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Sequence stratigraphy and the Yamama Formation platform in Southern Iraq

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Abstract

The Yamama Formation consists of two types of sediments (granular units) consisting of Oolitic and Peloidal grainstone in addition to benthic Foraminifera (reservoir units), which grow towards the center basin during Highstand conditions within the environment confined between (Inner-Mid Ramp), and that they represent a shallowing upward cycle.

Granular sediments formed on top of a base consisting of mud-supported limestone (impermeable rocks) to create the second type of sediments that formed during transgressive conditions, which extend over most of the ramp platform and increase the mud support towards the outer ramp. Yamama Formation consists of multiple reservoir units separated by impermeable rock units. Reservoir units with high hydrocarbon potential are considered because petroleum systems are available. In southern Iraq, they are considered an exploratory target within the deposits of the early Cretaceous period. The study area contains (SS-3, SS-2, SS-1, and LL-1) wells. Yamama Formation is divided into four sub-cycles (YA, YB, YC, and YD). The structural maps represent the stratigraphic units of the Yamama Formation by interpreting the data of the seismic cube, which indicated that (the SS and LL) fields represent a structural axial, whose axis extends north-south. SS field consists of two domes and three wells in the southern dome penetrated Yamama Formation, but the northern dome is the most closed, with dimensions (14 x 10) km with closure of about (60) meters, no borehole has been drilled in it, which makes it an exploration target. Yamama Formation in the LL field penetrated by the LL-1 well only and shows the existence of a structural closure with dimensions (4 x 2.5) km and a closure of (30) m. The seismic stratigraphic interpretations explained the development of the Yamama Formation platform, which contributed to the formation of three stratigraphic traps.

Keywords: Sequence stratigraphy, Seismic Interpretation, Carbonate ramp, Yamama and Sulaiy formation, Geological model, Early Cretaceous, South Iraq.

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طباقية المتتابعات ومنصة الكلسية لتكوين اليمامة في جنوب العراق

الخلاصة:

تكوين اليمامة في جنوب العراق يتالف من نوعين رئيسيين من الرواسب (الوحدات الحبيبية): الحجر الجيري السرئي والبلويدي الحبيبي، بالإضافة إلى الفورامينيفيرا القاعية (وحدات الخزان)، والتي تتطور نحو مركز الحوض خلال ظروف سطح البحر العالي (Highstand conditions) ضمن بيئة محصورة بين (المنحدر الداخلي-المنحدر المتوسط)، وتمثل دورة تضحلية نحو الأعلى.

تتراكم الرواسب الحبيبية على قاعدة مكونة من الحجر الجيري المدعوم بالطين (صخور غير نافذة)، مما يخلق النوع الثاني من الرواسب التي تتشكل خلال ظروف الاغمار البحري (Transgressive conditions)، وتنتشر على معظم منصة المنحدر، مع زيادة في الدعم الطيني باتجاه المنحدر الخارجي. يتكون تكوين اليمامة من وحدات خزان متعددة مفصولة بوحدات صخرية غير نافذة. وتعتبر وحدات الخزان هذه ذات إمكانات هيدروكربونية عالية وتعد أهدافًا استكشافية لأنها تحتوي على العناصر اللازمة لنظام البترول. يعتبر تكوين اليمامة، الذي ترسب خلال العصر الطباشيري المبكر، هدفًا استكشافيًا هامًا في جنوب العراق.

تتضمن منطقة الدراسة الآبار(SS-3 و SS-2 و SS-1 وLL-1)، وتم تقسيم تكوين اليمامة إلى أربع وحدات طباقية (YA, YB, YC, and YD) ، تم إنشاء خرائط تركيبية للوحدات الطبقية لتكوين اليمامة من خلال تفسير بيانات المكعب الزلزالي.

تشير هذه الخرائط إلى أن حقلي (SS و LL) تقع على طول محور تركيبي يمتد شمال-جنوب. حقلي SS يتالف من قبتين، تم حفر الآبار في القبة الجنوبية) الآبار(SS-1 ، SS-2، و SS-3)، بينما تُعد القبة الشمالية الأكثر إغلاقًا، حيث تبلغ أبعادها حوالي (14 × 10 كم) مع إنغلاق تركيبي بحوالي 60 مترًا، ولم يتم حفر آبار فيها بعد، مما يجعلها هدفًا استكشافيًا مهمًا.

الحقلLL ، فقد تم اختراق تكوين اليمامة بواسطة البئرLL-1، اكتشف وجود إغلاق تركيبي بأبعاد (4 × 2.5 كم) مع إنغلاق تركيبي قدره 30 مترًا شمال الحقل، توضح بيانات التفاسير الزلزالية الطبقية تطور منصة تكوين اليمامة، التي ساهمت في تشكيل ثلاث مصائد طبقية ضمن منطقة الدراسة.

1. Introduction

The study area is in the southern part of Iraq within the administrative borders of Basrah and Dhi Qar governorates, and the seismic survey cube occupies an area of (1650) square kilometers, Figure (1). Three wells were drilled penetrating the Yamama Formation in the SS field, while one well (LL-1) penetrated the Gotnia Formation at a depth of (4029 meters) in the LL field.

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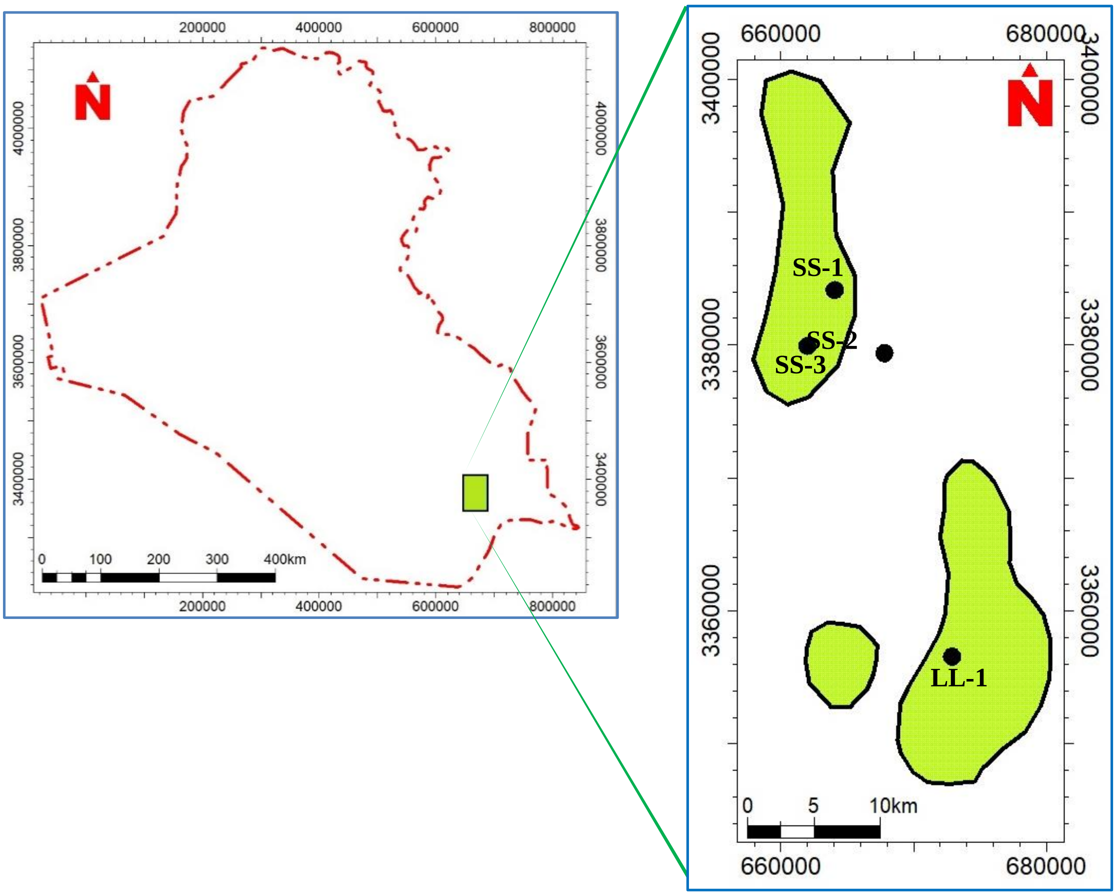

