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Depositional architecture and sequence stratigraphy of the Upper Jurassic Hanifa Formation, central Saudi Arabia

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ABSTRACT

To document the depositional architecture and sequence stratigraphy of the Upper Jurassic Hanifa Formation in central Saudi Arabia, three composite sections were examined, measured and thin section analysed at Al-Abakkayn, Sadous and Maashabah mountains. Fourteen microfacies types were identified, from wackestones to boundstones and which permits the recognition of five lithofacies associations in a carbonate platform. Lithofacies associations range from low energy, sponges, foraminifers and bioclastic burrowed offshoal deposits to moderate lithoclstic, peloidal and bioclastic foreshoal deposits in the lower part of the Hanifa while the upper part is dominated by corals, ooidal and peloidal high energy shoal deposits to moderate to low energy peloidal, stromatoporoids and other bioclastics back shoal deposits. The studied Hanifa Formation exhibits an obvious cyclicity, distinguishing from vertical variations in lithofacies types. These microfacies types are arranged in two third order sequences, the first sequence is equivalent to the lower part of the Hanifa Formation (Hawtah member) while the second one is equivalent to the upper part (Ulayyah member). Within these two sequences, there are three to six fourth-order high frequency sequences respectively in the studied sections.

1. Introduction

The Upper Jurassic rocks in Saudi Arabia appear in a graben area renowned as Tuwaiq mountains that comprise non-clastic rocks intercalated with minor clastic ones and is regarded as one of the main reservoirs in the Arab Gulf countries. These rocks are concentrated in Central Saudi Arabia and constitute the most prominent features in the Arabian Shied (Fig. 1). The Tuwaiq Mountains are divided by several valleys system such as Hanifa valley (El-Asa'ad, 1991). Aigner et al. (1989) reported that the Hanifa Formation formed in an epeiric shallow-water platform that exemplifies a model of an intrashelf basin. The depth of this basin is considered a main factor for the deposition of productive source-rocks in the eastern Saudi Arabia (Hughes et al., 2008). Al-Husseini et al. (2006) believed that eustatic sea-level rise and the continuous subsidence as the major causes of the growth of the Hanifa intrashelf basin.

Fischer (2001) classified the Hanifa Formation on the basis of paleoenvironment into inner lagoon environment in the lower part, back reef environment in the middle part and reef environment in the upper part. The main target of the present work is to determine the microfacies types and associations, construct the depositional model and clarify the high-frequency sequence stratigraphy of the Hanifa Formation in central Saudi Arabia.

2. Geological setting and lithostratigraphy

The Saudi Arabia is surrounded by many tectonic systems. The Zagros fold belt borders the eastern and northern margins; the Gulf of Aqaba–Dead Sea transform fault system borders the north-western margin and the Red Sea-Gulf of Aden active rift system bounds the southern and western margins (Sharland et al., 2001; El-Asmar et al., 2015). During the Late Jurassic Epoch, the present day Saudi Arabia was situated at the north-eastern side of Gondwana, contrary to the Tethys (Klemme and Ulmishek, 1991). The most of the Jurassic deposits were accompanied by the initiation of oceanic basins on the south-east side of Saudi Arabia. That initiation has been created when many microcontinents began to separate from the Gondwanaland margin (Beydoun, 1991). The Indian Plate was considered the first plate separated from the

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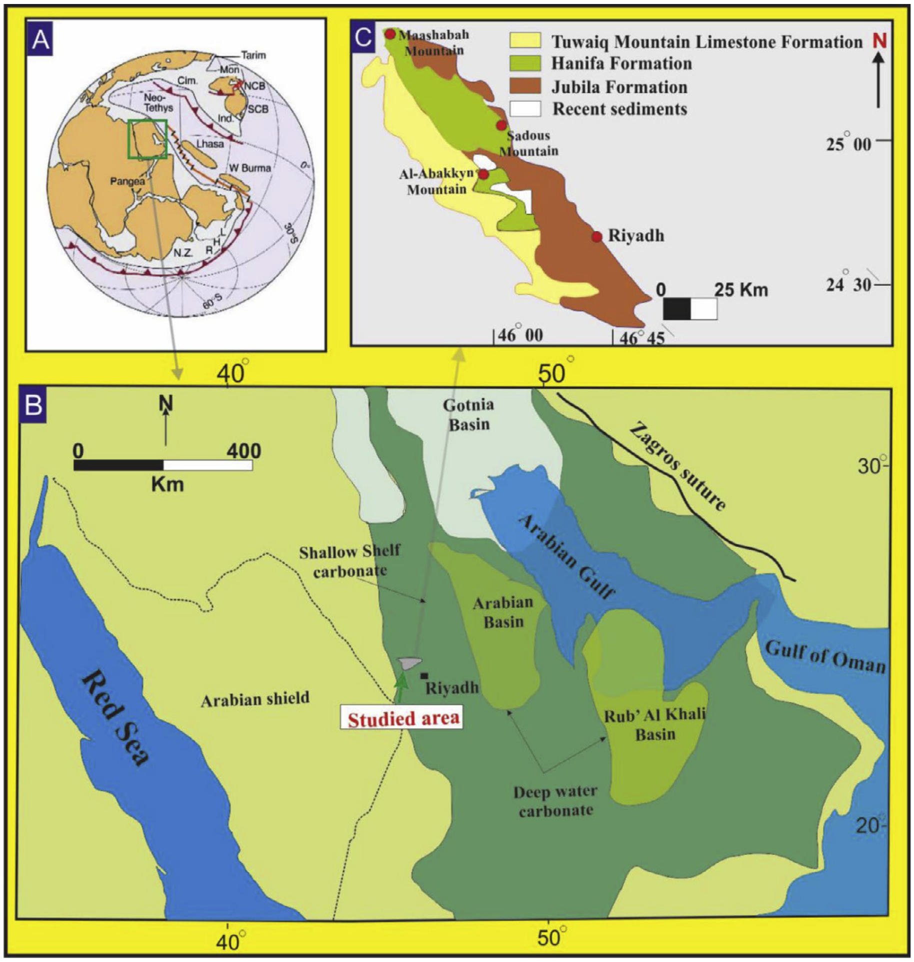

Fig. 1. A. Paleogeographic configuration during the Mid- Jurassic, just before Pangea breakup (Li and Powell's, 2001), with the Arabian plate position enclosed in the blue square. B. General location map of Saudi Arabia including the studied area (green arrow) and the main intra-shelf basins in the Middle and Late Jurassic (Modified from Al-Awwad and Collins, 2013). C. Detailed map of the studied mountains.

Gondwanaland in the Jurassic (Grabowski and Norton, 1995), and completing its split off from the Arabian plate in the upper Jurassic (Haq and Al-Qahtani, 2005). During the Jurassic period, Haq et al. (1988) differentiated four intra-shelf basins: Gotnia and Arabian basins in the north and center part of Saudi Arabia and UAE and Rub' Al Khali basins in the south of Saudi Arabia. The figuration of these basins has been related to renovate north trending Hercynian tectonic movement in the midst the Gotnia and Arabian basins (Bordenave and Burwood, 1990).

The Hanifa Formation is the fourth formation of the seven formations that forms the Shaqra group of Saudi Arabia (Table 1). The Hanifa Formation (Table 2) lies unconforamably upon the Callovian Tuwaiq Mountain Limestone Formation with an erosional surface and is overlain by the Kimmeridgian Jubaila Formation (Hughes, 2008). The first attempts to study the lithostratigraphy, biostratigraphy and unconformities of the Hanifa Formation have been carried out by Steineke (in Arkell et al., 1952) and Powers et al. (1966). They measured and described the Hanifa Formation at Al-Abakkayn Mountain, in which the lower part (94.4 m) consists mainly of bioclastic wacke-to packstone and the upper part (19 m) consists mainly of pack-to grainstones. The uppermost part of the Hanifa is characterized by oolite-pellet calcarenite bed. Vaslet et al. (1983) and Manivit et al. (1985) divided the Hanifa Formation into the Hawtah (H1) and Ulayyah (H2) members. Hughes et al. (2008) defined the boundary between the Hanifa and Jubaila formations as a ferruginous oyster bed overlain by the conglomerate beds at the basal part of the Jubaila Formation. He also identified pelloidal grains with gastropods in the last bed of the Hanifa Formation that is exposed in the Riyadh-Mecca highway.

