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Facies Associations and Sequence Stratigraphy of the Toarcian Marrat Formation (Saudi Arabia) and Their Equivalents in Some Gondwanaland Regions

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ABSTRACT: The Toarcian Marrat Formation is exposed in outcrops in central Saudi Arabia and displays a variety of clastic and carbonate facies associated with well-preserved depositional geometries. It is unconformably overlies the Triassic Minjur Formation and it in turn is overlaid by the Middle Jurassic Dhruma Formation. Thirteen lithofacies types can be identified that permit the recognition of five lithofacies associations in a mixed clastic/ carbonate platform. These lithofacies range from low-energy peritidal, intertidal, and back-shoal to moderate- and high-energy shoal and foreshoal lithofacies associations. The Marrat Formation exhibits three depositional sequences, each sequence is grouped into a transgressive systems tract (TST) and a highstand systems tract (HST) and then bounded by sequence boundary surfaces (SBSs). The TSTs are generally identified in clastic tidal-flat beds and back-shoal wackestones, while the HST is generally recorded in the carbonate tidal-flat and shoal. The vertical succession of facies associations from peritidal to foreshoal depositional environments is indicative of a deepening upward and retrogradational systems tract, from Lower to Upper Toarcian. The correlation between the studied sections reveals a general shallowing towards the south and the similarities between the studied sequences and others in the Arabian Gulf, the northern Neo-Tethys Plate, and Gondwanaland countries.

KEY WORDS: stratigraphy, sequence stratigraphy, Lower Jurassic, Marrat Formation, Saudi Arabia, Neo-Tethys, Arabian Gulf, Gondwanaland.

0 INTRODUCTION

The Lower Jurassic Marrat Formation in Saudi Arabia was deposited on a stable shallow marine shelf as shown by several studies in the Arabian Gulf (Ehrenberg et al., 2007). Those sedimentary deposits were associated to a transgressive trend (Alsharhan and Magara, 1994). According to Tang et al. (2011) the Early Jurassic Marrat carbonate has emerged as an increasingly important exploration target in the area between Saudi Arabia and Kuwait. Outcrops of the Marrat in central Saudi Arabia contain an abundance of clastic rocks and a minor amount of limestone. In the subsurface, the Marrat occurs in the eastern part of Saudi Arabia and consists mainly of shale (Alsharhan and Nairn, 2003). Most researchers pay little attention to the Marrat Formation, so few studies have been carried out in the past although some are underway to understand the regional settings and sequence stratigraphy of the Lower Jurassic deposits in the Arab Gulf countries. Early works stating this formation mostly focused on the analysis of the litho- and biostratigraphy in the studied area. A more detailed description and analysis of the studied formation has been reported by (Al-Mojel et al., 2018; El-Sorogy et al., 2018, 2017, 2014; Hughes et al., 2008; Al-Husseini and Matthews, 2005) which determined its paleontological content and the regional distribution of the Marrat Formation.

The regional correlation of the Toarcian rocks is difficult due to the limited availability of the sequence stratigraphic data in this stage, but this paper tries to provide insights of the controlling factor on the sea level change and/or tectonics in Saudi Arabia and some neighboring, Neo-Tethys and Gondwanaland countries in the Lower Jurassic. Therefore, the aims of this paper are: (1) to determine lithofacies associations and depositional environments in the studied sections exposed along the west side of Riyadh City (Fig. 1) based on analysis of the depositional geometries, the lithofacies types distributions and biogenic components, (2) to refine the sequence stratigraphic interpretation by detailed sedimentological investigations, and (3) to place this work in a more regional context to establish similarities and differences with existing sequence stratigraphic subdivisions.

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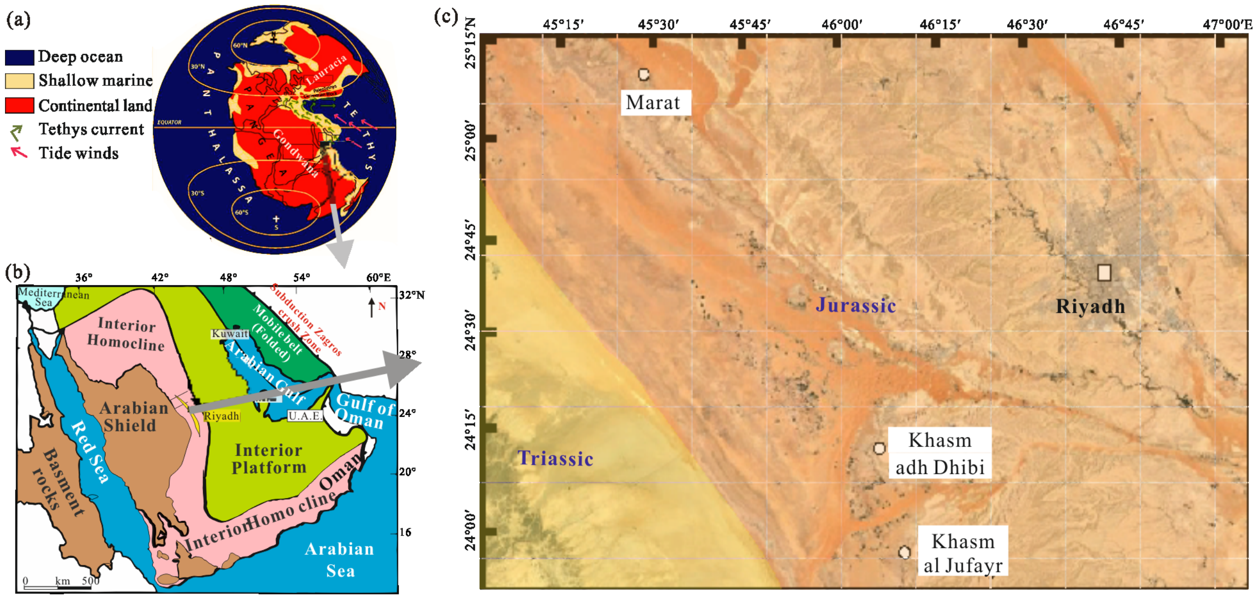

Figure 1. (a) Paleogeographic configuration during the Lower Jurassic, just before the breakup of Pangaea (modified from Sorkhabi, 2010), with the Arabian Plate position enclosed in the blue square. (b) General location map of Saudi Arabia, indicating the studied area (modified from Alsharhan and Nairn, 2003). Note the location of the studied section south-west of the capital Riyadh. (c) Geological map for the studied sections.

1 REGIONAL TECTONIC SETTING

During the Jurassic Period, the Arabian Platform formed part of Gondwanaland and occupied the northern part of the Arabian Continent. The open-sea domain covered the area of the present Arabian Gulf (Dercourt et al., 1993). Although the Marrat Formation was deposited in the Arabian graben system (Hancock et al., 1984), the impact of tectonic activities upon the Marrat rocks was moderate as study area was located tectonically, on a stable shelf. Abdula et al. (2015) reported that during the Lower Jurassic, sedimentary successions were deposited in shallow water settings and the major changes in the sedimentological facies were due to changes in sea level. Near the end of the Late Toarcian, an increasingly damp climate prevailed that prevented further deposition of evaporates. Simultaneously, the transgression led to the opening and the overall connection of previous isolated basins (Jassim and Buday, 2006). According to Beydoun (1991) the Arabian-Gondwana/Iranian-Laurasia supercontinent was broken up in the Permian and ultimately rifted along the Zagros line to create the Neo-Tethys Sea (the eastern margin of the Arabian Plate) by the Early Triassic. During the Jurassic, the Arabian Plate was comparatively tectonically stable and its position near to the equator was responsible for the development of a shallow-water shelf on the western passive margin of the Neo-Tethys. Moshrif (1987) stated that during the Toarcian (Lower Jurassic), the arcuate shoreline which is bounded by pre-Jurassic sediments, was formed by the stretching of the Tethys Sea towards Arabia. Most regions of the Arabian Plate were submerged, as illustrated by the occurrence of shallow-water marine deposits, such as lagoon sediments, in central and eastern parts of Saudi Arabia, Oman, southern parts of Yemen, Jordan, Sinai, northern part of Syria, Lebanon, and central and eastern Iraq and Iran. Fischer et al. (2001) suggested that the Marrat sequences are regressive corresponding to a rapid subsidence at the base followed by a slow aggradation.

