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Lower Permian Fluvial Sediments, Ga'ara Depression, Western Iraq: Depositional Environment and Hydrocarbon Potential

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Abstract
Synthesis of sedimentologic, paleocurrent, and organic geochemistry data of the Lower Permian Ga'ara Formation from the Western Desert, western Iraq, shows good hydrocarbon potentiality and deposition by high sinuosity and mixed-load channels, likely by a meandering river system. The Ga'ara Formation includes kaolinitic mudstone beds of various colors and channelized quartzitic sandstone beds. Based on the lithofacies identification, five lithofacies associations have been recognized: channel-floor, point-bar, abandoned channel plug, crevasse splay, and interchannel flood basin. In addition, the paleocurrent analysis and sandstone percentage map indicate a variation of the paleoflow spatially and temporally with a general direction range between NE and Sw, and the depositional environment has been interpreted as a meandering river system.
To unravel the hydrocarbon potentiality of the Ga'ara Formation deposits, Pyrolysis and TOC% analyses were conducted on selected samples. The studies indicated that the Ga'ara Formation in western Iraq could be a moderate to excellent rock source. The PCI agrees with TOC content, suggesting that the generation potentiality of the mudstones as a source rock is poor and poor to excellent. All the analyzed samples show that their hydrocarbons are indigenous. The Ga'ara mudstones of the Nijili and West Tayyarah have very good generative potential, whereas the Ubairan samples have excellent generation potentiality. The Nijili and Ubairan samples are at an early stage of oil generation, i.e., immature. In contrast, the Tayyarah sample represents a postmature phase at the end of oil generation. Collectively, these new data on spatial distribution, geologic characters, and organic geochemistry propose that the Ga'ara Formation in western Iraq could be a valuable economic asset with good hydrocarbon potentiality.

Keywords: Ga'ara Formation, Meandering river system, Rock-Eval analysis, Hydrocarbon potentiality, Iraq

الترسبات النهرية لعصر البيرمي الأسفل في منخسف الكعرة غرب العراق : البيئة الرسوبية وإمكانية توليد الهيدروكاربونات

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الخلاصة

أظهرت نتائج الدراسة الرسوبية ودراسة التيار القديم وتحاليل الجيوكيمياء العضوية لتكوين الكعرة بعمر البيرمي الاسفل في الصحراء الغربية ، غرب العراق ، إمكانية توليد هيدروكربونات جيدة وانه وترسب بواسطة قنوات التوائية ، على الأرجح بواسطة نظام نهري متعرج التوائي .يتألف تكوين الكعرة من طبقات من الحجر الطيني الكاؤوليني بالوان مختلفة وطبقات قنواتية الشكل من الحجر الرملي الكوارتيزي . واعتمادا على المشاهدات والدراسة الحقلية للسحنات الصخرية تم تمييز خمسة ترافقات سحنية صخرية وهي قاع القناة و الحواجز النهرية و والقنوات النهرية المهجورة و والسهل الفيضي .وبالإضافة الى ان تحاليل التيار القديم وخريطة النسبة المئوية للرمل اثبتت التغاير في مجرى النهر و اختلاف التيار القديم مكانيا وزمنيا مع نطاق اتجاه عام بين جنوب شرق وشمال شرق وتم تفسير بيئة الترسيب على أنها نظام نهر متعرج التوائي.

ولبيان إمكانية توليد الهيدروكربونات لرواسب تكوين الكعرة، أجريت تحليلات الانحلال الحراري ونسبة الكربون العضوي الكلي على عينات مختارة من الحجر الطيني وبينت النتائج ان الترسبات الطينية لتكوين الكعرة في غرب العراق يمكن أن تكون مصدرا لتوليد الهيدروكربونات بنسبة قليلة الى إلى ممتازة. وتطابقت نتائج المحتوى الكاربوني العضوي الكلي مع معامل انتاج الهيدروكربونات وهذا يدل على إن الصخور الطينية تعد صخور مصدرية فقيرة الى متوسطة وأحيانا ممتازة. وبينت النتائج ان نوع الهيدروكربونات فيها هو من نوع الهيدروكربونات غير المهاجرة. اتسمت صخور تكوين الكعرة الطينية في النيجيلي وغرب الطيارة بإمكانات توليد هيدروكربونات جيدة جدا، في حين أن عينات العبيران لديها إمكانات توليد هيدروكربونات ممتازة.

الكلمات المفتاحية : تكوين الكعرة , نظام النهر الالتوائي, تحليل الانحلال الحراري, قابلية توليد الهيدروكربونات, عراق

1. Introduction

The Ga’ara Formation is the oldest exposed formation in western Iraq. It is exposed only at the Ga’ara Depression (Figure 1 a and b). 15 outcrop sections and three subsurface sections have been selected to study the formation. Table (1) reveals the coordinations and thicknesses of these sections. The formation is composed of cross-stratified siliciclastics sandstone and mudstone (Figure2). It comprises stacked sandstone channels, often with lags of intraclasts such as ironstone and extraclasts pebbles. Passing upwards into grey and mottled varicolored mudstone is overlain occasionally by purple to red (locally pisolitic and concretionary) ironstone. The Ga’ara mudstones are rich with plant debris such as rootlets, leaves, and barks [1] and [2].

The clastic unit of the upper exposed part of the Ga’ara Formation, which is 50 m thick at Tel Afaif–Ga’ara Depression in western Iraq, was initially named “Ga’ara Sandstone Formation” Boesch, 1938 in [3] Previously, in the Ga’ara Depression, the Nijili Formation was introduced Dunnington, 1954 in [3] for an outcrop about 7 km east-northeast from Bir Mulussa (hand-dug water wells). The formation comprises ~16 m of variegated marls and shale with thin sandstone beds near the base. Later [4] disputed the status of the two lithostratigraphic units Ga’ara and Nijili formations for the first time and realized that both units belong to one formation. Still, they developed into a little different facies. All workers familiar with the area's geology accorded their views concerning the stratigraphy of

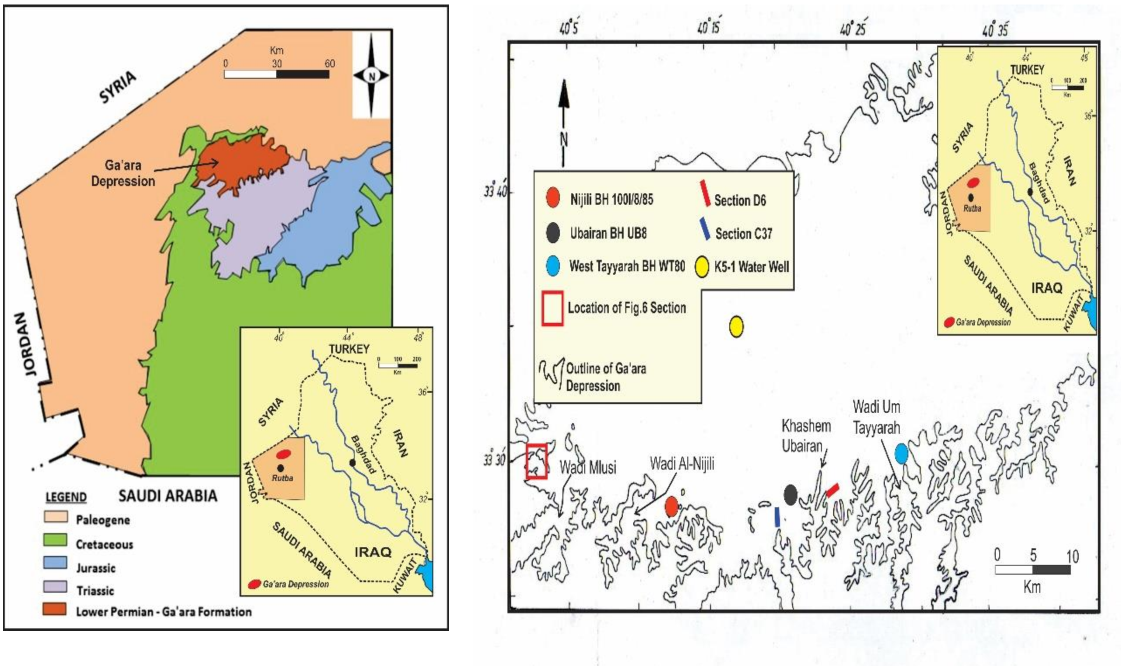

Figure 1: a. Geological map of the Western Desert of Iraq after [5]; b. Location map of boreholes, water wells, sections, and Figure 9.

