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RESEARCH ARTICLE

Reservoir Characterization of Eocene Carbonates and Cambrian Sands in the Eastern Potwar Region, Pakistan

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Abstract

Hydrocarbon prospectivity in fold-and-thrust belts remains inherently uncertain due to the combined effects of structural complexity and heterogeneous reservoir properties. The Eastern Potwar region of Pakistan, characterized by imbricate thrust systems, anticlines, and synclines, represents a typical example where conventional approaches often fail to adequately constrain reservoir quality. This study integrates seismic interpretation with rock physics modeling to evaluate the hydrocarbon potential of the Missakeswal area. Seismic analysis delineates the structural framework controlling trap development, while rock physics modeling of well log data provides quantitative constraints on lithology, porosity, and fluid effects within Eocene carbonates and Cambrian sandstones. The results demonstrate a clear inverse relationship between velocity and porosity in the carbonate units, together with significant deviations from standard empirical models in both carbonate and sandstone intervals. In particular, the Eocene carbonates exhibit deviations of up to 25% from the Raymer model for water-saturated limestone, indicating probable hydrocarbon saturation, whereas the Cambrian sands show dispersion consistent with clay-influenced elastic behavior. The integrated interpretation highlights the Missakeswal area as a promising exploration target, and demonstrates that the combined use of seismic and rock physics analysis provides a robust framework for reducing uncertainty and improving reservoir characterization in tectonically complex basins.

Keywords: reservoir characterization, velocity-porosity relationship, seismic interpretation, rock physics modeling.

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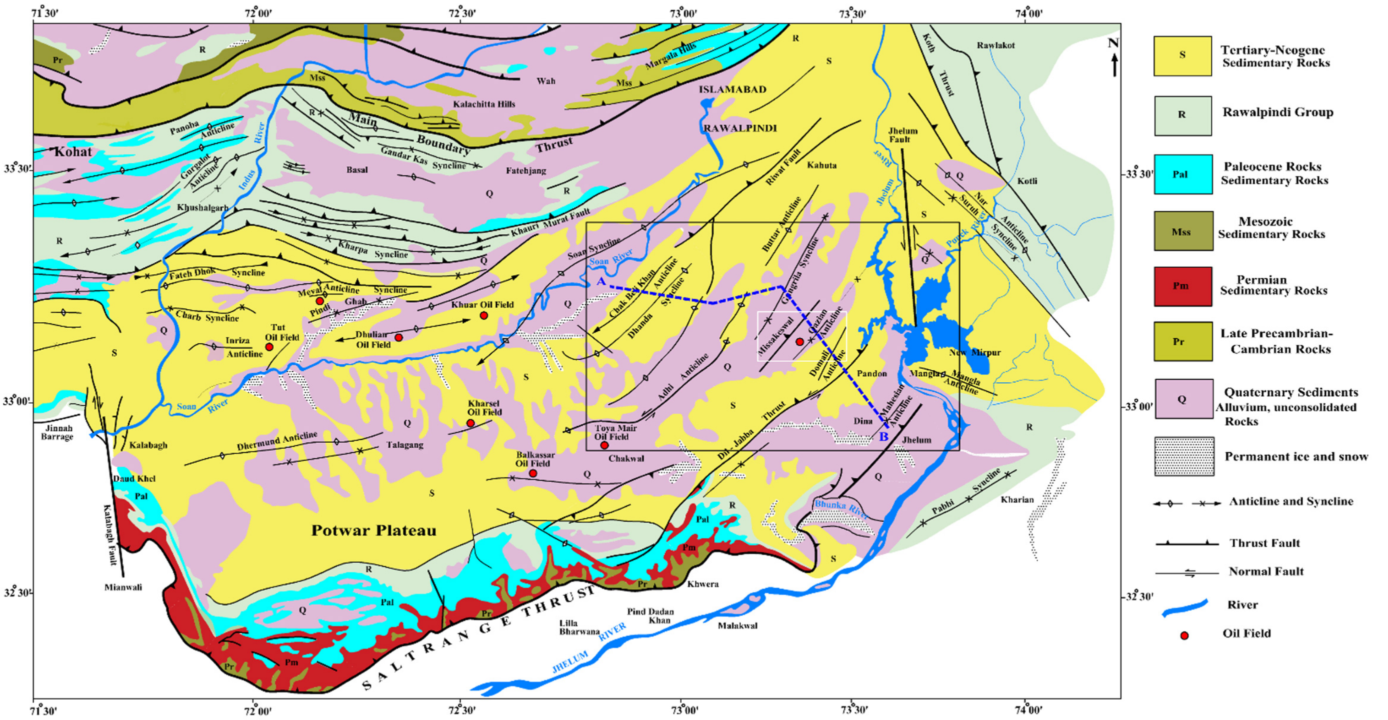


Figure 1. Geological Map of Potwar region (modified after Searle et al. [1]). The studied region (Eastern Potwar) is shown by white rectangle. The regionally covered structural features are covered by black rectangle.

1 Introduction

Reservoir characterization plays a key role in evaluating hydrocarbon potential in both conventional and unconventional plays. The accurate prediction of lithology, porosity, fluid content, and elastic properties is critical for reducing geological uncertainty during exploration and development. In structurally complex and lithologically heterogeneous settings, such as foreland basins and fold-thrust belts, imaging and interpreting subsurface formations becomes challenging. Carbonates and tight sandstones often display significant variability in texture, diagenesis, and pore system development, which affects their seismic and petrophysical responses. These complexities require the integration of multiple datasets to constrain reservoir properties effectively, especially in settings influenced by intense deformation and burial history [2–4].

Several approaches have been developed to improve reservoir understanding, combining seismic interpretation, rock physics modeling, and well-based empirical relations. Seismic data remains the primary tool for mapping subsurface structures and stratigraphy [5], while seismic inversion techniques allow indirect estimation of acoustic and elastic impedance. To link these seismic responses to physical rock properties, rock physics provides a quantitative framework that relates petrophysical parameters such as porosity, mineralogy, and saturation to elastic moduli and velocities [6]. Widely used models include Gassmann's fluid substitution, Castagna's mudrock line for clastics, Han's velocity–porosity–clay relationships, and Tosaya and Nur's formulations for shale-dominated systems [7, 8]. Crossplot analysis of velocity versus porosity, density, or clay content has become a standard workflow for assessing lithological variability and fluid sensitivity, particularly when calibrated with borehole measurements [10].

