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Integrating Geological Data for Enhanced Understanding of Carbonate Heterogeneous Reservoirs

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Abstract: This study presents a comprehensive geological modeling approach to understanding the Hartha Formation in the Balad Oilfield. Utilizing Petrel software, a 3D geological model was developed, integrating well data, seismic contour map, and log analyses to delineate the reservoir's structural and petrophysical properties. Data preparation involved organizing well headers, tops, and logs from five key wells, followed by the creation of a structural contour map that identified major and minor faults influencing the reservoir. Structural modeling further enhanced the understanding of the Hartha Formation's geometry, illustrating how tectonic influences and faulting impacted the spatial distribution of reservoir units. Facies modeling identified a predominance of mudstone and wackestone in the upper Hartha Formation, with improved reservoir qualities in the Har.UA and Har.UB units. Petrophysical modeling demonstrated variations in porosity and water saturation, highlighting the impact of structural features on fluid distribution. The findings underscore the complex geological interplay within the Hartha Formation, providing critical insights for future exploration and optimized hydrocarbon recovery strategies.

Key words: 3D geological modeling, reservoir characterization, Hartha formation, facies and petrophysical analysis.

1. Introduction

Geological modeling is a critical component in the exploration and production of hydrocarbons, facilitating the visualization and understanding of subsurface structures and properties. By integrating geological and geophysical data, this process allows for the construction of three-dimensional (3D) models that represent the complex interactions within the Earth's crust. The advancement of computational tools and software, such as Petrel, has revolutionized the field by providing powerful means to simulate geological formations and assess their potential for resource extraction [1, 2].

The Hartha Formation, located within the Balad Oilfield, presents a significant opportunity for detailed geological modeling. This formation, characterized by its intricate stratigraphy and varying lithologies, plays a crucial role in hydrocarbon accumulation and migration. Understanding the geologic framework of the Hartha Formation is essential for optimizing reservoir management, enhancing oil recovery strategies, and reducing exploration risks. Previous studies have highlighted the formation's complex structure, influenced by faulting and sedimentation processes during the upper Cretaceous period [3]. Research on similar formations has shown that accurate geological modeling can significantly improve production outcomes by informing drilling strategies and resource allocation.

Many previous studies have focused on geological modeling to enhance understanding of complex reservoir characteristics. For instance, Alghanemy and Mahdi (2021) [4] developed a 2D geological model of the Hartha Formation in the Majnoon oilfield, utilizing well log data from eight wells, core samples, and microfacies analysis. Their findings indicate that the upper part of the formation features mid-ramp, shoal,

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and inner ramp facies, with the shoal facies exhibiting high effective porosity and low water saturation, making it the primary reservoir. The study highlights significant vertical and lateral variations in petrophysical properties, suggesting high hydrocarbon saturation in the upper sections of the formation. Al-Hadidy et al. (2022) [5] evaluated the Hartha Formation in the Y and J oil fields of North Iraq, utilizing open hole logs to determine key petrophysical parameters such as porosity and water saturation. Their findings indicated that the reservoir thickness ranges from 40 to 120 meters, with an average porosity of 33.3%. The study highlighted the potential for economically viable hydrocarbon production in the area, emphasizing the quality variations across different reservoir units.

This study aims to construct a comprehensive 3D geological model of the Hartha Formation in the Balad Oilfield using Petrel software. The model will encompass key aspects such as structural features, facies distribution, and petrophysical properties, including porosity and water saturation. By integrating well data, seismic information, and geological interpretations, this research seeks to improve the understanding of the Hartha Formation's reservoir characteristics and support effective decision-making in hydrocarbon exploration and production. Ultimately, the findings are expected to contribute valuable insights into the management of hydrocarbon resources in the region.

2. Geological Setting

The Balad Oilfield, situated in the Salah Al-Deen Governorate, lies approximately 9 km from the town of Balad and about 60-70 km north of Baghdad (Fig. 1). This field is located on the western bank of the Tigris River, adjacent to the Samara field to the north and the East Baghdad field to the south, within the broader framework of the Mesopotamian Basin [6].

