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ORIGINAL PAPER

Facies architecture and sequence development of the Euphrates formation in western Iraq

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Abstract The Euphrates formation is widely exposed in western Iraq near Al-Qaim area. It extends eastward parallel to the Euphrates River on both sides, crossing Anah, Hadetha, and Al-Baghdadi vicinities. Based on the benthic foraminiferal assemblages and microfacies features, 12 different microfacies types have been recognized into two Stratigraphic sections that are lime mudstone, wackestone, bioclastic wackestone, miliolids wackestone, alveolinids wackestone, packstone, bioclastic packstone, peloidal packstone, miliolids packstone, peneroplids packstone, rotaliids packstone, grainstone, peloidal grainstone, oolitic grainstone, and miliolids grainstone. Accordingly, the depositional environments were recognized on the basis of microfacies identification and interpretation ranging from restricted marine, shoal, to open marine environments. The exposed Euphrates succession is represented by four fourth-order cycles (A, B, C, and D); they are mostly asymmetrical showing slightly lateral variation in thickness and symmetry. These cycles represent a succession episode of sea level rises and stillstands. The nature of these cycles reflects variation in the relative sea level resulted from eustatic and tectonic subsidence. Cycle A is underlain by SB1 of Sheik Alas formation in Al-Baghdadi section and by Anah formation in Wadi Hjar section. Cycle D is overlain by SB1 of Fatha formation in Al-Baghdadi section and by conformable contact of Nfayil formation in Wadi Hjar section. According to sequence development, the study area shows low rate of subsidence and the major controlling factor that affects eustatic sea level fluctuation.

Keywords Facies architecture sequences development · Microfacies analysis · Euphrates formation · Iraq

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Introduction

The Euphrates formation is widespread in outcrops and subsurface sections in the western desert along the upper Euphrates valley on the southern and western sides of the Euphrates River. It extends from Al-Qaim in the northwest to Samawa in the southeast, where it interfingers with and passes laterally to the Ghar formation (Sissakian and Mohammed 2007); it crops out in the cores of some southwestern and northeastern foothill areas of Iraq.

The location selected in this study lies in the type locality, upper Euphrates valley, where extending from the town of Al-Baghdadi to the Hadetha western Iraq. The outcrops are well represented in different deep-cut wadis such as Wadi Al-Baghdadi, Wadi Horan, Wadi Banat Al-Hassan, Wadi Esghadan, Wadi Heqlan, and Wadi Hjar (Fig. 1).

Two surface sections were chosen in this study; the first one is at Al-Baghdadi area exactly at Wadi Al-Baghdadi. The section was measured in detail at 33°51′17″N and 42°32′E and the other one at Wadi Hjar, Hadetha area. The section was measured in detail at 34°6′20″N and 42°22′50″E. Previously, the term "Euphrates formation" was introduced by De Beockh and others in 1929 (in Van-Bellen et al. 1959). Van-Bellen et

Fig. 1 Location map for the studied sections in Western Iraq

al. (1959) proposed that section type of this formation at Wadi Fuhaimi, 32 km southeast of old Anah town in stable shelf, comprises (8 m thickness) solely shelly, chalky, and well-bedded recrystalized limestone and assigned it to "Lower" Miocene Age. Jassim et al. (1984) recommended a supplementary type section in Wadi Chabbab, near Anah, consisting of lower and middle units (A and B) and another supplementary type section in Wadi Rabi for the upper unit (C). Later, the upper unit (C) was named as Nfayil formation (Sissakian et al. 1997). Al-Ghreri (2007) mentioned that Euphrates formation deposit was restricted to open marine environment. Recently, Al-Ghreri et al. (2010) suggested another section at Al-Baghdadi area as a reference section because the type section at Wadi Fuhaimi was submerged by the Al-Qaddisiyah Lake. Jassim et al. (1984) suggested a type locality in Wadi Chabbab, near Anah, where the thickness of the formation attains 110 m representing the best exposures of Euphrates formation. In Al-Baghdadi, the present outcrops are not typical presentation for the formation.

