavy minerals.

Keywords: Jurassic; software; reservoir; seismic; well logs; Indus Basin.

1. Introduction

Pakistan faces a critical energy crisis that demands not only creative approaches but also immediate strategic intervention to overcome on going severe energy crisis. However, these solutions must be developed as quickly as possible, as there are severe negative impacts on the development industry due to the lack of adequate energy supplies. According to published research, only 10 to 20 percent of Pakistan's 827,365 km^2 of sedimentary outcrops have been explored (Jamil et al., 2012; Kuuskraa, 2013). The increase in the demand for energy in Pakistan continues to grow due to an increase in population and a lack of discoveries of new hydrocarbon resources within less explored energy provinces (Jamil et al., 2012).

The major source of hydrocarbons found in Pakistan to date is the Indus Basin. During the Jurassic Period, thick sedimentary layers were formed in the Indus Basin, Pakistan. Apart from the coal, shale, clay, and economic layers of silica sands, the formations in the strata are dominated by shallow marine limestones and sandstones as mixed-carbonate-siliciclastic sequences. These originate close to the equator on the northern edge of the Indian Plate. Previous researchers have investigated varying Jurassic rock exposures in the stratigraphic section exposed in the Salt and Trans Indus Ranges regarding sediment deposition, sequence framework, source rock geochemistry, and bio with litho-stratigraphy

(Danilchik and Shah, 1967; Fatmi, 1972; 1974; Fatmi et al., 1990; Mertmann and Ahmad, 1994; Ahmed et al., 1997; Ali et al., 2018; 2019; 2020; 2022; 2023; Hakimi et al., 2025). With focus on the Shinawari and Samana Suk formations, Ahmed et al. (1997) examined the entire Jurassic sequence in the Salt and Trans Ranges to interpret the broad framework of sequence stratigraphic signature by using the tool of microfacies analysis. While the biostratigraphy interpreted from the palynology indicates Toarcian-Bathonian age to the studied formation from the previously published literature (Ali et al., 2018).

It is worth mentioning that before palynology, the age was assigned only on the presence of certain ammonites without proper biozonation, exactly marking the upper and lower boundary. The study of palynology not only provides correction of basin stratigraphy by correcting its age, i.e., Toarcian-Bathonian, but it also documents various flora and fauna of the other Eastern Tethys oceans. Besides the sedimentology, the Jurassic source and reservoir rocks' potential is also documented in the previous literature, enhancing their importance in the oil industry in the Indus Basin, Pakistan. Additionally, the most recent location in the oil and gas fields of Nashpa, Makori, Manzali, and Meyal focuses on Jurassic source rocks for oil and gas exploration and exploitation (Wandrey et al., 2004a-b; Ali et al., 2019; 2021; Hakimi et al., 2025). Regarding the assessment of conventional and unconventional reservoir features along with their key role in the energy sector in Pakistan's Indus Basin, the sedimentary sequence has received very little attention with respect to reservoir characterization. It is worth mentioning that the goal of the current study is to fill the gap in existing literature by conducting a thorough analysis of subsurface data through a geophysical approach for reservoir features. The geophysical approach covers the area of seismic and petrophysical analysis.

2. Geological setting

In the Upper Indus Basin, Middle Jurassic rock includes the Shinawari Formation sandwiched between the Datta Formation below and the Samana Suk Formation above. The Shinawari Formation is deposited in a shallow marine transitional setting (Fatmi, 1974; Khan et al., 1986; Bender and Raza, 1995; Kazmi and Jan, 1997; Shah, 2009; Ali et al., 2019). The Middle Jurassic, Shinawari Formation represents diversified lithology having mixed strata of fossiliferous and unfossiliferous limestone, neat and clean sandstone, with organic shale, and thin coal layers with disseminations (Ali et al., 2018; 2019).

Indus Basin, Pakistan, has diversified reservoir rocks ranging from Precambrian to the Miocene (Khan et al., 1986; Quadri and Quadri, 1996; Jaswal et al., 1997; Wandrey et al., 2004; Fazeelat et al., 2010). From the Precambrian to the Eocene periods, two broader TPS (Total Petroleum Systems) were recognized, i.e., Patala–Nammal and Sembar–Goru petroleum systems. The broader TPS is due to the limited national and international published literature available in the Indus Basin, Pakistan (Wandrey et al., 2004a,b). The famous reservoir rock in the TPS is represented by the Eocambrine, Permian, Triassic, Jurassic, Cretaceous (Lower), Paleocene, Eocene, and Miocene (Lower) (Khan et al., 1986; Raza, 1991; Jaswal et al., 1997; Tobin and Claxton, 2000; Wandrey et al., 2004a; Raza et al., 2008). The major classification of reservoir rocks in the Indus Basin can be attributed to the lack of availability of comprehensive national and international data reports related to petroleum geology, reservoir characterization, and reservoir simulation disciplines.