The accurate age of the Hanifa Formation is controversial. Arkell et al. (1952) regarded the Hanifa Formation as of Oxfordian age. Powers et al. (1966) and Powers (1968) assigned it to Oxfordian/Kimmeridgian depending on the large foraminifers. They considered the existence of *Kurnubia morrisi* (Redmond) and *Pseudocyclammina jaccardi* (Schrodt) is a sufficient evidence to assign the upper part of the Hanifa Formation to the Lower Kimmeridgian. Vaslet et al. (1983) considered the Hawtah member as Middle to upper Oxfordian age based on the ammonite *Euaspidoceras* sp. and Ulayyah Member as also Middle to upper Oxfordian age based on the foraminifera, *Pseudocyclammina Jaccardi*. Moshrif and El Asa'ad (1984) investigated the Hanifa Formation at Wadi Hanifa and they related it to a Late Oxfordian-Early Kimmeridgian age based on the existence of foraminifers. Other studies have been summarized in Table 2.

3. Material and methods

Three sections have been studied in the northern west of Riyadh city. The first of them is Al-Abakkayn Mountain which is located in Wadi Hanifa at lat. 24° 54 24″ N and long. 45°55′ 38″ E. The other

Table 1
Shaqra group of Jurassic Saudi Arabia (Modified from Tawfik et al., 2016).

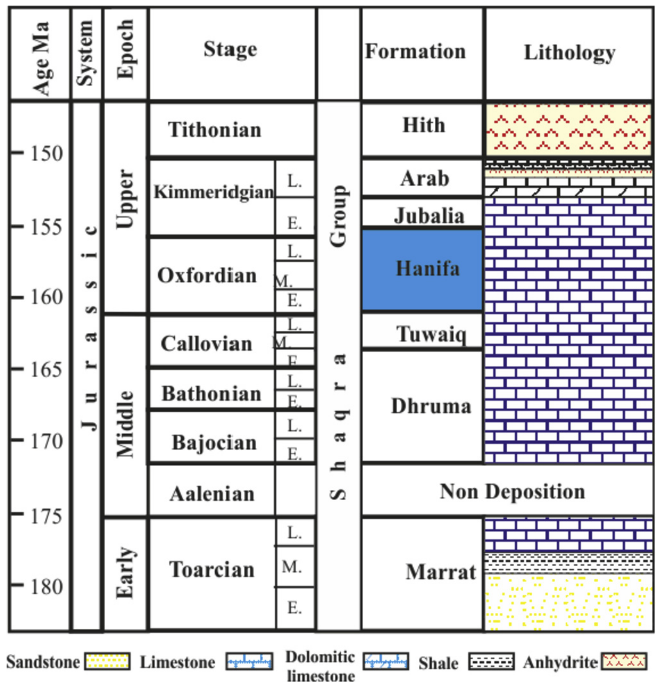

Table 2
Lithostratigraphic classification of the Hanifa Formation in Saudi Arabia.

Age			Powers et al. 1966		Vaslet et al. 1983, 1984		Moshrif & El-Asa'ad 1984		Manivit et al. 1987, 1990		Fischer et al. 2001	Hughes 2009	Basyouni 2011	El-Sorogy & Al-Khatany 2015	Present study
System	Series	Stage	Litho Str	IF	Litho Str	IF	Litho Str	IF	Litho Str	IF					
Jurassic	Upper	Kimmerdgian	Jubaila Fm		Jubaila Fm		Jubaila Fm		Jubaila Fm		Jubaila Fm	Jubaila Fm	Jubaila Fm	Jubaila Fm	Jubaila Fm
			Hanifa Fm	Km Pj			Hanifa Fm	Kp Kw	Hanifa Fm	An Ro Pt	Hanifa Fm: Unit H2 – Ulayyah Mb		Hanifa Fm		
		Oxfordian			Hanifa Fm: Ulayyah Mb	Pj Nl						Hanifa Fm	(TML)	Hanifa Fm	Hanifa Fm: Ulayyah Mb
					Hanifa Fm: Hawatah Mb						Hanifa Fm: Unit H1 – Hawatah Mb				Hanifa Fm: Hawatah Mb
	Middle	Callovian	(TML)		(TML)		(TML)		(TML)		(TML)	(TML)		(TML)	(TML)

TML: Tuwaiq mountain Limestone Fm Litho: Str Lithostratigraphy IF: Index fossils *Pj: Pseudocyclammina jaccardi* Fm: Formation Mb: Member *Km: Kurnubia morrisi*
Kp: Kurnubia palastiniensis *Kw: Kurnubia wellings* *Ro: Rhabdocidaris orbignya* *Pt: Pseudocidaris thurmani* *An: Acrocidaris nobilis* *NI: Nanogyra lumachelle*

two sections (Sadous and Maashabah) are located at the northern part of this section, according to the following coordinates respectively, lat. 25° 02′ 33″ N and long. 46°10′ 47″ E, lat. 25° 24′ 12″ N and long. 45°24′56″E. 55 thin-sections were made from the 155 samples collected from the studied sections to study lithology, paleontology, structure and diagenesis. On the principles of thin-section elaborations using light microscopy, various variables were visually quantified to identify the microfacies including accurate lithology, grain type and size, texture, microstructure, sorting, diagenesis and porosity. Three images have been taken of each thin section by microscopic camera and processed on CorelDRAW program to understand the stratigraphy, microfacies types and lithofacies associations. On the basis of Embry (2009), we have been interpret the cyclicity of the studied formation at different scales, sequence boundaries or maximum regressive surfaces, maximum flooding zones or surfaces, transgressive system tracts, highstand sequence tracts and depositional sequences on the basis of field investigation and laboratory works. The explanation of depositional environments concordant to a lithofacies code (Fig. 2) and the identification of carbonate rocks followed the terminologies of Embry and Klovan (1971).

4. Results and discussions

4.1. Microfacies types (LFT)

Fourteen microfacies types (MFT) have been recognized in the Hanifa Formation studied sections. Table 3 summarizes theses lithofacies types based on textural and/or compositional variations. Most of these microfacies were represented by carbonates and minor with marl, sandy claystones and shales. The lower part of the Hanifa Formation is dominated by thin to thick-bedded wacke-to boundstones (Figs. 3–5). These are mainly composed of lithoclastics, bioturbated limestones and burrows. The beds exemplify biostromal foreshoal to skeletal offshoal deposits. The upper part of the Hanifa Formation is dominated by stratified, low angle cross

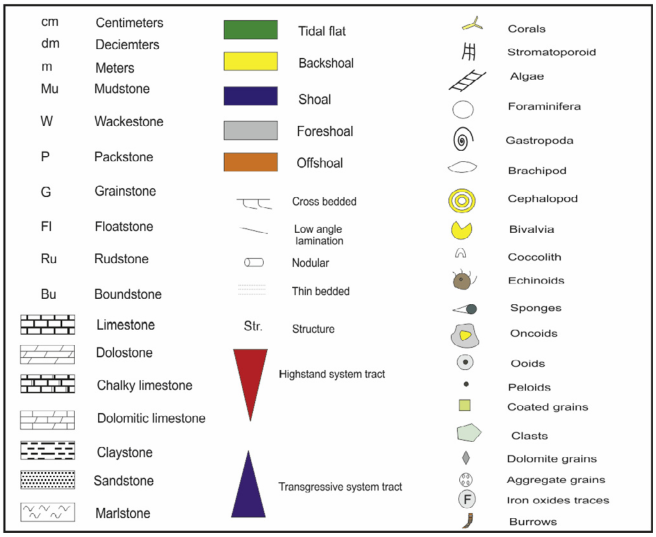

Fig. 2. Colour coded texture (Embry and Klovan, 1971), lithology, lithofacies associations and fossils.

lamination and micritized back-shoal and shoal wackestone to grainstone deposits with skeletal grains such as foraminifers, corals, stromatoporoid, dasyclad algae and echinoids and non-skeletal grains such as ooids and peloids (Figs. 3–5).