Ever since, many studies appeared for different aims, including those of Philip and Youash (1966), Ctyroky and Karim (1971), Al-Saddiqui (1972), Karim (1974, 1978), Buday (1980), Al-Mubarak and Amin (1983), Mahdi et al. (1985), Sissakian (1994), Al-Azzawi and Dawood (1996), Al-Ghreri (2007), Sissakian and Mohammed (2007), and of course, Al-Ghreri et al. (2010) detailed all these studies.

Methodology

The main objectives of this study (1) is to describe the main microfacies recognized in the Euphrates formation, (2) to describe and interpret the depositional environments, and (3) to describe and interpret the origin of sequences that developed in the study area. The best exposures are in Wadi Chabbab and it has been mentioned that the formation in the upper reach of the Euphrates valley has been studied. It is one of the best and typical exposure areas of the formation.

A total of 45 samples were collected from two surface sections in the locality type of the Euphrates formation; petrographic studies were carried out for microfacies analysis and paleoenvironmental reconstruction of the Euphrates formation. Definition of microfacies is based on depositional texture, grain size, grain composition, and fossil content.

Approximately 110 thin sections were examined; all these thin sections were prepared and examined under the petrographic microscope for their composition, microfacies, and texture macro- and microfaunal assemblage.

Stratigraphy

The Euphrates formation in the present area is composed of hard, crystalline, well-bedded, massive highly fossiliferous limestone in the lower part, and white yellowish, chalky limestone interbedded with marly limestone in the upper parts. Generally, the limestone is very rich in miliolids (*Quinqueloculina* sp.), peneroplids (*Peneroplis* sp.), rotaliids (*Ammonia* sp. and *Rotalia* sp.), oolitic and peloidal grains (fecal peloids), and micritized skeletal grains. It also contains fewer amounts of the algae, molluscan, and the skeletal debris particles.

In the present study, the lower contact of the Euphrates formation is unconformable with underlying Sheik Alas formation in Wadi Al-Baghdadi section and Anah formation in Wadi Hjar section. The upper contact is unconformable with Fatha formation in Al-Baghdadi section (Al-Ghreri 2007). In Wadi Hjar section, it is overlain unconformably by the Nfayil formation (Sissakian et al. 1997). The Fatha formation is not exposed in our studied area. The status of the Fatha formation and its outcrop areas was checked. In our studied area, the Nfayil formation forms the upper contact. For details, refer to Sissakian et al. (1997). The upper contact is conformable.

According to the variations in the lithologic characters and the fossil content, the Euphrates formation exposed at these sections can be divided into two distinct units, lower and upper units (Fig. 2). The lower unit "basal conglomerates" contain reworked fossils from underlying formations "Oligocene" (Sayyab and Abid 1990; Al-Bakkal and Al-Ghreri 1993) from gray, massive, hard, mainly crystalline, rich fossiliferous, algal limestone with silicified bands that characterize the lower unit. The upper unit "limestone unit" can be subdivided in to lower part contains thick bedded to massive limestone, dolomitic limestone, highly fossiliferous with greenish white, yellowish, and chalky limestone in the upper part. While the uppermost part contains highly deformed beds, called "Brecciated unit". Al-Mubarak (1974) considered the brecciaed rocks as a part of the Fatha formation. But later on, the brecciated rocks were grouped with the Euphrates formation (Jassim et al. 1984).

It also includes oriented fragments of hard silicified limestone within a mass of marly and chalky limestone (Fig. 3). This unit is overlain by highly undulated, jointed, and deformed limestone called "undulated limestone unites". Bolton 1954 in Fouad (2007) attributed this phenomenon to shakes originated from earthquakes during the deposition in the marine environment. While Hassan et al. (2000) regarded that brecciation and undulation in this unit are expression of synsedimentary episodes of tectonic unrest in the late Early Miocene.