3. Methodology

3.1 Database

Specifically, geophysical data, i.e., LAS file, and seg Y file at CDW 01 and MW 01 oil field in the Upper Indus Basin are utilized in the current research work (Fig. 1a). The data are obtained from Land Mark Reservoirs (LMKR) with the prior approval of the Directorate General Petroleum Concession (DGPC), Islamabad, Pakistan. The software is used to import the location of the studied wells and seismic line onto the basic map (having x and y axes).

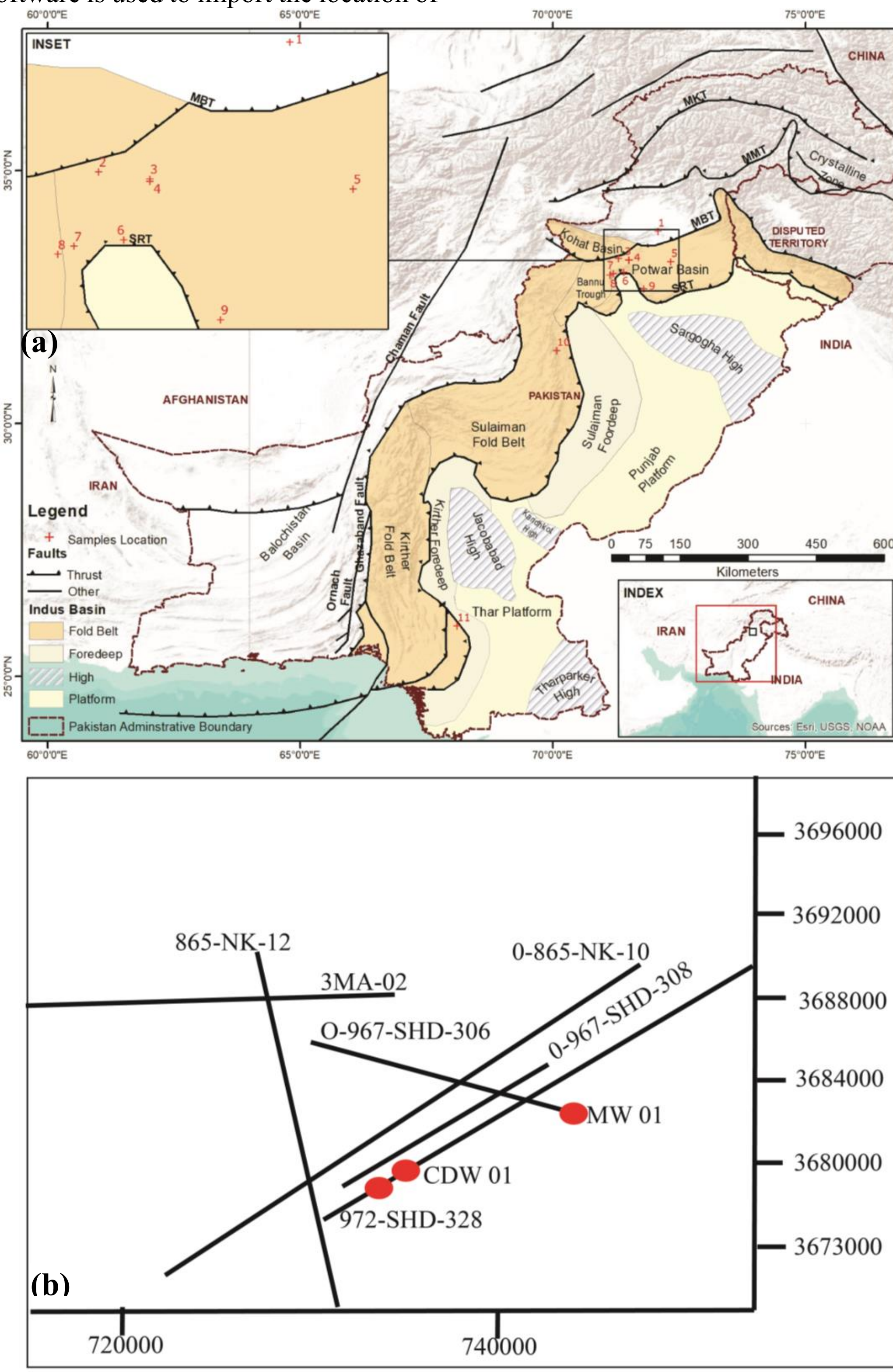

Fig. 1. Showing the position of the investigated wells in the Indus Basin, Pakistan, i.e., oil field 1= CDW 01 well, while 2=MW 01 well (map used after Ali et al., 2021) in sub figure a), while the base map displays the position of seismic lines and wells position in Upper Indus Basin, Pakistan in sub figure b). The MW 01 is located on the line 0-967-SHD-306, while CDW 01 is located on the line 972-SHD-328.

The data provided to the software for well logs is in LAS format, while for seismic, the data are in a SEG-Y file. The LAS and Seg Y data are utilized for the interpretation of the stratigraphy, structure, geology, and sequence stratigraphy of the studied lines and wells. The Seg Y file in the current seismic analysis is represented by seismic lines, i.e., 1=O-967-SHD-306 and 2= 972-SHD-328 (Fig. 1b).