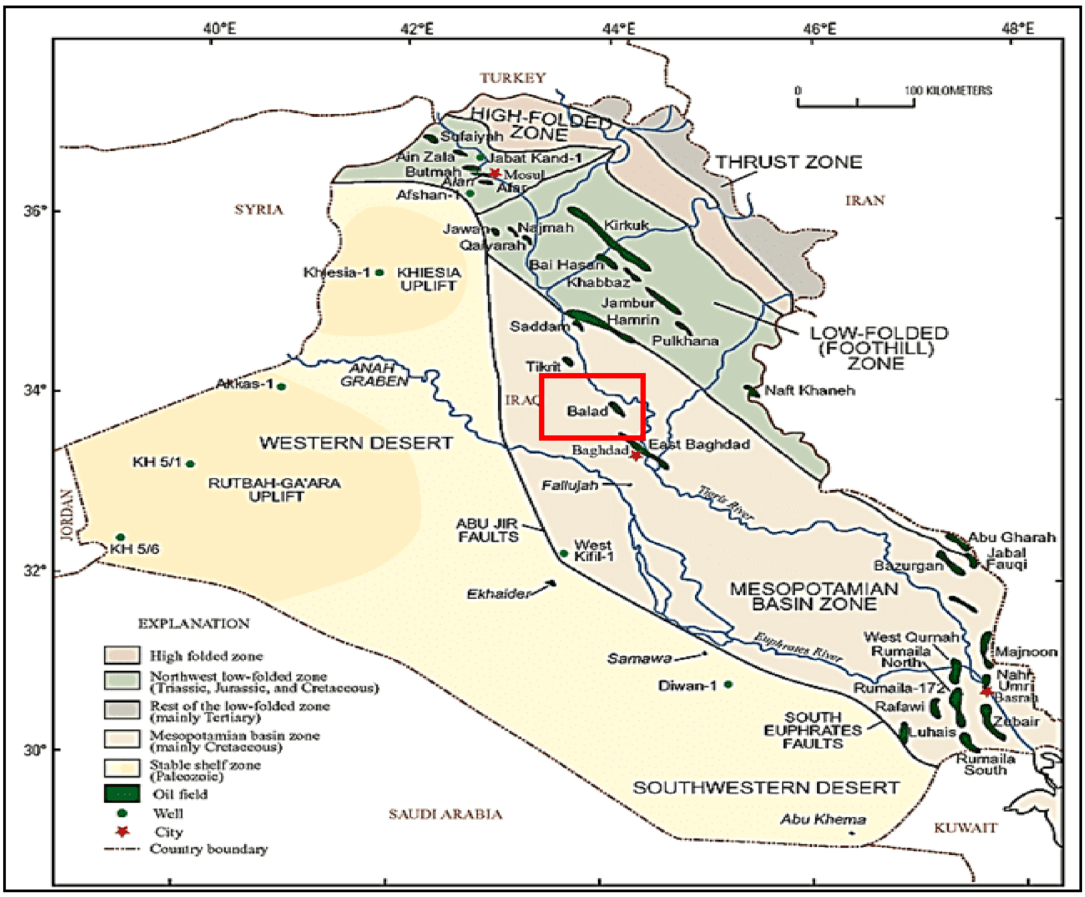


Fig. 1 Location map of the Balad Oilfield [7].

Geologically, the Balad structure is characterized by block faulting, which has resulted in a monocline that gently dips toward the east and northeast. This structural configuration illustrates the region's complex tectonic history and the influence of faulting on rock stratigraphy [7]. The area has seen extensive drilling, revealing multiple reservoirs within formations ranging from the Miocene Fars Formation at a depth of 872 m to the Jurassic Alan Formation, extending to depths of 4233 m true vertical depth subsea (TVDSS).

The sedimentological profile of the Hartha Formation indicates a depositional history within the Mesopotamian Basin during the Late Campanian to Early Maastrichtian period, reflecting conditions in a back-reef to lagoonal environment [8]. The Balad Oilfield lies within the Tigris subzone of the Mesopotamian Zone, which exhibits significant geological complexity. This area is characterized by extensive synclines and narrow anticlines, predominantly trending northwest-southeast and east-west, along with a system of normal faults [9]. The Hartha Formation at Balad is composed of two main lithological sections: the upper section, primarily limestone interspersed with argillaceous and marly layers, and a lower section characterized by porous, finely crystalline limestone, frequently associated with heavy oil deposits. The upper boundary of the Hartha Formation is conformably aligned with the overlying pelagic sediments of the Shiranish Formation, while the lower boundary is unconformably positioned above the Mushorah Formation, typically indicating a significant stratigraphic hiatus [10]. Additionally, a seismic contour map of the Hartha Formation, modified using Petrel Software based on the study by Al-Naemi (2012) [3], illustrates the major faults (F1 and F2) and minor faults (MF1, MF2, and MF3) within the area (Fig. 2).

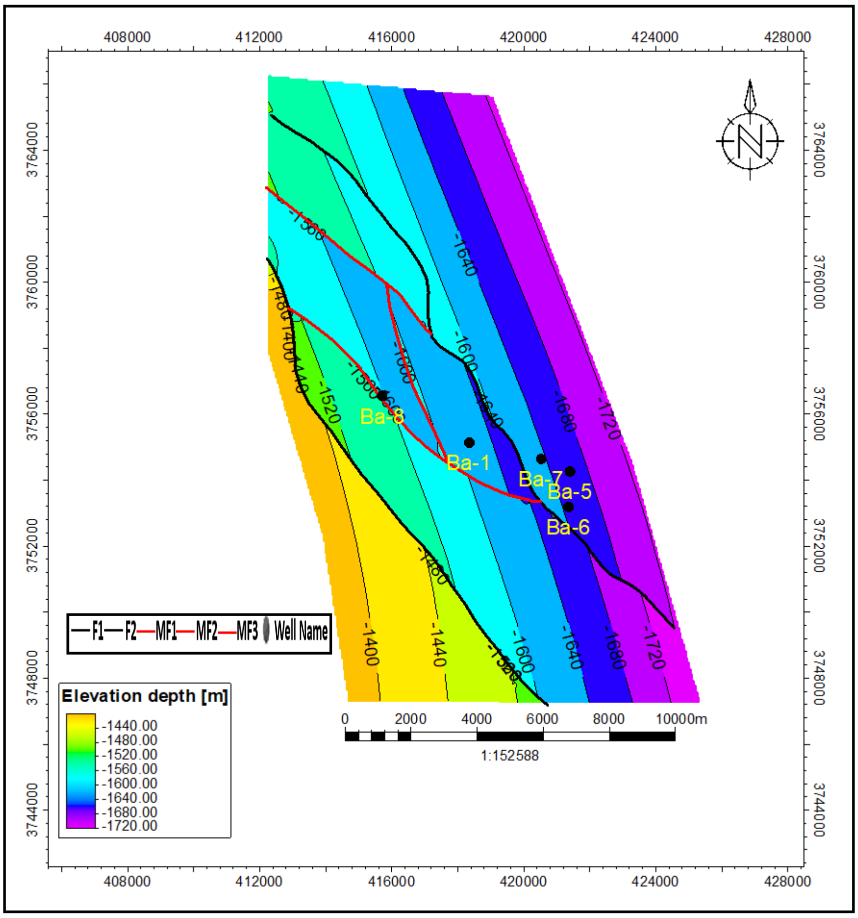


Fig. 2 **Seismic contour map of the five studied wells, modified after Al-Naemi (2012) [3].**

In the study area, the thickness of the Hartha Formation is influenced by the presence of major faults, with values ranging from 292 m at well Ba-5 to 444 m at well Ba-1. This variability in thickness highlights the significant impact of structural controls on sediment deposition within the formation. This geological setting underscores the Balad Oilfield's potential as a vital resource for hydrocarbon exploration, providing a rich context for ongoing research into its microfacies, depositional environments, and diagenetic processes. Moreover, the diverse lithological composition of the Hartha Formation, ranging from organic detrital and glauconitic limestones to dolomitic and marly layers, suggests a complex reservoir behavior that merits detailed petrophysical analysis. Understanding these variations is essential for optimizing hydrocarbon recovery strategies in this promising field [7].