4.2. Lithofacies associations (LFA) and depositional environments

According to Droste (1990), the Hanifa Formation has been developed upon a shallow marine carbonate platform located on the southern corner of the Tethys and the common feature of this platform was intra-platform basins. These basins have environmental diversities with different micro- and macropaleontological features (Hughes, 2004). Basyoni and Khalil (2013) stated that the Hanifa Formation formed when an extensive area in central Arabia was occupied by depositional setting ranging from shallow marine shorelines to open sea deep marine waters. In our study, five lithofacies associations are identified on the basis of different constituents of the lithofacies types. These lithofacies associations are exactly of five depositional environments and are represented here from shallow to deep depositional facies, which allowed us to form a major depositional environmental model (Fig. 6). A summarized description of each lithofacies association is involved in the text below:

4.2.1. Tidal flat to shallow lagoon lithofacies association

4.2.1.1. Description. This lithofacies association comprises MFT1a and MFT2b types (Table 3) and is present in the upper part of the Hanifa Formation (Ulayyah Member). The thickness of these beds ranges from 4 to 8 m and is dominated by carbonate rocks (sandy limestone and dolostone). The limestone beds are fossiliferous, cream to light gray color in the field while the dolostone beds can be distinguished by unweathered grey surface. The dolomite grains are fine to medium crystals with rare fossils. These facies are distinguished by laminated, thick bedded of peloidal wackestones and sandy packstones with skeletal grains such as foraminifers (*Nautiloculina* sp. and *Trocholina* sp.), dasycladacean algae, bivalves and gastropods and other non-skeletal grains such as peloids are recognized. The sand grains are small and the matrix constitutes of peloidal micrite. Thin layers of iron oxides, reworking of mudstone pebbles and bird eyes structure have been observed. Ferrugination and dolomitization are the main diagenetic feature in this lithofacies association and few of skeletal grains were dissolved and replacement with dolomite grains during the dolomitization process.

4.2.1.2. Interpretation. The fine grained texture, the predominance of mud and the presence of sand grains indicate a near shore to tidal flat setting (Flügel, 2010). Bird eyes and peloids and other components refer to shallow lagoon environment (Sattler et al., 2005). Fine grained sediments with peloids refer to a slow accumulation in shallow water conditions in the protected area (Armella et al., 2013). According to Kavoosi and Sherkati (2012), the presence of dolomite grains with rare fossils indicates intertidal zone of restricted shallow sea. Reworked fossils suggest an environmental setting influenced by a fair weather wave base (Gomez and Astini, 2015). According to Palma et al. (2007), dasycladacean algae point to a shallow lagoonal environment.

4.2.2. Lagoon and back-shoal lithofacies association

4.2.2.1. Description. This lithofacies association comprises MFT2a and MFT2c (Table 3) and is present mainly as the previous facies association in the upper part of the Hanifa Formation (Ulayyah Member) with thickness ranges from several decimeters to 3 m. The beds of this lithofacies association are creamy to yellowish white in color, form massive beds and dominated by moderate to poorly sorted bioclastic wackestones, packstones and floatstones. The bioclastic grains are dominated by brachiopods, bivalve shells, gastropods, echinoids, foraminifers, dasyclad algae, stromatoporoids and sponge spicules. Non skeletal grains such as peloids are encountered in the most lithofacies types of this lithofacies association. The rocks are partly bioturbated and contain micrite clasts. The matrix is made up of peloidal micrtie and sometimes of organic matter. The diagenetic alterations of these back-shoal beds include micrtization of the most bioclasts, partly recrystallization in some bivalve shells, biomoldic, intergranular and microporosity in other shells. Some of intragranular pores are filled with calcite.

4.2.2.2. Interpretation. The studied lithofacies types indicate a shelf lagoon behind barrier under wave-base (El-Sabbagh et al., 2011). According to Nichols (2009) and Gertsch et al. (2010), the bioturbated molluscan shells refer to low rate of sedimentation, nutrient-rich waters and shallow lagoon under low energy. The prevalence of mud clasts and peloids suggest deposition in a back shoal with open circulation below the normal wave base in the subtidal carbonates (Flügel, 2010). The characteristics of the bioturbation in the lagoon facies refer to quiet water oxygenated placement in a protected shallow water marine "behind shoals" (Palma et al., 2007). The fine grained wackestones with clasts of packstone layers having variable amount of reworked benthic fossils point to inner platform under open sea conditions (Solak et al., 2015).

4.2.3. Shoal lithofacies association

4.2.3.1. Description. The shoal deposits (LFT3a-LFT3d) form a vertical stacked pack-to grainstones and subordinate boundstones. The thickness of the shoal environment varies from few decimeters to several meters in the upper part of the Hanifa Formation (Ulayyah Member). The shoal lithofacies association is dominated by yellowish white poor to moderately sorted argillaceous limestone with stromatoporoids, corals and other bioclastics and creamy to grey limestone with aggregate grains, ooids and peloids. The main skeletal grains in the shoal deposits are stromatoporoids, (*Cladocoropsis* sp.), and isolated build up colonial and solitary broken and fragmented scleractinian corals such as *Actinastrea* sp., *Coenastraea* sp., *Stylina* sp., *Cryptocoenia* sp., *Montlivaltia* sp., and *Vallimeandropsis* sp. Most of these scleractinians have massive, globular,

Table 3
Microfacies types recognized in the Hanifa Formation at the studied sections based on textural and/or compositional variations.

