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Impact of Fault and Reef on Reservoir Pressure Behavior and Production Profile: Case Study- South Iraqi Oilfield

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ABSTRACT

The study area, which consists of carbonate, is located in the unstable Mesopotamian basin on the Arabian plate, which makes it a field with high heterogeneity. It has a discrepancy in its bubble point pressure, which raises concerns about the faults or reefs that caused it. The study's main objective is to determine how faults and reefs impact production performance and pressure behavior under a future development strategy. This goal will be achieved by completing the necessary seismic, static, and dynamic models. After re-evaluating the seismic survey data, the seismic analysis detected many irregular amplitudes of reflected events and abrupt discontinuities, indicating either a reef or a fault. The static model was built based on seismic possible results and to make them as inputs for building the reservoir model. Based on the history-matching results, faults were detected, while reefs were ruled out. The development plan was implemented for the next 20 years in four cases, and case four had the most favorable results among all the cases, with production plateauing at 140 MSTB/D and a cumulative volume equal to 1.09 MMMSTB. The reservoir pressure behavior shows a hierarchical drop in all cases, with some differences, including a sharp decline in the area of the proposed wells and the fault, which has become a compartment that prevents reservoir compensation from adjacent regions.

Keywords: Mishrif reservoir, Development strategy, Reef, Fault, Pressure behavior.

1. INTRODUCTION

In southern Iraq, the hydrocarbon reserves of the Jurassic-Cretaceous petroleum system are mainly situated in sandstone and carbonate reservoirs originating from the Lower Cretaceous periods (**Boschetti et al., 2020**). The crude oil is produced by extracting it from the organic-rich Upper Jurassic formations of Sargelu and Sulaiy, which results in the conversion of the Lower Cretaceous carbonates found in the Yamama and Zubair formations

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into a reservoir made up of clastic materials (**Al-Dujaili et al., 2023; Lazim et al., 2018**). Accurately estimating the initial oil in a particular area is crucial for the oil and gas industry. The precision of the estimated reserves depends on seismic and petrophysical data, which are used in both the volumetric approach and simulation methods (**Ahmed et al., 2019; Alhusseini and Hamd-Allah, 2022; Hashim et al., 2023; Baker and Al-Rikaby, 2017; Shamkhi and Aljawad, 2021**). The well logs are important for evaluating reservoirs and exploring oil and gas reserves. Many petrophysical characteristics, such as porosity, hydrocarbon saturation, thickness, area, and permeability, should be considered when evaluating a reservoir. Furthermore, reservoir geometry, formation temperature and pressure, and lithology may influence the reservoir's finalization, extraction, and assessment (**Abdulredah and Al-Jawad, 2022; Al-Zubaidy and Al-Jawad, 2023; Al-Dujaili et al., 2021**). Seismic surveys are a way to gather geophysical data from underground rock formations. This data can connect well-log and core analyses with tracer and well-test analyses. Most geological maps and models are based on 3D seismic data, which describes important factors like reservoir heterogeneity, vertical zonation, lateral compartmentalization, and directional fluid flow in the reservoir (**Mondol, 2010; Baker and Al-Rikaby, 2017; Al-Rubaye and Hamd-Allah, 2019; Almahdawi et al., 2023**). Seismic reflections create accurate graphical representations of the subsurface and geologic features. These reflections provide data on seismic velocity and time contour maps, which are used to identify structural, stratigraphic, and seismic facies traps (**Trezzi et al., 2022; Alher et al., 2018; Al-Jawad and Kareem, 2016**).

Seismic reflections can also be used to interpret the area's sedimentary architecture and environmental palaeogeography (**Ali et al., 2018; Khawaja and Thabit, 2021**). It is crucial for analyzing the 3D seismic reflections, post-stack times migrated data, and well data for the study area. The National Oil Company crew confirmed the oil reserves of Mishrif, Zubair, Ratawi, and Yamama reservoirs 1984 using a 2D seismic survey. After that, three exploratory wells were drilled. Subsequently, in 2009, the Oil Exploration Company (OEC) conducted a three-dimensional seismic survey, based on which a final development plan was drawn up (**Petronas, 2017**). Determining the oil originally in place (OOIP) involves utilizing the Volumetric or Material Balance Method. The Volumetric Method considers various geological characteristics of the reservoir, including net-to-gross ratio, porosity, initial water saturations, and reservoir thickness. In contrast, the Material Balance Method is a dynamic methodology that uses production and pressure data to predict the OOIP (**Asad and Hamd-Allah, 2022; Al-Dujaili et al., 2023; Al Musawi and Al-Jawad, 2019)**. To develop the dynamic model, pressure-volume-temperature (PVT) characteristics, special core analysis (SCAL) outcomes, production data, and pressure readings are crucial data that must be collected. Once the model is initialized, it calculates the OOIP, verified by performing a simulation for a specific period that aligns with the recorded production data. This process ensures that the dynamic performance of the model is verified and its resemblance to the reservoir is ascertained (**Baker et al., 2019; Al-Joumaa and Al-Jawad, 2019; Alher et al., 2018**). Geologic maps and models rely on three-dimensional seismic data to characterize reservoir heterogeneity, vertical zonation, lateral compartmentalization, and the variables that affect directional fluid flow or anisotropy within the reservoir (**Mondol, 2010; Al-Rubaye and Hamd-Allah, 2019; Almahdawi et al., 2023; Ahmed and Al-Jawad, 2020**).

In the study area, there was an issue regarding the discrepancy in the bubble point of the Mishrif formation. This issue led to a thorough re-evaluation of the formation to identify the causes, which included faults and reefs. The seismic survey was re-evaluated with the subscription of log data, such as density, sonic, and vertical seismic profile logs, to investigate the issue. These were essential components of the comprehensive re-evaluation of the formation or reservoir. The aim was to detect the responsible party for compartmentalizing the reservoir problem and determine the correct probability through historical matching of the reservoir model. After constructing a static model based on two probabilities, fault and reef, the study addressed the effect of reefs and faults on the development plan of oil production for more than 20 years and their impact on reservoir performance based on pressure and saturation behavior.

2. GEOLOGICAL SETTINGS

The study area is in the southern province of Thi-Qar in Iraq, approximately 5 km northwest of Rifai City and 85 km north of Nasiriya (**Petronas, 2017**). The oil deposits in the field were discovered in 1984 by the seismic survey team of the National Oil Company. Three exploratory wells were drilled to confirm the main four reservoirs' oil reserves. The research region is located in an unstable area within the Mesopotamian basin of the Arabian plate (**Al-Ameri et al., 2009**) (refer to **Fig. 1**). The area is surrounded by multiple oil fields that extract hydrocarbons from NW-SE-trending anticline formations, which are aligned with the direction of the Zagros folded axis (**Jassim and Goff, 2006**). Tectonic and isostatic processes govern the deposition of the Mishrif reservoir in Iraq. It belongs to the Cenomanian-Turonian Supersequence of the uppermost component of the tectonic stratigraphic Megasequence that was deposited along a passive border (**Oil Exploration Company, 2013**). The area is within the Mesopotamian structural zones, divided into Tigris, Euphrates, and Zubair tectonic subzones (**Jassim and Goff, 2006; Sharland, 2001**).