Multiple studies have applied integrated seismic and rock physics methods to various reservoir types and geological settings. In the North Sea, Avseth et al. [11] calibrated rock physics templates for sandstones using porosity and fluid trends. Xu et al. [12] modeled carbonate elastic properties by linking diagenetic textures with seismic velocity patterns. In the Barents Sea, Bredesen et al. [13] evaluated hydrocarbon indicators by integrating rock physics diagnostics with seismic attributes. Dræge et al. [14] proposed depth-dependent velocity–porosity trends to capture compaction and cementation effects in tight reservoirs. Mavko et al. [10] demonstrated the application of textural parameters in predicting velocity variations in mixed lithologies. Recent studies have also compared the performance of empirical and physics-based models in data-limited environments, highlighting the need for scale-consistent workflows that can transfer from core and log measurements to seismic interpretation [15–17].

In Pakistan, the Potwar Basin is part of the Himalayan foreland fold-and-thrust belt. It has been extensively studied for its petroleum systems [18–20]. The Eastern Potwar Sub-basin, including the Missakeswal area (Figure 1), is structurally complex, with multiple thrust sheets, triangle zones, and décollement levels developed in response to Cenozoic compression [21, 22]. Iqbal et al. [23] analyzed the thrust geometry and deformation style of the Eastern Potwar using seismic and well data, identifying major structures such as the Main Boundary Thrust, Salt Range Front, and backthrust systems. Ahmed et al. [24] used 2D seismic profiles to map subsurface geometries and established correlations between structural highs and hydrocarbon occurrences. Studies of the Missakeswal Triangle Zone reveal imbricated fault systems and uplifted blocks with Eocene carbonates and Cambrian sandstones forming potential reservoir intervals [25]. Although these studies provided important geological and structural interpretations, few have focused on the integration of seismic and rock physics models to evaluate the elastic behavior of these reservoirs.

Although seismic and borehole data have been widely acquired across the Eastern Potwar region, however, limited studies have integrated these datasets within a unified rock physics framework. In particular, the elastic behavior of Eocene carbonates and Cambrian sandstones in the Missakeswal area has not been evaluated using empirical or calibrated velocity–porosity–density relationships. This study applies an integrated approach that combines seismic interpretation with rock physics modeling to assess reservoir characteristics across these key stratigraphic units. Crossplot analyses based on established empirical models are developed using available well log data, and findings are interpreted in the context of seismic reflectivity and structural setting. The results aim to support improved lithological and fluid prediction in this geologically complex part of the Potwar Basin applicable to similar geological setting at global-scale.

2 Regional Setting

2.1 Tectonics and Basin Formation

The Potwar region (Figure 1), located within the Himalayan foreland basin of northern Pakistan, holds significant geological and petroleum significance due to its complex structural configuration, active tectonic processes, and proven hydrocarbon systems. The study region occupies a transitional position between the main Himalayan ranges to the north and the Indo-Gangetic plains to the south and has been the focus of regional geological investigations since the mid-20th century [29, 30]. It forms part of the Salt Range-Potwar Fold-and-Thrust Belt, a classic example of a thin-skinned tectonic regime, where sedimentary cover sequences have been transported southward along low-angle décollement surfaces [27, 31]. The Eastern Potwar Plateau, including the Missakeswal area, is structurally well developed and has been recognized for its petroleum prospectivity since the discovery of hydrocarbon fields such as Dhulian and Meyal [19, 25, 33].

Tectonically, the region has evolved as a result of ongoing convergence between the Indian and Eurasian plates, which initiated during the early Cenozoic and continues today [25, 32, 33]. The Potwar Sub-basin displays a complex style of deformation, characterized by imbricate thrusting, fault-bend folds, pop-up structures, and triangle zones [21, 40]. The primary structural features of the Eastern Potwar include the Salt Range Thrust to the south, the Main Boundary Thrust to the north, and major lateral boundaries defined by the Kalabagh Fault in the west and the Jhelum Fault in the east [22, 24]. Seismic data from the Missakeswal Triangle Zone show a well-developed roof-thrust system and southward-verging thrust stack geometry, with displacement localized above the salt-rich Eocambrian Salt Range Formation [23, 26]. The widespread presence of the Salt Range Formation as a basal décollement plays a key role in accommodating the regional compressional regime [27, 34].

Stratigraphically, the Potwar Basin hosts a discontinuous yet relatively complete sedimentary succession ranging from the Eocambrian to the Quaternary [21, 45]. The lowermost unit is the Salt Range Formation (Figure 2), composed primarily of halite, gypsum, and claystone, which serves as a mechanical detachment layer. This is overlain by Cambrian strata, especially the Jhelum Group, which includes fine- to medium-grained quartzose sandstones and shales that act as important reservoir intervals in deeper structural levels [27, 32]. Mesozoic units are largely absent due to non-deposition or erosional truncation, while Tertiary strata begin with the Paleocene Patala Formation and Lockhart Limestone, followed by the Eocene Sakesar Limestone

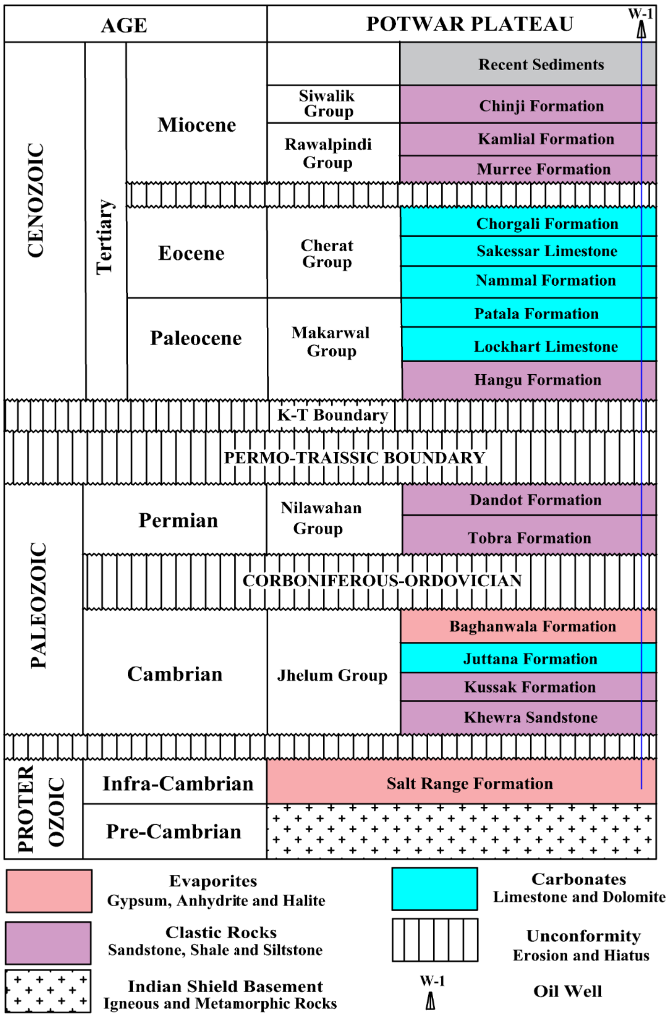


Figure 2. Regional Stratigraphy of the studied region.

and Chorgali Formation. The Sakesar Limestone is a well-established carbonate reservoir, whereas the overlying Chorgali Formation comprises marl and shale and serves as an effective regional seal [26, 27]. The Miocene Murree and Pliocene-Pleistocene Siwalik formations dominate the surface exposures and reflect synorogenic fluvial deposition. Figure 2 shows the generalized stratigraphic column of the study area.