Fig. (1): The study area is located southeast of Iraq.

1.1 Objectives of the study

The study aims to update the structural form of (SS and LL) fields based on the available data about the study area. Analyzing the sequence stratigraphy of the late Tithonian-Late Valanginian sedimentary cycle, diagnosing the lateral facies changes of the Yamama Formation in the study wells and the distribution of (sedimentary environments and effective porosity) according to the three-dimensional geological model. Divided the Yamama Formation into (reservoir and barrier units), and preparing structural maps.

1.2 Material and methods

Petrographic and microfacies study, the petrographic study was based on many thin sections of cores and cuttings. By using Corel Draw X9 and Schlumberger Petrel 2018 programs, the site map and cross-sections of the studied wells were drawn. The study area relied on the seismic cube interpretation of the Samawah-Diwan survey program. The interpretation of seismic reflectors of the early Cretaceous period, and the interpretation of seismic sections were used to explain stratigraphic and structural frameworks.

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The quality of the seismic data ranged between (medium -good), the predominance of stratigraphic phenomena of the confined period is also noted (1700-2000) milliseconds in the extended refractors of the Upper Yamama – the Lower Sulaiy formations. The quality of reflectors improves on the northern side due to the less influence of fault systems. Seismic features techniques were applied to the seismic cube and showed an improvement in the quality and continuity of the reflectors, such as (Remove bias, Frequency Filter, Structural smoothing, Second derivative, and Trace AGC (Automatic Gain Control)).

2. Sequence Stratigraphy

Sequence stratigraphy studies research how sediments are deposited, which depends on relative sea-level changes and subsidence, emphasize the importance of predicting significant facies distribution (stratigraphic traps) and looking to identify lateral relationships between sedimentary units of the Yamama Formation.

2.1 Sequence Stratigraphy of Yamama Formation

The Yamama Formation is located within a succession of the Early Cretaceous period (Late Tithonian- Late Valanginian), which consists of (Sulaiy and Yamama) formations, overlying the sediments of the Late Jurassic period. The first to study the Yamama Formation and describe its facies change and environments [1] was discovered from an outcrop in Saudi Arabia in the Al-Yamama area, in Iraq the formation was studied by [2] and called the name Yamama / Sulaiy locally Under the Ratawi Shale Formation in the (Ratawi-1) well. The erosional surface separated between Yamama and Ratawi) formations, [3].

Ratawi Formation consists of shale, silt, and marly limestone and is characterized by widespread cap rock overlying the Yamama Formation [4]. The Managish Formation (Yamama) in Kuwait is characterized by clean limestone [5], these sediments extend into Iran and form the (Fahliyan Formation) according to [6].

During this period, highstand conditions contributed to the deposition of shallow-water carbonates (Yamama Formation) on the ramp type, covering the eastern part of the Arabian plate [7]. The transgressive conditions contributed to the deposit of open marine sediments, consisting of shale and mud-supported argillaceous carbonate with an abundance of planktonic fossils, which formed the Sulaiy (Makhul) Formation according to [8], covering most of the Arabian plate.

The Yamama Formation in southern Iraq represents an extension of the depositional history

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of the Sulaiy Formation and the reflection of a relative decrease in mud deposition compared to the Sulaiy Formation due to changes in relative sea-level conditions. The Yamama Formation marks the beginning of restricted marine conditions. During the deposition of the Yamama Formation, the Arabian Plate was characterized by a passive margin, which led to the deposition of both the Yamama and Managish Formations in Iraq and Kuwait (respectively) during the Late Berriasian age, according to [5].

At the beginning of this phase, limestone production increases due to shallow-water conditions creating an extensive platform with high-energy sea currents. This phase culminates with the emergence of the erosional surface over the Yamama Formation sediments across much of the Arabian Plate during the Late Valanginian age, this event is associated with the opening of the South Atlantic [5] and [9].

2.2 Sedimentary history

Studying the formation of Yamama through a stacking pattern and considering the factors (tectonic and relative sea-level changes) that control the origin and development of the sedimentary basin of the platform of Yamama formation, which was deposited within the ramp shelf, which is characterized by the presence of Oolitic limestone alternating with layers of marly limestone [10]. The sedimentation processes are characterized by the nature of a cyclic sedimentation pattern, consisting of two types of sediment, granular sediments (reservoir) that grow towards the deep basin center during highstand conditions within the sedimentary environment confined between (Inner- Mid Ramp), it was exposed for short periods of subaerially erosion (Plate 1.G) as a result of the shallowing upward cycle, at top of the platform and the shallowest of the (Inner Ramp) environment. Shallow water layers are deposited on a base consisting of micrite represented by the second type of sediment formed during transgressive conditions to extend over most of the Yamama platform, with increased mud supported towards the outer ramp zone. As a result, the Yamama Formation is composed of multiple reservoir units separated by impermeable rock units. These form four sub-cyclic sedimentary sequences, each representing a shallowing-upward pattern. The overall sedimentary cycles reflect a regressive phase in the depositional history. The Yamama Formation is defined as an important hydrocarbon reservoir in southern Iraq and is considered an exploratory target in the early Cretaceous deposits.

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2.3 Study well

The study area includes four wells (SS-1, SS-2, SS-3, and LL-1) that penetrate the Yamama Formation, which is recognized as the deepest Cretaceous reservoir. The Yamama Formation has been subdivided into four distinct sedimentary sub-cycles: YA, YB, YC, and YD, which represent (reservoirs and non-reservoir) units in Figure (2). The sedimentary environments within these sub-cycles were determined based on the thin sections from the study wells, alongside data and findings from previous studies.