Table 1: Coordinations and thickness of the studied sections

Section No.	Easting	Northing	Thickness (m)
1	40 05 95	33 30 83	33
2	40 47 75	33 28 75	37
3	40 10 98	33 29 63	20
4	40 13 75	33 28 79	52
5	40 13 75	33 26 17	36
6	40 16 33	33 27 35	42
7	40 18 90	33 28 84	44
8	40 33 06	33 29 70	17
9	40 23 47	33 29 52	46
10	40 24 46	33 30 33	37
11	40 30 33	33 32 09	39
12	40 38 74	33 32 81	42
A27	40 41 41	33 34 35	8
C37	40 02 95	33 30 92	38
D6	40 02 18	33 29 61	23
Nijili BH100/8/85	40 11 06	33 28 23	53
UbairanBHL/88	40 18 85	33 28 71	49
West TayyarahBHWT80	40 26 17	33 30 24	55

The Ga’ara Formation belongs to the Tectonostratigraphic Megasequence AP5 (TMS AP5): Late Carboniferous to Mid Permian.This TMS was later modified by [4] to become the Modified Westphalian – Ufimian (Syn-Hercynian) Megasequence. TMS AP5 comprises two formations, the Ga’ara and Bir El Rah [6], yet [7] considered the Ga’ara Formation the only constituent of the TMS AP5. This megasequence was dominated by relatively thin, partly syn-rift, Permocarboniferous clastics that lasted ~40 my [8].

The Ga'ara Formation is extensively studied, mostly mineral resources such as kaolin clay, silica sand, and sedimentary ironstone. The Iraq Geological Survey set detailed mapping programs during the eighties and early nineties of the last century [1] and [2], mainly focusing on mapping and mineral prospecting. [9] reviewed the Paleozoic stratigraphy of Iraq's western and southwestern desert and summarized the earlier exploratory works concerning the petroleum systems and hydrocarbon potentiality (e.g., [10]; [11]; and [12].[8] concluded that the main Paleozoic source rocks in this area of Iraq are the Lower Silurian marine hot shale which is ~65 m thick in the Akkas-1 well. He added that other potential source rocks could be the black shale of the Khabour Formation (Ordovician), Ora Formation (Upper Devonian – Lower Carboniferous), and the lower shale beds of Chia Zairi Formation (Upper Permian). He questioned the potentiality of the Ga'ara Formation as a significant source of hydrocarbon. [13] reiterated the potential Paleozoic hydrocarbon sources and considered the shale unit of the Ga'ara Formation as a source.[14] concluded that the Ga'ara sandstone is sufficiently coarse-grained to be a promising exploration target and proposed that interbedded mudstones may locally act as an effective seal.

This study aims to reveal the depositional environment of the Ga'ara Formation by employing basin analysis techniques and to evaluate its hydrocarbon potentiality by conducting organic geochemical analyses. The studied part of the Ga'ara Formation is the uppermost portion, which totals about 60 m thick (Fig. 2).

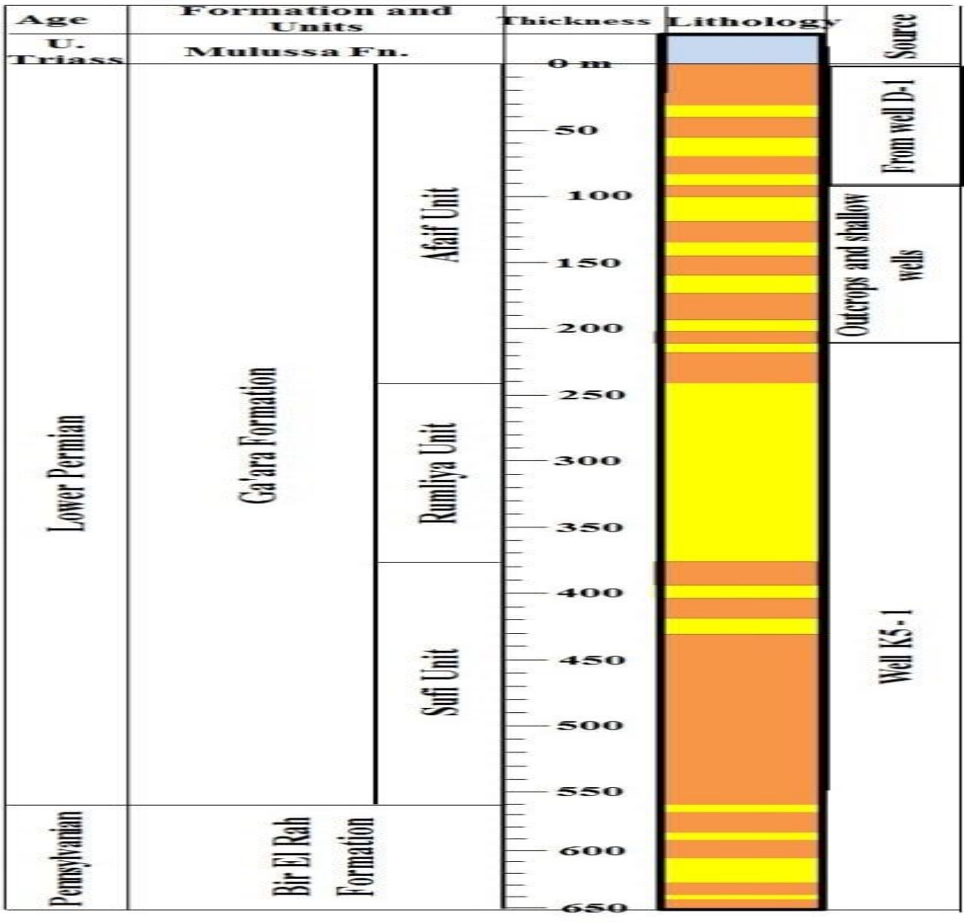

Figure 2: Stratigraphic column of the upper part of the Ga'ara Formation

2. Geological setting

The exposures of the Ga’ara Formation are almost restricted to the central parts of the Ga’ara Depression in western Iraq, with a veneer cover of friable sand and gravel. The investigated area is at the top of the Rutba High within the Rutba-Jezira Zone in the stable part of the Nubian-Arabian Platform at the northeastern part of the Arabian Inner Platform [15]. The Rutba High is manifested on the surface by gentle dips towards the northern, eastern, and southern margins of the Ga’ara Depression. The Ga’ara Depression is formed by deep erosion of the most uplifted part of Rutba High. The strata on the south margin of the depression dip south-southeastwards very gently (Figure3) and represent the older part (Permocarboniferous and Late Triassic).In contrast, the strata on the northern, eastern, and western margins dip very gently northwards and are represented by the younger strata (Late Cretaceous – Paleogene). This structural framework was considered anticline during the former geological survey and called Ga’ara Anticline. Yet, [16] and [17] argued for a more accurate description rather than an anticline because the two sets of dips were formed at different tectonic episodes (Figure4).

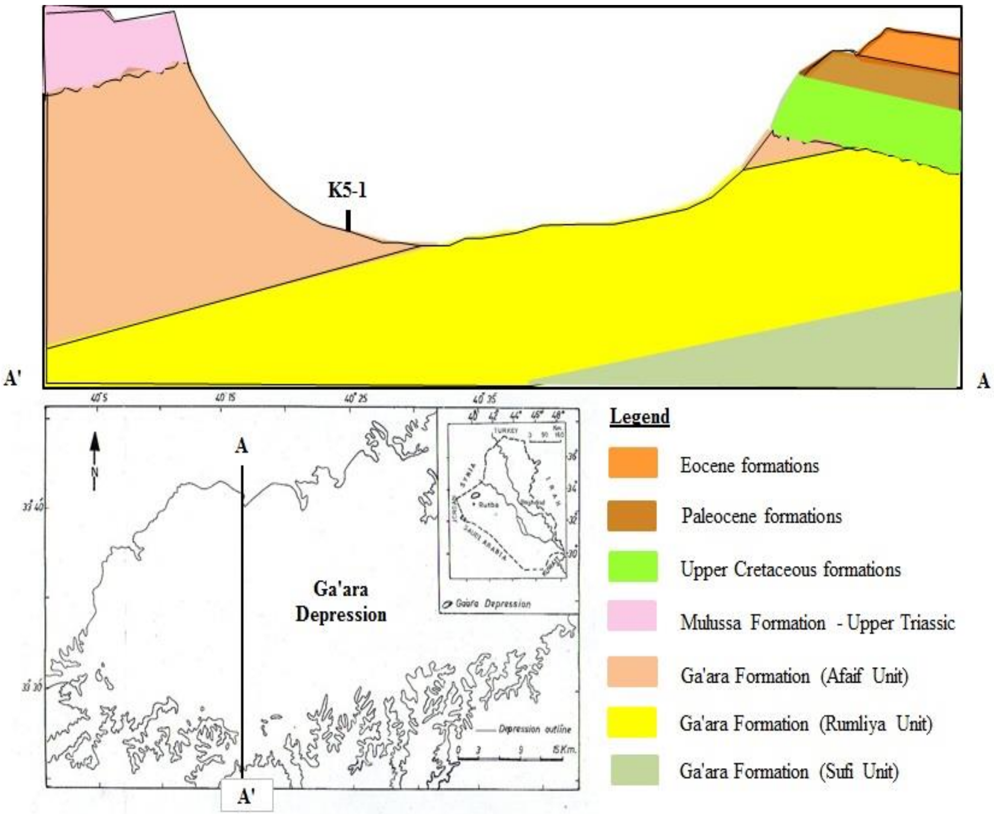

Figure 3: N-S schematic geologic cross-section (A-A’) in the Ga’ara Depression (not to scale) after[16].