The limestone of the Euphrates formation yielded the following assemblage such as: peneroplids mainly *Peneroplis evolutus* Henson, *Peneroplis farsensis* Henson, and *Peneroplis* sp., miliolids such as, *Quinqueloculina* sp. and *Triloculina* sp., Alveolinidae, *Borelis melo melo* (Fichtel and Moll), and *B. melo melo* (Fichtel & Moll) *curdica* (Reichel), which occurs in both the Indo-Pacific and Mediterranean provinces (Jones 2006; Jones et al. 2006). Rotaliids, *Rotalia umbonata* Leroy, *Ammonia beccarii* Linne', and less amounts of pelecypods, gastropods and bryozoan, and bioclasts are also recorded.

According to its stratigraphical attitude and faunal content, the Euphrates formation is assigned to the Miocene Age, this agrees with the opinions of Ctyroky et al. (1975), Karim (1978), Al-Hashimi and Amer (1985), Sayyab et al. (1988), Abid (1997), and Al-Ghreri (2007). Mahdi et al. (1985) studied the lithological constituent of the Euphrates formation in the Hadetha–Hit vicinity and divided into five units.

Fig. 2 Field photograph showing the lower contacts between the lower unit (basal conglomerate) and upper unit (Limestone unit), Wadi Al-Baghdadi section

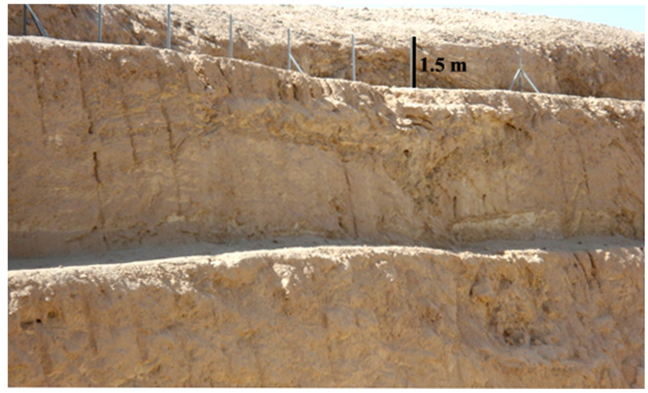

Fig. 3 Field photograph showing the upper contacts between the Euphrates and Fatha formations, Wadi Al-Baghdadi section

Facies analysis

Detailed microfacies analysis enabled the recognition of three major sub-environments within the carbonate platform. These are the restricted marine, shoal, and open marine environments. These environments are represented by the following facies associations:

1 Restricted marine environment

This environment is recognized by lime mudstone facies (1 in Plate 1 of Electronic supplementary material (ESM)). This facies is reported in several horizons vertically throughout the "limestone units"; three horizons at Wadi Al-Baghdadi section and four horizons at Wadi Hjar section, with different thickness ranges from 0.50 to 0.70 m. Furthermore, this microfacies also recorded in the rocks of the upper parts of the upper unit overlain alveolinids wackestone microfacies with an average thickness ranges from 4 to 5 m, represented by white chalky, fine-grained, poorly fossiliferous chalky limestone, and interbedded with white–green marl. Partially dolomitized mudstones have also been recorded overlain in the upper parts of the upper units which are sometimes cracked with fine crystalline calcite.

2 Shoal environment

This environment is represented by three main grainstone facies:

2.1 Peloidal grainstone microfacies: In the field, the rocks are gray, cavernous, massive, and very hard in the lower parts and are burrowed limestone in the upper parts. The peloidal grainstone occurs in one bed throughout the upper parts of sections 1 and 2 with average thickness of about 0.50 and 1.5 m. In thin sections, the main components are peloidal (45–50 %), ooids (14–20 %), sparry calcite cement (6–9 %), miliolids (4–5 %), and rotaliids (3–5 %). Generally, peloids are moderately sorted, well-rounded, or has oval particles cemented by sparry calcite (2 in Plate 1 of ESM).