3. Methodology

3.1 Data Preparation

The data preparation phase involved the systematic organization and integration of multiple datasets into Petrel software. Initially, well header data was compiled, consisting of essential information such as well names, geographic coordinates (latitude and longitude), total depth, and rotary table kelly bushing (RTKB) elevation. This foundational data was critical for establishing the spatial context of the studied wells. Subsequently, the tops of the Hartha Formation and its associated reservoir units (Har.UA and Har.UB) were delineated from the studied wells, providing a vertical stratigraphic framework necessary for further modeling. Well-log data were extracted from Techlog software, encompassing conventional logs such as gamma ray, neutron, density, and sonic, as well as processed data reflecting electrofacies and petrophysical properties like effective porosity and water saturation

3.2 Structural Modeling

The structural modeling component aimed to create a comprehensive framework of the Hartha Formation utilizing well data and seismic interpretations. The process began with fault modeling, where the extracted fault sticks were converted into a 3D grid through pillar gridding, a technique that generates a grid framework based on fault geometry [11]. This process involves creating a skeleton framework grid consisting of three layers (top, med, and base) aligned with the key pillars defined by the faults (Fig. 3). The structural model was further refined by integrating horizon surfaces, which delineated the top of the Hartha Formation and its units. Isochore maps were developed to represent thickness variations within the Hartha Formation, accounting for the influence of major faults that impacted the structural closure and non-uniformity of the reservoir. This modeling was instrumental in understanding the geological complexities of the formation.

3.3 Facies Modeling

Facies modeling aimed to capture the spatial distribution and architectural features of different sedimentary facies within the Hartha Formation. The process began with classifying facies using well log data and examining microfacies under a polarizing microscope, identifying five dominant microfacies types: mudstone, wackestone, wackestone to packstone, packstone, and rudstone.To construct 3D facies models, these microfacies underwent an upscaling process (Fig. 4).This process establishes a relationship between a fine-scaled geological grid and the coarser simulation grid. The average simulator requires a model between 100,000 to one million cells [12]. In Petrel, there are two methods available for distributing the discrete properties in a reservoir: deterministic and stochastic. Deterministic methods, also known as interpolation methods, are utilized when there is a dense dataset available. On the other hand, stochastic methods, also known as estimation methods, are pixel-based approaches used when dealing with sparse data. Stochastic methods employ upscaled cells as a basis for modeling the fraction of facies types. These methods are commonly used when modeling facies with unclear or undefined shapes, or when there is limited input data [11]. In this study, the stochastic (pixel-based) modeling algorithm is used to model Hartha facies in Balad Oilfield.

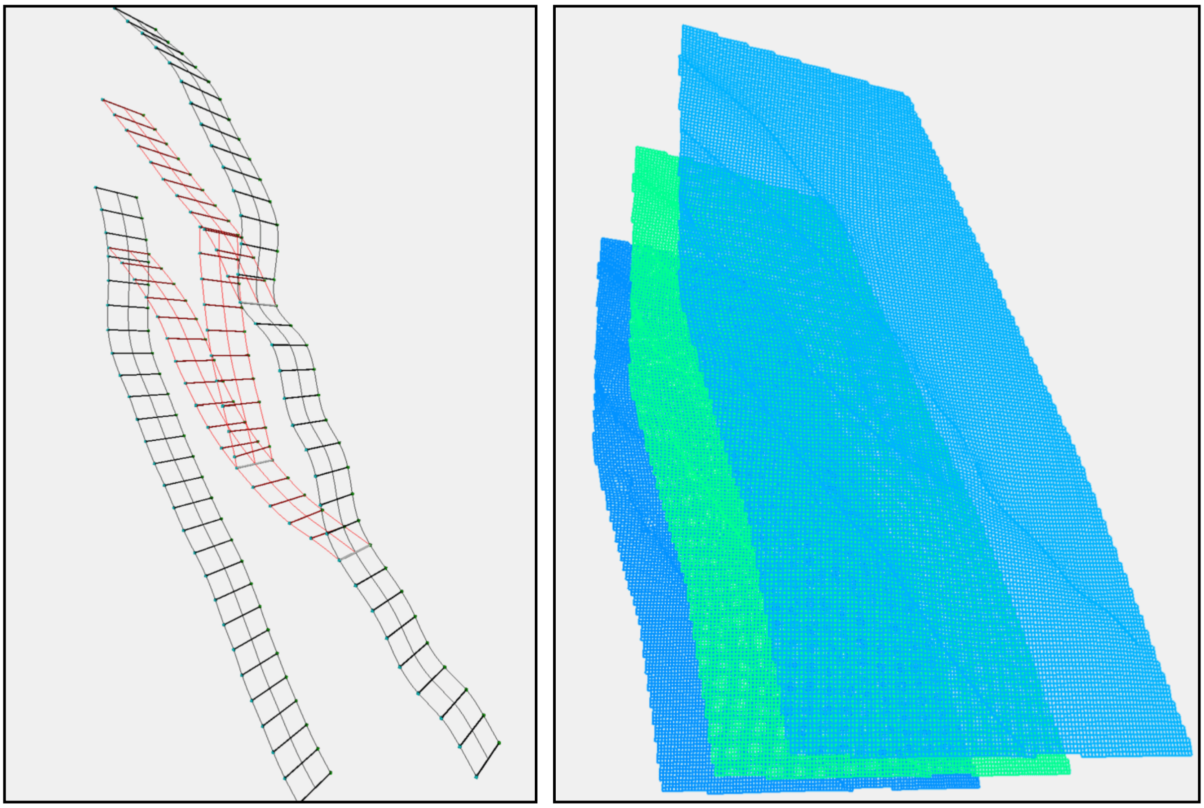


Fig. 3 3D window of fault pillar gridding and skeleton framework grid of the Hartha reservoir Layers.