2.2 Petroleum Systems

The Potwar Basin contains a functioning petroleum system with multiple working reservoir–seal–source rock pairs [18, 19]. The Cambrian Jhelum sandstones and Eocene Sakesar Limestone serve as the primary reservoir units, both exhibiting favorable porosity and permeability in uplifted blocks and structural closures [22, 23]. Source rocks include organic-rich shales of the Paleocene Patala Formation and Eocene Chorgali Formation [43, 44]. Regional seals are provided by the Chorgali marls, intraformational shales, and evaporites in the Salt Range Formation. Trapping mechanisms are predominantly structural, including fault-propagation folds, fault-bend folds, triangle zones, and pop-up structures, which are well-imaged on seismic profiles [22, 28]. Proven production from fields such as Dhulian, Meyal, and Toot demonstrates the viability of this petroleum system and highlights the potential for further exploration in structurally complex sub-basins like Missakeswal [41, 42].

3 Methodology

3.1 Data acquisition and processing

This study is based on 2D seismic profiles and a comprehensive suite of well logs acquired from the Missakeswal area in the Eastern Potwar Sub-basin (Figure 3). In general, a large volume of regionally oriented and deeply penetrated seismic data was acquired as part of exploration efforts. The seismic data were processed through a conventional workflow including geometry assignment, static correction, velocity analysis, normal moveout (NMO), stacking, and post-stack time migration. Well data were collected from MissaKeswal-03 (referred here as W-3), including compressional sonic, density, and neutron porosity logs. These data provided the basis for structural interpretation, seismic-to-well correlation, and rock physics modeling. Seismic interpretation and log analysis were carried out using Kingdom Suite and MATLAB.

3.2 Seismic Interpretation

Seismic interpretation was carried out following standard principles of structural and stratigraphic analysis of seismic data, emphasizing reflector continuity, amplitude character, and geometrical terminations to identify stratigraphic horizons and structural features [38, 39]. Particular attention was given to reflection terminations such as onlaps, truncations, and offsets that signal the presence of faults or unconformities using basic principles of seismic stratigraphy [34, 35]. Horizons were picked based on lateral continuity and correlation with formation tops identified in the well data. The reflector identification was constrained by synthetic seismograms, depth markers and log-based formation tops.

Fault interpretation relied on lateral reflector displacement and changes in dip geometry. Thrusts and backthrusts were identified based on their characteristic ramp-flat geometry, steep dips, and

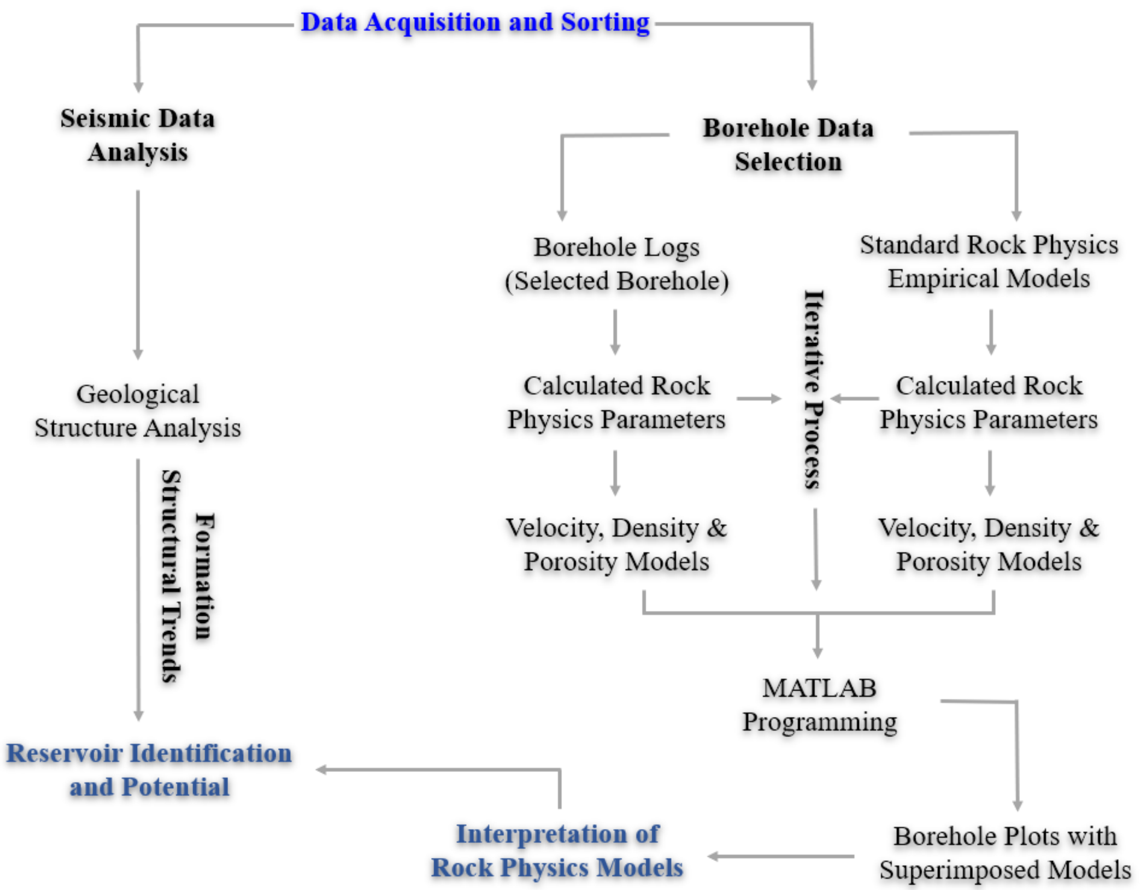


Figure 3. Workflow adopted.

terminations [36, 37]. Seismic data revealed a structurally complex setting marked by south-verging imbricate thrusts, duplexes, and roof thrusts which are features characteristic of triangle zones in thin-skinned tectonics [27, 32, 33]. The structural interpretation was integrated with stratigraphic knowledge from the well to associate reflectors with key reservoir units in the Eocene and Cambrian sequences.