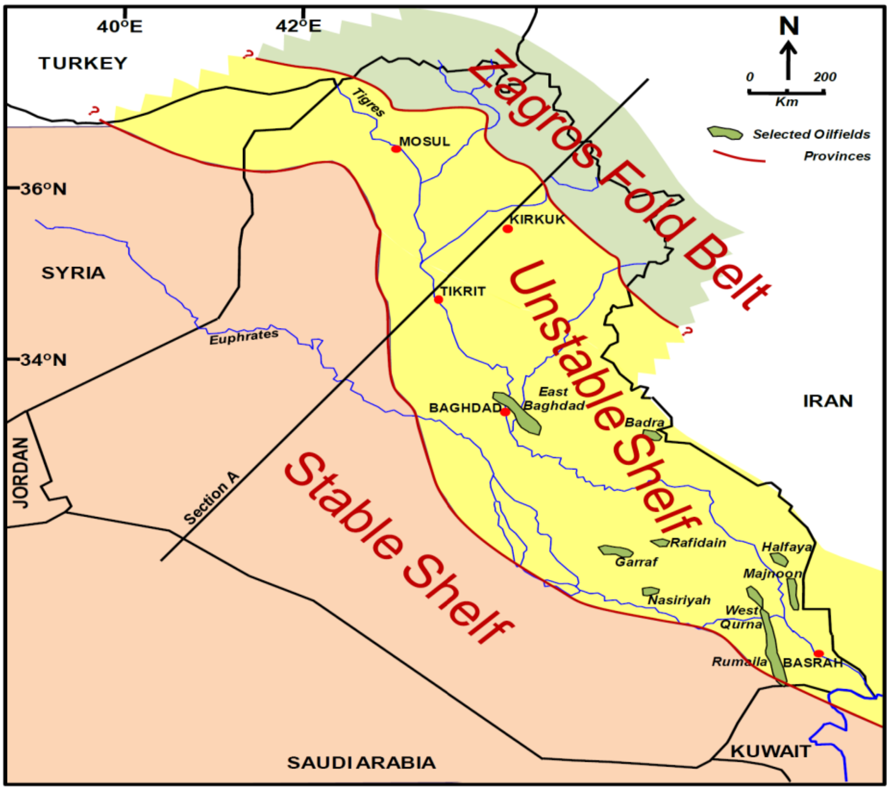

Figure 1. Tectonic provinces of Iraq (**Jassim and Goff, 2006**)

The stratigraphic profile of the Tigris subzone reveals a significant thickness of the Mishrif Formations, indicating high subsidence rates. During the Cenomanian and Early Turonian epochs, the deformation of the northeastern Tethyan border of the Arabian Plate resulted in the construction of distinct high and low structures in each subzone (**Buday and Jassim, 1987**). Negative residual gravity under some supergiant field structures indicated formations such as Rumaila and Zubair in southern Iraq from salt diapirism (**Khawaja and Thabit, 2021; Karim, 1989; Karim, 1993**). Several of these structures started to form during the Early Jurassic period (**Sadooni and Aqrawi, 2000**). The Mesopotamian basin requires Jurassic source rocks, Cretaceous and Tertiary reservoirs, and Paleozoic and Tertiary structural traps, the fundamental geological components necessary for hydrocarbon accumulations (**Alsharhan and Nairn, 1997**). **Fig. 2** overviews the basin-specific hydrocarbon system dynamics (generations, migrations, and accumulations).

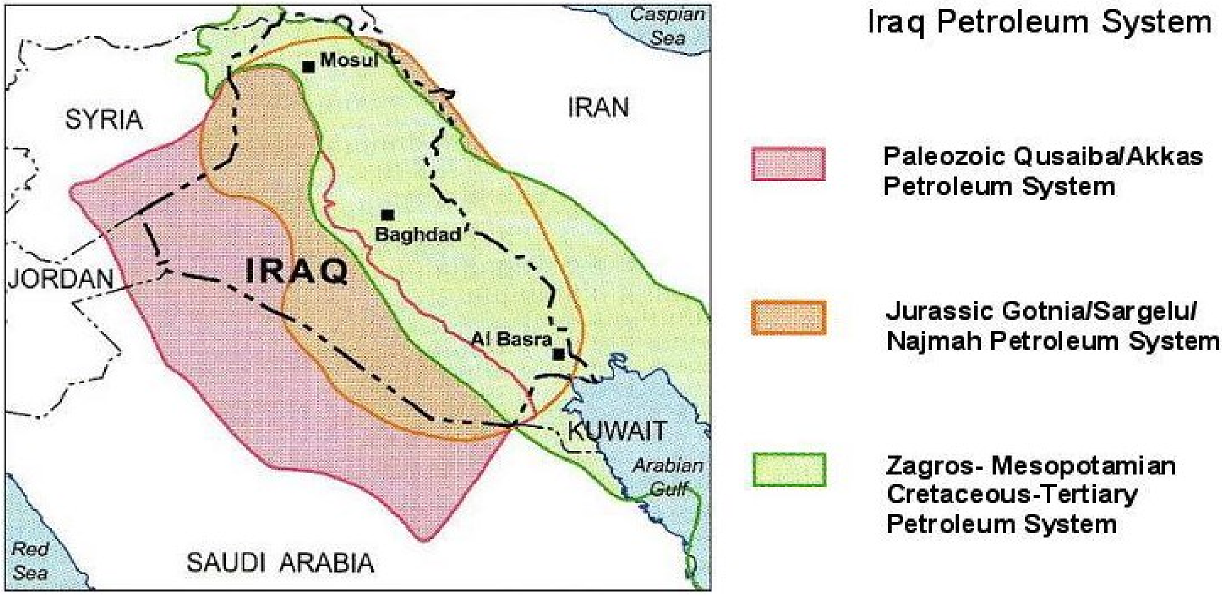

Figure 2. Petroleum system in Iraq and the surrounding area (**Ahlbrandt et al., 2000**)

3. MATERIALS AND METHODS

When developing seismic, static, and dynamic models using the Petrel platform for subsurface modeling and interpretation, it is crucial to prepare the data correctly. The data preparation process consists of three steps, customized to meet the specific requirements of the research area before oil production development can be planned. These steps are as follows :

1. Re-evaluating 3D seismic interpretation: The dataset includes a 3D seismic survey with subscriptions to well top, sonic, density, and VSP measurements to identify faults and reefs leading to differences in bubble point pressure. The seismic analysis revealed uneven amplitudes in the reflected events and sudden discontinuities, indicating the presence of a reef or a fault, as shown in **Fig. 3** . **Fig. 4** depicts the location of potential faults on the contour map.
2. Construction of the static model: The static model comprises two potential scenarios - reef and fault. There are no apparent differences in the distribution of petrophysical parameters and the estimation of oil reserves in both scenarios .

