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Hydrocarbon Exploration Potentials in the Tectonically Stable Parts of Western and Southern Parts of Iraq, NE of the Arabian Plate

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ABSTRACT

The development of tectonic units in Iraq has been linked to the ongoing interplay between the Arabian and Eurasian plates since the Late Cretaceous era. It is believed by all researchers who were working in the considered areas that the compressional forces are decreasing southwestwards. This opinion was achieved due to the decrease of the amplitudes of the anticlines southwestwards and disappearing (apart from the Anah anticline) south of the Abu Jir – Euphrates Active Fault Zone as a recognizable tectonic interface delineating the stable and unstable regions within Iraq. Accordingly, the oil exploration activities were emphasized in the considered unstable parts of Iraq, because the stable parts have no anticlines on the surface. High-quality satellite images, geological maps were used with field observations to prove that there are no regions in Iraq that are considered tectonically stable. Yet, there is attenuation for the compressional force's southwestward. Hence, the classification of Iraq into the "Stable Shelf" and "Unstable Shelf" tectonic domains fails to accurately represent the actual tectonic dynamics of the region. This means that there are no tectonically stable parts in Iraq. The possibility of finding hydrocarbons, especially in Ordovician and older Cambrian rocks that have not yet been studied, is discussed. A correlation between Iraq, Saudi Arabia, Jordan, and Syria has been performed, as the presence of hydrocarbons in different geological formations is concerned, with some data about the maturity of the hydrocarbons found in some deep-drilled wells.

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احتمالية وجود الهايدروكاربون في المناطق المستقرة بنيوياً في غربي وجنوبي العراق، شمال شرقي الصفيحة العربية

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الملخص

يقع العراق في اقصى الجزء الشمالي الشرقي من الصفيحة العربية. ان الانطقة البنيوية في العراق قد تكونت بسبب القوى الانضغاطية المنبعثة من اصطدام الصفيحتين العربية والاوراسية المستمرة منذ الكريتاسي المتأخر. وان جميع الباحثين الذين عملوا في المنطقة يعتقدون بان القوى الانضغاطية تضمحل باتجاه الجنوب الغربي. وهذه الفكرة تكونت بسبب اضمحلال سعة الطيات المحدبة وباتجاه الجنوب الغربي وتنتهي (باستثناء طية عنة المحدبة) جنوب نطاق فالق ابو جير – الفرات النشط والذي يعتبر الحد البنيوي الفاصل بين المنطقتين المستقرة وغير المستقرة في العراق. وعليه، فان عمليات الاستكشافات النفطية تركزت على المناطق غير المستقرة لان المناطق المستقرة لا تضم طيات محدبة على السطح. في هذه الدراسة، استخدمنا مرئيات فضائية ذات الجودة العالية وخرائط جيولوجية والملاحظات الحقلية لنثبت بانه لا توجد مناطق مستقرة بنيوياً في العراق، ولكن هناك تباطؤ بالقوى الانضغاطية باتجاه الجنوب الغربي. وعليه فان النوعين البنيويين الرئيسيين والمسميان الرف المستقر والرف غير المستقر لا يمثلان الوضع البنيوي الصحيح للعراق. وتمت مناقشة احتمالية العثور على الهايدروكاربون وخاصةً في صخور الاوردوفيشي والكامبري والتي لم تدرس بالتفصيل. وتم عرض مضاهاة عن وجود الهايدروكاربون بين العراق والسعودية العربية والاردن وسوريا وفي العديد من التكوينات الجيولوجية في صخور الاوردوفيشي والكامبري مع عرض بعض المعطيات عن نضوج الهايدروكاربون وكما استنبطت من الابار العميقة المحفورة في منطقة الدراسة.

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Introduction

Iraq is situated in the northeastern section of the Arabian Plate (Fig. 1) and is commonly divided into Unstable and Stable domains (Fouad, 2015; Jassim and Goff, 2006). The former Unstable Domain occupies about half of the territory and includes the following tectonic units (from the NE towards the SW): Shalair Terrane, Zagros Suture, Imbricate, High Folded, and Low Folded zones, besides the Mesopotamia Foredeep and the Stable Shelf (Fig. 2D) (Fouad, 2015; Sissakian, 2013).

Since the Late Cretaceous period, the collision between the Arabian and Eurasian (Iranian) plates has led to the formation of these tectonic units (Fig. 1) at an ongoing convergent tectonic boundary (Alavi, 2004; Alsharhan and Nairn, 1997; Berberian, 1995; Berberian and King, 1981; Burberry, 2015; Burberry *et al.*, 2010; Colman-Sadd, 1978; Fouad, 2015). Accordingly, the Zagros Foreland Basin (ZFB) has developed, which includes the Zagros Fold–Thrust Belt (ZFTB) and the Mesopotamia Foredeep (MF). The ZFTB consists of the mountainous parts of the Kurdistan Region of Iraq (KRI) where numerous folds and faults occur. The MF zone consists of two parts: the northwestern part (Jazira Plain), which is characterized by inverted grabens and Khlesia High, and the southeastern part (Mesopotamian

Plain), which is distinguished by the alluvial sediments of the Tigris and Euphrates rivers; several subsurface anticlines underlie the Mesopotamian Plain (Fouad, 2015; Jassim and Goff, 2006).

Previous studies on the geology of Iraq have divided the country into two tectonically distinct zones of Unstable and Stable parts (Al-Kadhimi *et al.*, 1996; Aqrawi, Goff, *et al.*, 2010; Buday and Jassim, 1987; Dunnington, 1958; Fouad, 2015; Jassim and Goff, 2006; Numan, 1997; Sissakian, 2013; Sissakian *et al.*, 2017). The area where the two regions meet is called the Abu Jir-Euphrates Zone, which stretches approximately south of the Euphrates River (Fig. 2).

Earlier studies (Fig. 2 A-D) indicated a diminishing trend of tectonic activity towards the southwest. Similarly, the intensity of folding decreases in the same direction, correlating with the increasing distance from the collision zone of the Arabian and Eurasian plates (Buday and Jassim, 1987;Jassim and Goff, 2006;Fouad, 2015). Nevertheless, Fouad (2015) has introduced distinct terminology for the primary tectonic domains, employing the terms "Inner Platform" and "Outer Platform" (Fig. 2D). These terms delineate the stable and unstable shelves, respectively. The unstable shelf in Iraq, where no surface anticlines exist, including the Mesopotamian Plain, only subsurface anticlines. These areas have been focused on since the second decade of the last century and are still under oil exploration activities. This is because the area is associated with subsurface anticlines, the majority of which represent promising sites for hydrocarbon deposits. However, other parts of Iraq, which are considered tectonically stable and with no apparent surface anticlines, remained almost out of focus for oil exploration interests.

In all previous studies, such as (Dunnington, 1958; Buday and Jassim, 1984 and 1987; Jassim et al, 1986 and 1990; Al-Kadhimi *et al.*, 1996; Numan, 1997; Sissakian, 2000; Jassim and Goff, 2006; Aqrawi *et al.*, 2010; Sissakian, 2013; Sissakian and Fouad, 2015; Fouad, 2015) Iraq has been segmented tectonically into two primary areas: the Unstable Shelf and the Stable Shelf. Each is characterized by distinct tectonic units and naming conventions. This categorization was established considering various factors: 1) the degree of folding intensity, 2) the characteristics of fold shapes and sizes, 3) the magnitude of fold amplitudes, 4) the physiographic provinces, 5) the prevalence of significant thrust faults, 6) the presence or absence of subsurface salt layers, 7) different tectonic theories (including the outdated Geosyncline Theory and the modern Plate Tectonic Theory), 8) the age of exposed rock formations, and 9) the depth of the basement. It is worth mentioning that the referred authors have not necessarily considered the mentioned nine aspects (altogether) in their tectonic classifications, which means not all mentioned aspects are present at each tectonic unit.