The peloidal facies is usually common in the shallow marine-protected, low-energy, and back-bank lagoonal environments (Tucker and Wright 1990; Tucker 1993; Gischler 2003). The peloidal packstone to grainstone facies was recorded from the lagoonal carbonate sediments (Evans et al. 1995). Moreover, the abundance of peloids with a low diversity of fossils suggests deposition in a restricted shallow subtidal water and slow sedimentation rate (Bathurst 1975).

2.2 Oolitic grainstone microfacies. The ooids grainstone is considered as one of the most distinct microfacies of the middle–upper parts of two sections with an average thickness of (2 m). In thin sections, the most important allochemcial grains are oolites (75–80 %), peloids (7–10 %), and less of 1 % benthic forams. This facies at hand is of normal ooids, moderately sorted, concentric to oval particles. The chemical compaction has intensely affected this microfacies and the nucleus may be dolomite crystal or fossil; sparry calcite is the usual cement (3 in Plate 1 of ESM). Throughout this facies, compound ooids appear, it is uniformly arranged and forming what is called "grapestone" (Scholle and Ulmer-Scholle 2003). Grapestones are actually aggregate grains and are commonly encountered in the grainstone microfacies at Wadi Al-Baghdadi and as well as the Wadi Hjar sections. The grainstone comprised entirely of grapestone are also found in other microfacies; however, the frequency of their appearance is not very high. Furthermore, the presences of aggregate grains support this interpretation as these are usually formed in subtidal and intertidal shallow-water environments which have a restricted circulation and a 10 m water depth. These sediments flank the restricted platform on its landward side (Wilson 1975). The features of this facies indicate high energy, shallow waters with much movement, and reworking of bioclasts to the production of ooids.

2.3 Miliolids grainstone microfacies. This microfacies is limited into one bed in the lower–middle parts of the Euphrates formation at Wadi Al-Baghdadi section and in the upper part at Wadi Hjar section, with attained thickness of about 1–1.5 m, and in the upper part of Wadi Hjar section. In thin sections, we found the most common foraminiferal particles representing miliolids (*Quinqueloculina* sp., *Triloculina* sp., and *Pyrgo* sp.) of more than 60 % of this facies besides rotaliids (3–5 %), ooids (3–4 %), peneroplids (2.5), and alveolinids (2 %; 4 in Plate 1 of ESM).

This microfacies consists mainly of skeletal particles and sparry calcite as cement. Furthermore, as said above, the miliolids are the main component of skeletal particles, so that the binding material between the skeletal particles is sparry calcite cement. The omnipresence of sparry calcite cement is an indication of strong currents capable of removing clay particles, thus creating passage ways for solution that deposited the cements.

3 Open marine environment

This is represented the following facies:

3.1 Bioclastic wackestone microfacies. This microfacies occurs in well-bedded fossiliferous limestone in the lower and middle parts of the limestone units overlain by miliolids wackestone microfacies in Al-Baghdadi section, while it occurs on the lower part of Wadi Hjar section, overlain by miliolids wackestone too. The bioclasts are chiefly composed of rotaliids (mainly *A. beccarii* and *Rotalia* sp.), while the middle part of this unit are mainly of foraminiferal miliolids mainly (*Quinqueloculina* sp.) and less amounts of peneroplids. These microfacies mainly consist of bioclasts (42–46 %) and micrite (40–45 %), while the other textural constituents include dolomites (2 %), terrigenous admixture (2 %), intraclasts and peloids (1–2 %, and) shell fragments (less than 2 %; 5 in Plate 1 of ESM).

3.2 Miliolids wackestone microfacies (2 in Plate 3 of ESM): This microfacies is observed in the lower and middle parts of the limestone units, exposed at Wadi Al-Baghdadi section attaining a thickness of 2 m. It is underlain by the bioclastic wackestone and overlain by the peloidal packstone. In the field, the rock is gray to white, hard, crystalline, burrowed, and thinly laminated. Under the microscope (thin sections), the presence mainly of miliolids (25–28 %), peneroplids (12–14 %), in addition to shell fragments less is than 2 % (6 of Plate 1 of ESM).