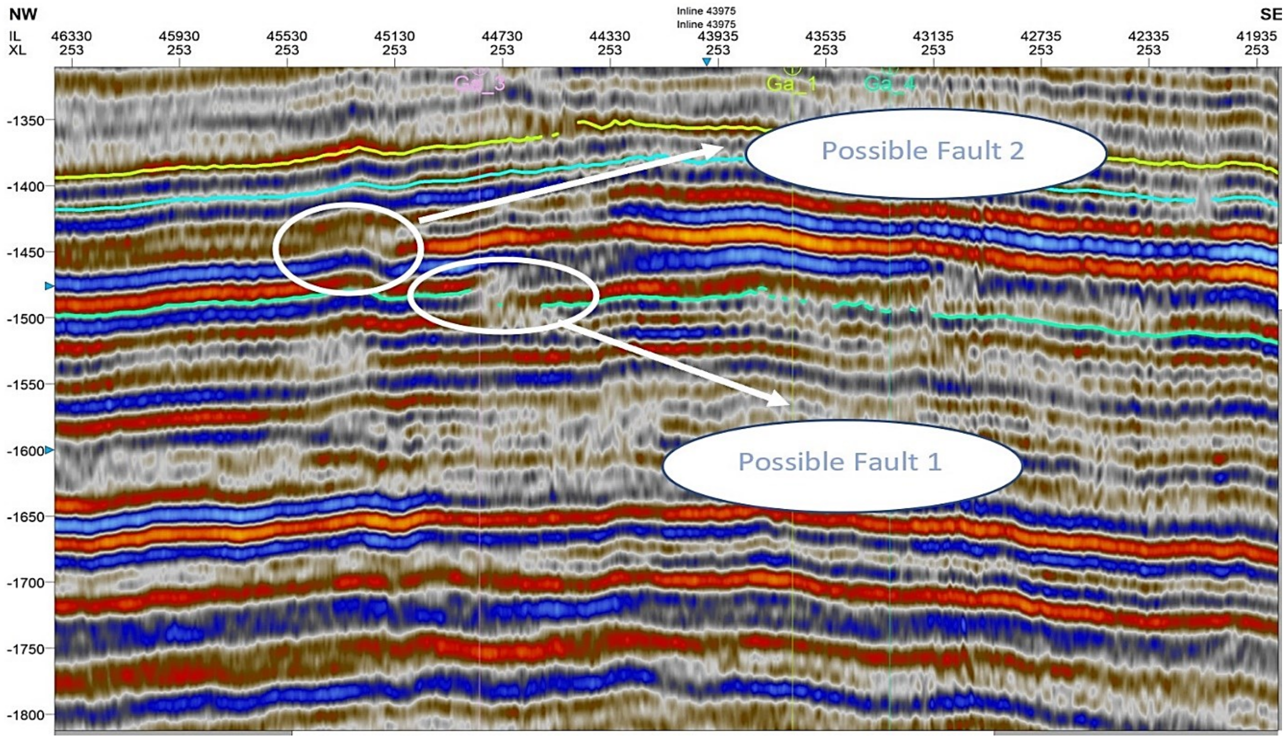

Figure 3. Location of possible faults on seismic inline section.

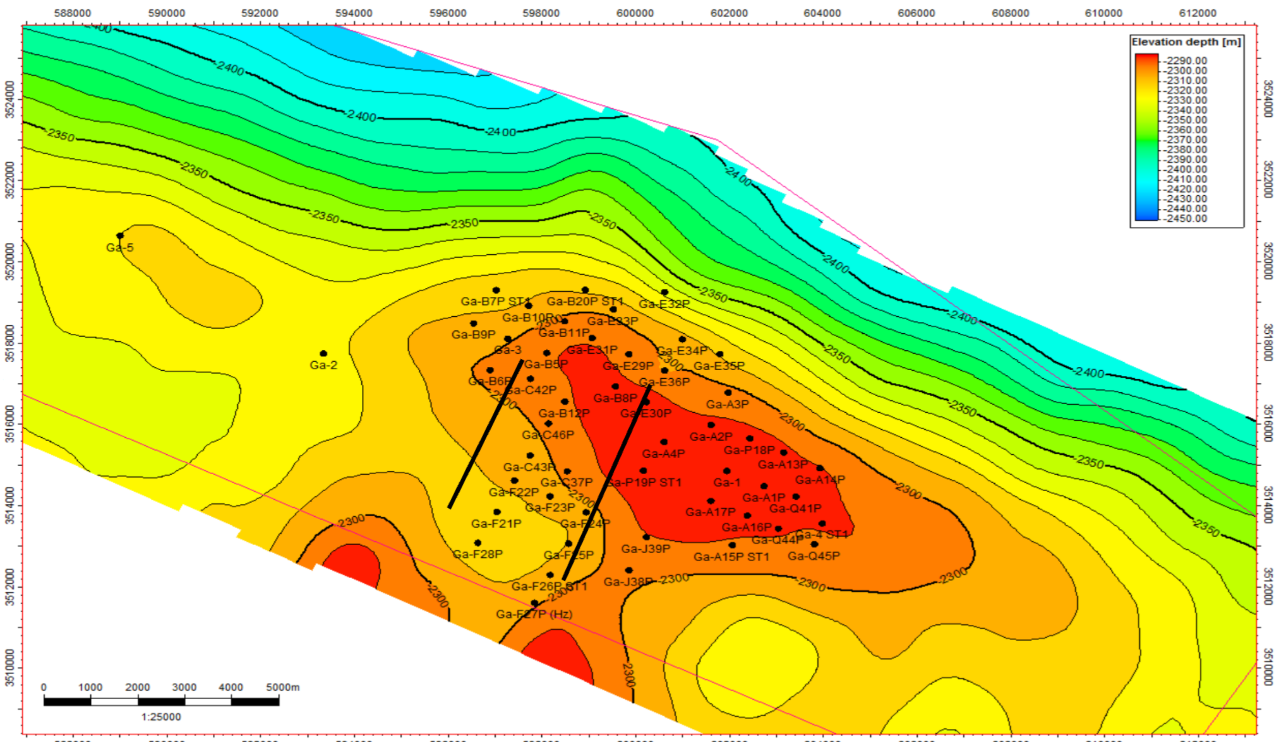

Figure 4. Contour map with possible fault location.

3. Construction of the dynamic model: The dynamic model is used to validate the feasibility. History matching is carried out by comparing actual and simulated gas production to determine the existence of faults and reefs. The adjustments were made for the Mishrif reservoir characteristics, and same regional classification for reef and fault cases. The fault region must be isolated as regions (1 & 2) for making a history matching of fault case with bubble point pressures (2335, 2135 psi) according to PVT of well pad (C, F), respectively. The remaining reservoir is set to bubble point pressure (2646 psi) according to the original PVT data obtained from the well (Ga-4) as region 3. For the reef case, a history match was made according to bubble point pressure (2646 psi) for the whole of the Mishrif reservoir (as one region). The results of the history-matching process indicated the existence of faults (green line) and ruled out the presence of reefs (red line) for selected wells, as seen in **Figs. 5 and 6**.

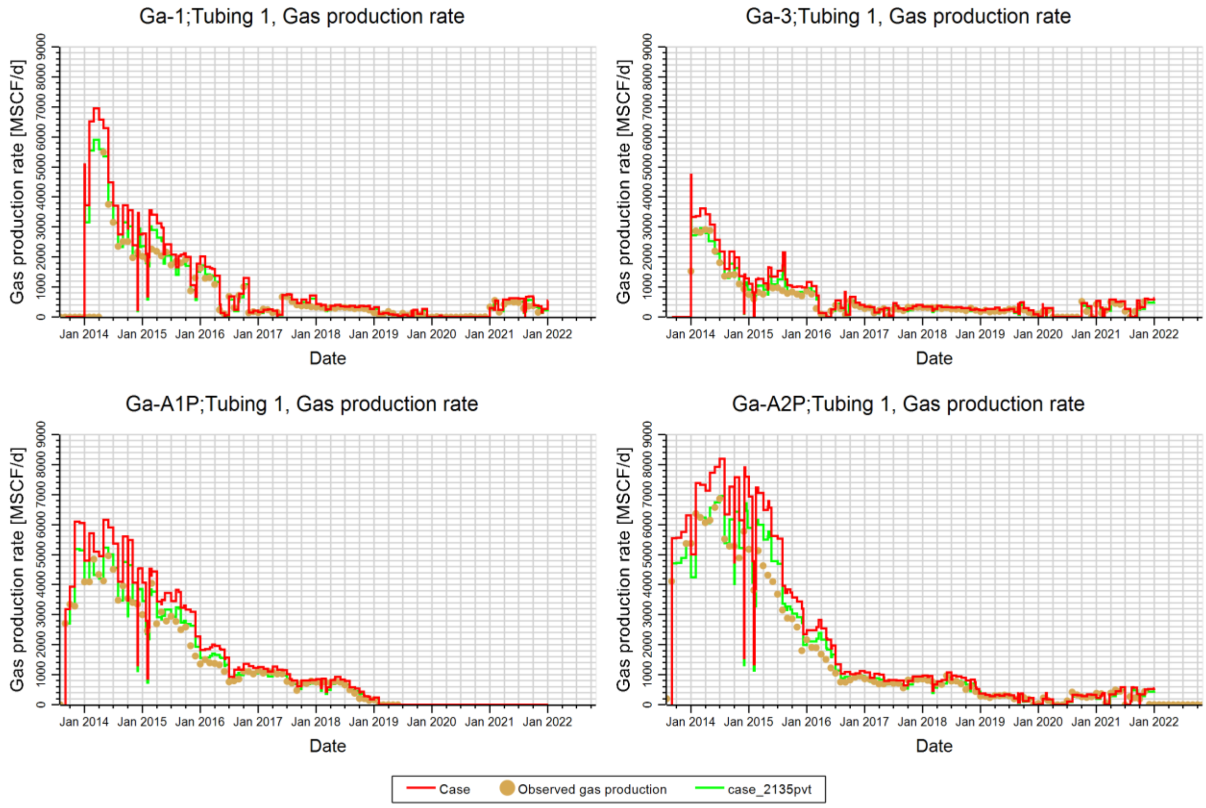

Figure 5. History matching of the gas production rate of wells selected- reef & fault cases.

