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Research Article

Estimating Total Organic Carbon (TOC) Content and Porosity of the Ranikot Formation in the Central Indus Basin, Pakistan, Using Seismic Inversion and Well Log Analysis

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An approach is proposed to improve modeling for shale gas reservoirs, integrating key parameters such as total organic carbon (TOC) and porosity. Seismic inversion uses seismic reflection data and well-log information to improve geological and geophysical interpretation and estimate rock properties with high-resolution subsurface acoustic impedance, including low and high frequencies. The Ranikot Formation in the Central Indus Basin, Pakistan, is a Paleocene-age formation with the potential to act as reservoir, seal, and source rock. The porosity of the Lower Ranikot reservoir in the Mehar Block was calculated using seismic inversion analysis with the Mehar-02 well. The petrophysical analysis yielded an effective porosity of 5.8%. Similarly, when calculated using seismic inversion, the porosity fell within the 5.5%–6.0% range. Determining the TOC content is crucial in evaluating unconventional shale resources. Petrophysical approaches, such as the $\Delta \log R$ method, offer a fast, convenient, and cost-effective means of estimating TOC from well logs. This method is commonly used in conventional source rock evaluation and applied to unconventional resource play evaluation. On the other hand, seismic inversion techniques were used to conduct TOC analysis in the absence of core data in order to estimate the source potential of the Upper Ranikot Formation. To estimate the TOC log for the Upper Ranikot shales in the Mehar Block, the Passey equation was used on the well logs of the Mehar-02 well. The estimated TOC for the Upper Ranikot shales is around 2.0%, which falls within the fair TOC range.

1. Introduction

Shale gas is an unconventional gas occurring in dark muddy-shale in adsorbed or free form. It has low porosity and permeability, lacks a gas–water boundary, and typically has low natural production. Shale gas is found in thick shale hydrocarbon source rocks and requires fracturing for commercial gas flow [1]. Due to hydraulic fracturing, which raises the natural bulk rock permeability and makes it possible to extract trapped gas from source rocks, gas shale plays have become more significant in the last decade. However, quantifying the potential resources of these unconventional petroleum systems is challenging due to limited data and physical tools, and analytical techniques and numerical models designed initially for conventional resources may not be suitable [2]. Shale plays require detailed characterization of the physical properties of source rocks during burial and maturation to estimate their economic potential. Recoverable oil and gas reserves estimation is challenging due to the complex nature of pore volume. Recent studies highlighted the importance of organic porosity and gas adsorption mechanisms within kerogen to evaluate the organic porous network in shale. The distribution of organic carbon and thermal maturity control hydrocarbons in place, including organic porosity creation and adsorption in organic matter [1–5].

Estimation of total organic carbon (TOC) content is an important step in geo-chemical assessment and rock Eval-pyrolysis to measure source rock potential [6]. Measuring the TOC content of rock samples directly is expensive and time-consuming. Spatial coverage and vertical resolution can also be limiting factors when creating quality resource potential maps for potential sweet spots. Petrophysical approaches, such as using well logs, offer a faster, more convenient, and cost-effective way to estimate TOC. Well logs are commonly available in known petroleum-bearing basins worldwide and are often used to evaluate source rock potential in conventional petroleum systems [5, 7–10]. Well-logging data can be used to evaluate various properties of shale gas reservoirs as well as conventional reservoirs, including lithologic components, TOC content, total porosity, gas content, and rock geomechanical properties. While some evaluation methods are well-established, there are few quantitative methods for total porosity and micropore composition using logging data. Recent studies provide references but have many parameters that are difficult to evaluate accurately [10–13]. It is also very important to incorporate the core-based results and geophysical logs for detailed characterization of the rock properties for any lithology of interest [14, 15].

From a geological standpoint, the study area is situated within the Middle Indus Basin. The study area is situated in the Mehar Block, which covers an area of 5,030 square kilometers. PCPL PETRONAS Cargali Pakistan Limited was solely responsible for all site activities, with 75% of its interest relating to work and management. Additional partners include Orient Petroleum Inc., which holds a 20% stake, and Government Holding Pakistan Limited, which holds a 5% stake. The area's most interesting geological formations are the Sui Main Limestone, an Eocene-aged limestone, and the Pab Sandstone, a Late Cretaceous-aged sandstone. The gas reserves in the Pab Sandstone, known as gas columns, are considered one of the block's most valuable assets; this is demonstrated by the presence of gas deposits in Bhit-2 and Zamzama-1, located south of the Mehar Block. The Marzarani-1 rogue well also discovered gas deposits in the Sui Main Limestone of the Mehar Block [16].

The Mehar Gas Field is a gas-producing field in the Central Indus Basin. The field's main reservoirs are represented in the Pab Sandstone and Lower Ranikot Formation. As input data for this study, a set of well logs from the Mehar-02 well and a 3D seismic data cube of the Mehar block were used. The main objective of this study is to estimate the TOC and porosity of Ranikot Formation. In the current study, we estimate the TOC and porosity of the Ranikot Formation in the Central Indus Basin, Pakistan, using seismic inversion and well-log analysis. This method was applied to evaluate well-logging data in the study area. The outcomes of this study will be beneficial for future exploitation of target formation in the study region.

2. Tectonics, Geology, and Stratigraphy of the Study Area

In the Ornach-Nal and Chamman Transform Faults area, the Oligocene and Miocene periods were characterized by plate collisions that formed numerous anticlinal structures on the eastern side of the Kirthar Fold Belt. The occurrence of ophiolites on the western slope of this belt suggests the existence of an active plate boundary in the past, which is further confirmed by seismic activity. Mafic to ultramafic rocks are the dominant rock types along this active plate boundary, according to Jadoon et al. [17]. The region being studied, located south of the Central Indus Basin (Figure 1), contains preexisting normal faults oriented in a NW–SE direction that runs parallel to the Jacobabad highs and disrupts the foredeep region. The development of the Mehar–Mazarani Trust in this region is primarily attributed to the Mehar–Mazarani Fold. This trust belt slopes westward in a north–south direction. Additionally, extensional faults between the core of the Mehar–Mazarani Fold structures have been reactivated. The orientation of the Mehar–Mazarani Fold indicates that it is not aligned with the preexisting normal faults. If it were, the orientation of the Main Mantle Thrust would have followed the fault plane of the preexisting NW–SE extensional faults [18].