2 STRATIGRAPHY AND AGE

The Jurassic succession in Saudi Arabia is well exposed in the central part of the Saudi Arabia especially in the Riyadh-Dhruma area. This succession is known as Shaqra Group, with a total thickness of more than 1 100 m. The Shaqra Group consists of seven formations, of which the Marrat Formation represents the basal one (Fig. 2). The Marrat Formation was first described by Powers et al. (1966) as a lower part of the Tuwaiq Mountain Formation. Successively, it was formally named the “Marrat Formation” by Powers et al. (1966) and consists of shallow marine facies developed in a basin near the Riyadh-Dhruma region. Eventually, the detailed lithological description of the Marrat Formation in Saudi Arabia was given by Powers et al. (1966). These authors subdivided the Marrat Formation into three informal members: the Lower, Middle, and Upper. The Lower Member consists mainly of dolomitized medium-crystalline and argillaceous limestone followed by multicolored sandstone, siltstone, and shale. The top of this member is characterized by medium- to coarse-grained, calcareous sandstone. The Middle Member contains clastic rocks, particularly cross-bedded and calcareous sandstone ended with thin bands of sandy limestone. The Upper Member comprises limestone rocks and the top of the formation is formed by argillaceous limestone. The disconformable contact of the Lower Jurassic Marrat with the underlying Triassic Minjur Formation is located between the cream-to-brown ferruginous and cross-bedded sandstone of the Minjur Formation and the brownish-green shale of the Marrat Formation, while the contact with the overlying Dhruma Formation is identified on the massive gypsiferous claystone at the top of the Marrat, as discussed later. Previous biostratigraphic analysis in this formation suggested a Toarcian age, depending upon the study of ammonites include (Im-

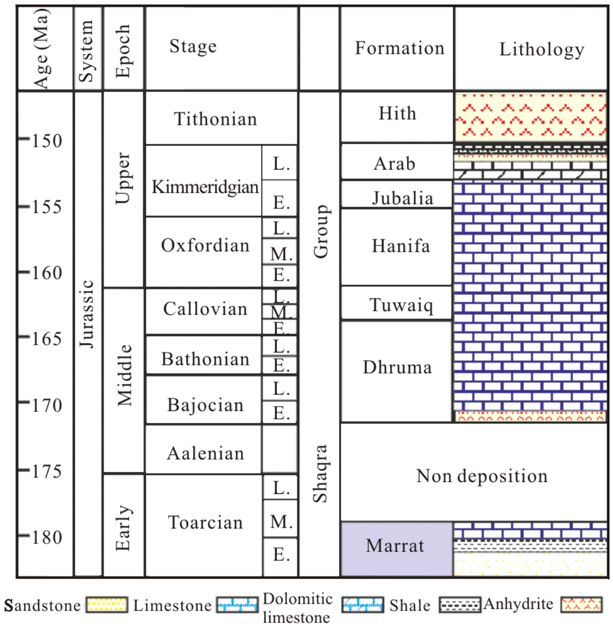

Figure 2. Shaqra Group of the Jurassic, Saudi Arabia (modified from Tawfik et al., 2016).

lay and Jones, 1970; Enay et al., 1967; Steineke et al., 1958; Arkell et al., 1952). These authors considered that the Lower Member of the Marrat Formation belongs to the Early Toarcian Serpentinum zone, while the Upper Member of the Marrat Formation assigns to the Middle Toarcian (Bifrons zone). Most subsequent biostratigraphic analysis and further work confirmed the Toarcian Age for the Marrat Formation (e.g., Enay and Mangold, 1994; Cooper, 1989; Enay et al., 1987) based on brachiopods and mollusks fauna.

3 MATERIALS AND METHODS

A detailed description of the stratigraphic sections of the Marat, Khashm adh Dhibi, and Khashm al Jufayr mountains in central Saudi Arabia includes the definition of texture, biota, grain-type and size, sorting, bedding style, sedimentary features of the rocks, and the appearance according to a lithofacies code. Two hundred and thirty-two representative samples were collected from a selection of 71 thin sections, were examined under a polarizing microscope. The integration of sedimentological and petrographic data such as lithology, paleontology, facies characterization, and sedimentary facies distribution, is aimed to define the sequence stratigraphy evolutions of the Marrat Formation. The nomenclature of carbonate rocks follows the classification of Dunham (1962), modified by Embry and Klovan (1971) while the clastic description is based on Pettijohn et al. (1987). Facies and their types were mainly analyzed based on Flügel (2010).

4 RESULTS

4.1 Lithofacies Description and Association (Figs. 3, 4, 5)

In our study, we identified thirteen lithofacies types based on field mapping, fossils, and petrographic analysis of the Marrat Formation in the study areas (Table S1). Based on sedimentological and paleoenvironmental analysis, five marine lithofacies associations (LFA) can be recognized (Table S1) from the shallowest to deepest facies: siliciclastic facies (peritidal flat and beach) and carbonate facies (ranging from tidal flat, backshoal, shoal, and shallow open-marine foreshoal settings).

4.2 Depositional Environment

The Marrat Formation in general is characterized by marine sedimentation in a tidal flat to foreshoal distal shelf setting (Fig. 6). The main evidence for the shelf deposits is the development of siliciclastic and carbonate deposits. Reworked fossils, sedimentary structures, and non-biogenic components point to a platform setting. Beach deposits have been interpreted from the presence of cross-bedded sandstone beds with no indication as to the non-marine origin of sandy conglomerates and plant remains of channel deposits or braided fluvial system. The rare and fragmented of fossils may indicate high storms and currents during the deposition of these clastic rocks. In the studied area, the beach sediments are followed upward by tidal flat sediments which are distinguished by multicolored shale with rare fossils, dark green sands, and dolostone beds. The scarcity of fauna may be related to the abundance of iron oxides, which may have poisoned the water during deposition (Al-Saad and Hewaidy, 1999); the gradual darkening of green sand grains implies increasing ferrous content (Udgata, 2007). The backshoal and lagoonal facies are dominated by gymnocodiacean algae, benthic foraminifers, stromatoporoids, and echinoid spines. These associated bioclasts flourish in a low-energy shallow-water setting with low to moderate circulation. The shoal lithofacies association has been defined by scleractinian coral boundstones and bioclastic grainstones dominated by reworked coral fragments. A foreshoal environment has been deduced as being the deepest environment in the Marrat Formation, which is characterized by graded packstone to grainstone, lithoclastic rudstone, and bioclastic wacke- to floatstone. These lithofacies types are characterized by graded bedding, bioturbation, lithified sediments, planktonic foraminifers, and radiolarians.

4.3 Depositional Sequence Analysis

The studied localities were selected for the sequence interpretation, based upon the superb quality of the exposure. The lithofacies associations show general transgressive-regressive 4th order cycles (Embry and Johannessen, 1993) "see below", and they are stacked into facies sequences of multiple hierarchies. Sedimentary texture, grain-size, and bio-components represent the main vertical changes in the studied successions. Each sequence consists of a transgressive part in the lower portion and a regressive part in the upper portion. The transgressive and regressive parts are separated by maximum flooding surfaces (MFSs) (Cross and Lessenger, 1995). In this work, because of lacking planktonic foraminifers which the shallower environments and clastic rocks are prevailed, the sequence boundaries have been identified on the differentiation between accommodation and sediment supply (Angela et al., 2003), erosional surfaces, and changes in stacking pattern and the position of system tracts. Three third-order transgressive/regressive sequences bounded by four sequence boundaries are recognized in the studied successions (Fig. 7), which evolve from base to the top.

