RGNZ/MGPB

Integrated Geoscience, and Geospatial Analysis for Hydrocarbon Exploration in the Khewari Block, Sindh, Pakistan

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2026.4.9

Original scientific paper

CC BY

Muhammad Junaid[1,2*], Muhammad Sajid[2], Taimoor Ahmad[2], Eko Kusratmoko[1], Reza Syahputra[3], Shaukat Khan[4], Adi Wibowo[1], Muhammad Kashif[5]

[1] *Department of Geography Science, Universitas Indonesia, Depok, Indonesia.*
[2] *Department of Earth Sciences, Abbottabad University of Science and Technology, Pakistan.*
[3] *Department of Geology, University of Indonesia, Depok, Indonesia.*
[4] *Geological Engineering and Geomatics, Chang'an University, Xi'an, China.*
[5] *Department of Earth Sciences, University of Sargodha, Pakistan.*

Abstract

The Khewari Block, located in the structurally complex Lower Indus Basin of Sindh, Pakistan, occupies a tectonically favorable yet insufficiently explored sector of a Mesozoic–Cenozoic rifted basin known for its hydrocarbon prospectivity. This study employs an integrated geophysical geospatial workflow to confine subsurface architecture and assess reservoir potential. Extensive interpretation of 2D seismic profiles identifies a system of NE-SW-oriented normal faults, horsts, grabens, and local compressional structures, producing a wide range of trap geometries, including fault-bounded closures, rollover anticlines, and tilted fault blocks. Time and depth structure mapping refines horizon geometries and identifies structurally isolated blocks with enhanced trapping potential. Bouguer and residual gravity anomaly maps further resolve density differences associated with uplifted carbonate platforms and sediment-filled troughs, confirming segmentation of the structure based on seismic data. Surface dataset complements, such as DEM-based elevation, slope models, and land-use classification, offer further limitations on terrain accessibility, drainage systems, and operational capabilities. The integration of surface and subsurface datasets reduces the uncertainty in the interpretation process, improves the delineation of traps, and contributes to the most effective well-placement planning. The multidisciplinary approach illustrates the effectiveness of integrating seismic reflection, gravity modelling, and surface-based GIS analysis to create a coherent structural framework of frontier basins. The workflow is transferable to other data-limited regions and provides a robust foundation for evidence-based hydrocarbon exploration and decision-making.

Keywords:
Hydrocarbon Exploration; Seismic Interpretation; Gravity Anomalies; Geospatial Integration; Khewari Block

1. Introduction

The Khewari Block, located in the Lower Indus Basin of Sindh, Pakistan, is a structurally favorable yet underexplored region with considerable hydrocarbon potential, owing to its complex tectonic framework and the presence of thick Mesozoic–Cenozoic sedimentary successions (**Jadoon et al., 2020**). While the Lower Indus Basin has historically contributed significantly to Pakistan's energy sector, exploration within the Khewari Block itself has remained limited because of its geological complexity and restricted accessibility (**Aftab et al., 2022**). Although the nearby blocks, such as the Kadanwari and Sawan gas fields, have undergone extensive geophysical and drilling operations, the Khewari Block, located in the southeastern part of the Lower Indus Basin between the Jacobabad High to the north and the Hyderabad Platform to the south, remains insufficiently characterized. Regionally, this area forms part of a rift-dominated structural regime associated with the breakup of Gondwanaland, which created a series of horsts, grabens, and tilted fault blocks that control hydrocarbon migration and entrapment (**Khan et al., 2021**). The proximity of the Khewari Block to productive reservoirs within the Lower Goru Formation in adjacent fields further highlights its exploration significance within the broader Indus Basin petroleum system.Unconsolidated Quaternary sediments also make geophysical images less clear, which makes it more difficult to define the structure of reservoirs with certainty (**Khayitov et al., 2021; Sajid et al., 2021**). The seismic reflection data have turned out to be essential in the detection of structural traps, especially fault-bounded closures that happened due to NE-SW trending normal faults related to the regional rifting (**Noureldin et al., 2023**). These faults define horst and graben geometries that segment

* Corresponding author: Muhammad Junaid
e-mail address: muhammadjunaidk22@gmail.com
Received: 15 October 2025. Accepted: 11 February 2026.
Available online: 21 July 2026

the basin and function variably as either hydrocarbon conduits or sealing barriers depending on lithological context (**de Jager, 2020**). Previous geophysical studies in comparable rifted basins have demonstrated that integrated interpretation of gravity-derived structural models can significantly improve the delineation of subsurface fault geometries and basin architecture (**Setiahadiwibowo et al., 2025**).

The Lower Goru Formation has emerged as the principal reservoir unit, and its internal continuity is often inferred through amplitude anomalies such as bright spots and flat spots, indirect indicators of gas saturation (**Singh, 2014**). Nevertheless, seismic imaging alone suffers from attenuation, velocity ambiguity, and limited vertical resolution, especially across lithologically heterogeneous zones (**Khaskheli et al., 2021**). The basin's stratigraphy spans from the Precambrian to the Quaternary, reflecting a long history of marine transgressions, regressions, and sediment accumulation (**Lučić & Bosworth, 2018**). This complex depositional record has yielded multiple reservoir and seal pairs, notably within the Lower and Upper Goru, Sui Main Limestone, and Ranikot Formation. The Lower Goru Formation typically occurs at depths averaging ~2233 meters, while seismic profiles capture subsurface horizons between 1970 and 3220 milliseconds in two-way travel time (**Mahmoud, 2015**). These depth intervals suggest significant stratigraphic thickness and structural deformation, but detailed fault and formation correlations across the Khewari Block remain sparse in the literature (**Zhou et al., 2025**).

Regionally, the Lower Indus Basin has a tectono-sedimentary history that was influenced by post-Mesozoic extension and Himalayan orogeny (**Inam et al., 2022**). This history has given rise to a subsurface architecture characterized by the existence of many structural traps and tilted fault blocks (**Dolson et al., 2018**). Previous exploratory wells and geophysical surveys have only partially assessed the block's hydrocarbon potential (**Sarhan, 2021**). Nevertheless, analogs from other parts of the basin and comparable rift basins worldwide support the likelihood of commercially viable hydrocarbon systems yet to be fully delineated (**Khan et al., 2024; Iqbal et al., 2022**). Despite the fact that seismic interpretation is still at the heart of subsurface mapping, more and more current hydrocarbon exploration requires the assimilation of geophysical and geospatial data. Integrated seismic and gravity data have been shown to significantly enhance subsurface structural imaging and improve geological interpretation in complex rifted basins (**Safani et al., 2026**). Traditional seismic data, including SEG-Y profiles, usually have issues with noise, resolution, and a lack of surface context (**Buttinelli et al., 2022**). This is especially the case in structurally complicated areas such as the Khewari Block, where fault interactions, lithological contrasts, and vertical heterogeneities make the detection of hydrocarbons challenging. Moreover, legacy workflows do not pay significant attention to surface logistics, which include slope stability, land-use restriction, and infrastructure accessibility, which are key to operational planning (**van Buren et al., 2019**).

Geographical Information Systems (GIS) and remote sensing technologies provide useful answers to the interpretational gap between the surface measurements and the underground structures (**Tshanga et al., 2024**). Digital Elevation Models (DEMs), slope inclinations, lithological variations, and drainage networks are examples of useful proxies used to identify fault-controlled geomorphological features (**Toppo & Sinha, 2024**). These surface datasets are combined with subsurface seismic and gravity data, which increase the support of structural traps by giving spatial associations with morphological manifestations of buried faults (**Lin et al., 2024**). Moreover, the application of spatial analysis to hydrocarbon exploration processes contributes to the logistical and environmental planning of the process, as it identifies potential locales of drills, which are geologically and operationally appropriate, a facet that has been underrated in the conventional seismic-based approaches (**Ali et al., 2024; Hussain et al., 2022**).

Furthermore, incorporating spatial analysis and GIS-based mapping into hydrocarbon exploration workflows provides critical insight for logistical and environmental planning by pinpointing drilling zones that are not only geologically favorable, but also operationally accessible on a dimension often underrepresented in purely seismic-based studies (**Saravanavel et al., 2020**). In order to resolve the geoscientific and operational uncertainties, the proposed research applies a multidisciplinary approach to include detailed seismic interpretation, gravity anomaly analysis, remote sensing, and terrain evaluation based on GIS (**Cao et al., 2024**). Time and depth maps are created using seismic data, which are processed in Petrel, and can be used to define faults and reservoir geometry (**Fan & Kong, 2023**). Meanwhile, topography, land cover, and environmental constraints are mapped and analyzed in ArcGIS to increase the surface-to-subsurface correlation (**Aboelhassan et al., 2024**). The overall workflow, a combination of workflows, leads to a strong 3D geological model that reflects the structural, stratigraphic, and spatial complexity of the Khewari Block. It is intended to enhance hydrocarbon prospect appraisal and minimize exploration risk, as well as offer a viable, transferable model to explore undeveloped frontier basins with comparable data, geological, and logistical issues (**Shastri et al., 2019**).

2. Methods

2.1. Data Collection

The geophysical and geospatial data used in this study, which were supplied by the Directorate General

of Petroleum Concessions (DGPC) and Landmark Resources (LMKR), and the fundamental data consisted of high-resolution 2D seismic reflection profiles in SEG-Y format gained in 2023 in the Khewari Block. Major seismic lines such as 021-KWI-40, 021-KWI-39, and 011-KWI-16 formed vital depth and strike information that facilitated mapping faults, anticlines, and stratigraphic horizons, which were important in the entrapment of hydrocarbons and characterization of reservoirs. A mix of geophones, dynamite charges, and vibriosis sources was used to record data to obtain high-intensity reflection signals that can penetrate complex layers in the subsurface to enhance imaging of regions contaminated by unconsolidated sediments and enhance reflector clarity in structurally rich areas. To complement the seismic dataset, gravity survey results were integrated to detect density variations in subsurface formations, assisting in the identification of horsts, grabens, and major fault systems often unresolved in seismic profiles alone. In addition, topographical constraints, accessibility, and geomorphic features within deeper structure patterns were assessed by the production of slope, elevation, and drainage maps using Geographic Information System (GIS), which were used to assess the topographical constraints. Bringing together the seismic reflection data, data on the gravity anomalies, and GIS-based terrain modelling generated a multi-layered dataset that reduced the amount of uncertainty in delineating the traps and improved the overall structure of the exploration of the hydrocarbons in Khewari Block.

2.2. Data Processing

The seismic data were processed using a structured and project-specific workflow to enhance data quality and improve subsurface imaging. As summarized in the seismic processing flowchart (see **Figure 1**), the workflow began with geometry assignment followed by static and dynamic corrections to compensate for elevation differences and near-surface velocity variations. Demultiplexing was applied to separate the recorded seismic traces into individual channels, enabling subsequent filtering and analysis. Band-pass filtering was then used to suppress unwanted noise and enhance the frequency bandwidth of interest, thereby improving the signal-to-noise ratio. Common midpoint (CMP) stacking was performed to increase reflection continuity and reduce random noise, and finally, migration was applied to correctly position dipping reflectors and fault geometries, resulting in a more accurate spatial representation of subsurface geological structures.

Gravity, satellite, GIS, and well log datasets were processed using dataset-specific procedures to ensure consistency with seismic interpretations. Gravity data were corrected for drift, latitude, free-air, Bouguer, and terrain effects to generate Bouguer and residual anomaly maps suitable for structural analysis. Satellite imagery underwent radiometric and geometric corrections prior to lineament extraction and surface structural interpretation. GIS-based datasets, including digital elevation models (DEMs), slope, drainage, and land-use layers, were standardized, reprojected into a common coordinate system, and prepared for spatial overlay analysis. Well log data were quality-checked and used to support lithological correlation and depth calibration where available. The integrated processing of all datasets ensured internal consistency and supported reliable multi-scale interpretation of subsurface structures and surface constrain.