3.2 Data Analysis

3.2.1 Petrophysical and seismic analysis

The sub-surface data wells, i.e., CDW 01 and MW 01 oil field, and Seg Y file are obtained from the LMKR (land mark reservoirs) with endorsements from DGPC. The current investigation aims to analyze the reservoir characteristics of the Shinawari Formation by analyzing the LAS files of CDW 01 and MW 01 oil wells and Sig Y data of the oil field. The reservoir investigation was performed by understanding the petrophysical analysis of various logs of the studied strata through Kingdom software. The considered logs are such as gamma ray logs (GR), spontaneous potential logs (SP), latrolog deep (LLD), calliper log, latrolog shallow (LLS), density log (RHOB), and sonic & neutron logs (NPHI). The petrophysical and seismic analyses were carried out using the methodology reported in the literature (Rider, 1996, Asquith et al., 2004, Naji et al., 2010, El-Din et al., 2013, Isyaku et al., 2016, Khan et al., 2016).

4. Results

4.1 Borehole stratigraphy

Different cross plots, like NPHI and RHOB, are utilized for the interpretation of litho-stratigraphy from the Las file data. For the interpretation of data, the RHOB is plotted on the vertical axis, and NPHI is plotted on the horizontal axis (Fig. 2).

Stratigraphy of Shinawari Formation in Indus Basin, borehole wells are indicated in Tables 1 and 2, showing that the formation thickness is 116 meters having recorded formation top of about 4799 feet, portraying the litho-stratigraphy of carbonate rock mixed with clastic units in the MW 01 well.

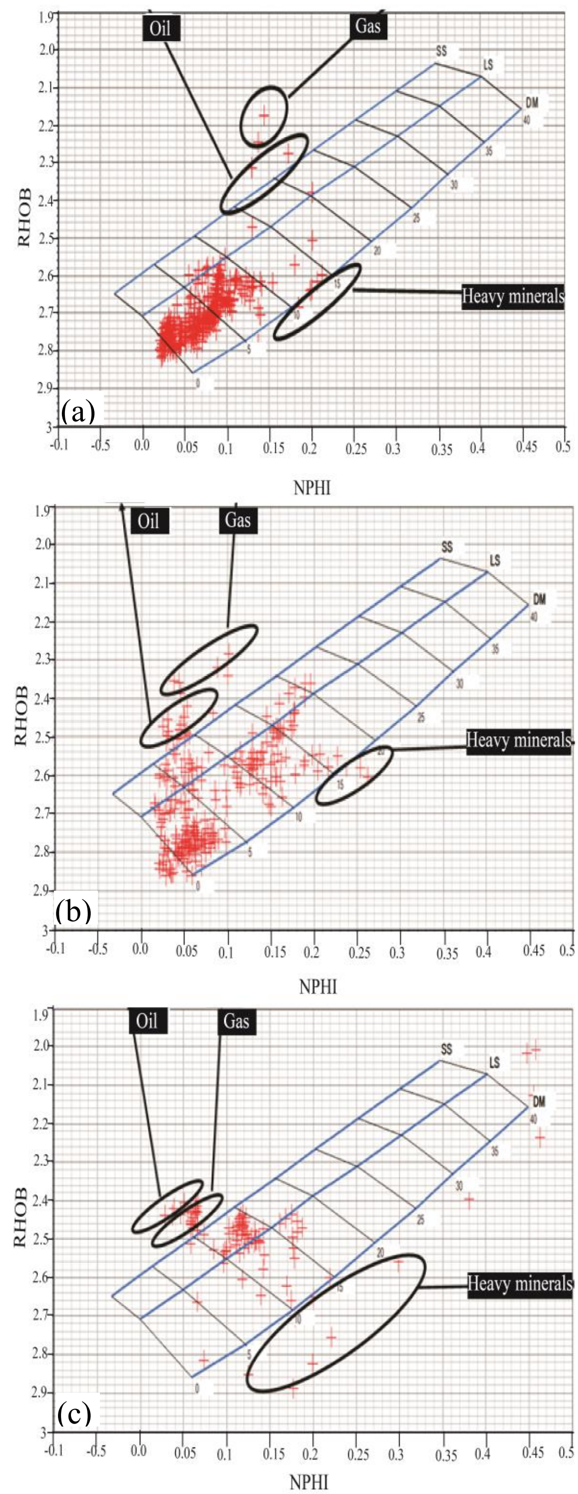

Fig. 2. Describing cross-plots presents lithological identifications for both wells, CDW 01 and MW 01, in sub-figure a). While the sub-figure b) cross-plot illustrates lithology descriptions for oil well CDW 01, and the sub-figure c) cross-plot illustrates lithology descriptions for oil well MW 01 in the Upper Indus Basin, Pakistan.

Table 1: Showing the borehole stratigraphy of MW 01 Well, Indus Basin, Pakistan.

