Arab J Geosci (2014) 7:559–588
DOI 10.1007/s12517-012-0820-2

ORIGINAL PAPER

# A new look on the Jurassic formations of the western part of Iraq

**Salim Q. Al-Naqib · Ali I. Al-Juboury**

Received: 29 April 2012 / Accepted: 21 December 2012 / Published online: 8 January 2013

**Abstract** The Jurassic succession of western Iraq includes the Ubaid, Hussainiyat, Amij, Muhaiwir, and Najmah formations. Each formation is composed of basal clastic unit overlain by upper carbonate unit. Extensive and huge erosional unconformity occurred at the Triassic–Jurassic boundary due to marked shifting of structural (E–W) strike of the Triassic (Rhaetic) Zor Hauran Formation to (NE–SW) Jurassic formations. Sea level falling (lowstand system tracts) would result in the progradation of the land on the expense of the sea forming the recognizable progradation of the fluvial and deltaic deposits of the lower clastic units of the Jurassic formations, whereas sea level rising (highstand system tract), i.e., sea prograding, causes deposition of the carbonate units of the Jurassic formations system. This progradation resulted to various carbonate environments of deposition ranging from subtidal, intertidal, to supratidal. The main target on most of the exploration blocks in the western part of Iraq focused on the lower Paleozoic successions, whereas prospects in Triassic, Jurassic, and lower Cretaceous targets are less extensive but may have significant potential on certain blocks in both stratigraphic and structural traps. The western part of Iraq was subjected to intermittent pulses of uplifting (sea regression) and subsidence (sea transgression) to form the Jurassic basin system in the area. The Jurassic formations lack the characteristics of petroleum systems. In contrast, in the central and northern parts of Iraq, the Jurassic formations (Najmah and Gotnia formations) were deposited in subsiding basins in which the reservoir and sealed evaporitic rocks existed. In turn, in the western desert of Iraq, the Jurassic formations lack these petroleum system characteristics. Hence, it can be proposed that the petroleum–nonpetroleum inflection could be proposed in the east of area km 160.

**Keywords** Jurassic succession · Western desert of Iraq · Progradation · Deposition · Petroleum systems

## Introduction

Because of the geological and economical importance of the Jurassic successions in the western desert of Iraq, they have been described in numerous geological projects mainly by the Directorate General of Geological Survey and Mineral Investigation (formerly the State Organization for Minerals) and several books and reports (e.g., van Bellen et al. 1959; Buday 1980; Buday and Hak 1980; Karim and Ctyroky 1981; Al-Mubarak 1983; Jassim et al. 1984; Al-Naqib et al. 1985, 1986; Qasir et al. 1992; Jassim and Buday 2006) in addition to many academic theses and research papers, the majority of which focused on the lithology and depositional environments of the successions and their economic significance. The present work reviews several of these previous studies and then examines the Jurassic successions in western Iraq in terms of their sedimentological, petrographic, and geochemical characteristics, nomenclature, and age controversy for a better paleogeographic reconstruction. By comparison with the Arabian Plate Jurassic sequence stratigraphic schemes, we then discussed the Jurassic successions in the western part of Iraq in the context of sequence stratigraphy and hydrocarbon prospects.

S. Q. Al-Naqib
Research Center for Dams and Water Resources,
Mosul University, Mosul, Iraq
e-mail: salim_alnaqib@yahoo.com

A. I. Al-Juboury (✉)
Geology Department, Mosul University, Mosul, Iraq
e-mail: alialjubory@yahoo.com

## Geological setting

The exposed Jurassic formations in the western desert of Iraq are located in the mid-northern portion of the Arabian Plate, specifically, about 20 km NE of Rutba City (Fig. 1). They aligned in a NE–SW regional strike. It is worth to mention that the underlying Triassic formations (Mulussa and Zor Hauran) have approximately E–W trending regional strike. Therefore, major or regional unconformity must have existed between Triassic and Jurassic formations. This may be a consequence of the Late Triassic orogenic movement that marked the end of the Rhaetic E–W trending depositional strike of the Zor Hauran Formation.

The Jurassic formations in concern, Ubaid, Hussainiyat, Amij, Muhaiwir, and Najmah, were affected by the Late Paleozoic Hercynian orogenic movement caused block faulting and relative uplift and resulted in a marked paleorelief (Ziegler 2001), which gives the paleogeologic and geomorphic architecture of the area, although there were many regression–transgression periods within individual formation.

Tectonically, the area of study lies in the Rutba–Jezira Zone of the stable shelf of Iraq (Fig. 2). The stable shelf is characterized by a relatively thin sedimentary cover and the lack of significant folding. The unstable shelf has a thick and folded sedimentary cover and the intensity of the folding increases toward the northeast (Buday 1980).

## Age controversy, stratigraphy, and sedimentation of the Jurassic formations exposed in the western desert of Iraq

From the discussion of orbital calibration of the Arabian Jurassic second-order sequence stratigraphy made by Al-Husseini and Matthews (2006) who concluded that the age estimation and correlation at the base of the Arabian Jurassic transgression is dated early Pliensbachian in Oman, Toracian in Saudi Arabia and ? late Sinemurian and early Pliensbachian in Kuwait. The early Pliensbachian age suggested by Al-Husseini and Matthews (2006) is consistent with the estimated ages for the start of transgression in Oman and probably Kuwait, while the main flooding appears to have reached central Saudi Arabia by the Toracian time. Accordingly and due to the lack of paleontological evidence within

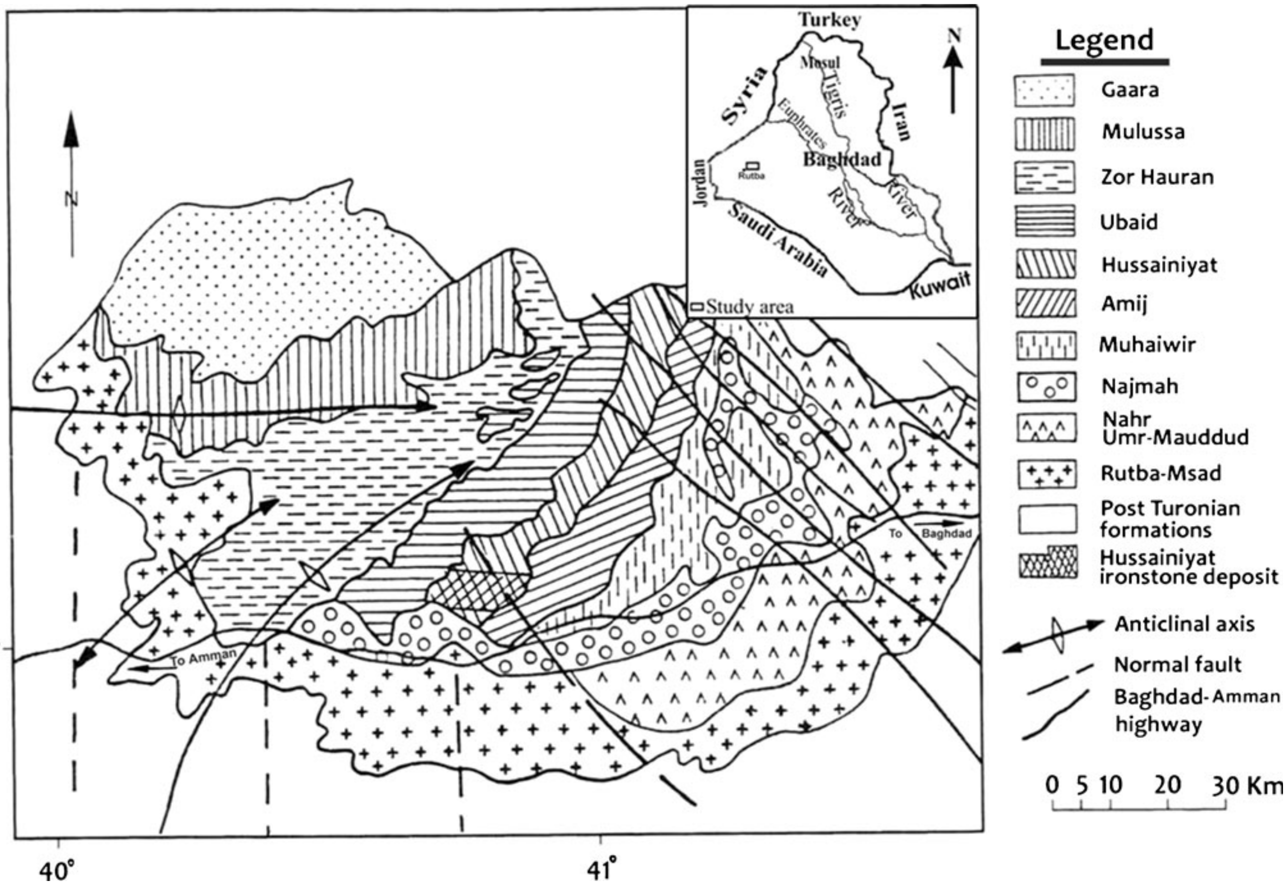


**Fig. 1** Jurassic formations exposed in the western desert of Iraq. Modified from Al-Bassam and Tamar-Agha (1998). Nahr Umr/Mauddud formation was mapped after Al-Mubarak (1983)

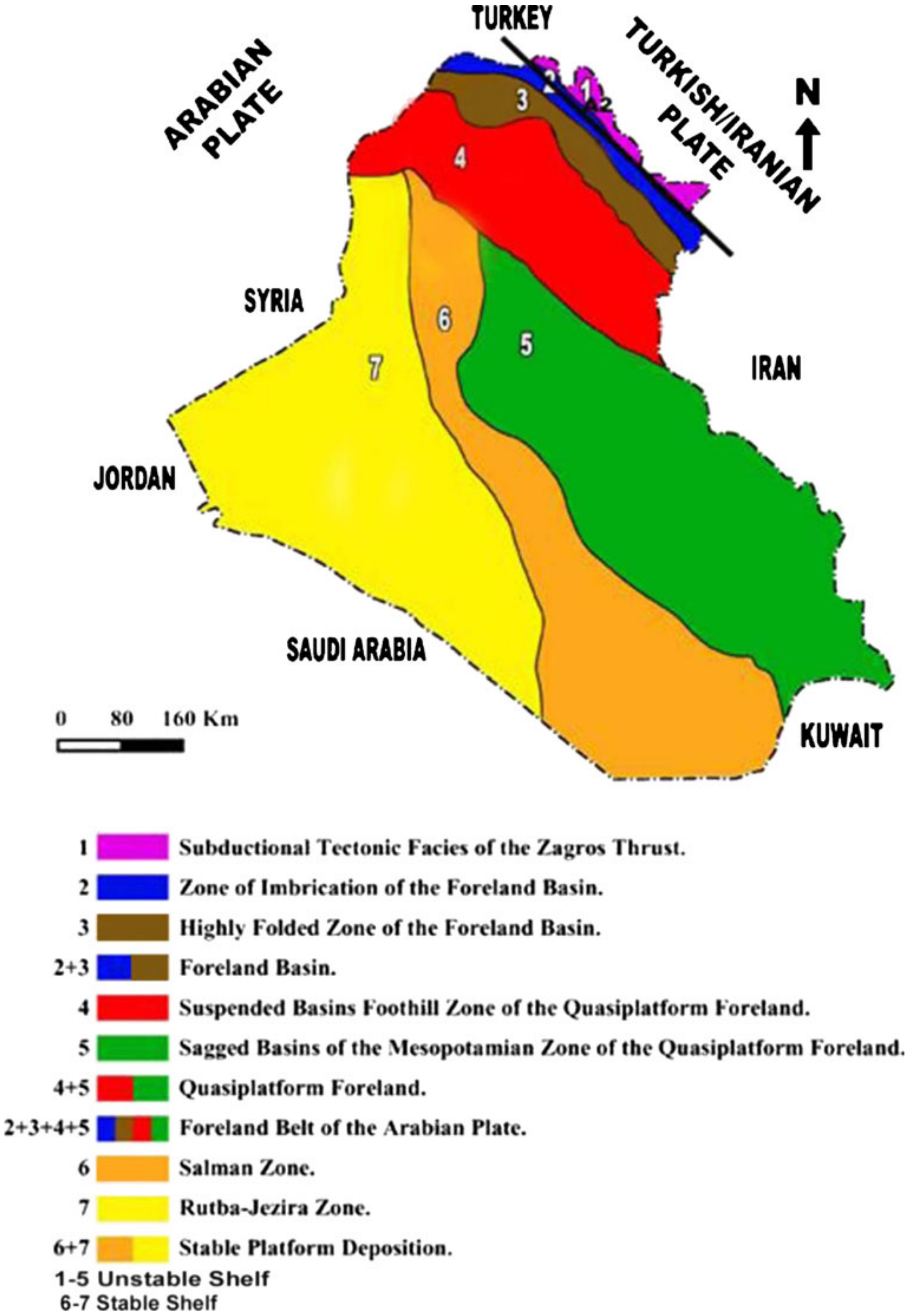
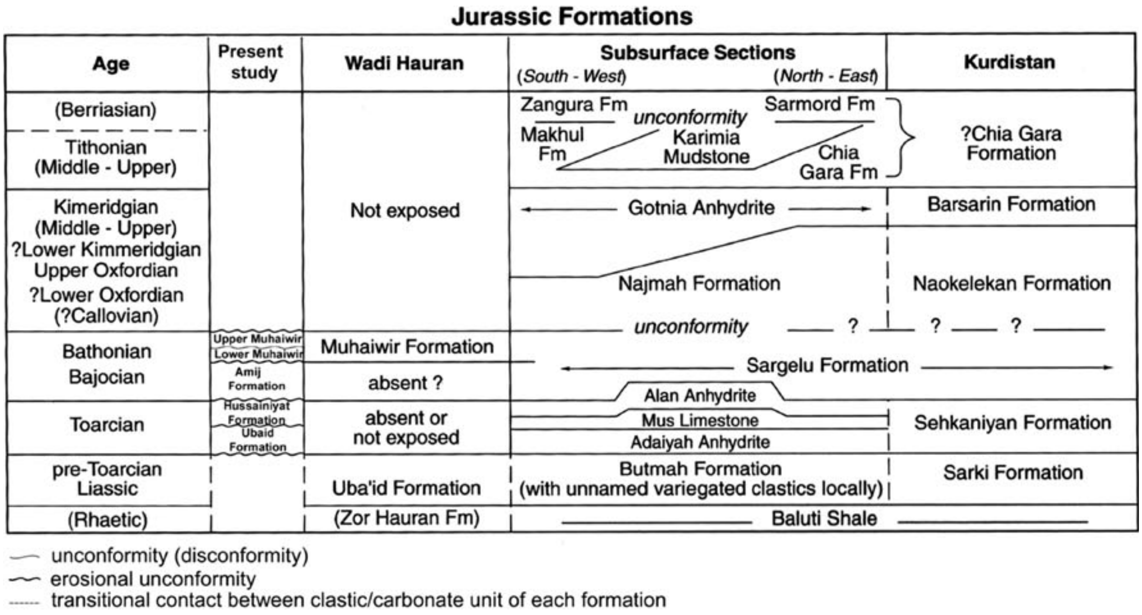
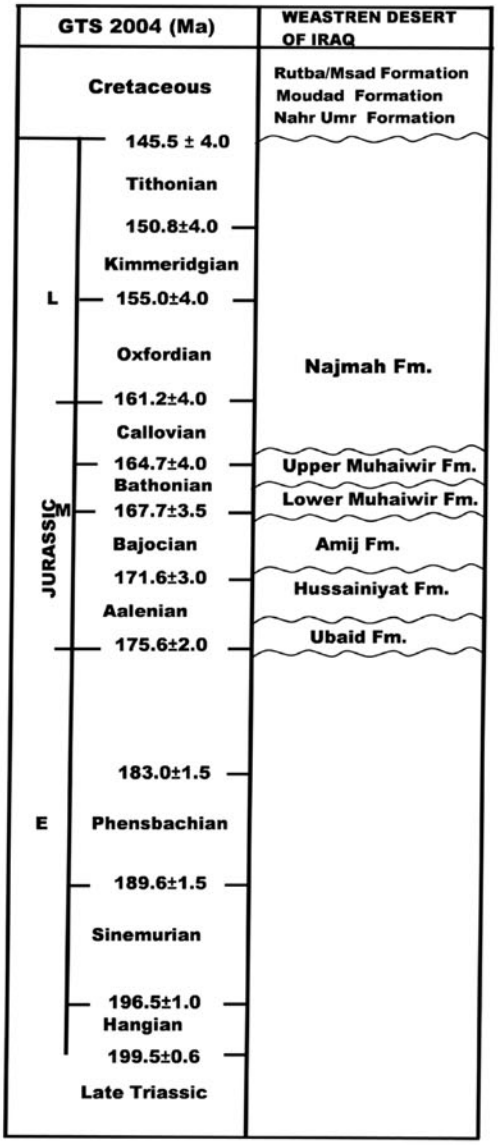


**Fig. 2** Tectonic divisions of Iraq. Modified from Numan (2001)

the Jurassic sequence of the western desert of Iraq, most of the Liassic (early Jurassic) age "if not of all" was probably eroded or "not present." This is concordant with the work of Al-Sangary (1987) and Hassan (1984), where the latter regarded the age of Hussainyat Formation as Bajocian, depending on some fossils like *Nuculoma* sp., cf. *Nuculoma stoliczhai*, *Gervilla* sp. *Gercilla orintalis*, *Astarte* sp., *Tancredia* sp., *Anisocardia* sp. *Isocyprina simplex*, *Pronocella* sp., and *Emoiodon* sp., though Ubaid Formation could have been deposited (particularly its carbonate unit) during the start of the Jurassic transgression, which may have began in Aalenian ? (175.6 Ma) (Fig. 3).

The total thickness of all exposed Jurassic formations in the present work ranges between 84.5 and 278 m and in both boreholes and outcrops range between 229.5 and 448 m. The maximum thickness of the Jurassic sequence was about 450 m (Fouad 2007).