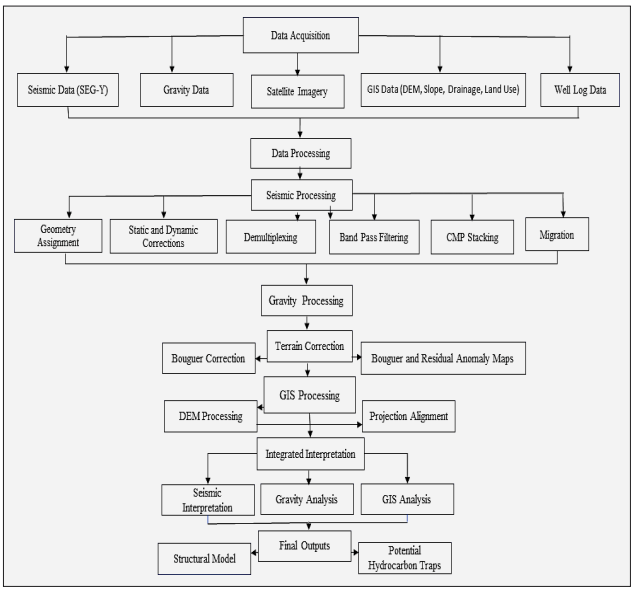


Figure 1: Integrated geophysical and geospatial workflow highlighting seismic, gravity, and GIS-based data processing and interpretation for the Khewari Block, Sindh, Pakistan.

2.3. Data Analysis

To evaluate the hydrocarbon potential of the Khewari Block, an integrated workflow combining seismic, gravity, and geospatial datasets was applied using Petrel 2010 and ArcGIS. These tools enabled consistent data processing, visualization, and interpretation across subsurface and surface domains.

1. Seismic Interpretation

In the analysis of 2D SEG-Y, seismic data was processed to identify the primary structural framework of the Khewari Block. The analysis focused on mapping key reflectors, faults, and stratigraphic horizons, with particular emphasis on the Lower Goru Formation, the main potential reservoir unit. Major extensional structures detected during the analysis are the horsts, grabens, fault-bounded closures, and rollover anticlines, which serve as hydrocarbon traps. Time contour maps represented the structural topography of subsurface zones with special emphasis on the Lower Goru Formation as the main potential reservoir (**Abdul-Majeed et al., 2020**). A depth conversion method was performed, based on average interval velocities derived from regional datasets and calibrated against the Khario-01

well. To provide structural consistency, several seismic lines were cross-correlated, which minimized the uncertainty in the interpretation and enhanced depth accuracy.

2. Gravity Analysis

The gravity interpretation method gave valuable information about lateral density variations and regional basin architecture. Bouguer and residual anomaly maps were generated to differentiate high gravity, which is usually defined as uplifted basement blocks or carbonate platforms, and from gravity lows that indicate sediments filled troughs or fault depressions. These anomalies validated and improved the seismic interpretation by highlighting deep structural trends and confirming the geometry of major fault systems.

3. GIS-Based Terrain and Suitability Analysis

The geospatial analysis was performed using ArcGIS to integrate and evaluate surface datasets derived from digital elevation models (DEMs), slope gradient, drainage systems, and land-use to determine the accessibility of the terrain accessibility and environmental suitability. Terrain parameters were systematically extracted to characterize changes in slope, elevation, and the morphology of the surface. The resultant thematic layers were spatially correlated with subsurface structural interpretations, to determine the relationships between geomorphological patterns and the underlying tectonic structures. This integrative evaluation helped to identify the areas with favorable topographic and logistical conditions for potential drilling operations, while also providing insight into the geomorphic factors that may have contributed to structural development within the Khewari Block.

4. Integrated Interpretation

An integrated geospatial system was developed to combine the results of seismic, gravity, and GIS-based analyses into a unified interpretational framework for the Khewari Block. The interpretation of seismic-derived subsurface structural features was spatially correlated with gravity anomaly patterns to confirm continuity and geometry of major fault systems, horst-graben structures, and uplifted basement blocks. The joint assessment indicates a high degree of correspondence between gravity highs and seismically mapped structural highs, while gravity lows are aligned with graben-like depressions identified on seismic time-structure maps. This cross-validation enhanced the confidence in the mapping of the possible traps of hydrocarbons and minimized structural uncertainty within the study area.

The integration of terrain suitability and geomorphological data based on GIS analysis further enhanced the interpretational context by linking surface morphology with subsurface deformation. The terrain layers were employed to evaluate logistical accessibility (slope, elevation, and drainage system) and to identify surface indicators potentially related to underlying tectonic activity. By merging these multi-source datasets within a common geospatial environment, the study obtained a coherent structural and geomorphic understanding of the Khewari Block. This integrative interpretation refined the tectono-stratigraphic model, strengthened exploration reliability, and demonstrated how geophysical and geospatial data can be effectively harmonized without methodological repetition.

2.4. Data Acquisition

The geophysical and spatial datasets used in this study originated from Landmark Resources (LMKR) and the Directorate General of Petroleum Concessions (DGPC) of Pakistan. The Khewari Block has three key types of data: (1) two-dimensional (2D) seismic reflection profiles in SEG-Y format, (2) regional gravity survey observations, and (3) digital elevation models (DEMs) of surface morphology. Collectively, these datasets give complementary data on subsurface structure and surface topography, forming the foundation for the integrated geoscientific interpretation conducted in this research.

1. Seismic Interpretation Using Petrel Software

The seismic analysis was performed using Petrel to interpret subsurface structure within the Khewari Block. The 2D seismic profiles were traced using reflective horizons to locate major faults, folds, and stratigraphic boundaries. These interpretations provided a precise representation of the subsurface geometry and served as a foundation for depth conversion and subsequent integration with gravity and geospatial analyses.

2. Generation of Contour Maps and 3D Visualization

The interpretation of the seismic horizons was used to generate structural contour maps and three-dimensional (3D) visualizations to show the underlying structure of the Khewari Block. The time and depth map highlights major structural features, such as fault-bounded anticlines and horst-grabens, which are possible traps of hydrocarbons. Three-dimensional models of chosen seismic sections enhanced the spatial understanding of structural geometry and facilitated correlation between subsurface features and gravity anomalies.

3. Gravity Survey Integration

The gravity data were used to optimize the basin geometry and to define density changes in the subsurface throughout the Khewari Block. The interpretation of Bouguer anomaly maps indicated that there were such important structural trends as uplifted basement blocks and graben-like depressions, which correspond to regional tectonic lineaments. These gravity anomalies offered key limitations to confirming the seismic interpretation and outlining deep structural features, which were not completely clarified in the seismic profiles

4. GIS-Based Terrain and Spatial Mapping

The integration of surface and subsurface data in a common spatiotemporal framework was conducted in ArcGIS to carry out geospatial analysis. Digital Eleva-

Table 1: Key research phases and tasks for data acquisition, processing, interpretation

Stage	Objective	Key Steps
Data Collection	Acquire all necessary geophysical and spatial datasets.	Collect 2D seismic (SEG-Y) from LMKR/DGPC- Obtain Bouguer and residual gravity data. Download DEMs and LULC layers
Data Processing	Prepare data for analysis by applying cleaning and georeferencing steps.	Apply filtering, stacking, migration in seismic software- Process gravity maps- Prepare GIS layers (slope, elevation)
Seismic Interpretation	Extract geological structures and horizon data from seismic profiles.	Interpret faults and horizons using Petrel- Generate time and depth maps for key formations
GIS-Based Mapping	Evaluate terrain conditions and integrate with subsurface models.	Use ArcGIS for slope/elevation/drainage modelling- Overlay seismic and gravity datasets spatially

tion Models (DEMs), slope gradients, drainage networks, and land-use layers were analyzed to generate thematic maps that characterize terrain morphology and surface constraints. These geospatial layers were later compared with seismic- and gravity-based structures to assess the spatial relationship between surface and subsurface deformation. This integration provided a basis for assessing terrain suitability for drilling operations and for linking geomorphological patterns with underlying tectonic structures in the Khewari Block.

5. Structural Analysis

Structural analysis was conducted by integrating seismic interpretations, gravity anomaly patterns, and geospatial datasets within a unified spatial reference system. The combined analysis enabled the identification and correlation of major tectonic features, such as fault zones, fold belts, and stratigraphic boundaries that determine the accumulation of hydrocarbons in the Khewari Block. This multidisciplinary methodology provided a refined understanding of the structural architecture and reservoir structure, forming a basis for interpreting the possible traps of hydrocarbons and evaluating the overall tectono-stratigraphic evolution of the study area.

2.5. Depth Conversion and Velocity Model Assumptions

In the absence of detailed velocity logs from multiple wells, depth conversion was carried out using average interval velocities derived from regional datasets and calibrated to the Kharo-01 Well, where reliable velocity control was available. The conversion process was performed in Petrel 2023 with the assumption of laterally continuous velocity layers across the interpreted seismic horizons. This assumption creates possible uncertainty in regions with steep structural relief or lithological heterogeneity. To reduce the number of uncertainties, a variety of seismic lines were cross-referenced to ensure structural consistency, and the measured depths of key reflectors, especially the top of the Lower Goru Formation and Sui Main Limestone, were marked against well-log depth markers and stratigraphic expectations. In addition, gravity anomaly trends were employed as secondary validation tools to ensure depth consistency, especially within structurally complex zones.

The overall workflow of the data collection, data processing, seismic interpretation, and GIS-based integration that supported this phase are outlined in **Table 1** which summarises the key research phases, research objectives, and major tasks undertaken. This workflow provided a structured and integrated approach that strengthened interpretational reliability and ensured that each dataset contributed meaningfully to the tectono-stratigraphic understanding of the Khewari Block. Although a detailed uncertainty analysis of the velocity model was beyond the scope of this study, further research incorporating vertical seismic profiles (VSP) or sonic log data is recommended to refine interval velocities and enhance the accuracy of depth prediction in future studies.

3. Results

Systematic analysis of seismic, structural analysis, reservoir characterization, and entrapping hydrocarbons in the Khewari block of the Lower Indus Basin, Sindh, Pakistan, was evaluated. The study relied on the integration of seismic reflection profiles, well log analysis, GIS-based reservoir modelling, and supplementary geophysical surveys to delineate potential hydrocarbon-bearing formations and define exploration viability. The distribution of seismic attributes, depth structure maps, and subsurface geometries was interpreted in more detail to identify structural traps, stratigraphic discontinuities, and fault-controlled accumulation zones. The resulting seismic horizon maps, structural cross-sections, and prospectivity models will give vital information about the underground framework of the basin, which will help to refine the study of the petroleum system architecture.