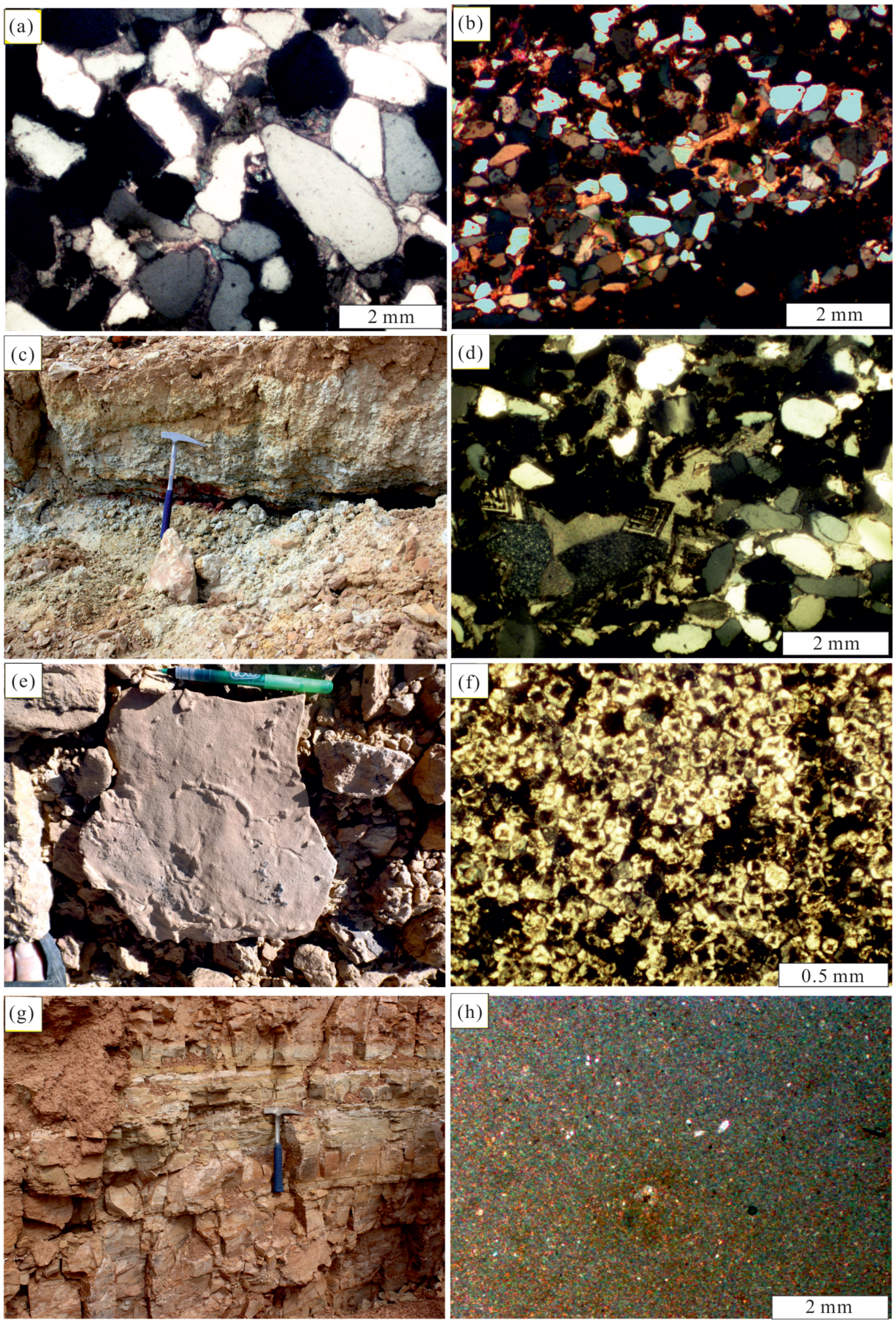

Figure 3. (a) Thin-section photograph of quartz arenite facies with calcite cement, Khashm al Jufayr Section; (b) thin-section photograph of ferruginous cement (red color) between quartz grains, Khashm al Jufayr Section; (c) varicolored shale layer with sand intercalations, Khashm adh Dhibi Section; (d) thin-section photograph of dolomitic quartz arenite dominated by glauconites, and cemented by iron oxides and dolomite, Khashm al Jufayr Section; (e) trace fossils of *Thalassinoides* in the sandstone beds, Marat Section; (f) thin-section photograph of euhedral to subhedral dolomite grains with cloudy centers cemented by iron oxides, Marat Section; (g) argillaceous limestone beds intercalated with shale layers, Khashm adh Dhibi Section; (h) thin-section photograph of sandy mudstone with few skeletal grains, Khashm adh Dhibi Section.

4.3.1 Sequence TO1, Lower Toarcian

Description: Sequence TO1 is 34–40 m thick and supports the interpretation of a tidal flat and backshoal deposition of the Lower Marrat Formation. The base of this sequence in all the studied sections is the boundary between the Upper Triassic sandstone Minjur Formation and the Lower Jurassic carbonate Marrat Formation (Fig. 8a). This boundary is well defined in all Arabian studied sections and is differentiated by vertical facies association changes from deltaic clastic facies to shallow marine facies. The sequence starts with sandy mudstones with shell hash (1–2 m) in all the sections followed by mudstone rocks in the Marat Section and clastic rocks in the

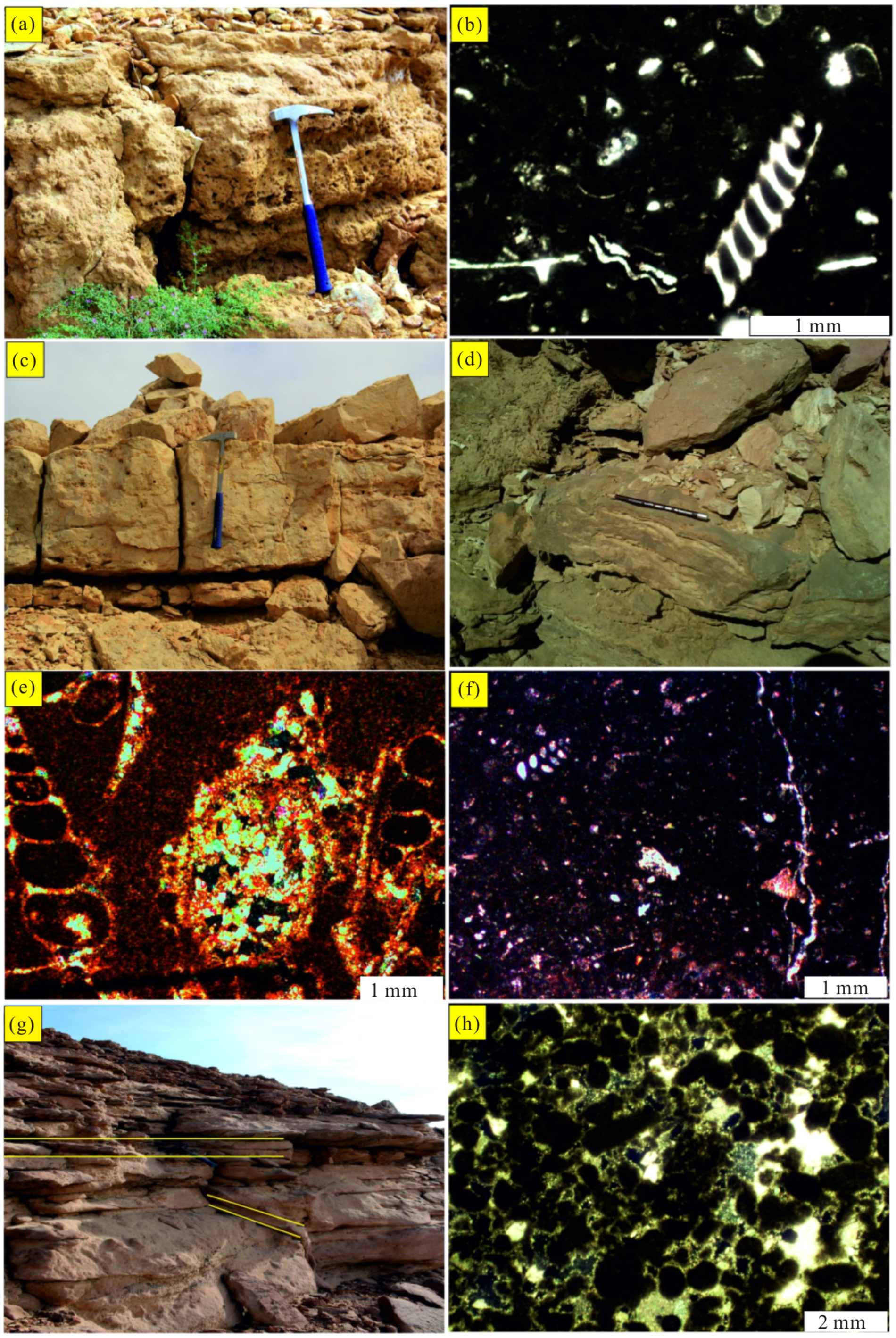

Figure 4. (a) Bioturbated limestone, Khashm al Jufayr Section; (b) thin section photograph of algal wackestone with gymnocodiacean algae and other bioclasts. Khashm al Jufayr Section; (c) massive and bedded limestone, Khashm adh Dhibi Section; (d) stromatoporoid limestone, Khashm al adh Dhibi Section; (e) thin section photograph of bioclastic wackestone with corals, bivalve debris, and gastropods, Khashm adh Dhibi Section; (f) thin section photograph of foraminiferal wackestone with *Textulariopsis* sp. and others, Marat Section; (g) low angle to planar stratification coated-grains limestone, Khashm al Jufayr Section; (h) thin section photograph of coated grains bioclastic grainstone, Khashm al Jufayr Section.

other two sections, consisting mainly of moderately sorted, calcareous and ferruginous quartz arenite, green sand, siltstones, and unfossiliferous varicolored shale (22–28 m). The shale is weathered, gypsiferous, and micaceous in several layers. Some sandstone layers contain numerous bivalve and gastropod shells. These clastic rocks are followed by limestone beds that mainly alternate between algal and foraminiferal wackestones, with gymnocodiacean algae, biserial foraminifers, echinoids, peloids, and intraclasts (2–4.5 m) (Fig. 8b). The upper part of this sequence (Fig. 8b) in the all studied sections (8–14 m) is mainly built up of massive, dissected blocks and cliff-scale sandy dolostone and minor argillaceous limestone in the lower beds with gastropods such as *Asterohelix*, *Ataphrus*, *Pseudomelania*, *Procerithium*, and *Akera* spp. and corals. The dolomite