Age		Formation	Thickness (meter)	Formation Top
Oligocene		Murree	1320	815
Eocene	Middle	Kohat	99	2135
Eocene	Middle	Kuldana	123	2234
Eocene	Lower	Jatta	28	2357
Eocene	Lower	Bahadukhel	562	2358
Eocene	Middle	Kuldana	32	2947
Oligocene		Murree	229	2979
Eocene	Middle	Kohat	39	3208
Eocene	Middle	Kuldana	92	3247
Oligocene		Murree	659	3339
Eocene	Middle	Kohat	68	3998
Eocene	Middle	Kuldana	82	4066
Eocene	Lower	Jatta	139	4148
Paleocene	Upper	Patala	96	4287
Paleocene	Middle	Lockhart	227	4383
Paleocene	Lower	Hangu	41	4660
Cretaceous	Middle	Lumshiwal	10	4701
Cretaceous	Lower	Chichali	48	4711
Jurassic	Middle	Samana Suk	40	4759
Jurassic	Lower	Shinawari	116	4799
Jurassic	Lower	Datta	37	4915
Total Depth				4951.7

The oldest stratigraphic unit is the Datta Formation, while the youngest unit is Muree Formation. While in the CDW 01, the studied formation thickness is 71 meters having recorded formation top of about 4579 feet, protraying litho-stratigraphy of carbonate rock mixed with clastic units having oldest units being the Wargal Formation and the youngest being the Nagri Formation.

4.2 Petrophysical Analysis

The subsurface data investigation is a reliable source to interpret the hydrocarbon-bearing zones through a petrophysical approach. The petrophysical approach shown in Table 3 and Figs. 3-4 provides deep insights into the reservoir characterization. The petrophysical analysis is essentially used to identify the reservoir zone through several logs (GR, LLD, NPHI, and SP). The potential reservoir zones demonstrate low GR and SP values, extraordinary LLD values, and high NPHI values, indicating good porosity. Furthermore, various cut-off parameters are set for rock having primary porosity based on the previous literature, such as Sw<60%, Vsh<30%, φE>07%. While for rock having secondary porosity/carbonate rock, the cut-off parameters are mentioned as Vsh<30%, Sw<60%, and φE=1%.

Table 2: Showing the borehole stratigraphy of CDW 01 Well, Indus Basin, Pakistan.

Age		Formation	Thickness (meter)	Formation Top
Pliocene		Nagri	503	0
Miocene		Chinji	1643	503
Miocene		Kamlial	718	2146
Miocene		Murree	1192	2864
Eocene	Middle	Kohat	12	4056
Eocene	Middle	Kuldana	34	4068
Eocene	Lower	Jatta	41	4102
Paleocene	Upper	Patala	86	4143
Paleocene	Middle	Lockhart	170	4229
Paleocene	Lower	Hangu	28	4399
Cretaceous	Middle	Lumshiwal	23	4427
Cretaceous	Lower	Chichali	49	4450
Jurassic	Upper	Samana Suk	80	4499
Jurassic	Middle	Shinawari	71	4579
Jurassic	Lower	Datta	160	4650
Triassic		Kingriali	19	4810
Triassic		Tredian	70	4829
Triassic		Mianwali	64	4899
Permian		Chhidru	81	4963
Permian		Wargal	56	5044
Total Depth				5100