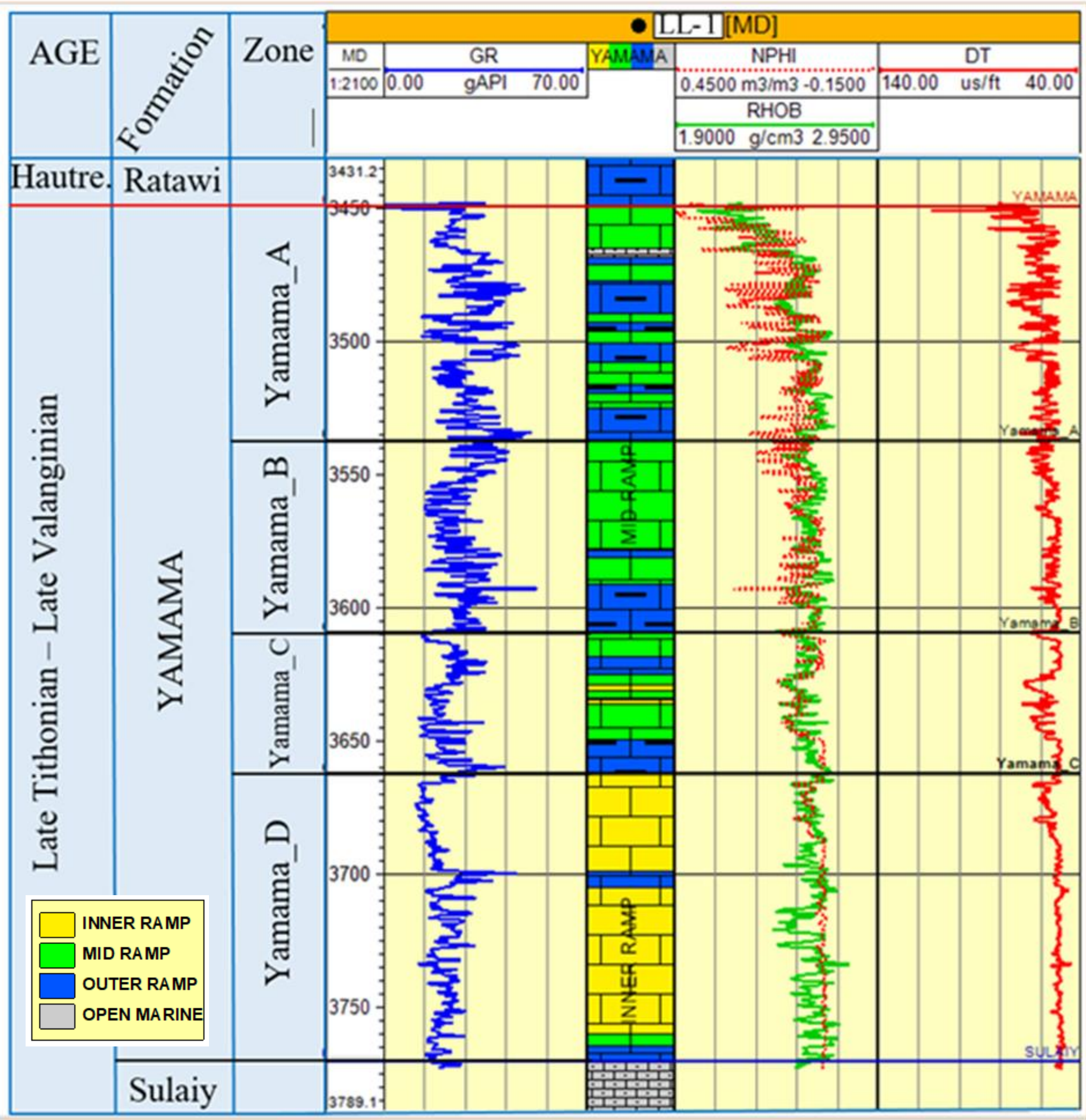

Fig. (2): Late Tithonian- Late Valanginian sedimentary cycle and sub- divisions of sedimentary environments of Yamama Formation in the well (LL-1).

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3. Seismic interpretations

The study area was subjected to three-dimensional (3D) seismic surveys for the SS and LL fields, which are notable for their development potential and high hydrocarbon concentrations. Integrating the 3D seismic surveys and well data is essential in refining the subsurface structural and geological model. This detailed seismic data facilitated more accurate interpretations of subsurface features, enhancing our understanding of reservoir architecture, fault systems, and stratigraphic traps. This data-driven methodology is pivotal in optimizing exploration and development strategies in hydrocarbon-abundant fields.

3.1 Seismic Cube Loading and Using Attributes for Quality Improvement

The three-dimensional seismic cube was loaded into the working project, as depicted in Figure (3). Overall, the seismic sections exhibited good quality and continuity of seismic reflectors. Based on these observations, seismic attributes were applied to enhance and highlight the seismic cube, ensuring the highest quality for interpreting seismic data related to the reflectors of the Yamama Formation, as illustrated in Figure (4).

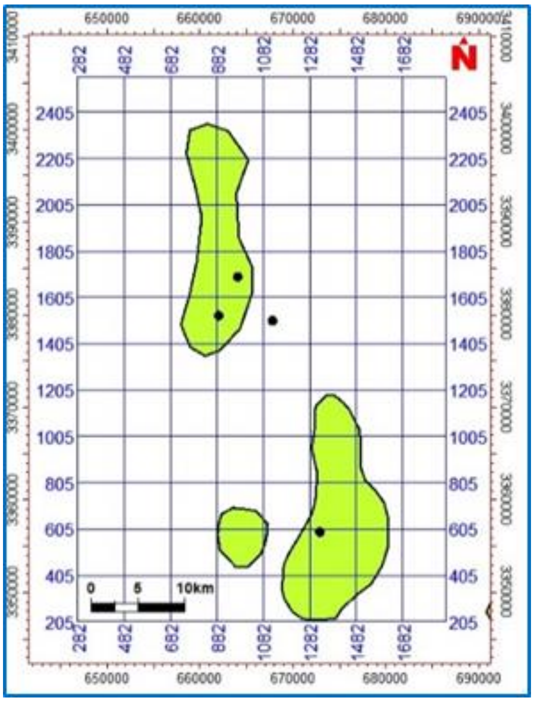

Fig. (3): The seismic cube that covers the study area.

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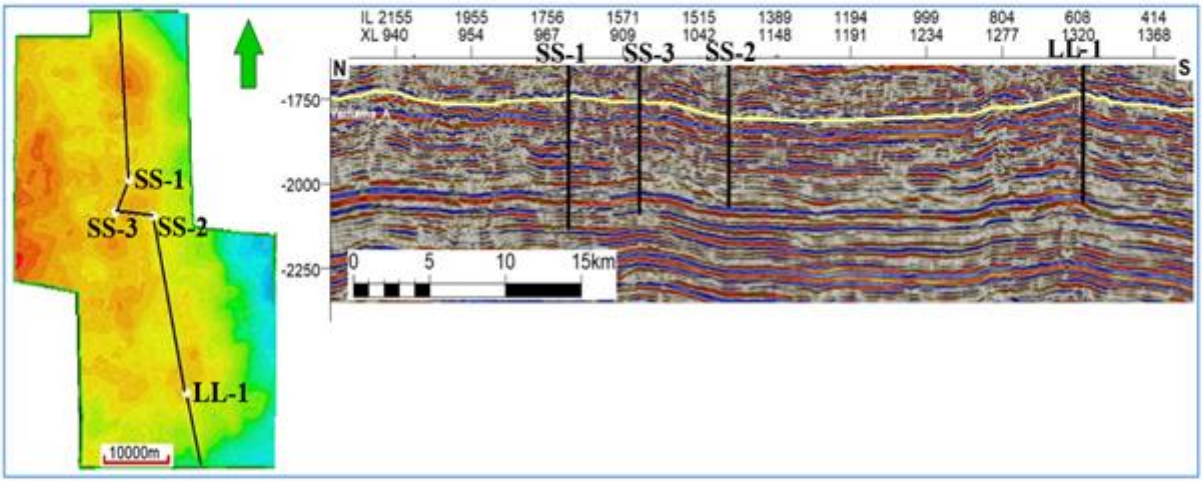

Fig. (4): Seismic sections show a good quality and continuity of seismic reflectors.