3.1. Seismic Horizon Identification and Interpretation

Seismic interpretation was conducted to define the structural properties of the Khewari Block and to determine the existence of traps with hydrocarbons. Six seismic lines: O-011-KWI-15, O-011-KWI-16, O-011-KWI-25, O-021-KWI-26, O-021-KWI-39, and O-021-KWI-40 were studied with the help of Petrel. These lines

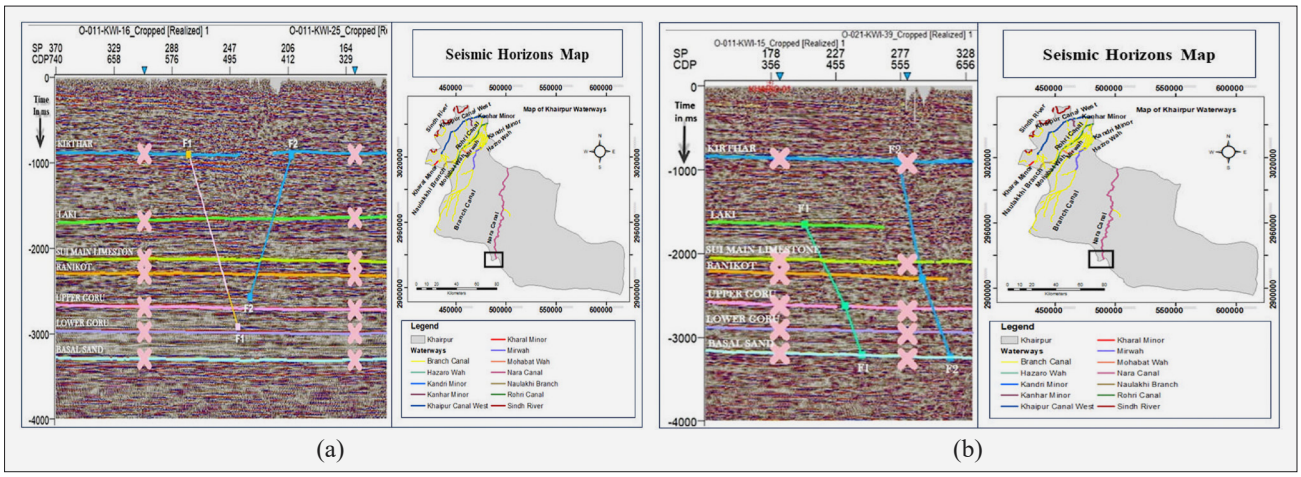


Figure 2: (a) Interpreted seismic line O-021-KWI-40, showing key reflectors, major faults (F1-F2), and a well log correlation from Khario-01**.** (b) Seismic line O-011-KWI-15 illustrates reflector's continuity and structural variations across faults. The Khario-01 well is represented by the pink X, and the inset maps denote the location of the lines within the Khewari Block.

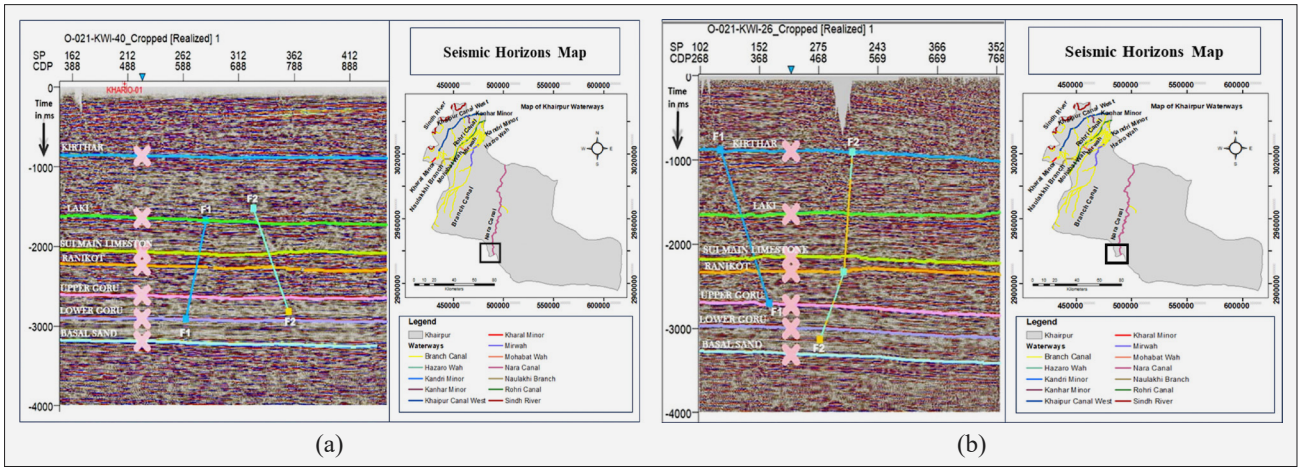


Figure 3: (a) Interpreted seismic line O-011-KWI-16 illustrating fault-controlled structural compartmentalization and the development of fault-bounded closures resulting from compressional overprinting of earlier extensional structures. (b) Interpreted seismic line O-021-KWI-26 reveals a fault-bounded structural high developed between faults F1 and F2, with adjacent down-dropped blocks consistent with graben development. The bounding faults demonstrate normal-fault geometry, as indicated by downward displacement of hanging-wall reflectors, reflector terminations, and vertical offset patterns. Insets show the spatial positions of the seismic profiles within the study area.

were chosen to ensure full coverage of the area and also to ensure regional structural variations. The seismic profiles identified a tectonically fragmented subsurface with horsts, grabens, fault blocks, and related folding designs as the primary landscape features. Key features that may control hydrocarbon entrapment were identified as reflector continuity, amplitude changes, and fault geometries.

Extensional tectonics are the dominant structural regime in the study area, as evidenced by the prevalence of NE–SW-trending normal faults that segment the subsurface into alternating horst and graben blocks. These features are particularly well developed on seismic lines O-011-KWI-15 and O-011-KWI-16, where high-angle fault planes define deep, structurally bounded grabens. The Lower Goru Formation and Sui Main Limestone, recognized as the region's primary reservoir units, are clearly imaged within these grabens, highlighting their structural control and potential as hydrocarbon traps. The reflector terminations and variable fault throws within these horizons suggest vertical displacement and fault-assisted migration pathways.

Notably, compressional features were also identified in several sections, indicating that the area has undergone multiple tectonic phases. Seismic line O-021-KWI-39 clearly shows fault-propagation folds and reverse faults, which suggest a later phase of compressional deformation following the initial extension. These structures modify and uplift previously horizontal layers, leading to the formation of closed structures that can effectively trap hydrocarbons. In several places, reservoir formations are pushed against impermeable layers due to this folding and faulting, creating favorable conditions for hydrocarbon sealing. This overprinting of ex-

tensional features by compressional forces has significantly enhanced the structural complexity and trap integrity in parts of the study area.

The seismic features of reflector continuity, dip variation, amplitude dimming, and fault shadow zones offered further interpretative support. The properties assisted in confirming the geometry of large fault systems and detecting small-scale closures and secondary faults that might represent obstacles or pathways to hydrocarbon flow. In particular, dimming and reflector terminations near fault planes suggested possible lithological changes or fluid contacts. The interpreted data confirm the presence of multiple trapping mechanisms, including fault-assisted closures, roll-over anticlines, and tilted fault blocks. These findings form the basis for constructing time and depth structure maps and serve as essential inputs for drilling risk assessment and volumetric analysis in the Khewari Block.

The interpreted seismic sections in (see **Figure 2**) show the structural heterogeneity of the khewari Block under an extensional tectonic regime. Seismic lines O-021-KWI-40 and O-011-KWI-15 (see **Figure 2a-2b**) depict NE-SW-oriented normal faults that divide the subsurface into horst and graben structures. These profiles also delineate the Lower Goru Formation and Sui Main Limestone, which are imaged as principal reservoir units within grabens. These seismic lines display reflector terminations, amplitude anomalies, and variable fault displacements, which draw attention to the role of fault geometries in trapping hydrocarbons and suggest the existence of fault-facilitated migration pathways. On the whole, the evidence that is provided in **Figure 2** highlights the pre-eminent role of the extensional tectonics in governing the possible trapping positions across the study region.

In addition, **Figure 3** shows the compressional overprinting that later reformed the extensional architecture of the Khewari Block. The fault-bounded closures and compartmentalized reservoirs can be identified with the help of seismic line O-011-KWI-16 (see **Figure 3a**), and the fault-propagation folds and reverse faults can be identified with the help of seismic line O-021-KWI-26 (see **Figure 3b**). These formations testify to the fact that the area experienced subsequent compressional activity, causing the upward movement of previously horizontal layers and creating closed structural traps that could favor the entrapment of hydrocarbons. Collectively, the interpreted passages of **Figure 3** validate the interaction of the extensional and compressional tectonics, resulting in a number of trap styles, such as rollover anticlines, tilted fault blocks, and fault-aided closures, that have a net effect of maximizing the prospectivily of the area in hydrocarbons.

Furthermore, the spatial relationship between seismic horizons and fault architecture suggests a strong structural control on reservoir compartmentalization within the Khewari Block. Variations in reflector continuity and local changes in dip along the Lower Goru Formation and Sui Main Limestone indicate differential subsidence and uplift across fault blocks. In several seismic sections, the juxtaposition of reservoir units against sealing lithologies along fault planes implies the development of fault-bounded compartments that may enhance trap efficiency. These structural compartments are particularly significant in areas where extensional faults were later reactivated or modified during compressional phases, improving closure geometry and seal integrity. Such interactions between fault kinematics and stratigraphic horizons highlight the importance of integrated seismic interpretation for identifying viable hydrocarbon prospects and reducing subsurface uncertainty.

The interpreted seismic lines shown in **Figures 2** and **3** collectively illustrate the structural variability and stratigraphic complexity of the Khewari Block. **Figure 2a** and **Figure 2b** show seismic lines O-021-KWI-40 and O-011-KWI-15 have well-developed stratigraphic reflectors with the Sui Main Limestone, Lower Goru, and Basal Sand units being defined. Faults F1 and F2 show significant vertical displacement across these horizons, suggesting active structural control over reservoir positioning and potential trap formation. The fault-controlled compartmentalization, as seen in more detail in **Figure 3a**, which indicates line O-021-KWI-26, is further indicated by the visible offsetting of reflectors by a few faults crossing all of them. This reservoir zone classification is important in determining the distribution of hydrocarbons and possible obstacles to horizontal migration. Lastly, **Figure 3b** shows line O-021-KWI-16, whose line demonstrates a typical horst and graben system that has been formed by extensional tectonics and formed structural highs and lows conducive to the entrapment of hydrocarbons. The combination of these seismic sections demonstrates a structurally discontinuous basin structure, fault-assisted traps, stratigraphic endings, and geometries of folds interrelate and manage reservoir quality, continuity, and sealing.

3.2. Time and Depth Contour Maps

Time and depth structure maps were generated for four key formations: the Lower Goru, Upper Goru, Sui Main Limestone, and Ranikot. These maps were developed by converting interpreted seismic horizons from two-way travel time (TWT) to depth using velocity models. The time structure maps reveal major structural highs concentrated in the central and southwestern parts of the Khewari Block, particularly within the Lower Goru and Sui Main Limestone intervals. These structural highs are obvious in **Figure 4a**, Sui Main Limestone, and **Figure 4b**, Lower Goru, and are known as the most favorable areas of hydrocarbon entrapment because they are fault-bounded uplifted blocks observed in the seismic interpretation. On the other hand, fault-controlled lows and minor anticlines in the northeastern and central areas in time maps of the Ranikot and Upper Goru formations (see **Figures 5a** and **5b**) are indicative of secondary structural compartments that, as well, can be traps.