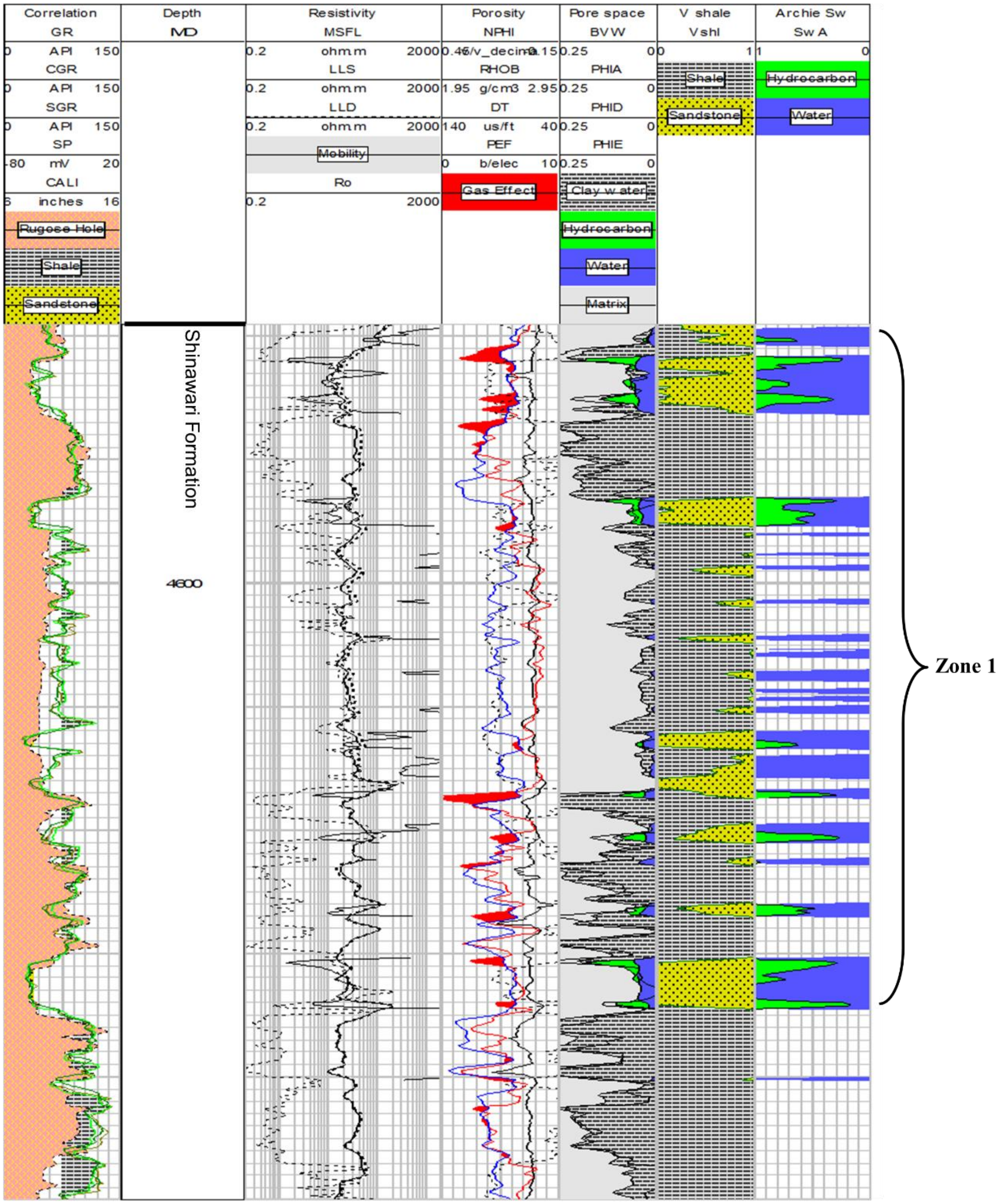

Fig. 3. Petrophysical analysis of the Shinawari Formation in oil well CDW 01, Upper Indus Basin, Pakistan.

Table 3: Petrophysical analysis of the Shinawari Formation, Upper Indus Basin, Pakistan.

Well	Formation	Zone	Volume of Shale (%)	Effective Porosity (%)	PHIE	Rw Ω·m	DT µs/ft	Water Saturation (%)	Hydrocarbon Saturation (%)
CDW 01	Shinawari Formation	Zone 1	62	8	4.2 %	0.39	58	68	32
MW 01		Zone 1	32	20	64 %	0. 49	50.64	42	58

