

Sedimentary and diagenetic history of the Aptian–Albian succession in the Bai Hassan oil field, Zagros Basin, northern Iraq

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ABSTRACT:

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The Aptian–Albian succession, consisting of the Lower Qamchuqa, Jawan, Upper Sarmord, and Upper Qamchuqa formations, from five boreholes in the Bai Hassan oil field, Zagros Foreland Basin, northern Iraq, has been studied in terms of facies, microfacies, diagenetic processes and sequence stratigraphy. Eight microfacies were identified: lime mudstone, orbitolina wackestone/packstone, orbitolina-miliolid wackestone, peloidal-miliolid-echinoderm packstone/grainstone, bioclast-mollusc-echinoderm wackestone/packstone, laminated evaporite-carbonate mudstone, planktonic foraminifera wackestone/packstone, and argillaceous pelagic lime mudstone. The succession was deposited in five stages characterised by changing facies patterns in a variety of environments, including: restricted shallow marine/lagoonal, shallow open marine, fore-reef, deep open marine and basinal. The studied deposits were subjected to several diagenetic processes, including: micritization, dissolution, recrystallization, cementation, anhydritization, compaction, and dolomitization, taking place in various diagenetic environments: meteoric phreatic, marine phreatic, vadose, mixing, and burial. Development of diagenetic processes was strongly affected by sea-level fluctuations, causing landward or seaward shifts of various diagenetic environments. In general, the succession is characterised by less cementation, constructive dolomitization and moderate porosity, resulting in moderate to good hydrocarbon reservoir properties in its parts represented by highstand stages, and by moderate porosity, resulting in moderate to good reservoir characteristics in its transgressive stages. The shallow environments represented by restricted and shallow open marine facies are typified by high values of porosity due to dissolution and early dolomitization. Therefore, tectonics was not the only factor that controlled the petrophysical properties and the reservoir distribution within the studied succession in the Bai Hassan oil field.

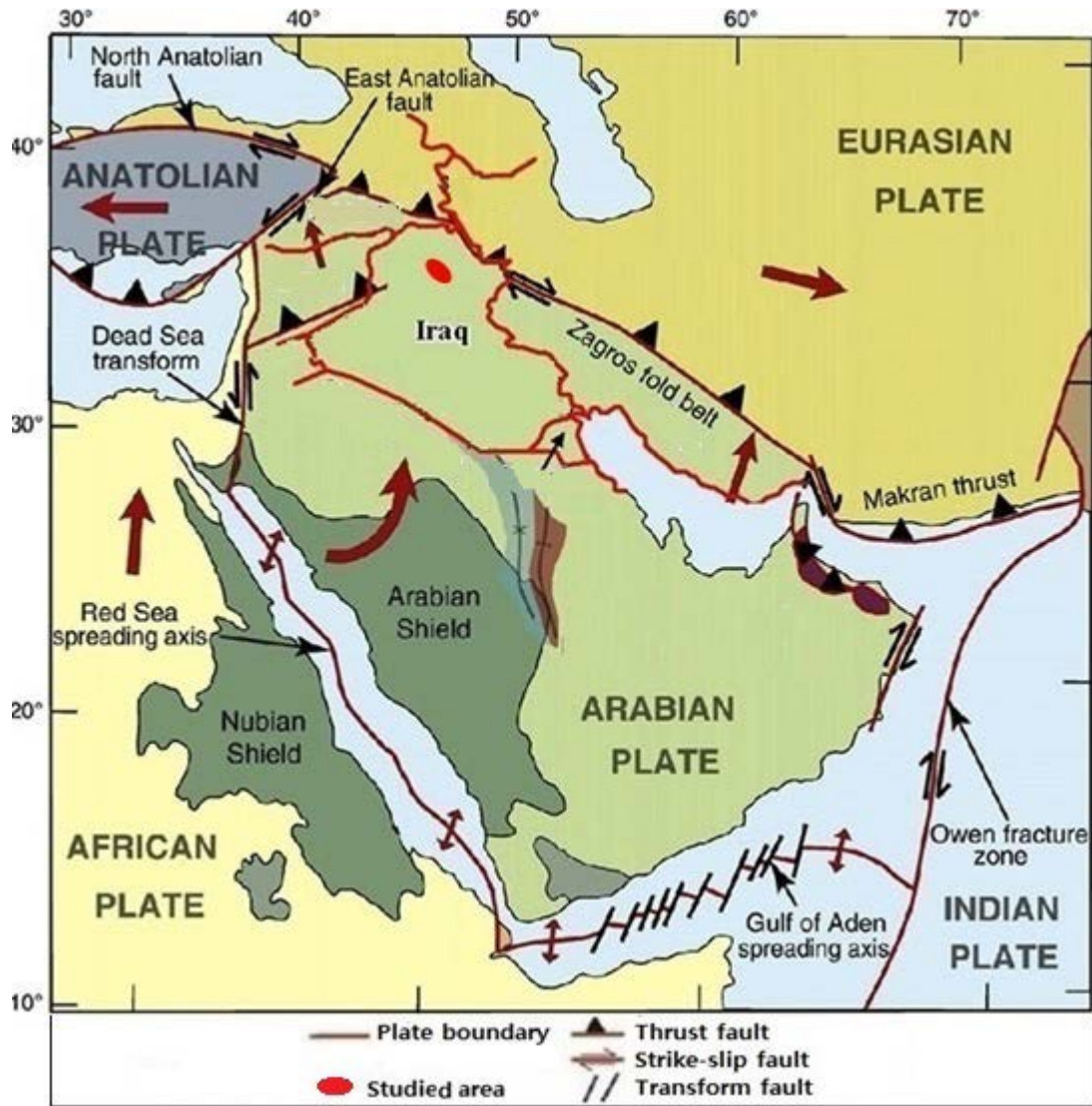
Key words: Bai Hassan oil field; Aptian–Albian; Zagros Foreland Basin; Microfacies; Sedimentary environment; Diagenesis and porosity development.

INTRODUCTION

Cretaceous deposits cover most of Iraq, as well as parts of Iran, the Arabian Gulf and the Arabian Gulf

countries, and contain great hydrocarbon reserves. The thickness of the Cretaceous succession in Iraq reaches 3 km (Sadooni and Aqrawi 2000). The Aptian–Albian succession studied herein is considered to host the big-





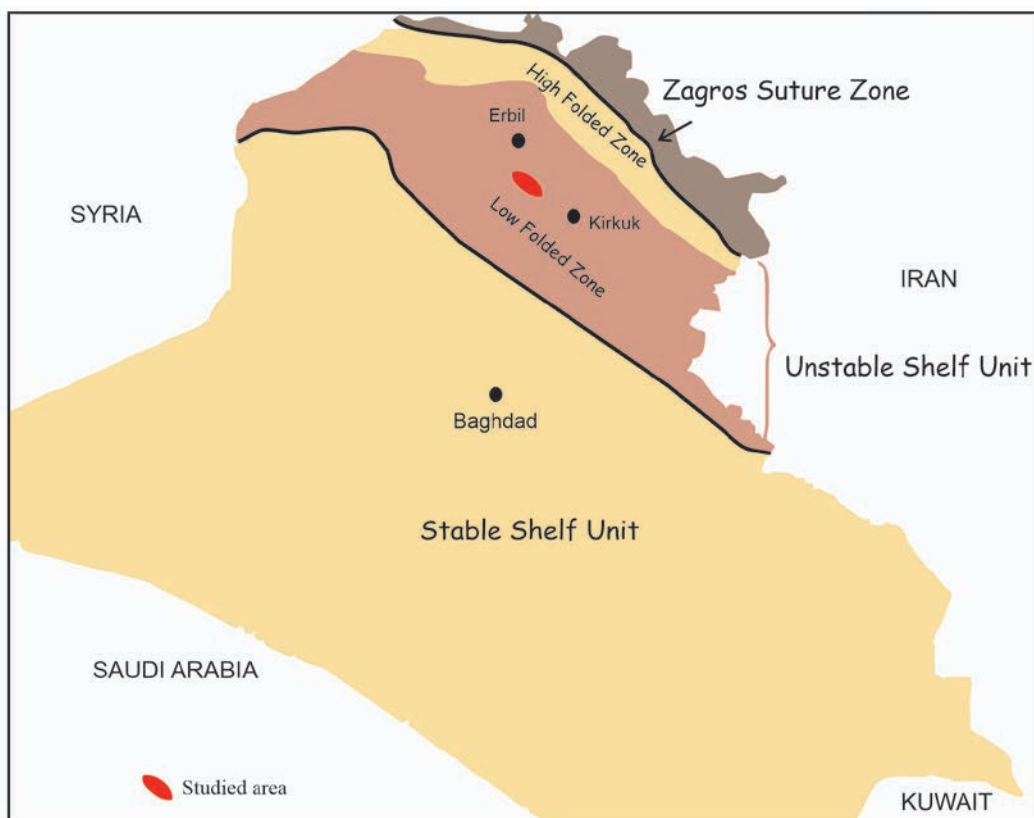
Text-fig. 1. Position of the studied area on the Arabian Plate (based on Stern and Johnson 2010, simplified).

gest oil and gas reservoirs in the Middle East (Buday 1980; Jassim *et al.* 1984; Jassim and Goff 2006; Fouad 2012, 2014). The properties of these reservoirs depend upon various factors, including their geological and tectonic structure, but also upon the petrography of the deposits, resulting from sedimentary development, facies distribution and diagenesis.

The studies presented herein were carried out on deposits acquired from 5 selected boreholes located in the Bai Hassan oil field in northern Iraq, in the vicinity of Kirkuk. The field was discovered in 1929, in the early stage of oil exploration in Iraq, and is considered to be one of the major reservoirs in northern Iraq. The Bai Hassan oil field is located in

the Low Folded Zone, an Unstable Shelf unit of the Arabian Craton in the northern part of Iraq. The collision between the Arabian and Eurasian continents, which began in the Late Cretaceous, resulted in the development of the Zagros Foreland Basin. During its geological history, the area has been affected by a number of tectonic events, which contributed to the formation of structural traps, represented by domes and anticlines. The reservoir rocks are represented by the Aptian–Albian succession consisting of the Lower Qamchuqa, Upper Sarmord, Jawan, and Upper Qamchuqa formations.

This study is an attempt to enhance knowledge of the petrography, stratigraphy, diagenetic processes



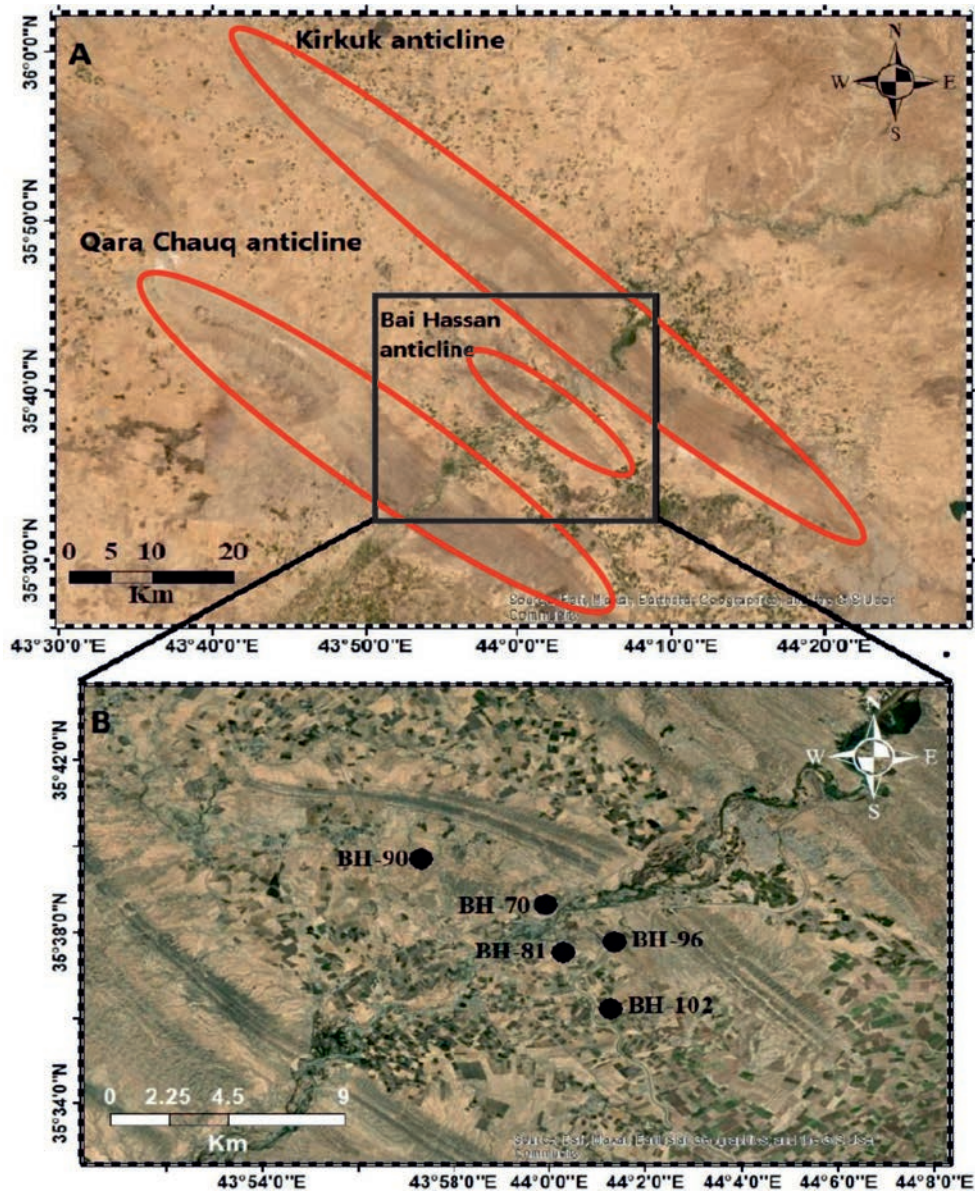
Text-fig. 2. Tectonic division of Iraq (after Jassim and Goff 2006, simplified).