3.2 Synthetic seismic and definition of reflectors

The borehoel data (SS-1, SS-2, S-3, and LL-1) including formation tops, velocity surveys (Check Shots), sonic P-wave logs, and density logs were used to generate the synthetic seismic response for well SS-2 (Figure 5). This enabled the identification of seismic reflectors corresponding to the Sulaiy Formation and the stratigraphic units of the Yamama Formation (YA, YB, YC, and YD). These reflectors were tracked throughout the seismic cube (Figure 6).

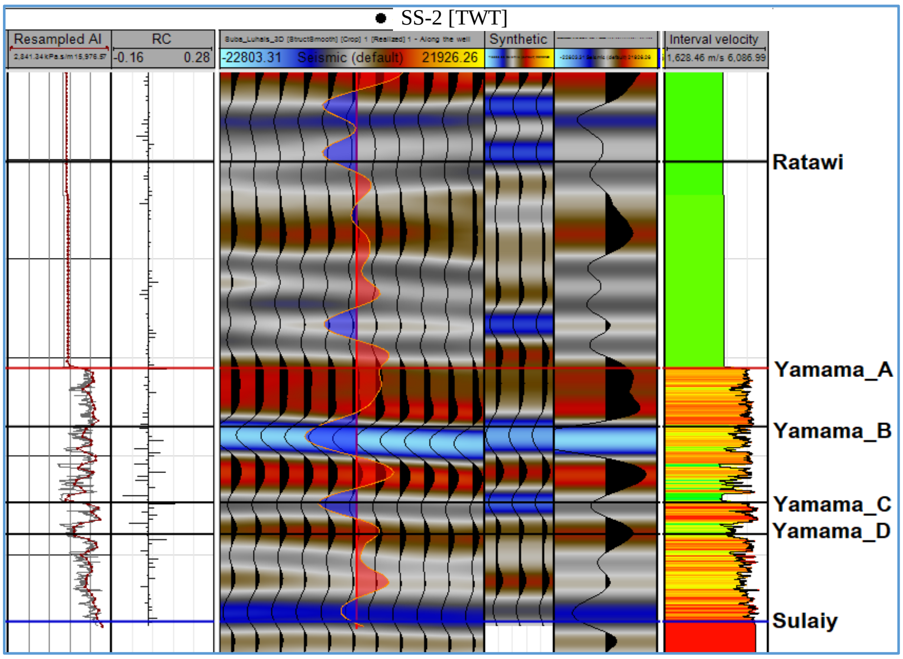

Fig. (5): Shows the synthetic seismic of the SS-2 well.

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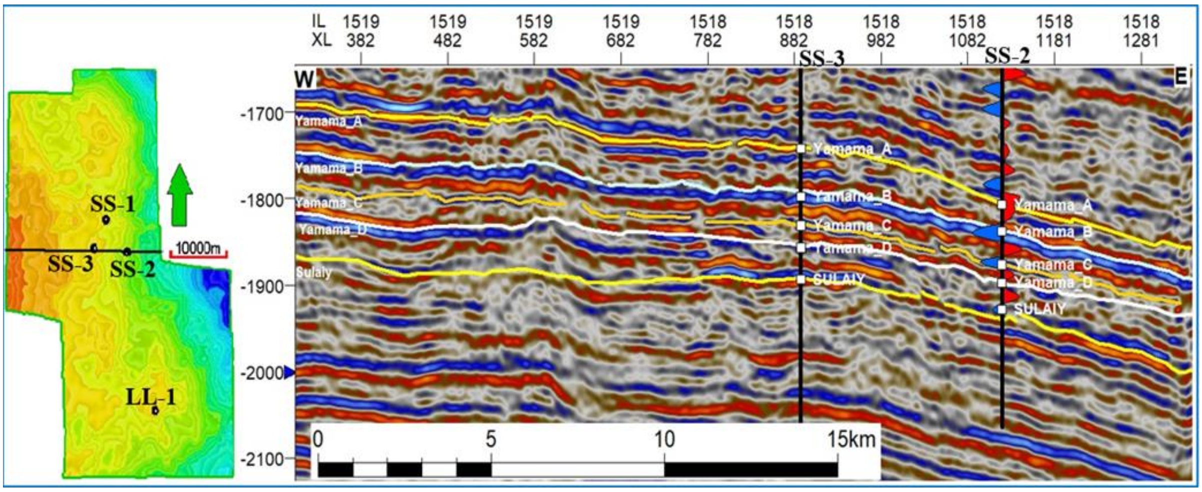

Fig. (6): The seismic section shows the tracking of reflector tops (Sulaiy Formation) and the stratigraphic units of the Yamama Formation (YA, YB, YC, YD) between wells (SS-2 and SS-3) through the synthetic seismic of the SS-2 well.

3.3 Time structural maps

Six structural maps were created in the time domain, representing the tops of the Yamama stratigraphic units (YA, YB, YC, and YD), Sulaiy, and Gotnia formations. These maps reveal a general structural dip toward the east and northeast, while the western part exhibits higher structural elevations (Figure 7). The SS and LL fields are located along a structural axis, an irregular fold trending northwest-southeast. The SS field is an irregular structural closure composed of two domes: the southern dome, which drilled three wells SS-1, SS-2, and SS-3, and the northern structure is devoid of wells (Figure 8). Reflectors at all studied levels indicate structural closures. In the LL field, the LL-1 well was drilled within the southern dome, while the northern dome, with a structural closure of approximately 50 meters, remains undrilled.

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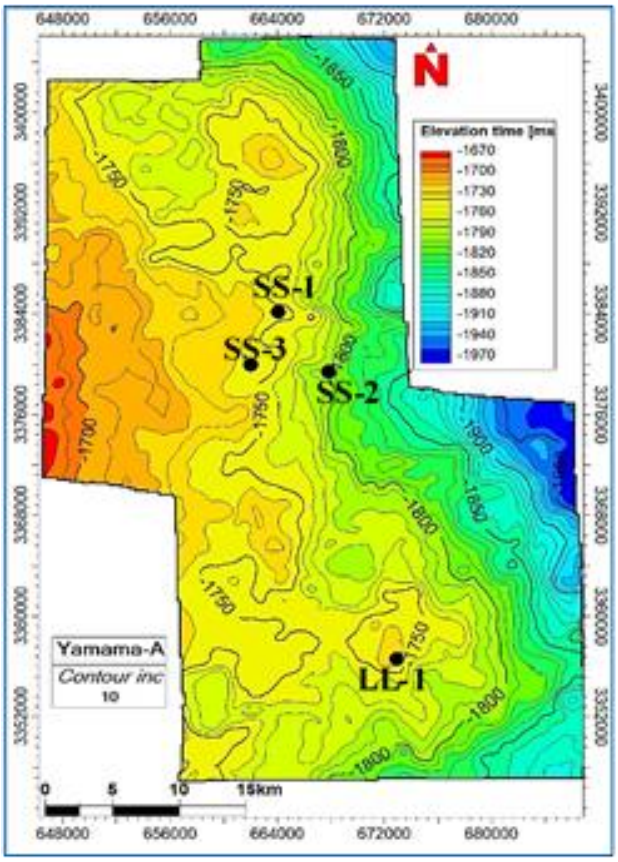

Fig. (7): Structural time map of the top of the Yamama-A.