From the Infra-Cambrian to the Late Cretaceous, a series of tectonic events caused uplift, rifting, and erosion in the Mehar–Mazarani Fold Belt. During these events, existing faults in the basement of the region were reactivated. The principal source and reservoirs of the Cretaceous age were deposited in a passive margin environment, while Late Cretaceous drifting caused the reactivation of preexisting normal faults and uplifted the area. Late Cretaceous sediments were observed to have eroded on the Jacobabad Highs. The wedge-shaped Oligocene and Paleocene strata in the Mehar–Mazarani Fold Belt indicate the occurrence of paleo-high phenomenon during this time period [20].

The rocks that were drilled in the studied region range from the Mesozoic era to the present day and are classified as sedimentary. The sedimentation process in this area has been affected by unconformities and other small sedimentary gaps, resulting in frequent changes in facies [21]. Figure 2 shows a generalized stratigraphic column of the Central Indus Basin. Sediments were deposited in passive margin settings during the Early Cretaceous due to the emergence of the Indian continent. This uplift caused thick deposition of the Sembar and Lower Goru formations along the passive margin, which acted as the primary source for the overlying sand reservoirs. The sands of the Lower Ranikot Formation were also deposited in these environments [22–27], which are the main target reservoirs in the Mehar Gas Field.

3. Methodology

Seismic and well logs can be used to estimate TOC content in a geological formation. By analyzing seismic data, one can identify areas with high acoustic impedance (AI), indicating higher TOC content. Well logs can also be used to measure TOC, as they provide direct measurements of the rock properties. Combining the two datasets can give one a more accurate picture of the TOC content in a given geological formation. The initial dataset used in this study consisted of 3D seismic data that had been processed for the purpose of interpreting the subsurface structures [28]. Seismic interpretation is a valuable tool for identifying subsurface structures, fault types, and trends in the Mehar Block on the eastern side of the Kirthar Fold Belt. This fold belt is one of the largest in South Asia and is characterized by a compressional regime resulting in reverse and thrust faults. The seismic interpretation's purpose was to determine the structures, fault types, and depth of the primary reservoir within the studied region [29, 30].

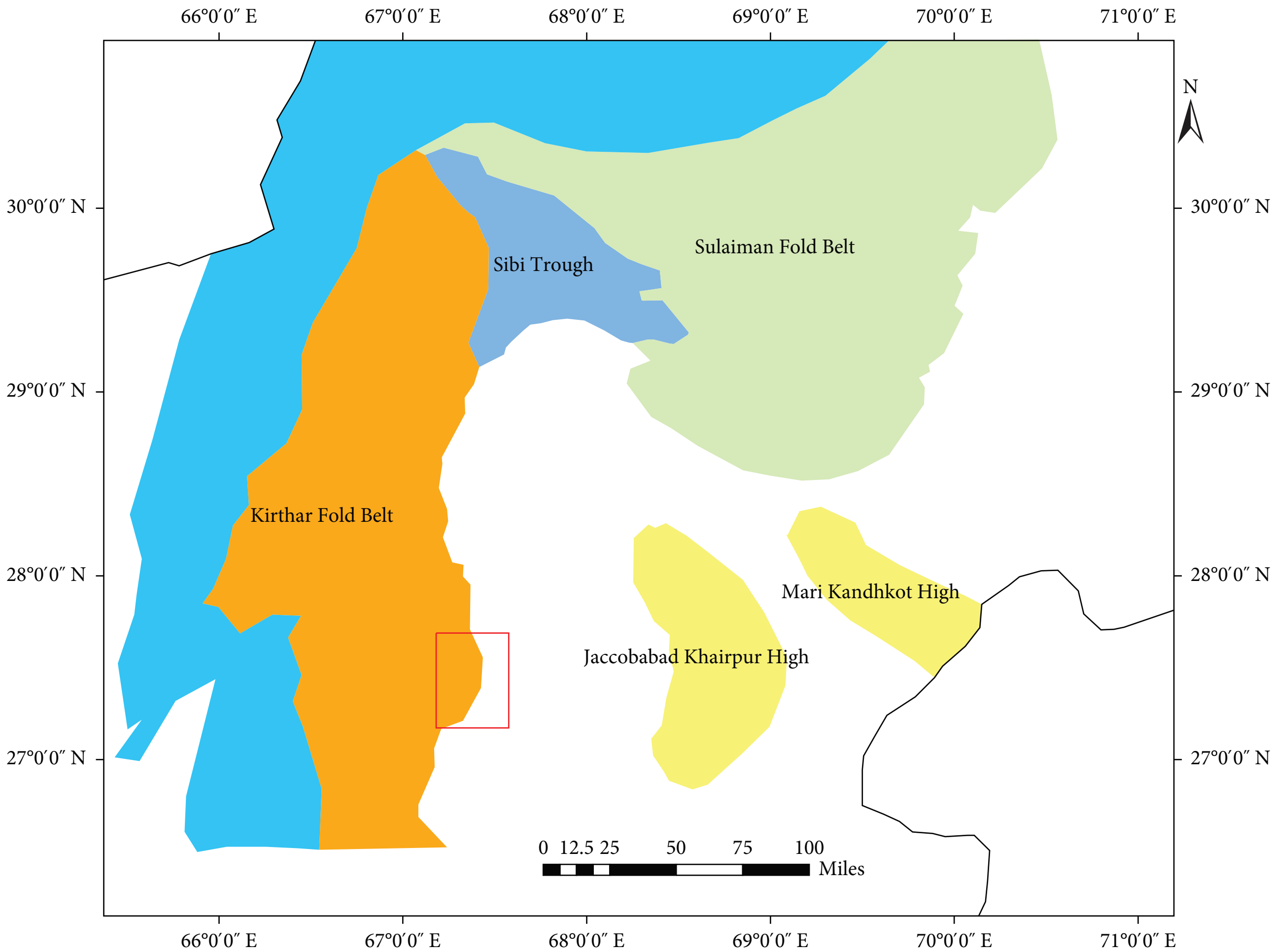


FIGURE 1: Generalized tectonic map, which shows the main features of the Central Indus Basin, with the study area highlighted by a red square (modified after [19]).

High-resolution seismic data help to identify the potential shale zones for hydrocarbon exploration. Poststack inversion quantitatively describes geological formations by analyzing porosity, TOC, impedance, and lithology. This technique is widely used to characterize conventional and unconventional hydrocarbon reservoirs. Seismic data are transformed into impedance values, allowing for the creation of a geologic structure using seismic and well data. In the study area, model-based seismic inversion produced images of AI translated into reservoir properties using algorithms based on various assumptions. Seismic inversion also created an AI cube for organic geochemical analysis [31–33].