3.3 Alveolinids wackestone microfacies. Alveolinids wackestone is represented in the upper parts in both sections, overlain by lime mudstone with an average thickness of 2 and 4 m. In the field, the rock is fossiliferous, white to brown limestone, with chalky limestone highly burrowed in several horizons in the upper parts.

This microfacies consists of about 11–14 % of the skeletal particles scattered throughout a micritic matrix. The foraminiferal shells is about 2–4 % of the rocks; they are represented mainly by alveolinids such as, *Borelis melo curdica* (10–13 %), miliolids (3–4 %), peneroplids (2–3 %), and intraclasts less than (1 %; 1 in Plate 2 of ESM). According to Hottinger (1983, 1997), alveolinids are important faunal contributors to open water sediment of the inner platform.

3.4 Bioclastic packstone microfacies. In this study, bioclastic microfacies usually occur in two beds in each section at the lower and the middle parts, range in thickness between 1 and 1.5 m, and overlie the peloidal packstone in the lower parts and mudstone microfacies in the upper parts in each section. The rocks in the field is white to gray, fossiliferous limestone. Under microscope (thin sections), it is composed of bioclasts (36–50 %), peloids (10–14 %), rotaliids mainly *Borelis melo* (6–9 %), peneroplids (5–8 %), miliolids (3–5 %), alveolinids (3 %), bryozoa (2 %), and ostracods less than (1 %; 2 in Plate 2 of ESM).

3.5 Peloidal packstone microfacies. These microfacies occurred in two horizons throughout the Euphrates formation at the lower and middle parts of Wadi Al-Baghdadi section with a total thickness of about 1 m overlie of miliolids wackestone. While occurring in one horizon in the lower part of Wadi Hjar section is the overlain of miliolids wackestone. The rocks are formed of whitish gray to white crystalline and burrowed fossiliferous limestone, overlain by fossiliferous limestone. In thin sections, the peloids found here are rounded, elliptical, or irregular in form. Some of them may have lost their central part due to solution. This facies consist mainly of fecal peloids, which is caused by micritization of the grains or pellets that caused breaking and coalescence of clays. Bathurst (1975) and Flügel (1982) revealed that the fecal pellets are a dominant constituent of the recent subtidal and shallow marine intertidal settings of low-energy water. The fecal peloids and micritized grains are the most abundant allochemical grains where they form about 50–55 % of the rock. Other components are miliolids (2–3 %), peneroplids (2 %), and less than (1 %) fragments of echinoidal plates (3 in Plate 2 of ESM).

3.6 Miliolids packstone microfacies. This microfacies occur in the lower part of the Euphrates formation at Wadi Al-Baghdadi section with an average thickness of 1.5 m and overlies the bioclastic packstone microfacies. Also, it is recorded in one bed in the lower part of Wadi Hjar section with a thickness of 2 m, overlain by miliolids grainstone facies. The rock is white, massive, compact, and burrowed. In thin section, this microfacies is made up of miliolids such as *Quinqueloculina* sp., *Triloculina* sp., *Dendritina* sp. (40–55 %), Peneroplids (*Peneroplis* sp.; 8–10 %), rotaliids, *A. beccarii* sp. (5–7 %), fossil algae (2 %), Bryozoa (1.2 %), and micritized grains (1 %; 4 in Plate 2 of ESM). The occurrence of a large number of imperforate tests indicates that the sedimentation took place in a shelf lagoon setting (Geel 2000; Romero and Rossel 2002). Brasier (1975) asserted that high diversification and the greater numbers of miliolids species are indicative of lagoonal or back-reef environments in tropical shallow, clean waters of normal salinity. Henson (1950) stated that the miliolids occur in shallow water of barrier reef lagoons, while Wilson (1975) regarded that the most common miliolids represent the shallow, restricted lagoon environments