3.3 Rock Physics Modeling

Rock physics modeling was applied to characterize the elastic behavior of Eocene carbonates and Cambrian sandstones, using well log data acquired in the study area. The modeling workflow is shown in Figure 3 and included data conditioning, porosity calculation, crossplot development, and calibration of empirical models for Vp–Porosity and Vp–Density relationships. The workflow includes the following steps:

- **Data Preparation:** Select depth intervals, log types, and any auxiliary data.
- **Crossplot Construction:** For each empirical model, construct crossplots of Vp versus porosity, density, or clay content. Analyze trends for each lithology.
- **Model Calibration:** Using known core data and log values, calibrate the constants for each empirical model.
- **Comparison and Validation:** Compare modeled Vp with observed data, and evaluate model performance.

3.3.1 *Log Selection and Data Conditioning*

The analysis focused on the depth intervals corresponding to the Sakesar Limestone, Chorgali Formation (Eocene carbonates), and Khewra Sandstone (Cambrian sandstone). Compressional velocity (V_p) was calculated from the sonic log. The bulk density and neutron porosity logs were quality-checked and corrected for borehole effects. Porosity was computed using the density log:

$$\phi = \frac{\rho_b - \rho_{\text{ma}}}{\rho_f - \rho_{\text{ma}}} \times 100 \tag{1}$$

where ρ_b is bulk density, ρ_{ma} is the matrix density, ρ_f

is the fluid density. For carbonates, $\rho_{\mathrm{ma}} = 2.71\,\mathrm{g/cm}^3$ and for sandstones, $\rho_{\mathrm{ma}} = 2.65\,\mathrm{g/cm}^3$.

3.3.2 *Vp–Porosity and Vp–Density Crossplots*

Velocity–porosity and velocity–density crossplots were constructed separately for the carbonate and sandstone intervals. Observed data trends were compared to empirical models. *Carbonates (Eocene):*

- The velocity–porosity crossplot showed a negative trend consistent with carbonate compaction behavior.
- Gardner's and Raymer's models were applied for comparison [48, 49].

Sandstones (Cambrian):

- Crossplots indicated that velocity decreased with increasing porosity, however, showed prominent dispersion.
- Clean sandstone models [50] overpredicted velocity; better results were achieved using clay-sensitive models [8, 9, 50].

3.3.3 *Empirical Models Applied*

Several empirical models were tested for their ability to replicate observed V_p-porosity-density trends:

(a) Han Model for Sandstones

Han's empirical model was used for estimating V_p in clean and shale sandstones. The basic principle behind Han's model is the velocity-porosity relationship, modified to account for shale content. It allows for the estimation of compressional-wave velocity from porosity and clay content.

$$V_p = a - b\phi - cC \tag{2}$$

where V_p = compressional wave velocity (km/s), ϕ = porosity, C = clay content and a, b, c are constants to be calibrated.

Stepwise methodology includes using well log data from the Khewra sandstone (Cambrian) for porosity and clay content, fitting the constants a, b, c based on laboratory measurements or log data for similar lithologies, then constructing a crossplot of V_p vs. porosity and validate the model with the log data. The model provides a clear framework to account for the effects of clay content and porosity on velocity in sandstones.

(b) Castagna's Mudrock Line

The Castagna Mudrock Line model is a widely used empirical relationship that estimates V_p based on porosity in shale-dominated systems.

$$V_p = 5.81 - 9.42\phi \tag{3}$$

Stepwise methodology includes using sonic and density logs from the Sakesar Limestone (Eocene carbonates) to determine porosity, applying the empirical relationship between V_p and porosity for shale-dominated lithologies, verifying the model against log data from Eocene carbonate formations. If the crossplot fits well, the model suggests an overpredicted velocity, likely indicating the presence of hydrocarbon fill in the pore spaces.

(c) Tosaya and Nur Model

The Tosaya and Nur model is an empirical relation for estimating V_p in shale-bearing formations. It is useful in sandstone-shale systems and adjusts for shale content.

$$V_p = 5.577 - 6.94\phi - 2.17C \tag{4}$$

Stepwise methodology includes using obtaining porosity and clay content data from well logs, the equation parameters (constants) are calibrated for the study area based on the lithology and formation type, and creating a V_p-porosity vs. clay content crossplot. The model can be validated using core measurements, seismic attributes, and well log data.

(d) Gardner's Density-Velocity Relationship

Gardner's relation is a widely used empirical model that establishes a relationship between bulk density and V_p for mixed lithologies.

$$\rho = aV_p^b \tag{5}$$

Stepwise methodology includes selecting well logs for density and V_p; the constants a and b are calibrated based on regional lithologies, applying the equation to predict bulk density from seismic velocities. Then, using the relationship to estimate lithology or identify potential hydrocarbon accumulations based on density-velocity contrasts.

(*e*) *Raymer-Hunt-Gardner Relation*

This empirical model is useful in predicting velocity for carbonates and sandstones using porosity.

$$V_p = \left[\frac{\phi}{V_f} + \frac{(1-\phi)}{V_m}\right]^{-1} \tag{6}$$

where V_f and V_m are the fluid velocity (dependent on the fluid type) and matrix velocity (dependent on lithology), respectively. Stepwise methodology includes well log data to obtain porosity, fluid velocities, and matrix velocities, estimate V_f and V_m based on known values for fluids (e.g., water or oil) and lithology (e.g., carbonate matrix), apply the model to estimate the compressional velocity V_p across different lithologies. Then, comparing the model's predictions against actual log data to validate the assumptions.