Nevertheless, the authors mentioned earlier did not include Neotectonic activities in their tectonic classification of Iraq. Despite clear evidence of active fault zones and other signs of Neotectonic activities, particularly in the Western and Southern deserts, all authors have considered the western and southern desert regions of the country as tectonically stable. Additionally, many previous authors have classified the Jazira Plain as tectonically stable, often regarding it as a component of the Mesopotamia Foredeep, and therefore, presumed to be tectonically unstable. Ameen (1991) investigated the influence of basement faults on surface fold formation in northern Iraq. He noted the significance of a decollement horizon near the sedimentary cover base, identified as the 'Infra-Cambrian Hormuz Salt', and highlighted the passive role of the Precambrian basement in the region's tectonic evolution. Additionally, he emphasized the significant role of basement faults in shaping folds in northern Iraq.

Al-Kadhimi et al. (1997) conducted a geophysical interpretation, primarily utilizing gravity and magnetic data, to identify numerous faults in the Western and Southern deserts, as well as Al-Jazira Plain (Fig. 2, B). Referring to the conclusion of Ameen (1991) regarding interpreted basement faults, Al-Kadhimi et al. (1997) also inferred that they might have had a significant impact on the formation of folds in the tectonically stable regions of Iraq. Abdulnaby (2019) is the only researcher who dealt with Neotectonic activities as part of tectonics.

Nevertheless, he also considered stable and unstable parts with little consideration of the data on the Neotectonic activities.

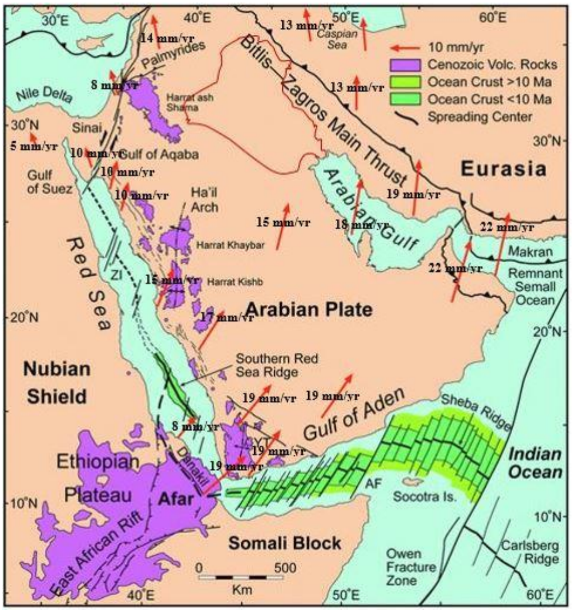

Fig. 1. Tectonic map of the Arabian, Somali, and African tectonic plates and their rates and directions of the Arabian Plate movement (after Bosworth, 2015).

The sole active tectonic area exhibiting numerous signs of Neotectonic movements is the Abu Jir – Euphrates Fault Zone, which is identified as the boundary between the "tectonically stable" and "unstable" regions. (e.g. Al-Kadhimi *et al.*, 1997; Buday and Jassim, 1984, 1987; Dunnington, 1958; Fouad, 2015; Jassim *et al.*, 1986, 1990; Jassim and Goff, 2006; Sissakian, 2000, 2013; Sissakian and Fouad, 2015). This tectonically active zone was geophysically studied by Al-Banna and Ali (2018) and they estimated the width of a transitional zone (i.e., between the stable and unstable zones) of about 50 km wide.

Iraq includes numerous oilfields in different parts (Fig. 3). The discovered oil reserve in Iraq is about 148.8 billion barrels, which forms 8.8% of the world's total reserve and the fifth rank among 15 countries with the largest oil reserves (Stebbins, 2019).

Although most of the oilfields, including those supergiants, are present on the Unstable Shelf (Outer Platform) (Fig. 3), a considerable number of fields are located on the "Stable Shelf" (Inner Platform). The structural orientations of oil and gas fields vary significantly across different regions of Iraq, as well as in neighboring countries like Syria and Jordan. In Iraq, the predominant trend within the Unstable Shelf follows a NW–SE direction. However, in the western regions of Iraq, particularly in the Akkas field, as well as in Syria and Jordan, the trend is primarily NE – SW (Fig. 3).

Al-Khirsan and Al-Siddiki (1989) suggested a distribution of proven oil reserves in Iraq as follows: Tertiary reservoirs accounted for 24 billion barrels, Cretaceous reservoirs held 76 billion barrels, and Jurassic and Triassic reservoirs contained approximately 100 million barrels. At that time, no hydrocarbons had been discovered in Paleozoic rocks (Aqrawi *et al.*, 2010). This is another indication that those areas that are considered tectonically stable are out of interest to the oil exploration strategy.

The current research aims to (i) assert that, unlike previous studies, all parts of Iraq are tectonically unstable, (ii) shed light on the areas previously considered as tectonically stable and" by-passed" by oil exploration activities relative to the tectonically active areas, and (iii) indicate that these less explored areas are very encouraging with good potential for hydrocarbon exploration.