T	LFA	Texture and figures	Sedimentary structures & diagenesis	Grain size and Sorting	Main components	Thickness	Interpretation
1a	Tidal flat and shallow lagoon	Bioclastic pelodial wackestone (Fig. 3a, b, c)	Laminated, thick bedded, bird eyes, ferrugination, dolomitization, Aggrading neomorphism	Siltite to fine arenite, moderately sorted	Peloids, foraminfers (forams) such as such as *Nautiloculina* sp. and *Trocholina* sp., bivalves	Few dm to cm	Peloids combined with bird eyes and other components are common in a tidal flat to shallow lagoon setting (Sattler et al., 2005).
1b		Sandy bioclastic packstone (Fig. 3d)	Low angle lamination, miciritization, dissolved shells silicification	Arenite to rudite Moderately to poorly sorted.	Peloids, forams, bivalve shells.	dm	The co-existence of poorly sorted quartz grains indicates near coast mixed siliciclastic-carbonate shelf in the tidal flat t setting (García-Hidalgo et al., 2007)
2a	Lagoon and back shoal	Bioclastic wacke- to floatstone (Fig. 3e, f, g)	Thinly to medium bedded, burrows, microbial coating, blocky, drusy, and syntaxial overgrowth cement	Rudite, moderately to poorly sorted	Stromatoporid, algae, echinoids, gastropods and forams.	dm	The relatively low diversity and low abundance normal marine fauna, in the bioclast suggest the deposition was in a quiet water and back shoal environment (Palma et al., 2007)
2b		Molluscan peloidal wacke- to floatstone (Fig. 3h and Fig. 4a)	Massive, thick bedded, microprosity and biomoldic	Siltite to fine arenite, moderately sorted	Peloids, echniods, forams, bivalve shells, monoaxon sponge spicules, gastropods.	few dm	the presence of molluscan fragments (especially oysters and *Turritella* sp.) with micrite matrix is attributed to reworking behind shoals by storm waves and redeposition in the quiet lagoon water (Berndt, 2002)
2c		Bioclastic wacke- to packstone (Fig. 4b and c)	Thick bedded, intraparticle, and intragranular pores filled by sparry calcite	Lutite & arenite moderately sorted	peloids, forams such as *Quinqueloculina* spp. dasyclad algae & bivalves	Few dm to cm	The predominance of peloids correspond to tiny rounded micrite clasts and the faunal association suggest deposition in a back shoal with open circulation; below normal wave base.
3a	shoal	Aggregate grains grain- to rudstone (Fig. 4d)	Planer cross stratified, micritization, cementation	Medium arenite to rudite, moderately sorted	micirtized grains Forams, aggregates & intraclastics.	dm	Angular lumps indicate some transport and reworking. Strongly micritized coated skeletal grains associated with benthic foraminifera indicates open-marine parts of back-shoal to shoal settings (Tawfik et al., 2016)
3b		Bioclastic grainstone (Fig. 4e)	Planer and low angle cross lamination. Interparticle, micritization & moldic	Arenite to rudite, Moderately to well sorted	peloids, forams, bivalves, Stromatoporid such as *Cladcoropsis* & echinoids	dm to few dm	Fossil debris indicates seaward shoal to an open marine setting. Well sorted and missing bioturbation may indicate reworking in a low accommodation setting (Palermo et al., 2010)
3c		Ooidal peloidal rich pack- to grainstone (Fig. 4f and g)	Hummocky stratification, micritization, partly intragranular	Lutite to rudite moderately to well sorted	peloids, forams, Stromatoporid, *Cladcoropsis*ooids & bivalves	Few dm to cm	The presence of ooids and peloids correspond to rounded clasts and the faunal association suggest deposition in an open circulation shoal deposits (Koehrer et al., 2010)
3d		Coral framestone (Figs. 4 h, 5a, b)	massive colonies and solitaires miricritization, intragranular cement, degree of fragmentation	Rudite, moderately to well sorted	Corals, peloids, forams and echinoids	dm	Textural features, stratigraphic relationship and the reworked characteristics of the coral fragments suggest that this microfacies formed in a shoal setting under medium to high energy.
4a	Foreshoal	Bioturbated pack-/pack- to-grainstone (Fig. 5c)	Nodular apperence, micritization, interparticle, interparticle, moldic, and intraparticle porosities	Siltite to medium rudite, moderate to poorly sorted	Peloids, shells, forams such as *Kurnubia*, echinoids & Juvenile brachiopods.	cm - dm	Due to intensive bioturbation and a low to locally high-energy storm beds, deposited below storm wave base (SWB) at open marine foreshoal setting (Sena and John, 2013).
4b		Poorly sorted lithoclastic bio-rudstone (Fig. 5d)	Hummoky cross stratification, imbrication and amalgamated beds. Moldic porosity.	Medium arenite to rudite. Moderate to poorly sorted	Corals, agglutinated forams such as *Alveosepta*, ammonites, echinoids, lithoclastics	dm	Imbrications of intraclastic and other components indicate moderate energy at foreshoal setting (Bendias et al., 2013)
4c		Biostromal boundstone (Fig. 5e and f)	Homogeneous, lateral extension Recrystallization, silicification, biomoldic separate vug porosity	Arenite to rudite, poorly sorted	Corals, forams such as *Pseudocyclammina*, sponge, bivalves, echinoids	dm to few m	The facies which contains rich fauna seems to have a homogeneous lateral extension in a foreshoal setting.
5a	Offshoal	Burrowed skeletal wackestone (Fig. 5g)	Low angle lamination, parallel orientation bioturbation & partly calcified	Siltite, moderate to well sorted	burrows, sponges, coccolith, Dinocysts, ostracods, tetra axon sponge spicules, echinoid fragments	Few dm to meters	Parallel orientation of spicules indicating bottom currents and water energy was sufficient to orientate the spicules, but not to winnow the carbonate mud in offshoal setting (Suttner, 2012)
5b		Bioclastic floatstone (Fig. 5h)	Grading, thick layers, minor bioturbation	Medium arenite to rudite. Moderate to poorly sorted	bivalvian shells, crinoids, forams such as *Nodosaria* & *Lenticulina*.	Cm to several dm	Floatstones with coarse shell and crinoid debris possibly represent storm-reworked deposits in an offshoal setting (Koehrer et al., 2010).

nodular and hemispherical growth forms. Dasyclad aglae, foraminifers, bivalves, echinoids and gastropods such as *Cossmannea* sp., and *Eunerinea* sp. are also recorded. The non-skeletal grains are mainly represented by oolitic grains and their nucleuses are formed by micrite or microcrystalline sparry calcite. The size of these ooids ranges from 0.4 to 1.2 mm and have rounded to elongated shape. Micritized rounded to angular lumps aggregate grains and peloids are also determined. Most of corals are affected by strong recrystallization and some inter-granular pores are entirely occupied by calcite spar cement.

4.2.3.2. Interpretation. Oolitic and peloidal pack-to grainstones indicate shoal water environment in the inner to middle ramp or platform (Palma et al., 2007). The domed stromatoporoids suggest a high energy bank margin on the oceanward flanks (Hughes et al., 2009). The presence of fragmented and broken skeletal grains

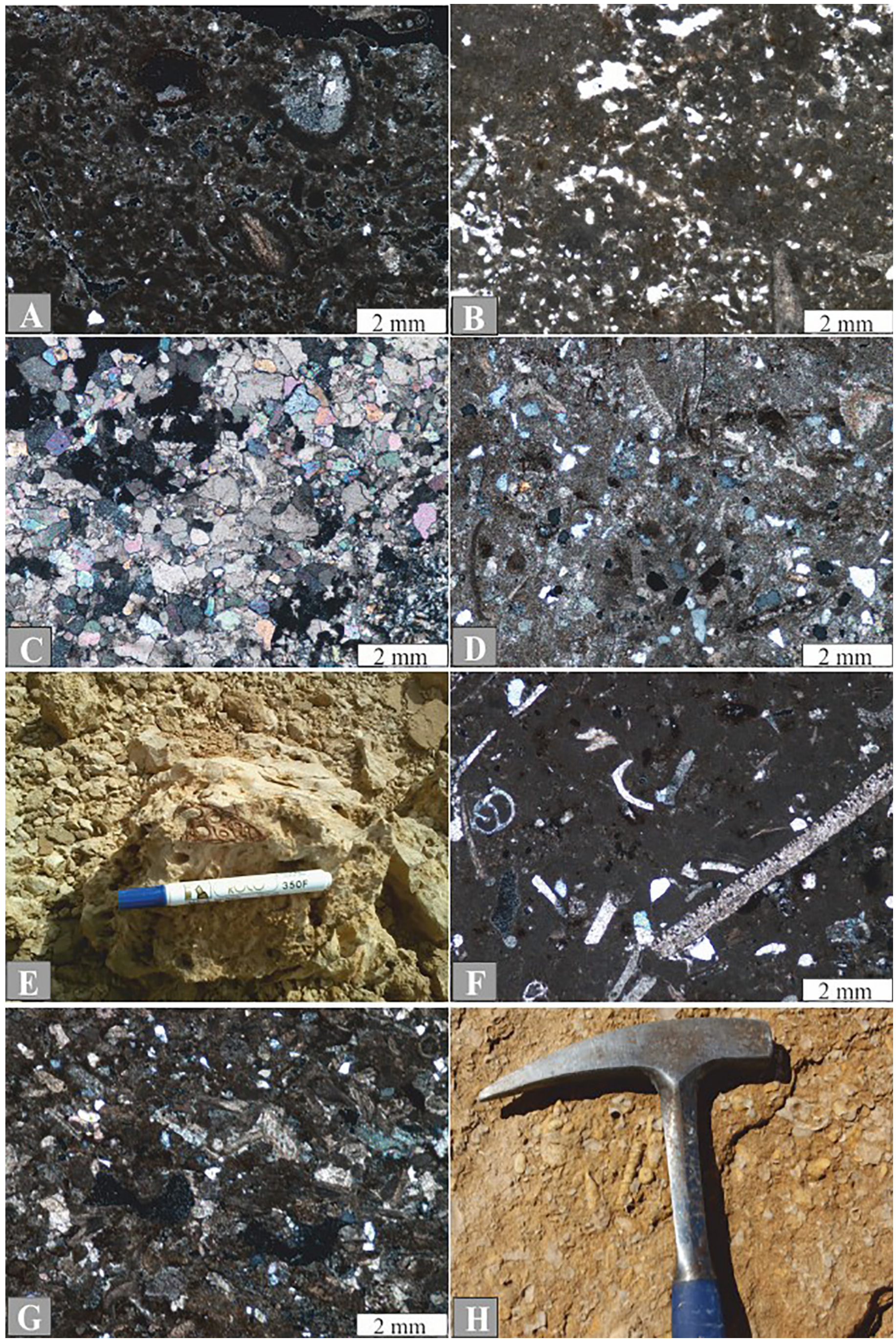

Fig. 3. Outcrop photographs and thin section photomicrographs: A. Bioclastic peloidal wackestone composed mainly of peloids, and benthic foraminifers B. Bird eyes and iron oxides traces in dolomitic wackestone. C. Microcrystalline dolomites (hypidiotopic texture) contain dark spots caused by tiny inclusions. D. Sandy bioclastic packstone contains sand grains, algae, echinoids embedded in micritic matrix. E. Bioclastic limestone contains gastropods and others. F. Echinoid spines, gastropods and others embedded in micritic matrix. G. Bioclstic sands form packstone texture of *Salpingoporella* sp., stromatoporid and peloids. H. Molluscan limestone contains gastropod species such as *Turritella* sp. and relics of oyster shells (All photos from Al Al-Abakkayn Mountain).

