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Sequence architecture of the Toarcian Marrat Formation, Saudi Arabia: The Khashm adh Dhibi reference section

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ABSTRACT

Since its introduction in the Middle East, nearly 30 years ago, sequence stratigraphy has yet to be consistently applied to define transgressive-regressive (T-R) depositional sequences. To illustrate this problem, we trace the stratigraphic representation of just one formation in one section between 1962 and 2019 by geologists from industry, geologic surveys and academia. We chose the reference section of the Toarcian Marrat Formation because it is accessible at outcrop near Ar Riyadh, the capital of Saudi Arabia. We show that since it was first interpreted as a T-R sequence and tied to the global framework in 1990, the interpretation of its sequence architecture has become increasingly confused. We therefore provide a detailed description of the reference section and interpret its high-resolution sequence architecture. We then compare our interpretations to those published in two recent peer-reviewed articles and the most recent global framework of T-R sequences.

1. INTRODUCTION

Between the 1930s and 1990s, nearly all the lithostratigraphic units (groups, formations and members) in Saudi Arabia were named, defined in type and/or reference sections, mapped at outcrop and in many cases assigned to chronostratigraphic stages based on age-indicative fossils. The definitions of the units were initially published in lexicon format (Powers et al., 1966; Powers, 1968), and subsequently updated by academics, international surveys and the national survey (now the Saudi Geologic Survey). Starting in the 1990s the concepts of sequence stratigraphy (Figure 1), catalyzed by compilations of global T-R sequences (Haq et al., 1987, 1988; Hardenbol et al., 1998), became adopted worldwide and in the Middle East (e.g., Le Nindre et al., 1990a, b; Grabowski et al., 1995; Goff et al., 1995; Al-Husseini, 1997).

In the past two decades the compilations and ages of global and Arabian Plate sequences have been revised (Haq and Al-Qahtani, 2005; Haq and Schutter, 2008; Haq, 2014, Haq, 2018a, b), and updated (e.g., Al-Husseini, 2009). Moreover, sequence-stratigraphic terminology has yet to be formalized, and various conflicting definitions have been proposed for how to describe a T-R sequence. Figure 1 shows how various authors describe T-R sequences in terms of systems tracts (FSST, LST, TST, HST, RST) and isochronous surfaces (SB, CC, MFS, MRS) in relation to changes in base level (BL) or relative sea level (RSL, Catuneanu et al., 2009, 2019). These conflicting definitions, together with the uncertainty inherent in most stratigraphic data sets, permeate many sequence-stratigraphic studies.

This study illustrates several issues relating to the interpretation of the sequence architecture of just one stratigraphic section and one formation – the reference section of the Toarcian Marrat Formation. It is located at Khashm adh Dhibi near Ar Riyadh, the capital of Saudi Arabia (Powers et al., 1966; Powers, 1968) (Figure 2). This section has been described by several authors since 1962, and its high-resolution sequence architecture has been variously interpreted in two recent peer-reviewed articles (Farouk et al., 2018; Al-Mojel et al., 2019).

In the present study, we document and interpret the sequence architecture of the reference section, and highlight several pitfalls that occur due to the inconsistent application of lithostratigraphic and sequence-stratigraphic terminology and concepts. Our objective is to emphasize the need for more consistent terminology, better data documentation and scientific analyses, and administrative procedures for naming and compiling T-R sequences, both globally and in the Middle East.