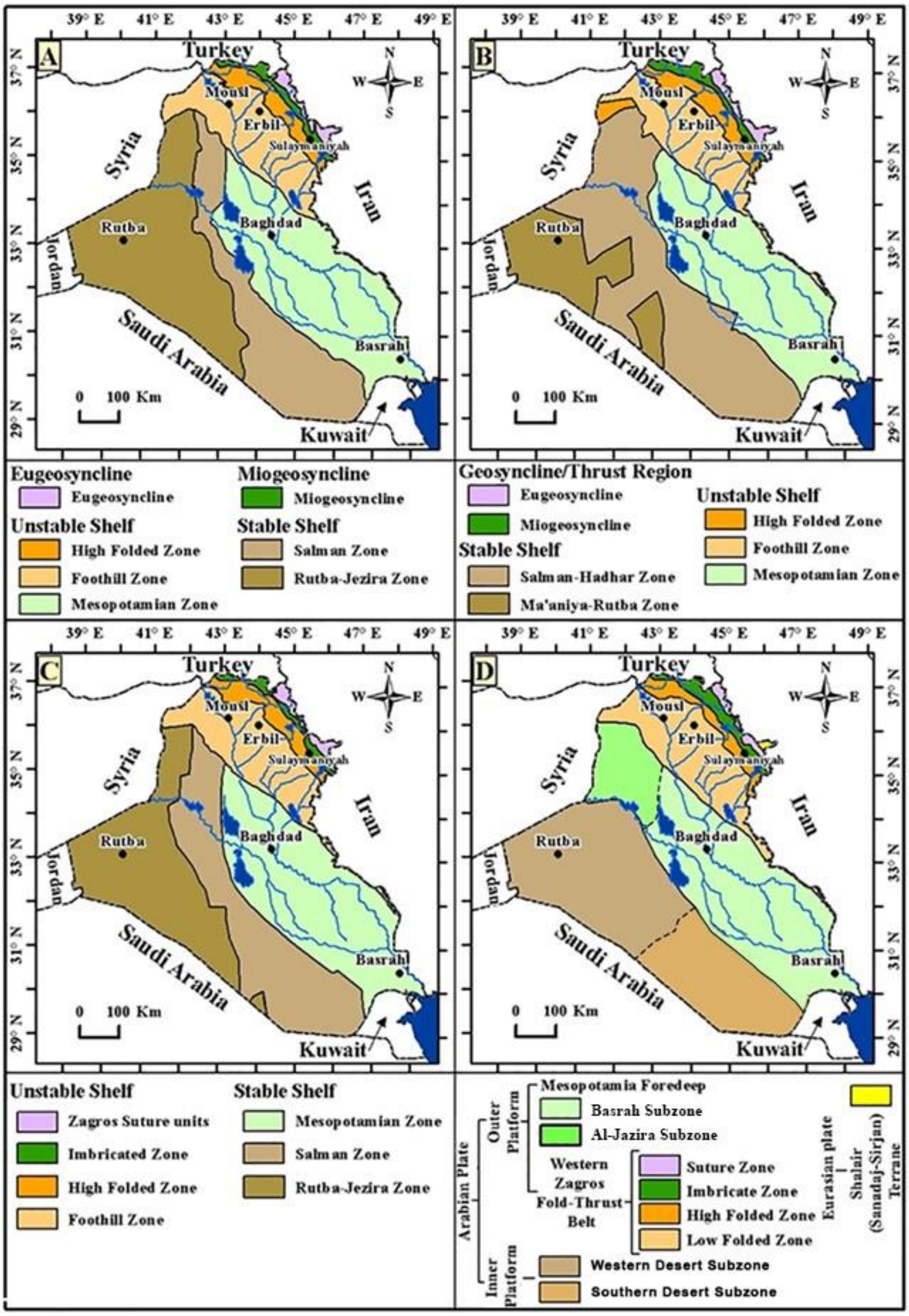

Fig. 2. Main tectonic units of Iraq, A) after Buday and Jassim (1984, 1987), B) after Al-Kadhimi et al. (1997), C) after Jassim and Goff (2006), and D) Compiled from Fouad (2015, 2008) and Sissakian et al. (2017).

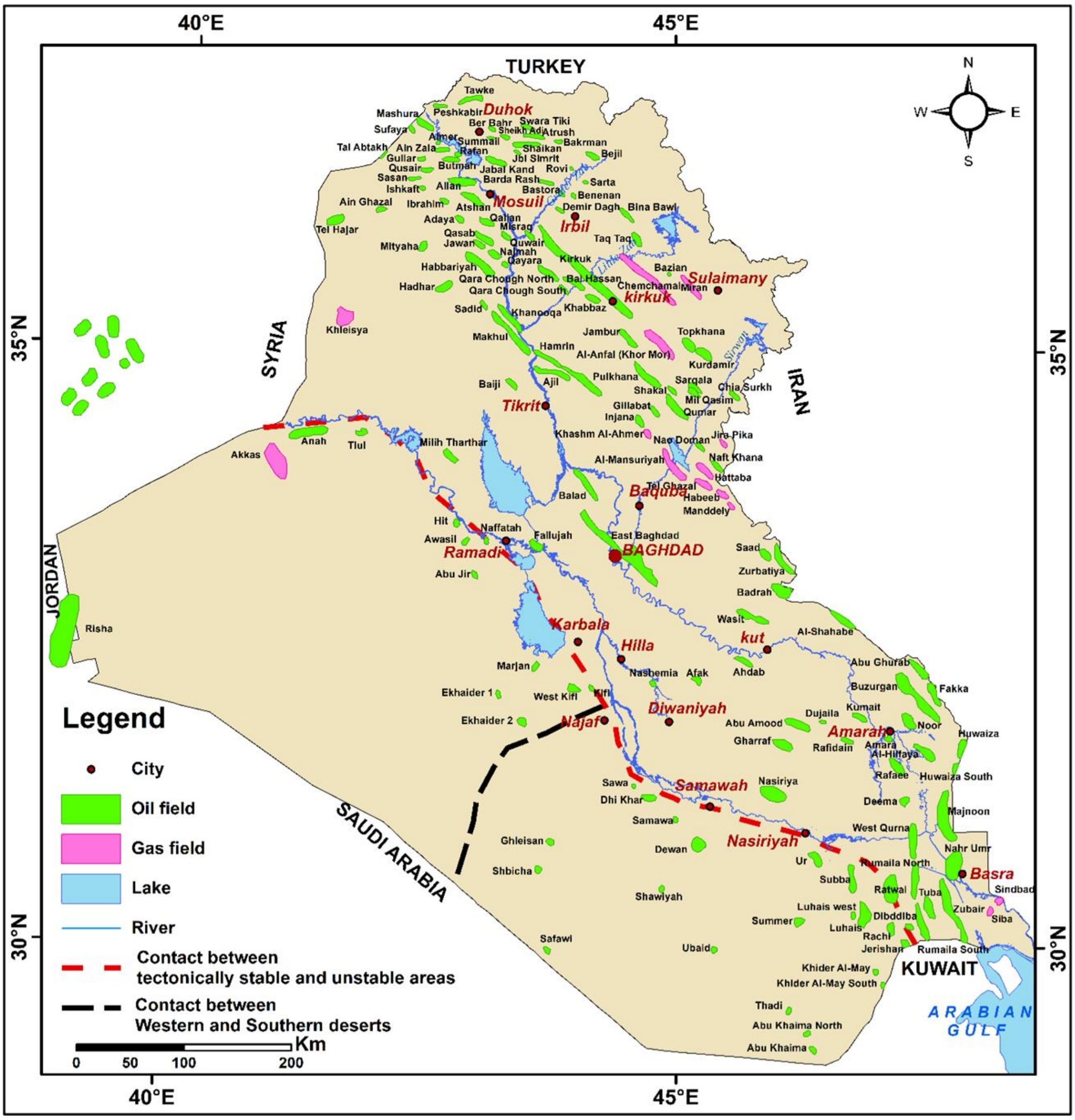

Fig. 3. Map of oil and gas fields in Iraq (Modified and redrawn by GIS from Al-Ameri, 2015). The authors added the red dashed line, which represents the boundary between the tectonically Unstable (north of the line) and Stable (south of the line) parts of Iraq, and the black dashed line to separate the Western desert from the Southern desert. Besides, the oil fields in Syria and Jordan.

Tectonic Regime in Iraq

Buday and Jasim (1984 and 1987), along with Al-Kadhimi et al. (1997), Numan (1997), Jassim and Goff (2006), Aqrawi et al. (2010), Sissakian (2013), as well as Sissakian and Fouad (2015), and Fouad (2015) have published various maps and articles addressing the tectonic framework of Iraq (Fig. 2). All of these authors concur on the fundamental tectonic configuration in Iraq: that it occupies the northeastern sector of the Arabian Plate and is undergoing collision with the Eurasian Plate (e.g. Alavi, 2004; Fouad, 2015). However, each author employed distinct terminology to describe the same tectonic units. Despite this variation, they unanimously acknowledged the existence of two domains: Stable and Unstable. Furthermore, while agreeing on the presence of these domains, different authors delineated the boundaries between them in various geographical areas (Fig. 2A, B, C, and D). The Tectonic Map of Iraq by Fouad (2015) (Fig. 2D) was utilized, making minor adjustments to the boundary between the two domains. This decision was based on the relevance of the depicted tectonic units in understanding Iraq's tectonic framework. However, although Fouad (2015) didn’t show stable and unstable terms, the map in its concept shows tectonically stable and unstable parts.

The western and southern regions of Iraq encompass areas classified as tectonically stable within the country (Buday and Jasim, 1984, 1987; Al-Kadhimi *et al.,* (1997); Numan, (1997); Jassim and Goff, (2006); Fouad, (2015) are under the tectonic influence of the spreading of the Red Sea (15 mm/yr) (Fig. 1) and the Dead Sea Fault (Levan Fault)(Fouad, 2015). Moreover, the westward motion (16 mm/yr) of western Iraq (Fig. 4) is attributed to the East Anatolian Fault, which extends in a northeast direction until intersecting with the North Anatolian Fault (Fig. 4). The faults in the western and southern regions of Iraq have given rise to a distinct folding system compared to those resulting from the collision between the Arabian and Eurasian plates. These folds exhibit an NE – SW trend, perpendicular to the predominant trend observed in folds formed by the convergence of these two plates.