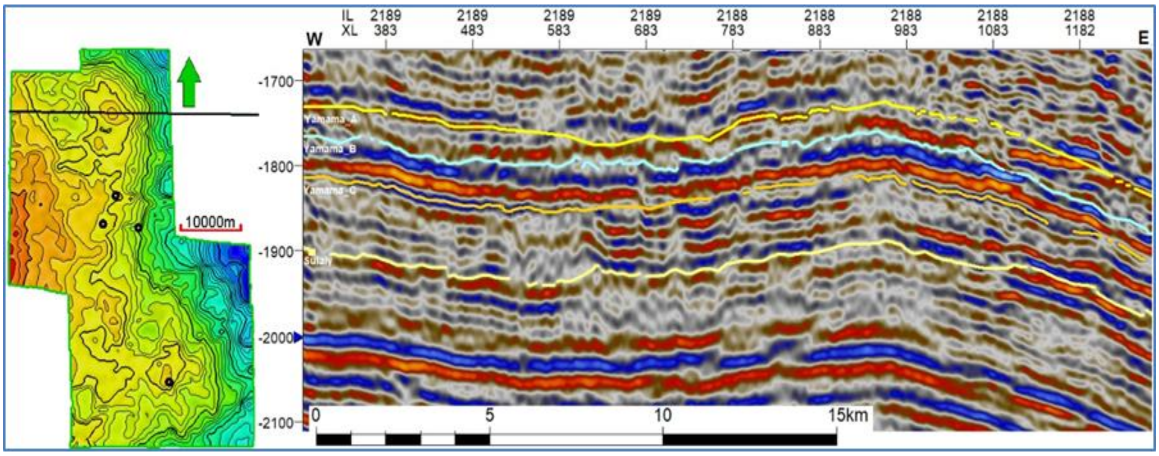

Fig. (8): The structural closure on the structural map north of the SS field is highlighted. It corresponds to the seismic section, and even though it is free of wells, it shows hydrocarbon potential.

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3.4 Interpretation of faults and preparation of structural models

The faults affecting the seismic sections were identified and systematically traced within the seismic cube for the SS and LL fields. The analysis revealed parallel fault systems trending north-south and northwest-southeast, significantly impacted deeper seismic reflectors. A three-dimensional structural model was constructed in the time domain (Structural Framework) to illustrate the influence of these fault systems on time surfaces (Figure 9).

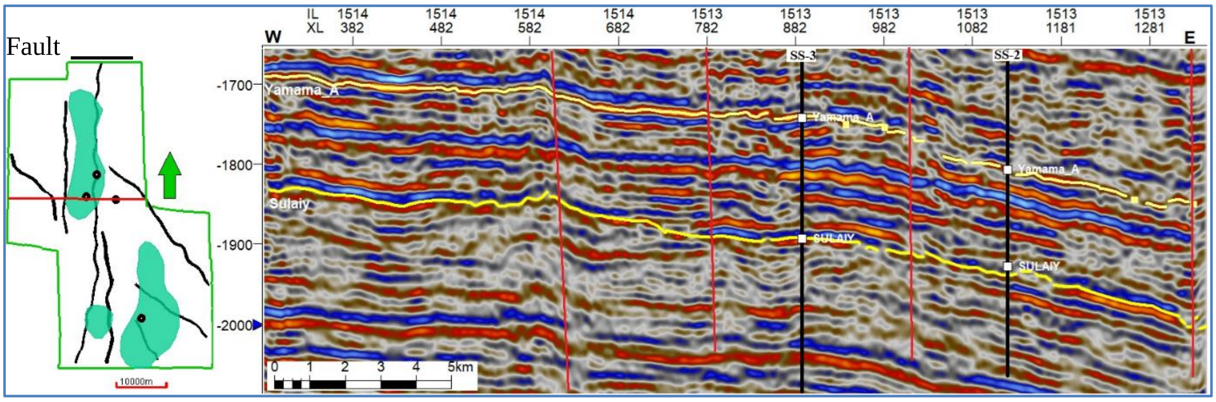

Fig. (9): The seismic section illustrates the tops of the formations Yamama, Sulaiy, and Gotnia, with the influence of fault systems in the SS field, extending through the wells SS-3 and SS-2. In addition, a map showing the distribution of fault systems within the study area.

3.5 The structural time model

The average velocity analysis was conducted using borehole velocity surveys of the Yamama and Sulaiy formations. This analysis employed a velocity model by inputting the time surfaces of the stratigraphic Yamama units (YA, YB, YC, and YD) and the Sulaiy Formation into the study wells. A three-dimensional average velocity model, shown in Figure (10), enables the conversion of any time surface into the depth domain. These average velocity maps indicate a gradual and homogeneous increase in velocity for the Yamama and Sulaiy formations, particularly outside the structural closure, extending towards the west and southwest.

3.6 Structural depth maps

The structural depth maps were derived using the average velocity model, which defines the correlation between time and depth. In this approach, the three-dimensional time model was transformed into a three-dimensional depth model, enabling the construction of structural depth maps. The depth maps for the top of the Sulaiy Formation and the stratigraphic units of

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the Yamama Formation (YA, YB, YC, and YD) closely resemble their corresponding time-domain representations. This consistency is attributed to the relatively uniform velocity distribution, which maintained a proportional relationship with depth, in the SS and LL fields. Irregular structural closures are evident due to the influence of faulting, as illustrated in Figure (11).