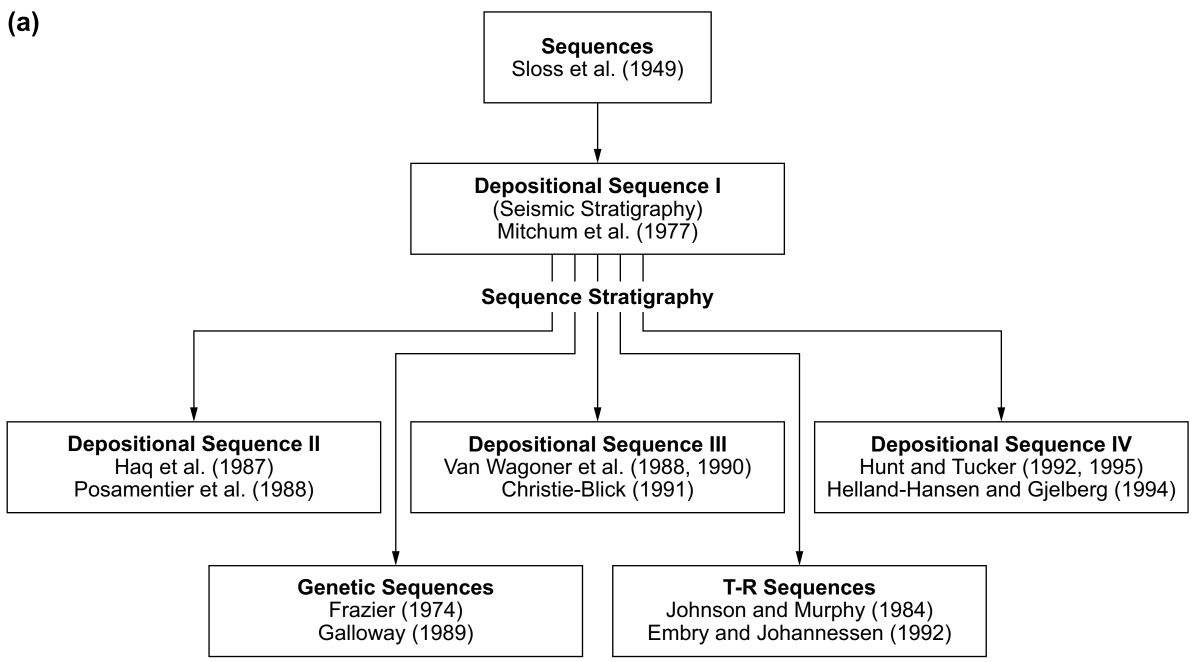


Figure 1: (a) Sequence stratigraphic models (from Catuneanu et al., 2010).

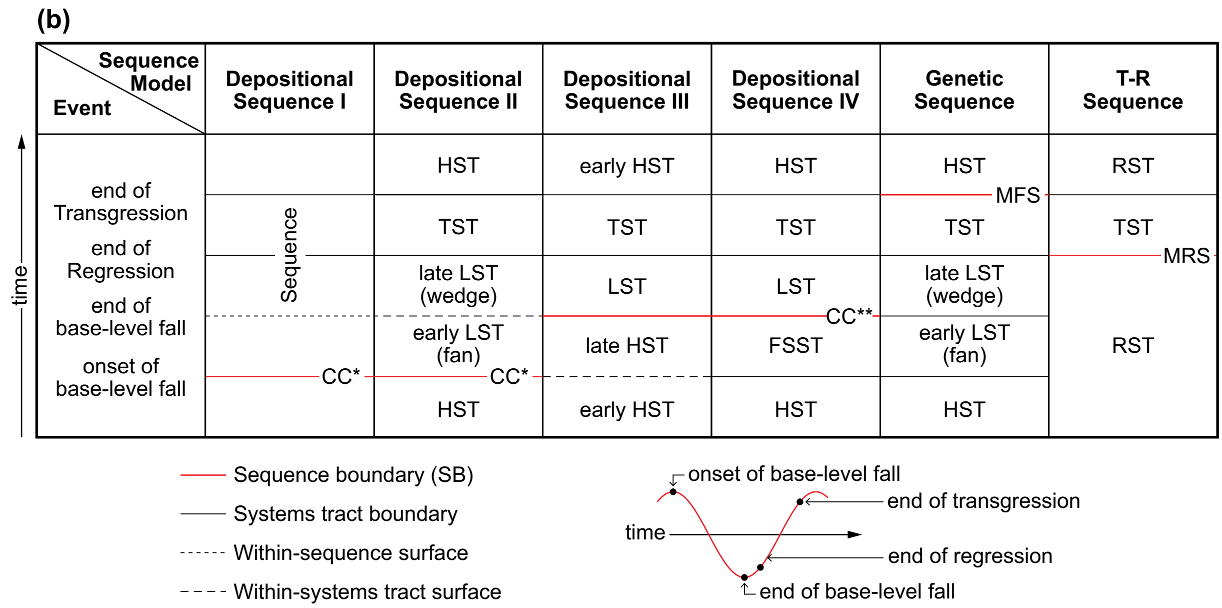


Figure 1: (b) Nomenclature of systems tracts, and timing of sequence boundaries (SB) for the various sequence stratigraphic approaches. LST - lowstand system tract; TST - transgressive system tract; HST - highstand system tract; FSST - falling-stage systems tract; RST - regressive system tract; T-R - transgressive-regressive; CC* - correlative conformity in the sense of Posamentier and Allen (1999); CC**- correlative conformity in the sense of Hunt and Tucker (1992); MFS - maximum flodding surface; MRS - maximum regressive surface (from Catuneanu et al., 2010).