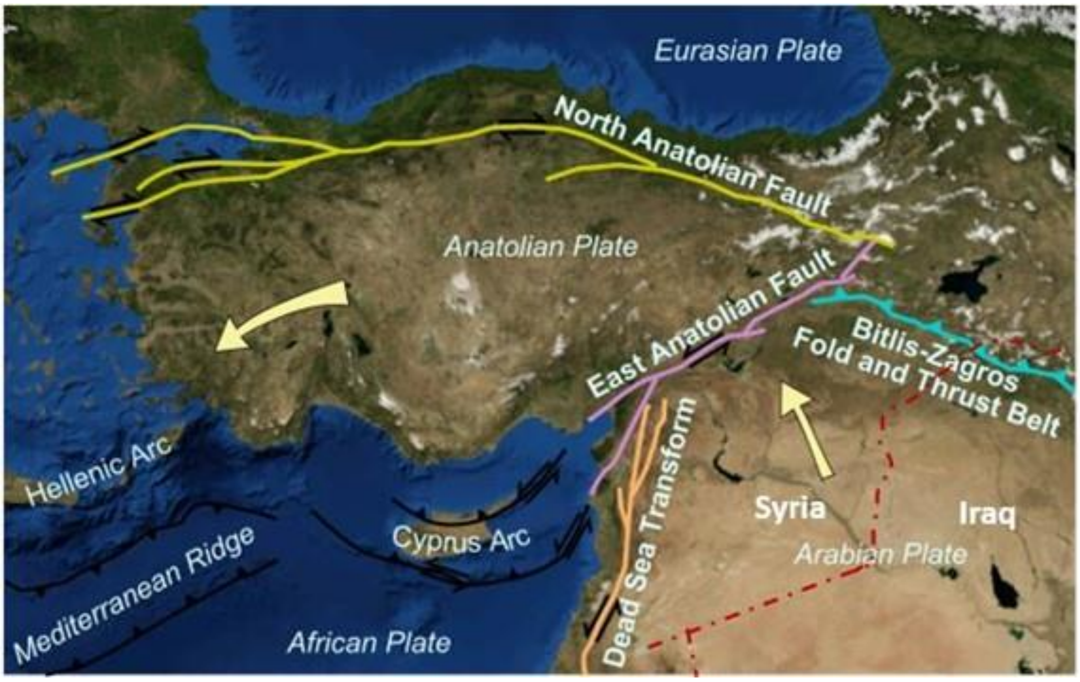

Fig. 4. The Dead Sea Transform, East Anatolian, and North Anatolian faults (Valentina, 2023)

Materials and Methods

To achieve the primary goal of this study, various resources are employed, including tectonic and geological maps, satellite imagery, and data extracted from relevant scientific literature and publications addressing the study's objectives. Additionally, field data have been collected from geological surveys conducted across diverse regions of the country.

The tectonic and geological maps, along with satellite images and various collected datasets, are employed to identify signs of active tectonic features, particularly in the Western and Southern deserts. Given that the current terrain and geomorphic features were shaped from the Pleistocene era onwards, any anomalous geomorphic forms and tectonic features identified suggest ongoing Neotectonic activities (e.g. Kumman, 2001; Marković *et al.,* 1996; Obruchev V.A, 1948).

Many oil wells and deep-water wells, especially in the stable parts of Iraq, and a few others were studied to indicate the differences between those located in the stable and unstable parts; some of them are producing wells. The Paleozoic succession, in the current study, is more emphasized because, in the stable parts of Iraq, the Paleozoic succession is more promising for hydrocarbon findings (Al-Haba *et al.,* 1994; Aqrawi, 1998; Jassim and Goff, 2006; Aqrawi *et al.,*2010).

Among the NE–SW and N–S trending gas fields are Akkas in Iraq (Fig. 5a) and Risha (Fig. 5 b) in Jordan. Moreover, in the Iraqi Western Desert, two regional joint systems are developed with NE – SW and NW – SE trends and many lineaments that indicate Neotectonic activity (Sissakian *et al.,* 2023a), besides the influence of the spreading the Red Sea and accompanied faults (Fig. 4). These intensely spaced lineaments may increase the secondary porosity of the rocks and increase the hydrocarbon potential of the region. It is worth mentioning that in the whole exposed sequence, there are marl, shale, and/or claystone beds, which can behave as seal rocks (Sissakian and Mohammed, 2007).

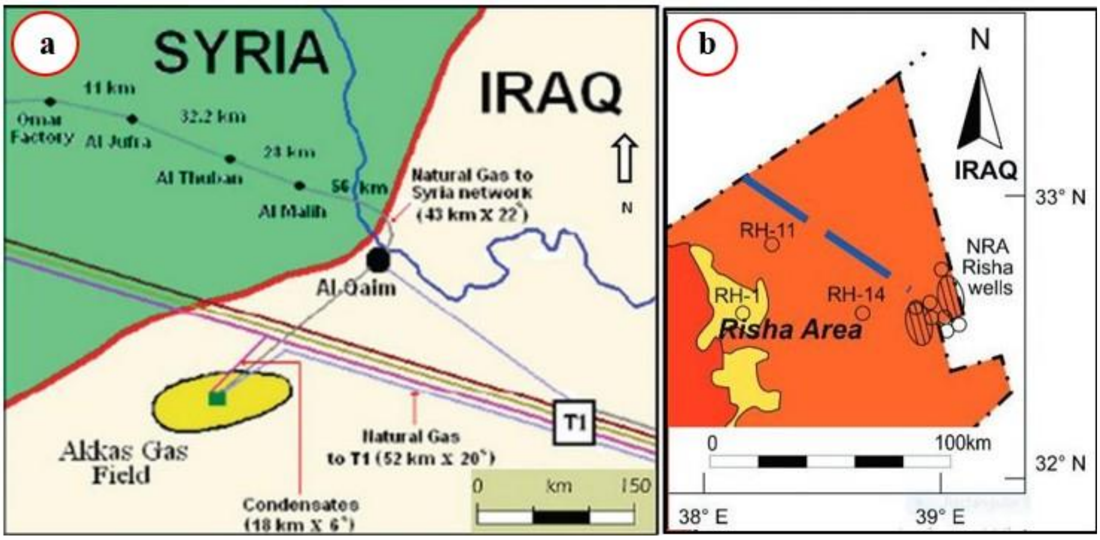

Fig. 5 a) Location of the Akas gas field (After Al-Juboury and Thani, 2016), b) Location of Risha gas fields, Jordan (After Lüning and Kuss, 2014).

Results

Regional Tectonics and Structure

The region is considered to be tectonically stable (Al-Kadhimi *et al.*, 1997; Aqrawi, Goff, *et al.*, 2010; Buday and Jassim, 1984, 1987; Fouad, 2015; Jassim and Goff, 2006; Numan, 1997; Sissakian and Fouad, 2015) including both deserts of Iraq (Fig. 2). Nevertheless, findings from the present study reveal evidence of both tectonic and Neotectonic features, suggesting that the region has not remained tectonically inactive for an extended period, as evidenced by preserved Cretaceous to Recent tectonic disturbances. The tectonic activity of the area of the current study is not as active as in the case of the High-Folded and Low-Folded zones. Therefore, there are no tectonically stable parts in Iraq, especially in the southern and western regions. The following indicators can be used to prove the tectonic instability of the Western and Southern deserts: 1) surface and subsurface folds, 2) active faults, 3) dislocated valleys and terraces, 4) valleys with acute meanders located along certain lineaments, 5) Knickpoints being located along certain lineaments, and 6) Karst formations are situated along specific lineaments. Subsequent sections will detail some of the identified markers for active tectonics and Neotectonics.