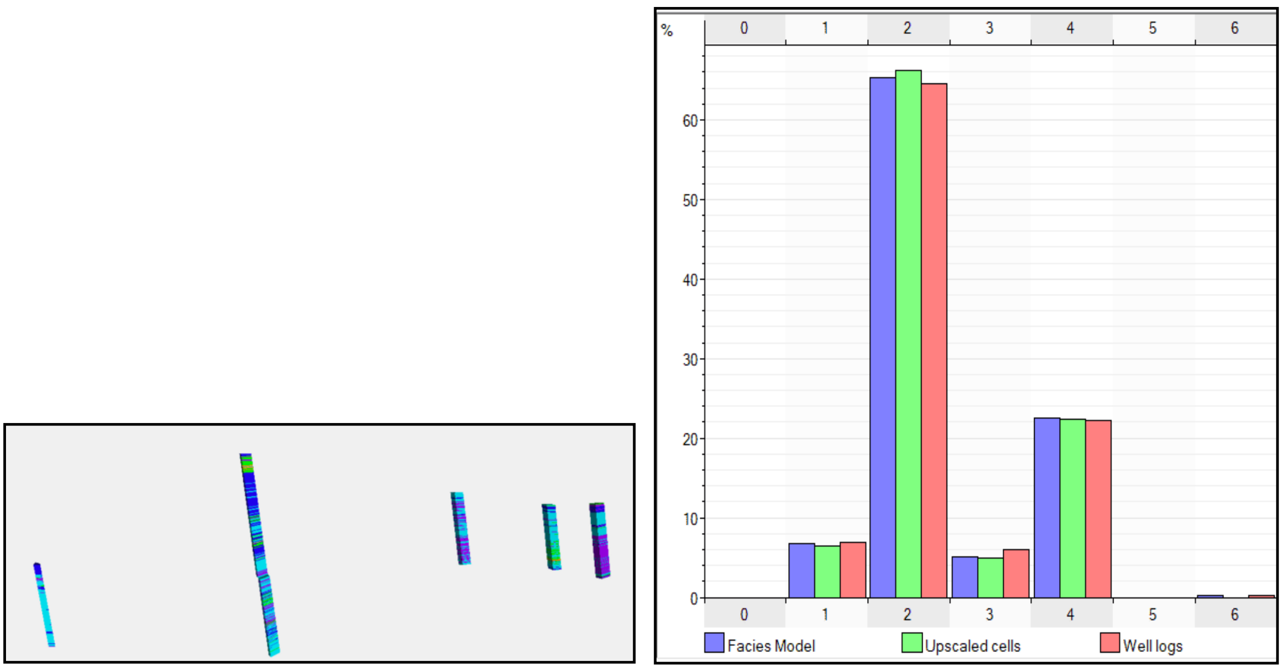


Fig. 4 Upscaling process of facies modeling in the Hartha Formation at five studied wells.

3.4 Petrophysical Model

The petrophysical model used in this study involves using upscaled petrophysical properties, such as porosity and water saturation to fill the cells of a grid with these properties (Fig. 5). Petrel, a software program, provides various geostatistical algorithms for modeling the distribution of petrophysical parameters in a reservoir [13]. The two most popular algorithms in Petrel are Kriging and Gaussian Simulation. Kriging is a deterministic interpolation mapping method that relies on statistical properties of the data, such as mean and variance. On the other hand, Gaussian Simulation is a stochastic method that builds upon kriging and is capable of capturing extreme values in a heterogeneous reservoir [11]. For this study, the Gaussian Simulation method is used to establish the basis for the initialization of the porosity and water saturation model within the Hartha Formation.

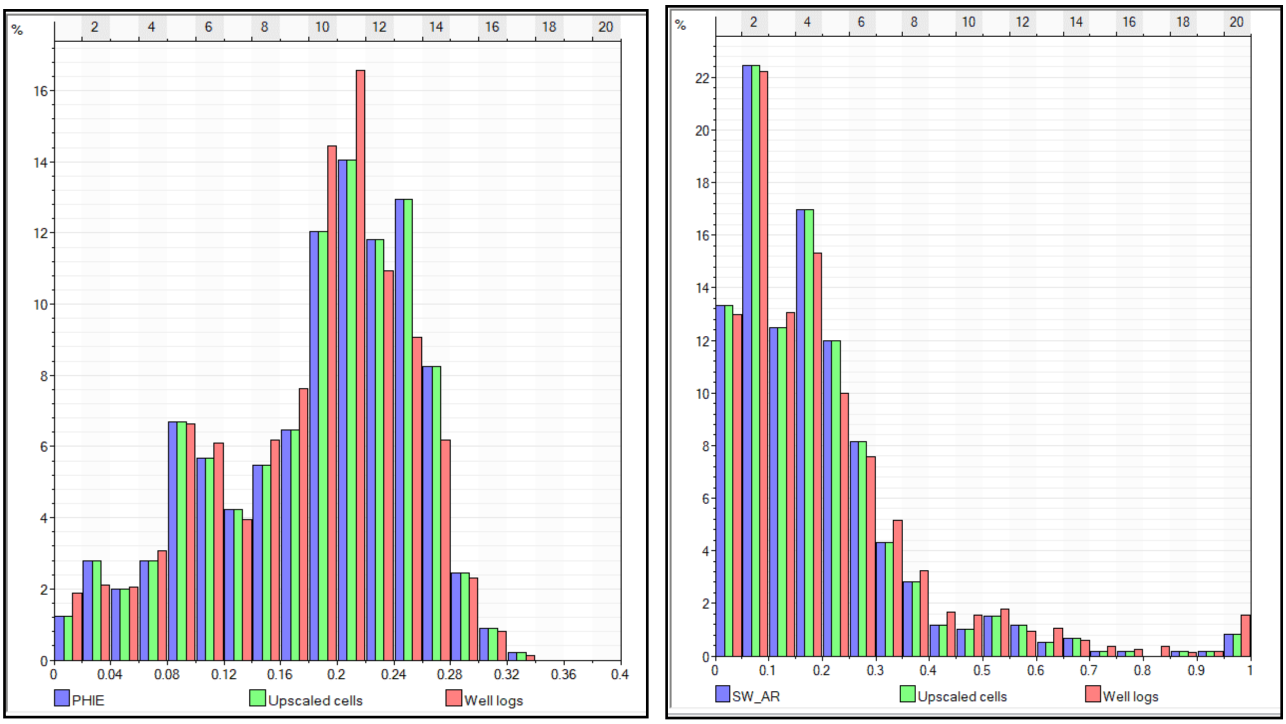


Fig. 5 Upscaling process of porosity and water saturation in the Hartha Formation at five studied wells.

4. Results

4.1 Structural Modeling

The structural modeling process illustrated the influence of tectonics on the Hartha Formation's geometry. Major faults, such as F1 and F2, were identified as primary factors controlling the structural configuration, leading to the disruption of stratigraphic continuity (Fig. 6). The structural modeling of the Hartha Formation illustrates the distinction between the graben area and the flank. In the graben area, the wells are positioned at greater depths compared to the wells in the flank. This variation can be attributed to the influence of major faults (F1) that disrupt the structural closure of the Hartha Formation unit, leading to its non-uniformity. An isochore map was generated to illustrate the thickness variations across the Hartha Formation, further supporting the structural interpretations (Fig. 7).