Jurassic Formations
Age
Present study
Wadi Hauran
Subsurface Sections
(South - West)
(North - East)
Kurdistan
(Berriasian)
Tithonian (Middle - Upper)
Kimeridgian (Middle - Upper)
?Lower Kimmeridgian
Upper Oxfordian
?Lower Oxfordian
(?Callovian)
Bathonian
Bajocian
Toarcian
pre-Toarcian Liassic
(Rhaetic)
Upper Muhaiwir
Lower Muhaiwir
Amij Formation
Hussainiyat Formation
Ubaid Formation
Not exposed
Muhaiwir Formation
absent ?
absent or not exposed
Uba'id Formation
(Zor Hauran Fm)
Zangura Fm
unconformity
Sarmord Fm
Makhul Fm
Karimia Mudstone
Chia Gara Fm
?Chia Gara Formation
Gotnia Anhydrite
Barsarin Formation
Najmah Formation
Naokelekan Formation
unconformity
? ? ?
Sargelu Formation
Alan Anhydrite
Mus Limestone
Adaiyah Anhydrite
Sehkaniyan Formation
Butmah Formation (with unnamed variegated clastics locally)
Sarki Formation
Baluti Shale
unconformity (disconformity)
erosional unconformity
transitional contact between clastic/carbonate unit of each formation


GTS 2004 (Ma)
WEASTREN DESERT OF IRAQ
Cretaceous
Rutba/Msad Formation
Moudad Formation
Nahr Umr Formation
145.5 ± 4.0
Tithonian
150.8±4.0
Kimmeridgian
L
155.0±4.0
Oxfordian
Najmah Fm.
161.2±4.0
Callovian
164.7±4.0
Upper Muhaiwir Fm.
Bathonian
Lower Muhaiwir Fm.
JURASSIC
M
167.7±3.5
Bajocian
Amij Fm.
171.6±3.0
Hussainiyat Fm.
Aalenian
175.6±2.0
Ubaid Fm.
183.0±1.5
E
Phensbachian
189.6±1.5
Sinemurian
196.5±1.0
Hangian
199.5±0.6
Late Triassic

◀ **Fig. 3** *Upper* the Jurassic formations in both surface and subsurface locations and the present work modification of the succession in Rutba area of the western desert of Iraq, modified from van Bellen et al. (1959). *Lower* the main unconformities between Jurassic formations in western Iraq and their proposed ages according to the Geologic Time Scale of Grandstein et al. (2004)

In their regional geological mapping of the area under study, Buday and Hak (1980) mentioned that the oldest exposure in Rutba area is the Mulussa Formation (Upper Triassic, Norian) and referred that the upper contact of the Zor Hauran Formation (Rhaetic) with the overlying Ubaid Formation (Liassic) can be placed on the sandstone with pebbly admixture and limonite nodules.

Furthermore, Al-Naqib et al. (1985) made a detailed geological mapping in Rutba area and stated that the oldest exposure in the Rutba area is the stromatolitic unit of Zor Hauran Formation and not the Mulussa Formation as Buday and Hak (1980) mentioned. Al-Naqib et al. (1986) divided the Zor Hauran Formation from bottom to top into four units: stromatolitic, cross-bedded, crystal mold, and stromatolitic and oolitic units, respectively.

Each Jurassic formation is composed of basal clastic unit overlain by upper carbonate unit, except Muhaiwir Formation, which is composed of two cycles of basal clastic and upper carbonate units. The lower contact of each clastic unit is almost erosional and unconformable, whereas the upper contact between the clastic unit and its overlying carbonate unit is transitional (Al-Naqib et al. 1986). Below is a brief description of the stratigraphic and sedimentologic characteristics of the Jurassic successions in the western part of Iraq.

## Ubaid Formation

The thickness is 65 m after Tobia (2005) and about 47.5 m after Al-Naqib et al. (1986). The division of the Ubaid Formation was a matter of controversy. van Bellen et al. (1959) defined the formation from the top of the Zor Hauran Formation (Upper Triassic, Rhaetic) to the bottom of the unconformable Rutba Formation (Upper Cretaceous, Cenomanian) in the area between the type locality which extends from latitude 33°32′00″ N, longitude 41°02′50″ E to the junction of Wadi Hauran and Wadi Ubaid at latitude 33° 30′20″ N, longitude 41°58′40″ E and Muhaiwir, i.e., they included the present Ubaid, Hussainiyat, and Amij formations.

Buday and Hak (1980) separated the Amij Formation from the Ubaid Formation of van Bellen et al. (1959) and divided the Ubaid Formation into Lower Ubaid, which represents the first clastic–carbonate units directly above the Zor Hauran Formation, and the Upper Ubaid, which represents the Hussainiyat members (ore-bearing horizons) and the overlaying upper dolomite on the top of the Hussainiyat members.

Al-Mubarak (1983) and Al-Naqib et al. (1985, 1986) thought that the previously mentioned divisions are invalid because each Jurassic formation from Liassic, i.e., Ubaid Formation, to the Upper Jurassic Najmah Formation were deposited cyclically with lower clastic unit and upper carbonate unit. Therefore, it is better to resolve the problem by giving a specific name to each clastic–carbonate unit and regarded them as one formation, as shown in Fig. 4.

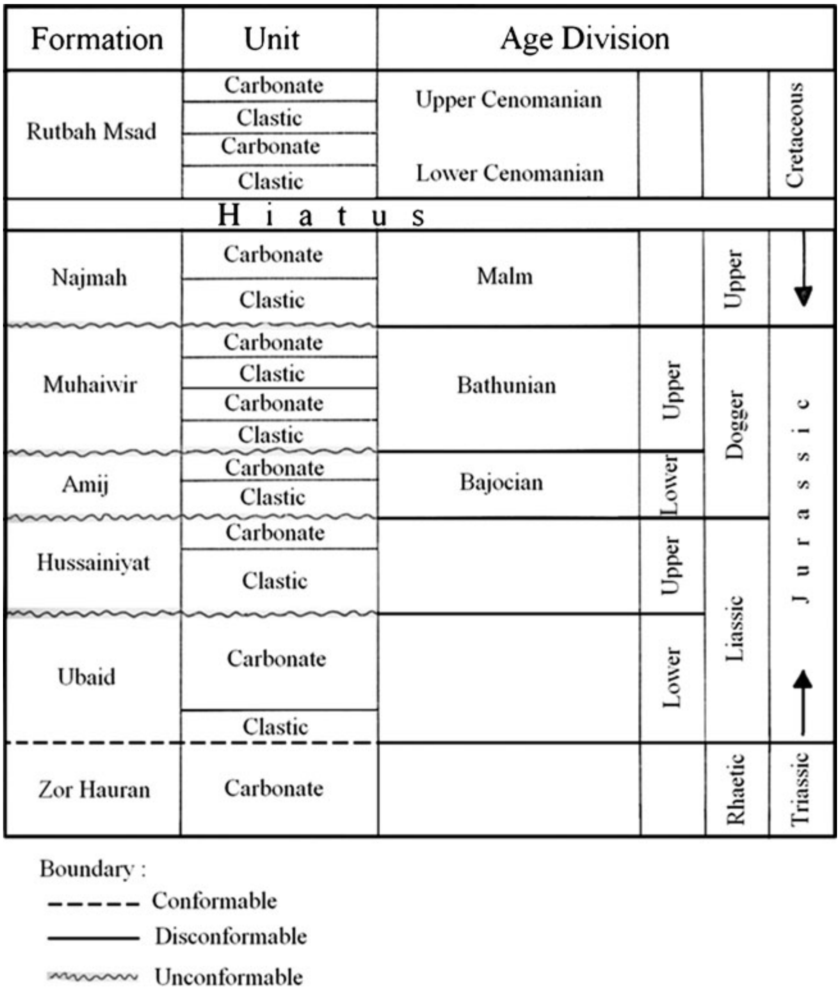
The present work is coincident with previous workers who suggested the Aalenian age for the Ubaid Formation.

The early Jurassic (Liassic) age was assigned to the Ubaid Formation due to its stratigraphic position between the Middle Jurassic Muhaiwir Formation above and supposed Rhaetic age Zor Hauran Formation below (Buday 1980).

Sedimentologically, the lower clastic unit of the Ubaid Formation is 2–5 m in thickness in the area about 10 km northeast of Rutba City. It consists of sandstone 0.2–0.9 m of different grain sizes that ranged from fine-grained to pebbly sandstones and of various colors of pink, yellowish gray, dark brown, dark gray, and yellowish brown (Fig. 5a). The unit displays coarsening-upward sequence, with various sedimentary structures, like trough-type cross-bedding, boring of horizontal type, flame structures, and convolute laminations which are assigned to liquefaction. Calcite cementing materials show some sort of poikilotopic texture. The quartz pebbles are generally rounded to well-rounded, which may indicate either recycling or relative long transportation distance. The upper carbonate unit is composed of about 42 m thick of cyclic alternations of marls and dolostones.

The lithologic succession of this unit shows an upward decrease in the thickness of the marl beds and an increase in the dolostone bed frequency. Both marls and dolostones are barren or sparsely fossiliferous (Amin et al. 1992). Generally, however, the unit is composed of four cycles of variable dimensions. Each of which begins with a basal marl overlain by dolostone. Two megacycles were proposed: lower megacycle and upper megacycle (Fig. 6). The lower megacycle consists of yellowish gray, thinly bedded, and laminated dolomitic marl at the base of the cycle and is devoid of macrofossil. The marls are overlain by dolostone bed about 5 km to the west. The dolostones have various sedimentary structures, like tepee structure, migrating or climbing ripple cross-stratification, planar cross-bedding, polygonal shrinkage cracks, bird's eye structure, crystal molds, calcite nodules, and burrows. These structures are collectively assuming a peritidal environment. The upper megacycle retain the cyclicity of marls and dolostones. Three cycles constitute the upper megacycle. In general, marls show a decrease in thickness with a concurrent

**Fig. 4** Stratigraphic table of the study area. After Al-Naqib (1994, 1995) and Al-Naqib et al. (1985, 1986)



| Formation | Unit | Age Division | | | |
|---|---|---|---|---|---|
| Rutbah Msad | Carbonate<br>Clastic | Upper Cenomanian | | | Cretaceous |
| | Carbonate<br>Clastic | Lower Cenomanian | | | |
| H i a t u s | | | | | |
| Najmah | Carbonate<br>Clastic | Malm | | Upper | Jurassic |
| Muhaiwir | Carbonate<br>Clastic<br>Carbonate<br>Clastic | Bathunian | Upper | Dogger | |
| Amij | Carbonate<br>Clastic | Bajocian | Lower | | |
| Hussainiyat | Carbonate<br>Clastic | | Upper | Liassic | |
| Ubaid | Carbonate<br>Clastic | | Lower | | |
| Zor Hauran | Carbonate | | | Rhaetic | Triassic |

Boundary :
- - - - - Conformable
——— Disconformable
〰〰 Unconformable

increase in dolostones thickness. The latter are characterized by parallel laminations, small ripples and cross-laminations, and shrinkage cracks. Horizontal and vertical burrows are ubiquitous with rare oblique types. Chert occurs as nodules, lenses, and bands up to 10 cm in thickness. The upper contact of the formation can be delineated by the marked karstification filled by the iron-bearing horizons of the lower clastic unit of the Hussainiyat Formation. This is called by Jassim and Buday (2006) as the karstified unit.

### Hussainiyat Formation

The thickness in the northern part (40–80 m) and in the southwestern part (10–15 m) was measured by Al-Naqib et al. (1985) and Qasir et al. (1992). The upper carbonate unit exceeds 50 m thick towards northeast of the Hussainiyat quarry.

Al-Mubarak (1983) and Jassim et al. (1984) regarded it as a unique formation. Al-Naqib et al. (1985) regarded the Rutba iron ore as the southwestern extension of the clastic unit of the Hussainiyat Formation and the second Jurassic cycle clastic (iron-bearing unit)/carbonate (dolostone) unit as Hussainiyat Formation and these were confirmed by Al-Naqib (1994), Al-Naqib et al. (1986), and Al-Naqib and Al-Youzbakey (2007).

The Hussainiyat Formation is correlated with the so-called Milleh Tharthar clastics in the subsurface section in central Iraq (well Milleh Tharthar No. 1) (Al-Mubarak 1983). In accordance with Al-Mubarak (opt. cit.) and Jassim et al. (1984), the present detailed study shows that the clastic unit (ore-bearing horizons) and the upper dolostones (Upper Ubaid of Buday and Hak 1980) may be regarded as one formation named “Hussainiyat Formation” because they are related to each other and may represent regression and transgression periods in megarhythmic fashion.

The age is considered as Liassic (according to its stratigraphic setting as suggested by Karim and Ctyroky 1981). Buday and Hak (1980) regarded the age as Liassic (early Jurassic) and as Bajocian according to Hassan (1984) depending on genus *Anisocardia* and also as Bajacian according to Al-Sangary (1987) depending on genus *Mesondothyrea creatica cusic*. The present work coincides

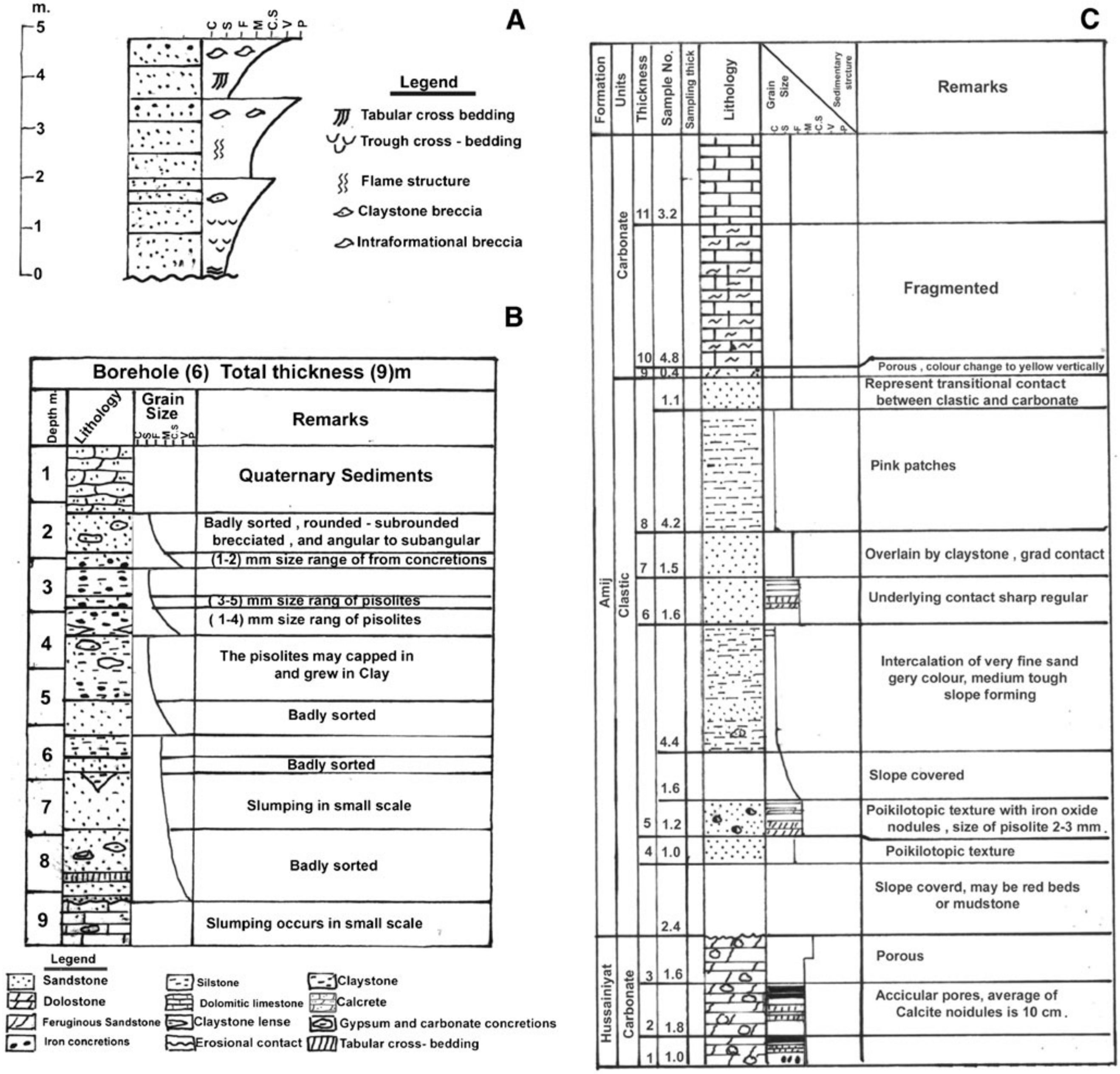


**Fig. 5** Lithological sections of the Jurassic formations in the Rutba area. **a** Clastic unit of Ubaid Formation, **b** Hussainiyat Formation, and **c** Amij Formation, reproduced from Al-Naqib (1994, 1995), Al-Naqib and Aghwan (2000), and Al-Naqib et al. (1986)

with the previously mentioned two authors who suggested the early Bajocian age for the Hussainiyat Formation.

The lower contact of the Hussainiyat Formation could be put on the base of the clastic unit (ore-bearing horizons) unconformably situated above the eroded carbonate unit of the Ubaid Formation, whereas the upper contact with the overlying clastic unit of the Amij Formation is unconformable and erosional (Fig. 3).

The lower clastic unit of the Hussainiyat Formation is composed almost exclusively of sandstones, clayey siltstones, silty claystones, and claystones reflecting fining-upward cycles (Fig. 5b). The sandstones include various grain sizes ranging from pebbly sandstone to very-fine-grained sandstone. All these sandstones occasionally become ferruginous in different stratigraphic levels.

Sedimentologically, the lower clastic unit is composed of several fining-upward cycles inferring a fluviatile origin. Al-Naqib (1994) divided this unit into five main subfacies:

1. The pebbly sandstone subfacies represents the channel lag (suggested the base of the erosional contact).

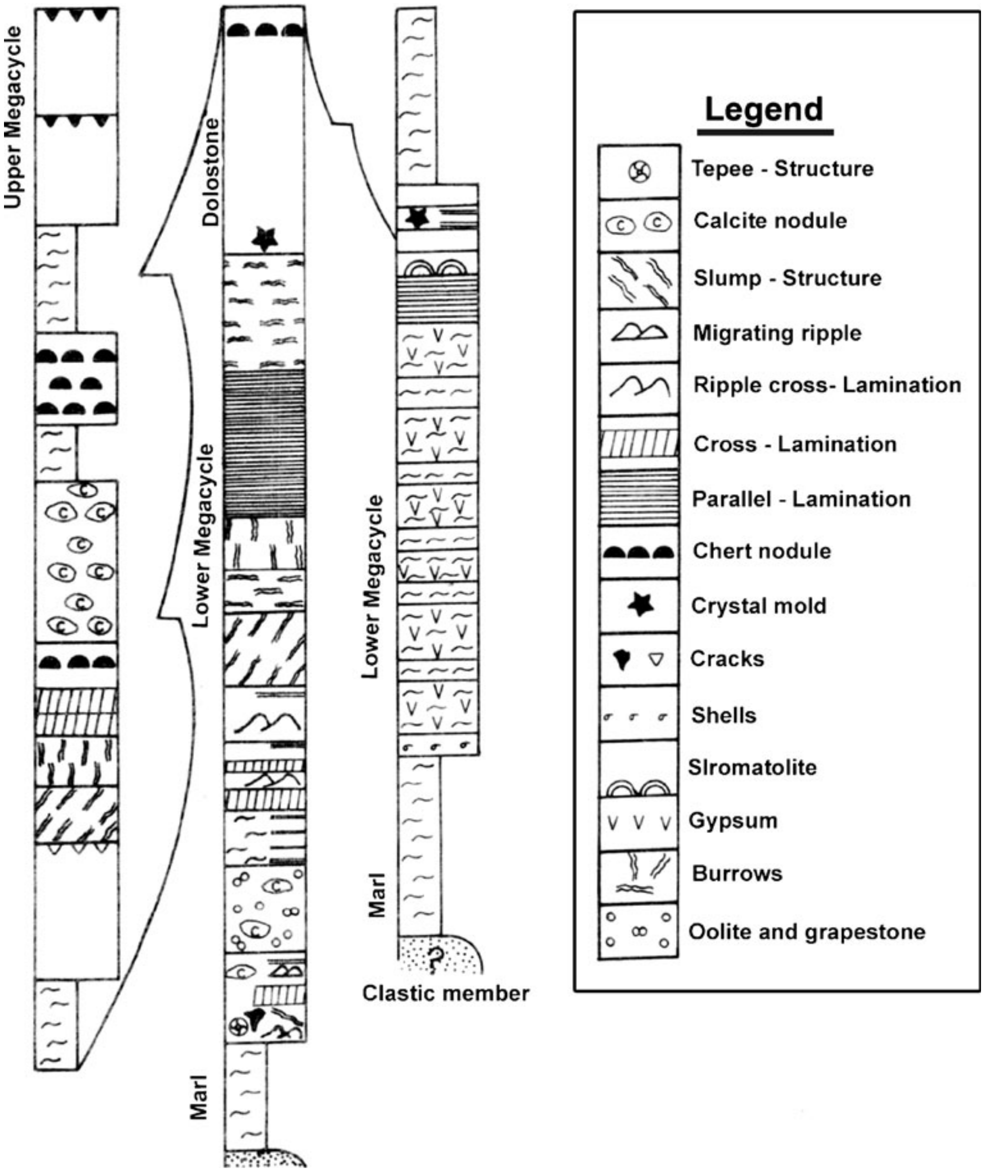


**Fig. 6** Cyclicity of the upper carbonate unit of the Ubaid Formation showing the lower and upper megacycles of this unit, reproduced from Amin et al. (1992)

2. The coarse-grained to medium-grained subfacies represents point bar deposits, characterized by cross-bedding of trough type more than 2 m width and 120° mean paleocurrent direction and about 110° mean paleocurrent direction of seven measured paleochannels.
3. The fine to very fine sandstone and siltstone subfacies is characterized by ripple marks and parallel laminations; the suggested environment is a transitional deposition of the overbank deposits.
4. Clayey siltstone and silty claystone subfacies characterized by fissility (bearing iron) suggested the beginning of the bank deposits.
5. Claystone subfacies characterized by different colors (bearing iron) suggested overbank deposits.