Successful exploration and production of shale rely on identifying major organic components and total porosity. As seismic data are often the only available source of information in most exploration phases, it is crucial to use them to indirectly identify TOC content and total porosity in promising shale formations [33]. Seismic inversion is converting seismic amplitude values into seismic impedance values. Deconvolution procedures are used to transform seismic traces into earth reflectivity. Inversion is a subsurface modeling technique that employs seismic data as input and well data as control. The ultimate goal of the subsurface modeling technique is to create a subsurface geological structure.

Poststack seismic inversion techniques utilize stacked (zero-offset) seismic data to construct artificial intelligence depth or temporal images [34].

The Passey method, also referred to as the ΔLog$R$ technique (Equation (1)), utilizes wireline log data to quantitatively estimate the TOC of source rock intervals or unconventional reservoirs while determining their maturity and organic richness. This technique examines the overlap of sonic log values and resistivity values [35]. Broadhead et al. [36] studied the relationship between the TOC and the amplitude of seismic data. By using the seismic (reflectivity) data obtained from inversion, it is possible to get information about the TOC [36]. Impedance and TOC have an inverse relation with each other [37]. Total porosity is the total available space in the rock for fluids such as water, gas, and oil to occupy. Since AI is the product of density and velocity, porosity can be calculated from the AI [33, 38]. Thus, the relation established at the well location between the AI and

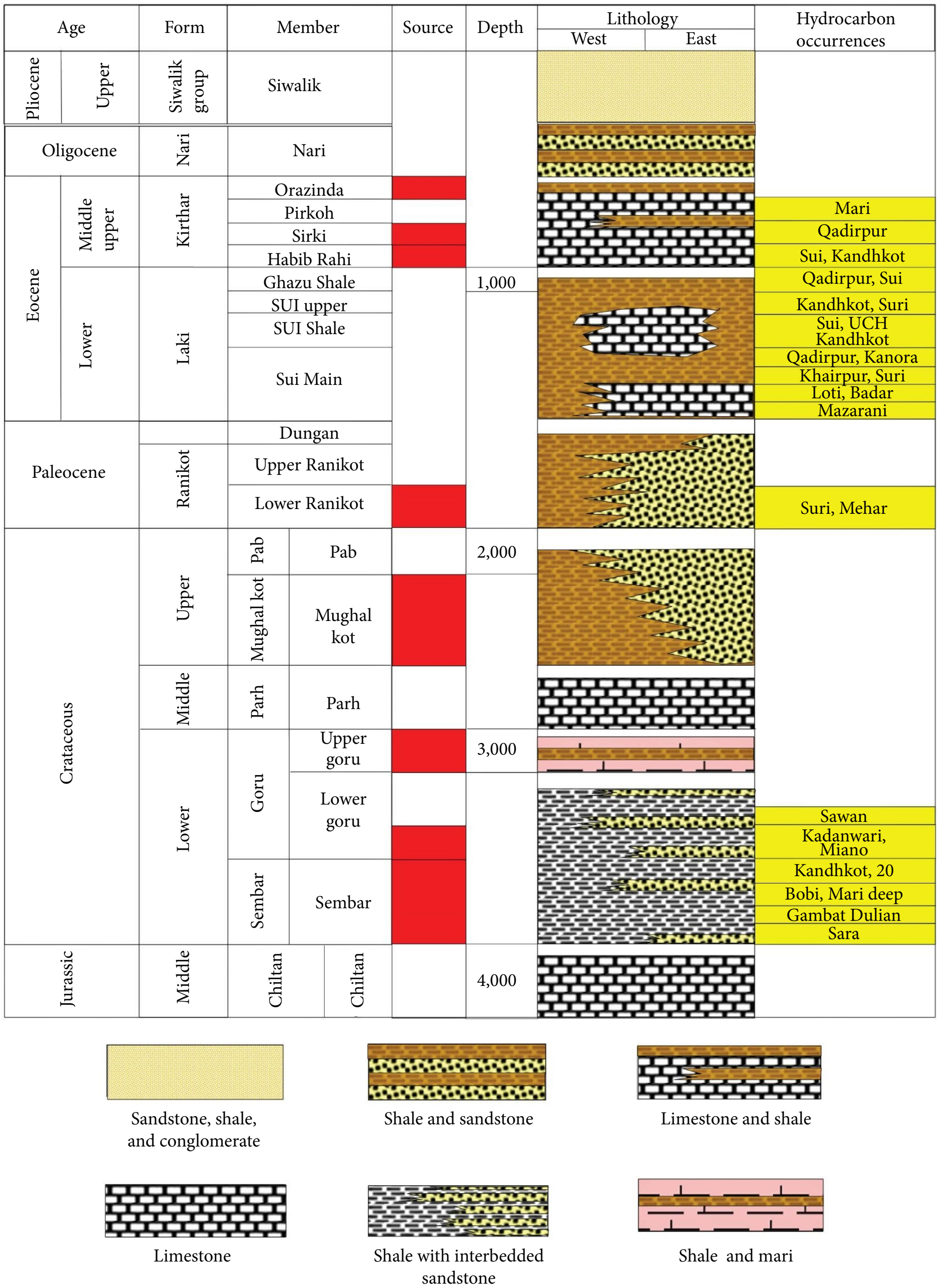


FIGURE 2: In a stratigraphic column, the generalized stratigraphic column of the Central Indus Basin with the main hydrocarbon field in which depth is measured in meters [22, 23].

porosity can then be used to extrapolate it over the entire impedance volume.

$$\Delta\log R = \log_{10}\left(\frac{R}{R_{\text{baseline}}}\right) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}}), \quad (1)$$

where R is the resistivity; Δt is the transit time measured in μs/ft; R_{baseline} is the resistivity corresponding to the $\Delta t_{\text{baseline}}$ when the curves are baseline in nonsource rocks.

$$\text{TOC} = \Delta\log R \times 10^{(2.297 - 0.1688 \times \text{LOM})}, \quad (2)$$

where LOM is the amount of level of organic metamorphism.