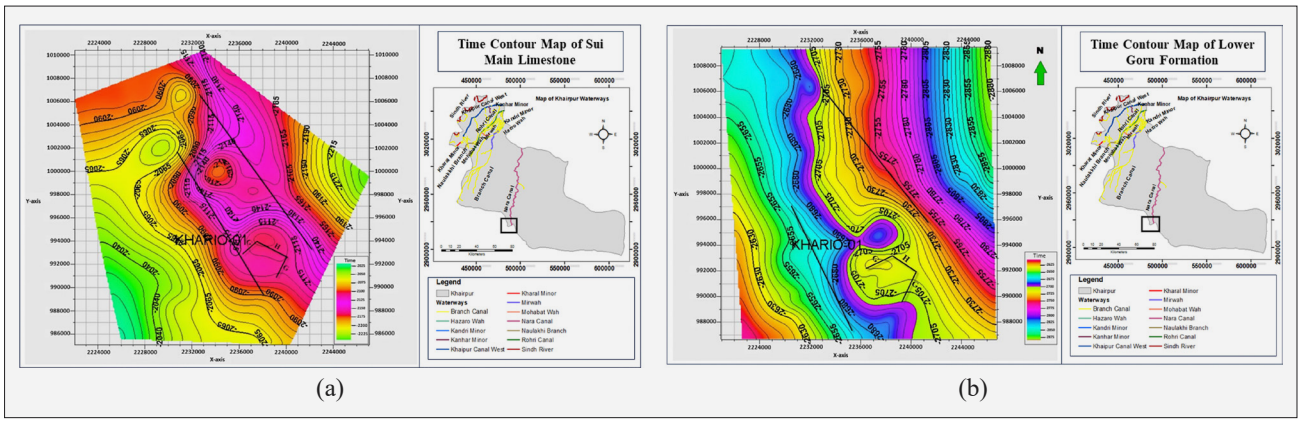


Figure 4: (a) Time contour map of the Sui Main Limestone showing NE–SW-trending fold structures and fault-bounded closures that influence reservoir development and hydrocarbon migration. The straight black lines represent interpreted fault traces identified from seismic data.(b) Time contour map of the Lower Goru Formation illustrating fault-controlled structural highs and lows that impact hydrocarbon migration pathways and reservoir sealing efficiency. All contour intervals are in milliseconds (ms), with coordinates referenced to the UTM projection used for the seismic.

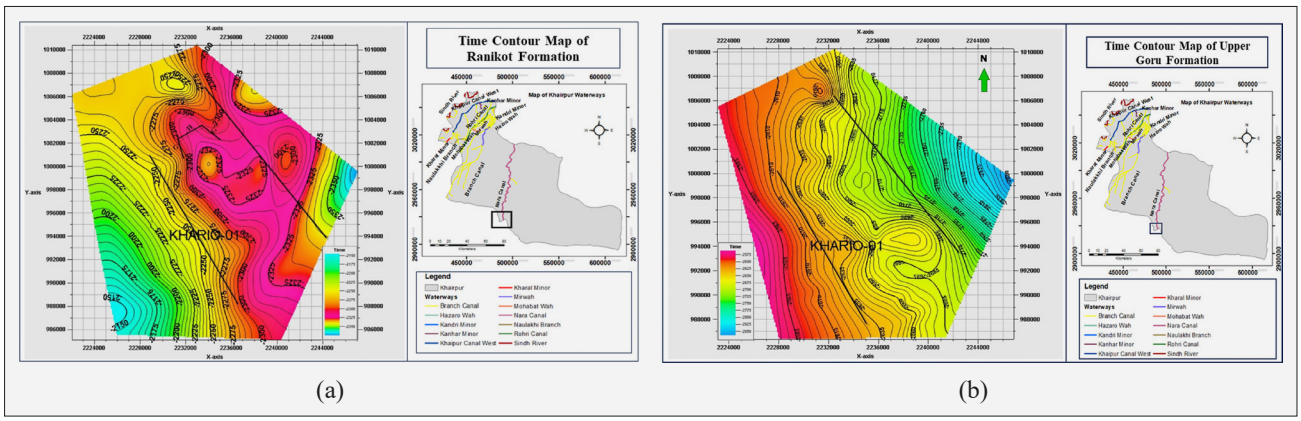


Figure 5: (a) Time structure map of the Ranikot Formation displaying fault-controlled reservoir segmentation and potential migration pathways.(b) Time contour map of the Upper Goru Formation depicting structural variations and mapped faults that affect reservoir connectivity and trap configuration. Straight lines represent interpreted faults, and contour values are in milliseconds (ms), referenced to the same coordinate system as the seismic and gravity datasets.

The depth structure maps further refine these observations by providing a more realistic representation of subsurface geometry and trap configuration. Depth conversion highlights the vertical separation between structural highs and lows and emphasizes the role of fault displacement in controlling reservoir thickness and closure extent. In particular, depth maps of the Lower Goru and Sui Main Limestone formations show well-defined fault-bounded closures with sufficient relief to act as effective structural traps. These closures are laterally continuous and coincide with areas of enhanced seismic reflector continuity, suggesting improved reservoir development.

In contrast, the depth maps of the Upper Goru and Ranikot formations display gentler structural relief, reflecting a diminished influence of faulting at shallower levels. Collectively, the integration of time and depth contour maps provides a robust framework for identifying drillable prospects and reducing structural uncertainty across the Khewari Block.

The time contour maps of the Sui Main Limestone, Lower Goru, Ranikot, and Upper Goru formations help to illustrate the most significant structural aspects that affect the migration of hydrocarbons and the formation of the reservoirs. The time contour map of Sui Main Limestone (see **Figure 4a**) shows the effect of folding in developing reservoirs, where structural highs indicate places that are conducive to the accumulation and migration of hydrocarbons. Faulting coupled with these folds gives the best conditions to trap the hydrocarbons. The Lower Goru Formation (see **Figure 4b**), shows the effects of faults on movement routes and the sealing efficiency of the reservoir as fault-bound compartments delimit portions that could potentially contain hydrocarbons. Fault-controlled reservoirs are observed in the Ranikot Formation (see **Figure 5a**), where faulting forms discrete migration pathways and reservoir compartmentalization. Finally, structural changes following faulting are demonstrated by the time structure map of the Upper Goru Formation (see **Figure 5b**), which affected the res-

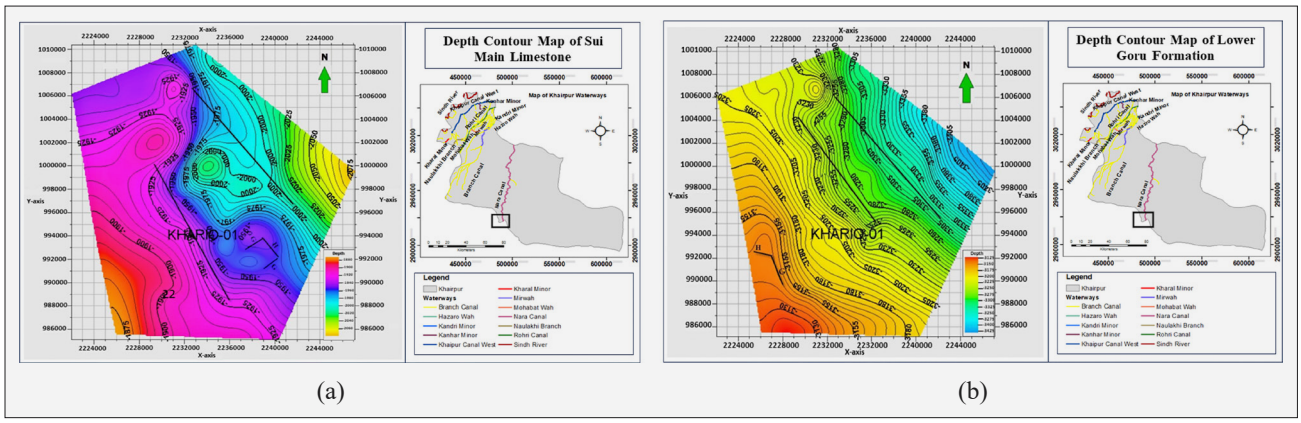


Figure 6: (a) Depth contour map of the Sui Main Limestone showing NE-SW trending structural elevations and fault-controlled closures interpreted as potential hydrocarbon traps. (b) Depth contour map of the Lower Goru Formation of depth variations and fault-controlled reservoir geometry. Straight black lines represents interpreted faults from seismic data, and contour values are in meters (m). Coordinates are referenced to the same UTM projection used for seismic and gravity datasets.

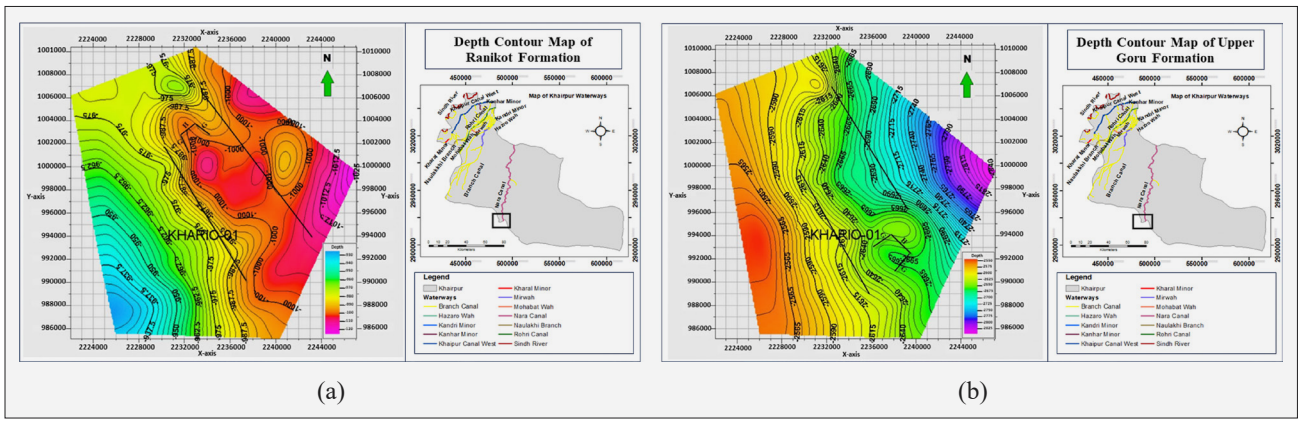


Figure 7: (a) Depth contour map of the Ranikot Formation showing complex fault-bounded depth structures and hydrocarbon-bearing zones. (b) Depth contour map of the Upper Goru Formation indicating the depth undulations and mapped faults that influence reservoir connectivity and potential trap formation. All contour are in meters (m), and coordinate references match the seismic and gravity interpretation framework.

ervoir connectivity and segmentation. Collectively, these maps offer important data on the structural dynamics of the Khewari Block and their contribution to the entrapment and migration of hydrocarbons.

3.2.1 Depth Contour Maps

The depth structure maps (see **Figures 6a** and **6b**) refine these interpretations by providing more accurate elevation data for the mapped closures. The depth map of the Lower Goru (see **Figure 6b**) confirms the presence of a well-defined closure at a drilling-accessible depth, supported by four-way dip and fault sealing conditions. Similarly, the Sui Main Limestone depth map (see **Figure 6a**) shows a NW–SE trending structural nose, flanked by bounding faults, confirming its structural isolation and reservoir potential. The Ranikot and Upper Goru (see **Figures 7a** and **7b**) show moderately inclined closures and inclined blocks of fault, which suggest smaller but potentially profitable traps. These maps, when combined with the seismic interpretation, prove that the Khewari Block contains various types of traps, such as fault-assisted closures, rollover structures, and tilted blocks with diverse levels of potential exploration. The time and depth structure maps together give a vital system of well placement, risk analysis, and volumetric analysis.