4.2 Facies Modeling

The facies modeling of the Hartha Formation revealed a complex distribution of sedimentary facies, primarily influenced by depositional environments and tectonic activity. The upper part of the formation predominantly exhibited mudstone and wackestone facies. These facies indicate low energy levels in the upper part of the Hartha Formation and represent two environmental systems: a deep shelf margin and an open shelf and lagoon circulation (Fig. 8). In contrast, the Har.UA unit showed slightly lower mudstone concentration compared to the upper part of the formation, but higher concentrations of wackestone and packstone, suggesting a moderate energy environment (Fig. 9). The lower part of the Hartha Formation displayed more diverse facies, including higher concentrations of wackestone to packstone and the presence of rudstone microfacies, indicating higher energy conditions associated with and foreslope environments (Fig. 9). The spatial distribution of facies was notably heterogeneous, significantly influenced by both major and minor faults within the formation. The modeling demonstrated clear lateral variations in facies types across the study area, complicating the prediction of reservoir connectivity and performance. The facies architecture suggested that while certain areas might exhibit favorable reservoir characteristics, others could present barriers to fluid flow due to their lithological composition.

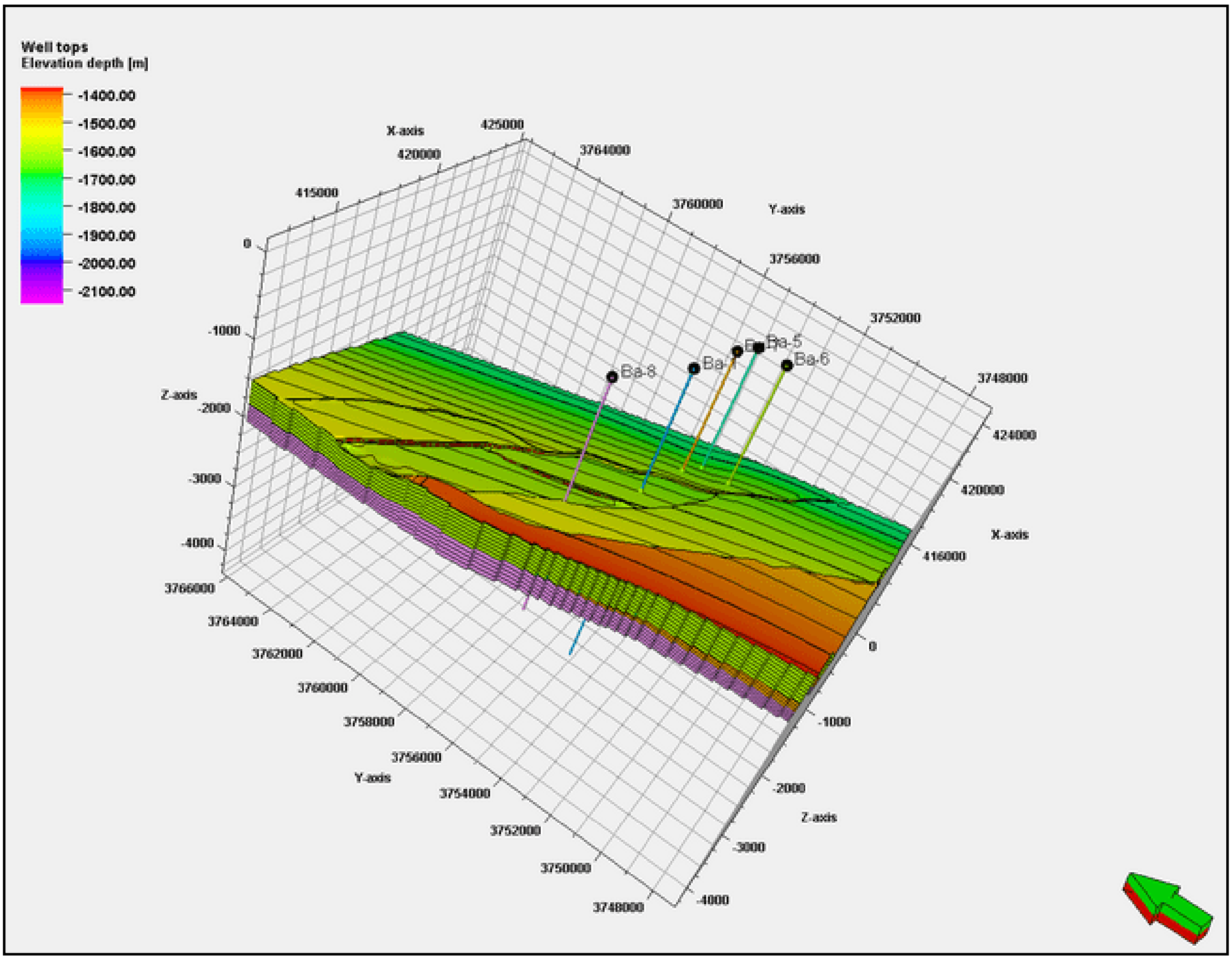


Fig. 6 The 3D structural model of Hartha Formation in Balad Oilfield.