3.7 Peneroplids packstone microfacies. This microfacies occur in one bed in the lower part of the Wadi Al-Baghdadi section with thickness of 2 m; while occurring in two beds in the lower and the middle part of the Wadi Hjar section is with a total thickness of 1.5 m overlain by rotaliids packstone. The main components of this facies are peneroplids (38–45 %) mainly (*P. farsensis*, *Peneroplis evolutes*, *Peneroplis* sp., and *Spirolina* sp.), miliolids (10–14 %), rotaliids (6–9 %), and other components of less than (2 %) of shell fragments (5 in Plate 2 of ESM). These microfacies is affected by micritization process; dolomitization also appears. Sayyab et al. (1988) mentions that infilling submicrofacies of peneroplids bearing wackestone packstone with clay lumps is due to recrystalization and dolomitization. Environmentally, Bandy (1961) concluded that all the peneroplidae including the genus *Peneroplis* prefer to live in shallow marine bottom, mainly attached to near-shore weeds as in case in Qatar (Arabian Gulf). Murray (1968) supported this view; *Peneroplis* sp. lives on sea weeds in environment of little sedimentation.

3.8 Rotaliids packstone microfacies. This microfacies are present in tow sections of overlain peneroplids packstone and overlain by mudstone microfacies with average thickness of 1–3 m and consists mainly of imperforate foraminifera, rotaliids (20–30 %), miliolids (18–22 %), peneroplids (10–15 %), *Borelis* spp. (3–5 %), gastropods (1.5–2 %), pelecypods (1–1.5 %), and less than (1 %) fragments of algae (6 in Plate 2 of ESM).

Murray (1991) considered that all the Rotaliids including the species *A. beccarii* is characteristic of lime mud in the middle of the lagoons in the Arabian Gulf. The occurrence of large numbers of porcelaneous imperforate foraminiferal tests such as *A. beccarii*, *R. umbonata*, *Quinqueloculina* sp., *Triloculina* sp., *Borelis* spp., *P. evolutus*, *P. farsensis*, and bivalve debris may point to the depositional environment being slightly hypersaline, and such an assemblage was described to be associated with an inner ramp environment (Wilson 1975; Flügel 1982, 2004).

Sequence development

Four fourth-order cycles were recognized in the Euphrates formation. These cycles are usually asymmetrical; they represent successive episode of sea level rise and stillstands. They are also bounded at bottom and top by type-1 sequence boundary (SB1). Cycle A is represented by a long episode of sea level rise, where a thick succession of open marine facies of transgressive system tract (TST), followed by short episode of stillstand thin succession of restricted marine facies of high-stand system tract (HST). This cycle is underlain by SB1 of sheik Alas formation in Wadi Al-Baghdadi section (Fig. 4) and Anah formation in Wadi Hjar section (Fig. 5). Cycle B is almost asymmetrical and its TST consists of bioclastic, miliolidal, and peloidal wackestone packstone followed by thin HST consisting restricted marine facies. Cycle B is subdivided into B1, B2, B3 at Wadi Hjar section, according to the minor eustatic fluctuation where tectonic subsidence was at its lowest rate. B1 consists of open marine facies of TST followed by HST represented by restricted marine facies, while B2 is symmetrical where the TST of open marine facies is followed by shoal facies of HST. B3 consists of peloidal packstone facies (TST) overlain by short episode of HST (restricted marine facies).