The Ga’ara Depression is an E–W 60x30 km elongated depression bordered by cliffs of ~100 m above its floor. The exposed part of the Ga’ara Formation is ~120 m thick, and the subsurface part is ~730 m based on the water well K5-1, which is drilled in the central part of the depression (total thickness is ~850 m). However, the Ga’ara Formation shows considerable thickness variation in the Western Desert of Iraq.

Isopach map for this formation indicates two sub-basins: a northern sub-basin southwest of Al-Qaim Town and a southern sub-basin extending toward the Widyan Basin in Saudi Arabia (Figure4). The Ga’ara Formation is the lithostratigraphic and chronostratigraphic equivalent of the Unayzah Formation in Saudi Arabia [18] and [9], Faraghan Formation in Iran [19] and [20], and Amadeus in Syria [11].

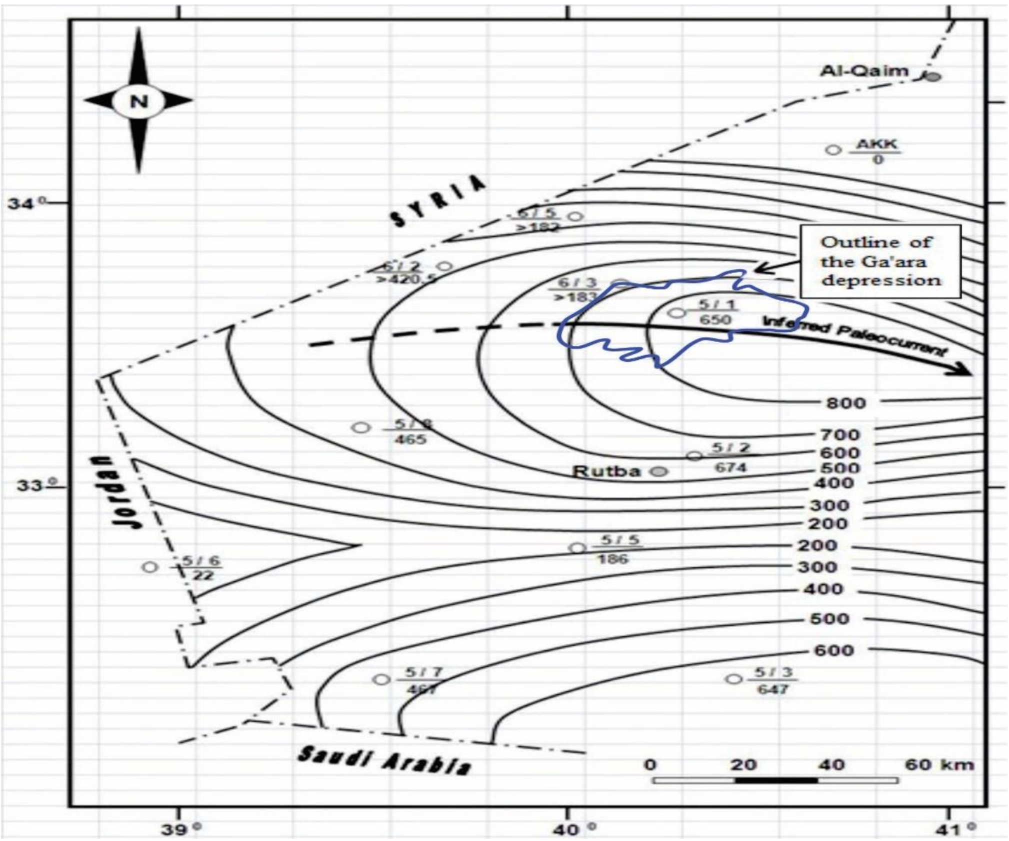

Figure 4: Isopach map of the Ga’ara Formation in Western Iraq

Paleobotanical studies revealed that the exposed part (uppermost) of the Ga’ara Formation belongs to the Middle to Upper Permian age [21]. In contrast, palynological studies suggested Upper Carboniferous – Lower Permian (Stephanian – Autunian) [22] and [23]. Additionally, based on palynological studies, [11] accepted the Westphalian – Artinskian age. [22] studied the same samples in this study and suggested Autonian age by palynological analysis. The stratigraphic record of the Ga’ara Depression includes hiatus from the Late Early Permian to the Middle Eocene between the Ga’ara Formation and the overlying lithostratigraphic units (Figure1). [1] revealed that several lithostratigraphic units overlie the Ga’ara Formation at different localities in the Ga’ara depression, ranging from the Middle Triassic to the Middle Eocene. These units wedge out abruptly. The lower contact of the Ga’ara Formation with the Westphalian – Stephanian Bir El Rah Formation in well K5-1 is gradational [6].

.3Methods

The lithofacies and paleocurrent data were based on fieldwork carried out by the Iraq Geological Survey in two seasons, in 1983 and 1986–1990 [1] and [2]. Data were collected from 15 outcrop sections (hand-dug trenches and machine excavated) and three shallow boreholes (core and auger drilled –up to 60 m deep). Table 1 illustrates the coordinations and thicknesses of these sections and about 1300 paleocurrent measurements from 12 outcrop sections (Figure5)

.

Eight core samples of mudstone are collected from shallow boreholes drilled in the Ga’ara Depression as follows: five samples from wadi Nijili (borehole BH.100/B/85), two representatives from Khashim Ubairan (boreholes U.B. 8 and UB8a), and one sample from West Wadi Umm Tayyarah (borehole WT80; see Figure 1b for map locations). All whole-rock samples are analysed by rock-Eval pyrolysis at the Central Laboratories of the Oil Exploration Company (OEC), Habibiya, Baghdad, Iraq. The samples were analyzed for total organic carbon.

TOC) and Rock-Eval pyrolysis. This technique followed in this study is based on the methodology described by [23]; [24]; [25]; [26]; and [27].

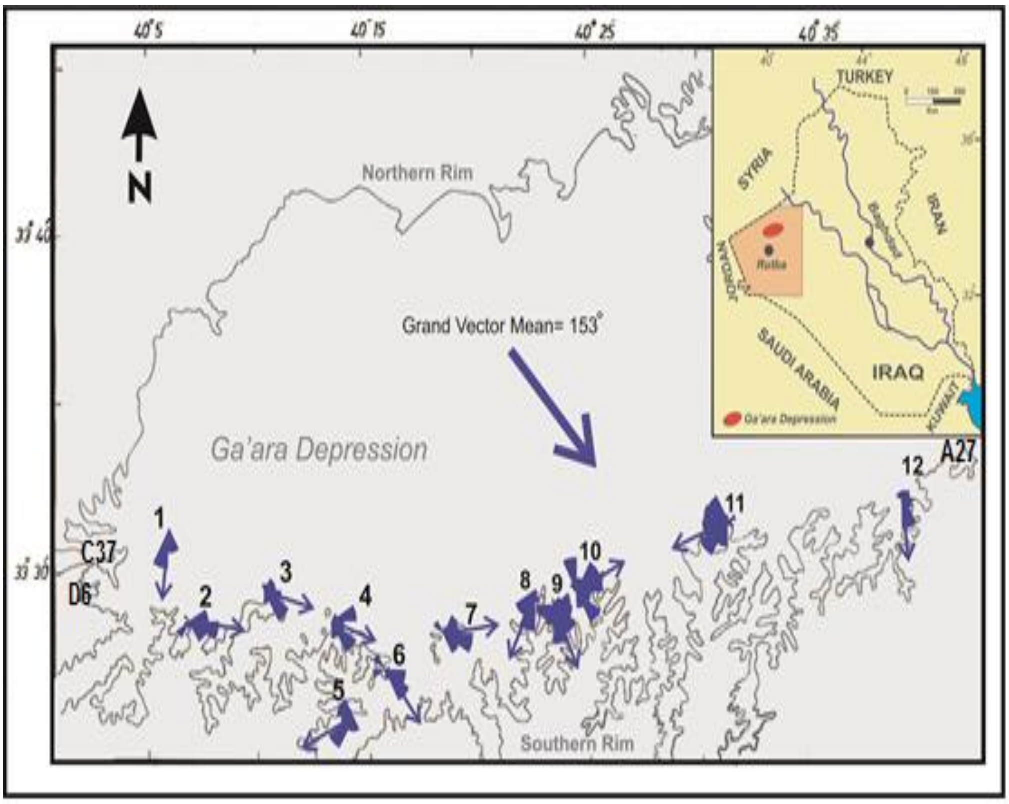

Figure 5: Location of outcrop sections

4. Results and Discussion

4.1The Ga’ara Formation sedimentary succession and depositional environment

The Ga’ara Formation shows considerable thickness variation in the Western Desert of Iraq. The upper part of the Ga’ara Formation consists of alternating sandstone and mudstone (Figure 6). The sandstones are usually in lenses of white, pale beige, or varicolored with cross-bedding. The sandstones are poorly cemented, quartzose (Quartzarenite), and occasionally ferruginous. The sand grains are subangular to subrounded with a very fine to the medium-grained size range. In some places, gravel can be seen at the bottom of the sandstone beds.