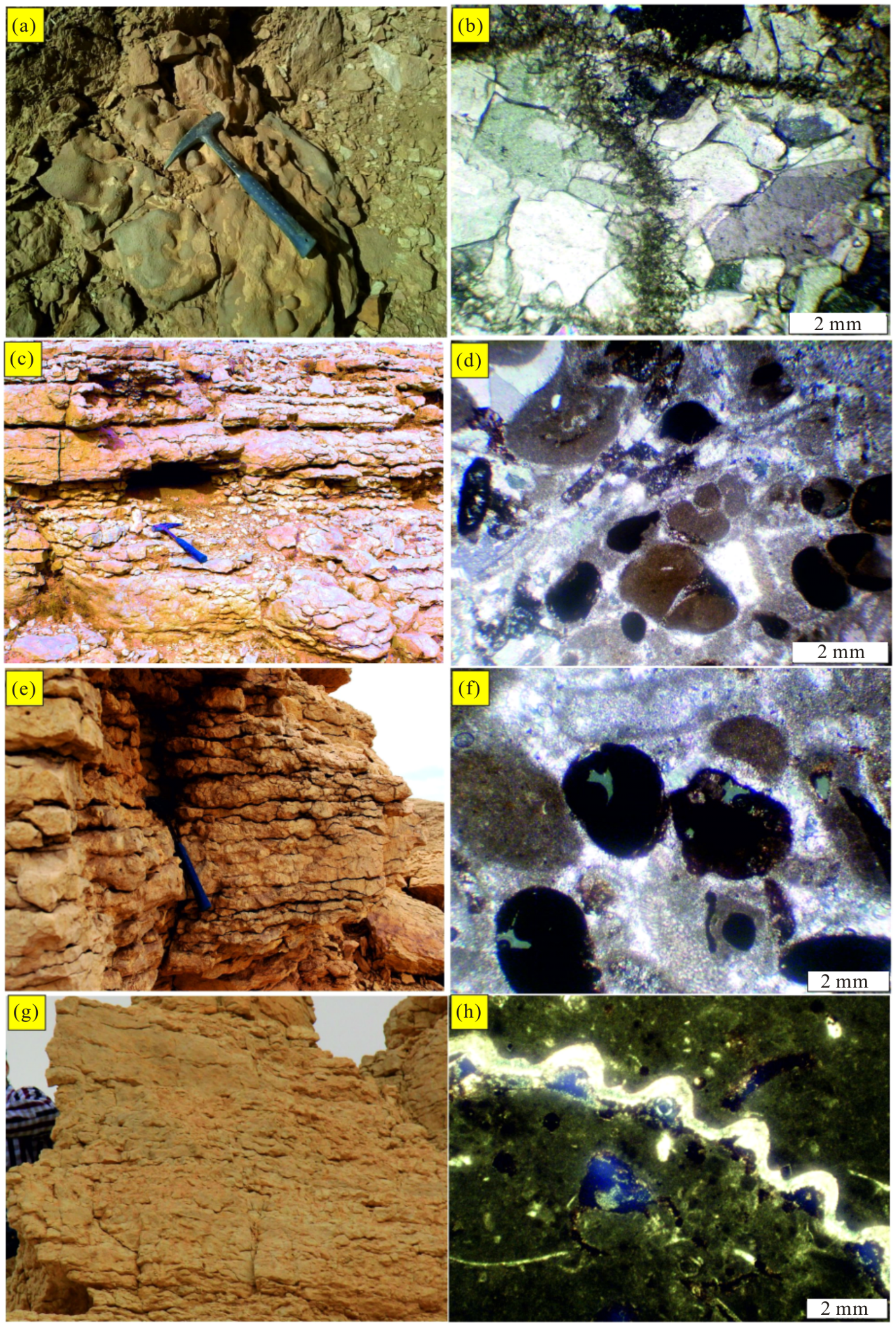

Figure 5. (a) Coral beds form a rigid framework, Marat Section; (b) thin section photograph of coralline framestone consisting of intergrown corals, Marat Section; (c) lower and upper surface of sharp planar limestone, Khashm adh Dhibi Section; (d) thin section photograph of graded packstone to grainstone crowded with different bioclasts, Khashm adh Dhibi Section; (e) nodular deposits of lithoclastic bioclastic limestone, Marat Section; (f) thin section photograph of lithoclastic bioclastic rudstone with clasts of packstone sediment, Marat Section; (g) thin-bedded argillaceous limestone with mud pellets and bioturbation, Khashm adh Dhibi Section; (h) thin section photograph of bioclastic peloids wacke- to floatstone containing brachiopod shells and micrite pellets, Khashm adh Dhibi Section.

rhombs exhibit cloudy centers with shell hash and echinoid spines. In contrast, the upper beds of the upper part consist of dissected marly limestone with ammonites (*Bouleiceras* and *Protogram* spp.), brachiopods (*Calyptoria*, *Zeilleria*, *Apothyris*, *Rugitela* spp.), and bivalve shells. The sequence is capped by a 50 to 75 cm of dolomitized limestone and dolostone in the Marat Section and ferruginous and gypsiferous sandy layer of 50–100 cm thickness in the other sections.

Interpretation: The base of this sequence represents the sequence boundary (SB1) between the continental clastic rocks in the lower portion and the marine non-clastic rocks in the upper portion. This sequence boundary may be related to a

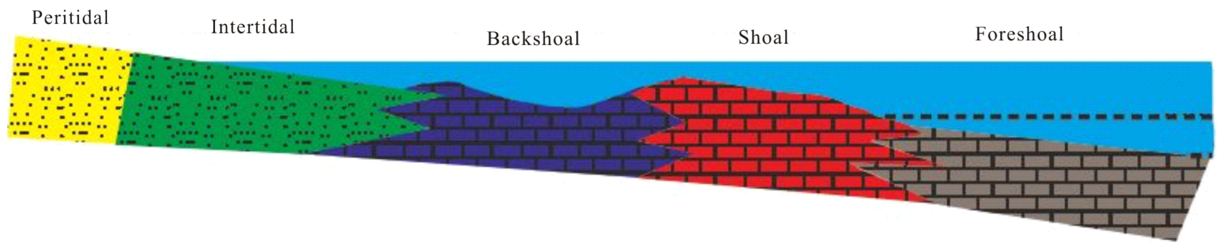

Figure 6. Depositional model of the Marrat Formation lithofacies association in the studied sections.

tectono-eustatic change related to sea-floor spreading in the South Atlantic (Hughes et al. 2008). Hence, this sequence boundary is classed as a type-1 sequence boundary. The base of this cycle can be identified by the transgressive surface (TS) and the clastic rocks, which are overlain. They are associated with the deposition in a tidal-flat setting that represents the (TST). The MFS of TO1 is represented by backshoal limestone beds that are rich in algae and foraminifers. The highstand systems tract (HST) is marked by the transition from the limestone back-shoal to the tidal-flat dolostone and argillaceous limestones. The dolomitic limestone and dolostone, ferruginous and gypsiferous sandy layer at the top of this sequence in all sections might be associated with a short-term exposure and marks the sequence boundary (SB2) between TO1 and TO2.

4.3.2 Sequence TO2, Lower Toarcian

Description: Sequence TO2, 35 – 57 m thick, is clearly identified by the presence of clastic beds in the middle part of the Marrat Formation. The lower part of this sequence in all of the studied sections is characterized by the presence of shale beds (20 – 33 m) that are red and green in color, poorly exposed, in part micaceous and laminated, gypsiferous, and calcareous. These shale beds are followed by an alternation of cross-bedded and calcareous sandstones that form a massive ledge, siltstone, and shale (approximately 10 m). The sandstone beds are fine- to coarse-grained, subangular to subrounded, and moderately to well-sorted. The beds exhibit parallel lamination in some layers and some shell hash are recorded in the calcareous layers. These clastic rocks are overlain by a 1–2.5 m thickness of sandy limestone beds, sandy mudstones with shell hash, and sandy bioclastic wackestone with bivalve and gastropod shells, foraminifers, and echinoid spines. The upper part (11.5 m) of this sequence is dominated by shale beds with shell hash. The upper-most part of TO2 is a ferruginous sandstone layer that is marked by a paucity of fauna and exhibits a sharp contact.

Interpretation: The clastic rocks in the lower part of this sequence indicate peritidal to tidal facies and can be interpreted as a TST. During a sea-level rise more distal back-shoal related facies types retrograded over the clastic beds and can be interpreted as a MFS (Fig. 9a). The clastic rocks in the upper part of this sequence could represent a HST, which indicates a further depositional shift towards a peritidal to tidal-flat setting. The ferruginous sandstone layer on the top of this sequence may be associated to a short-term exposure and it proves a great sea level fall and marks the sequence boundary (SB3) between TO2 and TO3.

4.3.3 Sequence TO3, Middle Toarcian

Description: Sequence TO3 is nearly 25 m thick. It is composed of carbonate rocks and forms the upper part of the Marrat Formation. The lower part of this sequence (10–15 m) starts with thin beds of bioclastic wackestone containing numerous brachiopods of *Liospiriferina* sp., gastropods such as *Asterohelix*, *Ataphrus*, *Procerithium*, and *Akera* spp., and brownish-yellow argillaceous limestone and claystone with ammonites of *Nejdia*, and *Hildaites* spp. Small foraminifers and echinoids are also recorded in the lower part of TO3. The wackestone and claystone beds are overlain by limestone beds of bioclastic wacke- to floatstone, bioclastic rudstone, and graded bioclastic pack- to grainstone in the Marat and Khashm adh Dhibi sections (2–4 m) and claystone beds (1–2 m) in the Khashm al Jufayr Section. These limestone beds are dominated by large skeletal components such as corals, gastropods, lithoclasts, and peloids. The upper part of this sequence in the all studied sections (10–15 m) forms a massive cliff. It begins with stromatoporoid wackestones followed by parallel- to cross-bedded coralline boundstones containing micritized and fragmented corals and is capped with coated-grain grainstones with micritized bioclastics of foraminifers, bivalves, and echinoids. The upper-most part of TO3 in all the studied sections is 1 – 3 m thick and consists mainly of gypsiferous and argillaceous limestone and gypsum bands without any distinct fauna (Fig. 9b), followed by a marl bed of the Dhruma Formation.

Interpretation: Argillaceous limestone and fossiliferous claystone at the lower part of the TO3 sequence indicate open-marine conditions in a low-energy lagoon and a backshoal depositional environment that can be interpreted as a TST. The upward increase in water-energy with a maximum ratio of open-marine fauna indicates a moderate- to high-energy MFS within a foreshoal setting. The facies stacking-pattern of the HST suggests a change from distal foreshoal to proximal shoal deposits in the upper part of sequence TO3. The gypsiferous and argillaceous limestone and gypsum band at the upper-most part of this sequence defines the sequence boundary (SB4) between the Marrat and Dhruma formations and characterizes the dropping in sea level. This boundary has been recorded in many sections in the Arabian Gulf countries (Farouk et al., 2018; Al-Husseini, 2015; Haq and Al-Qahtani, 2005) and represents the period of non-deposition.