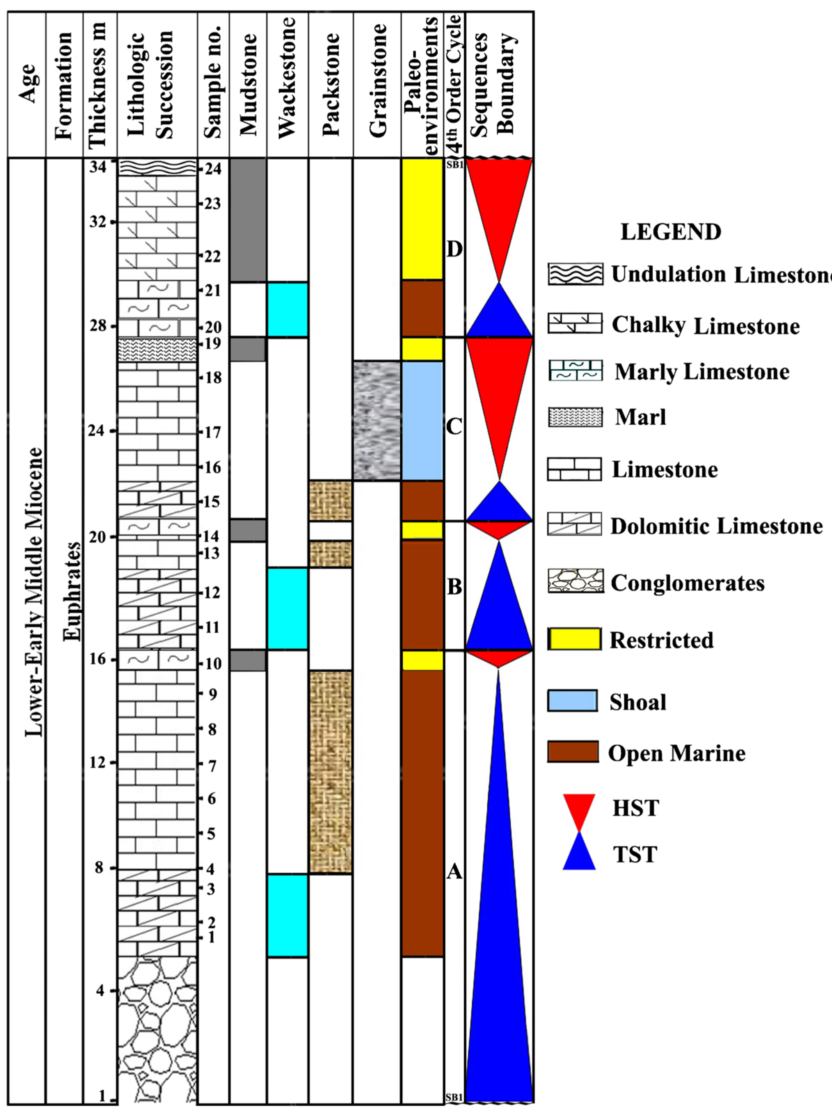

Fig. 4 Vertical facies distribution showing paleoenvironment and sequence-stratigraphic characteristics of the Euphrates Formation at Wadi Al-Baghdadi section