and petrophysical properties of the Aptian–Albian succession of the Bai Hassan oil field. The main aims of the study were to: (i) present a sedimentological model of the succession by using facies and microfacies analyses, (ii) reconstruct the diagenetic history and porosity development of the sediments, and (iii) reconstruct the influence of sea-level fluctuations on the development of diagenetic processes. One of the objectives of this study was to find a relationship between the facies changes and the petrophysical properties of the reservoir (porosity), which in turn control the type of petroleum traps. In other words, we intended to test the claim that tectonic structure is not the only factor controlling the petroleum traps in northern Iraq, the distribution of reservoirs also being affected by the occurrence of sedimentary cycles and their relation to diagenetic processes. This explains the differences in oil production and reserves in the same formations at various locations. The general conclusions presented may well apply to many other sedimentary successions and reservoirs with similar facies patterns and depositional histories worldwide.

GEOLOGICAL SETTING

The study area is situated in the northeast corner of the Arabian Plate (Text-fig. 1), which originated as a separate unit in the Oligocene by its splitting off northeast Africa, resulting in the closing of the Neo-Tethys Ocean on the northeast side and in the forming of the Red Sea and the Gulf of Aden in the southwest (Stern and Johnson 2010). The collision between the Arabian Craton, representing the continental component of the plate, and the Anatolian and Eurasian continents in the Neogene resulted in the formation of the Taurus and Zagros mountains, which represent the northern and north-eastern compressional boundaries of the plate.

According to Jassim and Goff (2006), the main structural divisions of Iraq include: the Stable Shelf, the Unstable Shelf, and the Zagros Suture Zone (Text-fig. 2). The Stable Shelf is characterised by reduced thicknesses of the sedimentary cover and lack of folding. The Unstable Shelf has a thick and folded sedimentary cover, with the intensity of folding increasing to the north-east. The Stable Shelf and Unstable Shelf

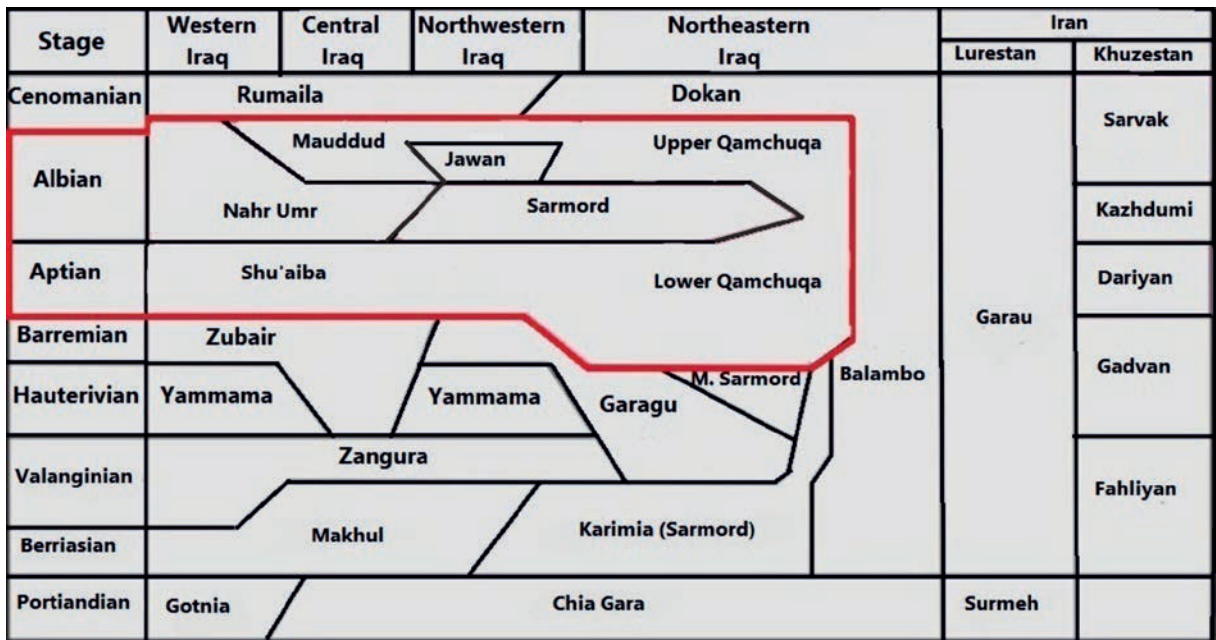


Text-fig. 3. Location of the studied area. A – Location of the Bai Hassan oil field among adjacent tectonic structures, B – Location of the boreholes studied within the Bai Hassan anticline.

units represent parts of the Arabian Shelf in Iraq. The study area is located in the Unstable Shelf zone.

The Unstable Shelf is the most structurally deformed unit of the Arabian Plate, as it has received (and continues to receive) major stress released from the collision of the Arabian and Eurasian Plates (Sissakian 2013). The Iraqi part of the Unstable Shelf unit consists of three zones: the Low Folded (Foothill) Zone, the High Folded Zone, and the Imbricate Zone. The study area is situated in the Low Folded Zone (Text-fig. 2). The Bai Hassan oil field is located in the

Bai Hassan anticline, which is one of several doubly plunging, asymmetrical and elongated anticlines that characterise the Foothill Zone in Iraq (Qays 2010). It lies northwest of the city of Kirkuk, and is situated between the Kirkuk and Qara Chauq anticlines, running parallel to them (Text-fig. 3A). The NW-SE trending anticline is 40 km long and 13.5 km wide (Text-fig. 3B). The structure is composed of two domes, i.e., Kithka and Dawood, separated by the shallow Shahel saddle. On the flanks, the bedding dip is around 40°. The Kithka dome is larger, more prolific, and has



Text-fig. 4. Correlation of Lower Cretaceous regional stratigraphic units across the northeast margin of the Arabian Plate including the studied Aptian–Albian succession (compiled from Bellen *et al.* 1959, with later changes).

a higher and more significant surface expression of about 335 m, whereas the Dawood dome is smaller, less prolific, and does not have a surface expression.

In the Early Cretaceous, the Arabian Platform became covered by thick sequences of limestones and dolomites, and this succession covers most of Iraq, including the study area, some parts of south-western Iran, the Arabian Gulf and the Arabian Gulf countries. At that time, the eastern margin of the Arabian Platform containing the studied succession was faced towards the opening Neo-Tethys Ocean and situated close to the equator. The Aptian–Albian succession is represented by carbonate-clastic sediments and is assumed to be one of the most important oil reservoirs of the Middle East. The studied succession is represented by the Lower Qamchuqa, Upper Sarmord, Jawan, and Upper Qamchuqa formations (Text-fig. 4).

Chatton and Hart (1960) divided the Qamchuqa Formation into a lower unit of pre-Albian age and an upper unit of Albian age (respectively the Lower and Upper Qamchuqa). They considered the Shu'aiba and Mauddud formations as wide-ranging individual tongues of respectively the Lower and Upper Qamchuqa formations in the central and southern parts of Iraq.

The Lower Qamchuqa (Shu'aiba) Formation has been distinguished and defined by Wetzel (1950) in the Qamchuqa Gorge in the High Folded Zone of

north-eastern Iraq. In its type section, the formation consists of massive fossiliferous and argillaceous limestones (often dolomitized), with some dispersed quartz silt and glauconite, interbedded with crystalline dolomites. The best equivalents of the Lower Qamchuqa (Shu'aiba) Formation outside Iraq are the Cudi Group in Turkey (Altinli 1966), the Shu'aiba Formation in Saudi Arabia and Kuwait, and the Dariyan and Fahlyian formations in Iran (Fürst 1970).

The original definition of the Upper Sarmord Formation was given by Wetzel (1950). The formation has been found in the subsurface between Mosul in the west and Kirkuk in the east (Jassim and Goff 2006). Laterally, the formation passes into the Nahr Umr Formation on the southeast sides of the Low Folded and Mesopotamia zones. In the Low Folded Zone, the formation consists of marls and neritic limestones.

The Jawan Formation was first described by Dunnington (1958) from the Jawan-2 borehole, south-west of Mosul city, in the Low Folded Zone. The formation consists of over 170 m of pseudoolitic, argillaceous, and recrystallized limestones, argillaceous dolomites, and anhydrites (Bellen *et al.* 1959). In the Low Folded Zone, the Jawan Formation conformably overlies the Upper Sarmord Formation in the Kirkuk area. In the Qara Chauq and Makhul areas, the formation occurs as a tongue within the Albian Upper Qamchuqa Formation (Templeton *et al.* 1956).

BH-Bai Hassan oil field							
Formation	BH-70	BH-81	BH-90	BH-96	BH-102	Cores	Cuttings
Upper Qamchuqa	1607-1699 m	1687-1816m	1651.5-1678 m	1730-1779 m	1834-2005 m	29	33
Jawan	1699-1748 m	1816-1835 m	1678-1841 m	1779-1900 m	Missing	2	33
Upper Sarmord	1748-1846 m	1835-1920 m	1841-1923 m	1900-1991 m	2005-2113 m	5	42
Lower Qamchuqa	1846-1900 m	1920-2096 m	1923-1975 m	1991-2040 m	2113-2154 m	27	26

Text-fig. 5. Depth intervals of the formations, with numbers of cores and cuttings.

Wetzel (1950) described the Upper Qamchuqa (Mauddud) Formation from its type section in the Qamchuqa Gorge, north of Sulaimaniya city. In north-eastern Iraq, the formation is composed extensively of dolomitized carbonate platform deposits. The Mauddud Formation is the most widespread Lower Cretaceous formation in Iraq. It is composed of organodetritic, and detritic, locally argillaceous limestones, with varying degrees of dolomitization. As a result of the Albian transgression, the formation is widely distributed and covers almost the entire territories of both Stable and Unstable Shelf units. Only in north-western Iraq, the formation is replaced by shallow lagoonal evaporitic deposits of the Jawan Formation. The upper part of the Asafir Formation developed as neritic dolomitic limestones in the Palmyrides and central Syria, and the Albian part of the Sarvak Formation in south-western Iran, are equivalents of the Mauddud Formation outside of Iraq (Jassim and Goff 2006).

MATERIAL AND METHODS

The study was performed on cores from five selected boreholes of the Bai Hassan oil field: BH-70, BH-81, BH-90, BH-96, and BH-102 (Text-fig. 3B). However, because coring is a costly process, cores have not been taken from all depth intervals in every borehole; in these cases cuttings were examined – small rock samples retrieved from the boreholes with drilling mud and separated from it by washing. The samples were collected from the Northern Oil Company in the Kirkuk province.