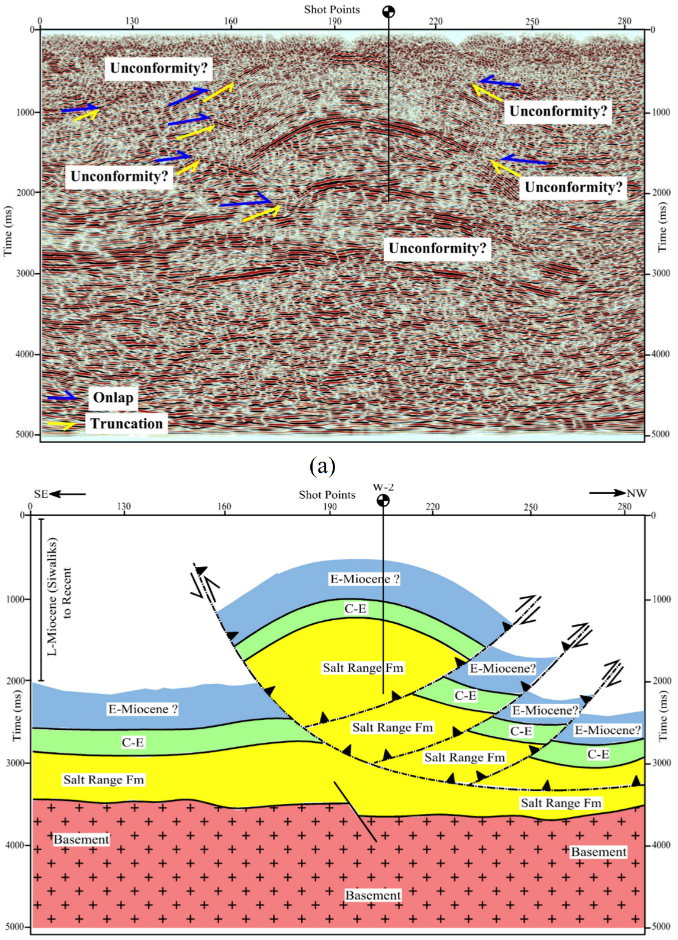
Each model serves a distinct role in the rock physics workflow. Han's and Tosaya's models are particularly useful for sandstones, while Castagna's Mudrock Line is optimized for shales and Gardner's and Raymer-Hunt-Gardner relations are appropriate for mixed lithologies or carbonates. By integrating these models, it is possible to robustly estimate elastic properties and assess the potential for hydrocarbon-bearing intervals.

4 Results and Discussions

Seismic interpretation and rock physics modeling have been integrated in Missakeswal area, Eastern Potwar Plateau to provide a comprehensive understanding of the geological structures, stratigraphy, and potential hydrocarbon reservoirs in this tectonically complex region. The results provide valuable insights into the subsurface characteristics of the study area and their implications for hydrocarbon exploration.

4.1 Geological Structures and Stratigraphy

Regional seismic data were interpreted to understand the subsurface structures and stratigraphy of the Missakeswal area. The interpretation of seismic data has helped mapping the structural configuration of the subsurface, particularly the relationship between thrust faults, anticlines, and synclines, which are crucial for identifying potential hydrocarbon reservoirs. The uninterpreted seismic profile (Figure 4(a)) reveals a series of reflectors with varying amplitudes and discontinuities, suggesting complex subsurface structures. The interpreted seismic profile (Figure 4(b)) shows key features such as thrust faults, anticlines, and unconformities, which are characteristic of the tectonic regime in the Eastern Potwar region. These features are indicative of fold-and-thrust belt tectonics that have significantly influenced the geological framework of the area [22].



(a)

(b)

Figure 4. (a) The un-interpreted regional seismic profile. (b) The interpreted regional seismic profile. C-E: Cambrian to Eocene sedimentary package, E-Miocene: Early Miocene, L-Miocene: Late Miocene.

The seismic interpretation showed that the study area is dominated by thrust faults, with reflector terminations and offsets marking the presence of major fault zones. These faults, which dip to the northwest, are associated with compressional forces that have shaped the Potwar Plateau and its foreland basin. The interpretation shows backthrusts with southeast dips, a feature that aligns with the findings from previous studies in the region [27]. The thrust faults in this area are indicative of active tectonic deformation, driven by the ongoing collision between the Indian and Eurasian plates, which has resulted in folding and faulting across the basin. The anticlines and synclines identified in the seismic profile are particularly significant in the context of hydrocarbon exploration. The anticlines, which appear prominently above the Cambrian-Eocene sequence, represent potential structural traps where hydrocarbons can accumulate. These anticlines, formed by compressional tectonics, are key features in fold-and-thrust belts that often trap hydrocarbons beneath impermeable layers. The synclines, on the other hand, may play a role in hydrocarbon migration, directing fluids toward the anticlines where they can accumulate. The seismic data show clear evidence of these fold structures, which are known to be hydrocarbon reservoirs in other similar tectonic settings, such as those in the Salt Range and other parts of the Potwar Plateau [21].

The unconformities observed in the seismic data, particularly between the Eocene and Cambrian units, reflect the complex geological history of the region. These unconformities suggest periods of non-deposition or erosion, which are key to understanding the stratigraphic framework of the area. The presence of these unconformities is representative of significant tectonic events, such as uplift and erosion, that have influenced the deposition and preservation of hydrocarbon-bearing formations. The seismic interpretation confirms that these unconformities act as seals for hydrocarbon accumulations, as they separate different stratigraphic layers and prevent the upward migration of fluids.

The Cambrian sandstones and Eocene carbonates emerge as the primary candidates for reservoir rocks. The Eocene carbonates (Sakesar Limestone and Chorgali Formation) exhibit strong amplitude contrasts in the seismic data, which suggest they have favorable porosity and permeability for hydrocarbon storage. The Cambrian sandstones are also indicated as promising reservoir units, as they show continuous reflectors and minimal structural disruption, which could facilitate the accumulation of hydrocarbons. These units, with their high porosity and permeability, are likely to serve as the main reservoir rocks in this region, as they are often associated with hydrocarbon fields in similar geological settings [20, 44]. Furthermore, the interpreted seismic data also revealed that the Salt Range Formation plays a crucial role in the structural development of the area. As a decollement layer, the Salt Range Formation has facilitated the development of thrust faults and folds, which are key features in the formation of structural traps. The Salt Range Thrust and other associated thrusts have created a complex system of folded anticlines and synclines, which are likely to host significant hydrocarbon reserves. These structures provide potential traps for oil and gas migration, with the thrust faults acting as barriers to the upward movement of fluids.