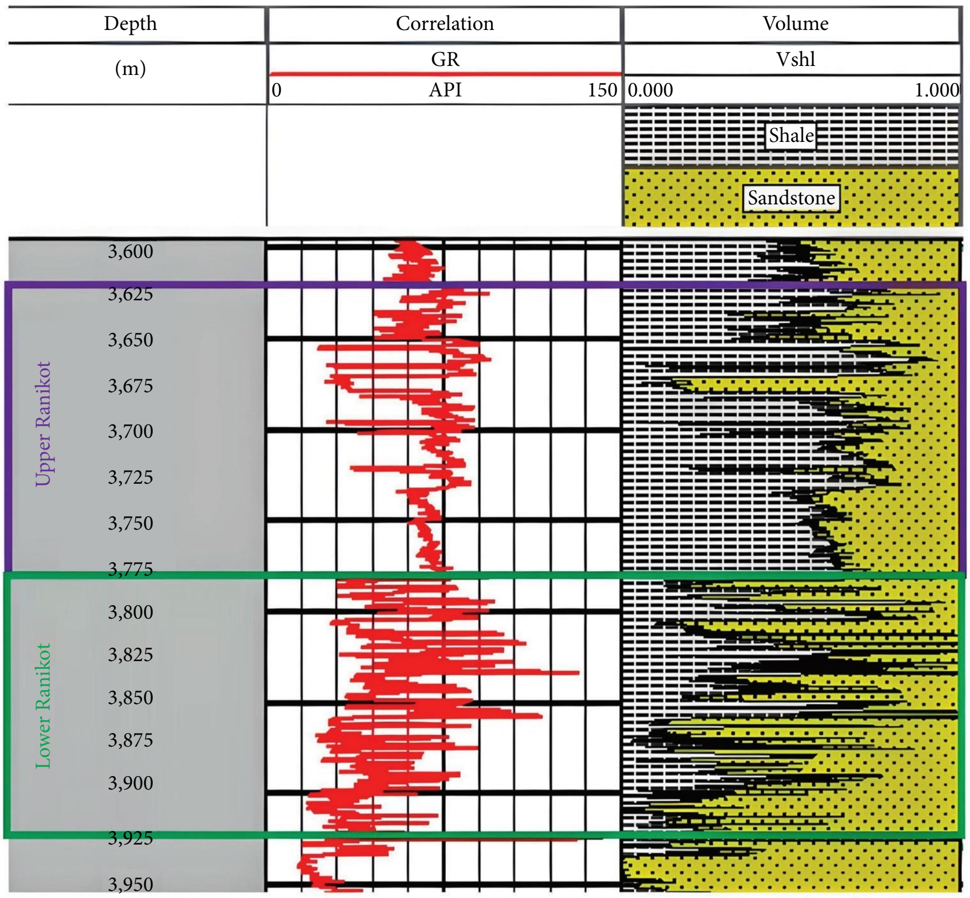


Figure 3: GR and Vsh curves for Mehar-02 Well with the boundary between the Upper and Lower Ranikot Formations.

The estimation of shale volume relies on the data obtained from a GR [39].

$$\mathrm{Vshl} = \frac{\mathrm{GR}_{\log} - \mathrm{GR}_{\min}}{\mathrm{GR}_{\max} - \mathrm{GR}_{\min}}. \quad (3)$$

Therefore, the mathematical expression for estimating density-derived porosity is provided in Equation (4).

$$\phi_D = \frac{\rho_m - \rho_b}{\rho_m - \rho_f}, \quad (4)$$

where ρ_m = matrix density, ρ_b = bulk density, and ρ_f = value of density of fluid.

To calculate the average porosity, both neutron and density porosity values were integrated. The mathematical Equation (5) was used for this purpose [40].

$$\phi_A = \frac{\phi_D + \phi_N}{2}, \quad (5)$$

where ϕ_D = density derived porosity and ϕ_N = porosity from neutron log.

The effective porosity (ϕ_E) was calculated by using Equation (6) [40].

$$\phi_E = \phi_A(1 - \mathrm{Vshl}). \quad (6)$$

4. Results and Discussions

4.1. Well-Logs Interpretation. Predicting the distribution of porosity in sandstone reservoirs can be challenging due to variations in depositional conditions, the presence of heterogeneous lithofacies, and the repetition of pore size variations [41, 42]. Gamma-ray, density, resistivity, and neutron logs are commonly used for formation evaluation [43]. The well-log data of the Mehar-02 well was analyzed to determine the subdivisions of the Ranikot Formation. The Lower Ranikot is one of the primary reservoirs of the Central Indus Basin, while the Upper Ranikot consists of shale with interbedded sand, serving as a source for younger reservoirs in the area and as a seal for the Lower Ranikot reservoir. GR log allowed to mark the boundary between the Upper and Lower Ranikot Formations, as shown in Figure 3 and estimate their respective thicknesses using GR log, which is a key log used for lithology determination. This information was useful during inversion analysis, where we estimated TOC for the Upper Ranikot Formation and porosity for the Lower Ranikot Formation (Figure 4).

First, porosity was calculated using the well-log suite, which was then used for correlation during seismic porosity inversion analysis. The zone of interest lies at a depth of 3,671–3,679 m and is 11 m thick. This zone exhibits a