Two to three fining-upward cycles appear in the boreholes, but were subjected to several and repeated periods of nondeposition, at least parts of the overbanks. This is supported by several crevasse splays and the channeling products of parts of the overbanks.

The upper carbonate unit is composed almost entirely of dolostone and arenaceous dolostone (doloarenite) alternating with each other in a cyclic form. They attained varied colors ranging from dark gray to dark reddish brown. They range from fine to coarse sand size and are often thickly bedded with rare thinly bedded, very tough, and cavernous (from few millimeters to half a meter).

The contact among bedding planes are sharp, flat, and sometimes irregular. Molds of gastropods and traces of pelecypods are common in the lower part. Calcite nodules occasionally occurred in different levels. Boring of vertical type are quite rare but confined to certain beds in the middle part. Chert occurs in the upper 12 m of this succession as nodules and bands of 10–15 cm thick (Fig. 7a, b) (Al-Naqib et al. 1986).

## Amij Formation

Thickness of 25 m was measured by (Tobia 2005) and about 42 m by Jassim and Buday (2006) 50 km east of Rutba town. Al-Naqib and Aghwan (2000) measured the thickness for the clastic unit of the formation recorded about 23 m, whereas the thickness of its carbonate unit exceeds 20 m. The thickness of Amij Formation in general increased towards the northeastern extension.

Buday and Hak (1980) were the first to discover this formation and define its age as Bajacian. Hassan (1984) and Al-Sangary (1987) considered it as Bathonian in age. Jassim et al. (1984) suggested late Liassic age for the formation. Stratigraphically, Middle–Late Bajocian age is assumed to be dependent in the present work.

Al-Mubarak (1983) regarded it as Upper Butmah Formation of early Jurassic (Liassic) age and considered it as the third Jurassic sedimentary cycle. Karim and Ctyroky (1981) found a similarity between the Sarki Formation's fauna and the carbonate unit of the third Jurassic sedimentary cycle due to the presence of the so-called Cyrenia beds which occur in the lower part of the type section of the Sarki Formation (an equivalent of the Amij Formation in the highly folded zone of northern Iraq). They correlate this cycle with the upper part of the Butmah Formation, known from the deep subsurface section west of the Tigris River in the central part of Iraq.

The lower contact of the Amij Formation with the underlying Hussainiyat Formation is unconformable, sharp, and irregular and, in some parts, marked by 0.4 m very tough fine-grained ferruginous sandstone with fragments of pisolites of lateritic deposits. The upper contact with the overlying Muhaiwir Formation is also unconformable, sharp, and irregular as indicated by the basal clastic of the later formation (Fig. 4).

The lower clastic unit of Amij Formation in the studied area comprised a maximum thickness of about 21 m. It consists of sandstones, clayey siltstones, silty claystones, and claystones with very thinly bedded and patchy

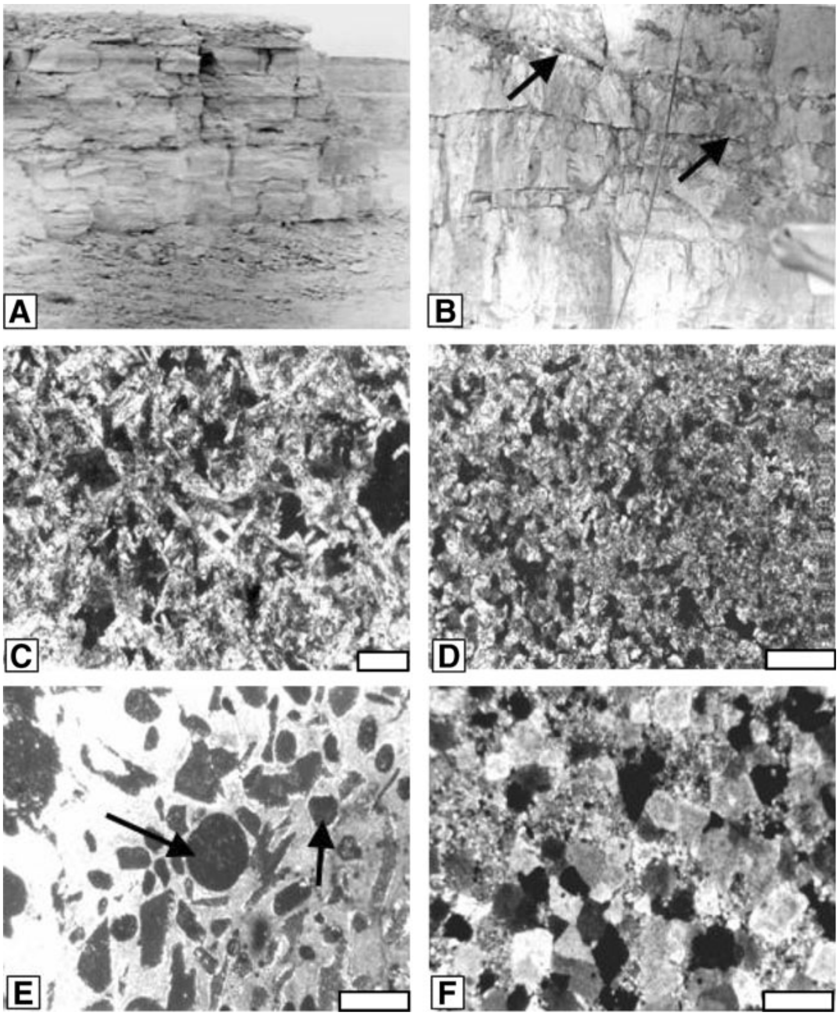


**Fig. 7** **a** Dolostone quarry in the upper carbonate unit of the Hussainiyat Formation. **b** Chert as bands and nodules (*arrows*) in the upper carbonate unit of the Hussainiyat Formation. **c** Dolomite replacement laths in gypsum of the Ubaid Formation, x-nicols. **d** Dolostone, porous, and aphanotopic (fine) crystalline, Ubaid Formation, x-nicols. **e** Phosphatic pisolites (*arrows*) in dolomite matrix in the carbonates of Ubaid Formation, x-nicols. **f** Dolostone, equidimensional, coarse crystalline, Hussainiyat Formation, x-nicols. Scale bars=0.2 mm

limestone (Fig. 5c). These lithologies indicate several fining-upward cycles of the large meander river system of high sinuosity (Al-Naqib and Aghwan 2000).

Sedimentologically, the lower clastic unit comprised three fining-upward cycles, with each cycle comprised of three lithofacies: sandstones, silty claystones, and clayey siltstones, suggesting deposition of rivers with high sinuosity. It is worth to mention that the lower cycle begins with medium-grained sandstones overlying hard ground composed of fine-grained sandstones with fragmented pisolites, an indicator of unconformity (Al-Naqib et al. 1986).

The upper carbonate unit displays 15–30 m thickness. It is composed of dolostone, marly dolostones, dolosiltite, dolomitic limestones, limestone, marly limestone, and rarely marl deposited in cyclic fashion. The manner of deposition was affected primarily by the relative structural position in the basin of deposition relative to Rutba uplift. However, rapid and local changes, both vertically and laterally, are common features to the lagoonal tidal flat complex rather than gradational sequence of progressively shallower environments (Friedman and Sanders 1978; Walker 1979). Al-Naqib and Aghwan (2000) discussed the cyclicity of this unit by taking two basic sections, one of them is situated on the flank of Rutba uplift and the other is situated about 15 km away towards the east (Fig. 8). Consequently, the environments were controlled to a certain extent by their relative paleogeographical setting, though the areas of the basin near Rutba uplift characterized by sharp uplift and sharp subsidence, whereas Rutba uplift has relatively little impact on the areas relatively far away from it. The latter is characterized by gradual uplift and gradual subsidence, as indicated by gradual lithological and facies changes.

### Muhaiwir Formation

Thickness is 110–200 m in the subsurface sections and 12–35 m in the outcrops (Mohemed 1989). Least thickness (12 m) of the exposed formation is recorded about 60 km east of Rutba City. Al-Azzawi et al. (1996) regarded them as two units.

The age of the formation was considered as Bathonian–Callovian by Jassim et al. (1984) and Al-Sangary (1987), which is concordant with the present work.

The Muhaiwir Formation was defined for the first time by R. Wetzel (1951, in van Bellen et al. 1959) in two separated localities owing to the low dip and small relief prevalence. A brief description of the Muhaiwir Formation with good environmental interpretation was given by Buday and Hak (1980). Later on, Al-Mubarak (1983) regarded the present Muhaiwir Formation as the fourth (Lower Muhaiwir) and fifth (Upper Muhaiwir) Jurassic sedimentary cycles in the western desert, with unconformable contact between them. Karim and Ctyroky (1981) proved that the Lower Muhaiwir Formation is mainly reefal, whereas the Upper Muhaiwir was deposited in a back reef environment depending on *Trocholina* spp., miliolids, and echinoids.

Accordingly, in the present work, the Muhaiwir Formation is divided into Lower Muhaiwir and Upper Muhaiwir. Each of them is divided into two units: the lower one is the clastic unit and the upper one is the carbonate unit. The underlying contact of the Muhaiwir Formation with the Amij Formation is sharp unconformable marked by the strata discordance between the top part of the carbonate unit of the Amij Formation and the basal clastic beds of the Lower Muhaiwir, where thin ferruginous sandstone lateritic bed is marked. The upper contact of the Muhaiwir Formation with its overlying Late Jurassic (Malm) Najmah Formation is erosional and unconformable, pointed out by the erosion of the Upper Muhaiwir and the occurrence of the lateritic horizons of the basal part of the Najmah Formation. Sharp contact was assigned between this unit and its overlying carbonate unit of the Lower Muhaiwir. The maximum thickness of the carbonate unit of the Lower Muhaiwir reaches about 5.6 m. The Upper Muhaiwir was found as patchy, wide, and low-relief outcrops that overlie the Lower Muhaiwir. The Upper Muhaiwir also retains the lower clastic unit and upper carbonate unit (Fig. 4).

Sedimentologically, two incomplete coarsening-upward cycles were recognized in some sections of the lower clastic unit of the Lower Muhaiwir (Fig. 9a), whereas three incomplete coarsening-upward cycles were recognized in some sections of the lower clastic unit of the Upper Muhaiwir (Fig. 9b). The environment of the two members could be assigned as deltaic deposition, although there are no clear evidence of the deltaic sequence.

The lower clastic unit of the Upper Muhaiwir has a maximum thickness of 4.2 m. It contributes mainly sandstones, very fine grained to coarse grained with pale brown to pale yellowish brown and yellow colors. Dolomite cement is abundant with subordinate calcite cement. It is thinly bedded, medium tough, and badly sorted. It shows not more than three small coarsening-upward cycles. Occasional yellowish green marl intercalations in the middle and lower parts of this unit with secondary gypsum enrichments are observed. Boring of vertical type was recognized in different levels throughout this unit. Finally, sharp irregular contact was found between this unit and its overlying carbonate unit. Al-Barazangi (1989) found four microfacies which pointed out to a depositional environment extending from subtidal, inner barrier, and shoal.

The carbonate unit of the formation is composed of highly porous limestone, dolomitic limestones, and dolomite and sandy dolomites with various types of textures that

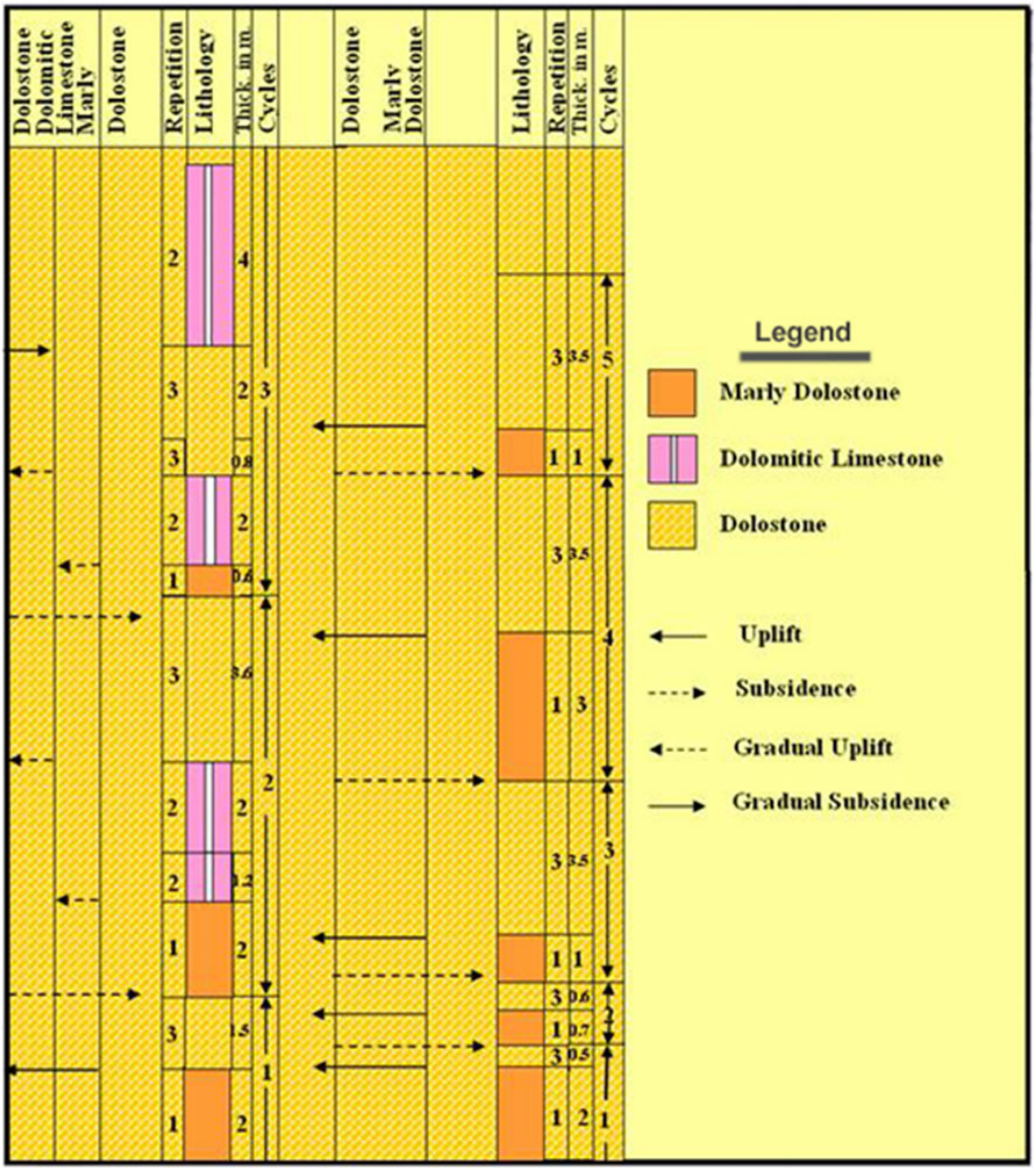


**Fig. 8** Cyclicity interpretation of the upper carbonate unit of the Amij Formation, reproduced from Al-Naqib and Aghwan (2000)

were deposited in intertidal to supratidal environments of deposition (Mohemed 1989)

Al-Naqib et al. (1986) have shown that the carbonate unit of the Lower Muhaiwir consists entirely of limestones in the lower part, followed by dolostones and subordinate marly limestone in the upper part. They are generally fine crystalline, pale brown to pale yellow in color, thinly bedded, and tough, whereas the carbonate unit of the Upper Muhaiwir has pink, yellowish brown, to violet colors of arenaceous dolostones and arenaceous limestones. Most are fine to coarse crystalline and tough.