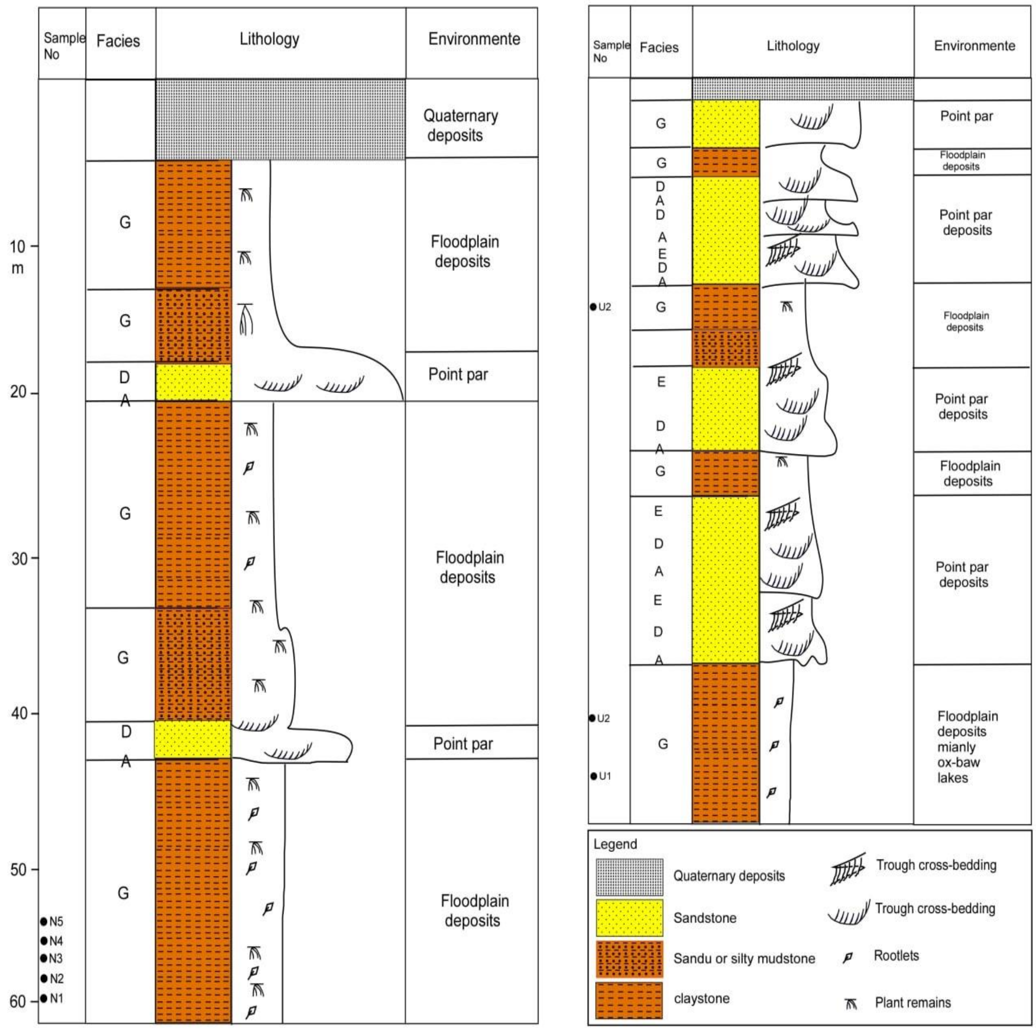

Figure 6: Stratigraphic sections of two boreholes: Nijili (BH.100/B/85) on the left and Ubairan (UB 8) on the right, show the lithofacies, depositional environment, and organic geochemistry samples. See Figure (1b) for the location.

Iron oxyhydroxides concretions and fragmented pisolite may also be associated with the gravels. Stacked channel fills occasionally contain sigmoidal cross-bedding similar to point bar accretionary structures. Mudstones form the major lithology, but siltstones are far less frequent than sandstones and mudstones. The siltstone color is variable and may change from black and grey to yellow, purple, and reddish-brown over a short distance. The mudstones are kaolinitic and ferruginous or carbonaceous (with pyrites). Iron oxyhydroxides are also present in the mudstone as pisolites and oolites (Figure 7) or concretions. The pisolites are solitary or grouped. The solitary pisolites are intact and appear as floated materials in the mudstone, indicating an endogenic (in situ) origin. Plant debris and rootlets are frequent, and some are well preserved (Figure 8). In some places, the organic matter is rich and thick, as in boreholes U.B. 8, WT80, and BH.100/B/85 (Figure 9), forming black horizons of apparent immature coal .

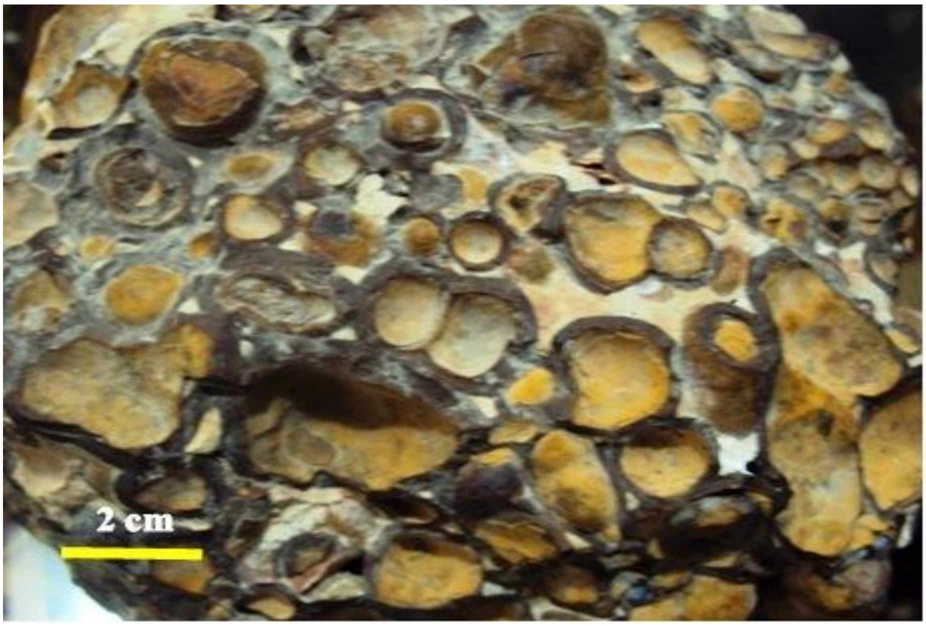

Figure 7: Crowded pisolites of iron oxyhydroxide with minimal matrix in the Mudstone lithofacies at document point C47 at the central part of the southern margin of the Ga'ara depression.

The channel systems have narrow belts, and their channel fills have average width/depth ratios, resting on a section of relatively thick muddy floodplain deposits (Figure 12). The percentage of the sandstone/mudstone is 1 to 4, and the scour has high relief. Paleocurrent analysis demonstrates

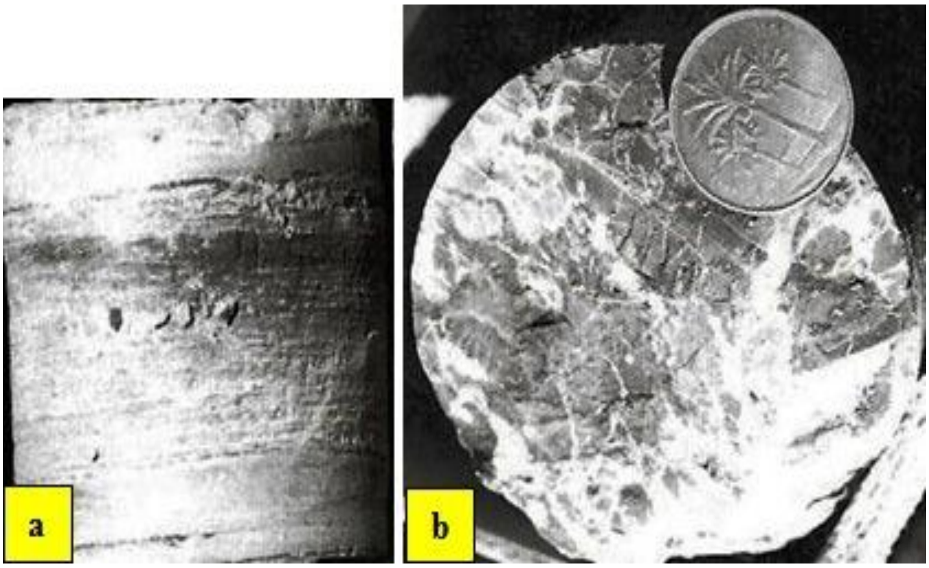

Figure 8: Plant debris in the mudstone gives the black color (the core diameter is 11 cm). (a) The black organic plant debris makes a wisp (S.no.N.58-59m depth). (b) In horizontal section shows leaf impressions and other plant debris.