Figures 6 and **7** depict Depth Contour Maps of the Sui Main Limestone, the Lower Goru, the Ranikot, and the Upper Goru formations, which are used to identify important structural features vital to the exploration of hydrocarbons. As seen in **Figure 6a**, the depth map of Sui Main Limestone shows that there is a structural high in the central area of the block, something viewed as a possible place of hydrocarbon traps. Fault systems enclose this high, and they may serve as sealing mechanisms by keeping the trapped hydrocarbons isolated. In **Figure 6b**, the Lower Goru Formation shows that depth variations are more significant, indicating a fault-controlled reservoir system. The faulting effects on the distribution of this formation have been noted by the map,

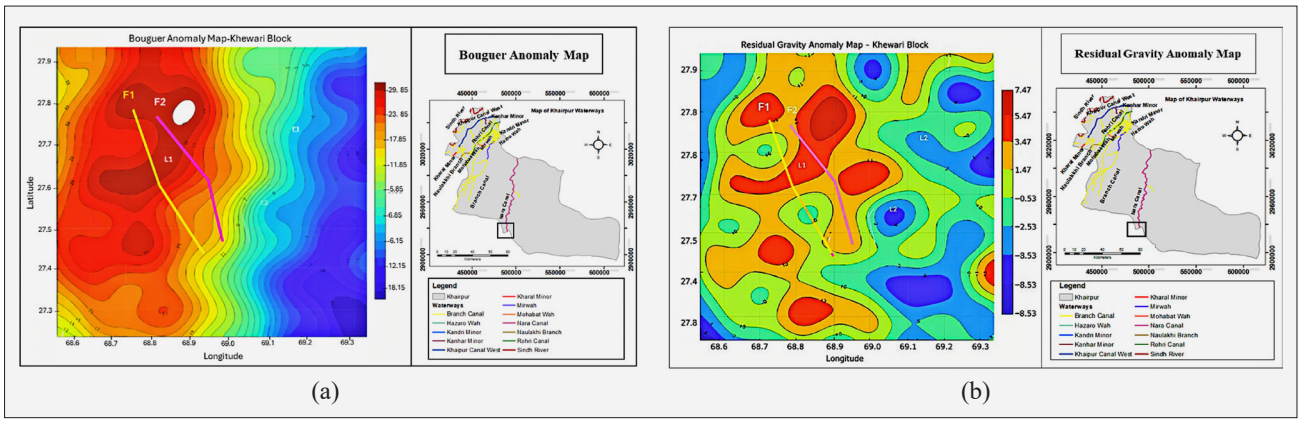


Figure 8: (a) Bouguer gravity anomaly map of the Khewari Block showing a prominent gravity high in the western sector (L1) and lower gravity values toward the eastern and southeastern areas (L2–L3), associated with structural variations and faults (F1–F2). (b) Residual gravity anomaly map highlighting localized density contrasts, including a central structural high (L1) and surrounding low-density zones (L2–L3) that reflect fault-controlled depressions and sediment-filled troughs.

with a several structural highs and lows indicating possible migration patterns and trapping areas. See **Figure 7a**, the Ranikot Formation of the faulted depth creating structural lows is depicted, which may be a sign of hydrocarbon accumulation or migration. Lastly, **Figure 7b** is the depth map of the Upper Goru Formation, which depicts a succession of tilted fault blocks having different depth contours that illustrate fault-controllable compartmentalization. All these depth maps contribute to the hypothesis of the presence of multiple structural traps throughout the Khewari Block, where faulting is very significant in the segmentation of the reservoir, migration of the hydrocarbons, and their entrapment.

3.3. Gravity Anomaly Analysis

Gravity anomaly analysis was conducted to complement seismic interpretation and give more restrictions on the density variations in the subsurface of the Khewari Block. Bouguer as well as residual gravity maps were used to outline regional as well as local structure maps, such as horsts, grabens, and buried uplift zones that are important in entrapment and migration of hydrocarbons. A general high appears in the central-western sector on the Bouguer gravity map (see **Figure 8a**), which is interpreted as hidden structural uplift that is probably related to carbonate platforms comprising the Sui Main Limestone. Conversely, the low gravity anomalies observed in the eastern region of the block are associated with fault-controlled grabens of the Goru Formation, which are troughs filled with sediments that could serve as the migration paths or potential traps. A localized minimum of gravity in the lowest eastward part of the area is associated with either shale or evaporite structures, possibly the Ranikot or Laki formations, which can serve as a stratigraphy seal in favorable structural situations.

Additional evidence of residual gravity anomaly mapping (see **Figure 8b**) is that of local, shallow density differences smoothed in the regional Bouguer field. The high-density zones (L1) indicate the presence of uplifted carbonate or basement blocks, which are possible to support the existence of hydrocarbon migration and trapping, whereas the long and narrow low-density areas (L2 and L3) are correlated with fault-bounded grabens and structural sags on seismic and depth contour maps. The interpretation of faults (F1- F2) along with their steep residual gradients indicates that they play a key role in the segmentation of the reservoirs and their compartmentalization into structural blocks. The combination of the gravity data with seismic interpretation and the surface geomorphology enhances the confidence in outlining the hydrocarbon traps and confirming possible drilling regions in the structurally complicated regions of the Khewari Block. These analyses give strength to geophysical frameworks of defining potential reservoir areas and streamlining exploration plans.

The Bouguer anomaly map (see **Figure 8a**) reveals distinct gravity variations across the Khewari Block, with relatively higher gravity values in the west (L1) and lower values in the east (L2–L3). These contrasts denote uplifted carbonate or basement structures in the west and sediment-filled grabens or troughs in the east. Faults F1–F2 align closely with the gravity gradients, emphasizing the role of faulting in structural compartmentalization. The residual gravity anomaly map (see **Figure 8b**), which filters out regional trends, highlights localized density contrasts that refine this interpretation. The L1 zone represents high-density anomalies associated with uplifted carbonate or basement blocks, while L2 and L3 indicate low-density zones corresponding to deeper sedimentary basins or fault-bounded depressions. The spatial overlap between these anomalies and the mapped faults (F1–F2) underscores their control on reservoir segmentation, hydrocarbon migration pathways, and trap formation within the Khewari Block. These relationships are further summarized in **Table 2**, which correlates gravity anomalies (L1–L2) with their corresponding geological features.

Table 2: Gravity Anomalies and Corresponding Geological Features in the Study Area.

Gravity Anomaly	Gravity Type	Geological Feature
L1	High	Carbonate Dome / Structural High
L2	Low	Graben / Sediment-Filled Trough
L3	Local Low	Shale Sag / Salt Trap

The gravity anomaly domains L1–L3 were defined based on the magnitude, spatial continuity, and gradient characteristics of the Bouguer and residual gravity maps. High-gravity zones (L1) were identified where Bouguer anomalies exceeded the regional mean value and were associated with steep positive gradients and coherent high-density blocks, indicating uplifted basement or structurally elevated carbonate units. Conversely, low-gravity domains (L2–L3) correspond to areas with negative anomaly values and subdued gradients, reflecting thicker sedimentary sequences or fault-bounded depressions. The segmentation into L2 and L3 was further guided by anomaly wavelength and residual filtering, distinguishing localized low-density pockets (L3) from broader regional lows (L2). The spatial correlation of these gravity domains with mapped faults (F1–F2) and structural trends supports their interpretation as structural highs and sediment-filled troughs. This approach follows widely established relationships between gravity signatures and geological structures in sedimentary basins (**Li et al., 2024; Safani et al., 2026**).

3.4. Geological, Geomorphological, and Topographic Characteristics of the Khewari Block

3.4.1. Geological Characteristics

The Khewari Block has a complicated geologic structure that has a significant role in exploring hydrocarbons. The region is primarily covered by various sedimentary formations, including the Tertiary rocks, Sui Main Limestone, and Ranikot Formation, which can be easily identified as having the potential of containing hydrocarbons. Important reservoir terrains are the Lower Goru Formation and Basal Sands, with the Laki Formation being a regional seal, especially in regions of compressional tectonics. The geological map of the Khewari Block (see **Figure 9**) shows the dispersion of these formations, major fault systems, and the central point of Khario Well-1, which is strategically located to test the deposits bounded by faults, anticlinal trap, and deep-seated migration tracks. Normal and reverse faults and anticlinal folds are co-occurring features that form structural highs and closures and numerous routes of hydrocarbon migration, which increases the trap development and makes the intersection of faults and raised structures within the block attractive sites of hydrocarbon formation and thereby augments the prospective exploration of the area.

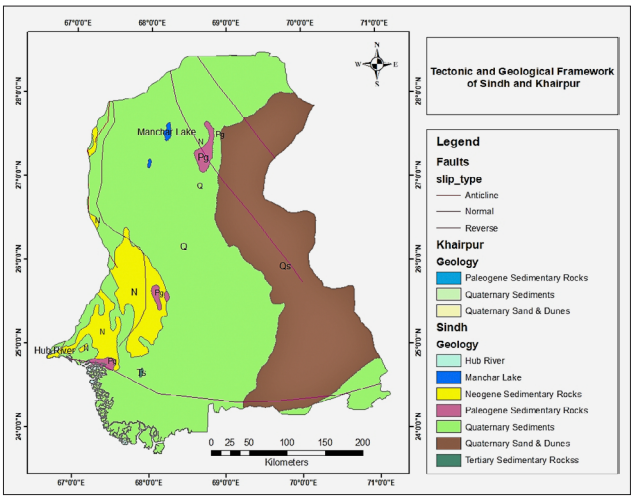


Figure 9: Tectonic map of Khairpur showing faults, stratigraphy, and Kharo Well-01.

3.4.2. Gemorphological Characteristics

The Khewari Block is predominantly flat with smooth plains, smooth ridges, shallow depressions, and wind-shaped structures characteristic of arid regions. These geomorphological factors define the patterns of surface runoff and the local drainage. Slope models and Digital Elevation Models (DEM) focus on small alterations of elevation that are indicative of subsurface faults, horsts, and grabens that dictate the surface terrain and drainage distribution. The road and canal network, as depicted in the geomorphological map (see **Figure 10a** and **10b**), indicates a high density of roads in the northern plains, which depicts stable ground, which can be used to settle people and develop infrastructure. The canal systems, including the Nara and Khairpur Canals, on the other hand, occur in low-lying regions and basins of depression which structurally are controlled by faults and are therefore considered important markers for mapping seismic surveys, locating appropriate drilling areas, and interpretation of structural traps of hydrocarbon traps.

The road and waterways maps presented in **Figure 10a** and **10b** illustrate the geomorphological framework of the Khewari Block and its influence on surface accessibility and infrastructure distribution. The northern part of the block shows a dense concentration of local, secondary, and major road networks, indicating relatively stable, flat, and gently sloping plains. Such terrain conditions are favorable for transportation, settlement development, and hydrocarbon exploration logistics, as they allow easier movement of seismic equipment and drilling machinery. The well-developed road connectivity in this region suggests that the surface materials are comparatively compact and suitable for long-term infrastructure expansion, supporting field operations and resource management activities.