indicates current transportation and the absence of bioturbation may refer to reworking in a low accommodation (Palermo et al., 2010). The flourishing of corals in Oxfordian beds indicates suitable substrate, hydrodynamic energy and light intensity in the photic zone (Leinfelder, 2001; Dupraz and Strasser, 2002; Martin-Garin et al., 2012). According to El-Sorogy and Al-Kahtany (2015), the scleractinians were flourished in shallow waters epicontinental tropical Tethys and parallel to the palaeoshoreline. Radial ooids point to moderate energy conditions in open platform marginal or shoals (Flügel, 2010; Védrine et al., 2007). The shatter and destruction of some skeletal grains and poor sorting refer to shallow deposition, moderate turbulence near to patch reef setting (Palma et al., 2009). Angular lumps suggest some reworking and transportation and the micritization of the aggregates indicates an open marine shoal setting (Tawfik et al., 2016).

4.2.4. Foreshoal lithofacies association

4.2.4.1. Description. The foreshoal lithofacies association constitutes

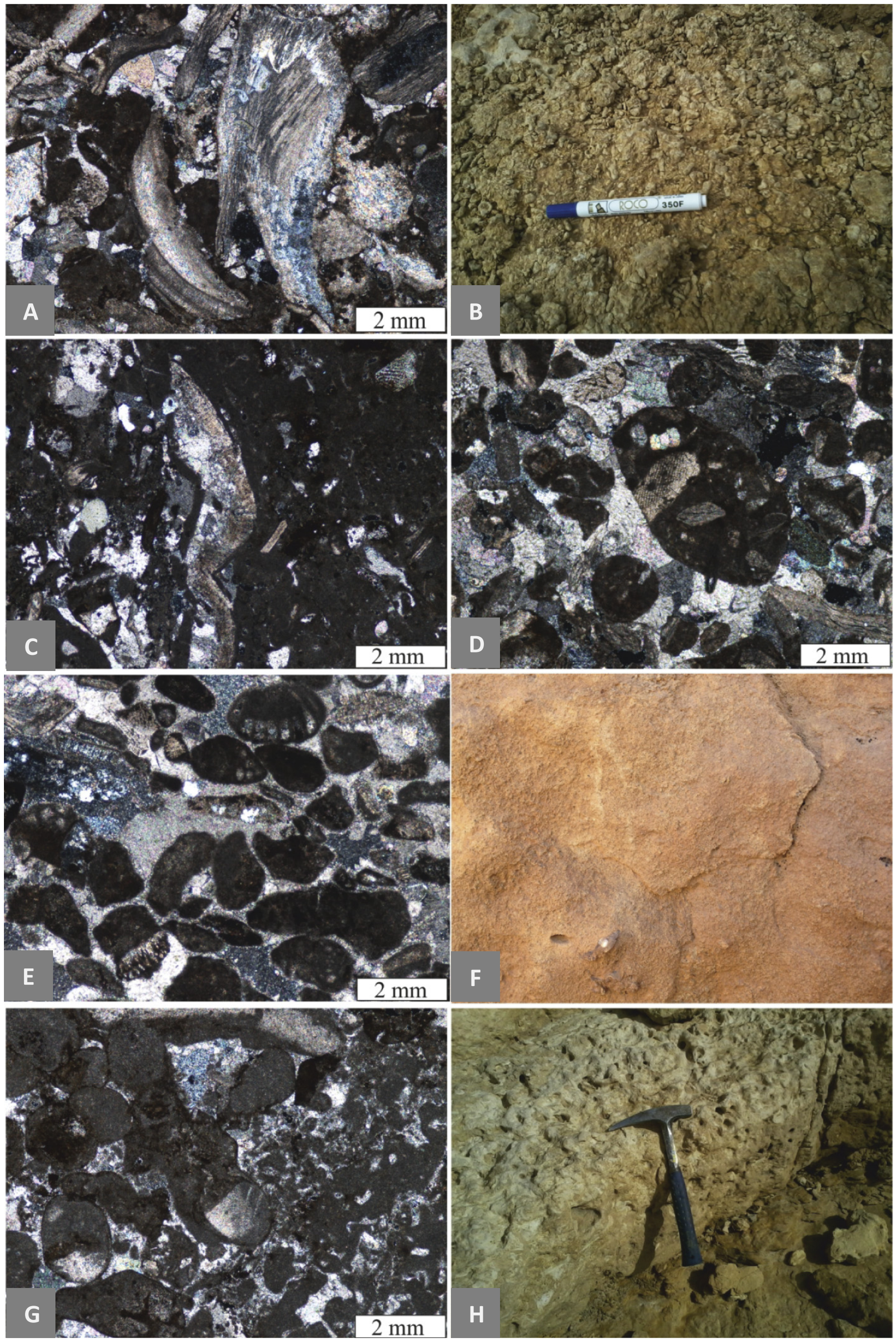

Fig. 4. Outcrop photographs and thin section photomicrographs: A. Molluscan peloidal floatstone composed mainly of oyster shells and peloids B. Bioclastic floatstone consists of relics of different fossils C. Bioclastic wacke-to packsotne with foraminiferal tests, bivalve shells, Echinoids and peloids. D. Aggregate grains grain to rudstone consists of ruditic lumps, peloids and micritised bioclastics E. Bioclastic grinstone contains different types of foraminifers, and other skeletal grains. F. Bioclastic peloidal pack-to grainstone consists of peloids and bioclastics. G. Ooidal peloidal rich pack-to grainstone consists mainly of micritised ooid and peloid grains H. coralline limestone consists mainly of colonial corals (All photos from Al Al-Abakkayn Mountain except 2a from Sadous Mountain).

the lower part of the Hanifa Formation (Hawtah Member) and consists of poorly sorted bioturbated bioclatic cross stratification pack-to grainstone and rudstone lithofacies types with intercalation of wackestone layers. Biostromal boundstones are also recorded. In the field, these beds are yellowish white to white, with nodular appearance of fossiliferous argillaceous limestone followed by yellowish white medium to thick and graded lithoclastic, intraclstic argillaceous limestone. The foreshoal facies is capped by grayish yellow bioclatic argillaceous limestone with intercalation of claystone layers contain ammonites. The thickness of the foreshoal beds varies from several decimeters to few meters. The main bioclastics are fragments of reworked corals, echinoids, foraminifers such as *Kurnubia* sp. and *Pseudocyclammina* sp., brachiopods such as *Zeilleria* sp., gastropods such as *Retusa* sp., cephalopods and bivalve shells. Non skeletal grains such as lithoclastics, imbrication intraclastics and peloids are encountered in the all lithofacies types. The carbonate lithoclastics are formed from penecontemporaneous erosion of older lithified limestone. The size of these lithoclasts ranges from fine to medium and the majority of these lithoclasts are subrounded to angular.

4.2.4.2. Interpretation. The frequency of grainstone–packstones with rudstone suggest a repetition of storm events (Aigner, 1985). The broken and fragmentation of some bioclasts and intraclasts refer to storm working and transportation from lagoon and shoal environments. The bioturbated pack/grainstones suggest high energy currents and oxygenated bottom conditions (Palma et al., 2007). According to Plint and Norris (1991), the packstone-grainstone lithofacies types with cross stratification indicate a storm-dominated setting above fair-weather wave base. Bendias et al. (2013) noticed that the imbrication of intraclastics refer to moderate energy at foreshoal environment. The origin of the intraclasts may reflect reworking by storm action. The poorly sorted lithoclast packstones, bioturbation, peloids and hummocky-cross stratification inidicate foreshoal environment (Koehrer et al., 2010). The similarity in size of skeletal grains of this environment and shoal lithofacies association refer to an open circulation of fully marine waters close to shoal environment.