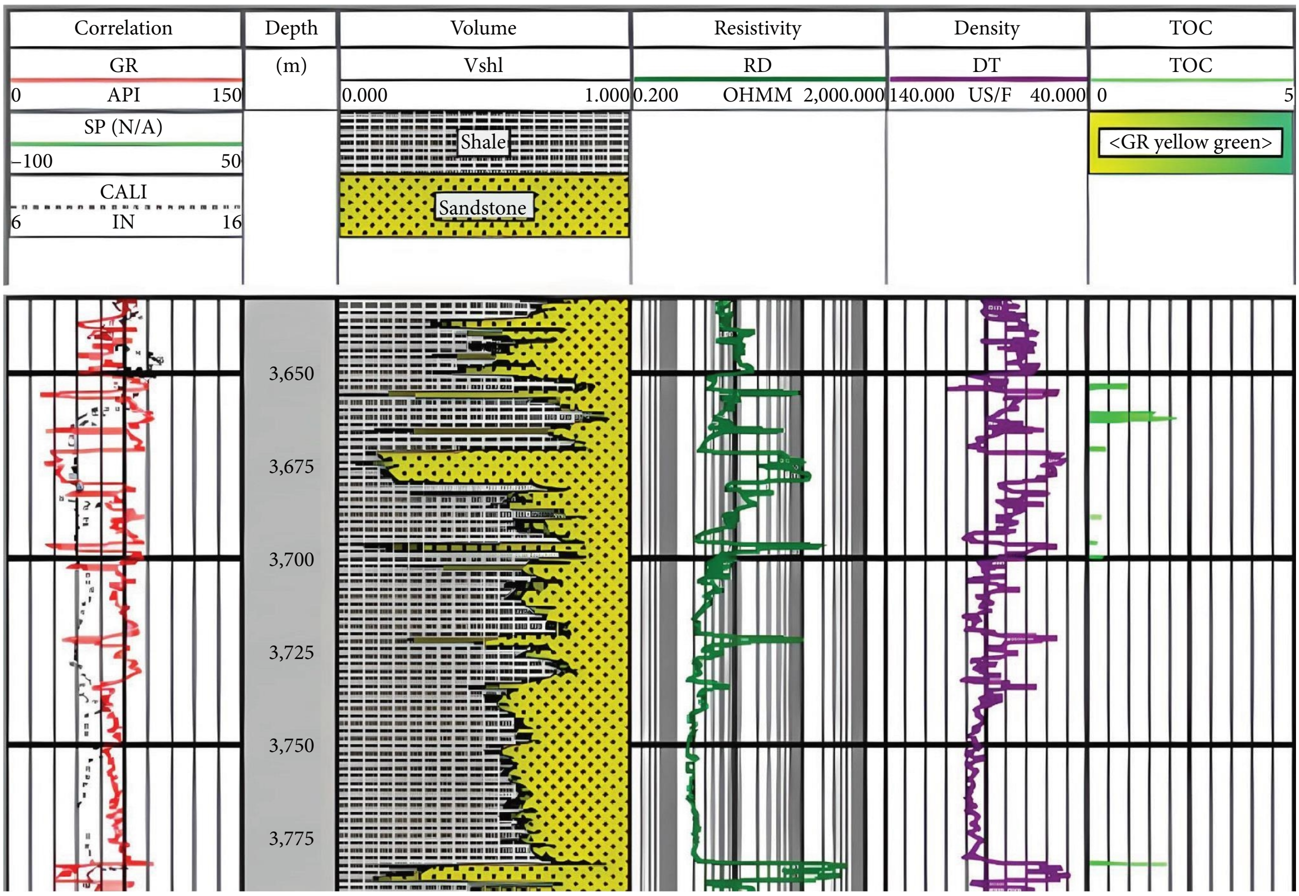


Figure 4: Display of well logs used for TOC estimation of the Upper Ranikot Formation using the Passey method.

significant difference between the MSFL and LLD values. The average apparent porosity for this zone is 10%, and the effective porosity is calculated to be 5.9%. The hydrocarbon saturation in this zone is calculated to be 69%, as shown in Figure 5.

4.2. Seismic Data Structural Interpretation. Accurately delineating stratigraphic and structural traps requires a thorough understanding of subsurface configurations. The seismic data show the existence of a thrusted anticline with accompanying thrust faults [23]. The seismic profile reveals two prominent structures in the study area: the Zamzama structure in the south and the Mehar structure in the north. The Zamzama structure is relatively shallower than the Mehar structure, and they are separated by a broad syncline. The seismic data indicate that the investigated region comprises of north–south oriented anticlines, which are deformed by westward dipping thrust faults with a throw of over a 100 m near the core of the structure. Additionally, two minor faults (a thrust fault and a back-thrust fault) with a throw of a few meters are present on the western side of the hanging wall. The Cretaceous shale seems to have provided the decollement for these reverse faults [44].

Subsurface analysis of the Ranikot horizon in the Mehar block reveals the presence of a massive fault-bounded anticline. All reflectors are steeply descending westward. There is a significant reversing fault to the east of the presented data that cuts through the entire Eocene to Cretaceous layers. This large fault appears younger because it sliced through layers of varying ages. The available seismic cube is limited making it impossible to determine the precise extent of the fault up until recent times. The fault from north to south extends throughout the entire seismic cube and exhibits a considerable displacement. As it descends toward the basement, the fault also bends. The fault's movement has caused multiple fractures to form within the fault zone, which complicates the identification of the horizon near the fault zone. Additionally, a distinct fracture affecting only the Cretaceous strata appears to have formed toward the end of the Cretaceous period and is currently concealed by more recent deposits. Figure 6 shows the structural analysis of the Ranikot Formation in the Mehar Block.

4.3. Seismic Inversion Analysis. The conversion of seismic data into AI through seismic inversion has gained widespread acceptance in both industry and academia. This process involves using seismic data to extract the physical properties of rocks and fluids. Various algorithms have been created in the past few years for generating AI maps from poststack seismic data and subsequently correlating them with the distribution of reservoir properties. This paper aims to assess the hydrocarbon potential of the reservoir formation in the study