In contrast, the southern and eastern parts of the study area are dominated by canal systems and distributaries, including the Nara Canal and associated branch net-

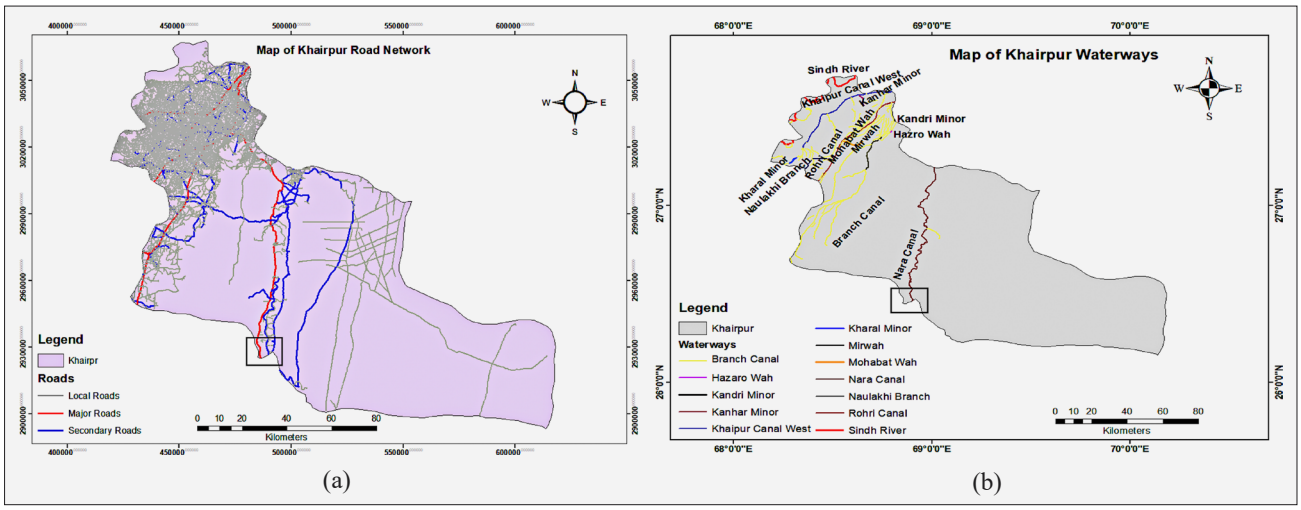


Figure 10: (a) Road map of Khairpur showing local roads, major roads, and secondary roads. (b) Waterways maps of Khairpur showing major canals and distributaries.

works, which follow natural topographic depressions and low-lying drainage pathways. The alignment of these waterways reflects the influence of subtle structural controls such as fault-related subsidence and sediment accumulation zones that guide surface water flow. These geomorphological patterns help in identifying structurally influenced landforms and provide essential information for planning water management and exploration access routes. The integration of road and canal network analysis therefore enhances the interpretation of terrain stability, subsurface structural trends, and the selection of operationally feasible locations for hydrocarbon exploration within the Khewari Block.

3.4.3. Topographical Characteristics

Khewari Block has a topography of mainly flat and slightly undulating land, having elevations between 24 and 144 meters above sea level. The regions at the center and south are made of low plain lands, and there is a gradual increase in elevation as one approaches the east and the north. Topographical differences are subtle features that indicate the geological formations, like faults, folds, and horst-graben systems. Such variations affect the surface drainage and the deposition of sediments and landform development, which must be a main consideration to determine the likely locations to explore and to plan the hydrocarbon operations.

3.4.3.1. Elevation

The topography of the Khewari Block ranges from approximately –7 m to 165 m above sea level. The terrain of the southern and western parts is dominated by flat, alluvial plains that are usually characterized by floods, whereas the central, eastern, and northeast parts have highlands, which are interpreted as structurally uplifted blocks. These high areas correspond to anticlinal and horst-type features identified in the seismic data, suggesting that surface topography is influenced by underlying tectonic deformation. Such elevated regions are considered favorable sites for hydrocarbon accumulation but may pose logistical challenges for drilling due to steep slopes and limited accessibility. The distribution of the elevation is spatially consistent with the boundary of the Khewari used in the seismic and gravity interpretations, ensuring direct comparability between surface and subsurface datasets. The categorized floodplain elevations are highlighted in **Table 1**, and their distributions are represented in **Figure 11**, where low floodplains appear in brown/orange and structurally uplifted zones are depicted in green/yellow/blue.

The elevation pattern across the Khewari Block provides important insight into the surface expression of subsurface structural architecture. The contrast between low-lying floodplains and relatively elevated structural highs indicates spatially variable uplift and subsidence that are interpreted to be controlled by deep-seated faulting and folding. Structurally elevated zones coincide with areas interpreted as anticlines and horst blocks in the seismic profiles, suggesting a genetic link between surface relief and subsurface deformation. In contrast, lower elevations correspond to structurally depressed zones, which may represent synclinal features or downthrown fault blocks. Although geomorphic processes such as erosion, sediment deposition, and seasonal flooding locally modify the topography, these processes do not obscure the regional pattern of elevation controlled by tectonic structures. Therefore, the elevation distribution serves as an independent qualitative indicator of structural segmentation within the Khewari Block and supports the integrated interpretation of seismic and gravity data in delineating potential hydrocarbon-prone structural highs.

The elevation map shows how the topography is changing in the Khewari Block, with the flood plains being low to the southwest in the west (brown/orange) and

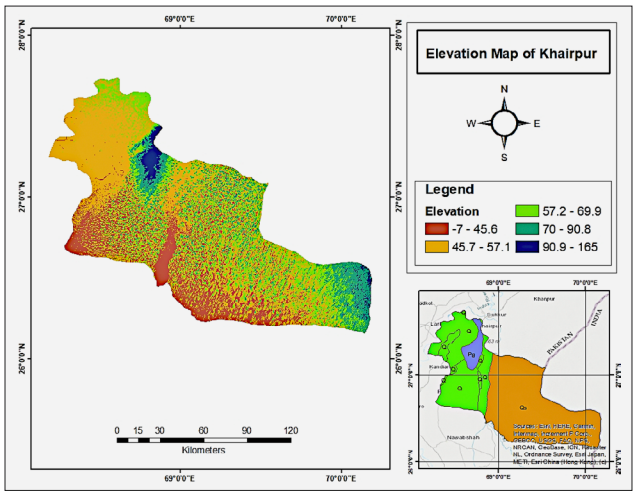


Figure 11: Elevation map (–7 m to 165 m) showing low floodplains (brown/orange) and higher uplands (green/yellow/blue)

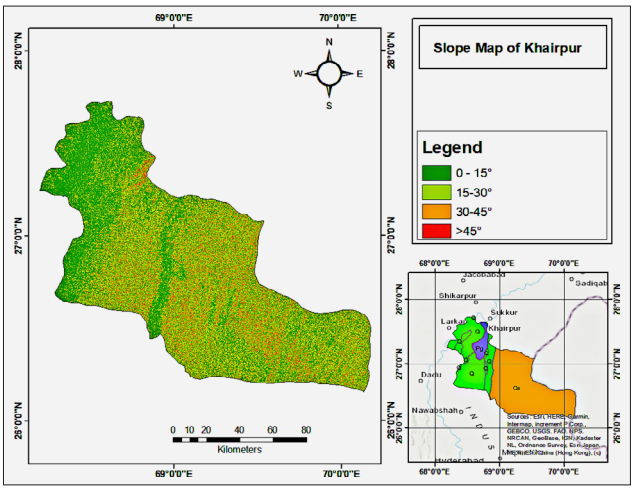


Figure 12: Slope distribution map of the Khairpur region, divided into four classes

Table 3: Elevation Classification of the Khairpur region

Class	Elevation Range (m)	Color on Map	Topographic Character
1	–7 – 45.61	Brown	Depressed plains, flood zones
2	45.62 – 57.08	Orange	Flat plains and low-gradient slopes
3	57.09 – 69.89	Green	Transitional uplands
4	69.9 – 90.8	Yellow	Gently elevated surfaces, structural warps
5	90.81 – 165	Blue	High terrain, potential horst/fault structures

the uplands slowly rising in the middle and northeast (green/yellow/blue). These differences represent fine geomorphological and structural controls, such as fault-related uplifts, horsts, and paleo-uplifted blocks. The plains are low and there is easy and stable land that can be used to build infrastructures, in seismic studies and drilling, but the plateaus are the highlands and are the possible structural traps of the hydrocarbons. The classifications of these elevation ranges and their associated topographic characters are compressed in **Table 3**, which provides a clear basis for planning field work with regard to surface elevation and accessibility.

3.4.3.2. Slope

The slope analysis indicates that the Khewari Block is made up of gentle slopes (less than 15 degree gradients). Such low gradients are favourable to seismic surveys, drilling, and infrastructural developments. The slope is between 15 to 30 degrees, which depicts mildly inclined slopes that are usually brought about by inclined tilting of the tectonic or the ground structure. The most frequently occurring moderately steep slopes (30-45°) are usually associated with erosional landforms, incised valleys, or fault-aligned escarpments. The steeper slides (>45 degrees) are limited in area, but usually represent fault scarps, ridges, or blocks raised by the paleo-tectonic plate, and are indicative of some recent or past tectonic action. These gradients are represented in the slope distribution map (see **Figure 12**), which identifies plain, slightly inclined, moderately steep, and steep regions in the region. Slope changes are indicated by understanding of slope variations, which is significant in planning seismic surveys, determining structural complexity, and identifying potential hydrocarbon traps.

Spatial variations in slope across the Khewari Block reflect the interaction between tectonic structuring and surface geomorphic processes. Zones of relatively higher slope gradients commonly occur along lineaments that coincide with interpreted faults and fold hinges observed in seismic sections, indicating that slope breaks may mark the surface expression of subsurface structural discontinuities. In contrast, extensive low-slope areas represent relatively stable depositional surfaces where sediment accumulation has smoothed earlier relief. Although erosional processes locally modify slope angles, the regional pattern of slope distribution remains consistent with the underlying structural framework. Therefore, slope characteristics provide an additional qualitative constraint for delineating structurally controlled geomorphic features and for identifying zones of increased structural complexity that may influence hydrocarbon trap development and drilling feasibility.

The slope distribution map indicates the change in the terrain of the Khewari Block under four categories: flat to gently sloping (0 to 15°), mild slopes (15 to 30°), moderately steep slopes (30 to 45°), and steep areas (more than 45°). The topography (green) is flat and slightly sloping, and thus the majority of the area is favorable to seismic surveys, drilling, and infrastructural construction. Gently to moderate (yellow to orange) slopes are patchy and are often correlated to regions of fault alignment, block uplift or paleo-channel. The

Table 4: Slope Classification of Khairpur Region

Class	Slope Range (°)	Colors on Map	Topographic Implication
1	0-15	Green	Flat to gently sloping terrain
2	15-30	Yellow	Mild Slopes; potential structural influence
3	30-45	Orange	Moderately steep; erosion-prone and structurally complex
4	>45	Red	Steep zones; rare, possibly fault-zones

steeper (steeper than 45°, red) areas are very small in scale and generally depict fault scarps, ridgelines, or structurally raised features, which can be potential hydrocarbon traps but pose logistical challenges. The classification of these slopes ranges and their structural implications is highlighted in **Table 4**, which provides a clearer understanding of surface morphology and supports the identification of structurally significant zones for exploration planning.

3.4.3.3. Land Use

Khewari Block has low land use, which is attributed to the arid weather, low rainfall, and low groundwater. The western and southern regions have small plots that are concentrated around irrigation along canal systems, and are generally seasonal in nature. Most of the land features are barren alluvial plains, dry riverbeds, and natural scrublands having sparse, drought-resistant vegetation. Cities are small, and the infrastructure is inadequate, hence the area is not highly developed. According to the land use/land cover (LULC) map (see **Figure 13**), the area is characterized by five classes, namely agriculture, bare land, forest, protected areas, and urban spaces. The summarized LULC data (see **Table 5**) can be used to plan the surface access, reduce the conflict with human activity, and sustain the hydrocarbon exploration logistics.