## Najmah Formation

Thickness ranges from 7 to 45 m in the area 10 km east of Rutba City towards the east. Al-Mubarak (1983) was the first to describe the Najmah Formation in the western desert of Iraq and correlate it with the so-called Najmah Formation in borehole no. 29, longitude 45°9′21″ E, latitude 35°55′14″ N, within the depth range of 4,784–5,902 ft and finally considered the formation as the sixth Jurassic cycle in the western desert. Al-Sangary (1987) considered it as the fifth Jurassic cycle, whereas Sagar Formation (Rutba/Msad

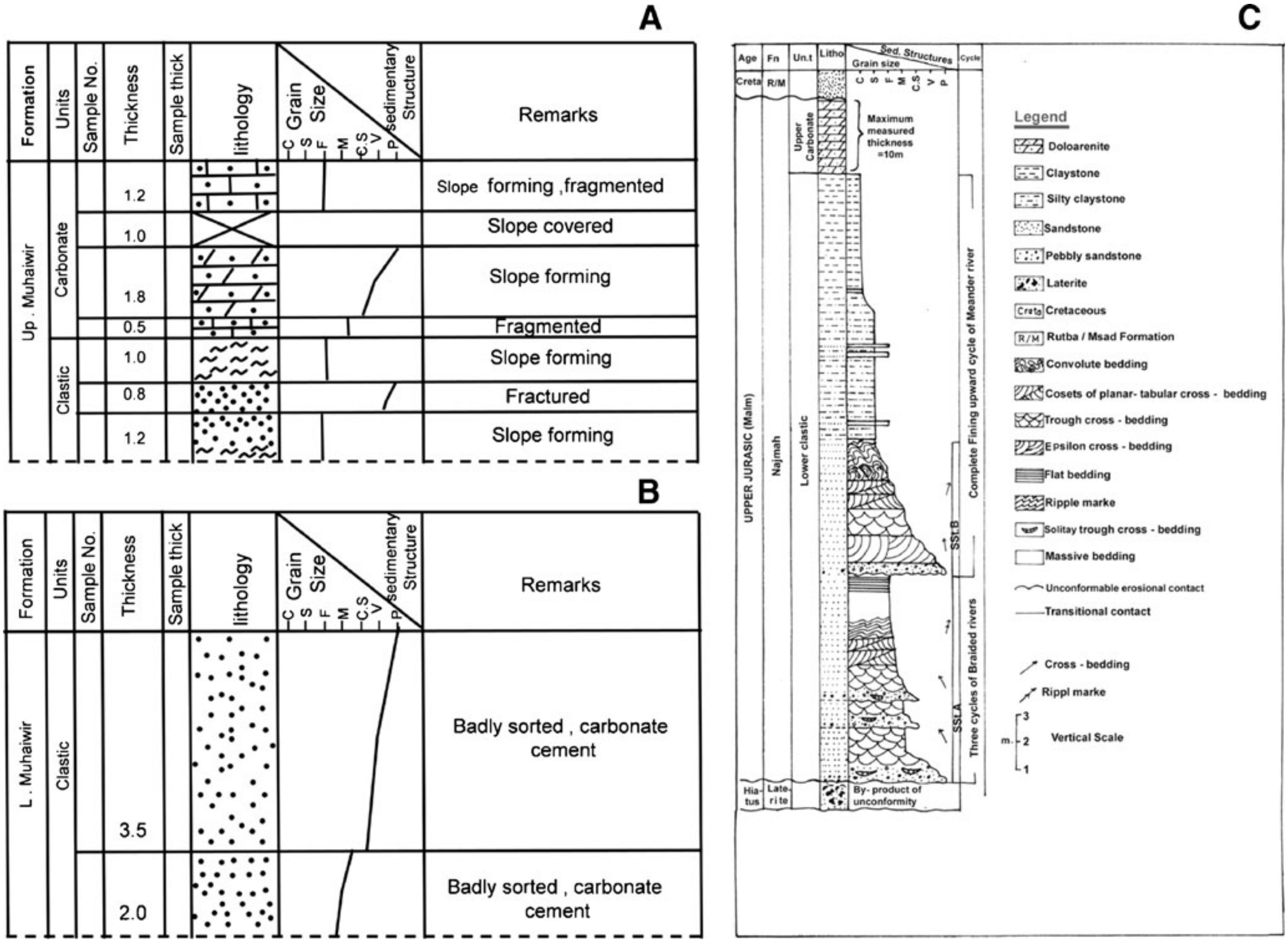


**Fig. 9** Lithological sections of the Jurassic formations in the Rutba area. **a** Muhaiwir Formation, Lower, **b** Muhaiwir Formation, Upper, and **c** Najmah Formation, reproduced from Al-Naqib (1994, 1995), Al-Naqib et al. (1986), and Al-Naqib and Aghwan (2000)

Formation–Upper Cretaceous) was considered as the sixth Jurassic cycle. The present work is concordant with the work of Al-Mubarak (1983), Al-Naqib et al. (1985, 1986), and Al-Naqib (1995), where they assured that each Jurassic formation of the western desert Fig. 4 displays lower clastic unit and upper carbonate unit, i.e., there were five Jurassic formations, and every formation was formed by regressive/transgressive cycle, except Muhaiwir Formation which constitutes two regressive/transgressive cycles due to their high similarity in their lithological constituents. Consequently, the Jurassic system of the western desert of Iraq represents six major cycles as Al-Mubarak (1983) thought.

The Najmah Formation was first described by H.V. Dunnington (1955, in van Bellen et al. 1959) as Najmah Limestone Formation in the M.P.C. well Najmah No. 29, longitude 45°9′21″ E, latitude 35°55′14″ N, between drilled depths of 4,784 and 5,902 ft. Later on, Al-Mubarak (1983) defined the Najmah Formation in the western desert for the first time not as Najmah Limestone Formation because Najmah Formation here consists of two main units: the lower one is mostly clastic, while the upper one is mainly carbonate (calcarenite).

Buday and Hak (1980) confused the present Najmah Formation with the lower part of the Rutba/Msád Formation. The present detailed work assured the presence of this formation in the western desert, correlating it with the area of Al-Mubarak (1983) to the east of the present area. The Late Jurassic age is accepted by van Bellen et al. (1959) and Al-Mubarak (1983). The present work suggests a Late Jurassic (Malm) age for the formation.

This situation marked very intense regional depositional strike deviation from NE–SW in the eastern part of the area to E–W direction in the western part of the area, indicating tectonic activity.

The Najmah Formation overlies the older Jurassic and Rhaetic (late Triassic) formations unconformably with different regional strike, so the underlying formations are Zor Hauran, Ubaid, Hussainiyat, Amij, and Muhaiwir from west to east, respectively (Fig. 4).

In the present study, Rutba/Msád Formation overlies the Najmah Formation unconformably with apparently same or relatively the same regional strike, at least in the area around the Rutba–Ramadi paved road.

Sedimentologically, the formation attains different sand sizes and claystones which were deposited in braided and meander river systems, respectively. The pebbly sandstone ranges in thickness from 10 to 40 cm. It always represents the channel base and considered as channel lag. This pebbly sandstone comprised pebbles of quartz, rounded to subrounded, indicative of either long transportation or recycling. The pebbles are ranging in size from 2 to 4 mm in diameter. Intraformational breccias are found sometimes made of clay and iron pisolites of the lateritic horizon of the underlying unconformity.

The coarse-grained to medium-grained sandstones are mostly white in color, but yellow patches occurred rarely and concentrations of iron oxides along foresets of cross-bedded unit. These sandstones are characterized as thinly to thickly bedded, friable to medium tough, and badly sorted; cross-beddings are often of planar tabular type and abundantly large to very large scale trough type. Ripple marks are quite rare but documented in some sections (Fig. 9c).

Poikilotopic texture occurred within these sandstones which assigned to the carbonate cementing materials. Nodular type of sandstone concretions has different sizes and occurrences.

The fine to very fine sandstones are always white in color occurring at the top. The medium, coarse, and pebbly sandstone occurred at the base. They are thinly bedded, medium tough to partially tough, and cross-beddings were found of planar tabular type and rarely trough type mostly of medium to small scale.

Al-Naqib (1995) divided the lower clastic unit into three major lithofacies: pebbly sandstone and intraformational breccia, sandstones, and claystones. Arenaceous limestone of white, pink, and reddish brown colors occurred within the top parts of the cycle. They range in thickness from a few centimeters to about more than 3 m. Thickness of the fining upward cycle ranges between 2.0 m and more than 10 m. This depends primarily on the bed load, mixed load, and suspended load of the river as well as its channel width and hydrodynamic flow conditions.

The upper carbonate unit in the area under study is composed of 10 m thick of dolomitized calcarenites, medium to coarse crystalline with pink, violet, and red colors. Different types of biogenic sedimentary structures could be recognized, these include horizontal, vertical, and oblique boring types and burrowing and stromatolitic structures. The nonbiogenic structures include wavy laminations and ripple marks, cross-laminations, flaser bedding, calcite nodules, and slump structures.

## Petrographic investigation

### Ubaid Formation

#### *Clastic unit*

The sandstone of the Ubaid Formation is either cross-laminated pale gray or banded and parallel laminated reddish brown. The sandstone in general is a carbonate lithic arenite of medium to coarse grain with scattered pebbles. Quartz grains form 70–77 % of the framework constituents. Carbonate cement was found as calcite and dolomite formed 15–30 %. Accessories of iron oxides formed up to 3 % comprising hematite, goethite, and chromite (Table 1). Majority of the quartz grains are corroded, some are fractured, others with vacuoles (Fig. 10a).

Heavy minerals are dominantly opaques forming about 82 % of the total heavies. The zircon, tourmaline, and rutile (ZTR) form about 18 % of the nonopaque constituents in addition to staurolite, corundum, and few alterites.

#### *Carbonate unit*

Texturally, the dolostones are fine to medium grained. In thin sections, they are dominantly of dolomicrite, whereas others consist of subhedral to anhedral and euhedral lath-like dolomite testifying the pseudomorphic replacement of gypsum (Fig. 7c, d) (Amin et al. 1992), sometimes including phosphatic debris bones and phosphatic pisolite in dolomite matrix (Fig. 7e).

### Hussainiyat Formation

#### *Clastic unit*

Sandstones are composed of quartz, which is the most abundant detrital component, forming at least 95 % of the framework constituents (Table 1), and that the sandstones are matrix-free, hence can be referred to as quartz arenite (Figs. 10b and 11a). The framework fragments are poorly cemented, ranging from poorly to very poorly sorted, and subrounded to subangular in shape.

Three distinct classes of quartz could be recognized: these are single grains with straight extinction, single grains with undulatory extinction, and composite grains. The majority of the composite grains are polycrystalline quartz with

**Table 1** Framework grain mode parameters and matrix and cement distributions of sandstones from the Jurassic clastic units

| Formation | *n* | Q | F | L | M | Matrix (%) | Cements (%) | | | Misc. (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Carbonate ferruginous | Silica | Clayey | |
| Najmah | 10 | Mean, 94; range, 92–98 | – | – | – | 3, 1.8–6 | 1.5, 0.8–4 | 0.6, 0–1.2 | – | 0.9, 0.2–1.7 |
| Muhaiwir | 8 | Mean, 76; range, 72–84 | 0.8, 0–1.6 | – | – | – | 16.5, 12–26 | – | 5, 2–8.5 | 1.7, 0.8–3.3 |
| Amij | 15 | Mean, 70; range, 64–80 | 2.5, 0.4–4 | 0.8, 0.3–1.5 | 0.7, 0–1.2 | 2.5, 1.4–3.5 | 17.5, 5–24 | – | 2.5, 0.9–3.8 | 3.5, 1–8 |
| Hussainiyat | 10 | Mean, 95; range 94–98 | – | – | – | – | – | – | 2, 1–3 | 3, 0.5–5 |
| Ubaid | 7 | Mean, 73; range, 70–77 | – | 1.6, 2–3 | – | – | 23.7, 15–30 | – | – | 1.7, 1–3 |

*Q* total quartz grains, *F* total feldspar grains, *L* total lithic fragments, *M* mica, *Misc* miscellaneous grains (heavy minerals and alterites)

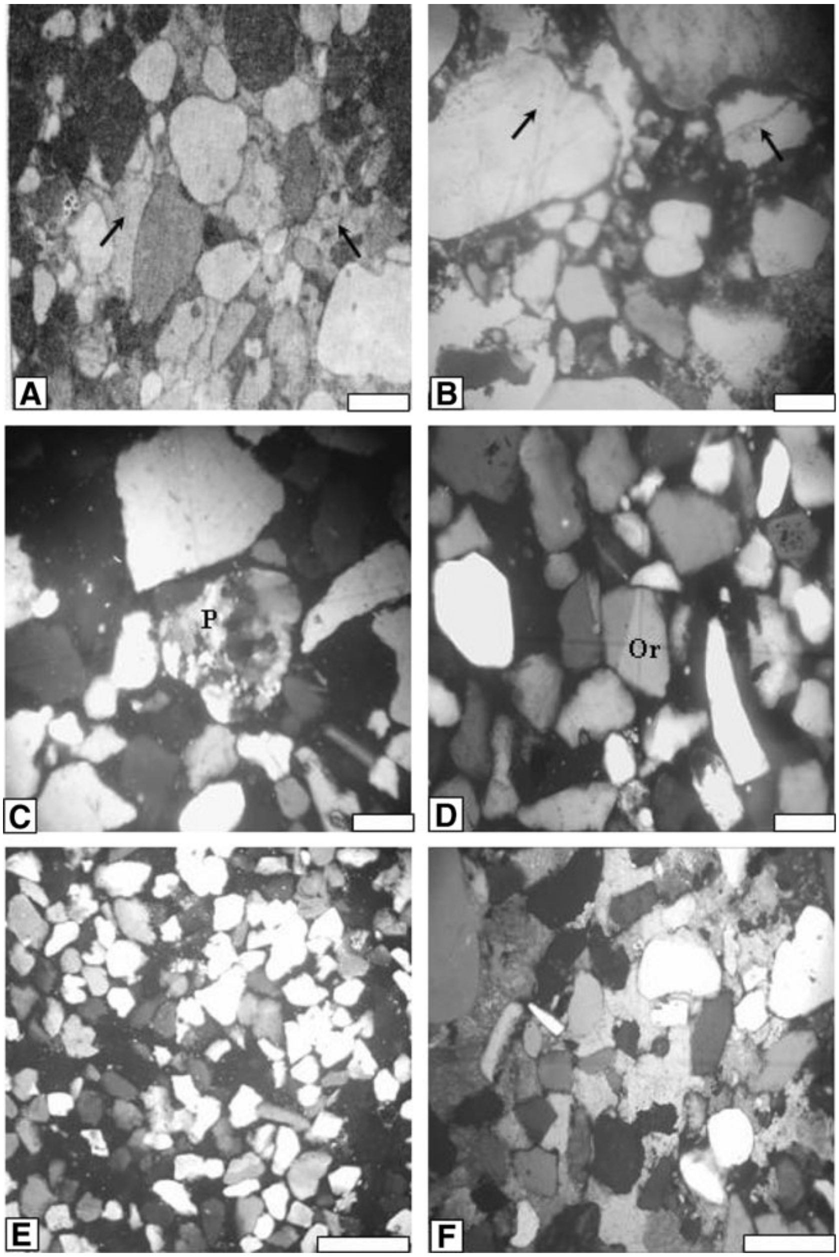


**Fig. 10** Photomicrographs of selected Jurassic sandstone. **a** Lithic arenites of the Ubaid Formation, corroded quartz grains floated in carbonate (calcite) cement (*arrows*). **b** Poorly sorted quartz arenite of the Hussainiyat Formation, quartz grains commonly fractured and with vacuoles (*arrows*). **c** Polycrystalline quartz (*P*) grain in the Hussainiyat sandstone. **d** Quartz arenite of the Amij Formaton with few feldspar (orthoclase) grains (*Or*). **e** Fine-grained quartz arenite of the Muhaiwir Formation. **f** Medium-grained quartz arenite of the Najmah Formation cemented by calcite cement. Scale bars=0.2 mm

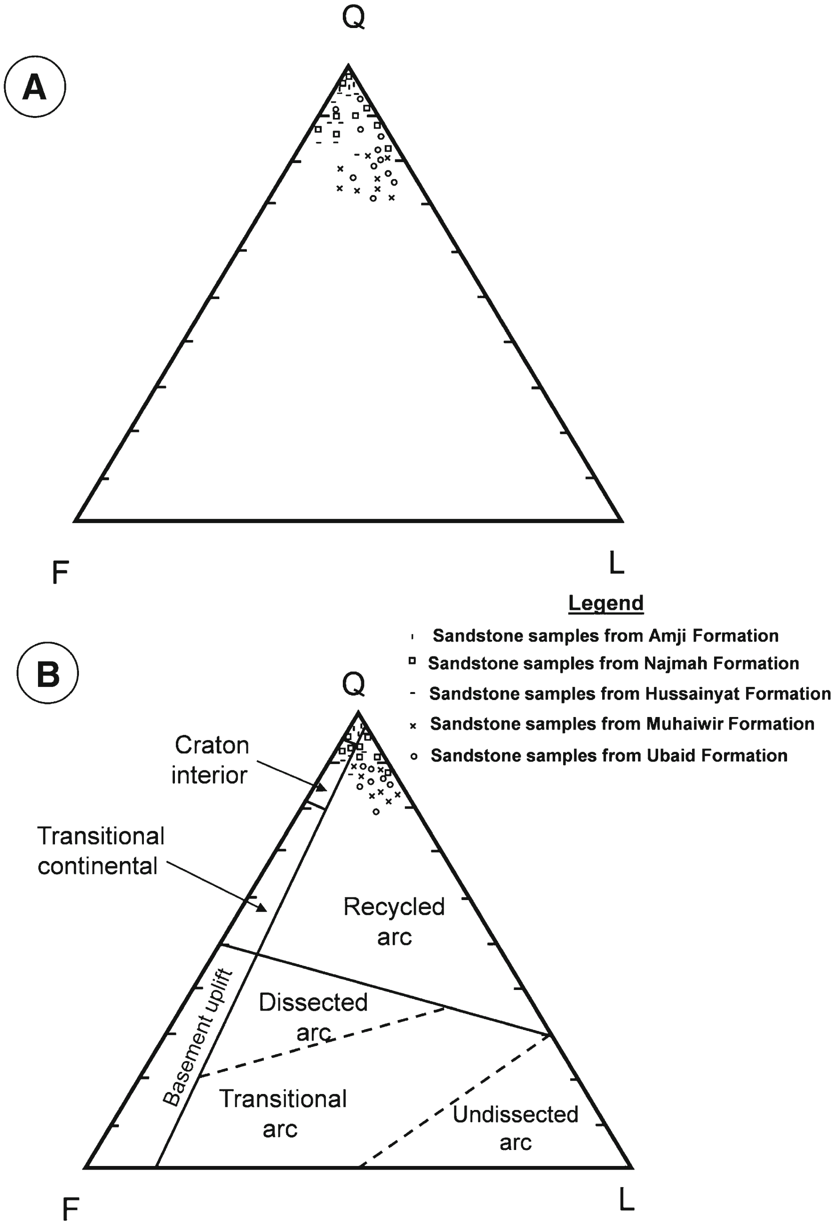


**Fig. 11** **a** Quartz–feldspar–lithic fragments (*Q*, *F*, *L*) ternary diagram showing the mineralogical composition of the studied sandstones. **b** Sandstone modal data of the Jurassic sandstones of western desert of Iraq. Tectonic discrimination fields defined by Ingersoll and Suczek (1979)

elongate and intensely sutured contacts (stretched mosaic) (Fig. 10c).

The Hussainiyat sandstones contain heavy minerals in 0.1–0.3 %, they are dominantly of opaques that form 40–81 % of the total heavies in addition to ZTR that form about 20 % and minor amounts of apatite, pyroxene, hornblende, epidote, and staurolite.

#### *Carbonate unit*

This unit comprises bioturbated dolosparites with ghosts of pellets and intraclasts, dolosparites with ghosts of bioclasts (mainly pelecypods and gastropods), and micritic limestones with detrital quartz and locally fossils. Mostly are equidimensional and coarse crystalline (Fig. 7f). The carbonates occasionally contain algal structures and were probably deposited in lagoonal to supratidal environments (Jassim et al. 2006).