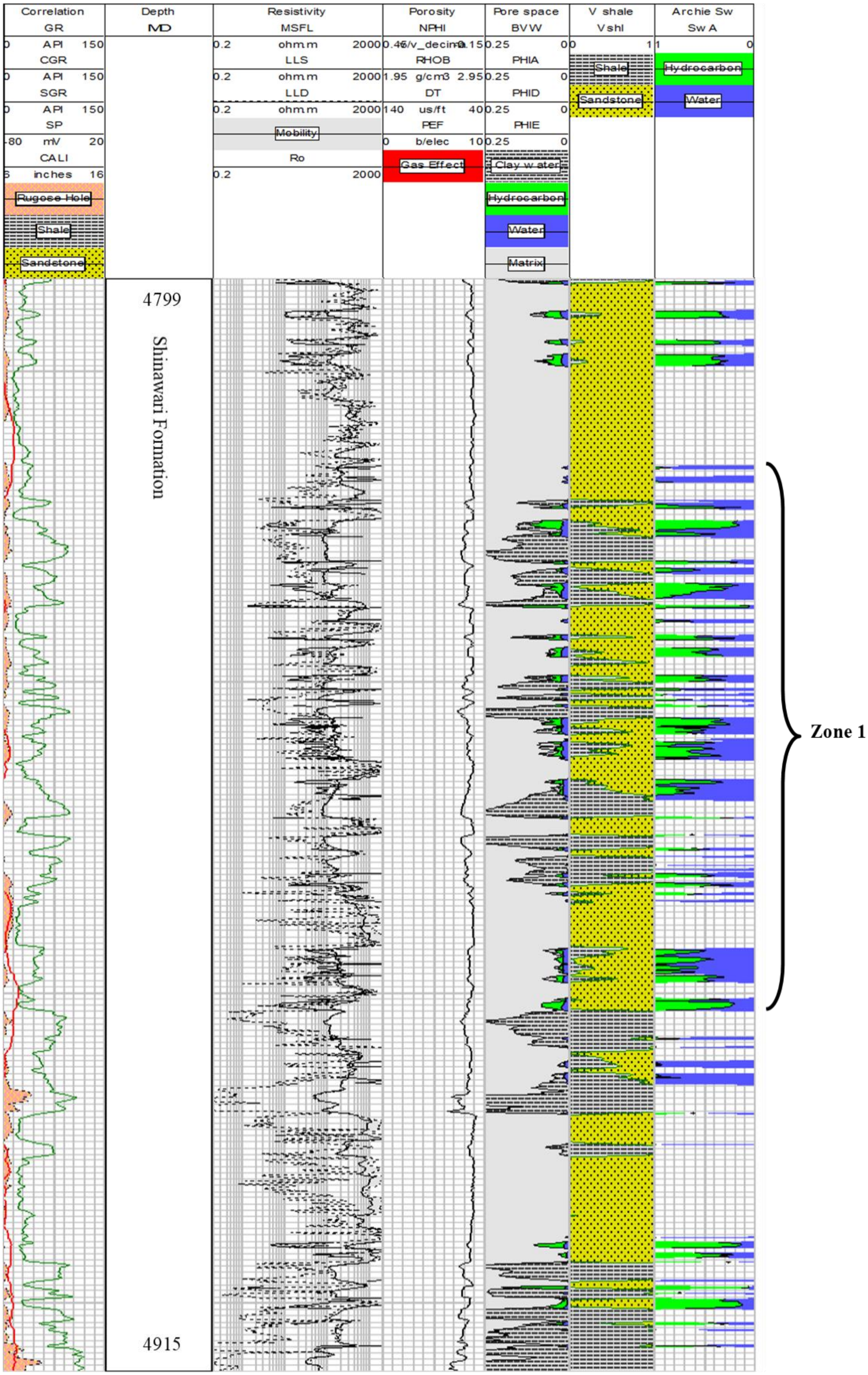

Fig. 4. Petrophysical analysis of the Shinawari Formation in oil well MW 01, Upper Indus Basin, Pakistan.

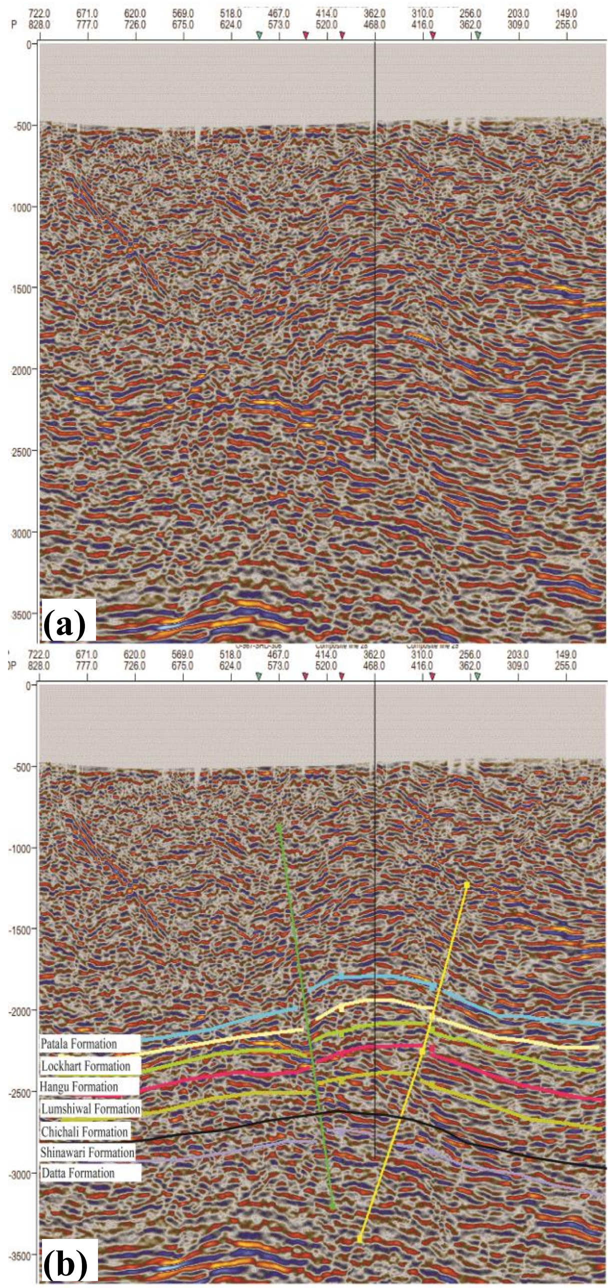

Fig. 5. a) Describing the seismic section that the amplitude does not clearly reveal any distinct features; b) well-to-seismic tie showing interpretation of various reflectors delineating stratigraphic units in seismic line O-967-SHD-306 (cropped).