1. Surface Folds

Our study recognizes several anticlinal features that occur in the study area. These features include: A) Anah Anticline: It has a monoclinal form trending almost E -W (Fig. 6). The dip of the southern limb is ~ 4°, whereas its northern limb is about 45° (Fouad, 2006, 2015). The position of the anticline lies in the northern section of the "Stable Shelf." B) Akash and Al-Ratgah Anticlines: These features are identified within the western expanse of the Iraqi Western Desert (Fig. 6). The dip direction of the rocks from the Euphrates Formation within both valleys serves as compelling evidence for the presence of these anticlines (Fig. 6).

2. Subsurface Folds

The subsurface analysis using seismic profiles within the study area indicates the occurrence of several subsurface anticlines (Fig. 3); such as A) Akaz (Akkas) Anticline: A doubly plunging anticline exhibiting a northwest to southeast orientation (Fig. 3)., B) Al-Samawa Anticline which has N–S trend, C) an NW-SE trending Diwan Anticline, D) an E-W trending Salman Anticline, and E) Abu Khaima Anticline, which is a subsurface anticline although its trend is not clear on the map due to insufficient data to delineate it (Fig. 3).

3. Dissected Quaternary Sediments

Some Quaternary sediments are dissected by faults, indicating Neotectonic activities among them are the sediments of the Al-Batin alluvial fan. A normal fault in the western part of the fan, with a trend of NNE-SSW, dissects the sediments of the fan with a vertical displacement of about 5 m and horizontal displacement of about 20 km (Sissakian *et al.*, 2014).

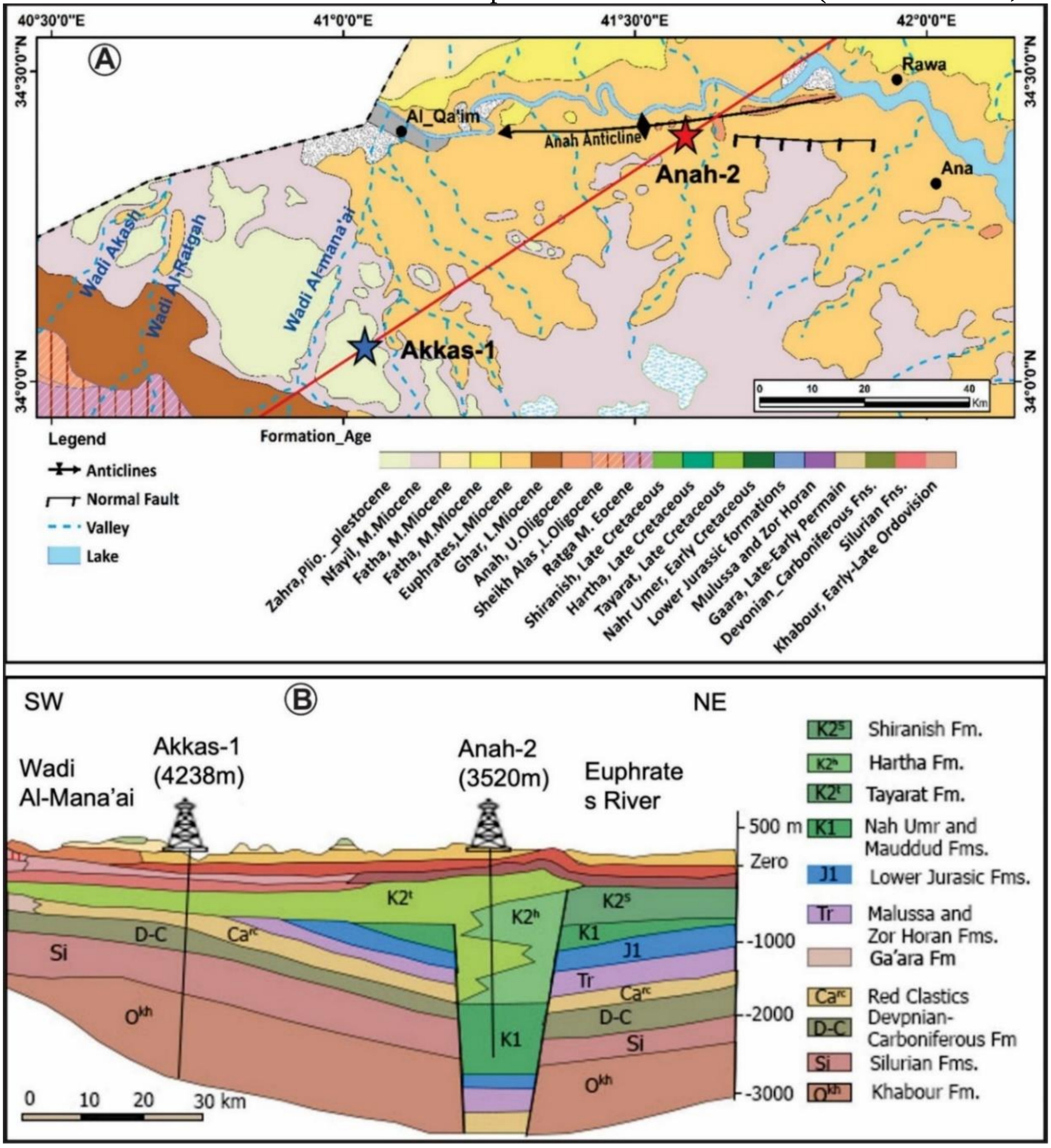

Fig. 6. A) Geological map of Anah anticline (converted graben). The red line shows the trend of the cross-section shown in B. Note the plunging of the rocks of the Euphrates Formation in Wadi Akash and Wadi Al-Ratgah (Sissakian and Fouad, 2015), B) NE-SW cross-section based on seismic interpretation along with the geologic information from Annah-2 and Akkas-1 oil wells. Note the Annah Graben, which was inverted during the Late Cretaceous to form the Annah Anticline. This can be inferred from the extensive thickness of the Hartha and Tayarat formations (equivalent to the Shiranish Fn.) and by comparing the thicknesses of the Cretaceous formations inside and outside the graben.

4. Tectonic Influence on Valleys and Cliffs

In the Western Desert, numerous valleys undergo tectonic dissection. These dissected valleys, as evidenced by prominent tectonic lineaments, exhibit trends predominantly in the northwest-to-southeast and east-northeast to-west-southwest directions (Sissakian *et al.*, 2023a and 2023b). These valleys signify a tectonic disruption and imply Neotectonic shifts extending beyond Iraq into Syria and Jordan. Consequently, widespread regional tectonic events persist, influencing the present drainage patterns and Quaternary faulting. A broad and shallow depression near the Al-Waleed border station (Fig. 7) includes thick Quaternary deposits (about 196 m thick) as evidenced by a borehole drilled near the Al-Waleed border station (Al-Bdaiwi *et al.*, 2005). The sediments consist of fragments of igneous basaltic rocks originating from the current basaltic flows in Syria, suggesting the ongoing activity of the depression. Besides that, all other depressions in the region are also filled by Quaternary deposits, and most likely are structurally controlled as indicated by their shapes. These depressions are neither circular nor oval, as usually all depressions in the region are, but two edges of the depressions are straight (not curved) with an NW-SE trend, which is the main direction of the existing lineaments in the region (Fig. 7).