The development plan plays a crucial role in managing future production and monitoring the decline of reservoir pressures. It serves as the foundation for reservoir development. Between 1st January 2022 and 1st January 2043, the development plan will be implemented in four cases. The first two cases, cases one and two, involve existing wells for the fault and reef probability. The remaining two cases, case three and case four, will include additional production wells to supplement the future production plan and better understand the pressure and saturation behavior of the fault and reef cases. Certain constraints were applied in all strategies to control oil production, maintain reservoir pressure, and reduce water production.

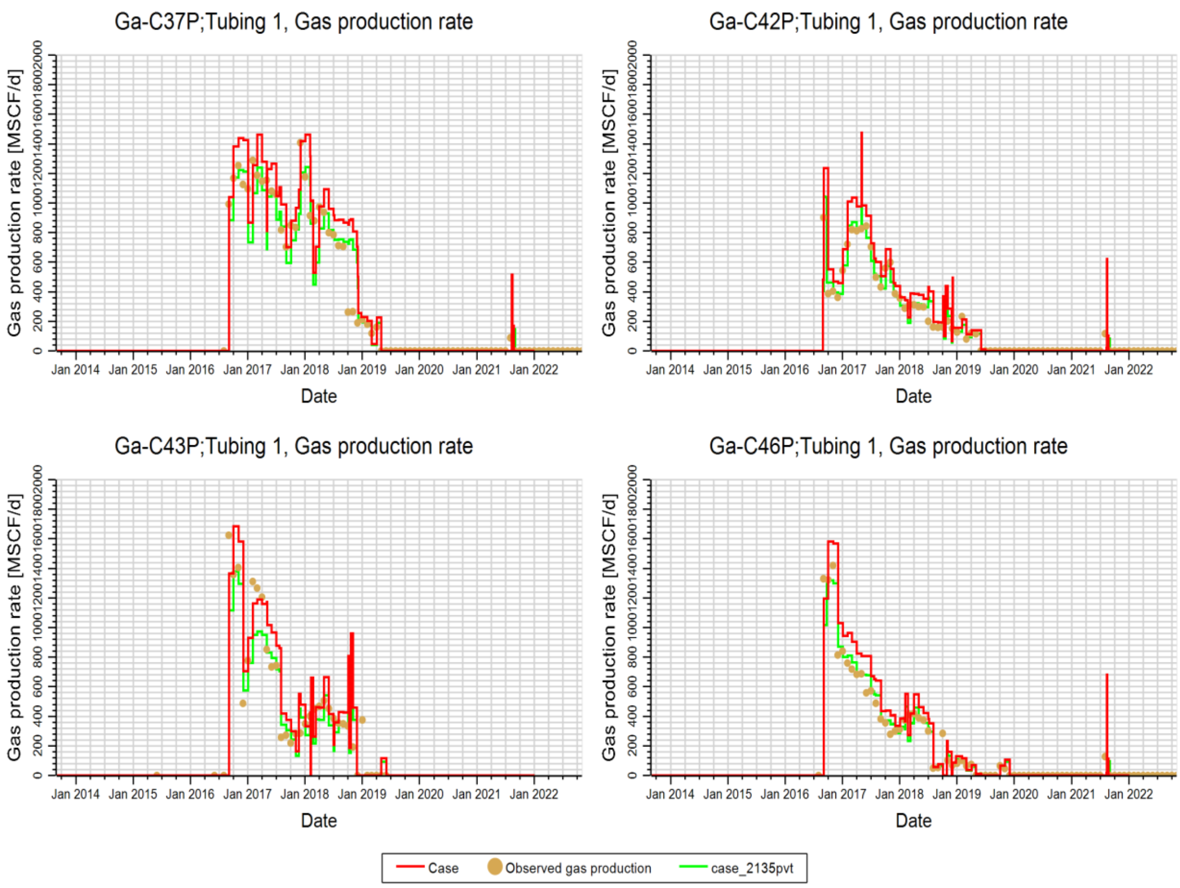

Figure 6. History matching of the gas production rate of wells selected- reef & fault cases.

These constraints included :

1. Setting a maximum oil production rate of 2,000 STB/D for all production wells.
2. Setting a maximum injector rate of 8,000 STB/D for 20 converted wells. The spacing between injection and production well 600 m with inverted nine spots of well pattern.
3. Ensuring that the bottom hole pressure for all wells was more significant than the reservoir bubble point pressure in reef and fault cases.
4. Setting the field water injection rate at 160,000 bbl/D.

4. RESULTS AND DISCUSSION

4.1. Development Strategy- 1

A strategy was developed based on the probability of the Mishrif reservoir's reef and 117 existing wells (97 produced, 20 injected). The strategy's results indicate that the field's highest production rate was 130 MSTB/D in mid-2024. The production rate was stable for around three years before gradually decreasing to 78 MSTB/D by the end of the period. The field's cumulative oil volume was reported at 1.01 MMMSTB, as shown in **Fig. 7.**

Fig. 8A shows the pressure behavior at the beginning of the forecast period (2022). The study observed a pressure decrease in the crest region due to the depletion from production operations (2013-2022) with modest support for injection wells. In contrast, the flank region remained at its pressure due to the decrease in productive wells on the reservoir's western side and the thickness of the productive layer on the eastern side. The pressure behavior at the end of the development plan (2043) is shown in **Fig. 8B**. It can be observed that the pressure drops hierarchically from the flank to the crest. Although most injection wells are located in the crest region, they still provide modest support to the pressure.