The material used in this study includes:

- Core and cutting samples of the Lower Qamchuqa, Upper Sarmord, Jawan, and Upper Qamchuqa formations. Core and cutting sampling intervals within particular boreholes are presented in Text-fig. 5. Approximately a total thickness of 1650 m of deposits was analysed, represented by 61 core samples and 131 cutting samples. Detailed sampling information is given in Appendix 1;
- Final reports of the five boreholes, obtained from the Northern Oil Company, which include coordinates, elevations, information about the beginning and completion of drilling, total depth, and the basic description of the lithology of particular formations in each borehole;
- Maps (structural, geological, and contour) from the Northern Oil Company;
- Geophysical logs for the five boreholes (complete logs for all boreholes, except borehole BH-102, with no logs for the 2030–2154 m depth interval and borehole BH-70 with no logs for the 1880–1900 m depth interval) from the Northern Oil Company;
- Thin sections prepared in the laboratories at the Faculty of Geology, University of Warsaw and the European Centre for Geological Education in Chęciny, Poland. A total of 193 thin sections was made, from samples taken at approximately 10 m intervals, from all formations in all five boreholes (Appendix 1).

The obtained data were interpreted in terms of: facies, microfacies, palaeoenvironments, diagenetic development, and petrophysical properties (porosity). The microfacies of the carbonate rocks were described according to the standard classification pre-

Borehole	Formation and depth interval	Lithology and characteristics
BH-70	Upper Qamchuqa (1607–1699 m)	Limestones (fine to coarse grained, vuggy, light grey), dolomitic limestones and dolomites (finely crystalline). Oil staining in porous and fractured parts.
	Jawan (1699–1748 m)	Anhydrites (massive, microcrystalline), limestones (brown) and dolomites (finely crystalline). No oil staining.
	Upper Sarmord (1748–1846 m)	Limestones (light grey to brown), partially subjected to various degrees of dolomitization, shales and marls. Pyrite. No oil staining.
	Lower Qamchuqa (1846–1900 m)	Limestones (chalky in parts, creamy, light grey to brown) partially subjected to varying degrees of dolomitization. Oil staining in all porous parts.
BH-81	Upper Qamchuqa (1687–1816 m)	Dolomites (fine to coarse-grained, recrystallized, brown), limestones (fine-grained, finely crystalline, partly marly and dolomitized). Oil impregnations and staining.
	Jawan (1816–1835 m)	Anhydrites (massive), limestones (finely crystalline, at parts marly and or/shaly, partly dolomitized, brown), fractured dolomites. Oil staining at the bottom part.
	Upper Sarmord (1835–1920 m)	Shales (compact, fissile), marls and marly limestones in the upper part. Limestones (fine grained, partly marly or dolomitized, grey) in the middle part. Shales (compact, fissile, green-gray), marls and dolomites in the lower part. No oil staining.
	Lower Qamchuqa (1920–2096 m)	Limestones (crystalline, brown to creamy), partially subjected to varying degrees of dolomitization, marls. Oil staining and impregnations in porous parts.
BH-90	Upper Qamchuqa (1651.5–1678 m)	Dolomites (vuggy, fine to coarse crystalline, fractured), limestones, and dolomitic limestones. Oil staining in porous dolomitic parts.
	Jawan (1678–1814 m)	Anhydrites (massive, thick bedded, crystalline), limestones (brown), dolomites (finely crystalline). Oil staining in dolomitic parts.
	Upper Sarmord (1841–1923 m)	Shales (light grey, fissile), Shaly limestones (fine-grained, grey to light grey). Pyrite. No oil staining.
	Lower Qamchuqa (1923–1975 m)	Limestones (chalky in parts, creamy to light brown). Pyrite. Oil staining.
BH-96	Upper Qamchuqa (1651.5–1678 m)	Dolomites (vuggy, porous, fine to coarse crystalline, fractured), limestones, dolomitic limestones. Oil staining in porous dolomitic parts.
	Jawan (1678–1814 m)	Anhydrites (massive, crystalline), limestones (brown), dolomites (finely crystalline). Oil staining in dolomitic parts.
	Upper Sarmord (1841–1923 m)	Shales (fissile, light grey), shaly limestones (fine grained, light grey). Pyrite. No oil staining.
	Lower Qamchuqa (1991–2040 m)	Limestones (fine crystalline, brown to creamy), partially subjected to varying degrees of dolomitization. Oil staining.
BH-102	Upper Qamchuqa (1834–2005 m)	Limestones (fine grained, grey), dolomites (porous, vuggy, fine to coarse crystalline, brown), dolomitic limestones. Oil impregnations in porous parts.
	Upper Sarmord (2005–2113 m)	Marly limestones (fissile, green to grey), shaly limestones, dolomites. No oil staining.
	Lower Qamchuqa (2113–2154 m)	Limestones (porous, brown to creamy) partially subjected to varying degrees of dolomitization. Oil staining.

Table 1. Lithology of the Lower Qamchuqa, Upper Sarmord, Jawan and Upper Qamchuqa formations in the studied boreholes.

sented by Dunham (1962) depending on petrographic criteria, such as: main components, rock texture, and matrix ratio. Facies analysis was carried out by using the standard facies models of Wilson (1975) and Flügel (2010). Porosity was classified according to the Choquette and Pray (1970) model. Special attention was paid to the effects of diagenetic processes on reservoir properties.

RESULTS

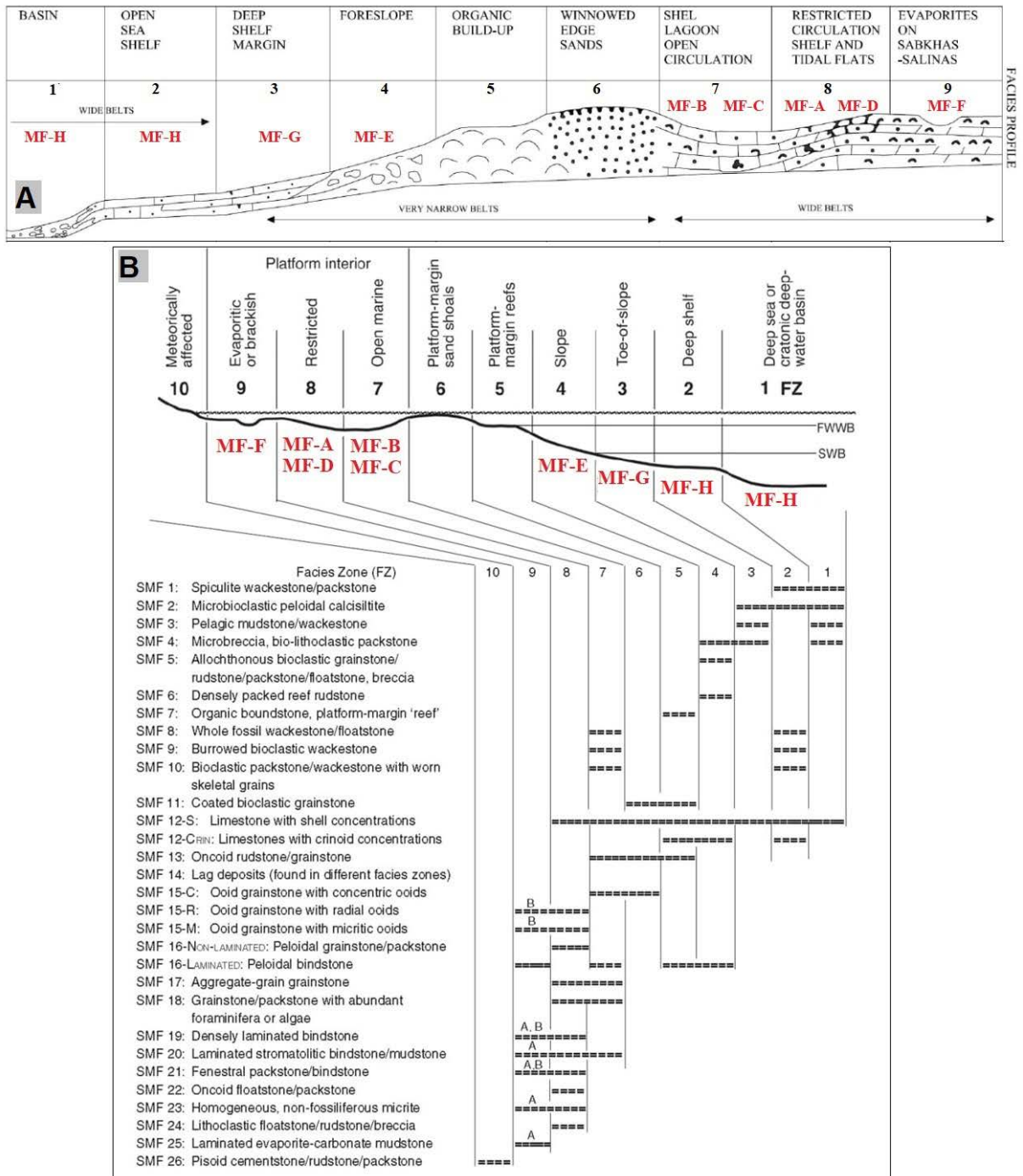
Lithofacies

The basic lithologies of all available cores and cuttings were determined from the five studied

boreholes from the Bai Hassan oil field (Table 1). Distribution of particular lithologies within the boreholes is presented in Text-fig. 6. Identification and description of the lithology throughout the whole lengths of the boreholes are based on the borehole final reports.

Microfacies and sedimentary environments

Eight microfacies (A–H) have been identified in the studied succession (Table 2). The distinguished microfacies occurring within particular formations in the studied boreholes are referred to as local microfacies units (e.g., UQ1, US1... etc.), with each unit named according to the formation it represents (LQ – Lower Qamchuqa, US – Upper Sarmord, J – Jawan,



Text-fig. 7. Distribution of the distinguished microfacies (MF) within the standard carbonate facies and microfacies models applied in the study. A – Carbonate depositional model showing standard facies belts and associated microfacies (after Wilson 1975, simplified). B – Distribution of standard microfacies (SMF) in facies zones (FZ) in the rimmed carbonate platform model. A: evaporitic, B: brackish (after Flügel 2010).

UQ – Upper Qamchuqa). The distinguished microfacies have been compared to the standard models in order to identify the sedimentary environments of particular deposits. The two most important microfa-

cies models applied here are those by Wilson (1975) and Flügel (2010) (Text-fig. 7). Wilson (1975) proposed a conceptual model and identified nine standard facies zones (FZ) distributed along a transect

Microfacies	Description and main components	Distribution in the studied boreholes	Local micro-facies units	Comparison with standard model	Depositional environments
A. Lime mudstone (Text-fig. 8A)	<ul style="list-style-type: none"> – Lime mudstones composed of brown to light brown microcrystalline calcite crystals (micrite) as the main constituent. Micrite partly transformed into neomorphic spar, peloids – Mainly unfossiliferous, locally with scarce bioclast grains – echinoderms and molluscs – Abundant dissolution cavities (vugs), stylolite seams, dolomitization of various types (pervasive, scattered, and saddle) locally intensive – Traces of hydrocarbon material 	Upper part of the Upper Qamchuqa Formation in all boreholes	UQ1	Standard microfacies SMF23 deposited in facies zone FZ8 (differs from the standard by scarce presence of bioclasts and absence of authigenic evaporite minerals)	Restricted shallow marine/lagoonal
B. Orbitolina wackestone/packstone (Text-fig. 8B)	<ul style="list-style-type: none"> – Orbitolina-bearing wackestones to packstones – Matrix composed of light to brown micrite – Skeletal grains, various content, usually constituting over 30% of rock volume, dominated by <i>Orbitolina</i> spp. tests accompanied by echinoderm and mollusc fragments and sponge spicules – <i>Orbitolina</i> spp. tests generally well preserved (complete) with internal pores filled by sparry calcite cement, in other cases subjected to micritization – Dolomitization, micritization – Scarce vugs, stylolites – Scarce traces of hydrocarbon material 	Upper Qamchuqa Formation in boreholes BH-70, BH-81 and BH-102; Upper Sarmord Formation in all boreholes; Lower Qamchuqa Formation in all boreholes	UQ2 US4 LQ2	Standard microfacies SMF18 deposited in facies zone FZ7 (differs from the standard by the absence of miliolid foraminifera and calcareous algae)	Shallow open marine
C. Orbitolina-miliolid wackestone (Text-fig. 8C)	<ul style="list-style-type: none"> – Wackestones to packstones with <i>Orbitolina</i> spp. and miliolid foraminifera; – Matrix composed of light to brown micrite – Skeletal grains, various content, dominated by <i>Orbitolina</i> sp. tests, accompanied by miliolids, benthic foraminifera and by echinoderm and mollusc fragments – <i>Orbitolina</i> spp. tests with internal pores filled by sparry calcite – Dolomitization, micritization – Scarce vugs, stylolites 	Lower Qamchuqa Formation in boreholes BH-70, BH-81, BH-96 and BH-102	LQ1	Standard microfacies SMF9 deposited in facies zones FZ7 (deeper parts of facies zone FZ7 if <i>Orbitolina</i> spp. are the dominant component, shallower parts of facies zone FZ7, close to facies zone FZ8, if miliolids are the main component)	Shallow open marine
D. Peloidal-miliolid-echinoderm packstone/grainstone (Text-fig. 8D)	<ul style="list-style-type: none"> – Packstones to grainstones with peloids as the main component accompanied by miliolids and echinoderm fragments – Matrix composed of brown micrite – Occurs in two sub-facies: a – peloidal, and b – pelletal – Subfacies a composed of peloids of fine to coarse sand sizes, moderately sorted – Subfacies b composed of pellets of silt size, well sorted – Intense micritization and dolomitization – Interparticle porosity, dolomite crystals 	Upper Qamchuqa Formation in all boreholes; Jawan Formation in all boreholes except BH-102	UQ3a UQ3b JA1	Standard microfacies SMF16 deposited in facies zone FZ8	Restricted shallow marine/lagoonal
E. Bioclast-mollusc-echinoderm wackestone/packstone (Text-fig. 8E)	<ul style="list-style-type: none"> – Wackstones to packstones dominated by skeletal debris – Various shell fragments occurring in various proportions and sizes, usually constituting 30-40% of rock volume – Matrix composed of light to brown micrite – Bioclasts with internal pores filled by sparry calcite cements – Intense dolomitization and micritization, dolomite crystals – Stylolites, traces of hydrocarbon material 	Upper Sarmord Formation in all boreholes except BH-81; Lower Qamchuqa Formation in all boreholes	US1 LQ3	Standard microfacies SMF4 deposited in facies zone FZ4 (differs from the standard by lack of turbidites and grading textures)	Fore-reef