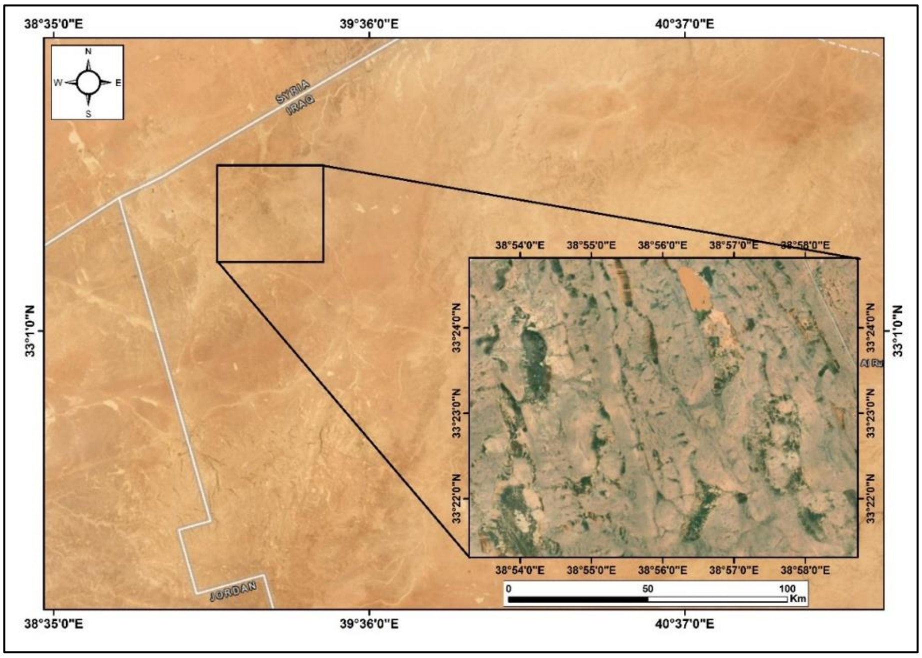

Fig.7. Satellite image showing many depressions with straight edges. Also, note the regional lineaments in the NW–SE direction.

Tectonic Stability

The data presented from the Western and Southern deserts indicate that both regions have experienced tectonic disturbances, contradicting the findings of all previous researchers (J. A. M. Al-Kadhimi *et al.*, 1997; Buday and Jassim, 1984; Fouad, 2015, etc.). However, Sissakian et al. (2023a and 2023b) presented sound data indicating that there are no stable parts in Iraq as far as tectonic activity is concerned.

1. Hydrocarbon Finding Possibilities

One of the hydrocarbon potential areas to explore in the southwestern region of Iraq (i.e., the moderately stable areas) is within Al-Anbar Governorate (Fig. 8). Al-Anbar Governorate is the largest among the 18 governorates of the country and occurs within the suggested extension of the Unstable Shelf (the current study). The exploration activity within this region has been revived since late 2020 as international exploration companies have shown interest in the region. However, no exploration activities have started, hitherto (January 2025).

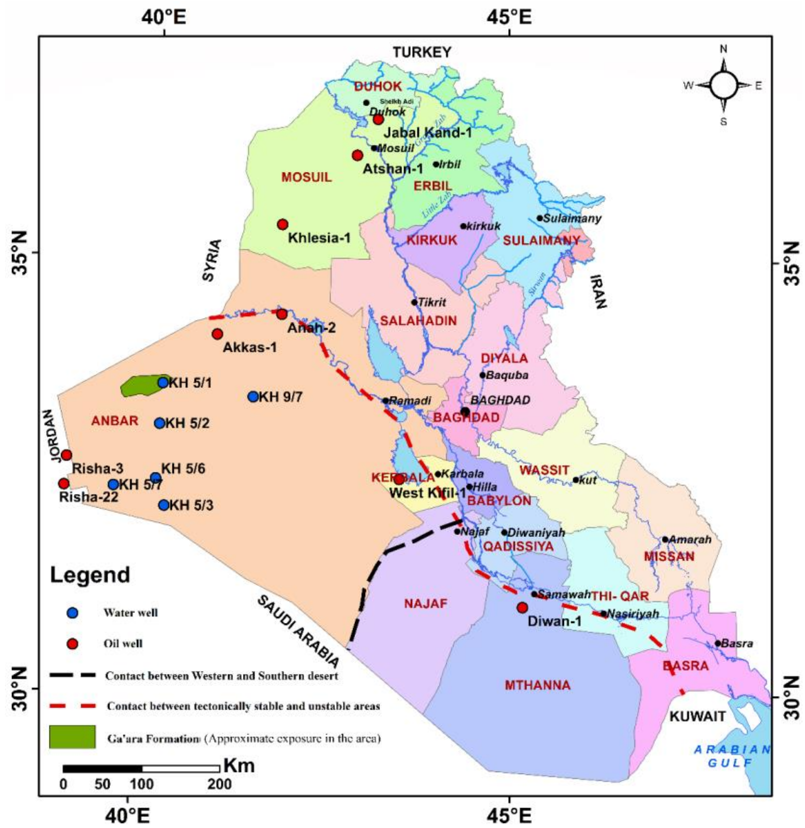

Fig. 8. Governorates map of Iraq showing two main tectonic domains. (Approximate scale, coordinates, locations of oil and water wells, and tectonic contacts are added by the authors)

The Paleozoic stratigraphy of the region contains thick sandstone and shale formations that occur throughout the moderately stable region. Figure 9 shows the Paleozoic succession of different zones within the study area (Aqrawi, 1998). The most promising rocks in Al-Anbar Governorate as potential reservoirs for hydrocarbon are the sandstone strata (Aqrawi, 1998; Sissakian *et al.*, 2022); however, the only exposed rocks in the suggested extension of the Unstable Shelf within Al-Anbar Governorate are those of the Ga'ara Formation (Permian). The main constituents of the Ga'ara Formation are reddish-brown sandstone alternated with reddish-brown claystone; both are deposited in fluviatile basins with large meandering rivers (Tamar-Agha, 1986).

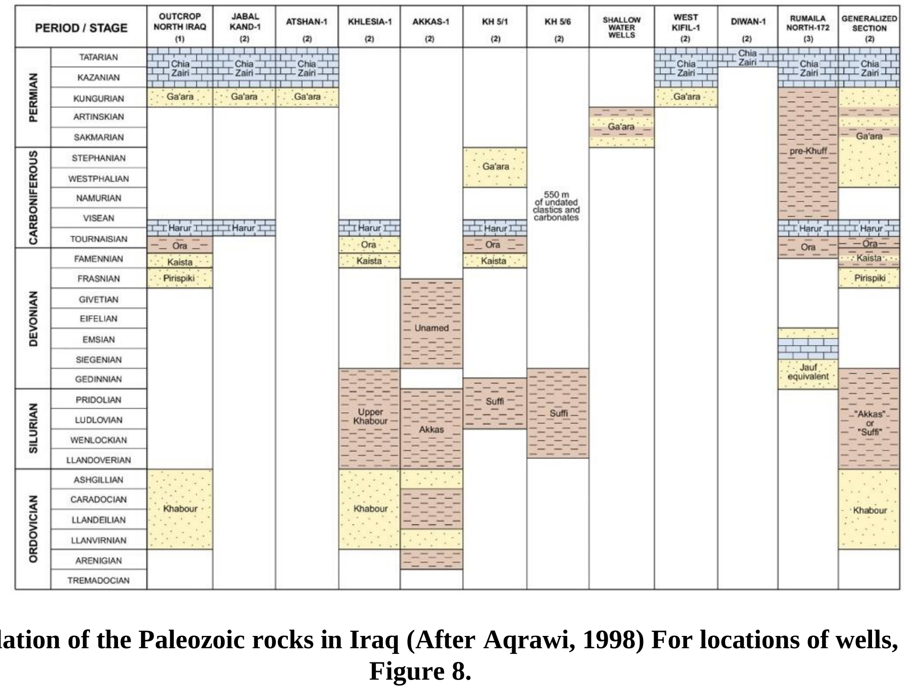

Fig. 9. Correlation of the Paleozoic rocks in Iraq (After Aqrawi, 1998) For locations of wells, refer to Figure 8.