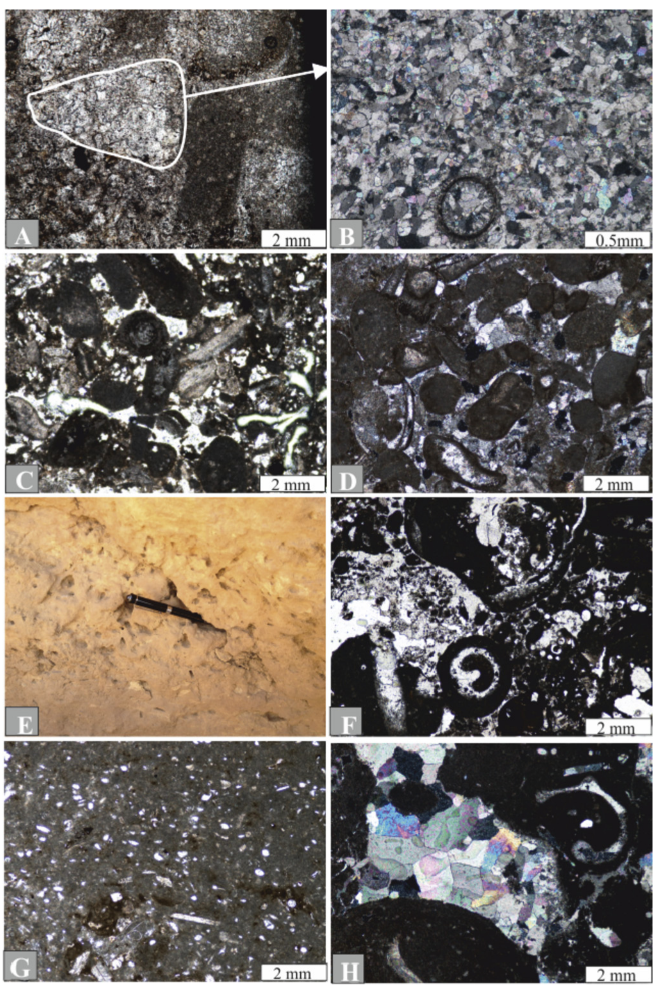

Fig. 5. Outcrop photographs and thin section photomicrographs: A. Coralline framestone forms a rigid framework B. Close up view of the neomorphised coral skeletons C. Bioturbated pack-/pack-to- grainstone consists mainly of micritised bioclastic grains and peloids D. Abundant poorly sorted lithoclastics embedded in sparry calcite cement E. Bistromal boundstone consists of different fossils. F. Bioclastic boundatone consists mainly of corals, bivalve shells and other bioclastics G. Burrowed skeletal wackestone, with *Bositra* sp., Dinocyst and others H. Bioclastic floatstone consists of bioclastic fragments in the mud matrix (All photos from Al Al-Abakkayn Mountain except 3f from Maashabah Mountain).

4.2.5. Offshoal lithofacies association

4.2.5.1. Description. This lithofacies association is just several decimeters to few meters thick in the lower part of the Hanifa Formation (Hawtah Member) and represents the deepest environment in the studied section. It is composed of beige to yellowish white, moderately to poorly sorted, fossiliferous limestone with occasional clay layers. Burrows are recorded and the bioturbation is locally present in the bioclastic floatstone lithofacies type. The offshoal beds contain low diversity skeletal debris of foraminifers (*Nodosaria* sp. and *Lenticulina* sp.), bivalves (*Bositra* sp.), brachiopods, abundance of coccoliths such as *Cyclagelosphaera, Ellipsagelosphaera,* parallel orientation of sponge spicules and echinoids.

4.2.5.2. Interpretation. Burrowed and local bioturbation skeletal wackestones suggest low energy open-marine deposits of offshoal setting (Koehrer et al., 2010). According to Taylor and Goldring (1993) the diverse burrows indicates marine open shelf. The skeletal debris indicate low sedimentation rates and reduced circulation. The lack of detrital grains and the existence of micrite indicate a low energy environment below storm wave base.

5. Sequence stratigraphy

The Hanifa, Jubaila, Arab and Heith formations represent the upper Jurassic rocks of the Arabian Peninsula (Table 1). According to Haq and Al-Qahtani (2005), during the upper Jurassic, the global sea-level curve matches the Arabian plate sea level curve due to the stability in the tectonic movements during this period. In our work, integrating the microfacies types, and the stacking patterns of the lithofacies associations, and the surface boundaries allow to identify two major depositional sequences (labelled 1 and 2) in the Hanifa studied section in Al-Abakkayn Mountain (Fig. 7). These sequences are of Oxfordian age based on field and laboratory examinations. The studied sequences and their boundaries are illustrated below in a stratigraphic order:

5.1. Sequence 1

5.1.1. Description

Sequence 1, 35–55 m, represents the lower deposits of the Hanifa Formation (equivalent to Hawath Member), in the studied outcrops. The base of the Hanifa Formation exhibits the hiatus between the underlying light colored, ferruginous and dolomitic wackestones of Callovian Tuwaiq Mountain Limestone and overlying dark colors shale and marly beds of Oxfordian Hanifa Formation. The general lithology of this sequence is yellowish red fossiliferous limestone, marly limestone, argillaceous limestone, and shales with bioturbation and burrows in some layers. The sequence seems to consist of stacked asymmetrical three resemble foreshoal to offshoal cycle sets (4th order cycles). Each of sequence 1 cycle sets (Figs. 7 and 8) is about 8–15 m thick and consists of packstones, grainstones and boundstones. The lower part of these resemble cycle sets (3–5 m) consist of yellow and grey with

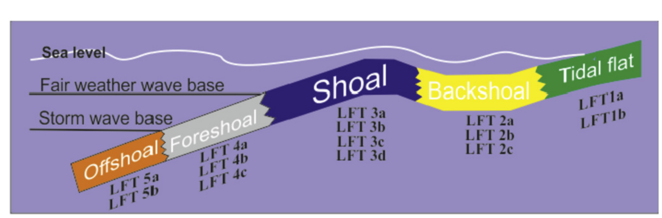

Fig. 6. Depositional model of the Hanifa Formation lithofacies association from tidal flat to offshoal in the Al-Abakkayn Mountain.

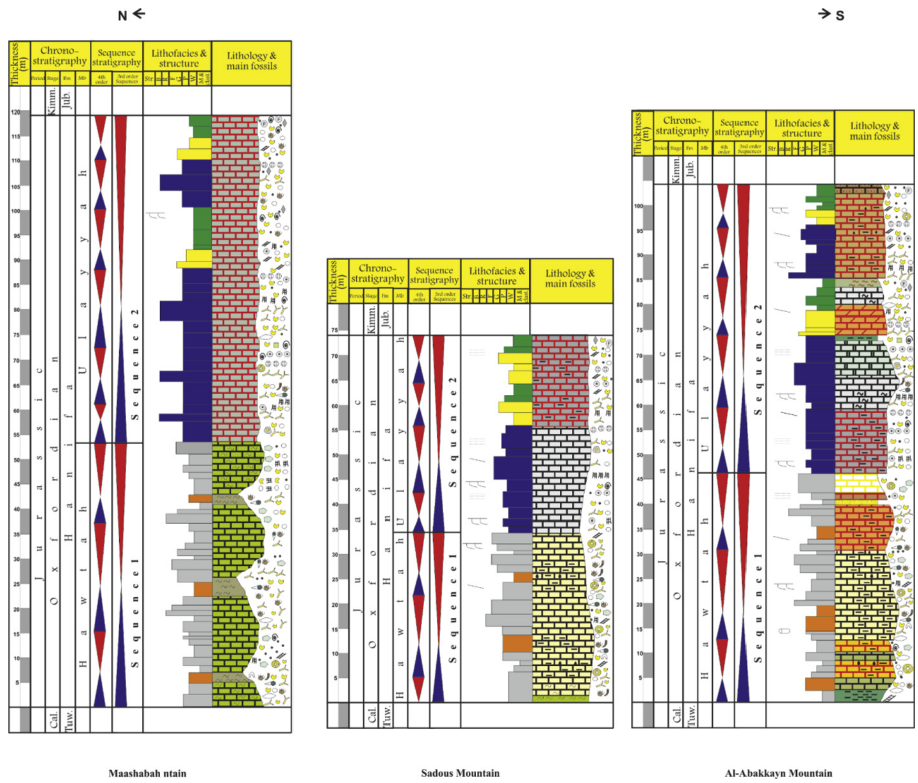

Fig. 7. Texture, facies and interpreted medium- and large scale cycles of the Oxfordian Hanifa Formation studied sections.