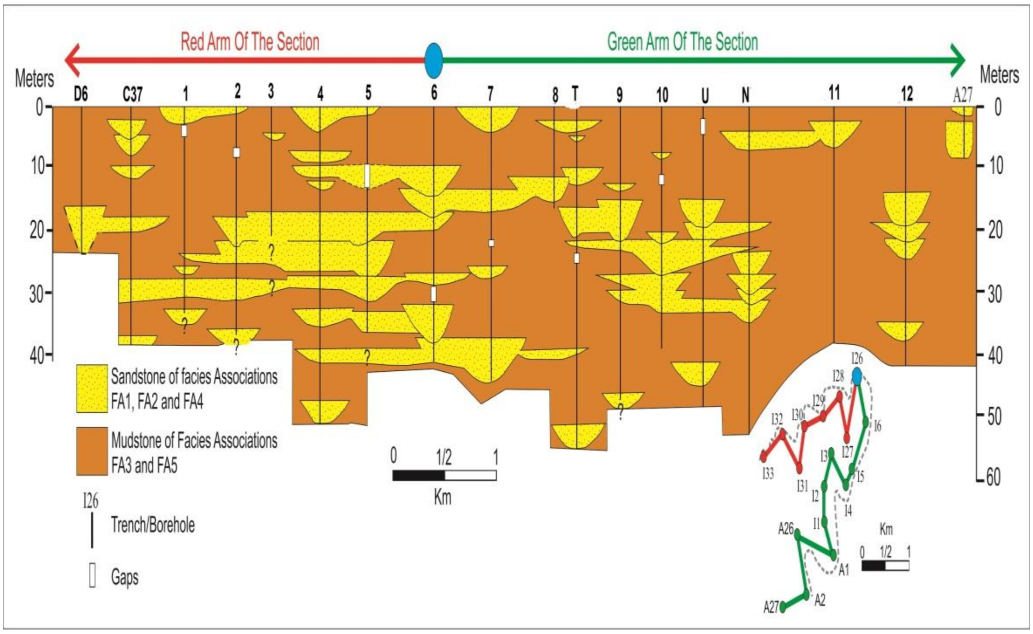

Figure 9: Stratigraphic profile showing correlation of the lithofacies and the nature of channels. See Figure 1b and Figure 6 for the location of the section.

The vector means of the paleo flow direction range from 60º to 248º with a Grand Vector Mean of 153º and vector magnitude ranging from 34% to 89% (Table 2). It displays changes up to 360º, unimodal, bimodal, and polymodal (Figs 13 and 14). The mean vector direction of the paleocurrent varies greatly spatially and temporally. Channels flow in almost any direction relative to the river's mean vector direction, thus having a greater spread of flow directions (lower dispersion value). [28] showed that meandering rivers have a more significant flow direction than braided rivers. There is a marked difference between the mean flow direction from the sandstone percentage map (Figure 15) and the paleocurrent analysis (Figure 14).

Table 2: Paleocurrent analysis of twelve outcrop sections at the southern margin of the Ga'ara depression showing the vector mean of the paleoflow direction and grand vector mean magnitude(for location, see Figure6)
W/V = sin x / cos x = tan x = 0.513
Grand vector mean = tan-1x = 27 180 – 27= 153º
Grand vector magnitude (R) = (W2 + V2)1/2 = 6.64
L (Vector magnitude %) = R / n (number of stations) = 0.56

Station no.	Vector Mean θ (V)	Vector Magnitude (L%)	sin x (W)	cos x (V)
1	189	89	-0.156	-0.988
2	125	46	0.819	-0.574
3	103	61	0.974	-0.225
4	111	72	0.934	-0.358
5	248	67	-0.927	-0.375
6	144	34	0.588	-0.809
7	81	55	0.988	0.156
8	206	79	-0.438	-0.899
9	164	42	0.276	-0.961
10	6	45	0.866	0.5
11	248	49	-0.927	-0.375

12	178	80	0.035	-0.999
	138	60	3.032	-5.907

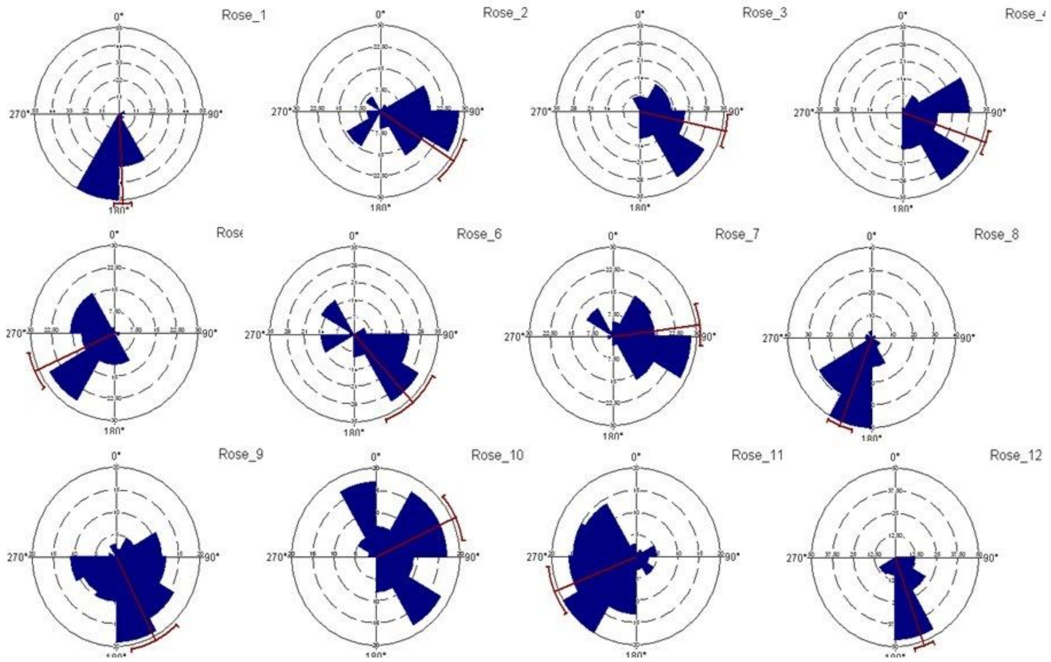

Figure 10: Rose diagrams of 12 document points covering the outcrops at the southern margin of the Ga’ara depression

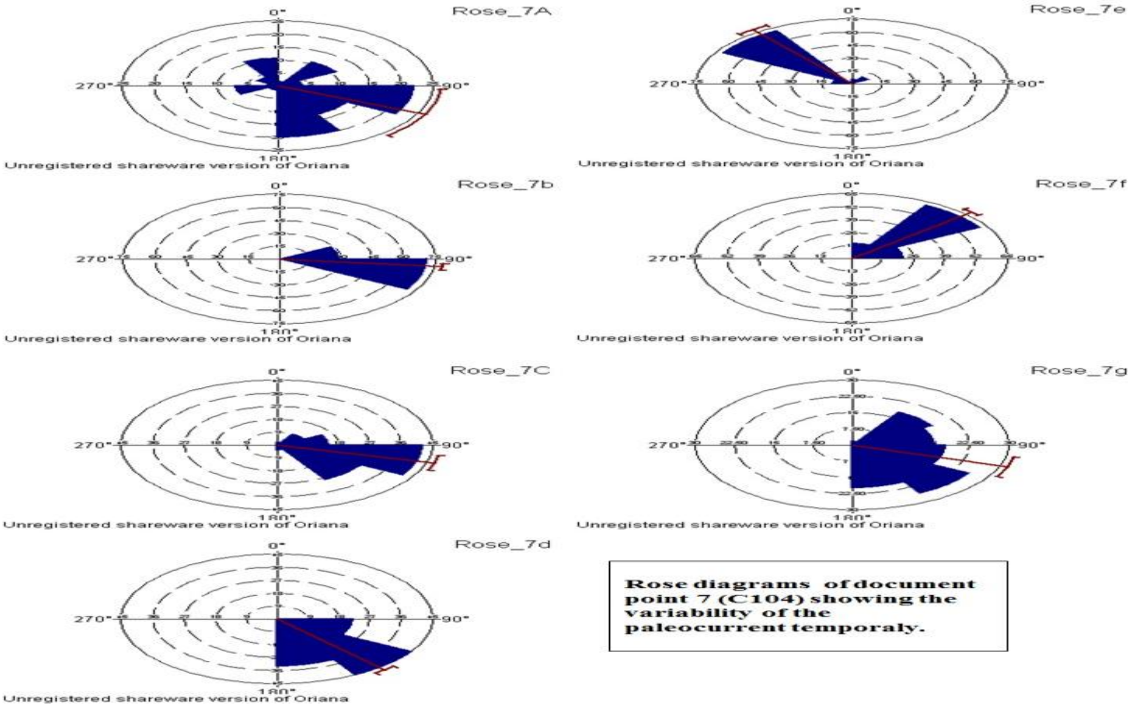

Figure 11: Rose diagrams of the paleo flow at stations in document point C37 and D6 to show the temporal variation (i.e., from bottom to top)