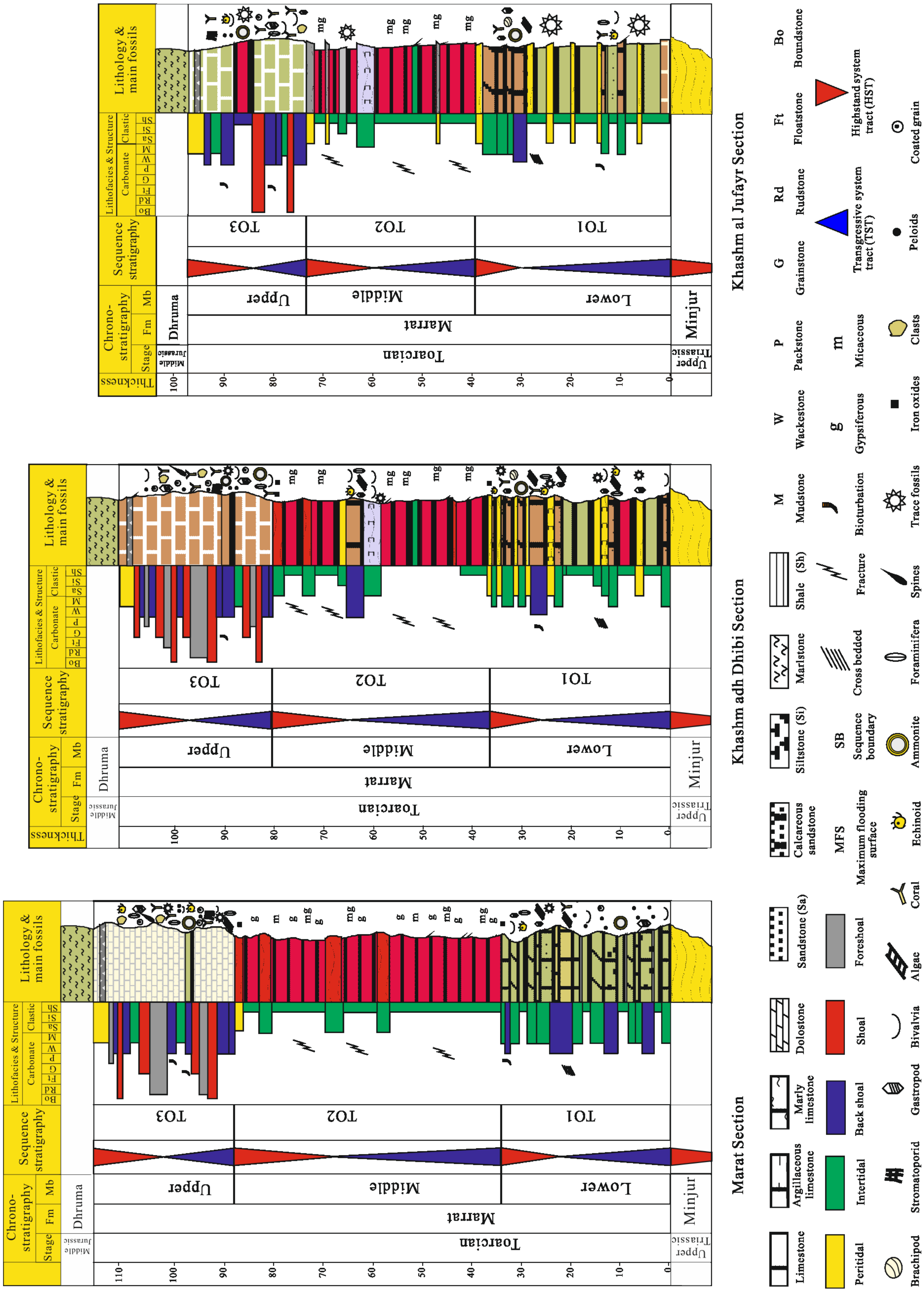

Figure 7. The Marrat Formation in the studied sections.

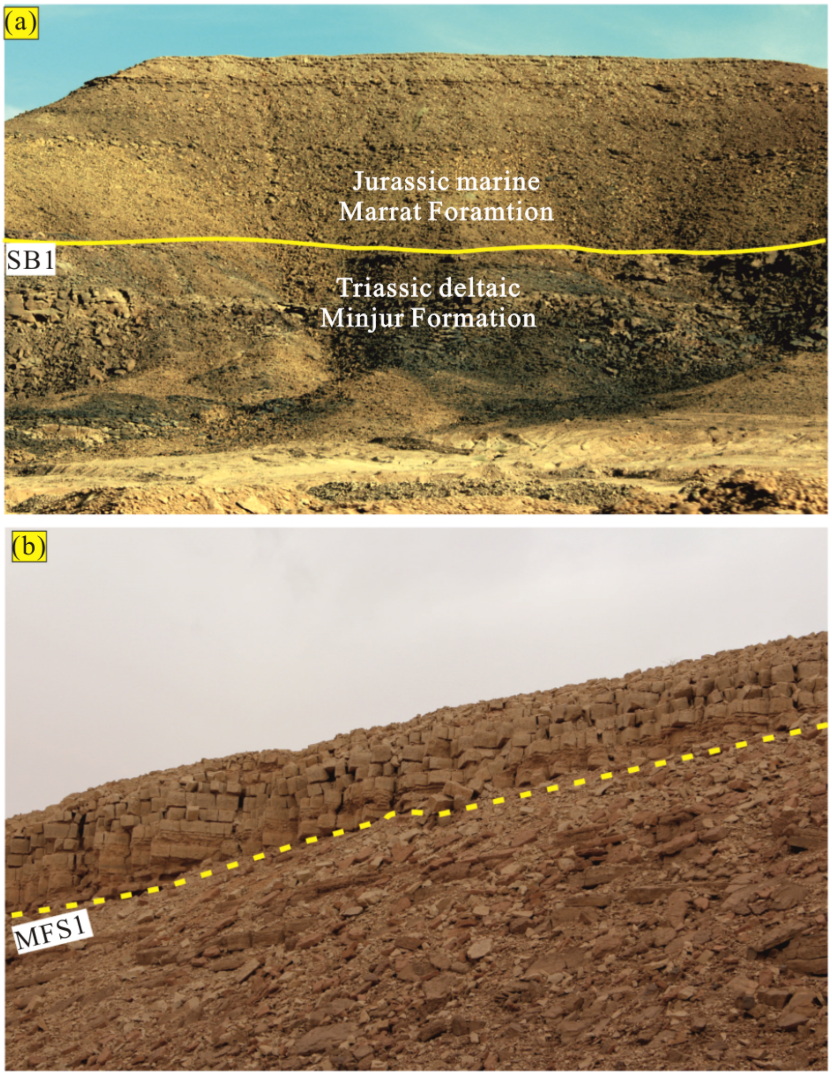

Figure 8. (a) The sequence boundary between the Minjur and the Marrat formations at the Khashm adh Dhibi Section. (b) the MFS 1 of sequence TO1, Khashm adh Dhibi Section.

5 CORRELATION

5.1 Studied Sequence Boundaries

The arrangement of sequences provides the key for the 2D-correlation of the sections. The sequence boundaries (solid lines) of the studied sequences are used as timelines. In this correlation, the sequences are labelled (TO1, TO2, and TO3) and traced from north to south. In general, the studied sequences exhibit some similar lithofacies types along the same timeline. Based on the correlation, the northern section (i. e., the Marat Section) is interpreted to represent a deeper depositional environment than the other sections (Fig. 10). Detailed analysis shows some intercalations between these lithofacies associations. TO1 is represented in the studied sections through the tidal flat lithofacies association and the MFSs are identified in the wackestone beds of a lagoon environment. The thickness of the lagoon beds decreases towards the south, whereas the peritidal lithofacies associations increase towards the south. The sequence boundaries between TO1 and TO2 reflect a minor lateral change from a carbonate tidal-flat in the north to clastic peritidal facies in the south. TO2 in the examined sections displays tidal-flat facies in the TST and HST, with minor intercalations of peritidal facies towards the south. These system tracts are separated by a MFS of lagoonal facies association in the Marat and Khashm adh Dhibi sections, whereas they are located within a tidal flat environment in the Khashm al Jufayr Section. The sequence boundaries between TO2 and TO3 have been identified in the peritidal environment of the clastic rocks. The last sequence, TO3, shows more distal facies types, grading from foreshoal and shoal lithofacies in the north to lagoon and tidal-flat facies in the south. The last sequence boundaries have been identified on the top of gypsiferous limestone and gypsum beds, which are overlain by marl beds of the Middle Jurassic Dhruma Formation and reflects the major regressive phase and sea level fall during the end of the Marrat Formation.