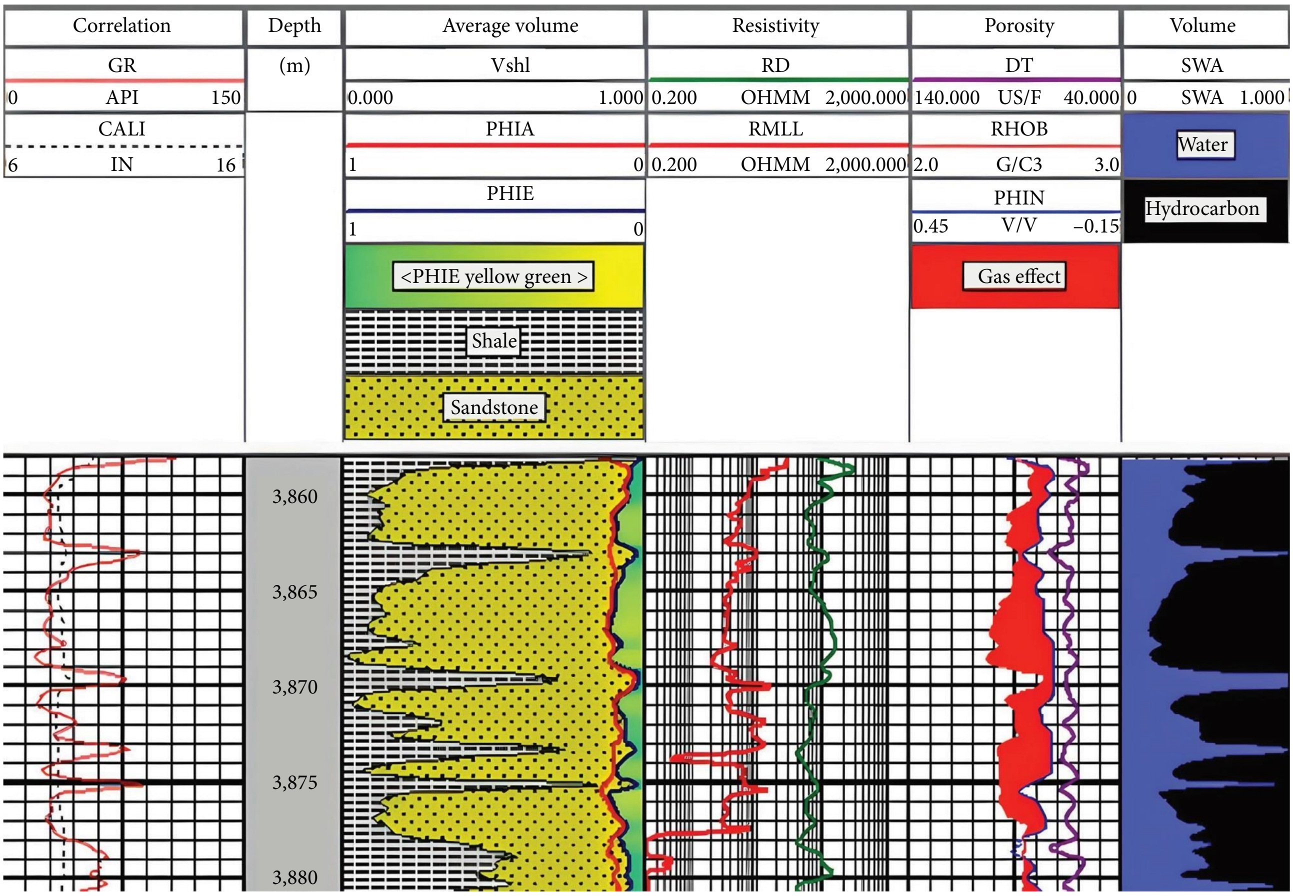


Figure 5: Displays porosity estimation and saturation results for the Lower Ranikot potential zone.

area. This evaluation procedure utilizes poststack seismic inversion in conjunction with wireline log analysis. The wireline log analysis, conducted directly within the borehole, serves as a method of investigation to determine reservoir properties such as P and S-wave velocities, shale volume, porosity, density, AI contrast, and saturation [45, 46].

Seismic inversion analysis was done for the same 3D cube of Mehar block data. The inversion analysis showed variations based on AI between the lithologies. A wavelet was generated, and a well correlation was done, followed by the generation of a low-frequency impedance model. Quality control analysis was performed prior to completing the inversion, as shown in Figure 7. After running 20 iterations, the results were very appropriate. The blue curves represent the original log, and the red curve represents the inverted result. The correlation between seismic in (black) and synthetic in (red) is 0.98%, with an error of 0.081.

Figure 8 presents the final impedance model for the Mehar-02 well. The Pab Sandstone and Lower Ranikot Formation are the primary gas-producing reservoirs of Mehar Field, and the results of the final impedance model suggest low to moderate impedance values across these reservoir zones, with increased porosity, particularly at the well location, which is dependent on the hydrocarbon content. The inversion model also reflects the same subsurface geometry, including a thrust fault and some high variations in impedance along faulted zones due to fractures and lithological intermixing.

4.3.1. Porosity Estimation. To determine the reservoir potential of the Ranikot Formation in the Mehar Field, the porosity of the Lower Ranikot Formation was estimated by conducting an inversion analysis on seismic data. The log correlation method was used to perform this estimation, which indicated the trend of changing porosity in the sandy portion of the Ranikot Formation by associating the porosity log and impedance log of the Mehar-02 well with a regression line from linear regression (Figure 9 (a)). The estimated porosity in the Lower Ranikot Formation ranged from 5% to 6%, as shown in Figure 9(b).

4.3.2. TOC Estimation. TOC is the organic carbon concentration in source rock, such as shale. TOC is usually found in higher amounts in source rocks, and its degree of maturation is variable and dependent on several factors, including pressure, temperature, and time. The quality of source rocks can be determined by the type of TOC present [37]. The lab technique used for estimating TOC is called vitrinite

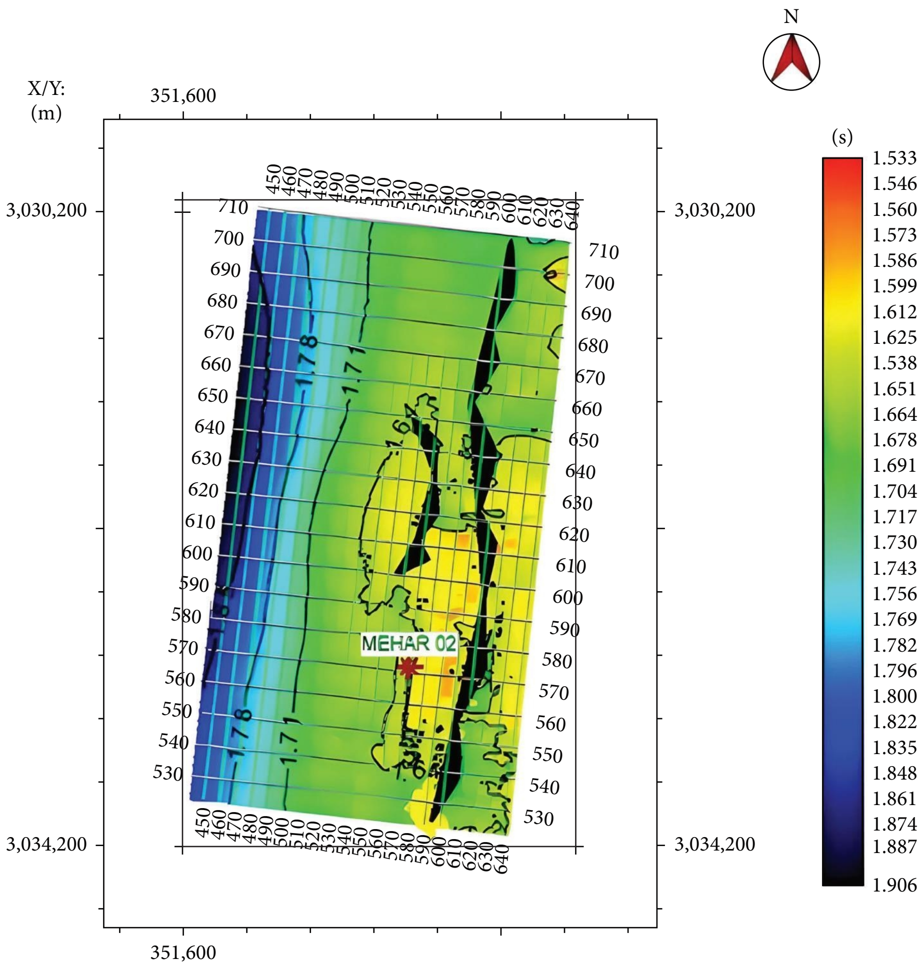


Figure 6: The contour map display of structural analysis of the Ranikot Formation, Mehar Block.