nodular appearance and bioturbated pack-to grainstone and poorly sorted biogenic biostromal boundstone with rich fauna such as echinoids, corals, foraminifers (*Kurbubia* sp.), brachiopods (*Zeilleria* sp.), gastropods (*Retusa* sp.), bivalve shells and cephalopods. The biostromal beds can be easily distinguished in the field by big molds and moldic porosity. Intergranular and intragranular porosities are also recognized in the bioclastics of these beds. The packstones and grainstones are overlain by thin to thick, graded, poorly sorted, fossiliferous wacke-to floatstones with intercalation of claystone layers. Brachiopods, coccolith, sponge spicules, echinoids, bivalves (*Bositra* sp.) and foraminifers (*Nodosaria* sp. and *Lenticulina* sp.) are recorded in wackestones and floatstones. Burrows are also recorded in the most cycle sets and the diversity of skeletal grains is low. Poorly sorted lithoclastic bio-rudstone built the upper part of each cycle set (5–9 m), and contains lithoclasts with subrounded to angular shape and siltite to lutite size, flat pebbles, intraclasts and some skeletal debris such as ostracods, bivalve shells and echinoids. The upper most part of these cycle sets is a weathered yellowish white grainstone hardground (0.5–0.75 cm) with peloids and shell hash in some cycle set.

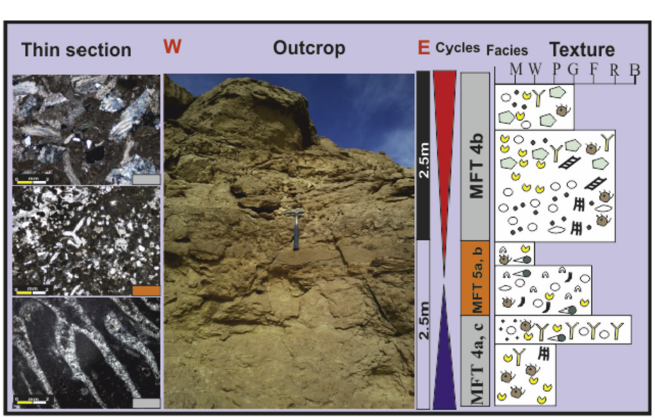

Fig. 8. Foreshoal to offshoal cycle set.

5.1.2. Interpretation

Packstones, grainstones and boundstones at the lower part of each cylceset indicate fully open marine conditions of moderately water energy foreshoal lithofacies association and represent the transgressive system tract (TST) of each 4th order cycles. During the subsequent sea level rise, mudstones and skeletal floatstones indicate a maximum relative water depth of low energy offshoal depositional environment and are interpreted as a maximum flooding zone (MFZ). The thickest MFZ is recorded in the second cycleset of sequence 1, so it represents the MFZ of cycleset 2 and the MFZ of the sequence 1 (Fig. 7). This MFZ is equivalent to MFS J50 of Sharland et al. (2001). Following to the MFZ, the foreshoal lithoclastic and bioclastic rudstones at the upper part of each cycle set prograde on the offshoal deposits and represent the highstand system tract (HST). The grainstone hardground at the top of each cycleset as well as the top of this sequence refers to subaerial exposure and represents a fourth-order sequence boundary between the cycle sets and a third-order sequence boundary between sequence 1 and sequence 2.

5.2. Sequence 2

5.2.1. Description

Sequence 2 is 37–67 m thick at the studied sections (Fig. 7) and represents the upper part of the Hanifa Formation (Ulayyah Member). The sequence exhibits shallower conditions and less species diversity than the previous one. Sequence 2 is stacked to 4–6 backshoal cycle sets (Figs. 9 and 10). The lower part of the shoal cycle set (4–6 m) starts with yellowish gray to gray, low angle lamination fossiliferous argillaceous grainstones with branched and domed stromatoporoids, echinoids, bivalves and gastropods. Above stromatoporoids beds, yellowish white to white, massive, isolated buildup of silicified scleractinian corals, echinoids and foraminifers. The thicker upper part of this cycle set is composed of gray to yellowish white ooidal peloidal pack-to grainstones and the upper most part is a hardground of aggregate grains grainstone. The other cycle set in this sequence is a backshoal cycle set, whose lower part (Fig. 10) consists of thinly to medium bedded, massive and few times thick bedded white to yellow poorly to moderately sorted bioclastic wackestones and floatstones with interclation of packstones. These bioclasts contain bivalve shells such as *Gryphaea* sp., dasyclad algae, brachiopods such as *Tubithyris* sp., gastropods such as *Procerithium* sp., foraminifers, echinoids and relics of stromatoporoids and sponges. Peloids and sand grains are recorded as non-skeletal grains in the wackestones and packstones. While the upper part of the backshoal cycle set consists mainly of white to gray, moderately sorted dolo-wackestones and packstones with peloids, sand grains, foraminifers such as *Nautiloculina* sp., miliolids and bivalve shells. The top of this cycle set is grayish yellow to red hardground of an argillaceous ferruginous wacke-to mudstones (30–50 cm) with dolomitization and aggrading neomorphism diagenetic features, sometimes oyster shells (Fig. 11) and represents the sharp contact between the Hanifa Formation and overlain Jubilia Formation. The thickest shoal cycle set in this sequence is the cycle set number 2 (Fig. 7).

5.2.2. Interpretation

Stromatoporoids beds in the lower part of the shoal cycle set are interpreted as moderate energy shoal deposits and represents the TST of this cycle set. The deepening-upward trend is accompanied to an increase of skeletal debris especially corals and water energy which represents the maximum flooding zone. The fall in the sea level is associated with the change from skeletal to oolitic and peloidal grains and is marked the highstand system tract of this cycle set. Aggregate grains hardground at the top of this cycle set represent a maximum regression and is interpreted as the cycle set boundary. The other cycle set "back shoal cycle set" recorded mainly in the highstand system tract of the sequence 2 and the lower part of this cycle set indicates backshoal deposits and represents the TST of the backshoal cycle set. The upper part of this cycle set refers to low energy and more restricted conditions of tidal flat and shallow lagoon lithofacies association and is interpreted as HST. The top of the HST is marked by hardground wacke-to mudstone and represents shallower and calm sedimentation conditions. The thickest shoal cycle set (cycle set 3) represents the maximum flooding zone of this sequence, which overlain the transgressive system tract and underlain the highstand system tract and symmetric with the MFS J60 of Sharland et al. (2001) (Fig. 7). The upper-most part of the HST of sequence 2 is represented by hardground gray to grayish yellow argillaceous vuggy limestone and marked the sequence boundary between the Upper Hanifa Formation and the light brown and weathered limestone of the Jubalia Formation.

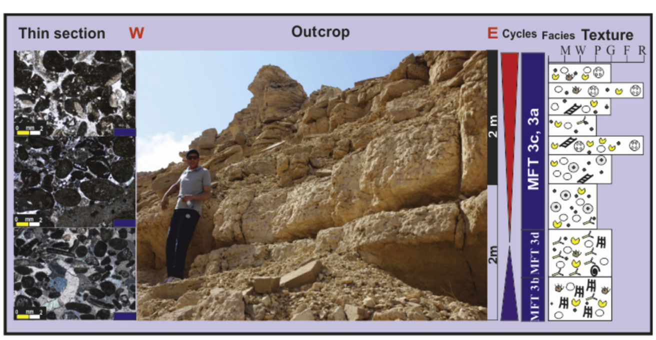

Fig. 9. Shoal cycle set.