5.2 Other Regions in Saudi Arabia and the Arabian Gulf Countries (Fig. 11a)

Tang et al. (2011) studied the Marrat Formation across some localities in Saudi Arabia on the surface and subsurface. They concluded that the Marrat Formation comprises a composite third-order sequence and that the Lower Jurassic beds

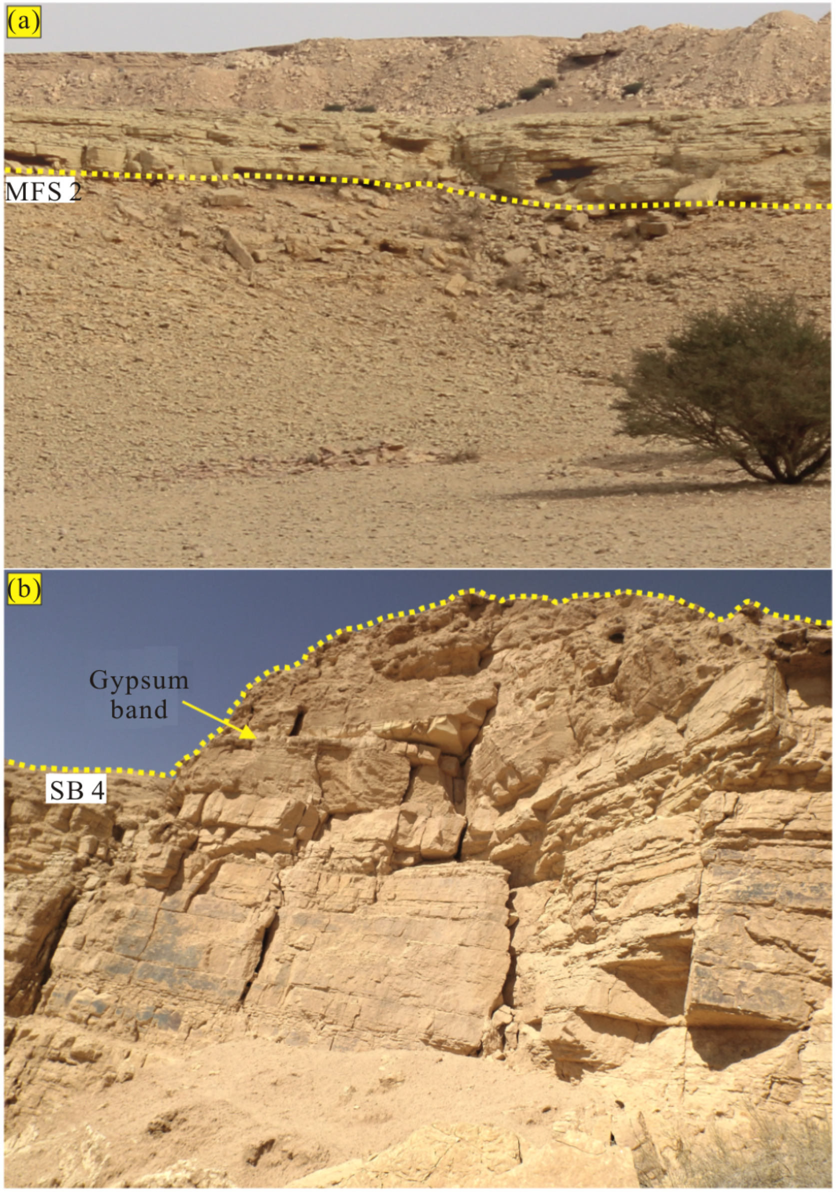

Figure 9. (a) Close up view of the MFS 2 of sequence TO2 in the Khashm adh Dhibi section; (b) the SB4 on the top of the Lower Jurassic Marrat Formation, Khashm adh Dhibi Section.

disappear in the southwestern Arabian Gulf. In the subsurface of eastern Saudi Arabia, the Marrat consists mainly of shale in the lower and middle parts and a dense limestone unit toward the east.

Sharland et al. (2001) established the Arabian Plate sequence stratigraphy based on ammonites. They represented MFS J10 during the Early Toarcian of the Lower Marrat Formation in Saudi Arabia, equivalent to Lower Mafraq Formation in Oman. Kadar et al. (2015) correlated the Lower Jurassic in the Arabian Peninsula and they placed MFS J10 in the lower part of the Middle Marrat.

In the other regions of the Arabian Plate, such as in Kuwait, Alsahlan et al. (2010) recognized 11 depositional sequences in the Marrat Formation and established that the first three sequences in the lower part of the Marrat Formation belong to the pre-Toarcian Pliensbachian stage. The uppermost part of the Lower and the Middle Marrat consist of four third-order sequences belonging to the Toarcian stage and the upper part of this formation comprises four sequences belonging to the post-Toarcian Aalenian and Bajocian stages. Kadar et al. (2015) found that the lower portion of the Marrat Formation denotes a Pliensbachian Age and the Marrat of Kuwait has older sediments which is missing in Saudi Arabia. In Oman, Alsahran and Magra (1994) examined the Lower Jurassic and they concluded that the Norian-Bajocian ought to be known as the Mafraq Formation. The Lower Mafraq is variable and usually clay-dominated; it may be a lateral equivalent of the Upper Triassic Minjur Formation of Saudi Arabia. The Upper Mafraq is essentially equivalent to the Marrat Formation and the basal clastic unit of the Dhruma Formation of Saudi Arabia. In the south-western Arabian Plate (Qatar offshore, Abu Dhabi and Dubai), there is no evidence of the Marrat Formation. So, in the Arabian Gulf countries, the Lower Jurassic rocks appear in the central and north parts of Saudi Arabia, Kuwait, Oman,

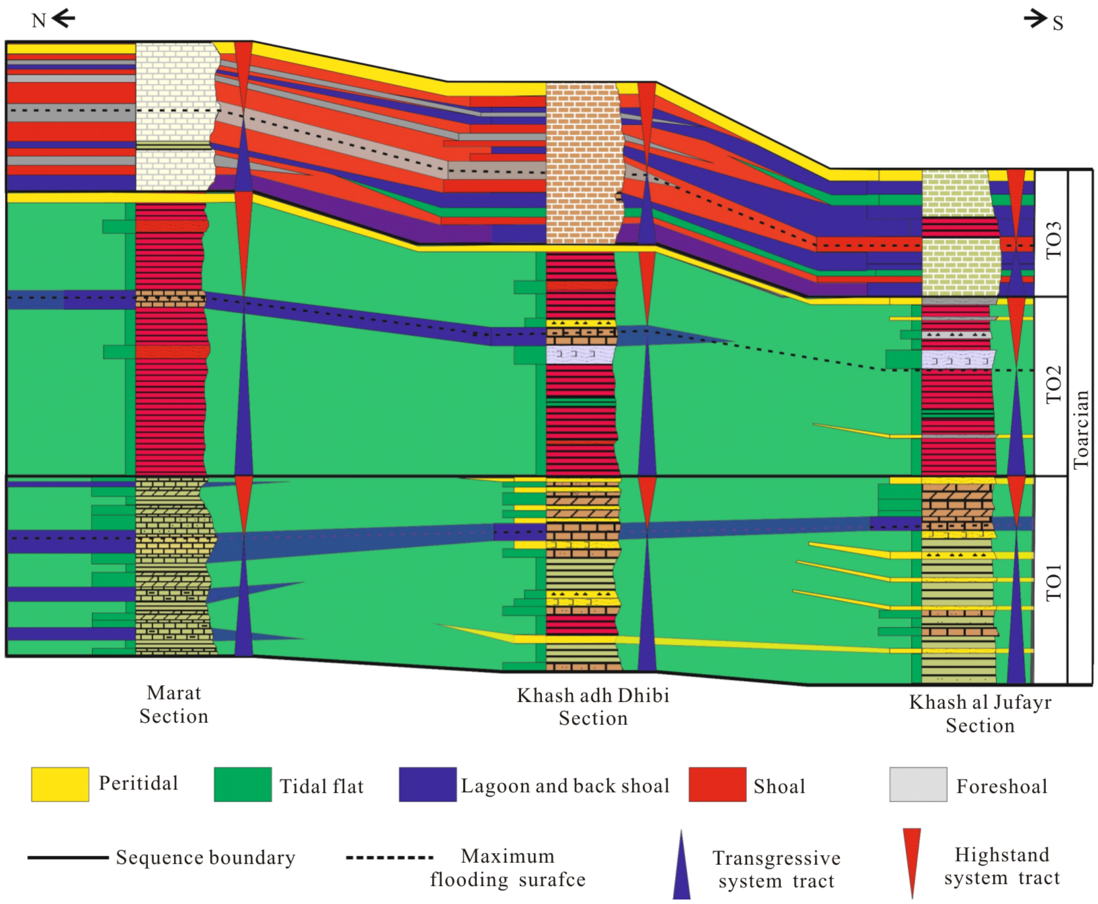

Figure 10. Lithofacies associations of the studied Toarcian sections within a chronostratigraphic framework correlation.

and Qatar onshore, while disappear in the most parts of UAE and western parts of Saudi Arabia.

5.3 North of the Arabian Plate and the Gondwanaland Margin (Fig. 11b)

In the northern east of the Arabian Plate and the Gondwanaland margin, Al-Naqib and Al-Juboury (2014) studied the sequence boundaries of the Jurassic succession in the Rutba outcrop in the Western Desert of Iraq. They determine that two formations, the Ubaid and Hussainiyat, belong to the Toarcian stage, which is consistent with the previous studies on this area. They also detected two unconformable boundaries, one at the top of the Ubaid Formation and another at the top of the Hussainiyat Formation, which separate the Upper and Lower Jurassic. Gayara and Al-Gibouri (2015) also studied the Lower Jurassic succession of Western Iraq on the surface (the Ubaid, Hussainiyat, and Amij formations) and in the subsurface (the Butmah, Adayah, Mus, and Alan formations) in more detail than Al-Naqib and Al-Juboury (2014). They determined seven third-order sequences on the surface of the studied area. The Ubaid Formation in the lower succession contains three sequences, of which the first comprises only a HST. The second, the Hussainiyat Formation, consists of two sequences and the last formation consists of two sequences. In the subsurface they concluded that the Butmah Formation was deposited on an evaporitic shallow-marine platform during the Hettangian lowstand, followed by the Toarcian transgression, which was widely recognized on a global scale. The Early Jurassic ended with the Sinemurian lowstand during which, the Adayah, Mus, and Alan and their siliciclastic-carbonate equivalents in the Rutba area, the Hussiniya and Amij formations, were deposited.