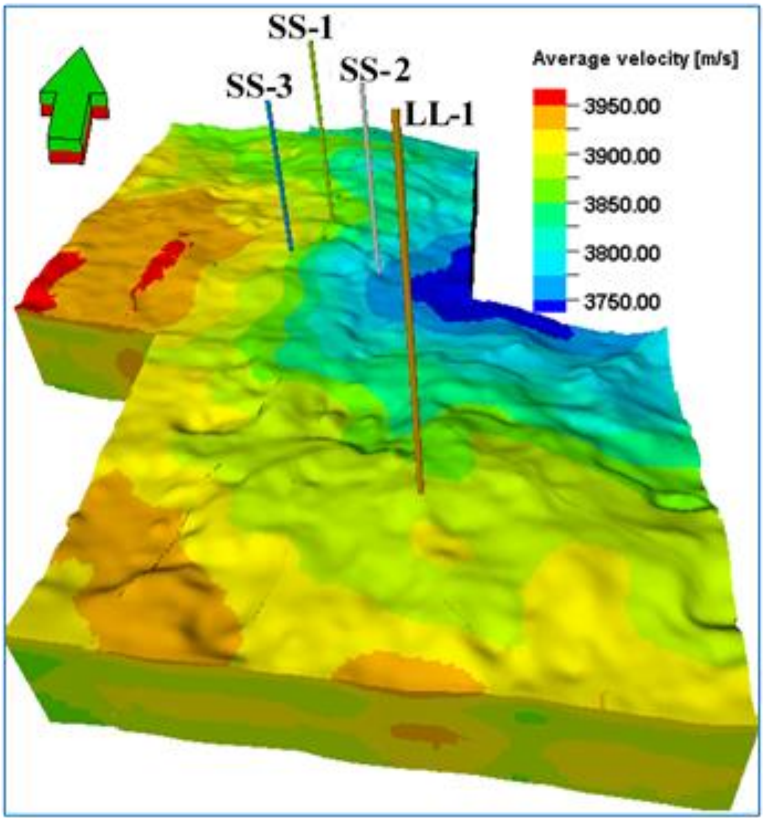

Fig. (10): Three-dimension model of the average velocity to (Yamama and Sulaiy) formations for the (SS and LL) fields.

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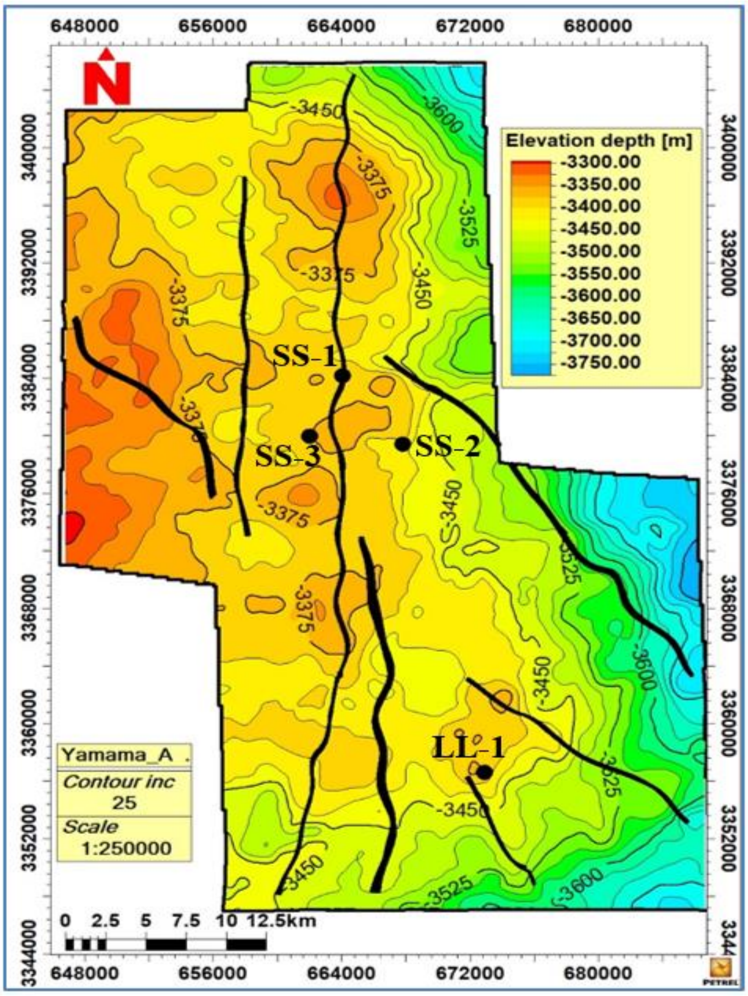

Fig. (11): Structural depth map of the top (Yamama-A) surface to the (SS and LL) fields and faults distribution, which lead to irregular structural closures.

4. Stratigraphic and quantitative interpretations

Seismic stratigraphic interpretation is a fundamental methodology that significantly enhances seismic analysis in both exploratory and developmental domains. It provides a detailed perspective on the stratigraphic framework, illustrates the subsurface structural image, depositional environments, and platform architecture of target formations. This technique plays a pivotal role in delineating the evolution of the lateral and vertical extents of stratigraphic traps, defining the direction of improving reservoir specifications, and constructing the model of the depositional environment and petrophysical of the Yamama Formation.

4.1 Seismic stratigraphy and Geological model

Quantitative seismic stratigraphy study is a vital interpretative method that provides insights into stratigraphic stacking patterns, reservoir unit migration nature, the lateral extents of stratigraphic

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traps, and the petrophysical properties of stratigraphic units. The Late Tithonian–Late Valanginian sedimentary cycle comprises the Sulaiy and Yamama formations. The Sulaiy Formation is characterized by open marine sedimentation, including organic-rich source facies that constitute significant hydrocarbon source rocks.

The relative sea-level change significantly influenced lateral facies' transitions within the Yamama Formation, leading to the development of stratigraphic traps. The thin-section examination from the study wells, combined with correlations to interpreted horizons, facilitated the construction of an environmental and effective porosity model (Figure 12a& 12b). The Yamama Formation predominantly consists of oolitic and peloidal grainstone, Miliolids, Permocalculus algae, and benthic foraminifera (Pseudocyclammina Lituus) within micrite sediments (Plate 1) in an inner ramp depositional environment. These attributes contribute to constitution reservoir specifications and hydrocarbon potential due to the availability of petroleum system elements. Three stratigraphic traps have been identified:

Trap A: Situated in the upper part of the SS field, with dimensions of approximately 14 ×10 km and a structural closure of around 60 meters across most studied horizons (Figure 13).

Trap B: Extends beyond the boundaries of the study area (Figure 13).

Trap C: Located in the LL field, with dimensions of approximately 4 × 2.5 km and a structural closure of about 30 meters (Figure 14).