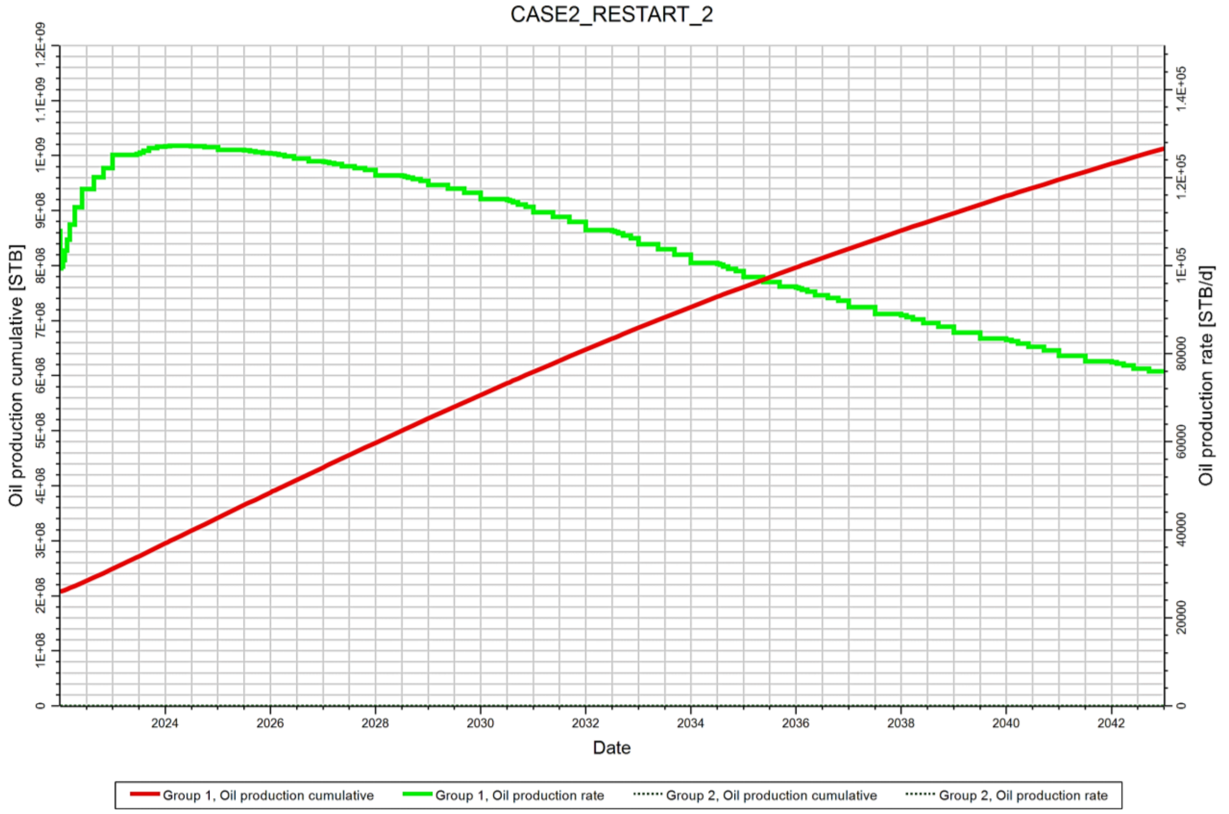

Figure 7. The results of production rate and cumulative for case one.

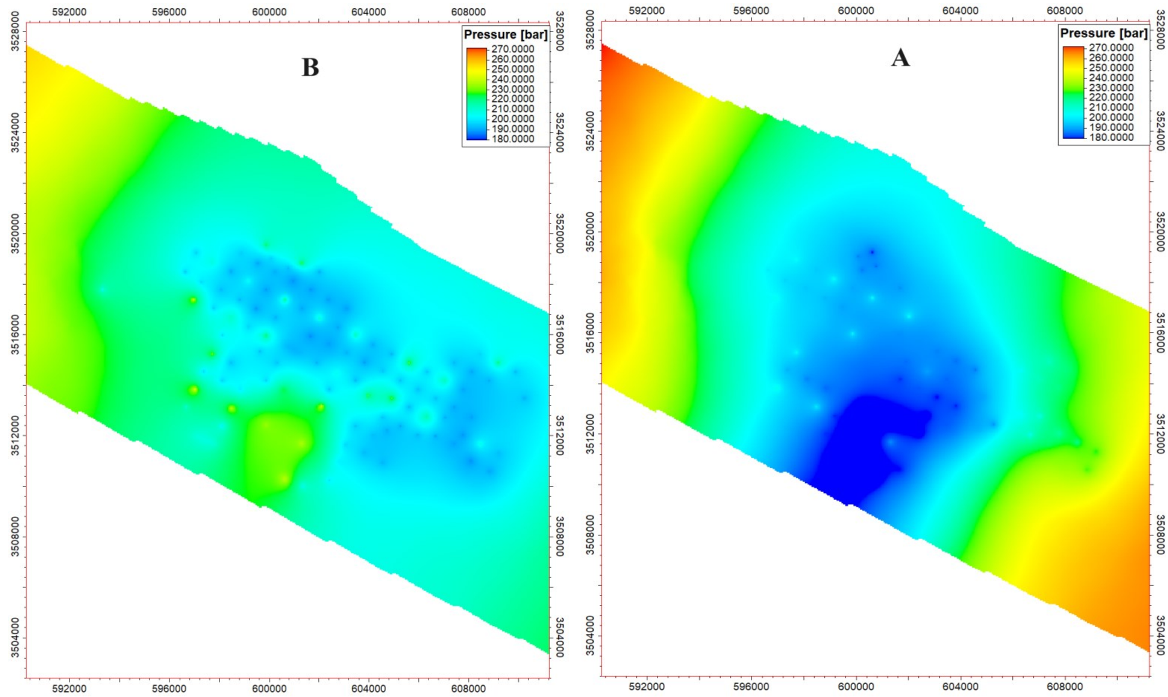

Figure 8. The map of pressure behavior for the start and end strategy of case one.

4.2. Development Strategy- 2

A strategy was developed based on the probability of faults in the Mishrif reservoir and the input data from the wells in case one. The strategy results showed that the field's highest production rate was 135 MSTB/D in 2024. The production rate remained constant for about 2.8 years before gradually declining to 78 MSTB/D by the end of the period. The field's cumulative oil volume was estimated to be 1.03 MMMSTB, as shown in **Fig. 9**.

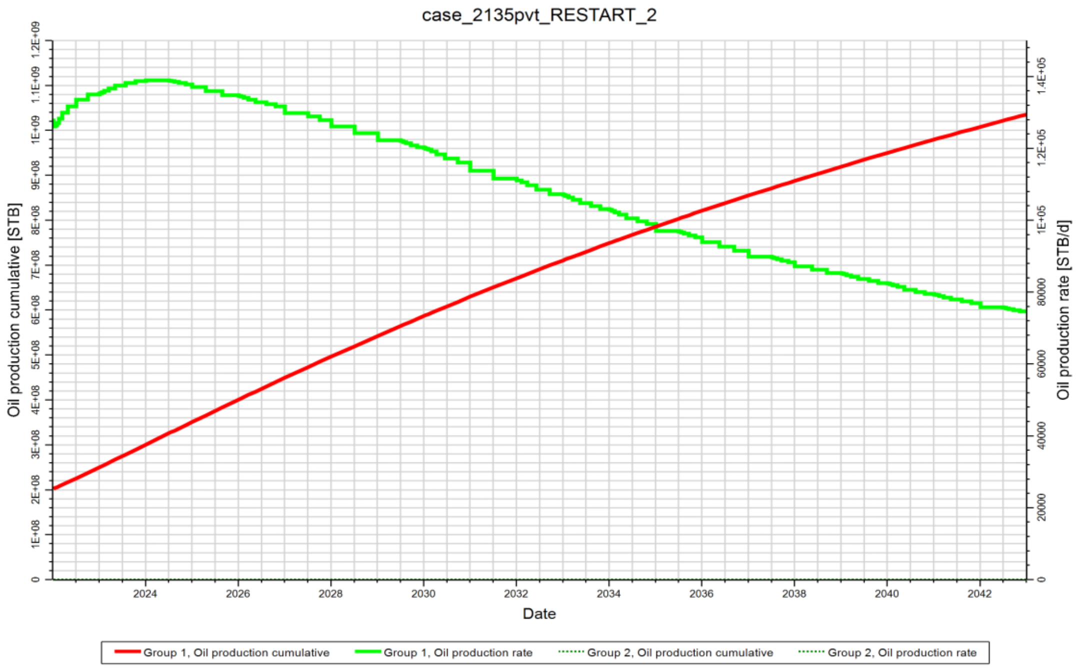

Figure 9. The results of production rate and cumulative for case two.

Fig. 10 represents the pressure behavior of the development strategy - 2, which considered the presence of faults in the Mishrif reservoir and its impact on production performance.