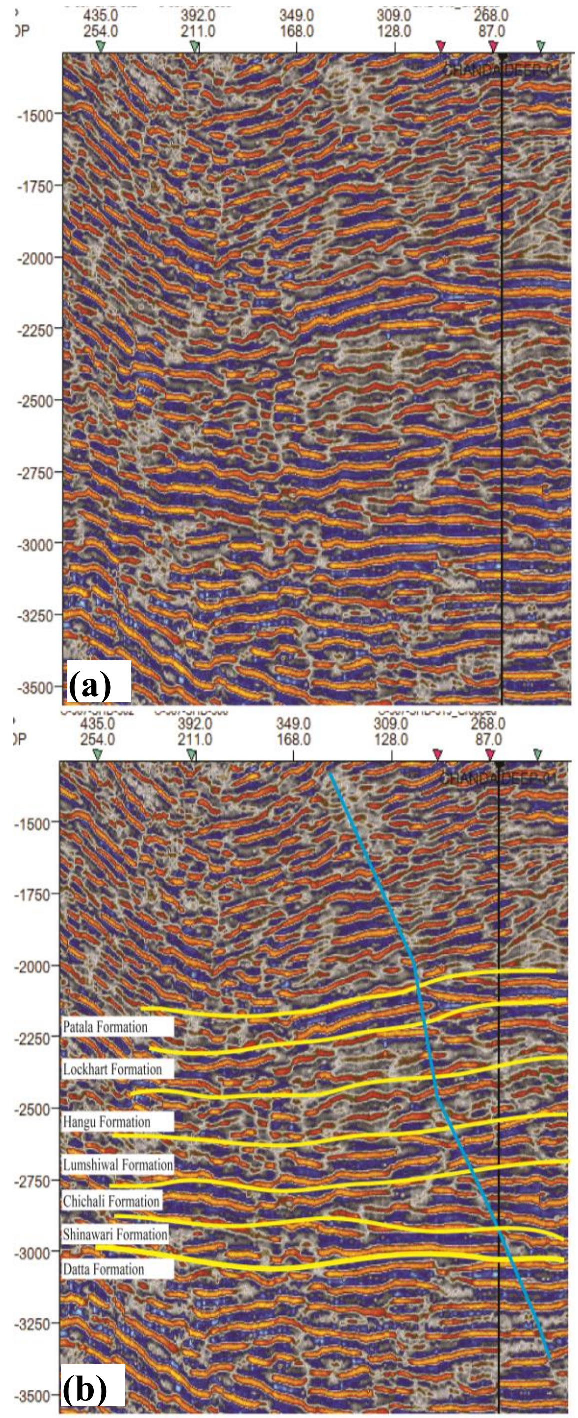

Fig. 6. a) Describing the section presents the original amplitude data for seismic line 972-SHD-328; b) interpreted well-to-seismic tie showing the Paleocene, Cretaceous formations, and Jurassic formations, i.e., Datta and Shinawari.

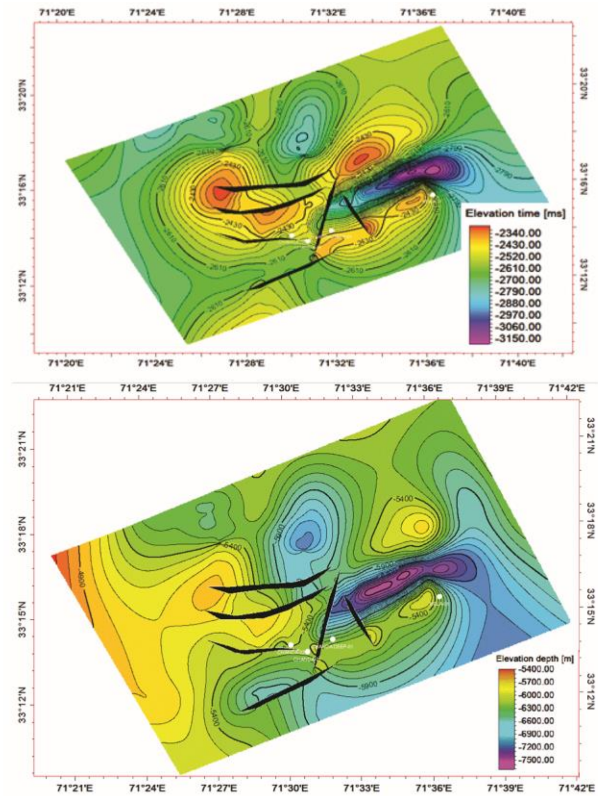

Fig. 7. Describing a two-way travel time map of the Middle Jurassic, Shinawari Formation in sub-figure a), while a depth map of the Middle Jurassic, Shinawari Formation, is described in in sub-figure b.

4.3 Seismic

The seismic data are utilized to interpret the horizon, fault data, interpretation of various stratigraphic units, well-to-seismic tie, two-way travel time map, and depth contour map. Based on well-to-seismic tie data, the stratigraphic units identified along line no O-967-SHD-306 include Paleocene (Hangu, Lockhart, Patala formations), Cretaceous (Lumshiwal, Chichali Formations), and Jurassic (Shinawari and Datta formations). While from seismic line no 972-SHD-328, the well-to-seismic tie data indicate the same Paleocene, Cretaceous formations, and Jurassic formations, i.e., Datta and Shinawari formations are reported (Figs. 5-6). Furthermore, the time contour map of the Shinawari Formation was constructed using a 0.05-second contour interval within a time range of 2.510 to 3.527 seconds. Analysis of the time contour and depth maps indicates that the upper boundary is at 4579 meters, while the lower boundary is at 4650 meters (Fig. 7).