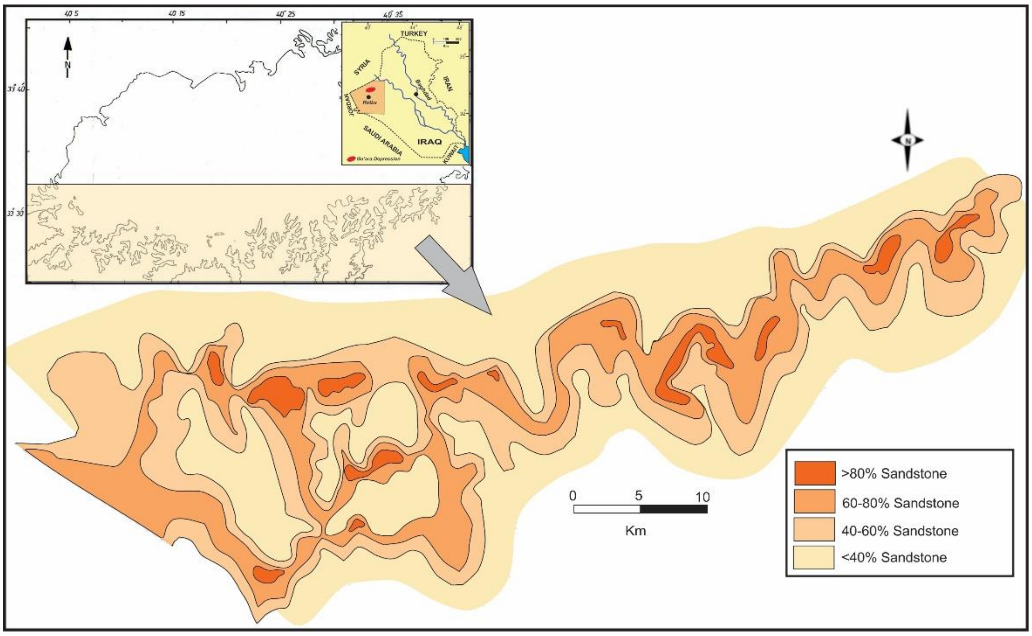

Figure 12: Sandstone percentage map of the top 50 m of the Ga'ara Formation at the southern margin of the Ga'ara Depression

4.2. Lithofacies analysis

Seven lithofacies have been recognized in the deposits of the Ga'ara Formation. These lithofacies are Scoured surfaces (A), Poorly-defined trough cross-bedded sandstone (B), Plane-bedded sandstone (C), Well-defined trough cross-bedded sandstone (D), Tabular (Planar) cross-bedded sandstone (E), Cross-laminated sandstone-mudstone (F), and Mudstone (G). A rhythmic pattern of deposition characterizes the Ga'ara Formation. The rhythms represent a channel system mainly isolated, lenticular geometries and well-developed point bar deposits. The rhythms invariably commence with scouring in the sediments of the previous rhythm (lithofacies A; Figure 16) .

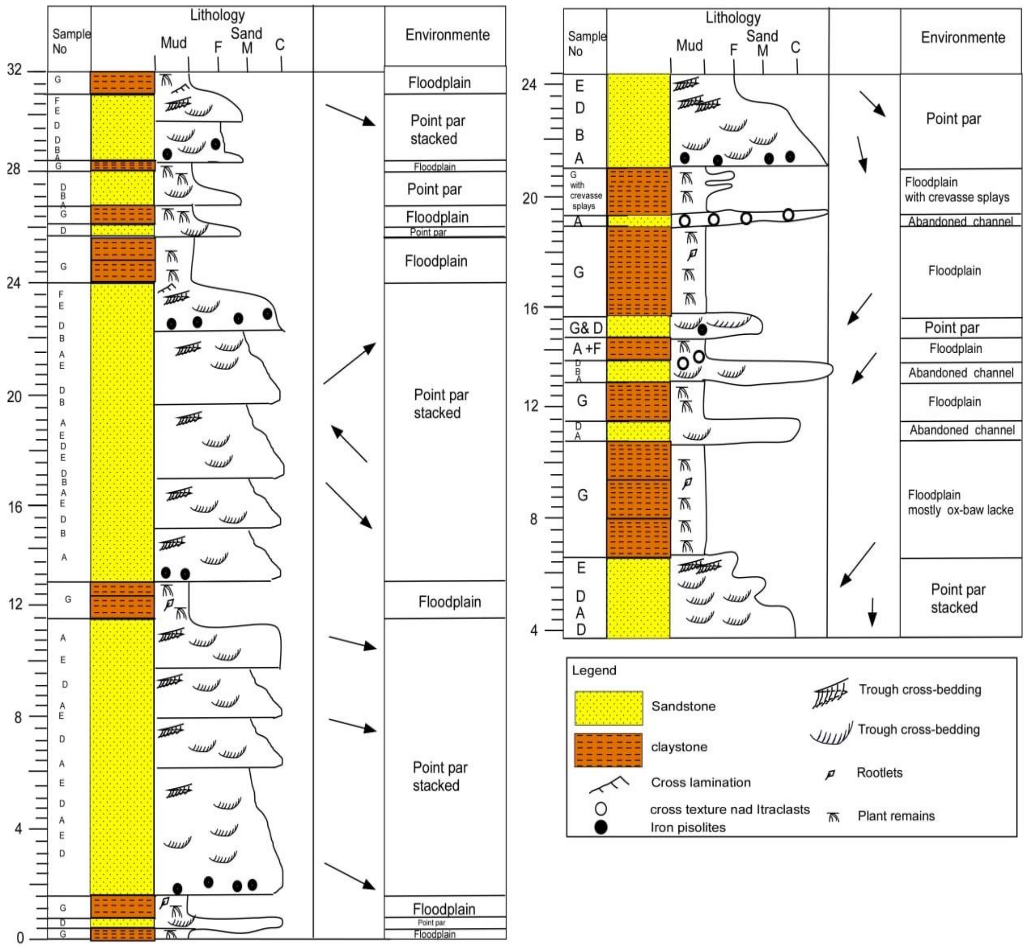

Figure 13: Stratigraphic sections of two outcrops (C37 on the left and D6 on the right) show the facies, depositional environments, and paleo flow. See Fig 6 for the location of the outcrop sections.

The in-channel lithofacies are trough and planar cross-bedded fine to medium-grained sandstone and point bars (Figs. 13 and 16). The floodplains are broad, thick, and fine-grained with dense vegetation, forming about 62% of the total thickness of the measured sections. Such conditions stabilize the banks and allow the generation of sinuosity.

.4.3Lithofacies associations

4.3.1 The channel-floor lithofacies association (FA1)

The channel-floor facies association begins with scoured surfaces (A), which are sharp and irregular. The erosion depth is usually in a couple of ~2-3 m. The scoured surfaces are commonly overlaid by massive looking (featureless), often ill-sorted, generally coarser-grained sandstone, about the rest of the sandstone members with exogenetic and endogenetic gravels. The endogenetic clasts are mostly portrayed as fragmentary iron pisolites and concretions and more scarcely mudstone from the nearby mudrock layers, whereas the exogenetic gravels are mostly granitoid. The massive sandstone occasionally develops into poorly-defined trough cross-bedded sandstone (B). It comprises the coarsest clastic fraction of the individual sandstone beds, with medium-grained sandstone to pebbly, coarse-grained sandstone. The thickness of lithofacies B ranges from ~0.3 m to ~1.0 m. The vague development of the sets probably results from the bad sorting in the sediments. B commonly grades upwards into well-defined trough cross-bedded sandstone (D) or, more rarely, to plane-bedded sandstone (C). Lithofacies D is expected in the sandstone members of the Ga’ara Formation. Its thickness ranges from ~0.5 m to several meters and comprises medium- to coarse-grained sandstones. The depth of the troughs varies from 10 to 80 cm, though most are in the order of ~30 cm and can be traced horizontally to ~2 m. The size of the sand grains generally correlates positively with the magnitude of the trough cross-bedding (Fig . 16). The forests usually show distributed graded bedding, i.e., a decrease in the size of the grains upwards with no mixing of different sizes. Endogenetic clasts are hardly found in these sediments, but exogenetic clasts are not uncommon. This facies is usually formed by unidirectional migration of dunes. Such lithofacies association represents the channel-lag and in-channel deposits (lower and mid bar, Figure 16).

4.3.2 Point-bars lithofacies association (FA2)

The channel floor facies association (FA1) passes upwards into another set of lithofacies. The new set is usually complex, commonly beginning with smaller-scale trough cross-bedding (D), occasionally followed by tabular (planar) cross-bedded sandstone (E), and sometimes passes to cross-laminated sandstone (F) lithofacies. The lower contact is gradational if it begins with lithofacies D and is sharp. It starts with lithofacies E. Point-bars facies association (FA2) is ~2-7 m thick fining upward succession consists of several lithofacies. This facies association is called epsilon cross-bedding by Allen (1970) and [18], heterogeneous and gently sloping. Plant roots commonly modify the bar surfaces.

4.2.3Abandoned channel plug lithofacies association (FA3)

This facies association is not infrequent in the Ga'ara Formation and is ~4-7 m thick. It starts with a scour surface (A), followed by poorly-defined trough cross-bedded sandstone (B), and occasionally by either plane-bedded sandstone (C) or cross-laminated sandstone (F), and culminates with mud plugs. The mud plug consists of fine sediments, more refined than the channel-fill deposits. The mud plugs range in thickness from ~1-5 m and have grey color shades due to the coalified plant debris.