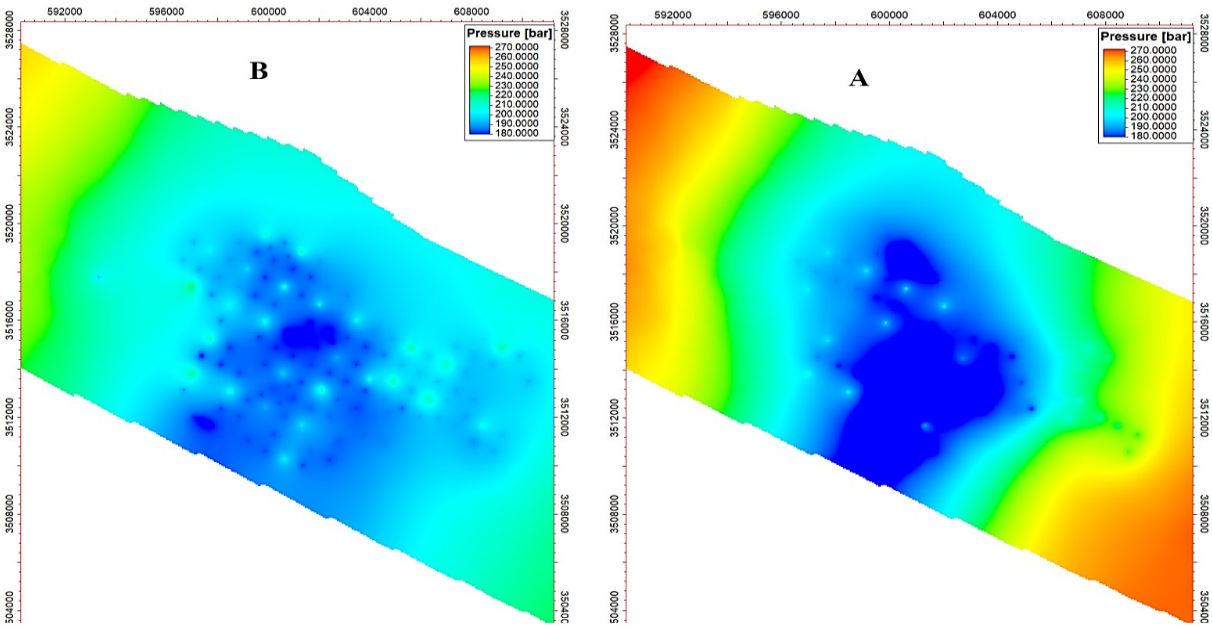

Figure 10. The map of pressure behavior for the start and end strategy of case two.

A decrease in reservoir pressure was observed in the crest area, especially at the end of the period, as seen in **Fig. 10-B**, more significant than what is found in development strategy - 1. The reason for this is due to the presence of the fault, which has become a compartment that prevents reservoir compensation from neighboring regions.

4.3. Development Strategy- 3

This approach's success relies on a reef's potential to accommodate 20 wells that produce oil. These wells are named test1, test2, test3, ... test20 and are distributed based on the permeability and oil saturation of the Mishrif reservoir, As shown in **Fig. 11**. The highest production rate in the field reached 130 MSTB/D in mid-2029. This rate was maintained for around 6.8 years, with minor fluctuations because of closing and opening some wells, before gradually declining to 78 MSTB/D by the end of the period. **Fig. 12** illustrates that the cumulative oil volume for the field was 1.05 MMMSTB. Some of the limitations resulting from this strategy are the closure of some wells due to high production and the drop in reservoir pressure to the bubble point. However, other wells with high reservoir pressure compensated them, resulting in slight fluctuations along the plateau line.
The pressure behavior in this strategy is similar to that of development strategy 1, with one exception. Towards the end of the period, as seen in **Fig. 13 B**, the eastern region of the reservoir experienced a decline in pressure due to the proposed wells. These wells cause depletion in the productive layer of the reservoir, resulting in a decrease in its pressure.

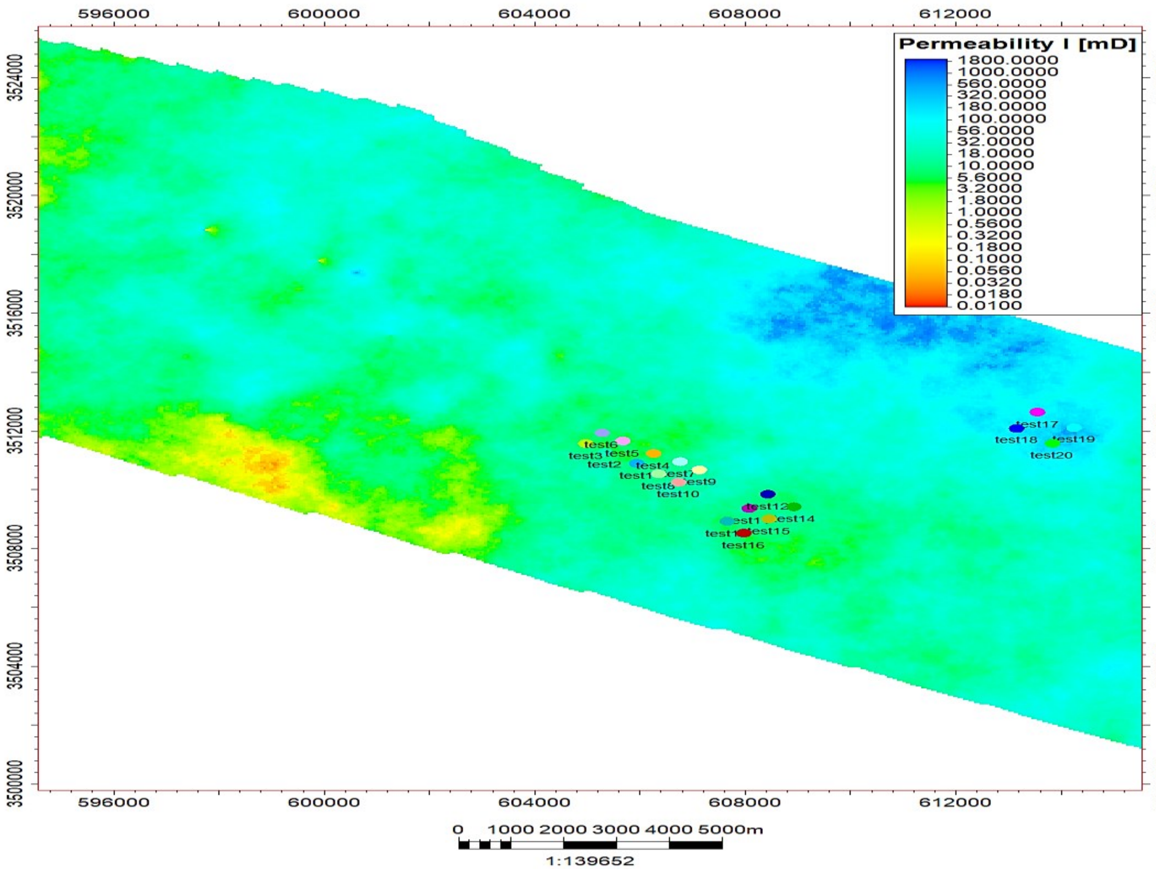

Figure 11. Location of additional wells on permeability map of Mishrif reservoir.