Microfacies	Description and main components	Distribution in the studied boreholes	Local micro-facies units	Comparison with standard model	Depositional environments
F. Laminated evaporate-carbonate mudstone (Text fig. 8F)	<ul style="list-style-type: none"> – Granular and laminated evaporites associated with carbonates – Lack of fossils or other symptoms of bioactivity – Various anhydrite fabrics 	Jawan Formation in all boreholes except BH-102	JA2	Standard microfacies SMF25 deposited in facies zone FZ9	Restricted shallow marine/lagoonal
G. Planktonic foraminifera wackestone/packstone (Text-fig. 8G)	<ul style="list-style-type: none"> – Wackestones to packstones with abundant planktonic foraminifera (Globigerinidae and Hedbergellidae) – Minor amounts of calcispheres and other bioclasts – Foraminifera tests filled by sparry calcite – Matrix composed of brown micrite 	Upper Sarmord Formation in all boreholes	US2	Standard microfacies SMF3 deposited in facies zone FZ3	Deep open marine
H. Argillaceous pelagic lime mudstone/wackestone (Text-fig. 8H)	<ul style="list-style-type: none"> – Light grey mudstones to wackestones – Shale texture, fissility – Lack of fossils – Traces of organic matter 	Upper Sarmord Formation in boreholes BH70 and BH-90	US3	Standard microfacies SMF1 deposited in facies zones FZ1 and FZ2 (differs from the standard by lack of bioclasts)	Basinal

Table 2. Microfacies of the Lower Qamchuqa, Upper Sarmord, Jawan and Upper Qamchuqa formations in the studied boreholes, and their comparison to standard microfacies and facies zones.

stretching from an open deep marine basin, across the slope, through a platform marginal rim (including reef and sand shoals), and an inner platform, up to the coast. The rimmed carbonate platform model of Wilson (1975) was revised and modified by Flügel (2010), who designated conceptual models for an unrimmed ramp carbonate platform, proposing 30 ramp microfacies (RMF), as well as for a rimmed carbonate shelf, introducing 26 standard microfacies (SMF). In this study, the latter model has been used as a reference. Distribution of the identified microfacies in the boreholes is shown in Text-fig. 6.

Detailed macroscopic (lithologies, facies and sedimentary structures) and microscopic (grain type characteristics and depositional textures) studies of the Aptian–Albian succession has allowed the determination and diagnosis of the microfacies of the studied deposits (Table 2). The identified microfacies have been compared with the standard facies zones of the rimmed carbonate platform model of Wilson (1975), and with the modified standard microfacies models of Flügel (2010) for a rimmed carbonate shelf (Text-fig. 7). This in turn allowed the determination of a variety of sedimentary environments corresponding to particular facies zones, in which the studied succession was deposited (Table 2). Five depositional environments have been identified in the investigated succession: restricted shallow marine/lagoonal, shallow open marine, fore-reef, deep open marine, and basinal.

Diagenetic processes and porosity

Diagenesis has played an important role in creating the porosity system in the studied succession, and thus making the Bai Hassan oil field one of the most prolific petroleum reservoirs of Iraq. Several diagenetic processes that affected the studied Aptian–Albian succession have operated in a variety of diagenetic environments, including meteoric phreatic, mixing, marine phreatic, and deep burial. The most common visible diagenetic effects in the studied succession are: micritization, anhydritization, dissolution, recrystallization, compaction, cementation, and dolomitization. The most important processes that directly influenced the petrophysical properties of the succession were: cementation, dissolution, and dolomitization. Constructive diagenetic processes, such as dissolution and dolomitization, enhance the reservoir properties by producing and preserving the pore spaces, while destructive processes, such as cementation and compaction, reduce reservoir properties by occluding the pore space. The diagenetic processes, to which the studied successions have been subjected, can be divided into: i) early (syndepositional) – micritization and formation of isopachous cements, ii) intermediate – dissolution, formation of blocky equant calcite cements, recrystallization, and physical compaction, and iii) late – pore filling by blocky coarse calcite cements and chemical compaction (stylolitization). The intensity of particular

Borehole	Formation	Diagenetic processes						
		Micritization	Dissolution	Cementation	Recrystallization	Compaction	Anhydritization	Dolomitization
BH-70	Upper Qamchuqa	•	•••	• • •	•	••		••
	Jawan	•	•••	• • •		•	•••	•
	Upper Sarmord	•••	•••	•• ••		•••		•••
	Lower Qamchuqa	••	•••	•• • • •		••		••
BH-81	Upper Qamchuqa	•••	•••	• • • • •	•	•••		•••
	Jawan	•	•		•		•••	••
	Upper Sarmord	•	•	• • • • •	•	••		•
	Lower Qamchuqa	•••	•••	••• • • • •	••	•••		•••
BH-90	Upper Qamchuqa	••	•••	•• •• •	•	•••		••
	Jawan	••	•	• • •	•••	•••	•••	••
	Upper Sarmord		••	• • •				•••
	Lower Qamchuqa	•••	•••	••• • • • •	•	••		••
BH-96	Upper Qamchuqa	•	•••	• • • •	•••	•••		••
	Jawan	•••	•••	• • • • •	•••	•••	•••	•
	Upper Sarmord	•••	••	• • • • •	•	•		•
	Lower Qamchuqa	•••	•	• • • • •	••	•••		•
BH-102	Upper Qamchuqa	•••	•••	• • • • •	•••	•••		•••
	Upper Sarmord	•••	•••	• • • • •	•••	•••		••
	Lower Qamchuqa	•••	••	• • • • •	••	••		•

Table 3. Distribution and intensity of diagenetic processes in the deposits of the Lower Qamchuqa, Upper Sarmord, Jawan and Upper Qamchuqa formations in the studied boreholes. Intensity: ••• – strong, •• – present, • – rare. Cementation: • – isopachous marine, • – syntaxial rim, • – drusy mosaic, • – blocky.

processes in the four studied formations from the five investigated boreholes is presented in Table 3. Detailed information on the distribution of particular diagenetic processes is presented in Appendix 2.

Micritization

In the studied deposits, micritization has preferentially affected skeletal bioclast grains and benthic foraminifera of the restricted environment microfacies (Text-fig. 9A), especially the miliolids of the peloidal-miliolid-echinoderm packstone/grainstone microfacies D. Micritization is usually represented by a micritic envelope surrounding skeletal bioclasts. In some cases, intense micritization resulted in a loss of the internal structure of some skeletal grains. It is a selective process, which has increased the porosity properties of the succession.

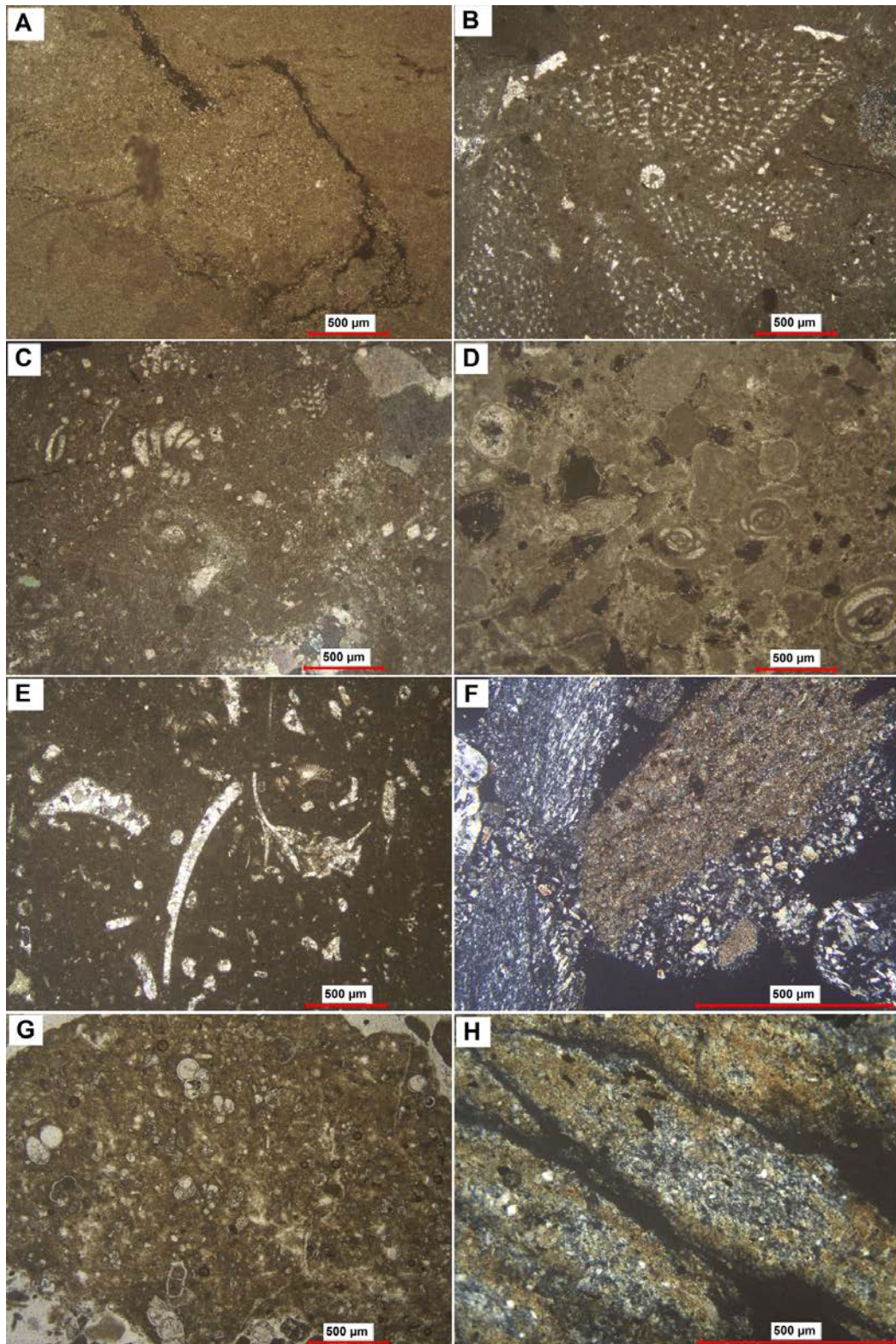
Dissolution

Evidence of dissolution is very common in many horizons in the studied succession, in all boreholes and formations. The process resulted in the formation