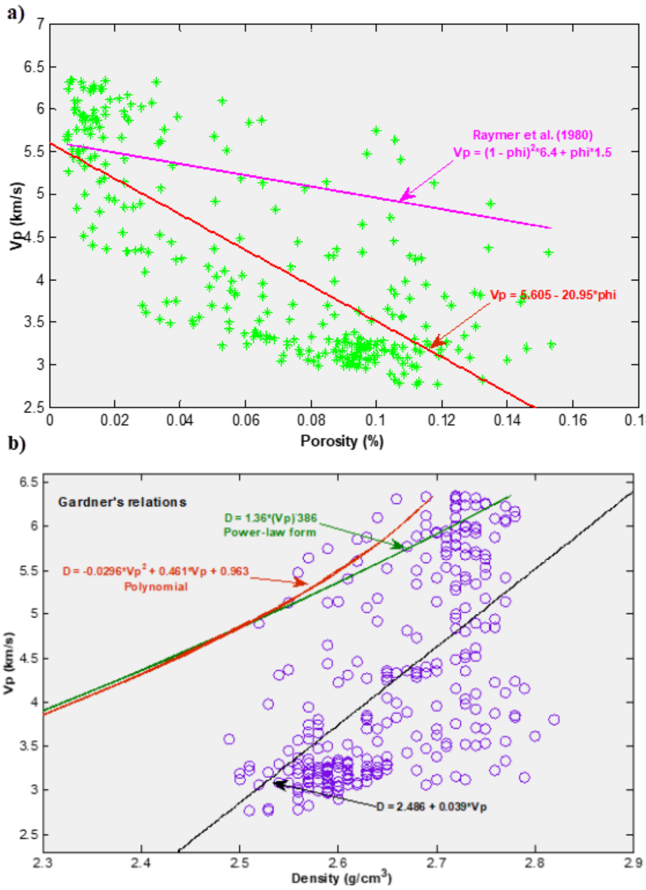


Figure 5. Cross-plots for Formation-1. (a) Velocity vs (b) Density.

The velocity-porosity crossplot for the Chorgali Formation (Figure 5(a)) reveals the expected trend of decreasing Vp with increasing porosity, a characteristic commonly observed in carbonate rocks due to compaction. The data, ranging from 1% to 14% porosity, shows significant scatter. The best-fit line derived from the regression analysis is consistent with a negative correlation between Vp and porosity, confirming the typical behavior of carbonates where porosity increases as compaction decreases. However, the Raymer model for water-saturated limestone, when applied to this data, overestimates the P-wave velocity, suggesting that the Chorgali Formation is likely not fully water-saturated. The deviation from the Raymer model indicates that the formation may be hydrocarbon-saturated, as hydrocarbons typically cause a reduction in velocity, which aligns with the observed trend in the data.

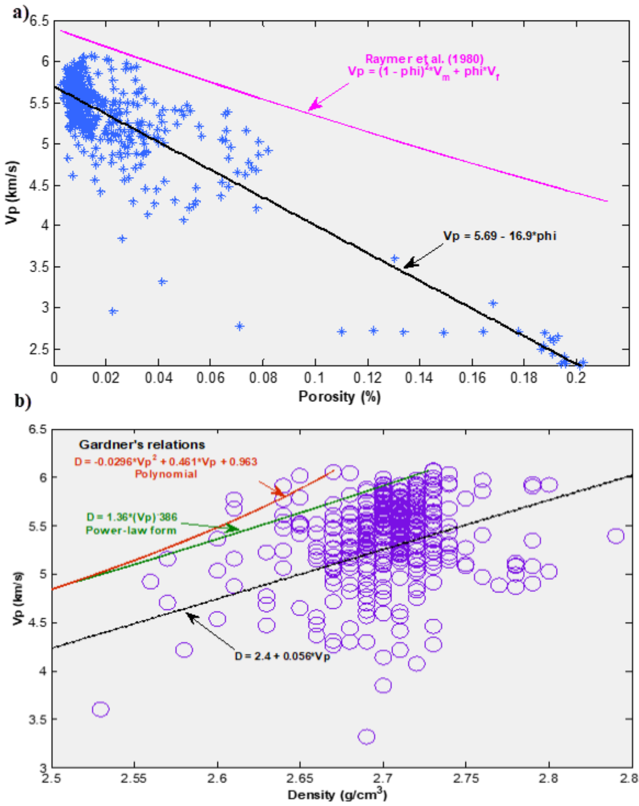


Figure 6. Cross-plots for Formation-2. (a) Velocity vs (b) Density.

Similarly, the Sakesar Formation (Figure 6(a)) shows a similar relationship between Vp and porosity, with Vp decreasing as porosity increases. The data for this formation is more scattered, particularly at lower porosities, however, still follows the expected compaction trend. The regression analysis for the Sakesar Formation gives a best-fit line with a negative slope, which again indicates a typical carbonate behavior. When the Raymer model for water-saturated limestone is superimposed on the data, it overestimates the P-wave velocity for the Sakesar Limestone, further supporting the hypothesis that this formation is not fully water-saturated. The overestimation in velocity is consistent with the presence of hydrocarbons, which is likely influencing the velocity-porosity relationship.

In addition to the velocity-porosity crossplots, the velocity-density crossplots for both the Chorgali Formation (Figure 5(b)) and the Sakesar Formation (Figure 6(b)) were also analyzed. For the Chorgali Formation, the velocity-density crossplot shows a clear positive relationship between P-wave velocity and bulk density. The data points generally align with the best-fit line, but when the Gardner model for water-saturated limestone is applied, it overpredicts the P-wave velocity, suggesting that the Chorgali Limestone may be hydrocarbon-saturated rather than water-saturated. This overprediction is typical for formations where hydrocarbons replace water in the pore spaces, as hydrocarbons often cause a decrease in seismic velocities compared to water-filled pores.

The Sakesar Limestone also exhibits a positive correlation between P-wave velocity and density, with the best-fit line showing a similar trend. However, when compared with Gardner's model for water-saturated limestone, the model again overestimates Vp values, indicating that the formation is likely hydrocarbon-saturated. The data from both formations suggest that the velocity-density relationship is influenced by the presence of hydrocarbons, as indicated by the significant deviation from models assuming water saturation.

These results from the velocity-porosity and velocity-density crossplots for the Chorgali Limestone and Sakesar Formation provide strong evidence that both formations are likely to contain hydrocarbons. The deviations observed from the theoretical models suggest that hydrocarbons are influencing the elastic properties of these formations, making them suitable candidates for hydrocarbon storage. The modeling confirms that both the Chorgali Formation and Sakesar Limestone exhibit the typical characteristics of carbonate reservoirs, where hydrocarbon saturation significantly alters their seismic properties.

4.2 Rock Physics Modeling of Cambrian Sands

The Khewra Formation (Cambrian sands) was analyzed using rock physics models to examine its velocity-porosity relationships and assess its potential as a hydrocarbon reservoir. This analysis included the application of the Castagna, Tosaya, and Han models, each incorporating different assumptions regarding clay content, which is a significant factor influencing the formation's seismic properties.