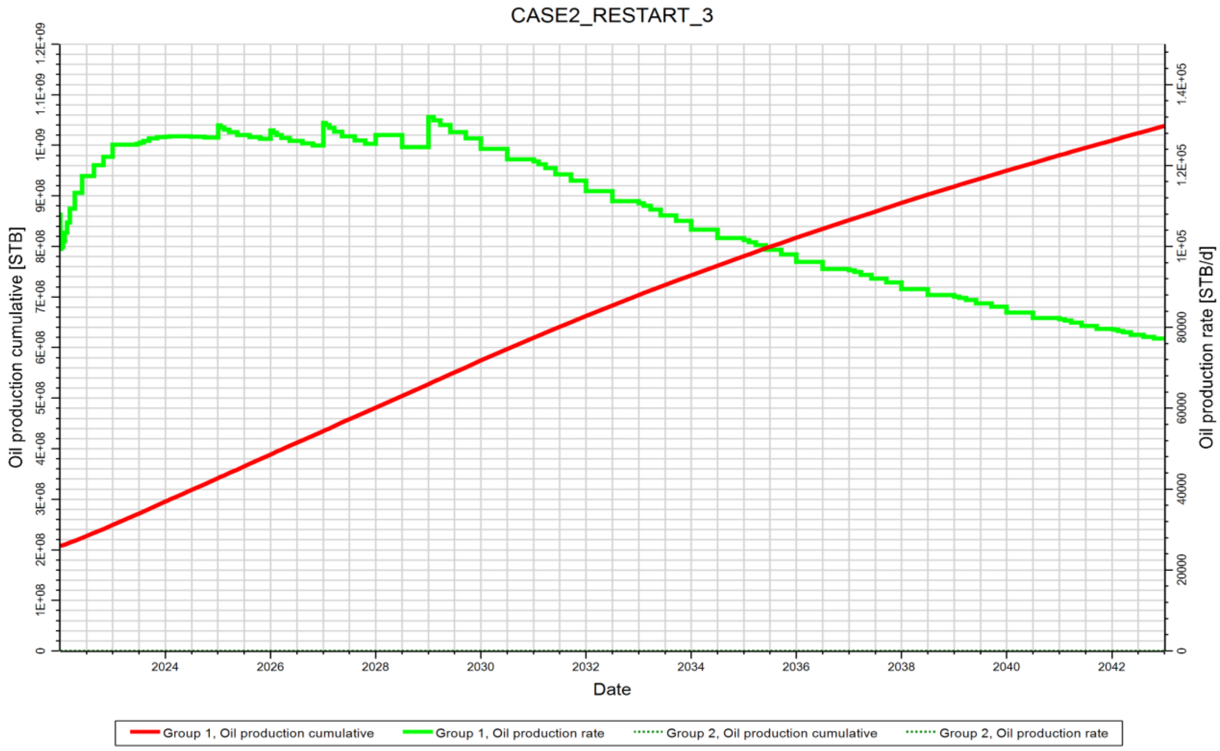

Figure 12. The results of production rate and cumulative for case three.

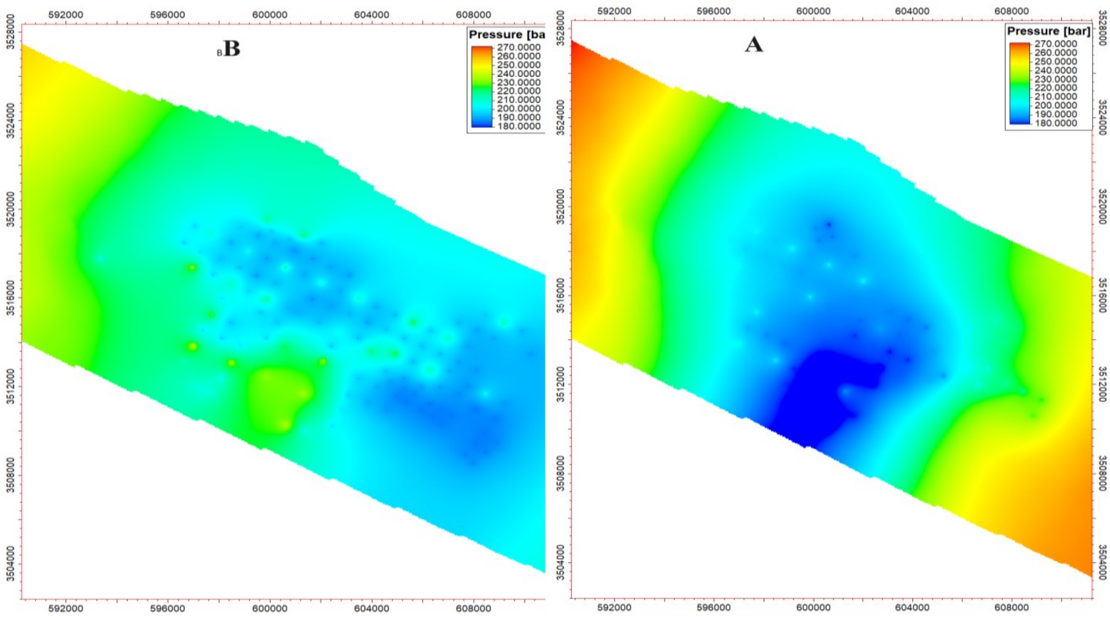

Figure 13. The map of pressure behavior for the start and end strategy of case three.

4.4. Development Strategy- 4

This strategy is based on the fault probability and uses the same inputs as case three. The results showed that the highest production rate of 140 MSTB/D was achieved at the beginning of 2025. The production rate remained stable with minor fluctuations for almost seven years before gradually declining to 76 MSTB/D by the end of the period. The cumulative oil volume produced in the field was estimated to be 1.09 MMMSTB, as shown in **Fig. 14**.

The pressure behavior observed in this strategy is similar to that of development strategy 2. Towards the end of the period, as depicted in **Fig. 15-B**, the eastern region of the reservoir experienced a decline in pressure due to the proposed wells. These wells led to depletion in the productive layer of the reservoir, resulting in a decrease in its pressure. Despite most injection wells being located in the crest region and only a few in the flank, they still provided modest support to the pressure. **Table 1** illustrates comparison between four scenarios according to production plateau rate, and cumulative oil production.

Table 1. A comparison between four scenarios.

Development Strategy	Production plateau rate MSTB/D	cumulative oil production MMMSTB	Plateau age year
Development Strategy 1	130	1.01	3
Development Strategy 2	135	1.03	2.8
Development Strategy 3	130	1.05	6.8
Development Strategy 4	140	1.09	7