### Amij Formation

#### *Clastic unit*

The petrographic constituents of the Amij sandstones include mainly quartz, less feldspar, micas, rock fragments (mostly carbonate), and heavy minerals. Generally, these constituents were cemented by carbonate (calcite) and, to a lesser extent, by ferruginous cement (Fig. 10d). The conventional quartz–feldspar–lithic fragments (QFL) classification points, on the whole, to the presence of three distinct types of sandstone (Fig. 11a). Quartz arenite forms about 70 % of the studied sandstone, whereas quartz wacke and lithic arenite form about 30 % of the Amij sandstone. Few micas (both muscovite and biotite) are recorded in some samples of Amij sandstones. They occur as fine flakes or laths commonly bended between detrital quartz grains.

The Amij sandstones contain relatively higher percentages of heavy minerals as compared with other Jurassic formations of western Iraq. The proportion of heavy minerals ranges between 0.6 and 55.9 %, with a mean of 4.46 %. They occur generally either randomly forming sinking structures that gives high radiometry or in distinct laminae. Two assemblages of heavy minerals are distinguished: opaque minerals including goethite, hematite, magnetite, leucoxene, and chromite and nonopaque minerals which include ZTR, monazite, celestite, staurolite, sphene, kyanite, apatite, garnet, and topaz.

#### *Carbonate unit*

Dolostones and marly dolomitic limestones generally are fine crystalline and porous, occasionally are fossiliferous (mostly of pelecypods and gastropods) with dedolomitization (Fig. 12a). Diagnostic features of supratidal–intertidal zone are shrinkage cracks, bird's eye, stromatolites, calcite pseudomorphs after evaporites, and local persistence of gypsum. Many of peritidal sedimentary structures have been obscured by dolomitization.

### Muhaiwir Formation

#### *Clastic unit*

The clastic unit of the Muhaiwir Formation is composed of sandstone that forms beds ranging in thickness from 0.8 to 2 m. It is dominantly calcareous and pebbly, with the pebbles reaching 15 mm in size.

Petrographic investigation shows that quartz is the most common framework constituent forming 72–84 %, few feldspar (microcline) in <1 %, carbonate cement (calcite and/or dolomite) 12–26 %, and ferruginous cement forming up to 5 % of the total constituents (Table 1). Generally, the sandstones can be classified as quartz and lithic arenite (Figs. 10e and 11a). Quartz grains are fine to coarse grained and contain vacuoles, zircon, and tourmaline inclusions.

#### *Carbonate unit*

The limestones of the Muhaiwir Formation was divided by Mohemed (1989) into four microfacies, they are lime mudstone, wackstone, packstone, and grainstone microfacies. The environment of deposition was recorded as subtidal, inner barrier, and shoal environment of the middle shelf. The dolostones comprise idiotopic with euhedral rhomb, idiotopic with subhedral to anhedral rhomb, porphyrotopic, and xenotopic varieties. Various types of pores could be recognized: intercrystalline, vuggy, and moldic. The fine crystalline and porous nature of Muhaiwir dolostones is indicated in Fig. 12b.

### Najmah Formation

#### *Clastic unit*

The clastic unit of the Upper Jurassic Najmah Formation in the study area has a considerable thickness variation from one area to another. The clastic unit is composed of sandstone, siltstone, and claystone with a thickness of 23–25 m, whereas the upper carbonate unit has 10 m thick. It lies unconformably and truncated to the south and southwest (Fig. 1) over the erosional surface of the Ubaid, Hussainiyat, Amij, and Muhaiwir formations of Middle Jurassic.

The sandstones are pale gray and rusty brown in color with friable to medium tough, medium to coarse grained, and moderately sorted to well sorted. They show fining-upward cycles, each cycle consists of subcycles of thickness range from 50 to 60 cm which are differentiated on the basis of surface erosional cut, with each erosional cut characterized by scattered pebbles of maximum size of 10 mm.

The sandstone is classified as quartz arenite and is composed of quartz (95 %), clay matrix (3 %), calcite cement (1.5 %) (Figs. 10f and 11a), and rare chalcedony cement (0.5 %) (Fig. 12d).

Heavy minerals are dominated by opaques in addition to ZTR, epidote, staurolite, kyanite, biotite, garnet, hornblende, and pyroxene. The siltstones are clayey and resemble the same colors as sandstones with parallel and cross-laminations, sometimes occurring in massive beds of thickness ranging from 0.3 to 5 m, with scattered iron concretions.

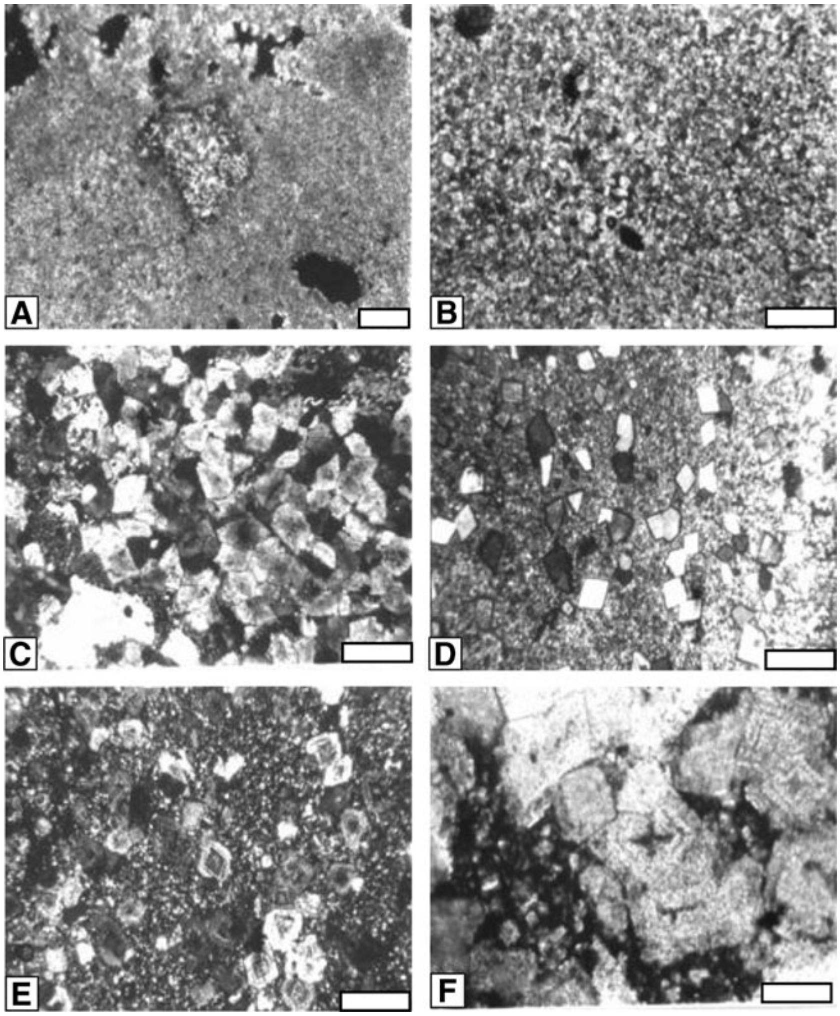
#### *Carbonate unit*

According to Jassim and Buday (2006), the upper carbonate unit comprises pale gray to buff recrystallized limestones with burrows alternating with hard recrystallized argillaceous to sandy limestones and white to gray and buff fossiliferous lithographic limestone with burrows and algal structures which may refer to the lagoonal environment of deposition. In the present work, the dolomite is fine to coarsely crystalline, mostly ferruginous, and with common zonation (Fig. 12c–f).

### Diagenetic stage

Detrital composition has been altered by diagenesis, leading, in particular, to the reduction of feldspar and lithic fragments in the studied sandstones.

**Fig. 12** **a** Dedolomitization, patchy, fossiliferous, porous, and very fine crystalline dolostone of the Amij Formation, x-nicols. **b** Fine crystalline dolostone of the Muhaiwir Formation, x-nicols. **c** Coarse dolomite as cavity filling by secondary sparry calcite, Najmah Formation, x-nicols. **d** rhombic dolomite with iron oxides rim scattered in a fine clayey dolomite matrix, Najmah Formation, x-nicols. **e** Dolostones, ferruginous, fine to coarse crystalline with zonation, Najmah Formation, x-nicols. **f** Small dolostone crystals are combined to form coarser dolomite with central cross. Najmah Formation, x-nicols. Scale bars=0.2 mm



Cementation is the common diagenetic event in most of the sandstone samples. Poikilotopic, pore-filling, and patchy carbonate (sparry calcite, micrite, and dolomite) are common (Fig. 13a, b). Hematite, goethite, and clayey cements are important cement in some samples (Fig. 13c). Fine crystalline, acicular chalcedony sometimes fills pores between detrital frameworks (Fig. 13d).

Compaction is reflected by deformation of the soft or labile fragments, bending of mica between rigid quartz grains, and highly sutured contacts of the detrital grains (Fig. 13e, f). Sometimes, the quartz grains are deformed in the highly sutured pressure–solution contacts. The deformed grains show some microcracks with common fluid inclusions (Fig. 10b).

Replacement of quartz grain by carbonate cement occurs in some samples (Fig. 13b). Several diagenetic processes affect the carbonate rocks of the Jurassic successions, depending on the rock type. Dolomitization is the common process in Ubaid, Hussainiyat, Amij, and Muhaiwir formations and some beds of Najmah Formation. Compaction, cementation, authigenesis, dedolomitization, and silicification have also occurred.

## Modal composition

The Gazzi–Dickinson method has been used for the counting of sand particles in thin sections (Ingersoll et al. 1984). The results are used to show the modal composition of the studied clastics and to discriminate the tectonic fields of the studied sandstones by using the scheme of Ingersoll and Suczek (1979).

The analyzed petrographic data of the Jurassic sandstones have been plotted on the QFL ternary diagram of Ingersoll and Suczek (1979); in this plot, the sandstones of the Jurassic clastics plot largely in the craton interior/recycled arc (orogen) fields (Fig. 11b).

This tectonic configuration of the Jurassic clastics show that they were formed in continental blocks with contribution of sediments weathered from uplifted areas (recycled orogen provenance). The tectonic origin depends largely on the quartz type (Dickinson and Suczek 1979).

The dominance of monocrystalline quartz grains in the present study with rare rock fragments and feldspar indicate that they were formed in the craton interior and the

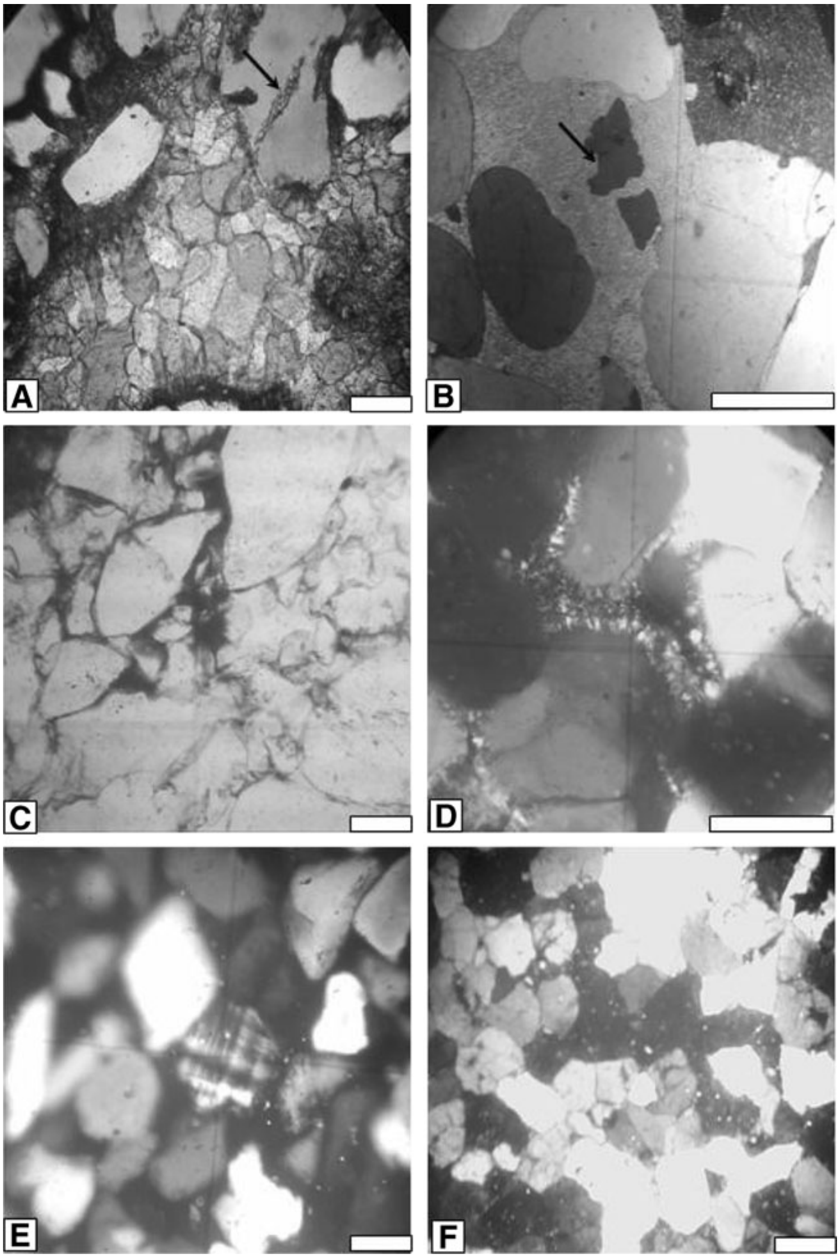


**Fig. 13** Photomicrographs illustrating the main diagenetic events affecting the studied Jurassic sandstones. **a** Patchy carbonate (dolomite) cement in the Hussainiyat sandstone forming drusy texture and fills cracks in quartz grain (*arrow*). **b** Micritic (calcite) cement in the Hussainiyat sandstone, note the replacement of part of quartz grain by calcite (*arrow*). **c** Clayey–ferruginous cement (*black patches*) in the Hussainiyat sandstone. **d** Fine silica (chalcedony) fills pores (*centered*) in the Najmah sandstone. **e** Point, tangential, and sutured contacts in the Muhaiwir sandstone, note the microcline (*centered*) with common cross-hatch twinning. **f** Sutured contact in compacted quartz arenite of the Amij sandstone. Scale bars=0.2 mm

sandstones were derived from the craton platforms and were deposited in continental marginal basins in addition to other uplifted areas. Additionally, the dominance of these fine monocrystalline quartz and the high proportion of k-feldspar/plagioclase may refers to the effect of weathering in the low-relief, gentle slope of the craton interior and long distance of transportation (Dickinson and Suczek 1979).

## Clay mineralogy

X-ray diffraction analysis was used to investigate the mineralogy of selected claystone samples. Claystones alternate with sandstone in some of the studied clastic units from the Jurassic succession of western Iraq (Figs. 5 and 9). The claystones are colored pale gray to brown due to common iron oxide content.

X-ray diffraction study shows that kaolinite is the dominant clay mineral in all samples analyzed with various proportions. Illite–smectite mixed layers, chlorite, illite, and palygorskite present sporadically.

The detrital origin of kaolinite and chlorite is manifested through different studies on Jurassic claystones from the western desert of Iraq (Ismail 1996; Tobia 2005). The predominance of kaolinite suggests a variety of possible source rocks, including shales, phyllites, schists, or feldspar-rich igneous rocks that were subjected to little leaching and intensive chemical weathering (Millot 1970; Chamley 1989).

Chlorite was derived from the weathering of rocks rich in ferromagnesian minerals that contains high Mg, Fe, and Ca and that is excellent in the basic igneous and metamorphic rocks (Millot 1970). Illite could be formed as a result of alteration of muscovite, biotite, and k-feldspar both in the weathering zone and during diagenesis (Hower et al. 1963).

Palygorskite commonly presents in association with dolomite in the studied samples. This may reflect the authigenic formation of this mineral in evaporative conditions that assist for dolomite formation. Palygorskite as fibrous mineral was formed either by chemical sedimentation as authigenically formed mineral in lagoons and evaporitic basins (Millot 1970; Chamley 1989) or by transformation from former clays during early diagenesis in epicontinental and inland seas and lakes. The authigenic formation of palygorskite in the Jurassic clastics of the western Iraq is also cited by Al-Sangary (1987), Ismail (1996), and Tobia (2005).

## Bulk rock geochemistry

Analysis of the bulk sandstone samples for major oxides was done using wet chemical analysis; for some trace elements, by using emission spectroscopy and X-ray fluorescence. The geochemistry of the Jurassic sandstone supports the petrographic results. Variation in major and trace elements analyzed reflects the variation in sandstone types. Sandstones samples show relatively high content of $SiO_2$ (Table 2). The source of silica is mainly quartz, feldspars, clay, and heavy minerals. $Al_2O_3$ and $K_2O$ content may relate to the presence of potassium feldspars (orthoclase and microcline), illite, and mica. The source of $Na_2O$ is principally related to plagioclase feldspar. Ti opaque minerals and rutile are the main holders of $TiO_2$. Higher content of iron may be related to the abundance of iron oxide, heavy minerals, and partly to Fe-containing clay minerals. In the Hussainiyat Formation, the high $Fe_2O_3$ relates to the presence of iron concretions, iron pisolites, iron oolites, and proto-oolites (Al-Naqib et al. 1985; Al-Naqib 1994). MgO content is related mostly to the presence of dolomite as cementing material. Calcite cement is the main source for CaO.

Generally, the results of chemical analysis reflect that the clastics are of high maturity, where $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and $TiO_2$ generally comprise more than 80 % of the chemical constituents. These oxides are controlled by kaolinite ($SiO_2$ and $Al_2O_3$), goethite and hematite ($Fe_2O_3$), quartz ($SiO_2$), and rutile and leucoxene ($TiO_2$). Consequently, these rocks are depleted in bases and alkalies.

Trace elements distribution reflects the contribution of intermediate and basic igneous rocks and various heavy minerals derived from these rock types. These sources are responsible for the higher content of Cr and relatively Co

**Table 2** Representative chemical analyses of sandstones from the Jurassic formations, Western Desert, Iraq (major oxides in weight percent; total Fe as $Fe_2O_3$; trace elements in parts per million)

| Formation | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | LOI | Total | Cu | Ni | Co | Cr | Zn | Sr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Najmah | 92.11 | 0.22 | 0.72 | 1.01 | 0.01 | 0.35 | 1.19 | 0.31 | 0.12 | 3.87 | 99.91 | 6.3 | 81 | 62 | 140 | 20 | 167 |
| Muhaiwir | 73.56 | 0.46 | 6.69 | 0.86 | 0.01 | 4.24 | 7.58 | 0.07 | 0.15 | 5.74 | 99.26 | 10.2 | 3.2 | 0.6 | 98 | 12 | 55 |
| Amij | 72.17 | 0.72 | 9.25 | 2.52 | 0.02 | 1.16 | 8.75 | 0.36 | 0.63 | 3.74 | 99.32 | 6.5 | 7.4 | 6.2 | 75 | 13 | 104 |
| Hussainiyat | 90.90 | 1.42 | 2.81 | 2.66 | 0.01 | 0.85 | 0.35 | 0.01 | 0.00 | 0.39 | 99.40 | 5.2 | 9.5 | 5.5 | 85 | 16 | 68 |
| Ubaid | 65.96 | 0.48 | 2.99 | 0.83 | 0.05 | 8.51 | 10.76 | 0.06 | 0.04 | 9.97 | 99.65 | 4.0 | 0.8 | 0.7 | 77 | 12 | 116 |

and Ni for the Najmah Formation (Table 2). Strontium commonly relates to carbonate content and to celestite which is recorded in small quantities in some of the studied samples.