4.2.4 Crevasse splay lithofacies association (FA4)

This facies association consists of massive (featureless) siltstone and very fine to fine sandstone (F). It exhibits coarsening upwards with lower and upper sharp contacts. It ranges in thickness between 0.2-0.6 m and is uncommon in the logged outcrops. This lithofacies association exists within the mudstone (G), representing a breach in the river bank during floods and partial buildup of sediments, mainly of the suspended load.

4.2.5 Interchannel flood basin lithofacies association (FA5)

It is also referred to as the floodplain lithofacies association. It comprises one major lithofacies, namely mudstone lithofacies (G). Interchannel flood basin is the most common lithofacies association in the Ga'ara Formation, making up about two-thirds of the studied part of the formation. The thickness ranges from ~0.2-42 m (at Wadi Al-Nijili, approximately interrupted). This lithofacies association may extend for several kilometers in sections parallel to the depositional strike. This facies association culminates with a fining-upwards succession, having lower gradual contact with cross-laminated or cross-bedded sandstones. The upper contact is sharp and irregular, marking the new fining-upwards sequence. It comprises varicolored claystone, mudstone, and siltstone and is often mottled.

The color varies, including pale grey, grey, black, yellow, purple, and red. Interchannel flood basin facies association represents the fine suspended-load sediments that reach the interchannel area during floods, i.e., floodplain deposits. Unlike the channel-fill deposits, they represent low sedimentation rates, allowing reworking by biota and plant growth. Pedogenic processes are revealed by plant rootlets and pyrite concretions or iron pisolites (Figure 10). The pisolites and plant rootlets are inversely proportional. Deposition of this facies association is from quiet water, as the clay particles need a long time to settle. It settles within the floodplain deposits, occupying a large area on both river banks. A drop in the current speed leads to the deposition of silt granules followed by clay particles. The presence of mudstone beds among siltstone beds is evidence of sudden fluctuation in the rate of the flowing water. This facies association occasionally contains hydrated forms of ferriferous oxide (crystalline and amorphous), such as goethite, giving rise to varicolored mudstones. In many cases, yellow-brown colors result from recent weathering and hydration, i. e. oxygenation of ferrous-iron minerals such as pyrite.

4.4 Depositional environment

Lithofacies associations in the Ga'ara Formation resemble the world-known ancient and modern examples of the alluvial sediments, e.g., [30]; [31]; and [32]. There is usually a general trend toward more overbank sediments downstream in a fluvial system. In wide alluvial plains that include lower parts of the fluvial depositional tract, meandering river deposits are commonly associated with a higher proportion of floodplain facies. Furthermore, downstream, these deposits will have equivalent age finer-grained deposits in swamps and other delta-plain settings and rich in vegetation, i.e., rich in organic matter. Carbonaceous plant debris is considered classic non-marine environment evidence [32] and [33]. Even minor amounts of plant rootlets are regarded as indicators of the alluvial environment. Hence, their presence in the Ga'ara deposits suggests a fluvial deposition condition. Also, the abundance of red staining of ferruginous matter has always been used to indicate an oxygenated environment and is most indicative of non-marine origin. The above-mentioned depositional settings suggest that the vertically stacked fining-upwards successions of the Ga'ara Formation represent high sinuosity, mixed-load channels, in other words meandering river system (Fig 6).

4.5 Source Rocks Potential

To present the organic matter (O.M.) content, thermal maturity and hydrocarbon potentiality of the Ga'ara mudstone, eight samples of mudstones were examined by using the total organic carbon (TOC) and Rock-Eval pyrolysis (Table 3). The hydrocarbon source evaluation is generally based on the organic matter quantity (organic richness), quality (kerogen type), and the thermal maturation generation capability [31]. The source rock evaluation, which is usually expressed as total organic carbon (TOC wt%), also depends on the type (or quality) of organic matter (kerogen) preserved in the petroleum source.

Table 3: TOC, Rock-Eval pyrolysis, HI, PI, and Tmax of the studied Ga'ara mudstone samples

Well No. Depth (m)	TOP %	Element Analysis		S1	S2	HI S2/TOC	PI S1/S1+S2	PP S1+S2	PCI	Ro %	TMAX
		H/C Atomic Ratio	O/C Atomic Ratio								
Nijili B.H. 100/B/85 55.6-56.0	1.16	0.63	0.20	-	0.82	70	-	0.82	0.68	0.51	426
Nijili B.H. 100/B/85 56.6-57.0	2.04	0.82	0.15	0.04	2.37	116	0.02	2.41	2.00	0.51	426
Nijili B.H. 100/B/85 57.0-58.0	2.10	0.79	0.10	0.02	2.60	123	0.01	2.62	2.17	0.54	428
Nijili B.H. 100/B/85 58.0-59.0	2.72	0.65	0.20	0.01	1.88	69	0.01	1.89	1.57	0.54	429

Nijili B.H. 100/B/85 59.6-60.0	3.35	0.75	0.19	0.03	3.02	90	0.01	3.05	2.53	0.53	430
West Tayyarah WT80 12.6	1.60	0.48	0.23	0.01	4.24	265	-	4.24	3.52	2.36	529
UBIRAN B.H UB.8 39.3-39.9	20.68	0.84	0.28	0.61	58.77	284	0.01	59.38	49.29	0.47	442
UBIRAN B.H UB.8 36.8-37.5	17.86	0.85	0.20	0.77	60.19	351	0.01	63.46	52.67	0.49	452

The geochemical data such as total organic carbon (TOC wt. %) and rock-eval pyrolysis are presented and discussed for the Ga'ara Formation mudstone (Table 2). Plots of Tmax (°C) against hydrogen index (H.I. mgHC/g of TOC) and hydrogen index (H.I.) against S2 from rock-eval pyrolysis are used to identify the kerogen type (quality) and depositional environment. Rock-Eval Tmax (°C) was used to evaluate the source rock maturity stage with the production index (P.I.). Pyrolysis is almost the best routine tool for determining the kerogen type [33]. The minimum acceptable TOC value for clastic rock type indicates good source potential is 1.0 % [34]. The mudstone of the Ga'ara Formation samples has moderate to high TOC content (1.16%-3.35%) in the Nijili area and moderate TOC (1.6%) in the West Tayyarah area, and very high content of TOC (17.86%-20.68%) in the Ubairan area. Based on the classification proposed by [35]. The Ga'ara Formation mudstone samples are considered moderate to excellent source rock. The PCI is Pyrolyzable Carbon Index was also calculated (PCI=0.83*(S1+S2)) [36]. In addition to S1 and S2 peaks, this parameter identifies the kerogen type and its hydrocarbon potential in agreement with TOC content, indicating that the mudstone samples are poor, poor to excellent generative potential source rock based on the classification by [35]. The other mudstone samples of the Ga'ara Formation in the Nijili and West Tayyarah areas are very good, except the Ubairan samples are excellent generative potential (Figure 17).

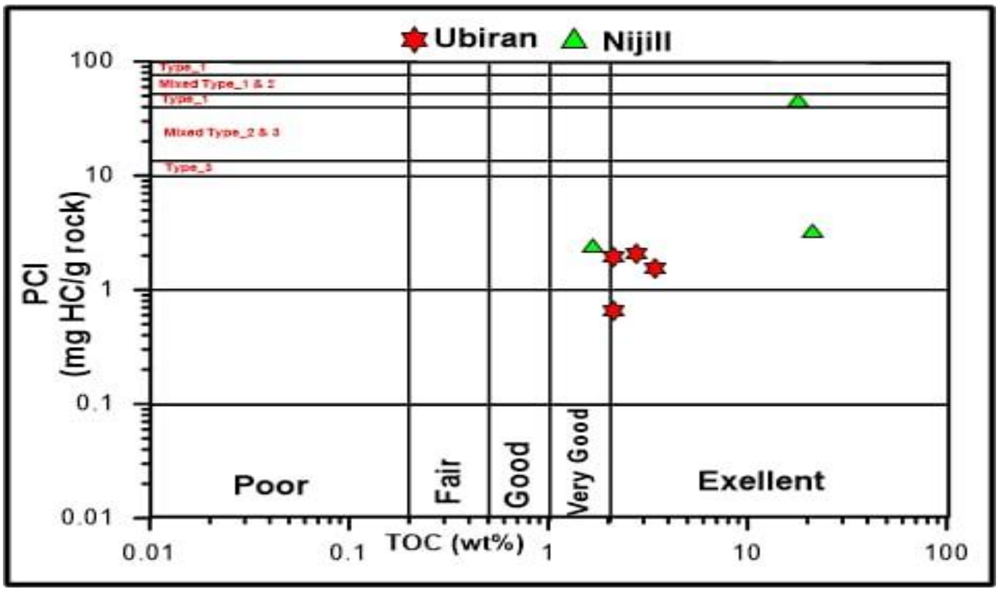

Figure 14: Assessment of the studied Ga'ara Formation mudstones as source rocks quality.

It is important to determine the kerogen types [37]. This can be achieved by drawing the relation between the TOC% and the S2. Such correlation for the Nijili and West Tayyarah samples are classified as type III kerogen gas prone while, Ubairan samples are type II kerogen oil and gas prone (Figure 18).