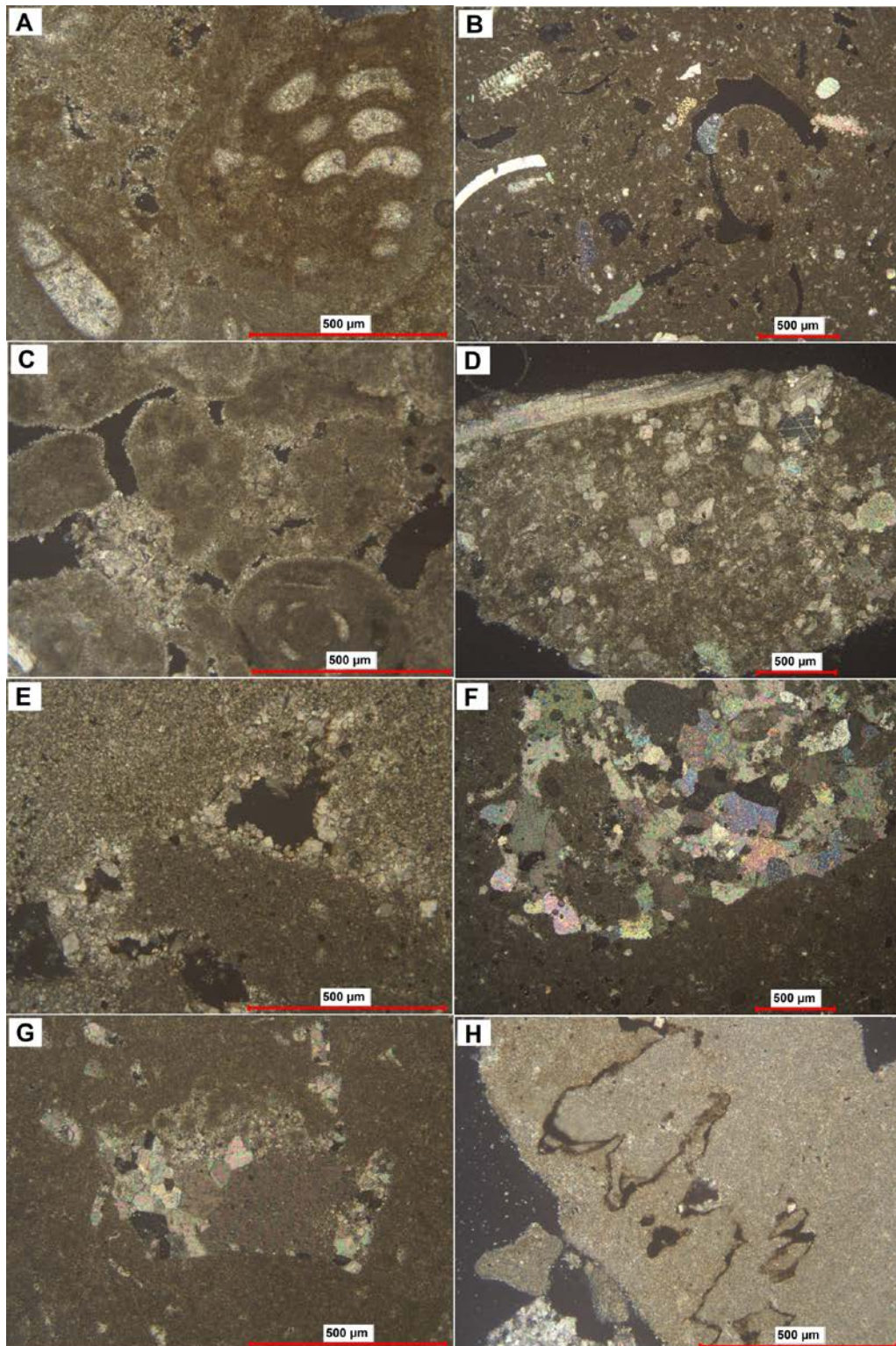
of various types of porosity; such as vuggy, moldic and intraparticle (Text-fig. 9B). Vugs occur in the studied succession either as separated or connected ones, depending on the degree of dissolution. The processes of rock dissolution are very important, as they increase the porosity and control its secondary distribution. Also in the Aptian–Albian successions of the Bai-Hassan oil field, dissolution has strongly contributed to increasing their porosity, and to making them a great reservoir for hydrocarbons.

Cementation

The cementation processes have decreased the porosity of the studied rocks by filling most of the voids, vugs, fractures, and other pore spaces by cements, especially in the wackestone and packstone microfacies. It has led to narrowing of the pore throats, as well as to complete isolation of pores, which reduced the permeability of the reservoir. Several types of cements were recognized in the studied succession, including isopachous cement (early diagenesis), blocky early equant, syntaxial, and drusy cements (intermediate diagenesis), and blocky coarse cements (late diagenesis).



Text-fig. 8. Microfacies from the Aptian–Albian succession in the Bai Hassan oil field. A – Lime mudstone; UQ1. B – *Orbitolina* wackstone/packstone; UQ2. C – *Orbitolina*-miliolid wackstone; LQ1. D – Peloidal-miliolid-echinoderm packstone/grainstone; UQ3a. E – Bioclast-mollusc-echinoderm wackstone/packstone; US1. F – Laminated evaporite-carbonate mudstone; JA2. G – Planktonic foraminifera wackstone/packstone; US2. H – Argillaceous pelagic lime mudstone/wackstone; US3.



Text-fig. 9. Diagenetic phenomena in the Aptian–Albian succession in the Bai Hassan oil field. A – Micritization. Micritized biserial benthic foraminifera shell, Lower Qamchuqa Fm. B – Dissolution. Moldic dissolution, Jawan Fm. C–F – Cementation: isopachous marine cement (C), Upper Qamchuqa Fm.; syntaxial rim cement (D), Upper Qamchuqa Fm.; drusy mosaic cement (E), Jawan Fm.; late coarse blocky calcite cement (F), Upper Qamchuqa Fm. G – Recrystallization. Calcite recrystallization of microcrystalline micrite to coarser spar, Upper Qamchuqa Fm. H – Compaction. High amplitude stylolites, Lower Qamchuqa Fm.

Isopachous marine cement. It is a common cement in shallow open marine, shoal, and semi-restricted marine environments, in vadose and marine phreatic diagenetic environments (Flügel 2010). In the studied successions it is observed as a single rim surrounding the grains, or filling their interiors (Text-fig. 9C).

Syntaxial rim cement. This type of cement is developed as a rim surrounding echinodermal skeletal grains, occurring in an optical continuity fabric with them. It forms in meteoric-phreatic, burial, and vadose environments (Longman 1977; Kaufman *et al.* 1988). In the studied succession it is observed as a rim around echinoderm grains (Text-fig. 9D).

Drusy mosaic cement. This type of cement is characterised by subhedral to anhedral, equant to elongated crystals filling vugs, fractures, and moldic pores of different sizes. It shows an increase of size towards the centre of the pore. It is formed in burial and near-surface meteoric environments (Flügel 2010). In the studied succession it is observed mainly in the packstone facies as an equant crystal cement filling the interparticle, intraparticle, fracture, and vuggy pores (Text-fig. 9E).

Blocky calcite cement. This type of cement indicates slow crystallization from an under-saturated solution and forms big crystals of calcite at the late stage of diagenetic history (Longman 1977). It often exhibits clear crystal boundaries. It is characterised by different sizes of crystals (Text-fig. 9F) and is typically formed in meteoric phreatic and vadose settings (Flügel 2010). Two types of blocky cement are present in the studied succession: the early equal cement and the late coarse cement.

Recrystallization

In the studied succession, the recrystallization process includes neomorphism from micrite to spar (Text-fig. 9G), and increase in the sizes of dolomite crystals. Neomorphic microspar is a common form of calcite in most carbonate rocks and the occurrence of microspar is a candidate for seals rather than for reservoir units. This process takes place in the sediments of shallow-water environments, under meteoric phreatic conditions (Longman 1977). Most strongly the recrystallization affected facies with abundant micritic material and was less effective in wackestone and packstone facies. Its effects are present in all formations, especially in the intervals, which were not affected by dolomitization and intense dissolution of

the matrix. This process may lead to a slight increase of porosity, by creating intercrystalline pores, but it decreases the porosity in its late stages.

Compaction

Compaction is a process of burial diagenesis and includes both mechanical and chemical compaction. The process results from an increasing pressure of thick overburden sediments due to the burial process. The effect of the compaction on the fabric includes pore-size reduction, porosity loss, grain penetration, distortion, fracturing, and breaking (Lucia 2007). In the studied succession, compaction has had a strong effect on the grain-supported facies and it is less important in the mud-supported facies. It has resulted in a general decrease of porosity.

Mechanical compaction. The process results in fracturing or deformation of carbonate grains, reduction of porosity, and rearrangement of grain packing. It is most important in mud-dominated deposits. In grain-supported sediments the effects of compaction include crushing of shells, ooids, and other grains (Bathurst 1975; Moore 1989). In the studied succession, mechanical compaction is represented mainly by the deformation and fracturing of various types of grains.

Chemical compaction. It is a process of the dissolution of carbonate rocks along distinct surfaces as a result of overburden or tectonic compaction (stress). This type of compaction is manifested mainly by the occurrence of stylolites and pressure dissolution seams. Generally, in mud-supported rocks, the stylolites are more common than in grainstones and packstones (Dickson and Saller 1995). In the studied succession, chemical compaction is represented by various types of stylolitic structures (Text-fig. 9H).

Shale compaction. This process has affected the petrophysical properties of the succession by decreasing the porosity and closing the primary and secondary pores. Compaction of shales is common in the Upper Sarmord Formation, with an abundant shale content.

Anhydritization

Anhydrite rarely forms at the surface, only in the presence of concentrated brine in hot and arid supratidal environments (Butler 1969; Shearman and Schreiber 1985). Anhydritization is a characteristic feature of the Jawan Formation. At the early stage, the process is represented by anhydrite crystals dis-

persed in carbonate facies, and with its continuation, it results in the formation of laminated and granular anhydrite that replaced the carbonate facies (Text-fig. 10A). Its effects are most intense in the north-west part of the studied area, the direction in which the evaporitic Jawan Formation replaces the Upper Qamchuqa Formation, and they decrease towards the south and southeast, where the evaporites interfinger with carbonate facies. The process has a bad effect on the porosity and permeability of the rocks.

Dolomitization

Dolomitization is the partial or complete transformation of limestone or its precursor sediment to dolomite. This was one of the diagenetic processes which contributed largely to the porosity development of the studied succession, transforming it into a good quality reservoir for hydrocarbon. It has improved the petrophysical properties of the succession in the early dolomitization stage by enlarging the size of the pores, led to the development of new porosity systems and increased permeability. Dolomitization had a lesser impact on the grain-supported facies, with high original porosity, but had a strong effect on the mud-supported facies, characterised by low original porosity. Three main types of dolomites were recognized in the studied succession: most common – pervasive (Text-fig. 10B), scattered coarse euhedral dolomite rhombs associated with stylolites and other pressure solution structures, and saddle dolomites formed in very late pore-filled cement.

Porosity

The following types of porosity, according to the classification of Choquette and Pray (1970), were recognised in the studied succession. Both fabric selective and non-fabric selective pores were identified.

Intercrystalline porosity. This type of porosity is most common in the zones of dolomitization and recrystallization processes. Patchy intercrystalline type of pore distribution is commonly associated with patchy cementation controlled by the depositional setting (Text-fig. 10C). It is widely distributed and observed between dolomite crystals. It is present mainly in the Upper Qamchuqa Formation.