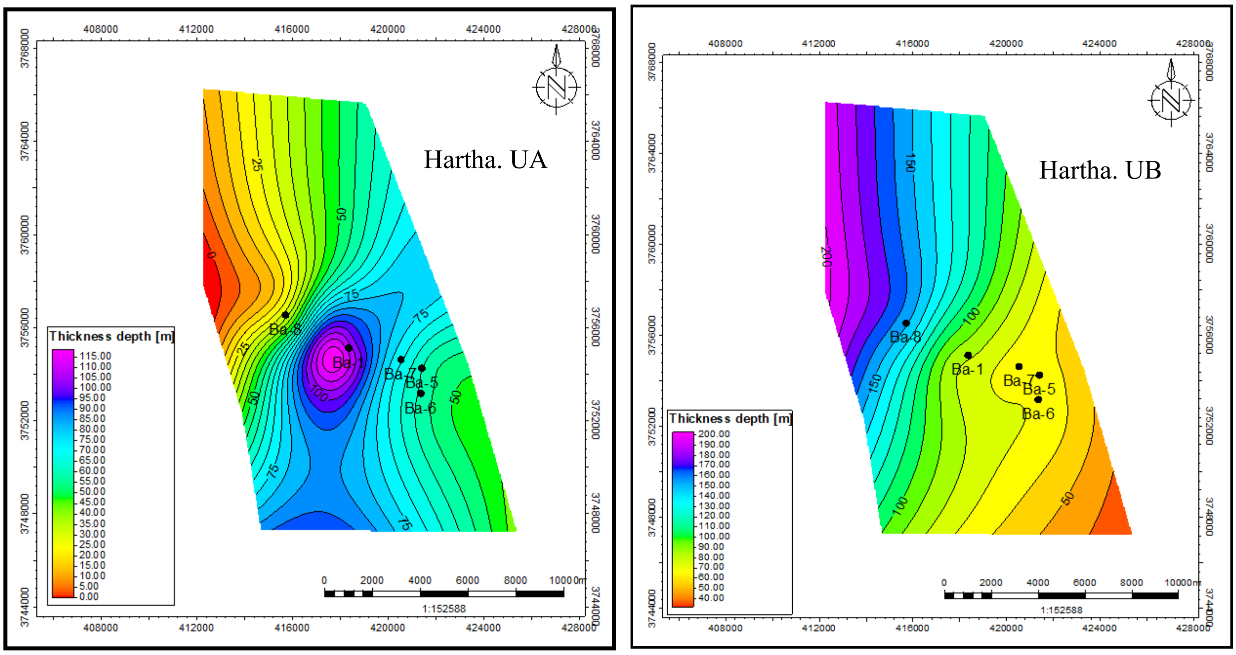


Fig. 7 The isochore (thickness) map of the Hartha.UA and Hartha.UB.

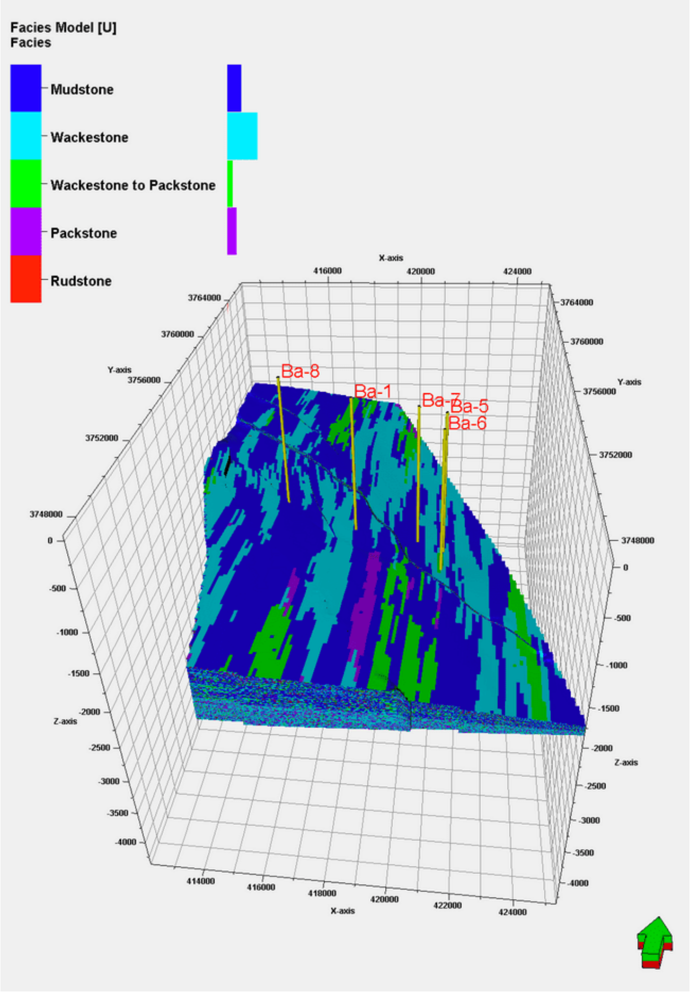


Fig. 8 3D facies model of Hartha Formation in Balad Oilfield.