The spatial distribution of these LULC classes provides important insight into operational feasibility and environmental planning within the Khewari Block. The predominance of bare land and scrub vegetation indicates relatively low anthropogenic disturbance, which favors seismic data acquisition and drilling activities due to reduced land clearance requirements. However, the scattered agricultural zones located along canal irrigation systems may impose seasonal accessibility constraints and require careful route planning to minimize impacts on cultivated land. Forested and protected areas, although limited in spatial extent, represent environmentally sensitive zones where exploration activities must comply with regulatory and conservation guidelines. Urban and settlement areas, though sparsely distributed, highlight localized infrastructure availability that may

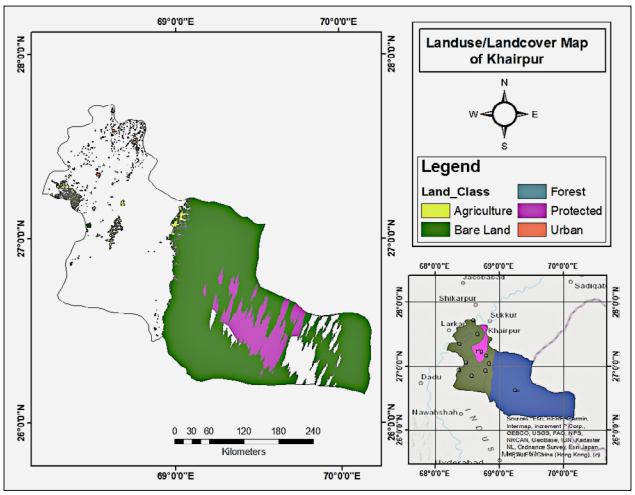


Figure 13: Land Use/Land Cover map of the study area for impact assessment and surface planning.

Table 5: Land Use Distribution and Boundary Extent in the Khairpur Region.

Land Class	Shape Length (km)	ShapeArea (sq.km)
Agriculture	10.036952	0.018225
Bare Land	19.286915	0.611315
Forest	0.08398	8.10E-05
Protected	2.984227	0.363805
Urban	7.041516	0.00491

support logistical operations such as workforce accommodation, transportation networks, and supply chain management. Therefore, integrating LULC analysis with terrain, slope, and drainage assessments enhances the identification of operationally suitable drilling locations while ensuring minimal environmental and socio-economic disruption across the study area.

The Land Use/Land Cover (LULC) map shows the spatial distribution of various land types in the Khewari Block, such as agriculture, bare land, forested areas, protected areas, and urban settlements. The agricultural land is clustered on small pieces of land, mostly in the western and southern regions, which represent the areas with access to canal irrigation. Bare lands take over a large part of the area, which is an arid alluvial plain and poorly vegetated, sparsely populated land. Protected and forested areas are few, whereas urbanized areas are minimal, and this shows low anthropogenic impact. The numerical allocations of these land classes, including shape length and area coverage, is outlined in **Table 5**, which indicates that bare lands constitute the maximum portion of the region. This categorization is especially useful for planning exploration logistics, geophysical survey, and drilling operations as well as assessing ecological considerations for hydrocarbon explorations.

The geospatial analysis extended beyond base mapping to provide spatial validation for the geophysical interpretations. Compared quantitatively to the terrain mod-

els obtained by the DEM and slope methods and the structural uplifts observed in seismic and gravity datasets, a uniform correspondence of the surface uplifts with the subsurface horsts and anticlines is observed. Similarly, drainage orientations coincide with mapped fault traces, indicating tectonic influence on both geomorphic and subsurface frameworks. This spatial correspondence supports the interpretation that neotectonic activity has controlled both the present-day topography and subsurface structure of the Khewari Block, thereby confirming the effectiveness of integrating geospatial and geophysical data for hydrocarbon prospect evaluation.

4. Discussion

The combined study of seismic, gravity, and geospatial data provides a coherent understanding of the structural and petroleum potential of the Khewari Block. Seismic interpretation reveals a structurally heterogeneous subsurface dominated by NE–SW-trending normal faults, horsts, grabens, and later compressional overprinting, consistent with regional extensional tectonics reported for the Lower Indus Basin (**Noureldin et al., 2023; de Jager, 2020**). Time and depth structure maps highlight structurally elevated blocks of the Sui Main Limestone and Lower Goru formation, confirming the presence of fault-bounded closures, rollover geometries, and tilted fault block trap styles previously recognized in other segments of the basin (**Sajid et al., 2021; Aftab et al., 2022**). These structurally isolated highs represent the most prospective zones for hydrocarbon entrapment in the study area.

Gravity anomaly interpretation provides an independent line of evidence that supports these seismic results. Bouguer gravity highs (L1) are associated with seismically mapped uplifted basement or carbonate platforms, and gravity lows (L2-L3) align with fault-controlled grabens containing thick sedimentary fill, patterns consistent with regional gravity–structure relationships documented within the Indus Basin by **Noureldin et al. (2023)**. Residual gravity anomalies sharpen these density contrasts and closely match the orientations of major faults (F1–F3), reinforcing the interpretation of structural compartmentalization and fault-mediated trap development. The correlation of gravity gradients and seismic relief affirms the reliability of determining reservoir level closures and migration routes.

Geospatial data contributes additional insight by illustrating the surface expression of subsurface structures. The elevation model (DEM) shows upland regions in the central and northeastern parts of the block that correspond spatially with seismic and gravity-defined structural highs, while low-lying floodplains match graben-bounded depressions, indicating a subtle geomorphic imprint of deep-seated tectonics (**Khayitov et al., 2021**). Slope analysis highlights gently sloping terrains over major grabens favorable for survey acquisition, whereas moderate to steep slopes reflect fault scarps and paleo-uplifted blocks, consistent with the basin's known neotectonic deformation (**Ehsan et al., 2021**). Land-use and land-cover patterns further show that much of the Khewari Block consists of undeveloped barren land, minimizing anthropogenic interference and supporting logistical feasibility for exploration operations.

Collectively, these datasets converge to indicate a structurally complex but highly prospective petroleum system. Fault-assisted seals, rollover anticlines, and tilted fault blocks identified on seismic sections correspond with gravity-defined density contrasts and surface geomorphic patterns, reducing exploration uncertainty and strengthening the structural interpretation Although variations in spatial resolution and acquisition scale limit perfect co-registration between all datasets, the combined results still establish a robust tectono-stratigraphic framework that improves understanding of reservoir geometry, seal integrity, and hydrocarbon migration pathways. This multidisciplinary strategy aligns with the suggestions of combined subsurface assessment of frontier basins (**Oppert et al., 2022**), demonstrating its applicability for structurally complex and underexplored regions such as the Khewari Block.

5. Conclusions

The integration of seismic, gravity, and geospatial data sets provides an integrated structural framework of the Khewari Block, demonstrating that the major tectonic elements identified on seismic profiles correspond directly with density variations observed in the Bouguer and residual gravity fields. Seismic sections delineate a system of NE–SW-oriented normal faults (F1–F3) that partition the subsurface into horsts, grabens, and tilted fault blocks. These same structures appear as gravity gradients in the Bouguer anomaly map (see **Figure 8a**), where the western high-amplitude anomaly (L1) coincides spatially with the uplifted structural highs mapped on the Sui Main Limestone and Lower Goru depth surfaces (see **Figures 6a–6b**). On the other hand, the low-amplitude anomalies (L2 and L3) directly overlap with the down-faulted graben complexes imaged along seismic lines O-011-KWI-15 and O-011-KWI-16. This geometrical correspondence between fault-bounded relief in seismic data and corresponding density contrasts in the gravity field substantiates the interpretation of structural closures and rollover geometries as viable hydrocarbon traps.

Geospatial datasets further reinforce this subsurface model, as they show that surface morphology is a reflection of the underlying tectonic arrangement. The digital elevation model (see **Figure 11**) has high topography in the central-northeastern parts of the block, which coincides with the structural culminations of the depth maps of the Lower Goru and Sui Main Limestone. In contrast, the southwestern depressed plains coincide with the

gravity low zones (L2–L3) and the seismic grabens that accommodate greater sediment thickness. The slope distribution (see **Figure 12**) also shows the orientation of the principal fault systems; linear slope breaks and gradient anomalies are spatially consistent with faults F1–F3, which means that basin-scale tectonics still have topographic control. These correlations are an independent confirmation that these geophysical interpretation signatures have been maintained in modern surface geomorphology and are a measure of structural segmentation that existed in the past.

The synthesis of seismic, gravity, and GIS analyses yields a robust multi-layered structural model in which the potential hydrocarbon traps are continuously found across all the datasets. Structural culminations mapped as closures on depth surfaces correspond to Bouguer gravity highs (L1) and to uplifted geomorphic highs in the DEM, reinforcing their status as high-certainty exploration targets. Conversely, gravity lows (L2–L3), seismic grabens, and low-lying plains delineate secondary compartments characterized by increased sediment fill and potential migration pathways but reduced structural integrity. This convergence of independent datasets significantly enhances confidence in the mapped trap geometries, improves prediction of reservoir continuity, and provides a more defensible basis for well-location selection, volumetric assessment, and overall exploration risk reduction within the Khewari Block.

Acknowledgement

We would like to thank the Directorate General of Petroleum Concessions (DGPC) and Landmark Resources (LMKR) for providing the data used in this study. We also extend our gratitude to the team at Petroleum Exploration and Production for their support in acquiring and processing seismic data. Special thanks to the research staff who assisted with the GIS-based analysis and geological interpretation.

Funding

The research has no external funding.

6. References

Aboelhassan, N., Tarabees, E., El Bastawesy, M., Mogren, S., Nabawy, B. S., Ibrahim, E., & Qadri, S. M. T. (2024). Integrated seismic, petrophysical, and geochemical studies for evaluating the petroleum system of the Upper Bahariya-Abu Roash G sequence in the Karama Field, Abu Gharadig Basin, North Western Desert, Egypt. *Journal of African Earth Sciences*, *219*, 105413. https://doi.org/10.1016/j.jafrearsci.2024.105413

Abdul-Majeed, Y. N., Ramadhan, A. A., & Jubair, A. (2020). Constructing 3D geological model for tertiary reservoir in Khabaz oil field by using Petrel software. *Journal of Petroleum Research and Studies*, *10*(2), E54–E75. https://doi.org/10.52716/jprs.v10i2.350

Aftab, F., Zafar, M., Hajana, M. I., & Ahmad, W. (2022). A novel gas sands characterization and improved depositional modeling of the Cretaceous Sembar Formation, Lower Indus Basin, Pakistan. *Frontiers in Earth Science*, *10.* https://doi.org/10.3389/feart.2022.1039605

Ali, A., Hadeed, M. Z., Safavi, S., & Ahmad, M. (2024). Leveraging GIS for environmental planning and management. In *Global Challenges for the Environment and Climate Change* (pp. 308–331). IGI Global. https://doi.org/10.4018/979-8-3693-2845-3.ch016.