## Discussion and conclusions

### Sequence stratigraphy of the Jurassic formations exposed in the western desert of Iraq

Several unconformities from Triassic to Upper Cretaceous passing throughout the questioned Jurassic system were indicated by Al-Naqib et al. (1986). They defined the Triassic–Jurassic boundary as very extensive and huge erosional unconformity occurred due to marked shifting of both structural and depositional (E–W) strike of the Triassic (Rhaetic) Zor Hauran Formation to (NE–SW) Jurassic formations. Schettino and Scotese (2002) stated that the most important rifting events in the Mediterranean region occurred in Bajocian–Mid-Tithonian time (175–148 Ma). It is likely that this rifting phase had begun in latest Toracian time (182 Ma) (Jassim and Goff 2006).

Comparably, two regional maximum flooding surfaces can be postulated in the western desert of Iraq, reflecting two orbital-forcing model second-order sequence boundaries (SB2) that can be suggested to be marked at the base of the Ubaid Formation in the very late Toracian time (175.6 Ma) (Fig. 14). Similarly, Yilmaz and Altimer (2001) used certain sedimentary structures in the recognition of sequence boundaries in Upper Jurassic–Upper Cretaceous peritidal carbonates of the western Taurides in Turkey, where approximately the same facies of subtidal, intertidal, and supratidal carbonates were identified in the Upper Jurassic (Kimmeridgian)–Upper Cretaceous (Cenomanian) peritidal carbonates of Fele area (western Taurides, Turkey). The present Ubaid Formation is characterized by a cyclic pattern, shallowing upward in the trend of facies. At the top of the Ubaid Formation, many karstic features and collapse breccias were recognized. In situ karstic breccia and collapse breccia are structures commonly indicative of third-order sequence boundaries (Yilmaz and Altimer 2001). They added that, however, mud cracks, solution pores or vugs, sheet cracks, and bird's eye structures are commonly delineated by parasequence boundary.

Consequently, the erosional unconformity that occurred on the upper carbonate unit of the Ubaid Formation could be regarded as a third-order sequence boundary (SB3). The concept in regard to the third-order sequence contains at least the following aspects: a sequence is a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Mitchun 1977).

The paleogeographic map (Fig. 15) indicates several depressions in karstic shapes forming disconformity for the Hussainiyat iron ore filling karsts. Charaosset and Pierre-Jean (2000) assured that most of the paleokarstic discontinuity corresponds to the boundaries of third-order depositional sequence. They added, paleokarstic discontinuities were geographically limited to the Grands Causses graben, whereas other paleokarstic features were observed within the uppermost parts of the Dollomies II Formation in the Horst de Saint-Bresson. Eventually, these features can be used as recognizable features as graben and horst, where they found in the area 20–60 km east of Rutba City.

The second one can be suggested to be marked or fixed at the end of the deposition of the Najmah Formation at the Mid-Tithonian (149 Ma) (Fig. 14), as assured by Jassim and Goff (2006); they regarded that this regional unconformity marks the boundary between megasequences AP7 and AP8, as postulated by Sharland et al. (2001).

It is very important to recognize the prominent unconformable boundary between Najmah Formation (Late Jurassic, Malm) and the overlaying (Upper Cretaceous, Cenomanian) Rutba/Msád Formation. This boundary is marked by huge laterite deposits between the two formations and particularly appear very well in outcrops is near km 55 east of Rutba City and in other small outcrops distributed in this area. In between these two major sequence boundaries, there were five recognizable unconformity surfaces on top of each carbonate unit of the Jurassic system.

In the absence of a detailed biostratigraphic description in Iraq's Jurassic formations, the five formations can be interpreted as six transgressive–regressive depositional sequences that could be named Uba'id Sequence, Hussainiyat Sequence, Amij Sequence, Lower and Upper Muhaiwir sequences, and Najmah Sequence. By stratigraphic position and similar paleogeography with central Saudi Arabia, these six Iraqi western desert sequences could correlate almost perfectly to the sequences in central Saudi Arabia (see Al-Husseini 2009):

Rhaetian Zor Hauran Formation=Late Norian and Rhaetian Minjur Sandstone
Early Jurassic Hiatus:

1. Undated Uba'id Sequence=Toarcian Marrat Sequence Semiregional Aalenian Hiatus excludes Uba'id is Aalenian in western Iraq
2. Undated Hussainiyat Sequence=Early Bajocian Lower Dhruma Sequence
3. Undated Amij Sequence=Bajocian–Bathonian Dhruma Sequence B
4. Bathonian Lower Muhaiwir Sequence=Bathonian–Callovian Dhruma Sequence A
5. Upper Muhaiwir Sequence=Callovian Tuwaiq Sequence
6. Oxfordian Najmah Sequence=Oxfordian Hanifa Sequence

Kimmeridgian and Tithonian missing in western Iraq outcrops

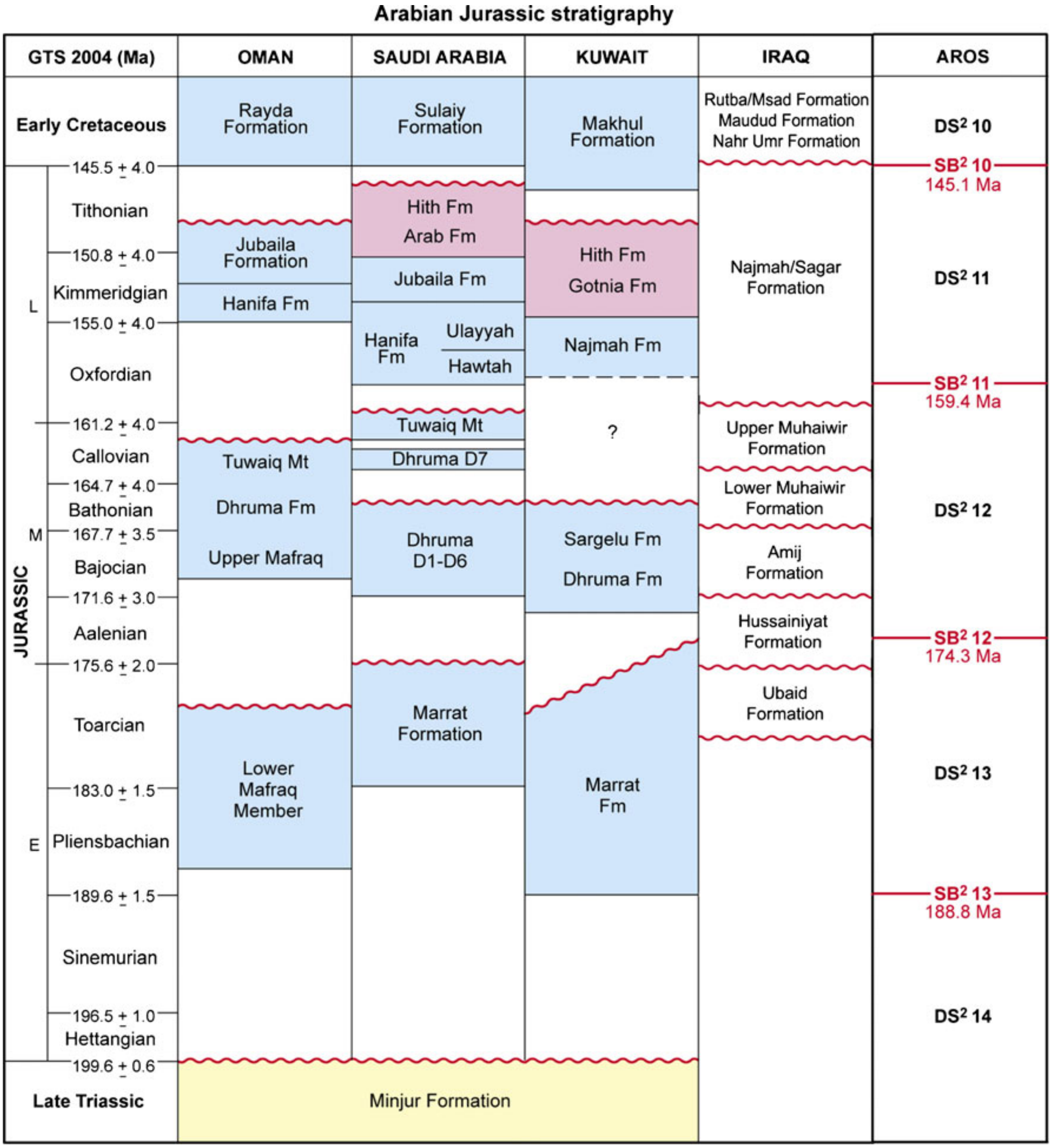


**Fig. 14** Correlation of the Jurassic formations and hiatuses in Kuwait, Saudi Arabia, Oman, and correlative formations in the western desert of Iraq (present study), modified from Al-Husseini and Matthews (2006)

## Accommodation space

As mentioned before by Al-Naqib et al. (1985, 1986) and Al-Naqib (1994, 1995), each Jurassic formation of the western desert comprised two main lithological components or units:

1. Lower clastic unit which represents the terrestrial deposits for the resultant regressive remnants of the sea.
2. Upper carbonate unit which forms the resultant transgressive phase of the sea level.

In general, the clastic units of these formations decrease in thickness to the west and northwest towards the main Rutba–Hail uplift. This is could be related to the intermittent rejuvenations of the tectonic activities of the Rutba–Hail uplift. These were reflected by the extensive erosional unconformity at the base of every clastic unit of the Jurassic formation. Eventually, sea level (lowstand system tracts) would resulted in the progradation of the land on the expense of the sea forming the recognizable progradation of [the fluvial and deltaic deposits of the clastic units of Hassainiyat (fluvial), Amij (mixed fluvial–deltaic), Muhaiwir unclear coarsening upward cycles "at

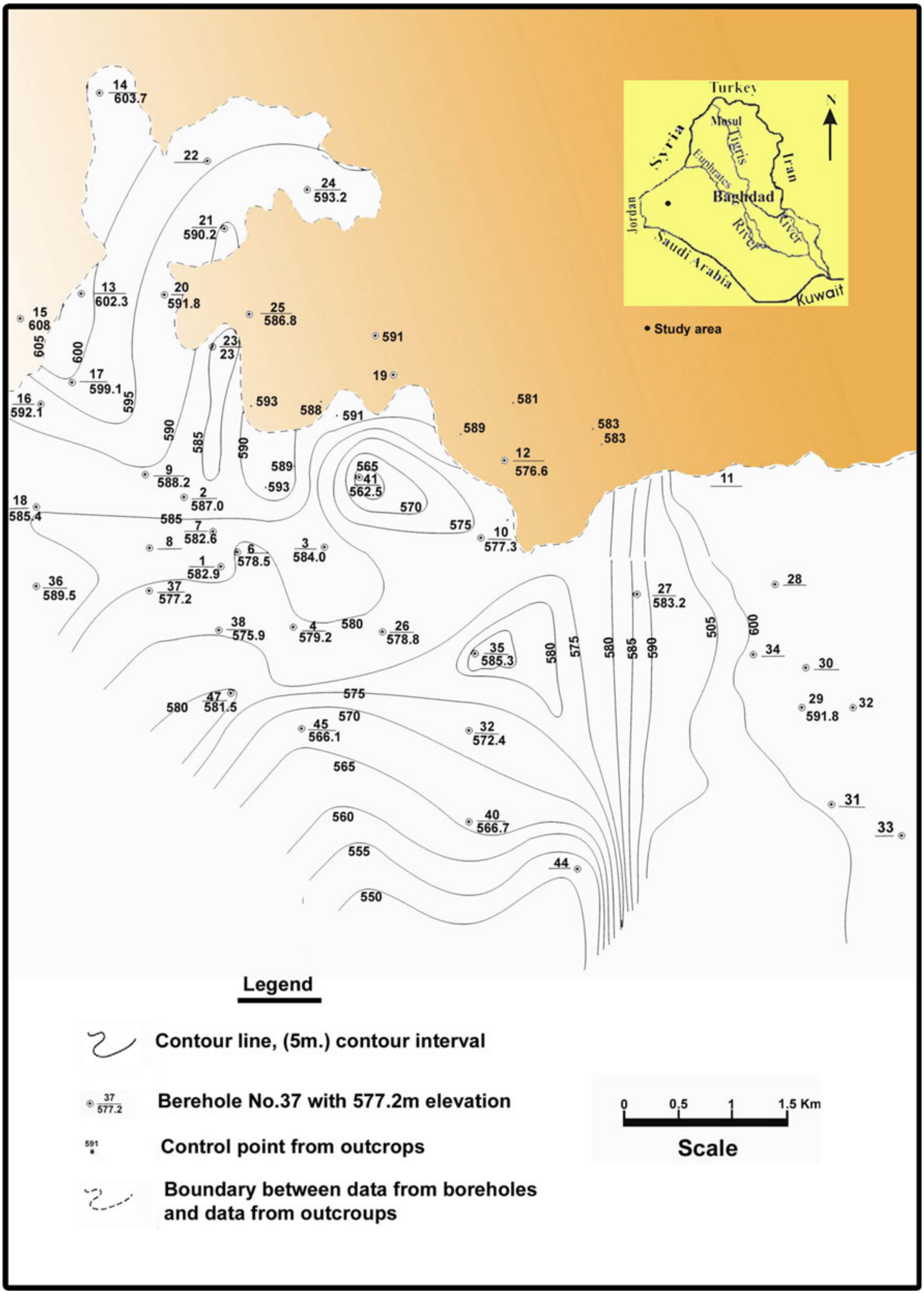


**Fig. 15** Paleogeographic map of parts of the Hussainiyat Formation. After Al-Naqib (1994)

least in the areas about 60 km east of Rutba City” and Najmah (fluvial)] on the sea.

Tectonism causes uplifting reproducing erosional unconformities and contemporaneously sea level regradation.

Detailed mapping of both surface outcrops and shallow boreholes (10–45 m) in depth, on the upper carbonate unit of Ubaid Formation in particular (Fig. 15), show the drainage pattern and Qasir et al. (1992) and Jassim and Buday (2006) called them as “the karst phenomenon.” These erosive images were filled later by the clastic constituents of the Rutba iron ore (in the area about 20 km east of Rutba City).

In turn, sea level rising (highstand system tract), i.e. sea prograding, causes deposition of the carbonate units of the Jurassic Formations system. The progradation resulted to various carbonate environments of deposition ranging from subtidal, intertidal, to supratidal.

## Paleogeographic reconstruction and historical geology

A window of older strata within Rutba uplift exposed rocks are of Triassic (Rhaetic) age which is represented by the Zor Hauran Formation at the western part of the study area. It attains a thickness of about 68 m (Al-Naqib et al. 1986). The Triassic rocks have an approximately E–W trending regional strike. The regional strike of the overlying Jurassic formations (Ubaid, Hussainiyat, Amij, and Muhaiwir) runs in NE–SW direction, except the Najmah Formation of Late Jurassic (Malm) which is entirely trending in the E–W direction, although its easternmost parts swing again fairly toward the same strike of its underlying Jurassic formations (Fig. 1).

The Upper Cretaceous (Upper Cenomanian) rocks, “the Rutba/Msád Formation,” capped the Najmah Formation unconformably in an approximately E–W trending regional strike. The most intensive major and final Triassic uplift cause the regional unconformity at the Triassic–Jurassic junction. This led to the changing of both the depositional and structural strikes of the Jurassic formations from E–W to the NE–SW direction. It is thought that this uplift can be regarded as the beginning of the Rutba uplift (i.e., activation of the basement blocks bordered by faults) in the Rutba area. It is argued for the restriction of the Jurassic basins of deposition to the southeast and east of the Rutba uplift. No other Jurassic rock types were recorded in both boreholes and outcrops in the west, northwestern, and northern parts of the present uplift.

After the Rhaetic emergence, a series of cyclic regressive–transgressive pulses occurred in the late Liassic which were well-developed along the edge of the Rutba uplift (Fig. 16). The sequence in western Iraq contains three cycles, each cycle comprises fluvial to fluviomarine clastics overlain by inner shelf to coastal carbonates. Towards Mesopotamia, the cyclicity is defined by alternating inner shelf carbonate and sabkha facies (Jassim et al. 2006).

At the Middle Jurassic (Early Dogger–Aalanian), three indistinct coarsening-upward cycles of the lower clastic unit of the Ubaid Formation took place. It is characterized by minor seismic shocks marked by the flame structure which was assigned for the quick sand action due to liquefaction. It means relative instability of the blocks of the basement on NE–SW axial planes interplay. It was followed by major transgression and/or rapid subsidence that led to the deposition of the basal marl beds of the upper carbonate unit of the Ubaid Formation with irregular paleogeographical surface of the basin (Amin et al. 1992). The irregularity of the basin caused the variable thicknesses of the marl beds of the subtidal zone (Al-Naqib et al. 1986).

Stratigraphically and due to the lack of paleontological evidence, the present work can adopt the relative age (Middle to Late Aalenian) and a remarkable intensive erosional unconformity took place (after the deposition of the Ubaid Formation). It formed a drainage pattern that nearly followed the NW–SE and the NE–SW valley patterns of the present days (Fig. 15). This unconformity in turn affected the thickness distribution of the lower clastic unit of the Hussainiyat Formation horizontally towards west. In addition, the thickness of the carbonate unit of the Hussainiyat Formation is also decreased towards the west, forming patchy outcrops and diminished to expose the underlying iron-bearing horizon in geomorphic depressions formed by faults.

One main set of vertical faults of NW–SE trend was initiated during this intensive erosional unconformity reflected the block basement twisting at that time forming styles of horst and graben. It affected the sedimentation of the clastic unit of the Hussainiyat Formation. Its hanging wall behaved as a barrier to define the terminal parts of the basin of deposition of this unit, while its foot wall received sediments of this unit. It is proved by both boreholes and outcrops. This fault runs parallel to the strike of Ubaid Formation. The horst and graben may be inherited from the paleotectonisms (Cambrian–Ordovician). This could be used in this area as an indication for Paleozoic petroleum richness as the case of Khleisia and Akkas oil fields (Fig. 17).