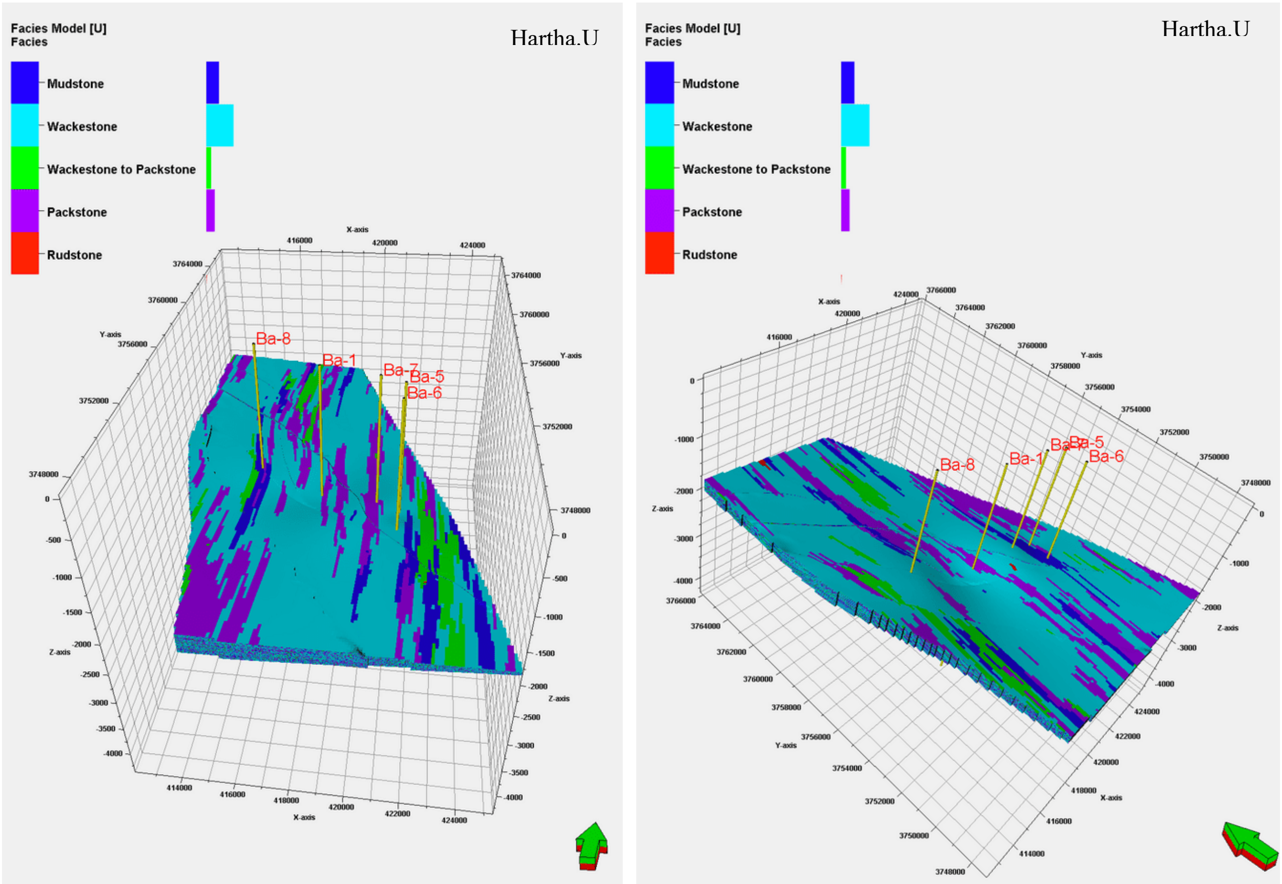


Fig. 9 3D facies model at the top of the Hartha.UA and Hartha.UB in Balad Oilfield.

4.3 Petrophysical Modeling

The petrophysical modeling results, encompassing effective porosity and water saturation, provided critical insights into the reservoir characteristics of the Hartha Formation. The effective porosity model indicated that the upper section of the formation generally exhibited lower porosity values (Fig. 10), while the Har.UA unit demonstrated enhanced porosity, particularly within the flanks of the Hartha dome (Fig. 11). The lower part of the formation, especially the Har.UB unit, showcased a higher concentration of porosity, which is advantageous for hydrocarbon storage (Fig. 11).

Water saturation modeling revealed high saturation levels in the upper part of the formation, with localized regions of slightly lower saturation on the northeastern flank (Fig. 12). The Har.UA unit displayed reduced water saturation compared to the upper section, while the Har.UB unit showed even lower saturation values, suggesting better reservoir quality in these zones (Fig. 13).

5. Conclusions

1) This study successfully demonstrates the integration of geological and geophysical data in creating a detailed 3D model of the Hartha Formation, enhancing our understanding of its structural and petrophysical characteristics.

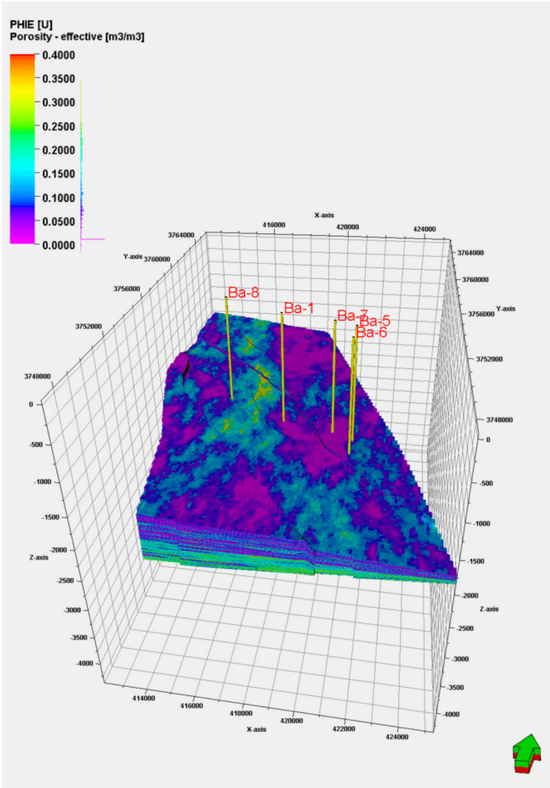


Fig. 10 3D Effective porosity (PHIE) model of the Hartha Formation in Balad Oilfield.

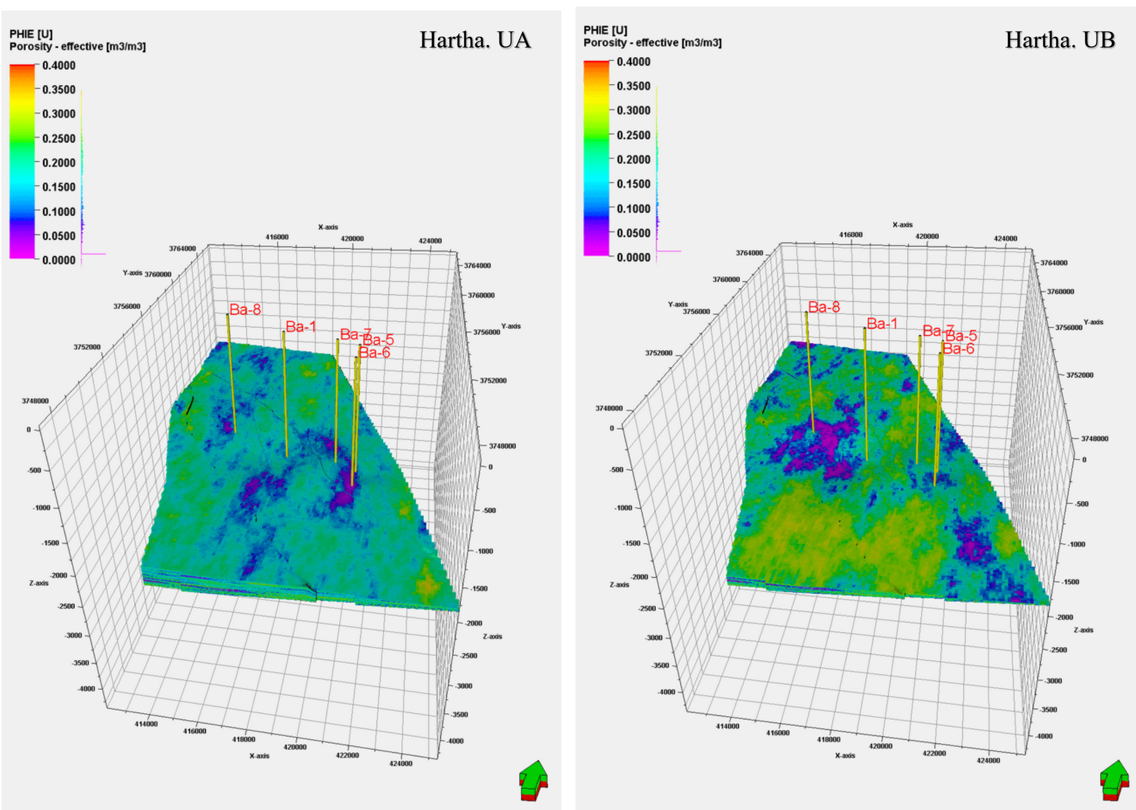


Fig. 11 Effective porosity (PHIE) model for Hartha.UA and Hartha.UB in Balad Oilfield.