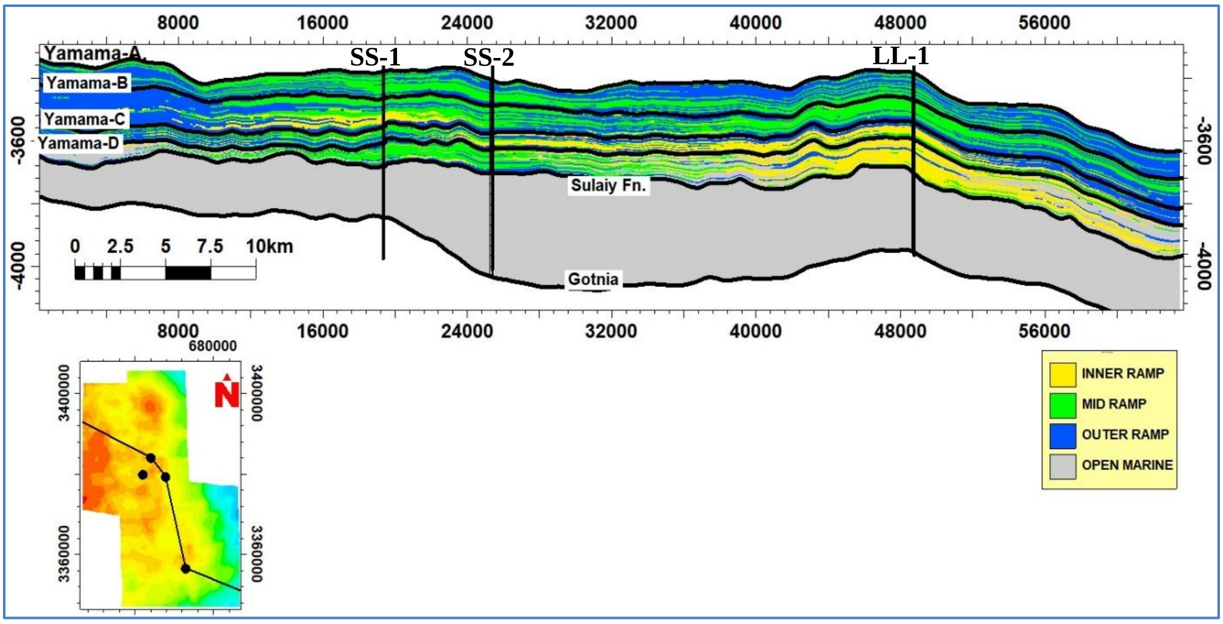

Fig. (12a): A NW-SE cross-section depicting the sedimentary environments model of the Sulaiy and Yamama Formations traversing through the (SS and LL) fields.

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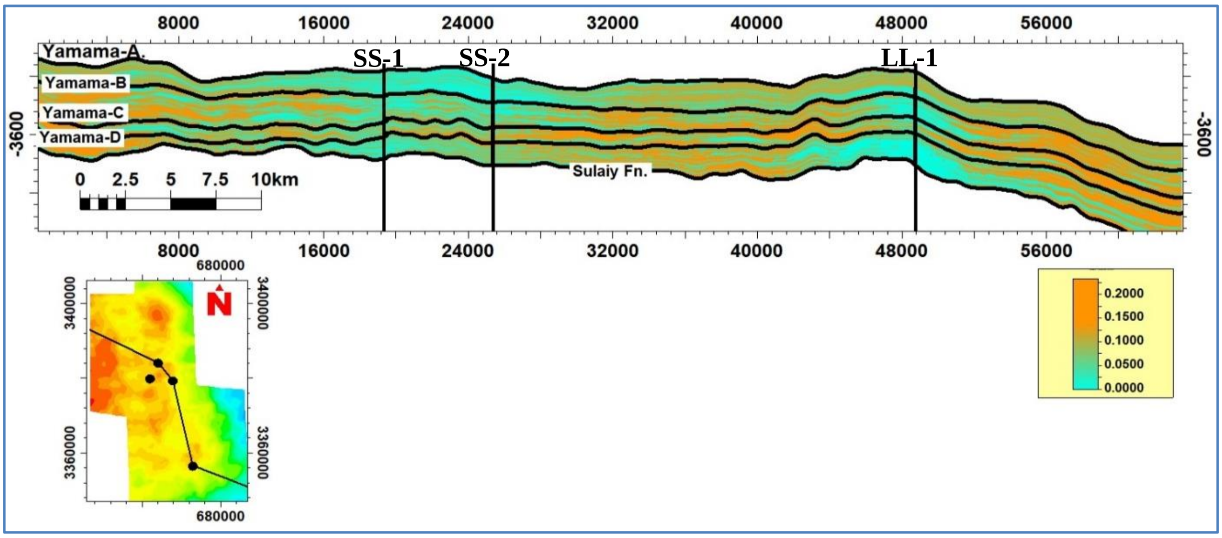

Fig. (12b): A NW-SE cross-section depicting the effective porosity model of the Sulaiy and Yamama Formations traversing through the (SS and LL) fields.

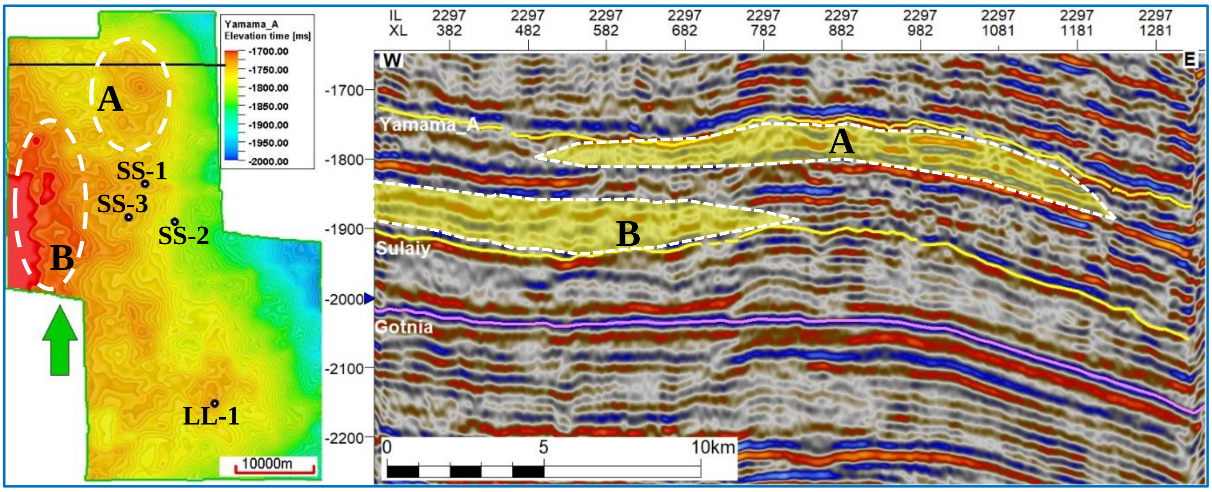

Fig. (13): Illustrates a seismic section showcasing the progressive stratigraphic stacking pattern that has resulted in the development of stratigraphic traps A and B within the Yamama Formation in the SS field.

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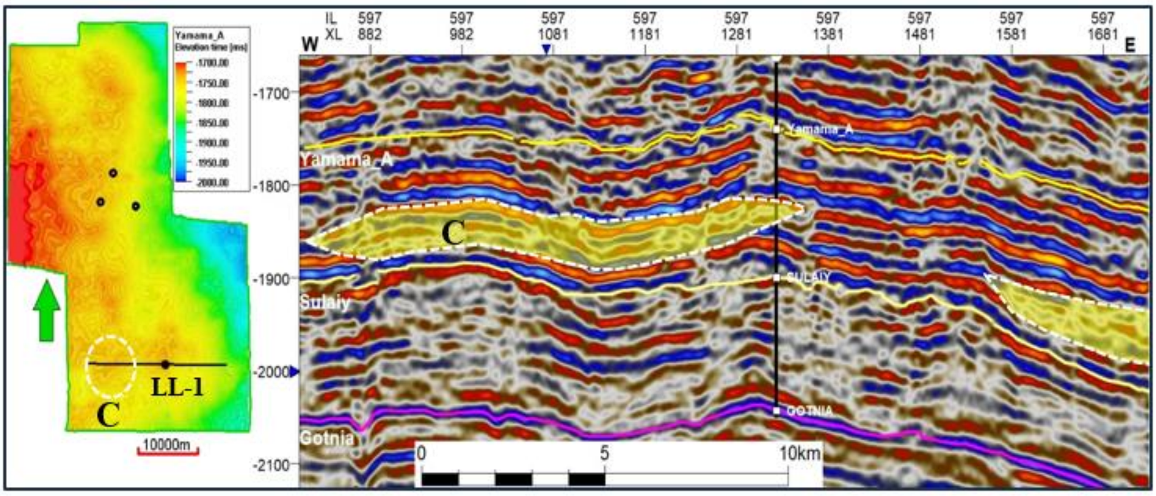

Fig. (14): The seismic section shows the stratigraphic trap C, which lies west of the LL field.