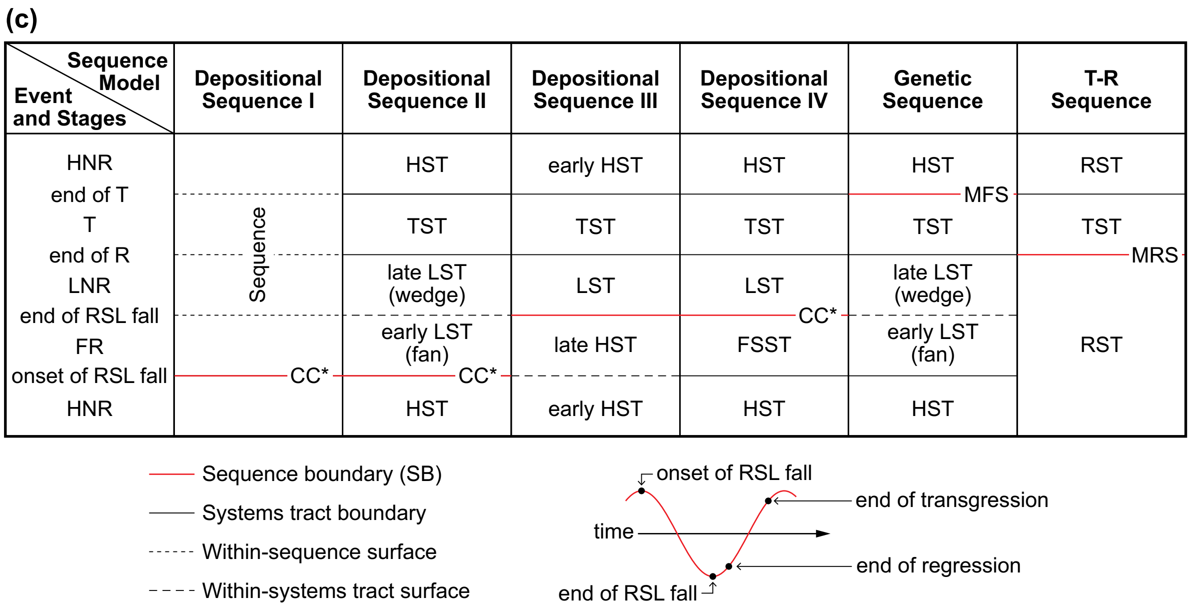


Figure 1: (c) Sequence stratigraphic approaches: nomenclature of systems tracts and timing of sequence boundaries (from Catuneanu et al., 2019). Abbreviations: CC* – correlative conformity in the sense of Posamentier et al. (1988), herein referred to as the "basal surface of forced regression"; CC** – correlative conformity in the sense of Van Wagoner et al. (1988), herein referred to as the "correlative conformity"; FR – forced regression; FSST – falling-stage systems tract; HNR – highstand normal regression; HST – highstand systems tract; LNR – lowstand normal regression; LST – lowstand systems tract; MFS – maximum flooding surface; MRS – maximum regressive surface; R – regression; RSL – relative sea level; RST – regressive systems tract; T – transgression; T-R – transgressive-regressive; TST – transgressive systems tract.

2. STUDIES OF THE MARRAT FORMATION

2.1 ARAMCO (1937–1968)

The Toarcian Marrat Formation crops out between the upper Triassic-lower Jurassic Minjur Sandstone and middle Jurassic Dhruma Formation (Powers et al., 1966; Powers, 1968, Figure 2). It was informally defined in 1937 by ARAMCO geologist Max Steineke and named after the town of Marah in Saudi Arabia (25°04′18″N, 45°27′26″E, Figure 2). In the following two decades ARAMCO geologists formally defined and ranked it as a formation in a composite type section near Marah, and based on ammonites assigned it to the Toarcian Stage of the Lower Jurassic Series (Bramkamp and Steineke, unpublished ARAMCO report, 1945; Arkell, 1952; Steineke and Bramkamp, *in* Akell, 1952; Bramkamp et al., 1956; Steineke et al., 1958).

In 1962, a better-exposed and more complete Marrat reference section at Khashm adh Dhibi was described at one-meter intervals by R.W. Powers and H.A. McClure and published in Powers et al. (1966, Figure 3). They divided the Marrat Formation into the informal Lower, Middle and Upper Marrat, and Powers (1968) extended the descriptions of these divisions at outcrop and in the subsurface in the *Stratigraphic Lexicon of Saudi Arabia*. In regards to the age of the Marrat Formation, Powers et al. (1966) reported:

> "*Nejdia bramkampi* Arkell and *Hilda/ties sanderi* Arkell were collected from the upper member, the middle member is barren, and lower Marrat beds have yielded *Bouleiceras nitescens* Thevenin, *B. elegans* Arkell, *B. arabicum* Arkell, *B. marraticum* Arkell, and *Protogrammoceras madagascariense* Thevenin. The *Bouleiceras* fauna is considered by Arkell to be lower Toarcian; the *Nejdia* fauna is dated by him as early upper Toarcian."