2. Petroleum System

This study deals only with the Paleozoic Petroleum System because the younger rocks are not promising, and they were extensively eroded due to the Early Alpine Orogeny (Sissakian and Fouad, 2015) (Fig. 6). A composite stratigraphic section that represents the Paleozoic succession of the study area (Fig. 10) illustrates the vertical arrangement of the potential source (shale) and reservoir (sandstone) rocks. The succession can be divided into 3 main cycles separated by prominent unconformities. The section also shows thick shale and sandstone intervals (formations) that are deemed to constitute potential source and cap rocks, and reservoir rocks, respectively. Carbonate strata occur in the later part of the Paleozoic Era, e.g., Harur and Chia Zairi formations. The juxtaposition of these various rock types is also expected to generate reliable stratigraphic traps. The source, reservoir, and cap rocks are presented hereinafter.

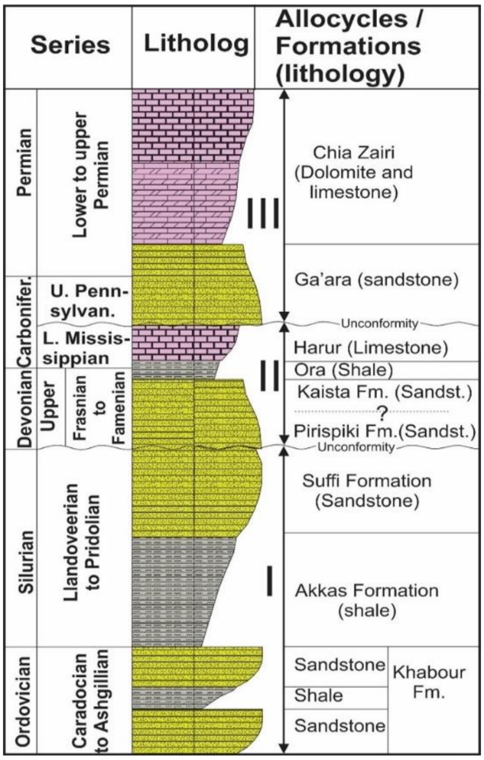

Fig. 10. Composite Paleozoic strata of the moderately stable region of southern Iraq.

2.1 Source Rocks

The Khabour Formation (Ordovician) was encountered in the Khlesia-1 oil well and its unnamed equivalent in the Akkas-1 oil well (Fig. 9). No other well was drilled in the Western Desert to reach the depth where the Khabour Formation and/ or Devonian rocks are expected to occur. At the Akkas-1 oil well, the Khabour Formation contains highly mature, marine, organic-rich hot shales dating back to the Ordovician Era. Al-Haba et al. (1994) stated that these hot shales, with a Total Organic Carbon Content (TOC) ranging from 0.9% to 5%, have the potential to generate light hydrocarbons. Ordovician source rocks are also found in the Risha gas field of NE Jordan (Armstrong *et al.*, 2005) (Fig. 8). The Lower Silurian "hot" shales represent the primary Paleozoic source rocks in the Middle East (Mahmoud *et al.*, 1992). In the Iraqi Western Desert, the Akkas Formation contains hot shales as observed in the Akkas-1 oil well, with Total Organic Carbon (TOC) ranging from 0.96% to 16.62% and a hydrocarbon potential of approximately 49 kg HC/ton (Al-Haba *et al.*, 1994). Additionally, the base of the Silurian at the Akkas-1 oil well holds oil with an API gravity between 42 and 49, along with wet gas.

The condensate fraction of the oil exhibits a high content of saturates and aromatics, with the oil containing 3.9% asphalt (Al-Haba *et al.*, 1994). The Lower Carboniferous Ora

Formation, primarily composed of shale, was encountered in the Khlesia-1 oil well (Fig. 9), displaying a Total Organic Carbon (TOC) content of 3.4%. The organic matter within it is predominantly of continental origin (Al-Haba *et al.,* 1994). In the Khlesia-1 oil well, the TOC varies from 1.0% to 9.94%, with an existing hydrocarbon potential to be around 49 kg HC/tons (Aqrawi, 1998). The Upper Carboniferous – Lower Permian Ga'ara Formation (mainly sandstone alternated with shales) in Jabal Kand-1, Atshan-1, and West Kifil-1 (Figs. 8 and 9) indicates the existence of continental organic matter with an average of 1% of TOC (Al-Haba *et al.,* 1994). These different shale layers constitute highly promising source rocks with high charging potential.

2.2 Reservoir and Seal Rocks

As for now, no confirmed reservoir and seal rocks have been evaluated to contain commercial hydrocarbon; apart from the Akkas field, where commercial gas was found. However, hydrocarbons may be trapped in the sandstone beds of the Khabour Formation of the Ordovician age, as in oil wells of Risha (at Jordan), and Akkas-1 (Fig. 8). Moreover, Ordovician sealing shales have been recorded in the Khabour Formation in the Akkas field (Al-Hadidy, 2007). Unfortunately, no drilled well in Iraq has penetrated rocks older than the Khabour Formation (Ordovician). Moreover, in the whole Iraqi territory, there are no rocks older than those of the Khabour Formation. Therefore, drilling a well in the Western Desert deeper than those that penetrated only the Khabour Formation will give new data about future possibilities of hydrocarbon discovery.

Sandstone layers within the Silurian sequence may also contain hydrocarbons. In these instances, traps are more likely to be stratigraphic rather than structural. However, some traps, known as Stratigraphic-Structural traps, may have developed along north-south trending horst structures formed during the Late Carboniferous and Early Permian Uplift (Jassim and Goff, 2006). Younger reservoirs can be found in the sandstones of the Ga'ara Formation, trapped by the Permian Chia Zairi Formation, which includes many anhydrite units (Jassim and Goff, 2006). Al-Ameri (2010) and Al-Haba et al. (1994) have recognized Silurian rocks and named them the Akkas Formation in the Akkas gas field. Al-Ameri and Baban (2002 and 2000) and Al-Hadidiy (2007) also have identified in deep water well KH 5/6 (Fig. 9) Silurian rocks using palynological data.

Al-Hadidy (2007) mentioned that at well Akkas-l (Fig. 8), the thickness of the Akkas Formation is 864 m, it was encountered at a depth of (1463 – 2327) m. Moreover, Al-Haba et al. (1994) recognized black shales in the well, they pass up into shales with occasional thin sandstone intervals. However, in well Khlesia-l (Fig. 9), only 152 m of the lowermost shales of the Akkas Formation are present (depth 2139 – 2291 m) (Al-Hadidy, 2007). In well KH 5/6 (Fig. 9), the succession comprises sandstones of Llandovery or younger age (Al-Naqshabandi, 1998). In water well KH 5/6, according to Aqrawi et al. (2010) **s**andstone beds found between depths of 560 to 1240 meters, consisting predominantly of quartz arenites and sub-arkoses, interspersed with siltstones and shales. These deposits were laid down in a continental setting, occasionally interrupted by short marine influxes. At deep water well KH 5/6 (Fig. 9), Early – Middle Devonian sandstone and shale beds (80 m) were reported (Al-Ameri *et al.*, 1991; Al-Haba *et al.,* 1994) overlying the uppermost Silurian rocks. According to Jassim and Goff (2006)**.** This interval may thicken in the Iraqi Southern Desert.

Discussion

Those areas, which are included within the tectonically stable parts, have paid less attention as oil explorations are concerned. The main reason is the lack of anticlines to be considered as structural traps for the developed and migrated hydrocarbons.