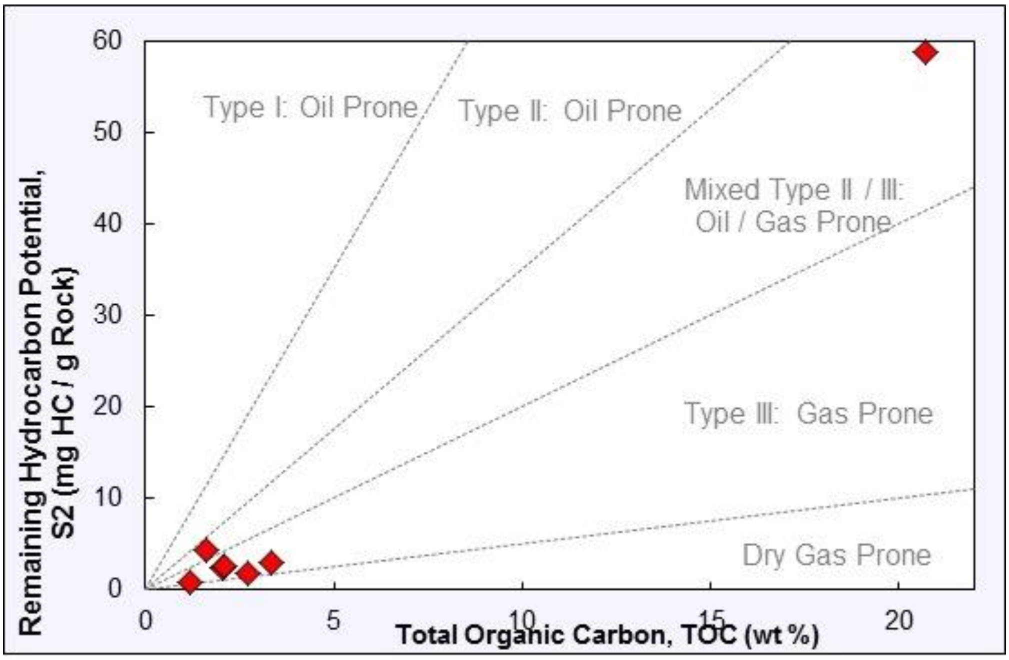

Figure 15: Type of kerogen and source rock potential of Ga'ara Formation mudstone in the studied wells

The pyrolysis results can be used to determine the organic matter types and depositional environment. [38] classified organic matter into three classes: types I and II are equivalent to sapropelic type, type III is identical to humic, whereas the presence of both II/III indicates mixed type sapropelic and humic. The term humic refers to land plant materials deposited in swamps with oxygen, whereas the sapropelic term is used for dark-colored marine sediments rich in organic matter. Accordingly, it can be inferred that the type of organic matter of Nijili and West Tayyarah samples is humic (plant material, continental environment) transported by rivers deposited within the mudstone in floodplains (swamps or lakes). Yet, the organic matter from the Ubairan samples is mixed between humic and sapropelic (nonmarine and marine organic matter) that are probably transported by rivers to the marine environment in the delta plain. Additionally, the production index (P.I.) versus Tmax diagram exhibits that all the studied samples are immature, except the West Tayyarah sample, which is mature (Figure 16).

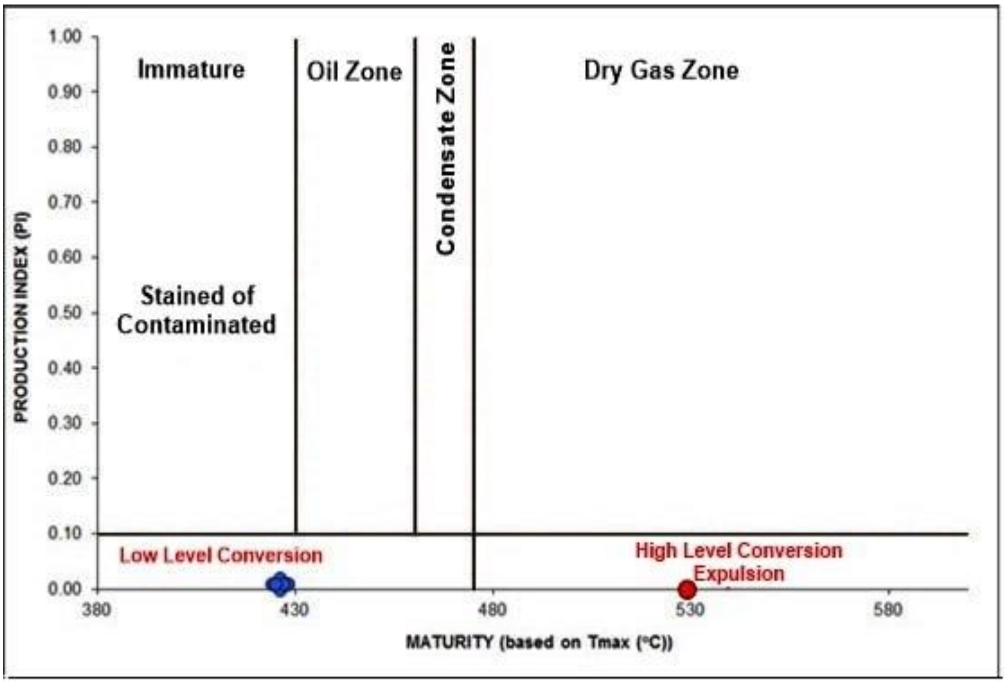

Figure 16: Maturity of the studied samples using production index (P1) and maturity (Tmax).

[39]considered that a vitrinite reflectance (Ro%) of 0.6% marks the early stage of oil generation, while the peak of oil generation is at Ro ≈ 0.8%, and the late-stage or the end of oil generation is marked at Ro ≈ 1.35%. According to this classification, the Nijili and Ubairan samples are immature and at an early stage of oil generation. In contrast, the Tayyarah samples are at the end of oil generation and classified as postmature. Depending on the TOC with the S.I. diagram, Hydrocarbon migration can be determined [40]. Based on the TOC with S.I. diagram, all the studied samples are indigenous hydrocarbons (Figure 17).

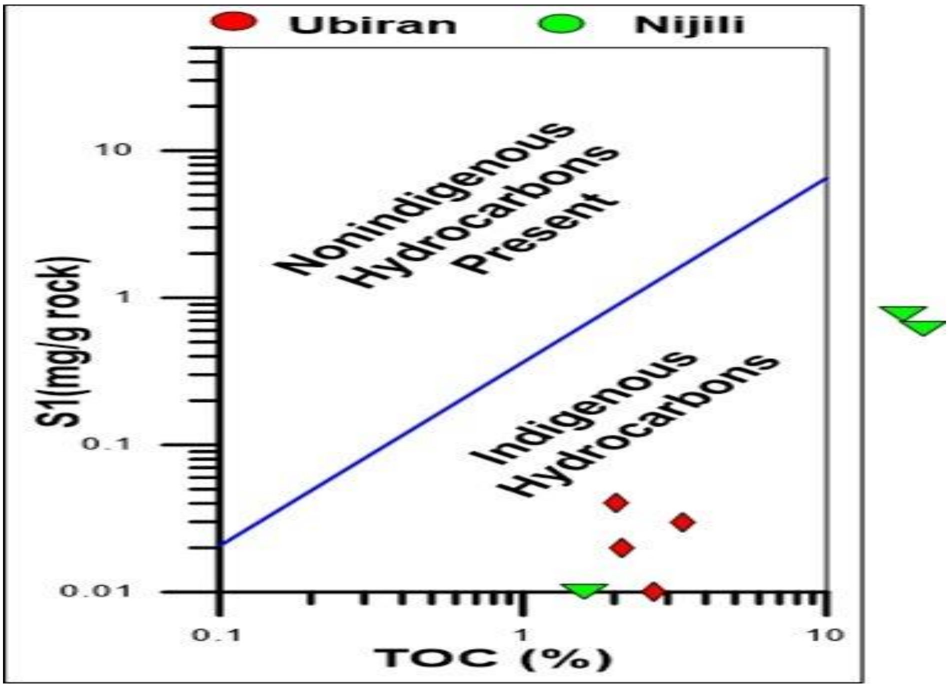

Figure 17: Type of hydrocarbon of the studied samples using TOC–S1 diagram after [38].

5. Conclusions

Lithofacies and paleocurrent analyses from the Ga’ara Formation revealed that deposition occurred in high sinuosity, mixed-load channels, possibly by the meandering river system.

The Ga’ara deposits consist of fining-upwards rhythms of scoured sandstones followed by mudstones. The sandstones represent channel systems, primarily isolated, lenticular geometries, and well-developed point bar deposits lying on thick muddy floodplain deposits. Paleocurrent analysis revealed a mean paleoflow of 153º (S.E.). However, the paleocurrent measurement varies greatly spatially and temporally. These variations in the paleoflow directions are characteristics of meandering river system deposits.

The mudstone samples have insufficient, inadequate source rock generative potential with indigenous hydrocarbons. Moreover, the source rock productive potential shows variation in maturation from the immature early stage of oil generation (Nijili and Ubairan samples) to the postmature end of oil generation (Tayyarah sample).

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