In the present study, the intervals that yielded the faunas are referred to as the 'Bouleiceras horizon' and 'Nejdia horizon'.

2.2 BRGM (1980s and 1990s)

During the 1980s and 1990s the Saudi Arabian Deputy Ministry for Mineral Resources (DMMR) contracted France's geological survey, BRGM, to map and evaluate the mineral resources of parts of the Proterozoic Arabian Shield and adjacent Phanerozoic cover rock. The maps were published by the DMMR at 1:250,000 scale with explanatory notes. The BRGM geologists mapped the Marrat Formation in the eight quadrangles in which it crops out and measured and described it in 23

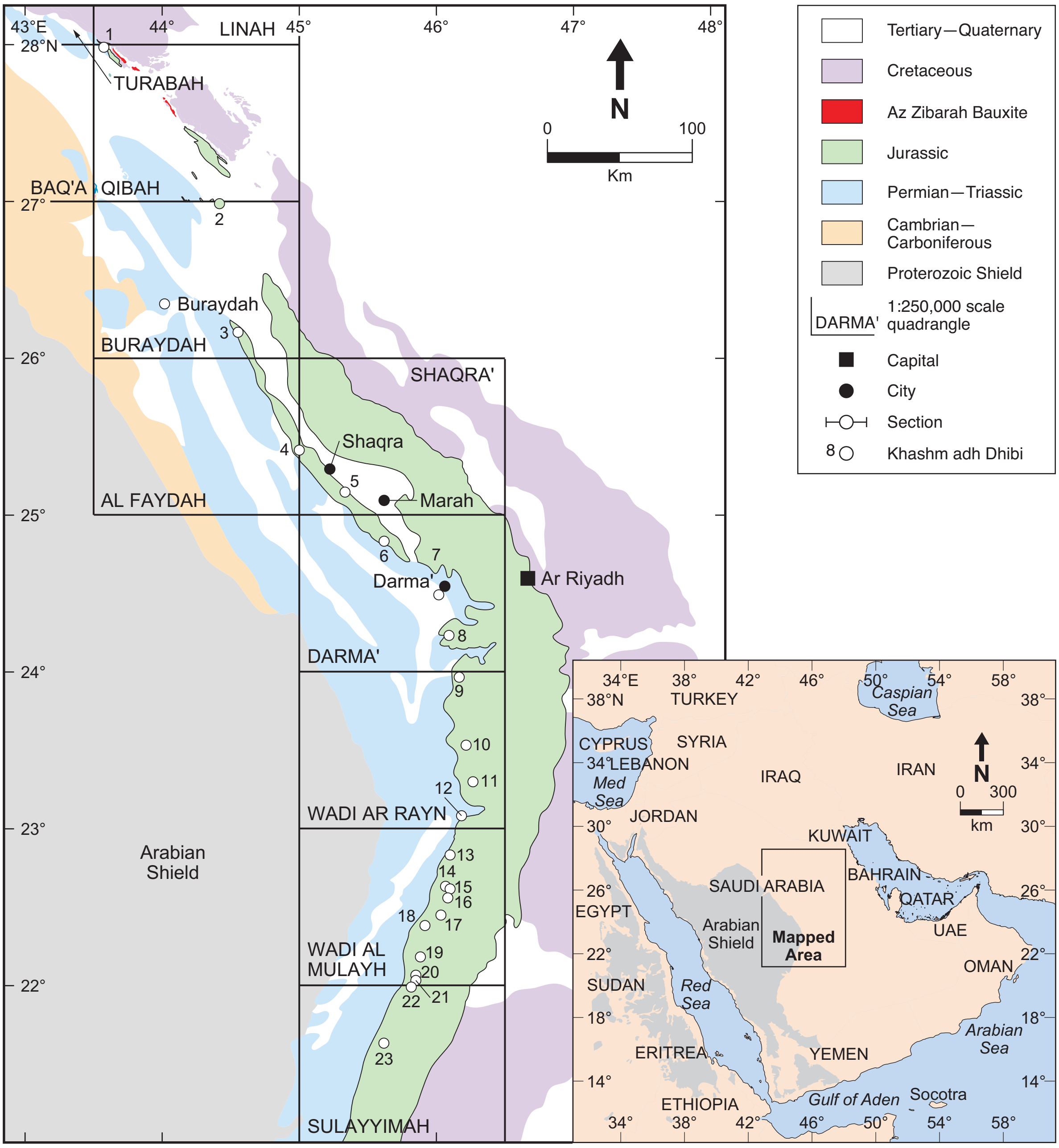


Figure 2: Phanerozoic outcrop belts in Central Saudi Arabia and 1:250,000-scale quadrangles in which the Toarcian Marrat Formation was mapped by France's geologic survey BRGM, and published by Saudi Arabia's Deputy Ministry of Mineral Resources (DMMR, now the Saudi Arabian Geological Survey, SGS). The Marrat Formation was described in 23 measured sections between latitudes 21°36'N and 28°03'N (see Table 1).

sections (Figure 2). Importantly, the Bouleiceras horizon was re-assigned from uppermost Lower Marrat to lowermost Middle Marrat by Vaslet et al. (1983). Also, the Nejdia fauna was assigned to Middle Toarcian instead of Upper Toarcian.

The revised informal definitions of the three Marrat subdivisions were adopted by BRGM geologists in the 23 sections and eight quadrangles; from north to south: Qibah (Robelin et al., 1994), Buraydah (Manivit et al., 1986), Al Faydah (Vaslet et al., 1985a), Shaqra' (Vaslet et al., 1988), Darmā where the Khashm adh Dhibi reference section is situated (Manivit et al., 1985a); Wadi Ar Rayn (Vaslet et al., 1983); Wadi Al Mulayh (Manivit et al., 1985b) and Sulayyimah (Vaslet et al., 1985b). The 23 sections represent a traverse along depositional strike that extends approximately 800 km between latitudes 21°36'N in the Sulayyimah Quadrangle, and 28°03'N in the southwest corner of the Linah Quadrangle, where the Marrat is one of the hosts of the Az Zabirah bauxite (Figure 2, Table 1).