Moldic porosity. This type of secondary vuggy porosity, formed by selective, complete, or partial dissolution and recrystallization of grains or crystals, controlled by both diagenesis and depo-

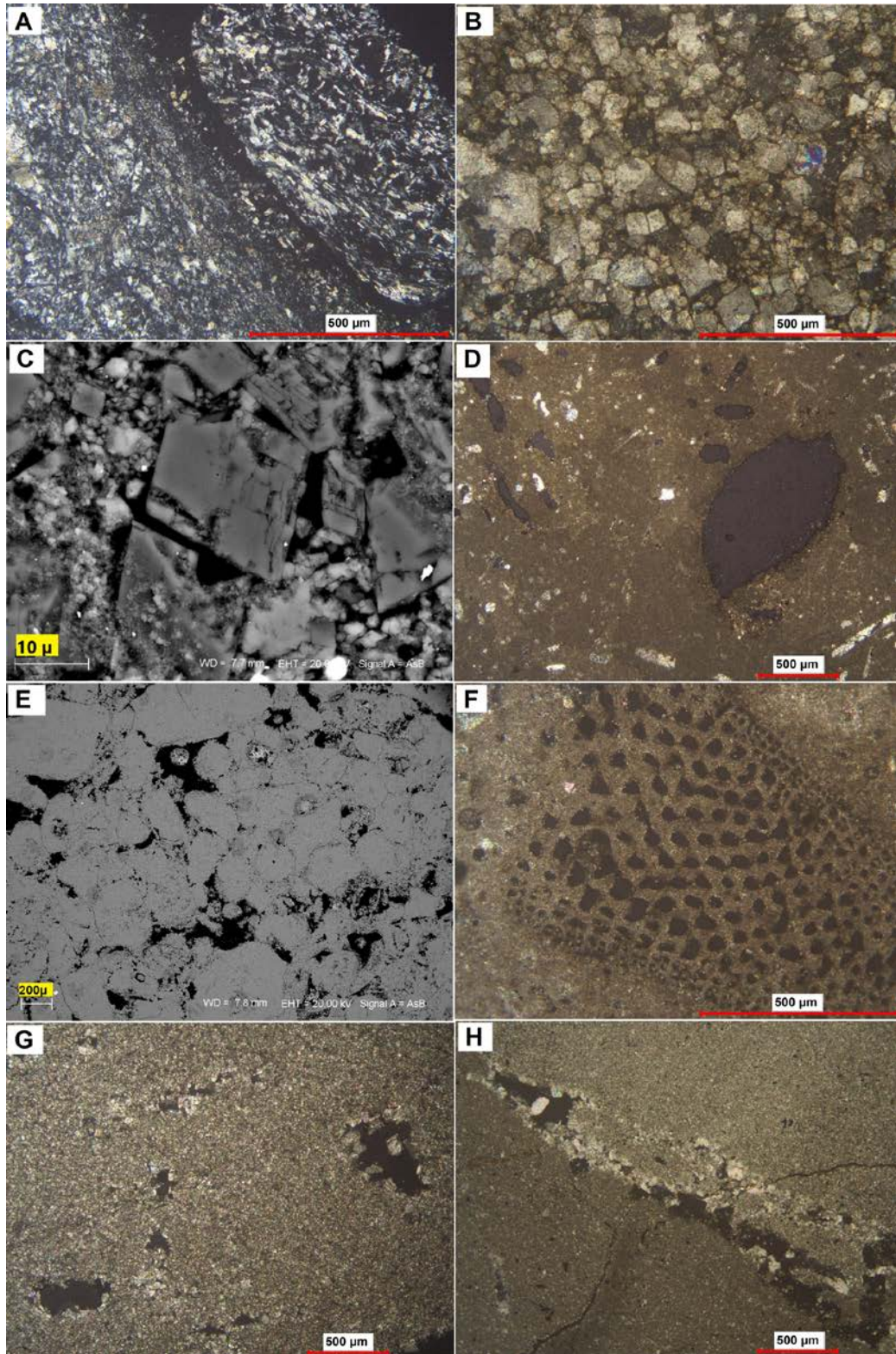
sitional setting, is widely distributed in the studied succession (Text-fig. 10D). It is caused by dissolution of both skeletal and non-skeletal grains. It is mainly present in the Lower and Upper Qamchuqa Formation.

Interparticle porosity. This type of porosity occurs between individual particles or grains. It is either of a primary origin, or formed by the decay of organic material in carbonate skeletons, and is common in mud-free carbonates. In the studied succession, this type is most commonly recognized in limestones dominated by grains (especially non-skeletal grains), such as the peloidal-miliolid-echinoderm wackestone/packstone microfacies D of the Upper Qamchuqa Formation (Text-fig. 10E).

Intraparticle porosity. This type of porosity is represented by voids within the skeletal grains, which are not filled by diagenetic cement (Text-fig. 10F). Often, this type of porosity is reduced by infiltration of the micritic matrix shortly after deposition. In the studied succession, this type is most abundantly recognized as void pores within the *Orbitolina* spp. skeletal shells in both orbitolina-miliolid wackestone microfacies C within the Lower Qamchuqa Formation and orbitolina wackestone/packstone microfacies B within the Lower Qamchuqa Formation.

Vuggy porosity. Pores of this type, developed independently of the original texture of the rocks, are irregular, with no definite shapes. Their creation is caused by irregularly distributed early and late diagenetic dissolution, which cuts through the grains and/or cement boundaries (Text-fig. 10G). In the studied succession, both types of vuggy pores are recognised; separate vuggy pores and touching (connected) vuggy pores. This type of porosity is present mainly in the Upper Qamchuqa and the Upper Sarmord formations.

Fractures and veinlets. These types of pores are common in brittle homogeneous carbonates – mostly in mudstone and wackestone facies. They form during the syndepositional, depositional, or post-depositional burial breaking of rocks, and may result from pressure solution and tectonic movements. In the studied succession, such types of pores are especially abundant in the wackestone facies within the Lower Qamchuqa Formation orbitolina-miliolid wackestone microfacies C, and in lime mudstone microfacies A within the Upper Qamchuqa Formation (Text-fig. 10H).



Text-fig. 10. Diagenetic phenomena in the Aptian–Albian succession in the Bai Hassan oil field. Porosity. A – Anhydritization. Acicular to fibrous anhydrite texture. Jawan Fm. B – Dolomitization. Dense interlocking dolomite crystals, Upper Qamchuqa Fm. C–H – Porosity: inter-crystalline (C), Upper Qamchuqa Fm.; moldic (D), Lower Qamchuqa Fm.; interparticle (E), Upper Qamchuqa Fm.; intraparticle (F), Upper Sarmord Fm.; vuggy (G), Upper Sarmord Fm.; fracture (H), Upper Qamchuqa Fm.

INTERPRETATION OF THE RESULTS AND DISCUSSION

Spatial and temporal distribution of sedimentary environments

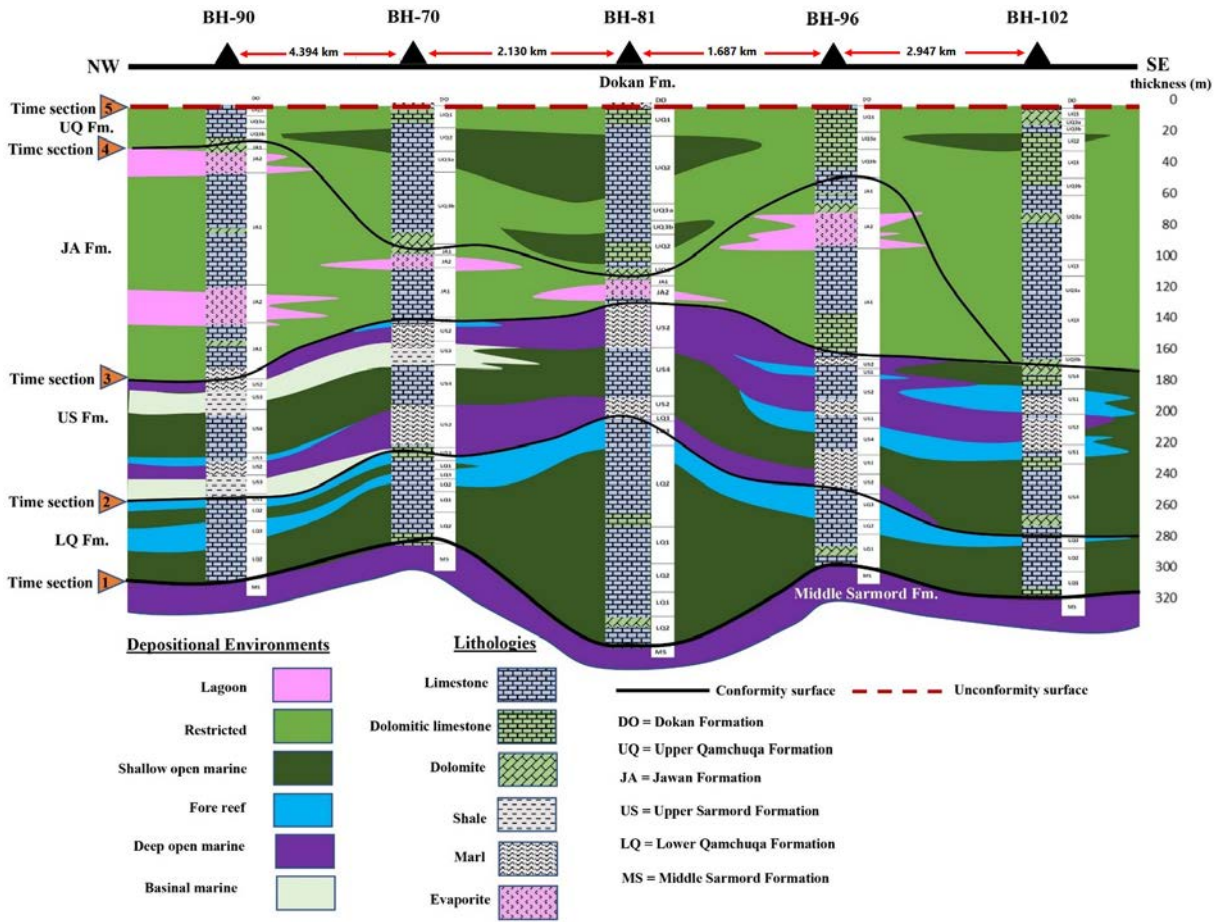
In previous studies (Bellen *et al.* 1959; Buday 1980; Sharland *et al.* 2001; Jassim and Goff 2006), the depositional environments of the studied Aptian–Albian succession were interpreted based only on outcrops in northern and north-eastern Iraq (including the study area). Facies distribution maps (Aqrawi *et al.* 2010) show that during the Barremian–Aptian, the east of today’s northern Iraq was dominated by the basinal (pelagic) facies of the Balambo Formation. Towards the west, the area is covered by the Middle Sarmord deep carbonate, shale and marl facies, and in the central part of northern Iraq, shallow carbonate facies of the Lower Qamchuqa Formation prevail. During the Early–Middle Albian, the basinal carbonate (pelagic) facies of the Balambo Formation continued to be deposited in the east. Towards the centre, the deep carbonate, shale, and marl facies of the Upper Sarmord Formation, and the shallow clastic facies of the equivalent Nahr Umr Formation accumulated. Towards the west there occurs the deltaic facies of the Nahr Umr Formation. In north-western Iraq, the restricted lagoonal evaporitic facies of the Jawan Formation was deposited. During the Late Albian, the eastern part of northern Iraq continued to be dominated by the basinal carbonate (pelagic) facies of the Balambo Formation. Towards the centre, sedimentation of the deep deposits of the Upper Sarmord Formation took place. Further towards the west, a vast area was dominated by the shallow carbonate deposits of the Upper Qamchuqa Formation. In north-western Iraq, the restricted lagoonal evaporitic deposits of the Jawan Formation continued to be deposited, later to be replaced by the Upper Qamchuqa Formation.

This detailed interpretation of the spatial distribution of particular environments in the study area and within the studied time interval, based on facies and microfacies studies of the analysed succession, is presented in five time sections representing five stages of deposition constructed along datum lines representing the beginning of deposition of consecutive formations (Text-fig. 11; black lines and red dashed line pointed by triangles), which in the scale of the study area are treated as isochronous. The contacts between particular formations in the study area are conformable and gradational.

The first stage of deposition (Text-fig. 12A) represents the transition between the deep open marine

depositional basin of the Middle Sarmord Formation and the shallow open marine basin of the Lower Qamchuqa Formation. The map is based on previous studies (Bellen *et al.* 1959; Jassim and Goff 2006). The second stage is represented by the top of the Lower Qamchuqa Formation, which is developed as shallow open marine and fore-reef facies in all studied boreholes. During this stage, basinal and deep open marine facies are present in the northeast, while the central part is dominated by fore-reef facies. Shallow water facies are limited to the southwest parts of the study area (Text fig. 12B). The third stage is marked by the first appearance of the deep marine and basinal environments of the Upper Sarmord Formation in the studied boreholes. It corresponds to a retreat of shallow water facies towards the south of the studied area, while deposition of basinal, deep open marine, and fore-reef facies took place in the central, and north-western parts of the study area (Text fig. 12C). Stage four is represented by the Jawan Formation and the corresponding lower part of the Upper Qamchuqa Formation. It represents a retreat of deep open marine and basinal facies to the east, outside of the study area and an onset of shallow open marine and restricted facies covering most of the study area (Text-fig. 12D). The northwest part of the area is covered by the lagoonal facies of the Jawan Formation. The fifth and last stage of deposition described here is represented by the shallow open marine and restricted facies of the Upper Qamchuqa Formation in the whole studied area (Text fig. 12E). The evaporitic lagoonal facies drifted far away to the northwest and the deep open marine and basinal facies retreated towards the northeast. This stage is terminated with a regional unconformity overlain by the Dokan Formation (Bellen *et al.* 1959; Jassim and Goff 2006).