5. Discussion

5.1 Lithology

The cross plots described the featured response of its inhibited depositional properties recorded in logs such as density and porosity of the studied formations. The models shown in Figs. 3-5 illustrate lithology identification and interpretation using this cross-plot method. The data in Figure 3 indicate that the lithology is sandstone, whereas Figures 5 and 6 indicate the presence of both sandstone and clay or shale within the Shinawari Formation of the Upper Indus Basin, Pakistan.

5.2 Reservoir characterization

The Middle Jurassic Shinawari Formation encountered in CDW 01 well has a stratigraphic thickness of about 71 meters, between 4579 and 4650 meters. In CDW 01 well zone 1, identified as the primary interval of interest, is located between 4580 and 4635 meters. The interested zone 1 has been marked with 62% (average shale volume), Rw (39% Ω·m), PHIE (4.2%), and DT (58 µs/ft Delta-T) with effective porosity (8%). %. The Rw is determined from the Schlumberger charts manually. The SWA in zone 1 is 68%, and hydrocarbon saturation is approximately 32% (Table 1 and Fig. 3). The Shinawari Formation in the MW 01 well is recoded between 4799 and 4951 meters, showing a stratigraphic thickness of about 116 meters. The zone 1 has been marked as a zone of interest with with 32% (average shale volume), Rw (49% Ω·m), PHIE (64%), DT (50.64 µs/ft Delta-T), with effective porosity (20.0 %). %. Though the SWA in zone 1 is 42%, and hydrocarbon saturation is approximately 58% (Table 1 and Fig. 4). The MW 01 well is considered suitable for both conventional and unconventional reserves, whereas the CDW 01 well is more favorable for unconventional resources and less viable for conventional prospects. Both oil wells, CDW 01 and MW 01, contain a designated zone 1 that consists of interbedded sandstone and shale.

5.3 Seismic Analysis

The well locations and seismic lines were also integrated into the base map to enhance the accuracy of the interpretation of the structure. The interpretation of the horizons was carried out in line with the seismic stratigraphic principles, where strong reflection indicates significant lithological boundaries. According to McQuillan (1985), the stratigraphic interpretation approach, seismic horizons can be identified on the basis of acoustic impedance contrast of the different lithologies. These horizons are established using available information, including acoustic impedance and lithology-stratigraphy. Strong reflections are as good at being interpreted as a boundary. In MW 01 and CDW 01, the interpreted horizons are presented in Figures 5-6. Based on the seismic profile, the Shinawari Formation shows good lateral continuity in the entire study area. The presence of two local faults dipping towards each other was identified, resulting in a dome-like structure known as the pop-up structure. Such a structure is likely to be hydrocarbon-bearing because it has both structural closure and seal. Based on two travel times and a deep contour map, the Shinawari Formation exhibits the presence of the same anticline structure with fault structure. The constructed time contour map shows structural variations in the study area. The contour interval used in the time contour map was 0.05 seconds to complete detailed structural evidence. The results have shown that structural highs and lows are associated with fault-related deformation zones. The depth map has confirmed that the depths vary between 4579 and 4650 meters in the study area. The depth map signifies the presence of the studied formation at a suitable exploration depth in the Indus Basin, Pakistan.

6. Conclusion

The following conclusions are induced from the current investigation of the Middle Jurassic, Shinawari Formation, Indus Basin, Pakistan:

- The lithology is mostly sandstone, with the presence of clay or shale interbeds within the Shinawari Formation of the Upper Indus Basin, Pakistan.
- The oldest stratigraphic unit is the Datta Formation, while the youngest unit is the Muree Formation in MW 01; in CDW 01, the oldest unit is the Wargal Formation, and the youngest is the Nagri Formation.
- The MW 01 well is considered suitable for both conventional and unconventional reserves, whereas the CDW 01 well is more favorable for unconventional resources and less viable for conventional prospects.
- The Shinawari Formation is present in good lateral continuity, intersected by two local faults dipping toward each other.
- The depth and contour map shows that the Shinawari Formation's upper boundary is present at 4579 meters, while the lower boundary is at 4650 meters.

7. Recommendation

This study focuses on the Shinawari Formation, which demonstrates potential as a reservoir rock. Furthermore, it is stated that the study is limited with respect to its coverage and the number of wells and lines, so for any strategic plane more wells and large cover area is needed to cover for future before it can be recommended for exploration and production (E and P) activities in the oil and gas sector.

Furthermore, this research holds dual significance, i.e., it is expected to benefit both academic and industrial stakeholders and to contribute to the socio-economic development of the Islamic Republic of Pakistan. The findings will improve the characterization of reservoir rock behavior relevant to future large-scale hydrocarbon production. The proposed study is anticipated to be the first of its kind in Pakistan and among the few globally, underscoring its economic importance

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Authors' Contribution

Fahad Ali and Shiqi Zhang proposed the main concept and were involved in the write-up. Muhammad Salman assisted in establishing the reservoir features of the section. Muhammad Salman, Rafique Ahmad, and Taqweemul Haq Ali collected field data. Asher Samuel Bhatti provided relevant literature and reviewed and proofread the manuscript. Syed Haroon Ali and Beenish Ali did a technical review before submission of the manuscript.

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