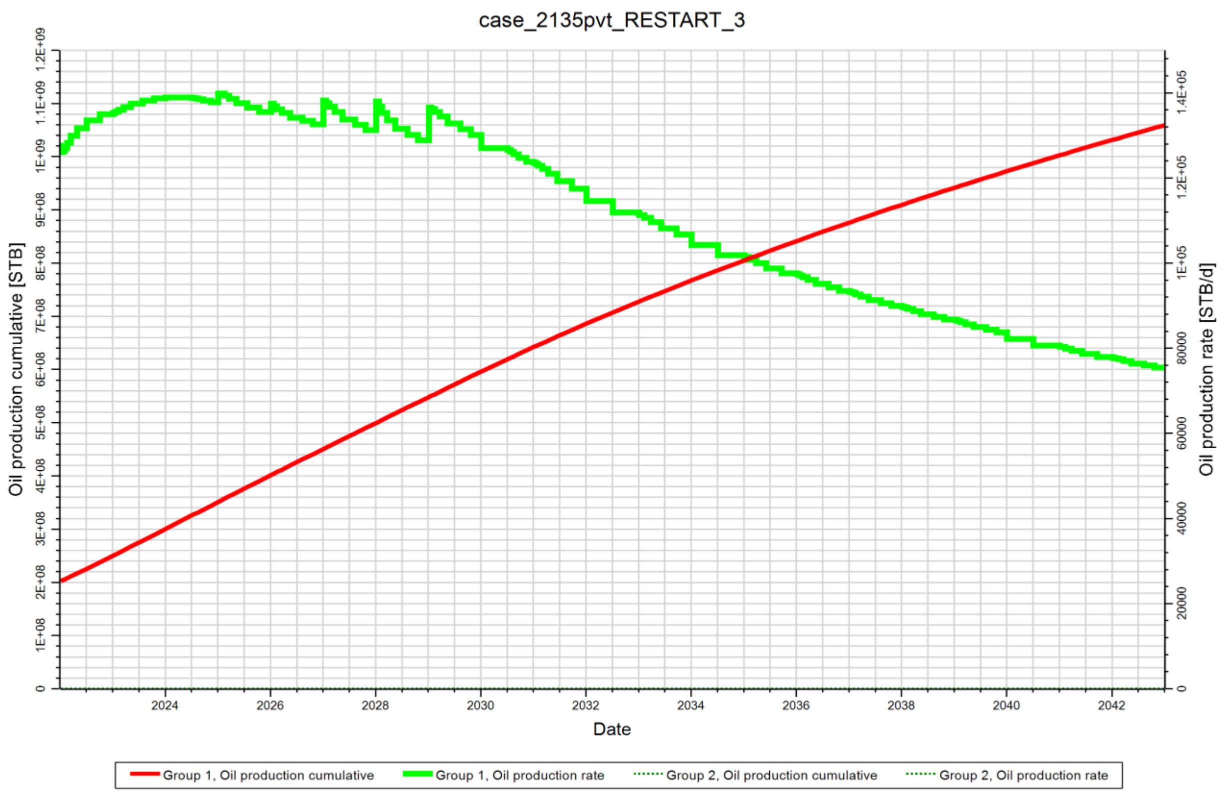

Figure 14. The results of the production rate and cumulative for case four.

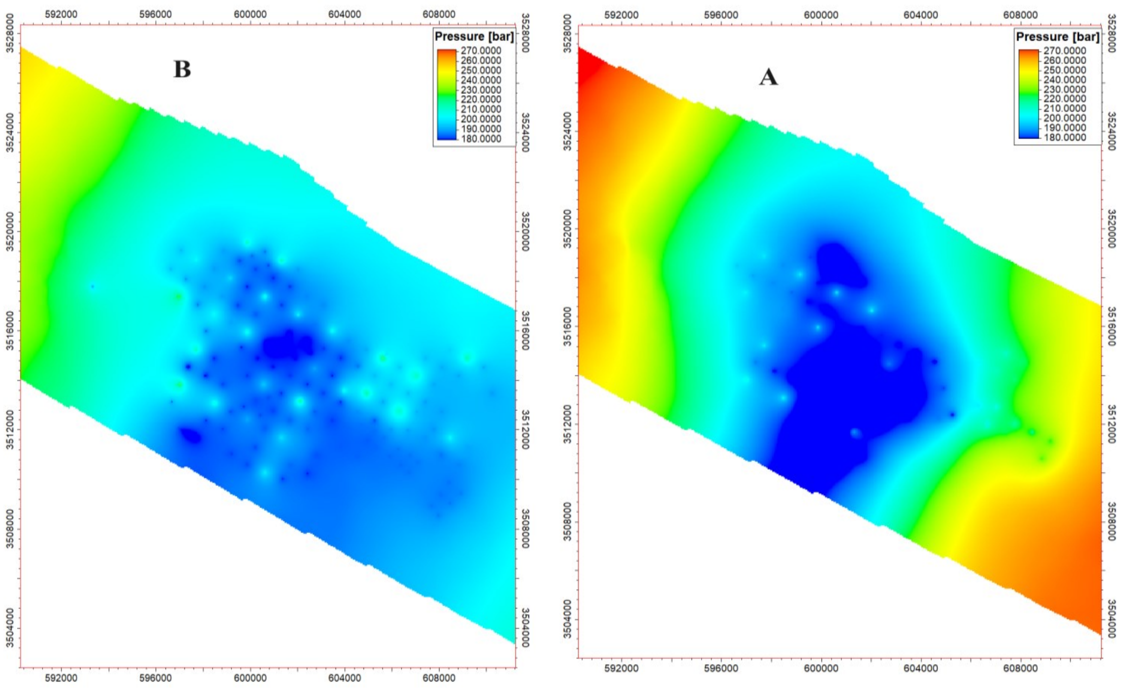

Figure 15. The map of pressure behavior for the start and end strategy of case four.

5. CONCLUSIONS

The Mishrif reservoir is located in an unstable region of the Mesopotamian basin of the Arabian plate. It is bounded by several fields that produce hydrocarbons from massive NW-SE-trending anticline formations, which are typically aligned with the direction of the Zagros folded axis. The producing reservoir unit has a discrepancy in its bubble point pressure, which raises concerns about the faults or reefs that caused it and their future impact on the development plan. The study aimed to determine the effects of faults and reefs on production performance and reservoir pressure behavior under a future development strategy.

The process involves three steps before implementing the oil production development strategy, including seismic, static, and dynamic models. The seismic analysis detected many irregular amplitudes of reflected events and abrupt discontinuities, indicating either a reef or a fault. Based on the results of history matching in dynamic simulation and seismic and static models, faults were detected, while the presence of reefs was ruled out. The development plan has been implemented for the next 20 years in four cases: two with the current wells for the fault and reef probability and two with the same input data and additional production wells. The study found that case four had the most favourable results among all the cases. This case showed a production plateau that lasted for seven years at a rate of 140 MSTB/D with slight fluctuations. The cumulative oil volume of the field was reported to be 1.09 MMMSTB. The behavior of the reservoir pressure shows a hierarchical drop from the flank down to the crest in all cases of the development strategy, with some differences, including a sharp decline in the area of the proposed wells and the presence of the fault, which has become a compartment that prevents reservoir compensation from the adjacent regions, in addition to the different bubble pressures in the case of the fault.

NOMENCLATURE

Symbol	Description	Symbol	Description
OOIP	Oil originally in place, STB	3D	Three dimensions, m^3
STB	Stoke tank barrel	2D	Two dimensions, m^2

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Credit Authorship Contribution Statement

Alaa S. Al-Rikaby: Writing – original draft, Validation, Software, Methodology.
Mohammed S. Al-Jawad: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تأثير الفالق والحيد المرجاني في سلوك ضغط المكمن ومخطط الإنتاج: دراسة حالة– حقل نفط جنوب العراق

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الخلاصة

تقع منطقة الدراسة التي تتكون من الكربونات في حوض وادي الرافدين غير المستقر على الصفيحة العربية مما يجعلها مجالا عالي لعدم التجانس. لديها تناقض في ضغط نقطة الفقاعة، مما يثير المخاوف بشأن العيوب أو الشعاب المرجانية التي تسببت فيها. الدراسة هدفت لأيجاد تأثير الفوالق والحيود المرجانية على أدائية الإنتاج وسلوك الضغط المكمني في ظل استراتيجية التطوير المستقبلية. تتضمن الدراسة ثلاث خطوات قبل تنفيذ استراتيجية تطوير إنتاج النفط، بما في ذلك النماذج الزلزالية والثابتة والديناميكية. كشف التحليل الزلزالي عن العديد من السعات غير المنتظمة للأحداث المنعكسة والانقطاعات المفاجئة، مما يشير إما إلى وجود حيد مرجاني أو فالق. واستنادا إلى نتائج مطابقة التاريخ، تم الكشف عن الفوالق، في حين تم استبعاد وجود الحيد المرجاني. تم تنفيذ خطة التطوير للسنوات العشرين القادمة في أربع حالات، وكانت الحالة الرابعة هي الأفضل من بين جميع الحالات، حيث أظهرت ثبات الإنتاج لمدة سبع سنوات بمعدل 140 MSTB/D بحجم تراكمي يساوي 1.09 MMMSTB. ويظهر سلوك ضغط المكمن انخفاضا هرميا في جميع الحالات، مع بعض الاختلافات، منها انخفاض حاد في مساحة الآبار المقترحة والفالق الذي أصبح مقصورة تمنع تعويض المكمن من المناطق المجاورة.

الكلمات المفتاحية: مكمن المشرف، استراتيجية التطوير، الفالق، الحيد المرجاني، سلوك الضغط.