The interpreted palaeoenvironments range from restricted, shallow open marine, and fore-reef, to deep marine and basinal. Lack of direct evidence of barrier reef facies does not mean that such a structure did not exist, as the study deals with only a small local area. The array of identified microfacies points to a rimmed carbonate shelf model. A substantial amount of reef fragments is observed in the studied succession, represented by skeletal debris in microfacies E, which is characteristic of the fore-reef environment within the Lower Qamchuqa and Upper Sarmord formations. The presence of a thick evaporitic Jawan Formation in the studied succession, representing a restricted basin closed by a continuous barrier, confirms the idea of the presence of the back-reef setting with restricted water circulation. Moreover, the occurrence of reefs can also be in-



Text-fig. 11. Stratigraphic cross-section showing the vertical and lateral distribution of depositional environments in the study area.

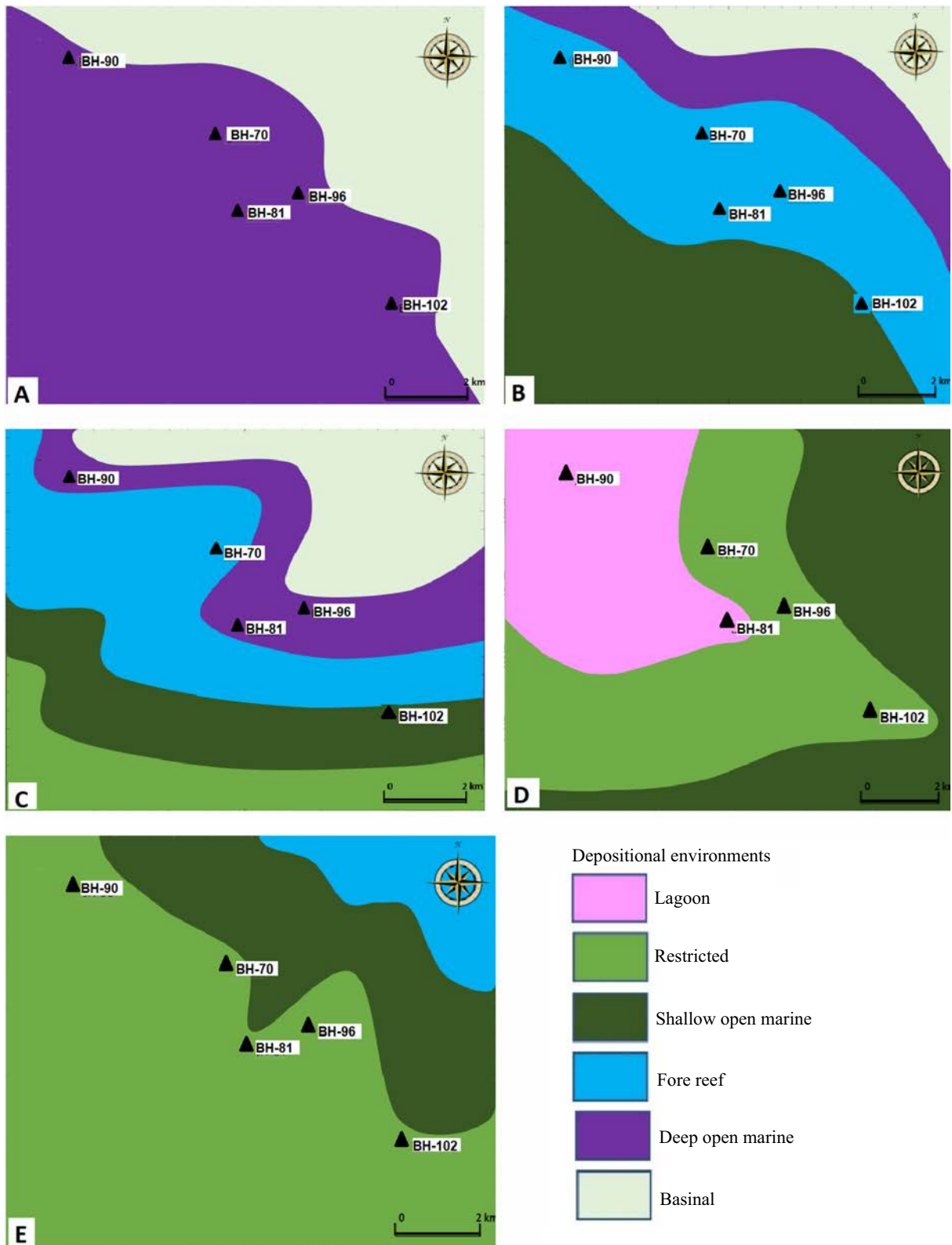
ferred from the abundance of *Orbitolina* spp., which according to Boudagher-Fadel (2008) typically grew and flourished around the barrier and inhabited reef and fore-reef environments. Lack of mixing of planktonic and benthic bioclasts confirms the presence of a barrier which absorbed and prevented the activity of currents. Sharp facies and microfacies changes within particular formations, such as the sudden disappearance of *Orbitolina* spp. and other fossils, are in accordance with the rimmed platform model

Moreover, in northern and north-eastern Iraq, at a distance of not more than 60 km from the study area, there are outcrops of the thick reef deposits of the Lower and Upper Qamchuqa Formation (up to around 650 m in one locality). Most of the previous studies (e.g., Dunnington 1958; Bellen *et al.* 1959; Ameen and Karim 2009) assumed the presence of an Aptian–Albian barrier in the north of Iraq (the Lower and Upper Qamchuqa formations). The barriers extend to the middle and south of Iraq, where this

stratigraphic interval is represented by the Shuaiba and Muaddud formations, as well as further south to Saudi Arabia and other Arabian Gulf countries.

Sequence stratigraphy and its control on diagenesis

The Arabian Platform passed through a complex tectonic history and was strongly affected by eustatic sea-level fluctuations. Both tectonics and eustasy played important roles in its sedimentary development. Much of the transgressive activity of the ocean that flooded the Arabian Platform was from the north and northeast directions (according to present-day orientation), while most of the sediment supply was from the highs located in the west, towards the north and northeast. Therefore, the onlap patterns of the dominant sediments also trend from the north and northeast. Although Sharland *et al.* (2001) did not identify sequence boundaries, they tried to date the



Text-fig. 12. Distribution of sedimentary environments at selected time sections representing the five main stages of deposition in the study area. A – stage one (top of the Middle Sarmord Formation), B – stage two (top of Lower Qamchuqa Formation), C – stage three (top of the Upper Sarmord Formation), D – stage four (top of the Jawan Formation and its equivalent), E – stage five (top of the Upper Qamchuqa Formation).

main maximum flooding surfaces (MFS) and correlate them regionally. The Arabian Platform regional cycle chart by Haq and Al-Qahtani (2005) combined the interpreted sedimentary onlap patterns on the platform margins with regional sea-level variations models, which controlled these patterns. These comparisons show that the patterns of sediment accumulation on the Arabian Platform were widely controlled by eustasy, with a strong overprint of tectonics for many long intervals. The relative sea-level curve for the Arabian Platform is derivative of the regional onlap curve, which displays a saw-toothed pattern.

According to Sharland *et al.* (2001) and Haq and Al-Qahtani (2005), regionally the main maximum flooding surface K70, which is recognised within the studied succession, corresponds to the rapid retreat of deltaic facies (Zubair Formation) and the shoreward advance of the carbonate ramp facies of the Lower Qamchuqa (Shu'aiba) Formation basal limestones (Al-Fares *et al.* 1998). The maximum flooding surface K80 corresponds to the top of the Lower Qamchuqa (Shu'aiba) Formation. At that time, a carbonate shelf system and its equivalents developed extensively across Kuwait, Qatar, Iraq, Syria, and into the Levant. In the western part of Iraq, the Shu'aiba Formation and its equivalents were eroded out (Bellen *et al.* 1959). The maximum flooding surface K90 is considered as a major regional maximum flooding event in the north of Iraq, and it is located at the base of the Upper Sarmord Formation (Bellen *et al.* 1959; Buday 1980).

The studied succession can be divided into five sequence stratigraphy stages, the first of which terminates at the bottom of the Lower Qamchuqa Formation (Text-fig. 13). Shifting in microfacies from shallow to deep, and an increase in gamma-ray value helped recognition of the Transgressive Surface (TS) and Maximum Flooding Surfaces (MFS).

Stage One. This stage precedes the deposition of the Lower Qamchuqa Formation and terminates with the MFS on top of the Middle Sarmord Formation in all studied boreholes.

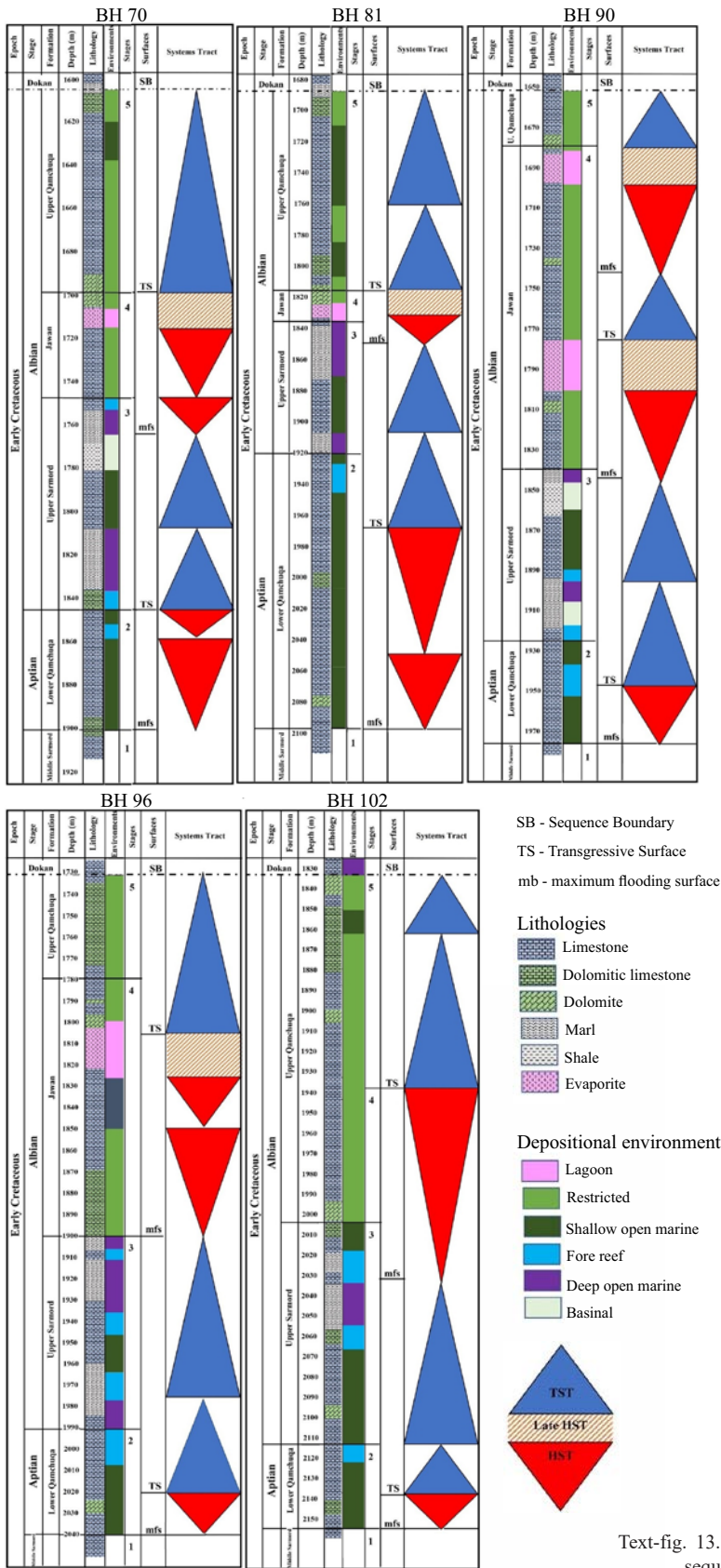
Stage Two. This stage is represented by the deposition of the Lower Qamchuqa Formation during two highstand systems tracts (HST) in borehole BH-70, by two HSTs and a transgressive systems tract (TST) in borehole BH-81, and by the HST and the TST in other boreholes. The boundary between the HST and TST is represented by a transgressive surface (TS), which separates the Lower Qamchuqa and Upper Sarmord formations in borehole BH-70. In other boreholes there is a transitional sequence

within the Lower Qamchuqa Formation, represented by the upper part of the formation deposited during the TST. The Lower Qamchuqa Formation was deposited during a highstand with a predominance of a shallow open marine environment in the study area. In all studied boreholes, the lower part of the Lower Qamchuqa Formation is represented by one HST, except for boreholes BH-70 and BH-81, in which two HSTs appear, with a fore reef association of facies near the end of this stage.