In southern Iran and the northeastern margin of the Arabian Continent, continental deposits prevailed in the Lower Jurassic. In northern Iran, Fürsich et al. (2005) studied the sequence stratigraphy of the Upper Shemshak Formation (Toarcian – Aalenian) and they noticed five third-order sequences in the Lower Jurassic (Middle and Upper Toarcian). These sequences range between sixty and a few hundred meters in thickness and are constrained by obvious erosional unconformities and/or marked shifts in facies. The corresponding depositional sequences are retrogradationally stacked, generally fining-upwards. As in southern Iran and Saudi Arabia, the Lower Jurassic rocks in Syria and Lebanon are represented by the clastic Mulussa Formation and tholeiitic basalts.

In Egypt, in the northern west of the Arabian Plate, in the East Maghara Basin in Sinai, the Lower Jurassic sequence belonging to the Toarcian stage rests unconformably on the Middle Triassic sequence and underlies the Middle Jurassic rocks (Zaghloul and Khidr, 1992). The Lower Jurassic sequence consists of three formations (Mashabba, Rajabiah and Shusha) based upon four sequence boundaries (EGPC, 1986). The first two formations are interpreted as fluvial system and the last one has been explained as a shallow marine facies association (Edress et al., 2018). So, in the northern east of the Gondwana-

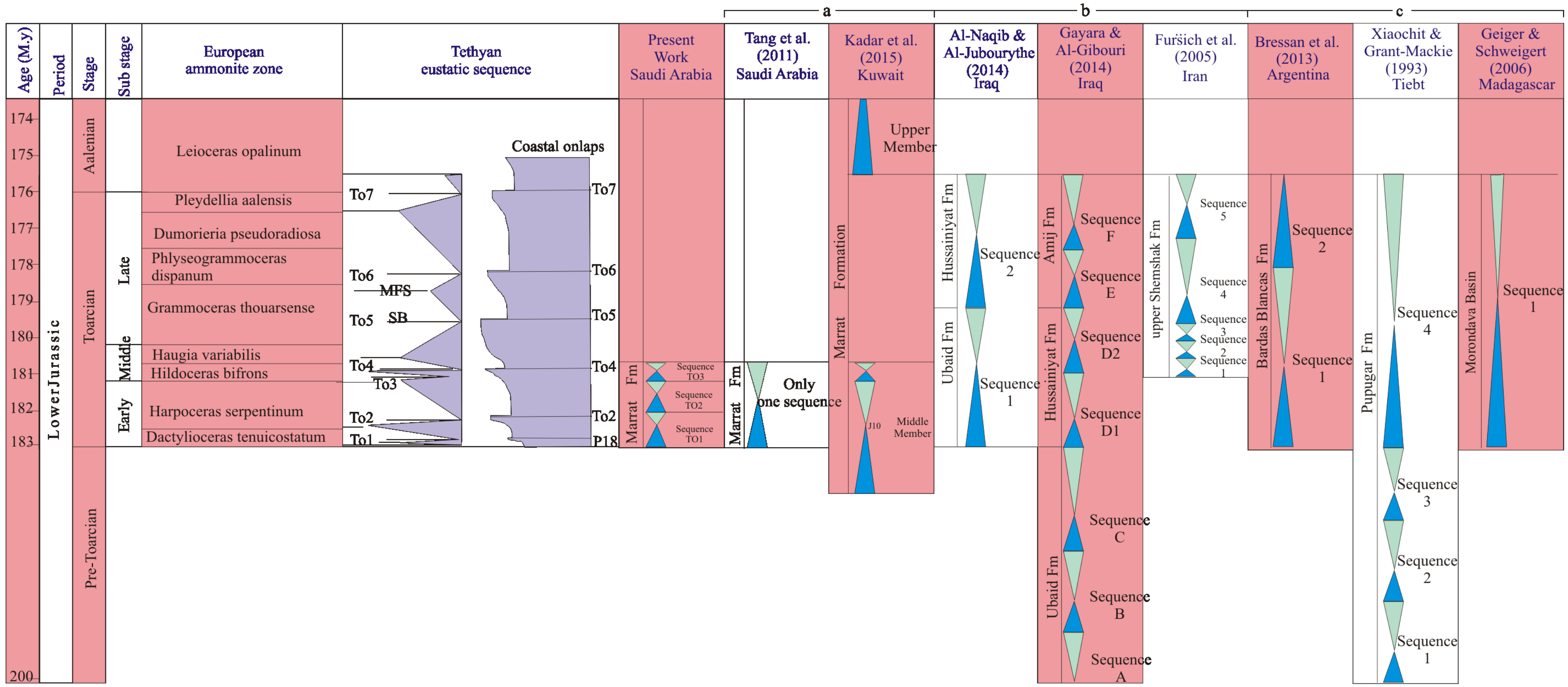

Figure 11. (Left) Ammonite biostratigraphy and sequence stratigraphic frame-work of the Toarcian stage as defined in the European eustatic reference chart of GTS2004 (Gradstein et al., 2005); (right) comparison between third-order eustatic sequence in the studied area and the different sequences in (a) other regions in Saudi Arabia and the Arabian Gulf countries, (b) north of the Arabian plate and the Gondwanaland margin, and (c) central and south of the Gondwanaland (notice the prevailing TST rather than HST in the most sections).

land margin during the Toarcian age, the shallow marine carbonate rocks are mainly prevailed in western Iraq and few parts of Egypt (Sinai), while the continental deposits have been recorded in southern Iran, and some parts of Syria, and Lebanon.

5.4 Central and South of the Gondwanaland (Fig. 11c)

Li and Grant-Mackie (1993) studied the Jurassic cycles and the eustatic sea-level in southern Tibet (near the central part of Gondwanaland) and they found that tectonism is the main reason for the sea-level changes. They also recognized four third-order cycles (sequences) and three sequence boundaries in the Lower Jurassic in southern Tibet. The first sequence, which overlies the Upper Triassic rocks in the Lower Pupugar Formation, corresponds to the Hettangian stage. The second sequence, which consists mainly of siliciclastic rocks, corresponds to the pre-Toarcian stage (Sinemurian). The third sequence, the Upper Pupugar Formation, which also consists of siliciclastics, corresponds to the pre-Toarcian (Pliensbachian) stage. The final sequence becomes shallower, which is indicated by shoreface sandstone beds, and corresponds to the Toarcian stage.

Geiger and Schweigert (2006) studied the Toarcian–Kimmeridgian depositional cycles in the south-western Morondava Basin in Madagascar. They recognized four transgressive-regressive sequences between the studied stages and recorded only one transgressive hemi-sequence. The MFS and the basal part of the regressive hemi-sequence is in the Toarcian stage.

Bressan et al. (2013) studied the shallow-marine and coastal succession of the Lower Toarcian to Lower Bajocian Bardas Blancas Formation in the northern Neuquén Basin, Argentina, at the western part of Gondwanaland. They analyzed the vertical distribution of facies and stratigraphic surfaces and they identified four transgressive-regressive sequences. The first sequence belongs to the Toarcian stage and was characterized by shallow coastal-marine deposits. The lower part of the second sequence (transgressive hemi-sequence) may also be related to the Toarcian stage, whereas the rest of the second sequence and the other sequences were deposited after the Toarcian stage. Briefly, during the Toarcian age, most of the central parts of the Gondwanaland have been prevailed by continental rocks as in southern Tibet and Madagascar, while the southern parts of the Gondwanaland (as in western parts as in Argentina) were covered by coastal and shallow marine deposits.

5.5 Global Sea Level Curve of Haq (2018)

In Comparison between the studied sections and the Early Jurassic sequences and global variations of sea level curve of Haq (2018), it was found that the sequence boundary between the Triassic and the Lower Jurassic is related to tectonic activities and equivalent to JTO1. Depending on the global ammonite zones, the two sequence boundaries between TO1, TO2, and TO3 in the studied sections are equivalent to JTO2 and JTO3. The last sequence boundary between the Middle/Upper Jurassic represents a hiatus and equivalent to JTO4. The other cycles of Haq (2018) JTO5 to JTO10 are missing in the Arabian Plate because of non-deposition and tectonic activities (Al-Husseini, 1997). In general, from the studied regions, Toarcian sediments were more deepening towards the eastern Gondwana along the Neo-Tethys where the shallow marine lithofacies associations have been prevailed, while the most continental deposits were recorded towards the central and the western parts of the Gondwanaland regions.