Before the deposition of the tidal flat (supratidal zone) of the upper carbonate unit of the Hussainiyat Formation, the area was also subjected to intensive erosion, particularly the northwestern parts of its basin of deposition, leading to variable thicknesses and the formation of the laterite-like soil. The erosion was accompanied by another epeirogenic activity dated by the initiation of the N–S trending vertical fault (Fig. 15)

The N–S vertical fault has the eastern upthrown wall and the western downthrown wall. It formed at later stages of the deposition of the lower clastic unit and shared in the erosion of this unit and formed a barrier in front of the extensions of the supratidal zone of the upper carbonate unit of Hussainiyat Formation. The northwestern extensions of the basin of deposition of the upper carbonate unit was defined

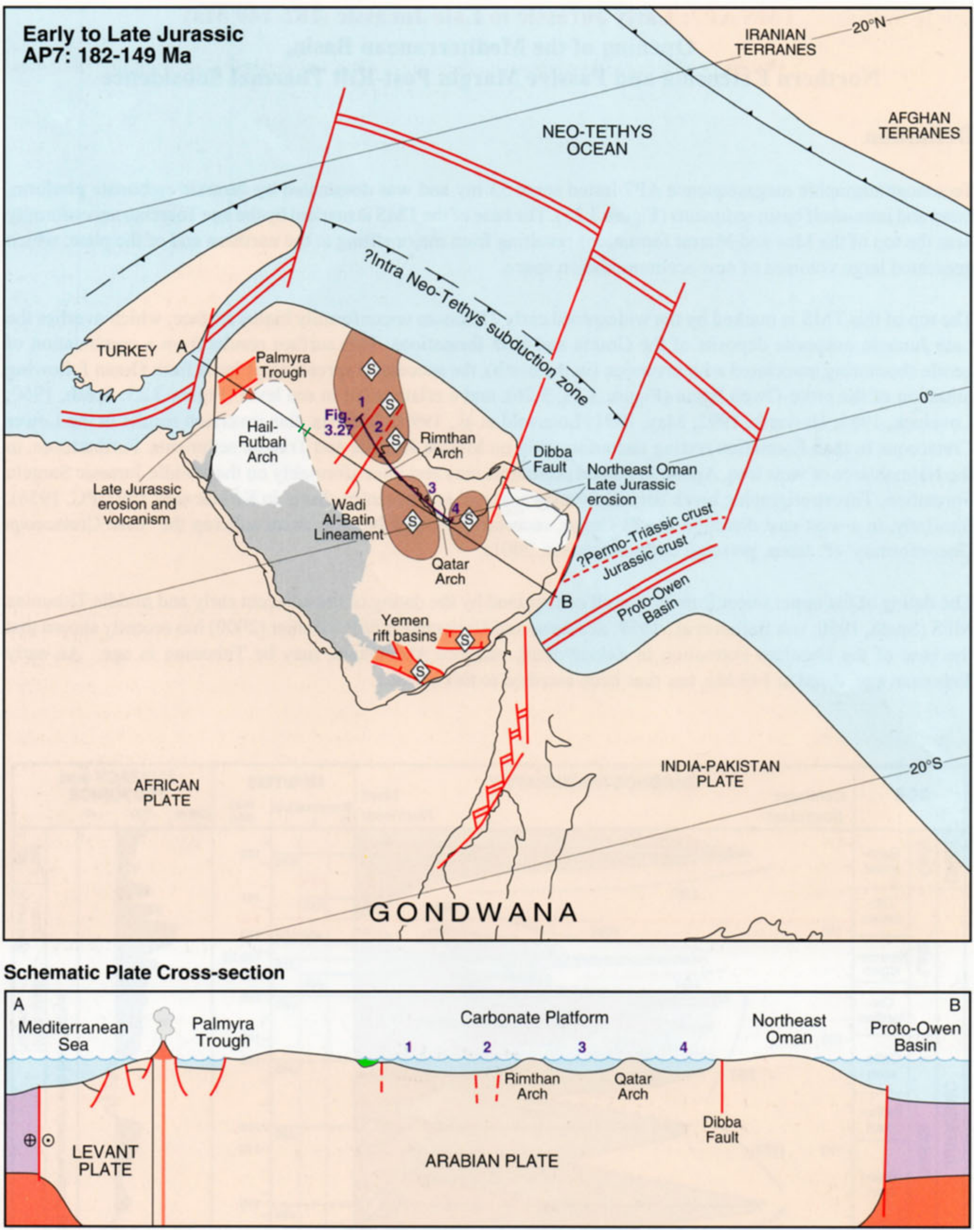


**Fig. 16** Paleotectonic map and cross-section for the megasequence AP7 of the Arabian Plate showing the location of the studied area (in *green* on cross-section), modified from Sharland et al. (2001) and reproduced by permission of Gulf PetroLink, Bahrain

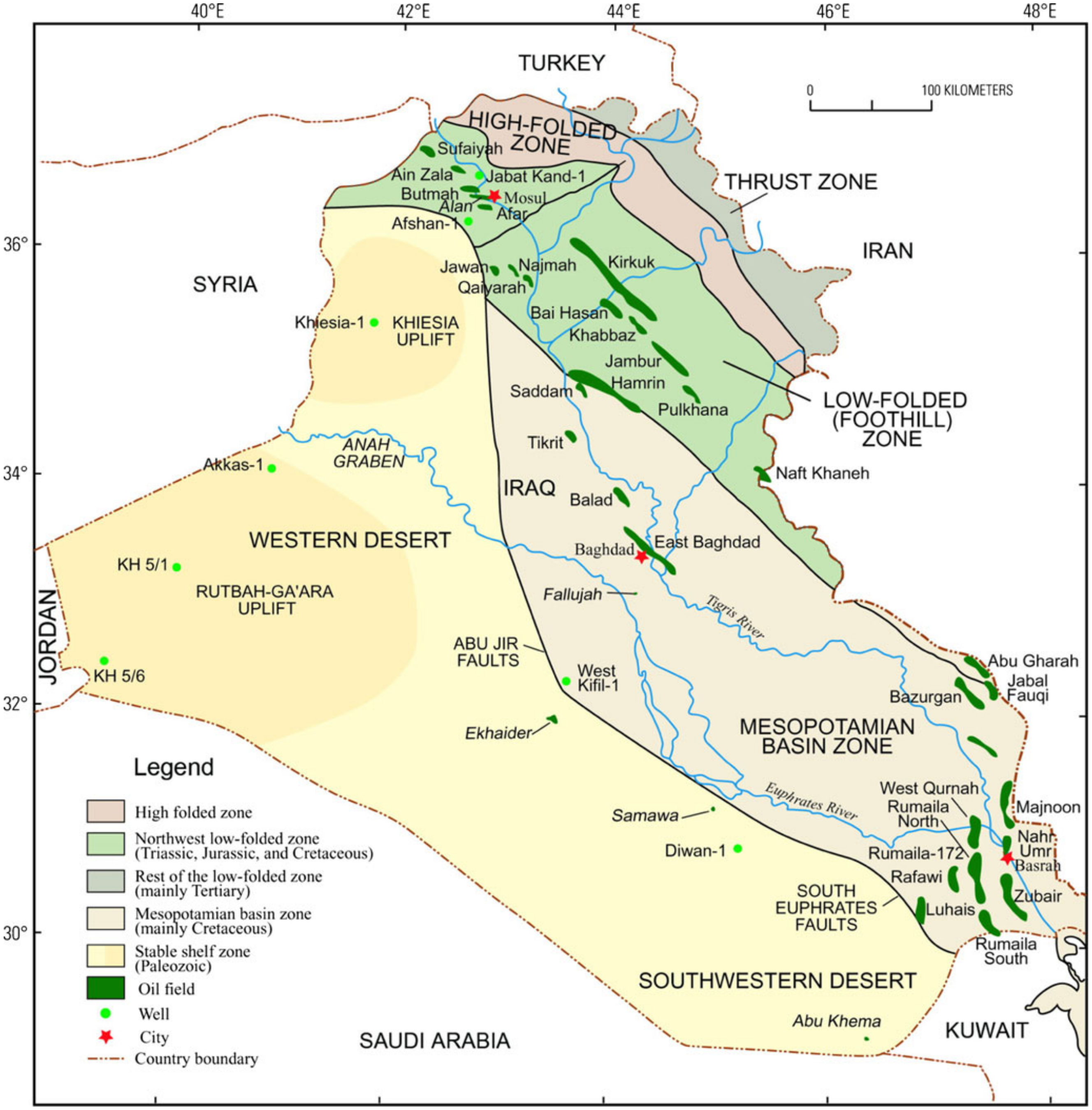


**Fig. 17** Major tectonic regions and petroleum fields of Iraq. Widyan Basin includes the western and southwestern deserts of Iraq (shown in *yellow*). After Fox and Ahlbrandt (2002) after modification from Aqrawi (1998)

and restricted by this fault and may be rejuvenated again in the same style that caused the retreating of the seawater towards the eastern and southeastern parts of the Rutba Uplift.

The NE–SW and the N–S trending faults may rejuvenate many times during or after the deposition of the overlying younger formations. In the field, the last distinctive effect on both Najmah and Rutba/Msád formations was recorded. Many small episodes of nondeposition were recorded during the cyclic deposition of the upper carbonate unit of the Hussainiyat Formation represented by the sharp irregular contact or bedding planes. This was reflected many times by small regressions and transgressions.

At Middle Jurassic (Bajocian), a prominent epeirogenic activity occurred after the deposition of the carbonate unit of the Hussainiyat Formation, indicated by its thickness variations in a few kilometers, which led to the deposition of the continental three major fining-upward cycles of the large meander river system of low sinuosity of the lower clastic unit of the Amij Formation.

After that and during the Bajocian time, a major subsidence or transgression of the sea also took place, leading to the deposition of the cyclic pattern of marly dolostone, dolomitic limestone, and dolostone or limestone, which suggested the deeper parts of the intertidal zone (transitional zone), the supratidal to intertidal zones, and the supratidal zone respectively.

At the beginning of the Bathonian time, other major epeirogenic activity occurred (after the deposition of the Amij Formation), indicated by the wide unconformity between the Amij Formation and its overlying Muhaiwir Formation, then the deposition of the lower clastic unit of the Lower Muhaiwir, followed by major transgression, which was responsible for the deposition of the upper carbonate unit of the Lower Muhaiwir.

Another major uplift occurred that caused the deposition of the lower clastic unit of the Upper Muhaiwir, followed by major transgression marked by the deposition of the upper carbonate unit of the Upper Muhaiwir.

In general, both the depositional and structural strikes of the Jurassic formations (except the Najmah Formation) changes in clockwise direction, i.e., the Ubaid Formation have about (N50E) regional strike, while the Muhaiwir Formation have (N60E) regional strike from older to younger, respectively.

A remarkable and huge regional uplifting was recorded between the Middle Jurassic (Bathonian) and the Upper Jurassic (Malm), indicated by the regional unconformity of the Rutba uplift, including all the deposited Triassic and Jurassic rocks. The unconformity was marked particularly by the occurrence of the lateritic horizon above the top part of the Muhaiwir Formation. The laterite in km 55 is variable in thickness and it may be of little economic importance (Al-Naqib et al. 1986).

At Late Jurassic (Malm), the braided river system of deposition was dominated by the lower part of the lower clastic unit of the Najmah Formation. Its major current direction was to the north, i.e., its source area was the Arabian Shield in the south. The Najmah Formation rests unconformably over the eroded Triassic (Rhaetic) and Jurassic (from Middle to Late Aalenian to Upper Bathonian) in E–W trending regional strike from about 10 km east of Rutba City towards the east. After the deposition of the lower clastic unit of the Najmah Formation, a major transgression of the sea took place, leading to the deposition of the upper carbonate unit of the Najmah Formation accompanied by many seismic shocks marked by the convolute lamination of the clastic unit of the Najmah Formation and the slumping structure of its upper carbonate unit. In this context, it is thought that the present Najmah Formation with its two units can be compared with the Najmah carbonate of the Jurassic system of northern Iraq, following the work correlation carried out by Al-Mubarak (1983).

During the end of the Late Jurassic (Malm) to the Upper Cretaceous (Upper Cenomanian) times, a recognizable unconformity was also found and the abrupt changes of the regional dip took place in the south of the study area, particularly along Rutba–Ramadi Road, i.e., along the regional strike (in the E–W direction) of the Najmah Formation. This unconformity is marked by the thinly to very thinly bedded, discontinuous, patchy form and of little economic importance ferruginous lateritic horizon.

## Provenance history

Petrographically, the studied sandstones of the clastic units from the Lower and Middle Jurassic formations are mainly made up of quartz arenite with subordinate lithic arenites and quartz wacke (Fig. 11). According to this variation, there is no conclusive evidence to specify one type to be the dominant source rocks.

These sandstones were derived largely from cratonic or recycled sources. These are commonly granitic or gneissic exposures which are supplemented by recycling of associated sediments (Dickinson 1985). This suggests that the dominant control on sediment petrography within the basin was the source area (the crystalline complexes of the basement rocks of Iraq) (Buday 1980).

The area of study was subjected to several uplifting and subsidence caused mostly by the basement blocks bordered by vertical faults interplays on various axial planes directions causing the rejuvenations of the structural elements and thickness variations of the present formations (Al-Naqib et al. 1986).

This provenance type implies Lower and Middle Jurassic formations (Ubaid, Hussainiyat, Amij, and Muhaiwir) mostly located in the western and southwestern directions. This evidence depends on measurements of the paleochannels of the clastic unit of Hussayniat Formation and some cross-bedding of the clastic unit of Amij Formation (Al-Naqib et al. 1986; Al-Naqib and Al-Youzbakey 2007), whereas in the Upper Jurassic (Najmah Formation), the major current direction for the clastic unit points to the north, which means that the source area was the Arabian Shield to the south. This idea is manifested by the fluvial system in this unit from braided to meander style, which may relate to tectonic disturbance and changing of the source area or a sharp climatic change within the source area (Al-Naqib 1995). The Arabian Shield constitutes a Precambrian metamorphic and igneous basement complex.

Concerning the previous provenance studies of the Jurassic successions of western Iraq, Al-Atia et al. (1997) have shown that the clastic sediments of the Hussainiyat and other Jurassic sediments were most likely derived from two sources: the Ga’ara Formation (Permo-Carboniferous) and the Arabian Shield Complex rocks, whereas Al-Naqib and Al-Youzbakey (2007) have suggested that both Hussainiyat and the older Ga’ara clastics were derived from the same source of the western and southwestern Arabian shield.

Deeply weathered in situ parent rocks occurred sometime in the Late Triassic and Early Jurassic under a humid and hot tropical climate favorable for the presence of Middle Aalenian Hussainiyat Formations (iron-bearing horizons). Intensive chemical weathering is evidenced at the close of Triassic and Early Jurassic in the Arabian Plate (Abed 1979; Goldbery 1979; Valeton et al. 1983). This tropical weathering is reflected by the deeply weathered and highly karstified upper carbonate unit of Ubaid Formation, development of lateritic red beds in Arabia of Early Jurassic age (Abed 1979), dominance of kaolinite and residual elements (Fe, Al, and Ti), and absence of alkalies in the residual sediments (Al-Bassam and Tamar-Agha 1998).

The weathering products were transported by rivers to an environment represented by deposition of wave-dominated deltas and interbedding of fluvial, coastal plains, and

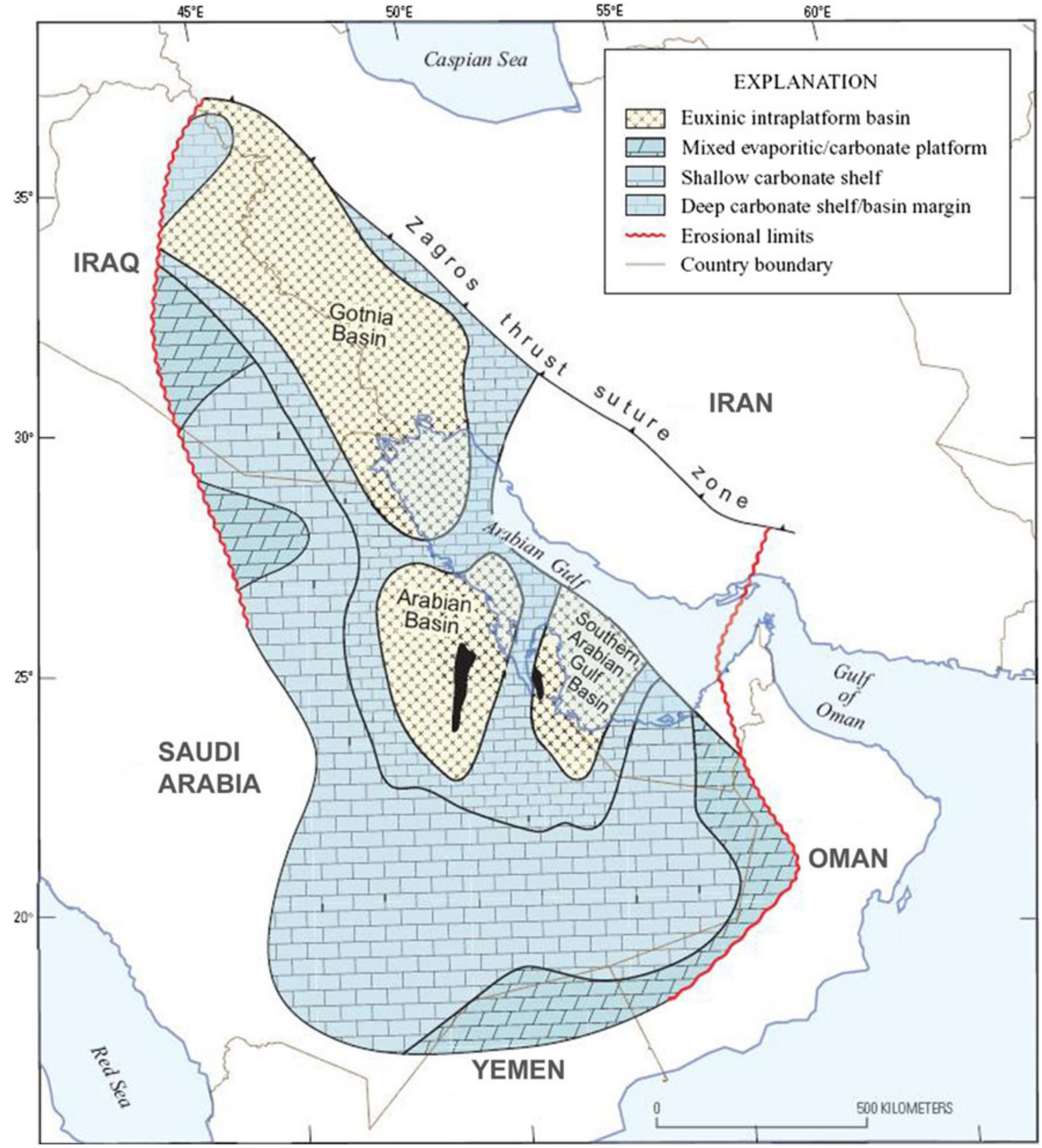


**Fig. 18** Gotnia, Arabian, and Southern Arabian Gulf Basins in which Jurassic hydrocarbon source rocks accumulated. After Fox and Ahlbrandt (2002) and modified from Al-Sharhan and Kendall (1986)

shallow marine facies of the studied sediments. Deposition in such environments leads to sorting and mineralogical maturity of sandstones (Franzinelli and Potter 1983). The previously mentioned conditions lead to the common increase of heavy mineral concentrations in the Jurassic clastics of the western desert of Iraq, specially those of Amij and Muhaiwir formations.