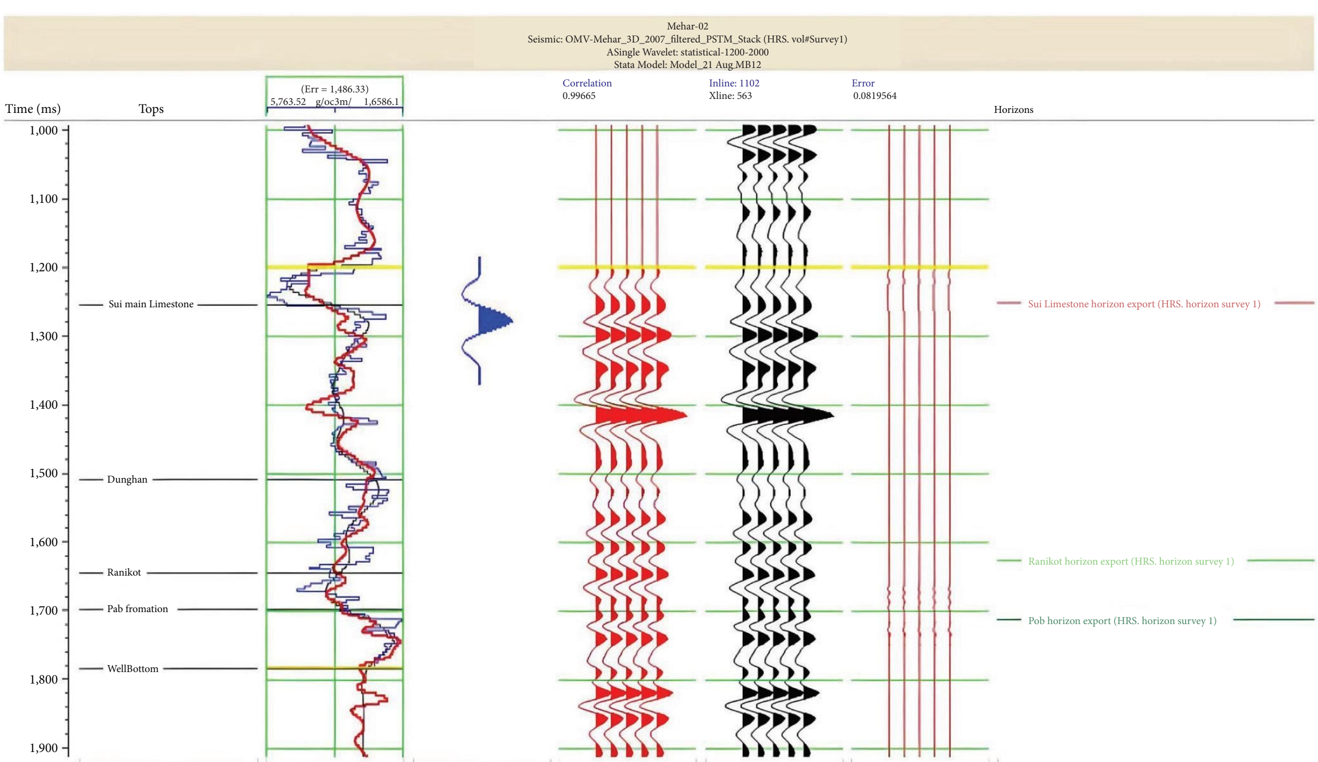


Figure 7: The seismic inversion analysis, based on the model, revealed a 98% correlation between the synthetic and seismic traces for the entire dataset after 20 iterations.

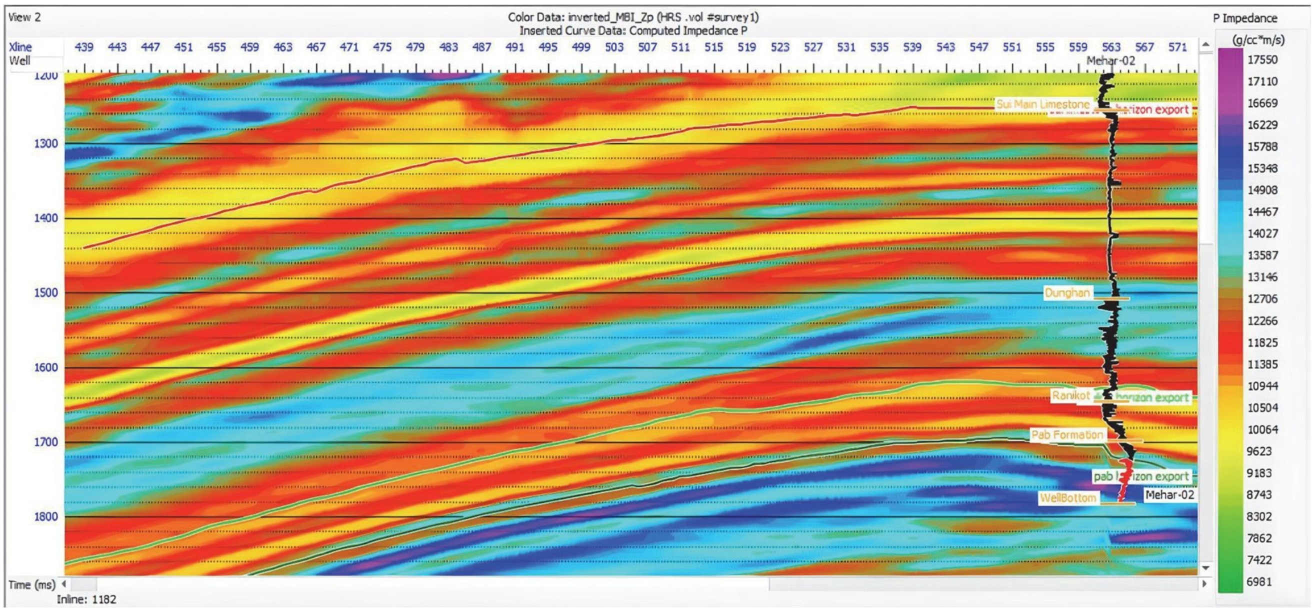


FIGURE 8: The impedance model on well line (Mehar-02) with marked horizons.