From the afore-presented data, however, it is clear that there are many anticlines; even on the surface, besides those which are in the subsurface, a good example is the Risha anticline

(Figs. 3, 5b, and 8). Moreover, the two surface anticlines shown in the geological map (Fig. 6) are also good examples of the presence of anticlines (surface and subsurface) which can be good structural traps, especially for the Paleozoic rocks. The studied Paleozoic rocks showed good and encouraging indications for hydrocarbon potential (Al-Ameri *et al.*, 1991; Al-Haba *et al.*, 1994; Al-Hadidy, 2007; Aqrawi, 1998; Aqrawi, Mahdi, *et al.*, 2010). Therefore, those surface and subsurface anticlines (partly not discovered yet) ought to be well-studied and explored to evaluate the hydrocarbon potential of the region. Moreover, the regional unconformity between the Upper Cretaceous rocks (i.e., Tayarat and Hartha formations) and underlying rocks of different ages (e.g., the Permian Ga'ara and older Silurian rocks) which extend from Anah Graben to 30 km west of Akkas-1 oil well (in total about 75 km) can be considered as potential stratigraphic and structural traps with the underlying rocks, such as the Silurian rocks.

In the neighboring regions, north of Saudi Arabia and Jordan, the Cambrian to Early Ordovician Saq Formation occurs under the Ordovician Khabour Formation (Khalifa, 2015). The Siq Formation, which is composed of sandstone, lies beneath the Saq Formation, dating from the Ediacaran to Early Cambrian period, with an unconformity between them (Khalifa, 2015). The Saq Formation is equivalent to the Saleb, Umm Ishrin, and Disi formations in Jordan (Khalifa, 2015). Based on the occurrence of Ediacaran to Early Ordovician strata in the neighbouring countries, it is very likely that they also occur below the Khabour Formation in the Iraqi Western Desert region.

In Saudi Arabia, the Saq Formation from the Ediacaran to Lower Cambrian period comprises polymictic conglomerates, which are found in localized channels created by the Najd fault system. Given that this fault system extends into Iraq (Jassim and Goff, 2006)**.** Probably, the same geological unit is also preserved in Iraq. The Saq Formation is composed of two units, with the lower unit consisting of sandstones and claystone, which were deposited in a fluvial or estuarine environment (Khalifa, 2015). The upper section comprises sandy siltstone and thinly layered, rippled sandstone, known as the Siq Formation in the northern area of Saudi Arabia. Above the Saq Formation lies the Anz Formation, which is characterized by thinly layered, bioturbated, and laminated sandstones, alternating with siltstone to mudstone. These facies indicate coastal and shallow intertidal environments (Khalifa, 2015).

The presence of such thick clastics below the Khabour Formation in the Akass-1 oil well area can represent the juxtaposition of excellent reservoir and seal rocks. Moreover, if they are limited by the Najd Fault system, then the reservoir quality of the rocks may be enhanced by fault-related fractures.

In the Risha gas field along the Iraqi–Jordanian international borders (Figs. 3 and 8), which covers 1500 km^2, the Ordovician tight sandstone produces hydrocarbon from a depth of (2425 – 2575) m. The sediments were deposited in faulted glacio–fluvial channels, as in the case of the Sag Formation. The gas reserve is proven in the Risha field with 34.2 billion barrels (Sorkhabi, 2009). However, estimates of total gas reserves in the field range from 400 Tcf to 2.3 Tcf (Sorkhabi, 2009). The same status may be present under the Khabour Formation in the Western Desert. Therefore, drilling an exploratory well(s) can detect the actual stratigraphic succession and indicate their suitability for hydrocarbon exploration or otherwise.

In the Southern Desert, the situation may be almost the same as in the Western Desert. There are several proven oilfields, like Al-Samawa, Diwan, Salman, and Abu Khaima (Fig. 3). However, due to the absence of deep wells (oil and/ or water), it is difficult to decide the subsurface geological setting. Nevertheless, since the surface geology of both deserts is mainly the same geologically (Sissakian, 2000)**.** Likely, the subsurface geology of the two regions is similar. Thus, the petroleum opportunities inferred for the Western Desert may also be available in the Southern Desert.

Apart from the Paleozoic rocks, the Euphrates (Lower Miocene) and Jeribe (Early – Middle Miocene) formations may contain hydrocarbons. Both are exposed widely in the Iraqi Western Desert (Fig. 6). It is worth mentioning that the Jeribe and Euphrates formations are lumped together in the geological map due to scale limitations (Fig. 6). Nevertheless, the Jeribe Formation terminates south of Wadi Hauran. Both the Euphrates and Jeribe formations are succeeded by the Nfayil Formation, which dates back to the Middle Miocene. The Nfayil Formation comprises three cycles of green marl and marly limestone, measuring between 13 and 18 meters in thickness (Sissakian and Fouad, 2015). Therefore, it is deemed to form an excellent cap rock that may take part in the hydrocarbon trapping system in the study area.

The Jeribe Formation (Lower – Middle Miocene) is a good reservoir at many oilfields (e.g., Jambur and Naft Khanah, Fig. 3) (Dunnington, 1958). The formation contains heavy oil at Qasab, Jawan, Najmah, and Qaiyarah fields (Fig. 3), and in the Jebissa field of NE Syria (Metwalli *et al.,* 1974). Both primary and secondary porosities are present (Jassim and Al-Gailani, 2006). As the Jeribe Formation, the Euphrates Formation has reservoir potential in basin-center locations, such as Tikrit, Balad, and Samarra. The "Main Limestone", which refers to the Miocene Euphrates and Jeribe formations, produces oil at the Judaida, Khabbaz, Ajeel, and Hamrin fields in north-central Iraq, and at Jebel Fauqi, Halfaiya, and Buzurgan in SE Iraq (Jassim and Goff, 2006). In summary, these Neogene strata of the study area are potentially promising, and exploration companies are recommended to bring their interest to both the Paleozoic and Neogene successions of southern and southwestern Iraq.

Conclusions

All researchers who regard the Iraqi Western and Southern deserts as tectonically stable areas seemingly lack promising sites for hydrocarbon exploration because of an apparent absence of structurally trapped formations caused by tectonic activity. This was one of the main reasons for not paying much attention to this area during oil exploration activities, although there were some. Our study demonstrates that both deserts of Iraq are rather tectonically active with several indications for Neotectonic activities, faults, and broad, low-amplitude folds like those present in Wadi Akash and Wadi Al-Ratgah. Moreover, the possibilities of finding hydrocarbon in the Western Desert are shown, especially in the Ordovician and Cambrian rocks, where excellent source, reservoir, and seal rocks occur in the Khabour Formation and the Silurian sequence. This inference is based on gas discovery in the Risha field within Cambrian – Ordovician rocks and the Saq Formation (Lower Cambrian) in Saudi Arabia. Moreover, in the Khabour Formation at Akkas-1 oil well, highly mature, marine, organic-rich hot shales of the Ordovician age were encountered, which can generate light hydrocarbon because the rocks showed TOC of 0.9% to 5%. The subsurface geological characteristics of the Southern Desert closely resemble those of the Western Desert. As a result, any data obtained in the Western Desert may also apply to the Southern Desert, suggesting a favorable potential for hydrocarbon presence. It is worth mentioning that several oil fields were discovered in the Southern Desert. Furthermore, there is the possibility of finding oil within the Neogene Euphrates and Jeribe formations in both deserts. This assumption is based on the presence of hydrocarbons within these two formations in many oil fields in Iraq, some of which are already oil-producing.

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Conflict of Interest

The authors declare that there is no conflict of interest as the current article is concerned.

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