Heavy minerals of the studied clastic units are dominated by opaque minerals which include hematite, magnetite, leucoxene, goethite, limonite, and chromite. The nonopaque varieties include the ZTR group, staurolite, epidote, kyanite, garnet, and minor amounts of hornblende, pyroxene, biotite, apatite, corundum, topaz, sphene, monazite, and celestite.

The heavy mineral grains being highly rounded, especially tourmaline and, to a lesser extent, the others, favor the view that the sandstones hosting these heavies were derived from a preexisting sediments. The ZTR group minerals were found as common in older clastics from the western desert of Iraq (Sadiq 1980; Tobia 1983; Al-Juboury and Hassan 1996).

The majority of heavy minerals recorded favor the contribution from metamorphic sources, such as staurolite and epidote, which indicate low-grade and medium-grade metamorphic sources, whereas others were derived from basic igneous sources.

However, iron oxides (goethite, hematite, and limonite) represent authigenic growth, while magnetite, ilmenite, and chromite suggest derivation from basic igneous and metamorphic rocks. Although ZTR group minerals as well as monazite, sphene, apatite, and topaz also occur in acidic and pegmatitic source rocks.

## Hydrocarbon prospectus

The platform part of Iraq is divided into two basic units, i.e., a stable (unfolded) and an unstable (folded) shelf (Buday 1980). The stable shelf is characterized by a relatively thin preserved sedimentary cover. The unstable shelf has a thick and folded sedimentary cover and the intensity of the folding increases toward the northeast (Buday 1980).

The western part of Iraq lies in the stable shelf zone and is a continuation of the Widyan Basin of Saudi Arabia which is controlled structurally by horsts and grabens like the case in Saudi Arabia. It includes a large area referred to as the western and southwestern deserts (Aqrawi 1998). The stable shelf zone occupies more than one third of the area of Iraq, including the Khleisia and Rutba–Ga'ara Uplifts and Anah Graben (Fig. 17). The unstable (folded) zone formed during the Late Cretaceous and Tertiary occupies the northern and northeastern mountainous area of Iraq. It is contiguous with the Alpine fold belts of the Taurus and Zagros Ranges of Turkey and Iran (Buday 1980).

Onset of oil generation in Iraq began about 250 million years ago, reaching peak generation, expulsion, migration, and entrapment during the Jurassic period (Fox and Ahlbrandt 2002).

Numerous prospects and structures have been identified in Iraq. Oil and gas are trapped in elongate N–S trending fault block anticlines over reactivated, deep-seated faults in the Mesopotamian Basin region. Also, there may have been early entrapment when Zagros folds were beginning to form during Late Cretaceous and Tertiary, coincident with peak petroleum migration. Later (during the Miocene–Pliocene), oil generation may

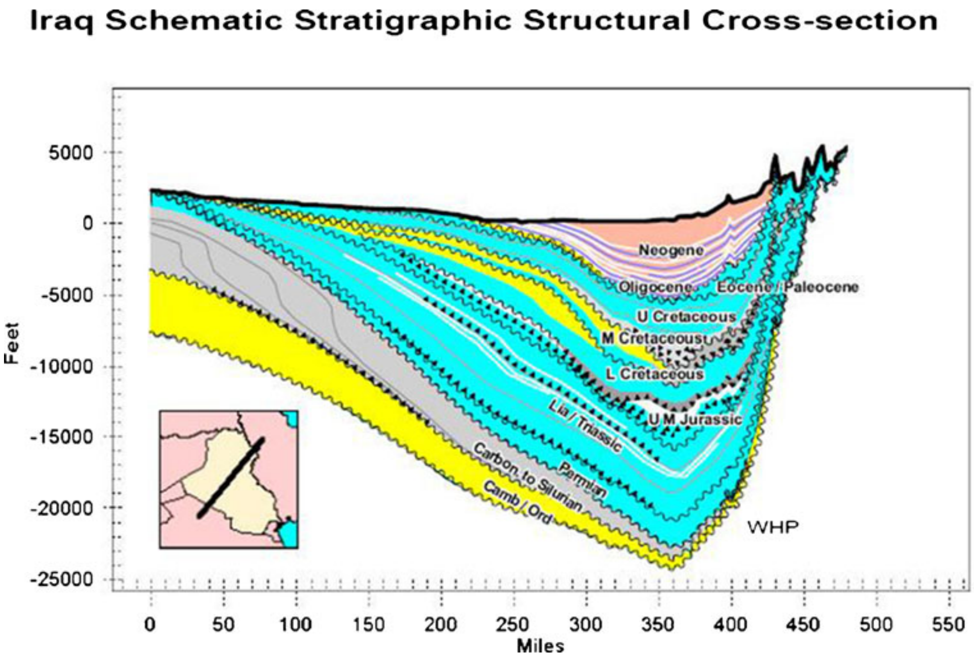


**Fig. 19** Schematic stratigraphic–structural cross-section of SE–NW of Iraq. After Pierce and Rutherford (2003)

have been renewed, associated with thick molasses deposition to the east.

Tectonic elements of the Mesopotamian Basin, Zagros Fold Belt, and Zagros Thrust Zones, along with the NW trending compressive folds accompany the Zagros collision zone, may contain significant volumes of petroleum that were derived from Jurassic source rocks (Fox and Ahlbrandt 2002).

In the western part of Iraq, the main target on most of the exploration blocks focused on the lower Paleozoic successions, whereas prospects in Triassic, Jurassic, and lower Cretaceous targets are less extensive but may have significant potential on certain blocks in both stratigraphic and structural traps (Bain 2001).

The present work assured these facts in the area of study and recommend to concentrate oil investigations particularly within the graben and horsts areas, i.e., in the area extends from about 20 km east of Rutbah city to further eastwards direction.

The Upper Jurassic reservoirs of the Najmah and Gotnia formations occur as lenses of marine bar or shelf margin calcarenites, calcarenite limestone, and dolomite (Fox and Ahlbrandt 2002).

In central and northern parts of Iraq, these strata grade eastward into organic-rich source rocks that were deposited under anoxic and dysoxic conditions in three restricted intrashelf basins, from north to south: the Gotnia, Arabian, and Southern Arabian Gulf Basins (Fox and Ahlbrandt 2002) (Fig. 18).

Stratigraphic traps may be present in the Gotnia Basin of Iraq, such as buildups or isolated platforms; these are not known elsewhere in Arabia (Aqrawi et al. 2010).

Maturation of the Upper Jurassic source rock formations (Sargelu and Naokelekan formations in Iraq; Fig. 3) began around 90 Ma; peak generation took place from 85 to 13 Ma. With time, the oil migrated updip and was trapped in calcarenite lenses. Later, oil remigrated and was trapped in anticlines that began to form in Early Cretaceous time. Younger Jurassic shale and anhydrite seal rocks are distributed throughout the total petroleum system.

Oil distribution in the context of Cenozoic subsidence is of Jurassic and Lower Cretaceous source rocks. Maturation begins in Late Cretaceous but dominant maturation began in Late Oligocene in the north part of Iraq and in Miocene to the south (Pierce and Rutherford 2003).

The western part of Iraq was subjected to intermittent pulses of uplifting (sea regression) and subsidence (sea transgression) to form the Jurassic basin system in the area (see Fig. 16). Reactivation of the Rutbah–Khleisia High in western Iraq in Middle Jurassic is continued in southeast Syria where Al-Hamad Uplift similarly underwent uplifting in the Kimmeridgian (Aqrawi et al. 2010). In contrast, in the central and northern parts of Iraq (Fig. 19), the Jurassic formations (Najmah and Gotnia formations) were deposited in subsiding basins in which the reservoir and sealed evaporitic rocks were existed.

In turn, in the western desert of Iraq, the Jurassic formations lack these petroleum system characteristics. Hence, it can be proposed that the petroleum–nonpetroleum inflection could be proposed in the east of area km 160. In the Gotnia Basin, the Najmah limestone is the primary reservoir which consists of oolitic limestone, dolomite, and anhydrite that were deposited in a shallow marine and transitional marine setting of lagoons and shoals, similar to the Arabian and Southern Arabian Gulf Basins. These reservoir rocks are laterally juxtaposed to argillaceous limestone marl and shale source rock facies of the Sargelu. As the sea regressed, the basin was covered with seal rocks of anhydrite with limestone and dolomite (Fox and Ahlbrandt 2002). In general, the region to the north of the western Widyan Basin and extending to the Tigris/Euphrates drainage area may have good source and reservoir facies but with limited continuity of evaporite seal facies.

## References

Abed AM (1979) Lower Jurassic lateritic red beds from central Arabia. Sediment Geol 24:149–156

Al-Atia MJ, Saadalaha NH, Al-Delaimy MR (1997) The relationship of Ga’ara Formation and other Jurassic formations in the Western Desert of Iraq and their mineral potential. Unpublished Report, Geosurv, Baghdad, Iraq

Al-Azzawi AM, Dawoud MR, Buni MR, Abdul-Karem S, Phillipe W, Abul-Lateef E, Ezzidin L, Salman B (1996) Detail geological mapping to investigate NW km 160—Rutba area, western desert. Internal Report, GeoSurv, Iraq (in Arabic)

Al-Barazangi ShTM (1989) Facies analysis of the Muhaiwir Formation, western Iraq. M.Sc. thesis, Baghdad University

Al-Bassam KS, Tamar-Agha MY (1998) Genesis of the Hussainiyat ironstone deposits, Western Desert, Iraq. Mineralium Deposita 33:266–282

Al-Husseini M (2009) Update to Late Triassic–Jurassic stratigraphy of Saudi Arabia for the Middle East geologic time scale. GeoArabia 14(2):145–186

Al-Husseini M, Matthews RK (2006) Stratigraphic note: orbital calibration of the Arabian Jurassic second-order sequence stratigraphy. GeoArabia 11(3):161–170

Al-Juboury AI, Hassan ZM (1996) Heavy minerals and provenance of the Paleozoic Suffi Formation, Western Desert, Iraq. Qatar Univ Sci J 16:151–160

Al-Mubarak M (1983) Regional geological mapping of the southern and western desert of Iraq. State Organization for Minerals (SOM), Report number 1380, Baghdad, Iraq

Al-Naqib SQ (1994) New occurrences of iron in Rutba area, western desert, Iraq. Confidential Report, Dams and Water Resources Research Center, Mosul University, Iraq

Al-Naqib SQ (1995) Sedimentological study of the lower clastic unit of Najmah Formation, Western Desert, Iraq. Iraqi Geol J 28(2):149–161

Al-Naqib SQ, Aghwan Th A (2000) Depositional environment interpretation of the carbonate unit in Amij Formation, western desert–Iraq. Proceedings of the 5th Scientific Conference of Dams and Water Resources Research Center, Mosul University, Iraq, pp 254–261

Al-Naqib SQ, Al-Youzbakey KT (2007) Origin of Ga'ara and Hussainiyat clays, Iraqi western desert. Rafidain Journal of Science, Mosul University, Iraq, 18(1):68–80

Al-Naqib SQ, Maala K, Saeed L (1985) Report on detailed geological mapping of Wadi Rejlat D-Dabe. SOM, Baghdad

Al-Naqib SQ, Saeed L, Taha Y, Al-Sharbati FA, Yakta SA, Hussain MS, Yacoub II, Al-Mukhtar LE (1986) Detailed geological survey of Rutbah area. Directorate General of Geological Survey and Mineral Investigation, Baghdad, Iraq

Al-Sangary AA (1987) Stratigraphy of the Jurassic system in Rutba area, W. Iraq. Ph.D. thesis, Baghdad University

Al-Sharhan AS, Kendall CG (1986) Precambrian to Jurassic rocks of the Arabian Gulf and adjacent areas, their facies, depositional setting, and hydrocarbon habitat. AAPG Bulletin 70

Amin MA, Al-Naqib SQ, Aghwan TA (1992) Peritidal sedimentary cycles in the upper carbonate member of the Ubaid Formation, Lower Jurassic, western desert, Iraq. Iraqi Geol J 21(2):115–128

Aqrawi AAM (1998) Paleozoic stratigraphy and petroleum systems of the western and southwestern deserts of Iraq. GeoArabia 3 (2):229–247

Aqrawi AAM, Goff J, Horbury AD, Sadooni FN (2010) The petroleum geology of Iraq. Scientific Press, UK

Bain R (2001) Hydrocarbon prospects of western Iraq. Rock the Foundation Convention, Canadian Society of Petroleum Geologists, p 107-1

Buday T (1980) The regional geology of Iraq, stratigraphy and paleontology. Directorate General of Geological Survey and Mineral Investigation

Buday T, Hak J (1980) Report on the geological survey of the western part of the western desert, Iraq. Internal Report, GeoSurv

Chamley H (1989) Clay sedimentology. Springer, Berlin

Charaosset P, Pierre-Jean (2000) Pedoginic and karstic features at the boundary of Bathonian depositional sequence in Grands Causses Area (Southern France) stratigraphic implications. Journal of Sedimentary Research 70 (Abstract)

Dickinson WR (1985) Interpreting provenance relations from detrital modes of sandstones. In: Zuffa GG (ed) Provenance of arenites. Riedel, Dordrecht, NATO Advanced Study Institute Series 148:333–361

Dickinson WR, Suczek CA (1979) Plate tectonics and sandstone composition. AAPG Bull 63:2164–2182

Fouad SF (2007) Tectonic and structural evolution. Iraqi Bull.Geol. Min. Special Issue, Geology of Iraqi Western Desert, pp 29–50

Fox JE, Ahlbrandt TS (2002) Petroleum geology and total petroleum systems of the Widyan Basin and interior platform of Saudi Arabia and Iraq. US Geol Surv Bull 2202-E:26

Franzinelli E, Potter PE (1983) Petrology, chemistry and texture of modern river sands, Amazon River System. J Geol 91:23–40

Friedman GM, Sanders JE (1978) Principles of sedimentology. Wiley, New York

Goldbery R (1979) Sedimentology of the Lower Jurassic flint clay-bearing Mishhor Formation, Makhtesh Ramon, Israel. Sedimentol 26:229–251

Grandstein FM, Ogg JG, Smith AG (2004) A geological time scale. Cambridge University Press, Cambridge

Hassan K M (1984) Jurassic Molusca from western Iraq. M.Sc. thesis, Hall University

Hower J, Hurley PM, Pinson WH, Fairbrain HW (1963) The dependence of K-Ar on the mineralogy of various particle size ranges in a shale. Geochim et Cosmochim Acta 27:405–410

Ingersoll RV, Suczek CA (1979) Petrology and provenance Neogene sand from Nicobar and Bengal fans. DSDP site 211and 218. J Sed Petrol 49:1217–1228

Ingersoll RV, Bullard TF, Ford RL, Grimm JP, Pickle JD, Sares SW (1984) The effect of grain size on detrital modes: a test of the Gazzi–Dickinson point counting method. J Sed Petrol 54:103–116

Ismail SA (1996) Mineralogy and geochemistry of the clastic rocks of the Amij Formation, western Iraq. Unpublished Ph.D. thesis, Baghdad University

Jassim SZ, Goff JC (2006) Geology of Iraq. Dolin, Prague and Moravian Museum, Czech Republic

Jassim SZ, Buday T (2006) Late Toarcian–Early Tithonian (Mid–Late Jurassic) megasequence AP7, Ch. 10, geology of Iraq. Dolin, Prague and Moravian Museum, Brno, Czech Republic, pp 117–123

Jassim SZ, Karim S, Al-Mubarak M, Basi M, Munir J (1984) Final report on the regional geological survey of Iraq, vol. 3, stratigraphy. GeoSurv, Iraq

Jassim SZ, Buday T, Cicha I, Prouza V (2006) Late Permian–Liassic megasequence AP6, Ch. 9, geology of Iraq. Dolin, Prague and Moravian Museum, Brno, Czech Republic, pp 104–116

Karim SA, Ctyroky P (1981) Stratigraphy of the eastern southern flank of Ga'ara high. SOM Internal Report

Millot G (1970) Geology of clays. Chapman and Hall, London

Mitchun RM Jr (1977) Seismic stratigraphy and global change of the sea level, part 11: glossary of terms used in seismic stratigraphy. In: Payton CE (ed) Seismic stratigraphy application to hydrocarbon exploration. AAPG Memoir 26, 205 pp

Mohemed SHT (1989) Facies analysis of the Muhaiwir Formation, western Iraq. Unpublished M.Sc. thesis, University of Baghdad

Numan NMS (2001) Cretaceous and Tertiary Alpine subductional history in Northern Iraq. Iraqi J Earth Sci 1:59–74

Pierce WH, Rutherford E (2003) Habitat and petroleum geology of Iraq: a 2003 review. StartExpo. Available at http://www.Startexpo.com

Qasir MR, Al-Marsoumi AH, Maala Kh, Abdul Karim S, Basi M, Al-Mukhtar LA, Dawood RM (1992) Detailed geological survey of the Hussainiyat area. Internal Report, GeoSurv, Iraq

Sadiq A (1980) Surface and subsurface mineralogical and geochemical study of clay and iron ores of the Paleozoic rocks in western desert of Iraq. M.Sc. thesis, Baghdad University

Schettino A, Scotese C (2002) Global kinematic constraints to the tectonic history of the Mediterranean region and surrounding areas during the Jurassic and Cretaceous. In: Lister GS (ed) Reconstruction of the evolution of the Alpine–Himalayan orogen. Journal of the Virtual Explorer 8:149–168

Sharland PR, Archer R, Casey DM, Davies RB, Hall SH, Heward AP, Horbury AD, Simmons MD (2001) Arabian Plate sequence stratigraphy. GeoArabia special publication 2. Gulf PetroLink, Bahrain

Tobia FH (1983) Geochemistry and mineralogy of Gaara iron deposits, western desert of Iraq. Unpublished M.Sc. thesis, Baghdad University

Tobia FH (2005) Mineralogy and geochemistry of the clastics of Jurassic system in Iraqi western desert. Unpublished Ph.D. thesis, Mosul University

Valeton I, Stutze B, Goldbery R (1983) Geochemical and mineralogical investigations of the Lower Jurassic flint-bearing Mishhor and Ardon formations, Makhtesh Ramon, Israel. Sedimentol 35:115–152

Van Bellen RC, Van Dunnington HV, Wetzel R, Morton D (1959) Lexique Stratigraphique International, Asie, Fasc 10a, Iraq, Paris

Walker RG (1979) Facies models. Geoscience Canada, Reprint Series 1, Geological Society of Canada

Yilmaz I, Altimer D (2001) Use of sedimentary structures in the recognition of sequence boundaries in Upper Jurassic–Upper Cretaceous peritidal carbonates of the western Taurides, Turkey. Int Geol Rev 43(8):736–753

Ziegler MA (2001) Late Permian to Holocene paleofacies evolution of Arabian Plate and its hydrocarbon occurrences. GeoArabia 6 (3):445–504