Buttinelli, M., Maesano, F. E., Sopher, D., Feriozzi, F., Maraio, S., Mazzarini, F., Improta, L., Vallone, R., Villani, F., & Basili, R. (2022). Revitalizing vintage seismic reflection profiles by converting into SEG-Y format: Case studies from publicly available data on the Italian territory. *Annals of Geophysics*, *65*(5), DM538. https://doi.org/10.4401/ag-8883

Cao, X., Liu, Z., Hu, C., Song, X., Quaye, J. A., & Lu, N. (2024). Three-dimensional geological modelling in earth science research: An in-depth review and perspective analysis. *Minerals*, *14*(7), 686. https://doi.org/10.3390/min14070686

de Jager, J. (2020). Concepts of conventional petroleum systems. In *Regional geology and tectonics (pp. 687–720).* https://doi.org/10.1016/B978-0-444-64134-2.00022-5

Dolson, J., He, Z., & Horn, B. W. (2018). Advances and perspectives on stratigraphic trap exploration-making the subtle trap obvious. *Search and Discovery, 60054*. https://doi.org/10.29222/ipng.2078-5712.2022-39.art6

Ehsan, M., Gu, H., Ali, A., Akhtar, M. M., Abbasi, S. S., Miraj, M. A. F., & Shah, M. (2021). An integrated approach to evaluate the unconventional hydrocarbon generation potential of the Lower Goru Formation (Cretaceous) in Southern Lower Indus basin, Pakistan. *Journal of Earth System Science, 130(2), 90*. https://doi.org/10.1007/s12040-021-01584-4

Fan, J., & Kong, D. (2023). Geological Modeling with Petrel Software. *OALib, 10(05)*, 1–7. https://doi.org/10.4236/oalib.1110106

Hussain, Y., Schlögel, R., Innocenti, A., Hamza, O., Iannucci, R., Martino, S., & Havenith, H. B. (2022). Review on the Geophysical and UAV-Based Methods Applied to Landslides. In *Remote Sensing (Vol. 14, Number 18)*. MDPI. https://doi.org/10.3390/rs14184564

Inam, A., Clift, P. D., Giosan, L., Alizai, A., Kidwai, S., Shahzad, M. I., Zia, I., Nazeer, M., Khan, M. J., & Ali, S. S. (2022). The geographic, geological, and oceanographic setting of the Indus River–an update. Large Rivers: *Geomorphology and Management, Second Edition, 488–520*. https://doi.org/10.1002/9781119412632.ch17

Iqbal, A., Sajid, M., Khan, N., Shah, F., Khan, S., & Rehman, F. (2022). Petrophysics based Reservoir Evaluation of the Cretaceous Lower Goru "C" Sands, Middle Indus Basin, Sindh, Pakistan. *International Journal of Economic and Environmental Geology, 13 (3)*. https://doi.org/10.46660/ijeeg.v13i3.37

Jadoon, S.-U.-R. K., Lin, D., Ehsan, S. A., Jadoon, I. A. K., & Idrees, M. (2020). Structural styles, hydrocarbon prospects, and potential of Miano and Kadanwari fields, Cen-

tral Indus Basin, Pakistan. *Arabian Journal of Geosciences, 13*(2), 97. https://doi.org/10.1007/s12517-020-5122-5

Khan, N., Khan, S., Rehman, F., & Sajid, M. (2024). Structural and seismic attribute analysis of the Paleocene carbonate reservoir from the Balkassar Field, Potwar Plateau, *Pakistan. Journal of Petroleum Research and Studies, 14(1),* 18–35. https://doi.org/10.52716/jprs.v14i1.871.

Khaskheli, M.R., Hassan Agheem, M., Ali Panhwar, M., Akram, U., & Nazir, J. (2021). 32 c Structural Styles and their Suitability for Hydrocarbon in Eastern Sindh Monocline, Lower Indus Basin, Pakistan. *International Journal of Economic and Environmental Geology, 12 (3).* https://doi.org/10.46660/ijeeg.v12i3.58

Khayitov, O. G., Salizhanova, G. K., Mutalova, M. A., Aminzhanova, S. I., & Mishareva, M. Y. (2021). Oil and Gas Potential in the Territory of the South-Eastern Part of the Bukhara- Khiva Region. *REVISTA GEINTEC-GESTAO INOVACAO E TECNOLOGIAS, 11(4), 4699–4708*.

Li, W., Yang, M., Feng, W., & Zhong, M. (2024). Improved Approaches for 3D Gravity and Gradient Imaging Based on Potential Field Separation: Application to the Magma Chamber in Wudalianchi Volcanic Field, Northeastern China. *Remote Sensing, 16(7*). https://doi.org/10.3390/rs16071187

Lin, L., Zhong, Z., Li, C., Gorman, A., Wei, H., Kuang, Y., Wen, S., Cai, Z., & Hao, F. (2024). Machine learning for subsurface geological feature identification from seismic data: Methods, datasets, challenges, and opportunities. *Earth-Science Reviews, 104887*. https://doi.org/10.1016/j.earscirev.2024.104887

Lučić, D., & Bosworth, W. (2018). Regional geology and petroleum systems of the main reservoirs and source rocks of North Africa and the Middle East. *In The Geology of the Arab World---An Overview* (pp. 197–289). Springer. https://doi.org/10.1007/978-3-319-96794-3_6

Mahmoud, S. (2015). Integrated sequence stratigraphy of the Cretaceous Lower Goru Deposits, Lower Indus Basin, Pakistan. *International Conference and Exhibition*. https://doi.org/10.1190/ice2015-2153029

Noureldin, A. M., Mabrouk, W. M., & Metwally, A. (2023). Structural and petroleum system analysis using seismic data interpretation techniques to Upper Cretaceous rock units: A case study, West Abu-Sennan oil field, Northern Western Desert, Egypt. *Journal of African Earth Sciences, 198, 104772*. https://doi.org/10.1016/j.jafrearsci.2022.104772

Oppert, S., Baker, K., & Bathija, A. (2022). Introduction to this special section: Seismic reservoir modeling. *The Leading Edge, 41*(12), 814–814. https://doi.org/10.1190/tle41120814.1

Safani, J., Wirawan, R., Ibrahim, K., Masri, & Hasmina T. Mokui (2026). Investigation of geothermal system using advanced processing and inversion of gravity data in Lainea non-volcanic geothermal field, Indonesia. *Rudarsko-geološko-naftni Zbornik, 40(1), 143–156*. https://doi.org/10.17794/rgn.2026.1.11

Sajid, M., Kashif, M., Zahid, M. A., Javed, A., & Shaikh, A. (2021). Petrophysical evaluation of reservoir rocks of rajian-01, daiwal-01, and kal-01 by well log data, potwar plateau, upper indus basin, Pakistan. *Bulletin of Geophysics and Oceanography*, *62*(1), 135–158. https://doi.org/10.4430/bgta0340

Saravanavel, J., Ramasamy, S. M., Palanivel, K., & Kumanan, C. J. (2020). GIS based 3D visualization of subsurface geology and mapping of probable hydrocarbon locales, part of Cauvery Basin, India. *Journal of Earth System Science, 129(1), 36.* https://doi.org/10.1007/s12040-019-1307-2

Sarhan, M. A. (2021). Geophysical assessment and hydrocarbon potential of the Cenomanian Bahariya reservoir in the Abu Gharadig Field, Western Desert, Egypt. *Journal of Petroleum Exploration and Production Technology, 11(11), 3963–3993*. https://doi.org/10.1007/s13202-021-01289-w

Setiahadiwibowo, A. P., Setiawan, A., Husein, S., & Sismanto, S. (2025). Subsurface structural modelling using the gravity method in the Pacitan Area, Indonesia based on derivative analysis and model inversion. *Rudarsko-geološko-naftni Zbornik, 40(1), 51–61*. https://doi.org/10.17794/rgn.2025.1.4

Shastri, N. L., Hanafy, S., & Mahmoud, S. E. (2019). On Geoinformatics Ecosystem Framework for Energy Resources Management in the Frontier Sedimentary Basins. Advances in Remote Sensing and Geo Informatics Applications: Proceedings of the 1st Springer Conference of the *Arabian Journal of Geosciences (CAJG-1), Tunisia 2018, 25– 27*. https://doi.org/10.1007/978-3-030-01440-7_6

Singh, R. (2014). Exploration application of seismic amplitude analysis in the Krishna-Godavari Basin, east coast of India. *Interpretation, 2*. https://doi.org/10.1190/INT-2013-0197.1

Toppo, M. M., & Sinha, J. (2024). Geomatics Application for Assessment of Groundwater Prospective Zones – A case study of Kanchi River Sub Basin, Khunti- Ranchi districts, Jharkhand. *Journal of Geomatics, 18(1), 12–20*. https://doi.org/10.58825/jog.2024.18.1.69.

Tshanga, M. M., Ncube, L., & van Niekerk, E. (2024). Remote sensing insights into subsurface-surface relationships: Unveiling geological structures and landforms at copper deposits. *Acta Montanistica Slovaca, 29(3), 689–702*. https://doi.org/10.46544/AMS.v29i3.15

van Buren, R., Turner, G., & Hird, G. (2019). Modern seismic is illuminating the depths. Proceedings of the Ninth International Conference on *Deep and High Stress Mining, 363–374*. https://doi.org/10.36487/acg_rep/1952_27_van_buren

Zhou, C., Fei, Y., He, X., Cai, H., Yao, X., & Hu, G. (2025). Fault-controlled oil and gas reservoir unit division based on graph. *Advances in Geo-Energy Research, 15(1)*, *68–78*. https://doi.org/10.46690/ager.2025.01.07

SAŽETAK

Integrirana geoznanstvena i geoprostorna analiza za istraživanje ugljikovodika u bloku Khewari, Sindh, Pakistan

Blok Khewari, smješten u strukturno složenome donjoindskom bazenu Sindha u Pakistanu, zauzima tektonski povoljan, ali nedovoljno istražen sektor mezozojsko-kenozojskoga riftnog bazena poznatoga po svojim potencijalima za ugljikovodike. Ova studija primjenjuje integrirani geofizički geoprostorni postupak za ograničavanje podzemne arhitekture i procjenu potencijala ležišta. Opsežna interpretacija 2D seizmičkih profila identificira sustav sjeveroistočno-jugozapadno orijentiranih normalnih rasjeda, horstova, grabena i lokalnih kompresijskih struktura, stvarajući širok raspon geometrija zamki, uključujući rasjedne zatvore, antiklinale prevrtanja i nagnute blokove rasjeda. Mapiranje vremenske i dubinske strukture poboljšava geometrije horizonta i identificira strukturno izolirane blokove s poboljšanim potencijalom zarobljavanja. Bouguerove i rezidualne karte gravitacijskih anomalija dodatno razjašnjavaju razlike u gustoći povezane s uzdignutim karbonatnim platformama i sedimentnim dolinama potvrđujući segmentaciju strukture na temelju seizmičkih podataka. Dopune površinskih skupova podataka, kao što su elevacija temeljena na DEM-u, modeli nagiba i klasifikacija korištenja zemljišta, nude daljnja ograničenja u pogledu pristupačnosti terena, sustava odvodnje i operativnih mogućnosti. Integracija površinskih i podzemnih skupova podataka smanjuje nesigurnost u procesu interpretacije, poboljšava razgraničenje zamki i doprinosi najučinkovitijem planiranju postavljanja bušotina. Multidisciplinarni pristup ilustrira učinkovitost integriranja seizmičke refleksije, gravitacijskoga modeliranja i površinske GIS analize kako bi se stvorio koherentan strukturni okvir graničnih bazena. Radni postupak prenosiv je na druge regije s ograničenim podatcima i pruža čvrstu osnovu za istraživanje ugljikovodika i donošenje odluka temeljeno na dokazima.

Klučne riječi:
istraživanje ugljikovodika, seizmička interpretacija, gravitacijske anomalije, geoprostorna integracija, blok Khewari

Author's contribution

Muhammad Junaid (MSc): Conceptualization, investigation, software, data curation, formal analysis, methodology, visualization, writing – original draft. **Muhammad Sajid** (PhD): Supervision, project administration, writing – review & editing. **Taimoor Ahmad** (MSc): Investigation, validation, writing – review & editing. **Eko Kusratmoko** (PhD): Methodology, resources, supervision, writing – review & editing. **Reza Syahputra** (PhD): Validation, software, visualization, writing – review & editing. **Shaukat Khan** (PhD): Validation, writing – review & editing. **Adi Wibowo** (PhD): Validation, writing – review & editing. **Muhammad Kashif** (Ph.D.): Validation, writing – review & editing.
All authors have read and agreed to the published version of the manuscript.