Stage Three. At this stage, the sea-level rose during the TST. The Upper Sarmord Formation was deposited during two steps of sea-level rise and a highstand. In borehole BH-70, the formation was deposited during two TSTs and one HST. The TST ends with the MSF within the Upper Sarmord Formation. In boreholes BH-81 and BH-90, the formation was deposited in two TSTs and one HST. In borehole BH-96, the formation was deposited in two TSTs ending with a MFS close to the upper contact with the Jawan Formation. In borehole BH-102, the formation was deposited in the TST and the HST, the TST ending with the MFS within the formation. The transgression continued from the late deposition of the Lower Qamchuqa Formation to the deposition of the Upper Sarmord Formation, marked by a preceding MFS. After that, the facies changed from deep to shallow. The nature of the boundary between stages two and three (Upper Sarmord and Jawan formations) varies between the boreholes. In most boreholes it is a transitional surface represented by the HST, while in borehole BH-96 it is represented by a sharp boundary marked as the MFS.

Stage Four. During this stage, the Jawan Formation was deposited in the HST. In its late phase, the deposition of evaporitic sediments took place. This stage represents sea-level regression, which started at the beginning of the HST and ended with a prograding evaporitic stage. The evaporitic succession (restricted association) in the upper part of the Jawan Formation refers to the late highstand systems tract (LHST), which is present twice in borehole BH-90. The disappearance of evaporitic deposits marks the onset of the following stage five. The Jawan Formation appears in all studied boreholes, except for borehole BH-102, in which stage four is represented by the restricted facies (without evaporates) of the lower part of the Upper Qamchuqa Formation.

Stage Five. This stage represents a sea-level rise resulting in the deposition of the Upper Qamchuqa Formation. After the HST, the sea-level rose and the



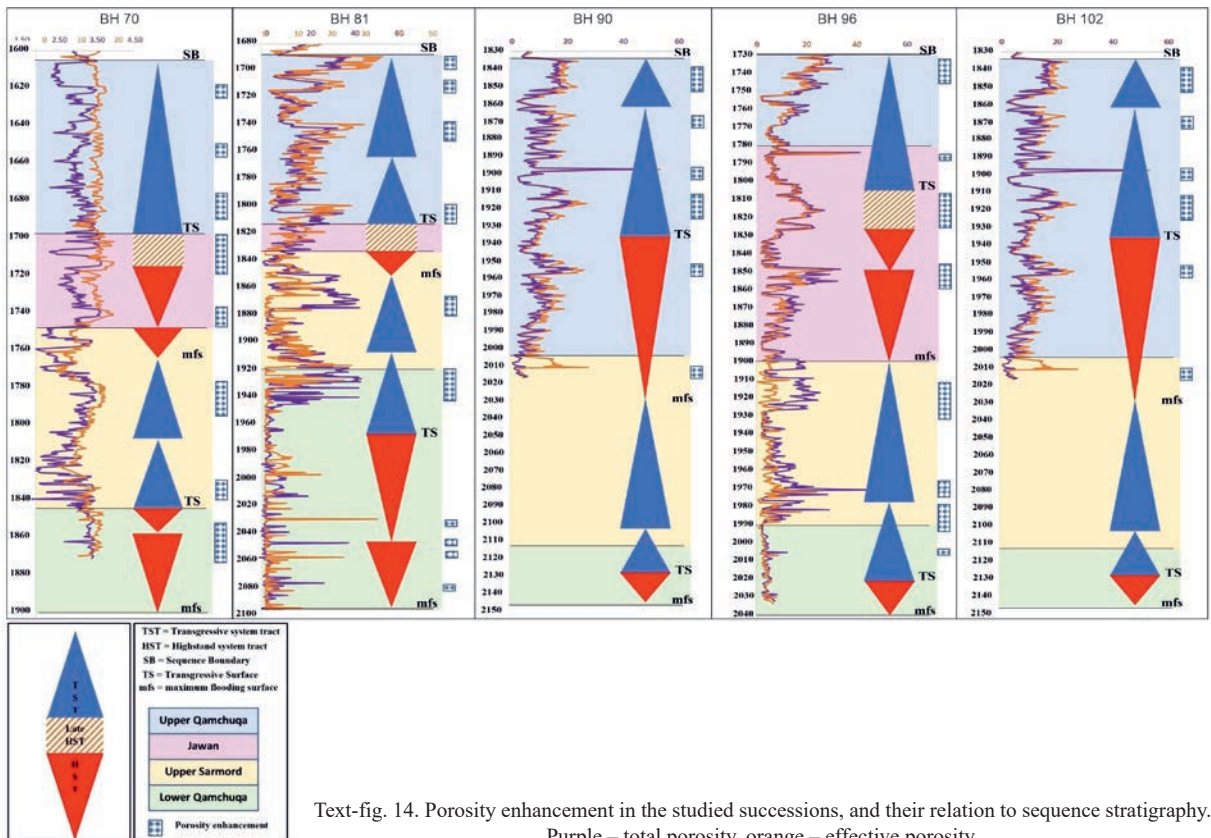
Text-fig. 13. Interpretation of depositional environments and sequence stratigraphy in the studied boreholes.

TST developed in all studied boreholes. In the boreholes located closer to the centre of the basin (BH-70, BH-90 and BH-96) one TST occurs, while in boreholes BH-81 and BH-102, located closer to the coastline, two TSTs are recorded. This confirms that the transgression progressed from the north to the south. The stage ended with a regional unconformity, which is represented by a sequence boundary (SB) underlying the Dokan succession.

The development of diagenetic processes in carbonate rocks is to a large extent governed by relative sea-level fluctuations. The main process influencing diagenesis is the landward and seaward shifting of various diagenetic environments (meteoric, mixing, and marine). The main diagenetic processes that affected the studied succession are dissolution, cementation, and dolomitization. They affected different parts of the studied succession with different intensities, depending on the nature of the cycle reflected by its facies stacking pattern. The changing values of effective and total porosity are indicated on the borehole logs (Text-fig. 14). Detailed distribution of particular diagenetic processes in the studied succession is presented in Appendix 2.

An important relationship between the diagenetic processes that affected the studied succession and

sea-level fluctuations has been clearly recognised. In general, the sediments deposited during the HST are characterised by weak cementation, constructive dolomitization, moderate porosity value, and moderate to good hydrocarbon reservoir characteristics. The sediments of the transgressive system tracts are also characterised by moderate porosity, which results in moderate to good hydrocarbon reservoir characteristics. There are some exceptions from the above model (less effect and control of sea-level fluctuation on diagenetic processes) due to an abundant content of argillaceous material in many intervals within the Upper Sarmord Formation, and due to differences between the grain- and mud-supported facies in other formations. In addition, the area of the Bai Hassan oil field, composed of two domes – Kithka and Dawood domes, separated by a shallow Shahel saddle, was subjected also to tectonic factors, which influenced the course of diagenesis. The tectonic factor led to the development of fracture systems that contributed to porosity increase, but it was by no means the only factor that controlled the petrophysical properties developments and the reservoir distribution within the studied succession in the Bai Hassan oil field. These are affected also by sedimentary processes and their relation to diagenesis.



SUMMARY AND FINAL CONCLUSIONS

The Aptian–Albian succession, consisting of the Upper Qamchuqa, Upper Sarmord, Jawan, and Upper Qamchuqa formations from five boreholes (BH-70, BH-81, BH-90, BH-96, and BH-102) in the Bai Hassan oil field, Zagros Foreland Basin, northern Iraq, has been studied in terms of microfacies, diagenetic processes and sequence stratigraphy. Eight microfacies have been identified: lime mudstone (A), orbitolina wackestone/packstone (B), orbitolina-miliolid wackestone/packstone (C), peloidal-miliolid-echinoderm packstone/grainstone (D), bioclast-mollusc-echinoderm wackestone/packstone (E), laminated evaporite-carbonate mudstone (F), planktonic foraminifera wackestone/packstone (G), and argillaceous pelagic lime mudstone (H). The identified array of microfacies indicates that the succession was deposited in a variety of environments, including: restricted shallow marine/lagoonal environments characterised by the presence of microfacies A and D, lagoon environment characterised by the presence of microfacies F, shallow open marine environment characterised by the presence of microfacies B and C, fore-reef environment characterised by the presence of microfacies E, deep open marine environment characterised by the presence of microfacies G, and basinal environment characterised by the presence of microfacies H. The studied succession was deposited on a rimmed carbonate shelf, on a passive margin of the Arabian Plate, before the start of the closing of Neo-Tethys Ocean during the Late Cretaceous.

The succession was deposited in five stages characterised by changing facies patterns. Stage one is represented by the Middle Sarmord Formation deposited in a deep open marine environment. Stage two represented by the Lower Qamchuqa Formation is characterised by shallow open marine and fore-reef environments. Stage three is characterised by the first appearance of deep open marine and basinal facies represented by deposition of the Upper Sarmord Formation and by the retreat of shallow open marine facies towards the south and southwest parts of the study area. Deposition of basinal, deep open marine, and fore reef facies took place in the north, northeast, central, and northwest parts of the studied area. Stage four represents the deposition of an evaporitic Jawan Formation and the corresponding lower parts of the Upper Qamchuqa Formation. It is characterised by a retreat of deep open marine and basinal facies to the east, outside of the study area, and by an onset of shallow open marine and restricted facies. The northwest and part of the central area was occupied by the

lagoonal facies of the Jawan Formation. Finally, stage five is characterised by the domination of the shallow open marine and restricted facies of the Upper Qamchuqa Formation in the whole studied area, by the elimination of the evaporitic facies of the Jawan Formation, and by the retreat of deep open marine and basinal facies towards the northeast. The end of this stage is marked by a regional unconformity with the overlying Dokan Formation.

The studied succession has been subjected to several diagenetic processes, including: micritization, dissolution, recrystallization, cementation, anhydritization, compaction, and dolomitization, taking place in various diagenetic environments; meteoric phreatic, marine phreatic, vadose, mixing, and burial. The processes with the greatest effects on the porosity of the studied deposits were: dissolution, cementation, and dolomitization. The most important type of porosity present in the studied succession is represented by secondary systems of pore spaces created by various constructive diagenetic processes, especially dissolution and dolomitization. In other parts of the succession, destructive diagenetic processes, such as cementation and compaction, completely or partially destroyed the pore space systems.

The identified vertical shifts of the distinguished microfacies, and the changing facies patterns of the studied succession in the investigated area, have allowed the presentation of an interpretation of relative sea-level fluctuations. These fluctuations have affected the development of diagenetic processes in the studied succession. The major effect is the landward or seaward shift of various diagenetic environments (meteoric, mixing and marine). In general, the succession is characterised by less cementation, constructive dolomitization, and moderate porosity, resulting in moderate to good hydrocarbon reservoir properties in its parts represented by highstand stages, and by moderate porosity, resulting in moderate to good reservoir characterisation in its transgressive stages. The shallow environments represented by restricted and shallow open marine facies are characterised by high values of porosity due to dissolution and early dolomitization. It follows from the above that tectonics was not the only factor influencing the petrophysical properties and distribution of deposits in the studied sequence in the Bai Hassan oil field; sedimentation processes and their relationship with diagenesis also had an impact.

The presented general conclusions may well apply to many other sedimentary successions and reservoirs with similar facies patterns and depositional histories worldwide.

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