4.2.1 Velocity-Porosity Crossplots

The velocity-porosity crossplot for the Khewra Formation (Figure 7(a)) demonstrates a clear inverse relationship between P-wave velocity (Vp) and porosity, typical of sandstones. In Figure 7(a), the data show a trend where Vp decreases with increasing porosity, confirming the expected behavior of a sandstone with increasing porosity due to compaction. The data exhibit some scatter, particularly at lower porosities, likely due to variations in clay content and potential hydrocarbon saturation. The regression line derived from the data suggests a negative correlation,

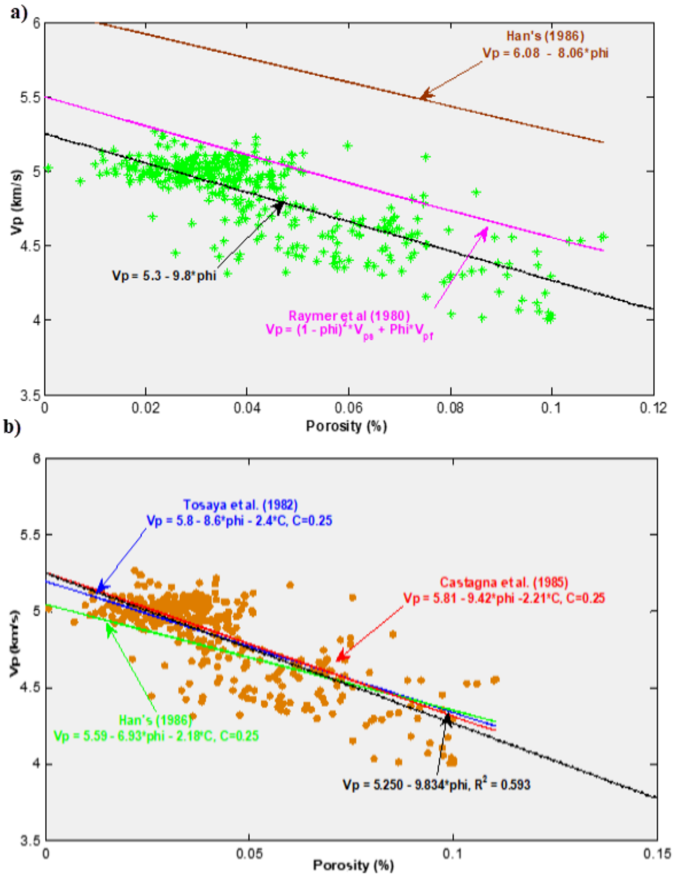


Figure 7. Cross-plots for Formation-3: Velocity vs Porosity Clean. (a) Velocity vs Porosity with superimposed models for water saturated shaley sandstone. (b) Black line: log data; green, blue, and red lines: Modeled data.

consistent with the behavior observed in typical sandstone reservoirs. This trend is especially useful in understanding the compaction properties of the formation.

Figure 7(b) shows a similar velocity-porosity relationship for the Khewra Formation, reinforcing the pattern observed in Figure 7(a). The scatter observed in both subfigures further indicates the heterogeneity of the formation, particularly due to the presence of clay and possible fluid saturation, which can affect the seismic properties of the formation. The overall trends observed in both subfigures suggest that the Khewra Formation is a complex rock unit, where clay content and fluid types likely contribute to the observed variability in P-wave velocity.

4.2.2 *Empirical Models: Castagna, Tosaya, and Han Models*

To refine the velocity-porosity relationship, empirical models were applied to the Khewra Formation data. In Figure 8, the Castagna model was used to account for the effect of clay content on P-wave velocity. The model shows that as clay content increases, P-wave velocity decreases for a given porosity, which is consistent with the behavior of sandstones that have significant shale components. The application of the Castagna model demonstrates how variations in clay content influence the overall velocity-porosity relationship, providing a more refined understanding of the seismic properties of the formation.

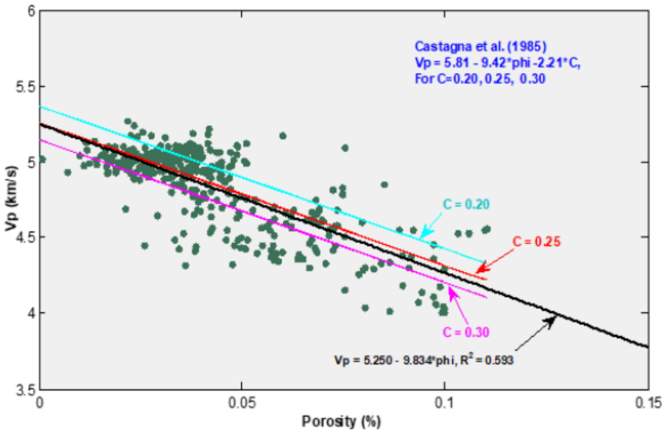


Figure 8. Velocity vs Porosity Cross-plot for Formation-3 with superimposed Castagna's model at different clay amount. Black line: log data; magenta, red, cyan colors: Modeled data.

The Tosaya model (Figure 9) provides an additional refinement to the velocity-porosity relationship by considering clay mineralogy and the specific shale content within the Khewra Formation. The model further supports the idea that the Khewra Formation is a clay-rich sandstone, with a P-wave velocity that decreases more sharply with increasing porosity when clay content is higher. The Tosaya model helps to clarify how shale content influences the overall seismic response of the formation, which is a critical factor in reservoir characterization.

The Han model (Figure 10) provides a third approach to modeling the velocity-porosity relationship by specifically accounting for the sandstone-shale mixtures in the formation. This model shows that as the clay content increases, P-wave velocity decreases, which is typical for mixed lithologies. The Han model aligns with the findings from the Castagna and Tosaya models, further confirming that the Khewra Formation is influenced by the presence of clay in varying amounts, which impacts its velocity-porosity relationship.

4.2.3 *Implications for Reservoir Characterization*

The integration of the Castagna, Tosaya, and Han models provides a comprehensive understanding

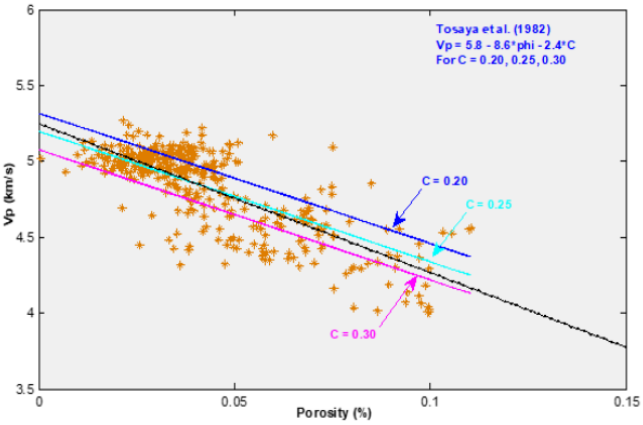


Figure 9. Velocity vs Porosity Cross-plot for Formation-3 with superimposed Tosaya's model at different clay amount. Black line: log data; magenta, blue, cyan colors: Modeled data.