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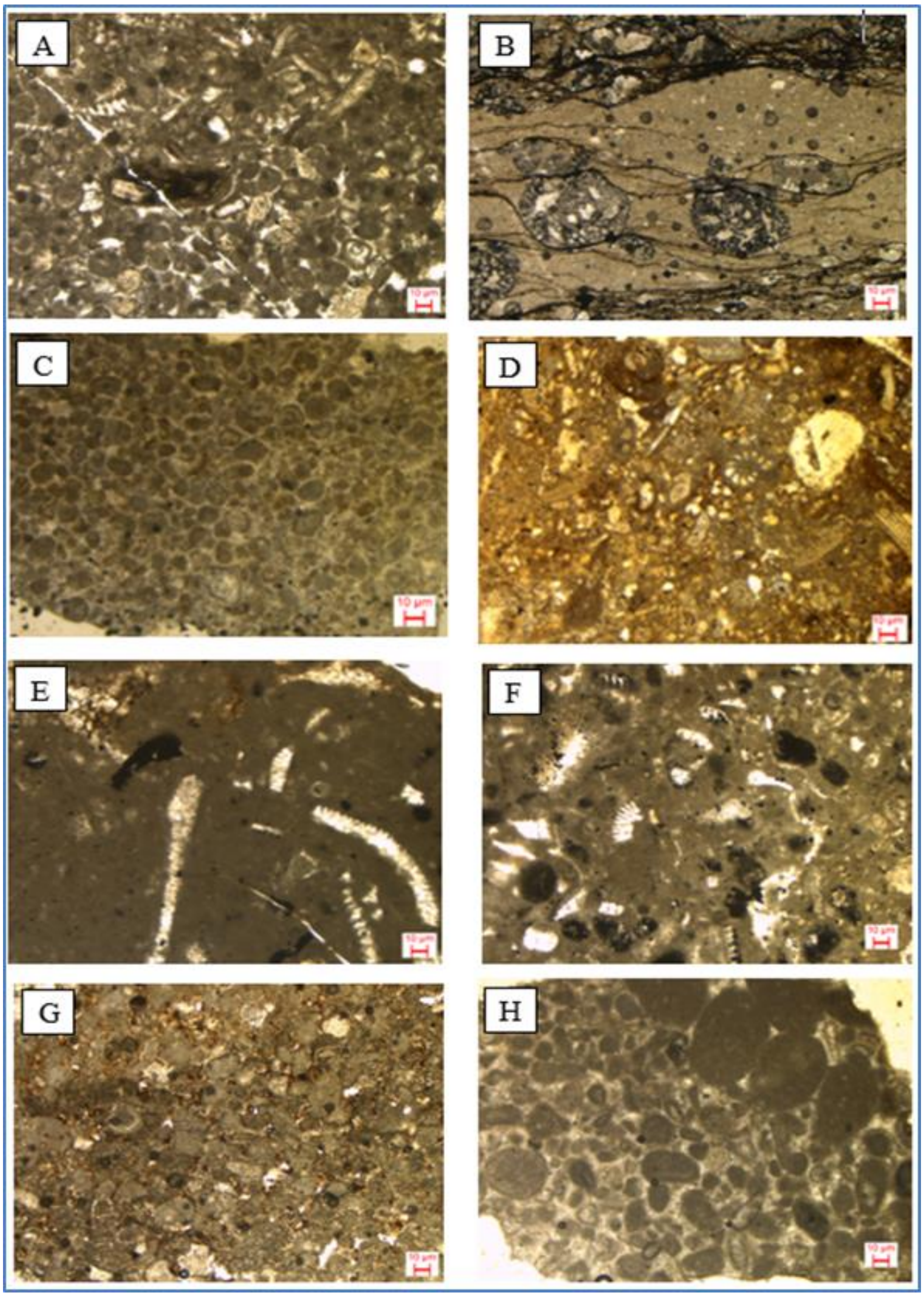
Plate (1) Yamama Formation:



A-Peloidal grainstone, LL-1, Depth (3660.25m); **B-** Benthic foraminifera (Pseudocyclammina Lituus) rooted in micrite, LL-1, Depth (3620.4m); **C-** Peloidal grainstone, SS-3, Depth (3609m); **D-** Bioclastic packestone (Miliolids) SS-3, Depth (3430.35m); **E-** Permocalculus algae. SS-2, Depth (3488m).

F- Bioclastic packestone with dissolution porosity and Pyrite, SS-1, Depth (3406m).

G- Peloidal grainstone with Associated with oxidation because of erosion LL-1, Depth (3629.7m).

H- Peloidal grainstone, SS-1, Depth (3554m).

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5. Conclusions

The study area is situated in southern Iraq (Basrah and Dhi Qar) governorates. Drilling activities in the SS field have penetrated the Yamama Formation through three wells, while the LL field contains a well (LL-1) that penetrated the Gotnia Formation at a depth of 4029 meters. The Late Tithonian to Late Valanginian consists of the Sulaiy and Yamama formations. Highstand conditions contributed to the deposition of shallow-water carbonates (Yamama Formation), which developed on a ramp-type setting. Conversely, transgressive conditions led to the deposition of open marine sediments, including shale and mud-supported argillaceous carbonates with a notable abundance of planktonic fossils, resulting in the Sulaiy (Makhul) Formation.

Six structural maps (YA, YB, YC, YD, Sulaiy, and Gotnia) reveal a general structural dip to the east and northeast, with elevated structural positions observed in the western portions of the area. The SS and LL fields are situated along a structural axis defined by an irregular fold, trending northwest-southeast. The SS field is characterized by an irregular structural closure that consists of two domes: the southern dome, which is penetrated by wells SS-1, SS-2, and SS-3, and a northern dome, which remains undrilled. In the LL field, the LL-1 well is located in the southern dome, while the northern dome, exhibiting a structural closure of approximately 50 meters, remains undrilled.

Faults influencing the seismic sections were systematically identified and traced within the seismic cube. The analysis revealed two primary fault trends: north-south and northwest-southeast. To evaluate the impact of these fault systems on structural surfaces, a three-dimensional structural model was constructed within the Structural Framework.

The Sulaiy Formation is characterized by open marine sedimentation, which includes organic-rich source facies, contributing to significant hydrocarbon source rocks. The relative sea-level fluctuations during deposition of the Yamama Formation significantly influenced lateral facies change, thereby facilitating the formation of stratigraphic traps (Trap (A), located in the upper section of the SS field; Trap (B) which extends beyond the study area’s boundaries; and Trap (C), situated within the LL field),These characteristics are pivotal in the formation of reservoir rock properties and hydrocarbon potential due to the presence of petroleum system elements. Thin-section petrographic analysis from the study wells, integrated with correlation to interpreted horizons, enabled the construction of an environmental model and an effective porosity model.

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