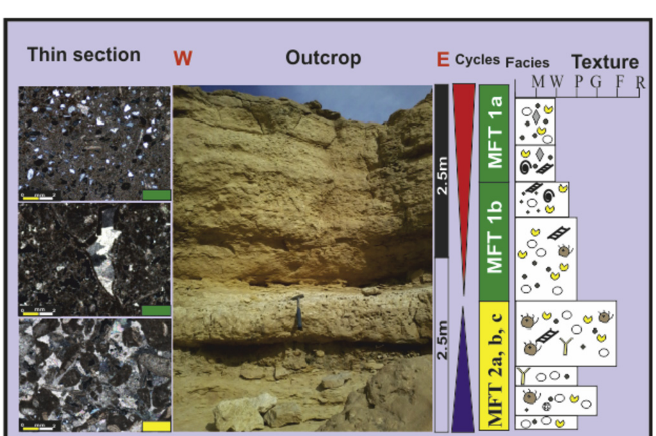

Fig. 10. Backshoal cycle set.

6. Sequence stratigraphy correlations and discussion

According to Coe (2003), the depositional sequences have been formed due to global sea level variations or tectonic activities. As we can see in (Fig. 11), the correlation between the studied sections does not abrupt facies variations, changes in features and thickness of the sequences neither any volcanic activates, so the main role of creating these sequences is the relative sea level change. Based on microfacies and facies associations, the sequence boundaries are

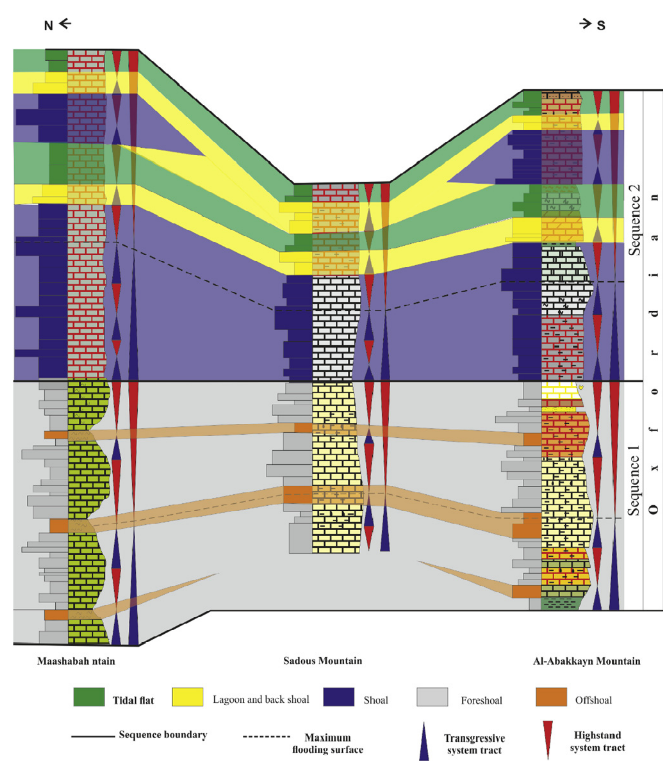

Fig. 11. Oxfordian studied sections lithofacies associations within chronostratigraphic cycles framework correlation.

identified in the grainstone beds in the first sequence and on wackestone, packstone and grainstone beds in the other sequence. The studied sequence boundaries in the examined sections have been identified as gradational and nonerosional and consider as sequence boundary 2 type. In the studied outcrops, the first sequence boundary has been detected between the Callovian Tuwaiq Mountain Limestone and the Oxfordian Hanifa Formation and Al-Husseini (2015), dated this sequence boundary to 163.5 ± 1.0 Ma, and accordant to the beginning age of SB 11 of Arabian Orbitons. This boundary is also represented by SB 11 of AROS 2008 (Al-Husseini and Matthews, 2006, 2008). The second sequence boundary has been identified on the grianstone bed between the studied two sequences and may be matched with SB Ox6 of eustatic sea level change of Snedden and Liu (2011) and the SB 11.2 of AROS 2008 (Al-Husseini and Matthews, 2006, 2008). The last sequence boundary in the studied sections has been determined on the dolomitized ferruginous limestone layer on the top of sequence 2 which characterizes the contact between the Oxfordian and Kimmeridgian beds. This sequence boundary is harmonic with the SB 11.3 of AROS 2008 (Al-Husseini and Matthews, 2006, 2008) and may be related to the tectonoeustatic event of rifting associated with the formation of Indian Ocean and the initial breakup of Gondwanaland (Hughes, 2008; Gibbons et al., 2013). The maximum flooding zones (MFZ) are located within offshoal marly or marly limestone beds in the sequence 1, while located within shoal limestone beds in the sequence 2. From the studied correlations, the sequence boundaries of the third order sequences are used as time lines and traced from north (landward) to south (sea ward). In general most of sequences exhibit the same facies along the same timeline. Sequence 1 in the studied sections represent foreshoal facies association in the TST and HST separated by MFZ of offshoal facies association (dashed line, Fig. 11), while sequence 2 represent shoal facies association in the TST and MFZ and backshoal and tidal flat facies association in the HST system tract in the upper part of the Hanifa Formation. The studied sections may also represent a shallower conditions to the north and the last cycles of the sequence 2 show more proximal facies types.

7. Conclusions

The Oxfordian sediments of the Hanifa Formation were deposited on an open shelf platform and consist mainly of carbonate rocks and minor clastic rocks. 14 microfacies types have been identified in the Al-Abakkayn, Sadous and Maashabah mountains based on lithology, rock color, sorting, thickness, skeletal and nonskeletal grains, bedding style, diagenesis and sedimentary features. These microfacies types were classified into 5 lithofacies associations ranging from tidal flat to offshoal deposits. Lithofacies types are stacked into two third-order sequences. Each sequence can be subdivided into a transgressive system tract (TST) and a highstand system tract (HST) separated by a maximum flooding zone between them. The sequence 1 is characterized by repeated 3 cycle sets (4th order sequence) of foreshoal cycle sets. The lower part represents a TST of the cycle set and it is dominated by foreshoal deposits of pack-to grainstones and biostromal boundstones. The MFZ is interpreted within the wackestones and floatstones offshoal deposits with coccolith, sponge spicules and echinoid fragments. The foreshoal lithoclastic biorudstone beds at the upper part of each cycle set prograde on the offshoal deposits and represent the HST. The weathered hardground grainstone with peloids and shell hash represents the sequence boundary between the studied cycle sets and the two sequences. The thickest MFZ in the sequence 1 is located on the second cycle sets and separates between the TST of sequence 1 in the lower part and the HST in the middle and the upper part. The second sequence is dominated by five shoal and backshoal cycle sets. The lower part of the shoal cycle set, mainly composed of bioclastic stromatoporoid grainstone, is interpreted as the initial transgression within this cycle set. During the sea level rise, bioclasts and coral beds retrograde over the grainstone beds and is interpreted as MFZ. Ooidal, peloidal and aggregate grain beds in the upper part of this cycle set, indicate shift towards shallower conditions and therefore, interpreted as HST. The other cycle set in this sequence “backshoal cycle set” is dominated by wackestones with dasyclad algae, relics of stromatoporoids, gastropods and foraminifers and is interpreted as TST. During sea level fall, the upper part of the backshoal cycle set records a shift from backshoal and open marine lagoon environment towards the tidal flat and restricted lagoon setting and represents the HST. As the previous sequence, the thickest shoal 4th order sequence clarifies the MFZ of the second sequence, which is overlain by the HST and underlain the HST. The upper-most part of the Hanifa Formation is described by hardground argillaceous vuggy limestone and well-marked the sequence boundary between the Upper Hanifa Formation and the overlain Jubaila Formation. The Oxfordian sediments are likely controlled by eustasy rather than tectonics and the studied sea level curve is partly matched to the universal sea level curve of Snedden and Liu (2011).

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