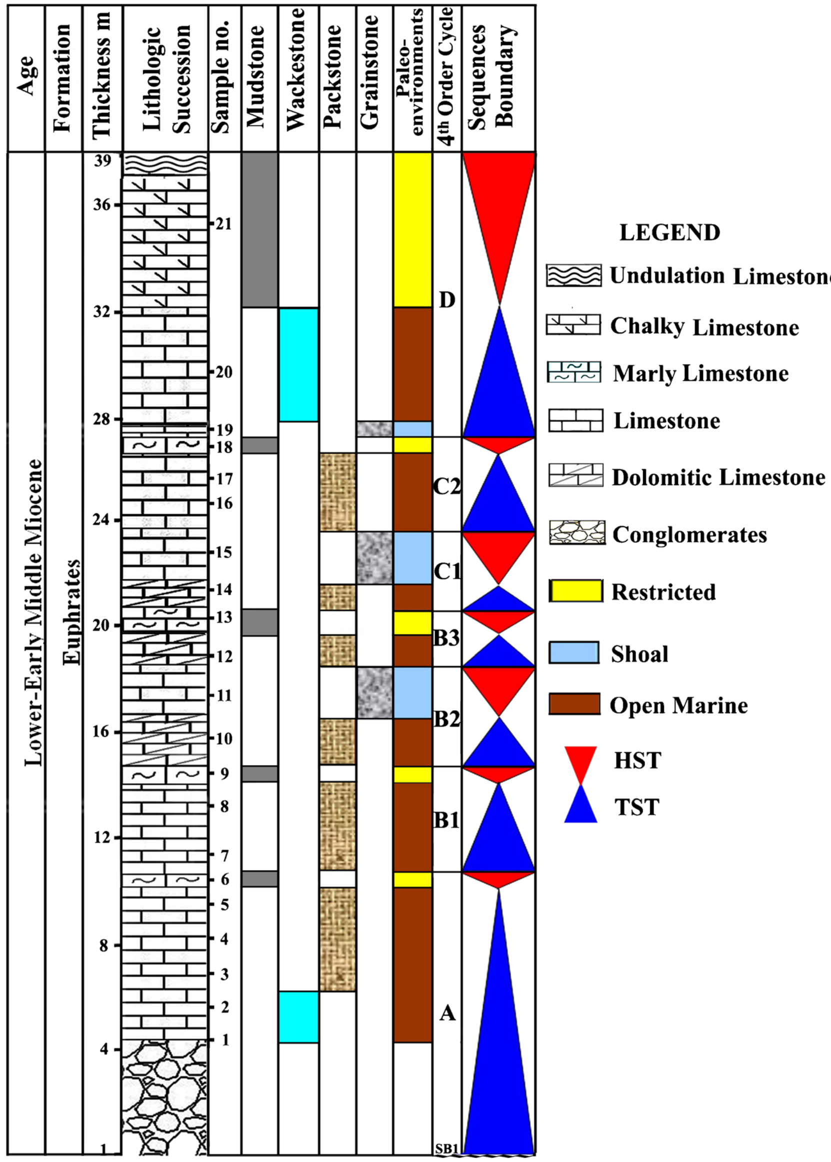

Fig. 5 Vertical facies distribution showing paleoenvironment and sequence-stratigraphic characteristics of the Euphrates Formation at Wadi Hjar section

Asymmetrical cycle C overlies cycle B and consist of short episode of sea level rise of TST followed by long episode of sea level stillstand. Cycle C can be divided into C1 and C2. C1 consists of the TST of bioclastic facies followed by HST of shoal facies. C2 is represented by long episode of sea level rise of open marine facies overlain by short episode of sea level stillstand.

Cycle D is symmetrical, reflecting a balanced situation, where the TST open marine facies followed by restricted marine facies of HST. This cycle is overlain by type 1 sequence boundary SB1 of the Fatha formation. The study area is of low rate of subsidence represented by short episode of HST; on the other hand, the eustatic sea level is the major controlling factors that affect the exposed Euphrates sequence development.

Summary and conclusions

The Euphrates formation exposed in the area between Al-Baghdadi and Hadetha west Iraq consists of hard, crystalline, well-bedded massive limestone, burrowed in the lower and upper parts, and chalky limestone interbedded with yellowish–greenish marl in the upper parts which is overlain by hard, massive undulation bands of silicified limestone equivalent to Fatha formation.

According to the lithologic variation and fossil content, the Euphrates formation can be subdivided into two units: the lower and upper units. Microfacies analysis may be divided into 12 microfacies that is: lime mudstone, wackestone (three microfacies associations), packstone (five microfacies associations), and grainstone (three microfacies associations). It is very rich in miliolids, peneroplids, rotaliids, ooids, and peloidal grains (fecal pellets and micritized skeletal grains) and contains an appreciable amount of the molluscan and skeletal debris particles. The depositional environment of the Euphrates formation range from restricted, shoal, to open marine environments.

The Euphrates succession may reflect deposition in an area of no or very low rate of subsidence, where the major controlling factor is eustacy. Four fourth-order cycles can be recognized (A, B, C, and D). Cycle A is represented by long episode of sea level rise, where a thick succession of open marine facies of TST, followed by short episode of stillstand. Cycle B consisting of bioclastic, miliolids, peloidal wackestone packstone, followed by thin HST consisting restricted marine facies. Cycle B is subdivided into B1, B2, and B3 at Wadi Hjar section according to minor sea level changes. Cycle C consisting of short episode of sea level rise of TST followed by long episode of sea level stillstand and subdivided into C1 and C2 at section 2. Cycle D shows TST, followed by restricted marine facies of HST.

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