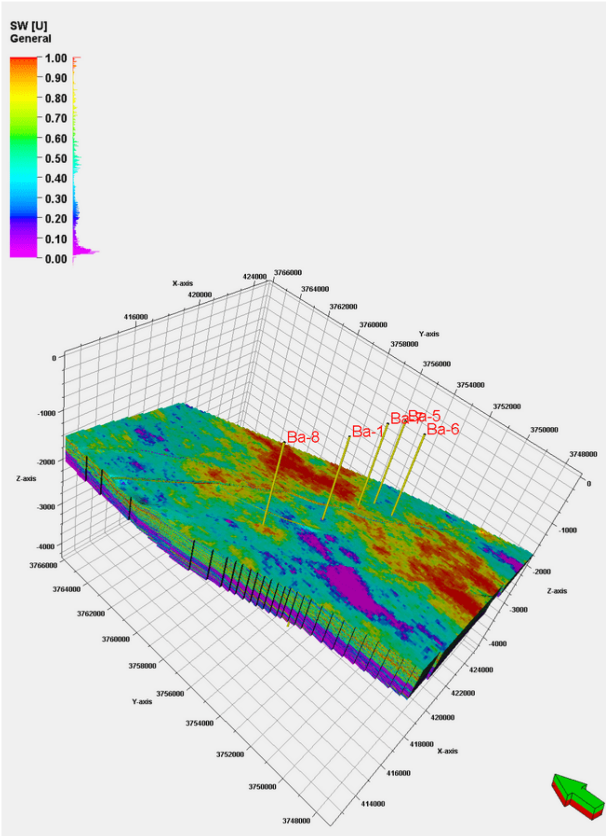
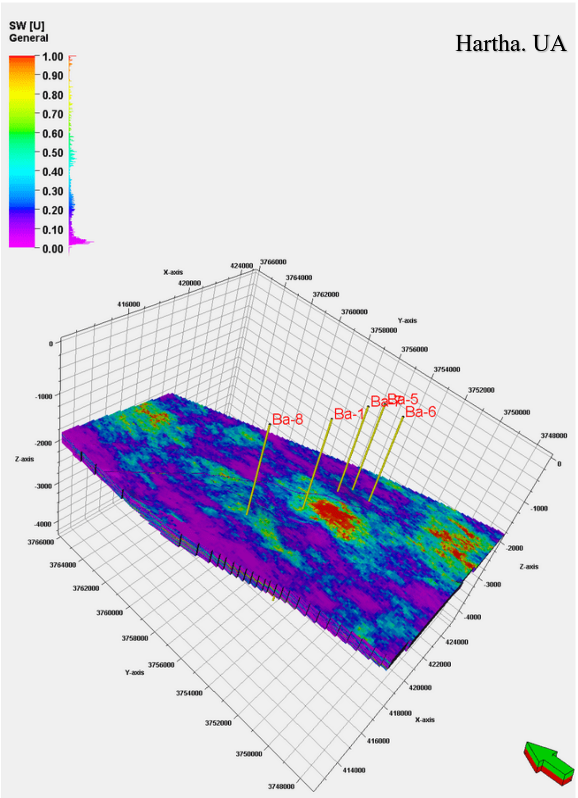


Fig. 12 3D water saturation (SW) model of the Hartha Formation in Balad Oilfield.



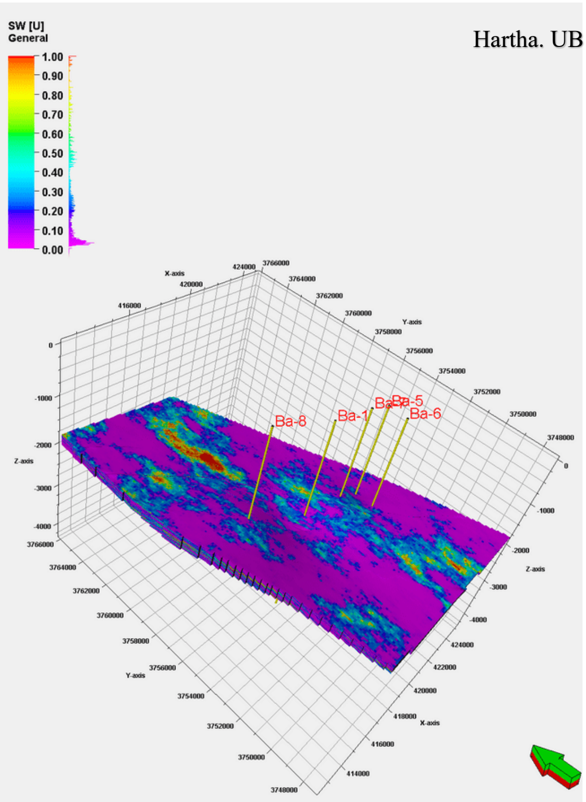


Fig. 13 3D water saturation (SW) model for Hartha.UA and Hartha.UB in Balad Oilfield.

2) The identification of major and minor faults, along with the complex facies distribution, reveals significant heterogeneity within the reservoir, underscoring the importance of structural controls on hydrocarbon accumulation.
3) Petrophysical modeling indicates critical variations in porosity, water saturation, and permeability across different reservoir units, providing valuable insights into areas with optimal conditions for hydrocarbon recovery.
4) The findings of this research contribute to improved decision-making in hydrocarbon exploration and production, offering a framework for future studies aimed at maximizing resource management in the Balad Oilfield.

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