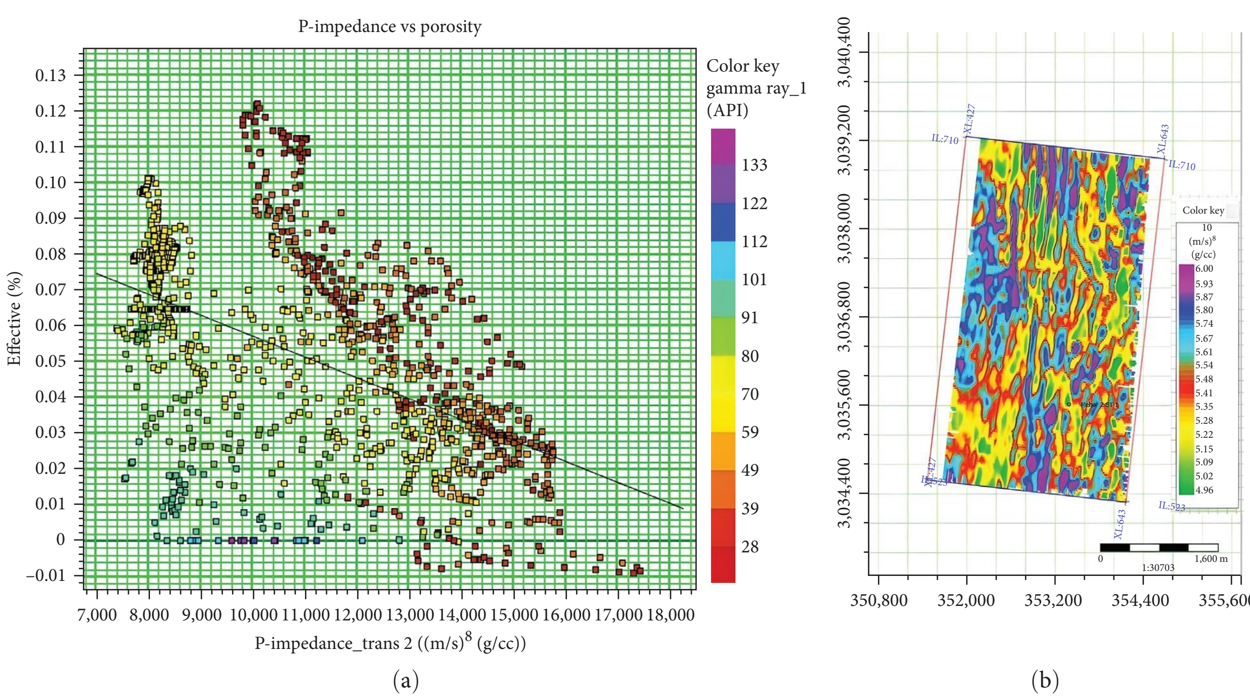
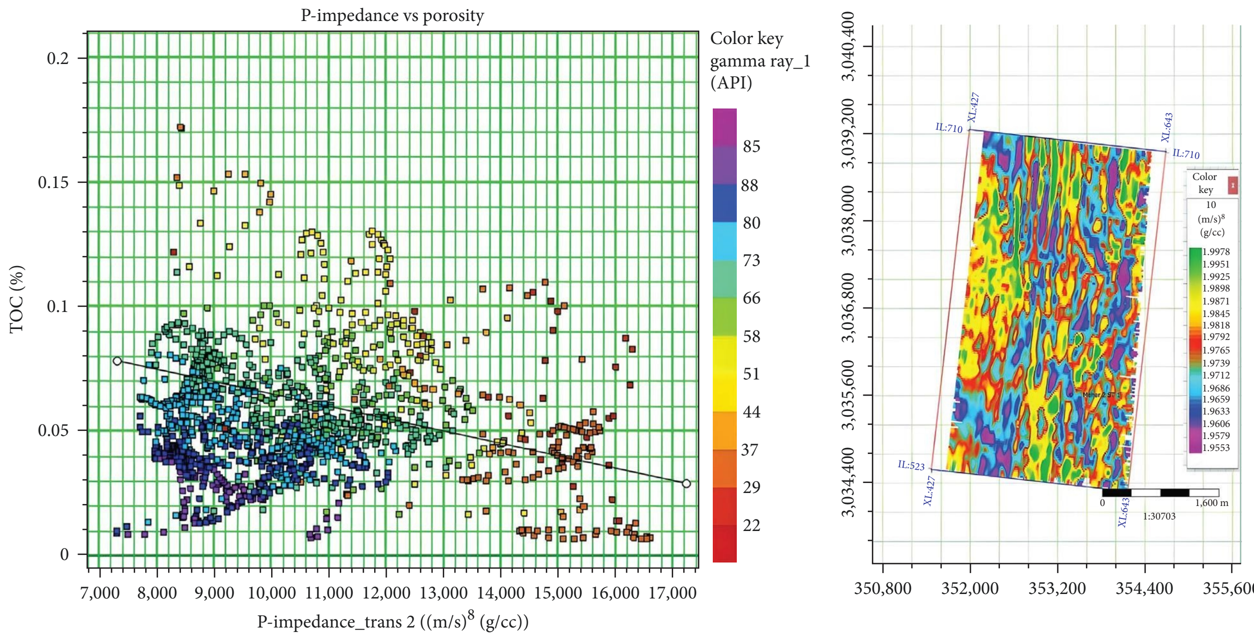


FIGURE 9: (a) Correlation of impedance log with the porosity log for computing the porosity model of the Lower Ranikot Formation of Mehar-02 well and (b) final model slice and distribution of porosity for the Lower Ranikot Formation of Mehar-02 well.

reflection, where a rock sample is crushed and examined, but this requires the core sample of the rock and is then integrated with the subsurface model [47, 48]. The correlation of logs makes it easy-to-get a general estimation of rock properties and helps in initial modeling, such as using a density log reciprocal model for TOC estimation [14]. Figure 10(a) shows a correlation between the impedance log and the TOC log for computing the TOC model of the Upper Ranikot. Figure 10(b) shows the final model and distribution of TOC for the Upper Ranikot, which indicates values of TOC around 2.0%.



(a) (b)

Figure 10: (a) Correlation of impedance log with the TOC log for computation of TOC model of the Upper Ranikot and (b) final model and distribution of TOC for Upper Ranikot Formation.

5. Conclusions

The Ranikot Formation of the Central Indus Basin, which contains both sands and shales due to fluctuating sea levels, has significant porosity for the accumulation of hydrocarbons in its Lower Ranikot. In contrast, its Upper Ranikot shales form a seal for the hydrocarbon pool and potentially serve as source rock for younger reservoirs with high TOC concentration. Seismic data were utilized to assess the porosity and TOC content of the most significant formation in the Mehar Block of the Middle Indus Basin; these were estimated to be between 5.5% and 6.0% and TOC values around 2.0%, indicating good potential. However, if available, seismic estimation is usually higher than actual values obtained from more precise laboratory analysis of core samples and high-efficiency well logs.

Data Availability

The seismic and well data used to support the findings of this study are restricted by DGPC in order to protect data confidentiality. The datasets presented in this article are not readily available because the data used for this research is highly confidential and is the property of the DGPC. It can only be provided to university students for research purposes with permission from the DGPC.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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