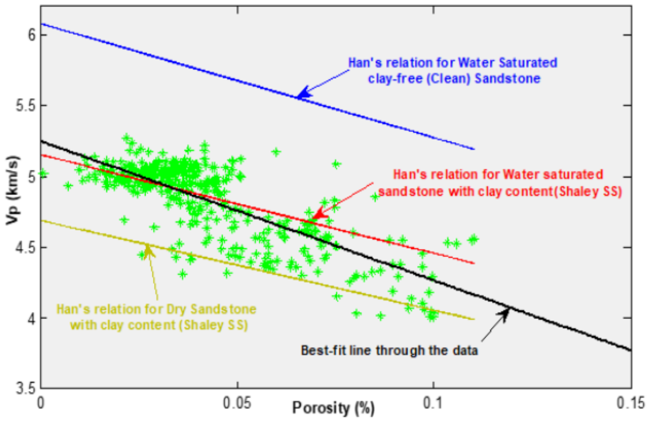


Figure 10. Velocity vs Porosity Cross-plot for Formation-3 with superimposed Han's model at different clay amount. Black line: log data; blue, red, and olive colors: Modeled data.

of the Khewra Formation's rock physics properties, particularly in the context of clay content and its effect on P-wave velocity. The crossplots and empirical models suggest that the Khewra Formation is a clay-rich sandstone with hydrocarbon potential, as indicated by the observed deviations from the standard velocity-porosity trends seen in pure sandstones. The presence of clay and the potential influence of hydrocarbons on the seismic properties make the Khewra Formation a complex but promising target for hydrocarbon exploration.

The modeling results further suggest that clay content plays a crucial role in defining the velocity-porosity and velocity-density relationships in the Khewra Formation. This complexity should be considered in reservoir characterization efforts, as the presence of clay can significantly modify seismic responses and hydrocarbon saturation predictions. The empirical models provide essential insights into the seismic properties of the formation and offer a robust framework for understanding its hydrocarbon potential.

4.3 Integrated Approach

The integration of seismic interpretation and rock physics modeling provides a comprehensive framework for understanding the hydrocarbon potential of the Missakeswal area. Seismic data offers essential information regarding the subsurface structures, such as anticlines, faults, and synclines, which are key features for identifying hydrocarbon traps. However, seismic data alone cannot provide the detailed insights required to assess reservoir quality, such as porosity, permeability, and fluid content. In this case, rock physics modeling provides additional constraints. By applying empirical models to well log data, rock physics modeling refines the interpretation of velocity-porosity and velocity-density relationships, providing a clearer understanding of the seismic properties of the formations [46].

When seismic data and rock physics models are integrated, the resulting insights lead to more accurate and comprehensive reservoir models. Seismic interpretation helps identify the structural features and hydrocarbon traps, while rock physics modeling adds critical information about the reservoir characteristics within these traps. For instance, seismic data suggested that the Eocene carbonates (Sakesar Limestone and Chorgali Formation) have the potential for hydrocarbon storage, and rock physics modeling confirmed this hypothesis by showing deviations from standard velocity-porosity models, indicative of hydrocarbon saturation [47]. In a similar way, seismic data highlighted the Cambrian sands of the Khewra Formation as promising targets for exploration. The application of rock physics models further refined this prediction, revealing the role of clay content and hydrocarbon saturation in influencing the seismic velocities and porosity. By combining these two approaches, the hydrocarbon potential of the region can be more accurately assessed, enabling better targeting of reservoirs and reducing exploration risk [20].

The integrated approach of seismic interpretation and rock physics modeling provides a more detailed and reliable method for reservoir characterization and hydrocarbon exploration. Future efforts could involve refining the models through the inclusion of core data and more detailed well log information, enhancing the accuracy of predictions for porosity, permeability, and fluid content [47]. Additionally, advanced seismic techniques such as inversion methods and full-waveform modeling could be employed to provide even higher resolution data, which when integrated with rock physics models, would further enhance the ability to accurately predict the hydrocarbon potential of the region. By combining seismic interpretation and rock physics modeling, the Missakeswal area can be better characterized for hydrocarbon exploration, making this integrated approach a critical tool for future drilling and exploration decisions.

5 Conclusions

This study provides a comprehensive analysis of the Missakeswal area in the Eastern Potwar region of Pakistan, using an integrated approach that combines seismic interpretation with rock physics modeling. By applying seismic data analysis and empirical rock physics models, the research successfully characterizes the hydrocarbon reservoirs, focusing on Eocene carbonates and Cambrian sands. The integration of these methods significantly enhances the ability to predict reservoir quality, hydrocarbon saturation, and the hydrocarbon potential of the region. Key conclusions drawn from this study include:

- Seismic interpretation identified significant structural features in the subsurface, such as anticlines, faults, and synclines, which are crucial for locating hydrocarbon traps and reservoir zones in the Missakeswal area.
- The Eocene carbonates (specifically the Sakesar Limestone and Chorgali Formation) exhibit favorable characteristics for hydrocarbon storage, with velocity-porosity relationships showing significant deviations from standard models, indicating potential hydrocarbon saturation.
- Cambrian sands, particularly the Khewra Formation, were identified as potential reservoirs, with rock physics models revealing the influence of clay content and hydrocarbon saturation on the velocity-porosity and velocity-density relationships.
- Integrated seismic and rock physics modeling provides a comprehensive understanding of the hydrocarbon potential in the region by combining structural information from seismic data with petrophysical insights from rock physics models. This approach allows for more accurate predictions of hydrocarbon saturation and better reservoir characterization. The results suggest that both the Eocene carbonates and Cambrian sands have significant potential for hydrocarbon exploration, with further refinement of the models possible through additional core data and seismic inversion techniques.
- The combined approach of seismic interpretation and rock physics modeling offers a powerful tool for reducing exploration risk, improving drilling decisions, and enhancing reservoir management for future hydrocarbon exploration projects in the region.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

Majid Khan served as an Editorial Board Member, and Naseer Muhammad Khan served as an Associate Editor of the *Reservoir Science* at the time of manuscript submission. To ensure the integrity of the peer-review process, neither Majid Khan nor Naseer Muhammad Khan was involved in the editorial handling, peer review, or decision-making process for this manuscript, which was handled independently by another editor. The remaining authors declare no conflicts of interest.

AI Use Statement

The authors declare that no generative AI was used in the preparation of this manuscript.

Ethical Approval and Consent to Participate

Not applicable.

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