6 DISCUSSION AND CONTROLS INFLUENCING THE DEPOSITION

During the Early Jurassic, the world underwent great changes (Fig. 12). Plate tectonic models indicate that this is when the supercontinent of Pangaea broke up and initiated the world's continents and modern ocean basins (Scotese and Schettino, 2017). Although the accurate motion of these plates in the Early Jurassic is not well-defined, three major events have marked this period. The first event was a major climatic change and an associated mass extinction (Pálfy and Kocsis, 2014), the second was the breakup of Gondwanaland, and the third event was related to the formation of the Neo-Tethys: "the Mediterranean Sea during the Early Jurassic" (Bernoulli and Jenkyns, 1974). Goldberg and Friedman (1974) linked the topography and development of the Neo-Tethys during the Toarcian to opening of the central Atlantic, which may have acted as a seaway for circulation between the Paleo-Pacific and the Neo-Tethys. As noted by Haq and Al-Qahtani (2005) and Le Nindre et al. (2003), eustatic changes were the main controlling factor on patterns of sedimentation in the Jurassic sequences in the Arabian Gulf area. In contrast, Li and Grant-Mackie (1993) related the majority of the Early Jurassic changes to the break-up of Gondwanaland and the northward drift of the Indian subcontinent and the associated microplates. During the Toarcian, Saudi Arabia was considered as a part of the Gondwanaland passive margin submerged under the warm equatorial waters of the Neo-Tethys near the equatorial line. These conditions are responsible for the organic-rich source rocks and thick carbonates that prevailed until the Cretaceous (Sorkhabi, 2010). The tectonics of the Arabian Plate were traced by Wilson et al. (1998). They took the view that the tectonic activities along the eastern Mediterranean margin started in the Triassic and continued until the Lower Jurassic to produce renewed regional faulting in the northern part of the Arabian Platform. This interpretation is confirmed by Flexer et al. (2000) from seismic lines, well logs, and the presence of tholeiitic basalts, which indicate the reactivation of the Permian rift fault during the Lower Jurassic in the northern Arabian Platform. The disappearance of the Marrat Formation in the southwestern Arabian Gulf has been attributed to local tectonic activity in this area (Alsharhan and Mogara, 1994) and the prevailing of shale in the eastern Saudi Arabia may indicate more marine conditions in the east. The omission of the Marrat Formation in Qatar and UAE also may probably be due to tectonism which resulted in non-deposition or erosion (Alsharhan, 1989). Stampfli and Borel (2002) related the prevailing continental deposits in northeastern margin of the Arabian continent (Iraq and Iran) to the fault plane resulting from the rupturing of the continental crust of Gondwanaland from the Triassic to the Lower Jurassic, during which a new taphrogeosyncline developed into a deep trough and the fault continued to erupt along the spreading center between the Arabian plate to the southwest Iran and northeastern Iran while the origin of the clastics in Syria and Lebanon is related to the Rutbah uplift, which started in the Late Triassic and continued during the Early Jurassic and separated the intra-shelf basin of Mesopotamia from the Neo-Tethys Ocean (Sissakian, 2013). Mouty (2000) linked the basalts to the rifting activity along the eastern Mediterranean margin. The Lower Jurassic boundaries in Sinai have been related to the deformations between the Eurasian and the African plates, the splitting of the Neotethys in the Eastern Mediterranean, the formation of small basins in Sinai, and the variations of sea-level during deposition (Edress et al., 2018).

The initiation of the breakup of Gondwanaland started in the Lower Jurassic (185 – 180 Ma) between Africa and Madagascar, and West Antarctica after a long term of rifting and volcanic eruption during the Permian and Triassic (Jourdan et al., 2005). This split was responsible for forming the Mozambique Basin and the West Somalia Basin, confirmed by the pre-rift structures along the conjugate margins (Müller et al., 2008). According to Cathles and Hallam (1991) the rifting in any region caused stresses and compressions on the plates and may have had an effect on the density of the lithosphere that caused changes in the elevation and subsidence of the plate, which were responsible for the observed transgression-regression cycles in the Arabian Plate. Geiger and Schweigert (2006) attributed the transgressive-regressive sequences in Madagascar to tectonic activity rather than eustatic changes and Bressan et al. (2013) related the evolution of the sedimentary basin during the Early – Middle Jurassic to the interplay between sea-level fluctuations and extensional tectonics.

From these studies, the Lower Jurassic sedimentation in Saudi Arabia and Gondwanaland regions was discontinuous and corresponds to three to six third-order sequences. These sequences are separated by disconformities generated by a combination of both eustatic processes and tectonics. The Lower Jurassic system-tracts in Saudi Arabia were only partly similar to those logged in other regions. This may be explained by differences in the tectonic activities and climatic changes of those regions. The TSTs in the Toarcian stage are dominant in the Neo-Tethys and Gondwanaland regions rather than a HST. This may be related to the global warming conditions during the Toarcian stage, which were responsible for most of the ice-melting processes and the rise of the eustatic sea-level (Dera and Donnadieu, 2012). Although biodiversity increased together with the eustatic sea-level rise (Hallam, 2001), the opposite occurred during the Lower Jurassic in the studied area and most of the regions of Gondwanaland. Pelagic carbonate production was rare and decreased, and many species disappeared. This scarcity and reduction are believed to be linked to the increase in greenhouse gases in deep water settings that led to an anoxic event (T-OAE) and caused a prominent extinction for many living organisms during this period (Song et al., 2019; Léonide et al., 2012). The repetition of shale beds within the carbonates in the Lower Jurassic formations may indicate eutrophic conditions as a result of nutrient availability and temperature increasing (Woodfine et al., 2008). Catuneanu et al. (2005) stated that the main events responsible for the accommodation space in the Middle African and some parts of the Neo-Tethys basins during the Early Jurassic were the tectonic activities. These activities varied from orogenic processes along the Paleo-Pacific margin, propagating to the south from the divergent Tethyan margin, to the extensional regime to the north. The Lower Jurassic lithofacies types in the Neo-Tethys and Gondwanaland are carbonate rocks with intercalations of terrigenous materials. These terrigenous materials may be reduced or even disappear in some regions due to the significant decrease in continental influence during the arid climate (Vörös, 1977).

Finally, even though the role of eustatic sea-level changes and climatic effects on the Toarcian rocks in Saudi Arabia and neighboring countries is clear, tectonic activities may have had a similar role and the future studies should pay more attention to the Toarcian magnetic field and tectonics.

7 CONCLUSIONS

The Toarcian sequences of the Marrat Formation at the studied sections in central Saudi Arabia were deposited on a shallow marine platform. Based on field and microfacies criteria, five lithofacies associations were recorded: peritidal, tidal-flat, backshoal, shoal, and foreshoal environments. Stacking

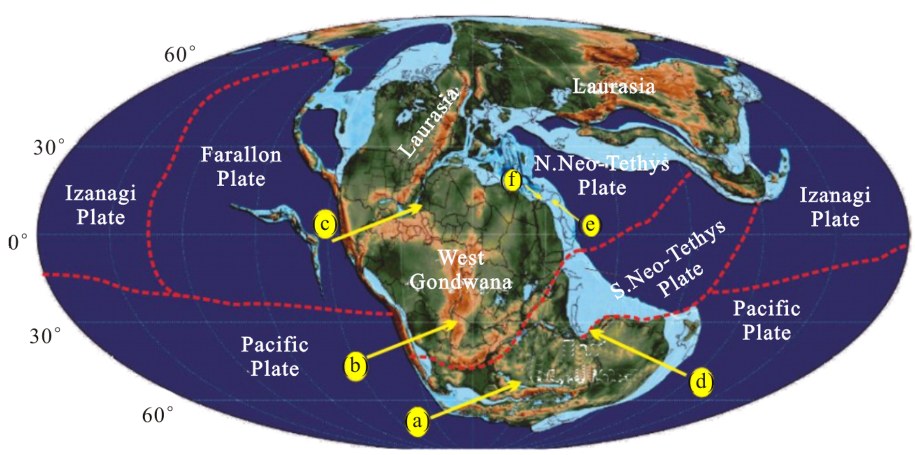

Figure 12. Arrangement of the continents during the Lower Jurassic (modified from Seton et al., 2012). (a) Initiated breakup of Gondwanaland; (b) initiated rifting between South America and Africa; (c) initiated rifting between East Gondwanaland and Laurasia; (d) South Tebet; (e) Zagros suture; (f) Rutbah uplift.

of these lithofacies associations enables us to subdivide the Marrat Formation into three third-order depositional sequences, separated by four sequence boundaries. SB1 separates the Triassic and the Jurassic strata and may be related to a tectono-eustatic event and equivalent to JTO1 of Haq's curve (2018). SB2 separates sequences TO1 and TO2, and SB3 separates TO2 and TO3 and they are equivalent to JTO2 and JTO3 of Haq's curve (2018). The last sequence boundary, SB4, is located at the top of the Marrat Formation, which is distinguished by gypsum layers and separates the Marrat beds from the overlying marl layers of the Dhruma Formation and equivalent to JTO4 of Haq's curve (2018). The TST of sequences TO1 and TO2 in the studied sections are interpreted as tidal-flat clastic rocks in the lower part of the sequence. During the sea-level rise, the backshoal limestone beds retrograde on these clastic rocks and represent the MFS in the TO1 and TO2. The clastic rocks in the upper part of the two sequences exhibit the HST. The last sequence, TO3, is represented by carbonate rocks alone, in all the studied sections and constitutes the upper part of the Marrat Formation. The TST of TO3 is represented by back-shoal wackestones. The MFS is identified in the foreshoal limestone beds that overlie the wackestones. The HST of this sequence is characterized by grainstone and boundstone shoal beds at the top of the Marrat Formation. The correlation between the studied Lower Jurassic rocks in Saudi Arabia reflects a general deepening towards the north, while the correlation with other Gondwanaland and Neo-Tethys countries reveals the prevalence of the TST due to the ice melting as a result of a global warming. A paucity of many species and pelagic carbonate production contributed to the increasing greenhouse gases. The prevalence of shale beds within the carbonates is a result of eutrophic conditions and an increased temperature. Two significant features of the tectonics of the Lower Jurassic that affected some regions in Saudi Arabia as well as Gondwanaland countries were the initiation of the breakup of Gondwanaland and the formation of Neo-Tethys. These two episodes have been responsible for most tectonic events in the Lower Jurassic paleo-world and were also responsible for the differentiation in third-order sequences in Saudi Arabia and other countries.

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