The BRGM project was supported by the identification and dating of the Bouleiceras and Nejdia ammonite faunas as Early and Middle Toarcian, respectively (Énay and Mangold, 1985, 1994, 2021; Énay et al., 1987; Table 2), and the stratigraphy was described in the legends of the maps (Figure 4). The mapping project was also supported by a comprehensive sampling and laboratory analyses of petrology, micropaleontology, macrofauna, chemistry and mineralogy.

Table 1: Marrat Formation Sections

	Section	Quadrangle	Base	Top
1	Qa` al Hifnah	Qibah	27°59', 43°33'	28°00', 43°36'
2	Nafud al Mazhur	Buraydah	26°55',44°13'	26°58', 44°25'
3	Jabal ar Rukhman	Buraydah	26°15', 44°32'	26°15', 44°34'
4	Jabal Ghurab	Al Faydah and Shaqra'	25°25', 44°55'	25°25', 45°08'
5	Khashm an Numayrah	Shaqra'	25°10', 45°13'	25°12', 45°20'
6	Khashm Munassa	Darma'	24°51', 45°33'	24°53', 45°43'
7	Graben Awsat	Darma'	24°28', 46°00'	24°31', 46°02'
8	Khashm adh Dhibi	Darma'	24°13', 46°05'	24°15', 46°06'
9	Khashm al Jufayr	Wadi ar Rayn	23°58', 46°10'	
10	Khashm al Khalta	Wadi ar Rayn	23°32', 46°13'	
11	Khashm Birk	Wadi ar Rayn	23°18', 46°16'	
12	Khashm al Hadafiyah	Wadi ar Rayn	23°05', 46°11'	
13	Khashm Mawan	Wadi al Mulayh	22°49'56", 46°05'49"	
14	Khashm al Fardah West	Wadi al Mulayh	22°37'58", 46°04'25"	
15	Khashm al Fardah South	Wadi al Mulayh	22°37', 46°06'07"	
16	Khashm al Juwayfah	Wadi al Mulayh	22°33'44", 46°04'58"	
17	Fara'id al Ahmar	Wadi al Mulayh	22°26'18", 46°01'41"	
18	Khashm Musayyifiyah	Wadi al Mulayh	22°23'08", 45°55'25"	
19	Khashm Munayyifiyah	Wadi al Mulayh	22°11'02", 45°53'03"	
20	Khashm Aba al 'Iqban	Wadi al Mulayh	22°04'04", 45°50'49"	
21	Jabal Fahhamah	Wadi al Mulayh	22°02'04", 45°51'17"	
22	Khashm Abu al Jiwar	Sulayyimah	21°59'37", 45°49'09"	
23	Khashm al Mukassar	Sulayyimah	21°38'46", 45°38'05"	

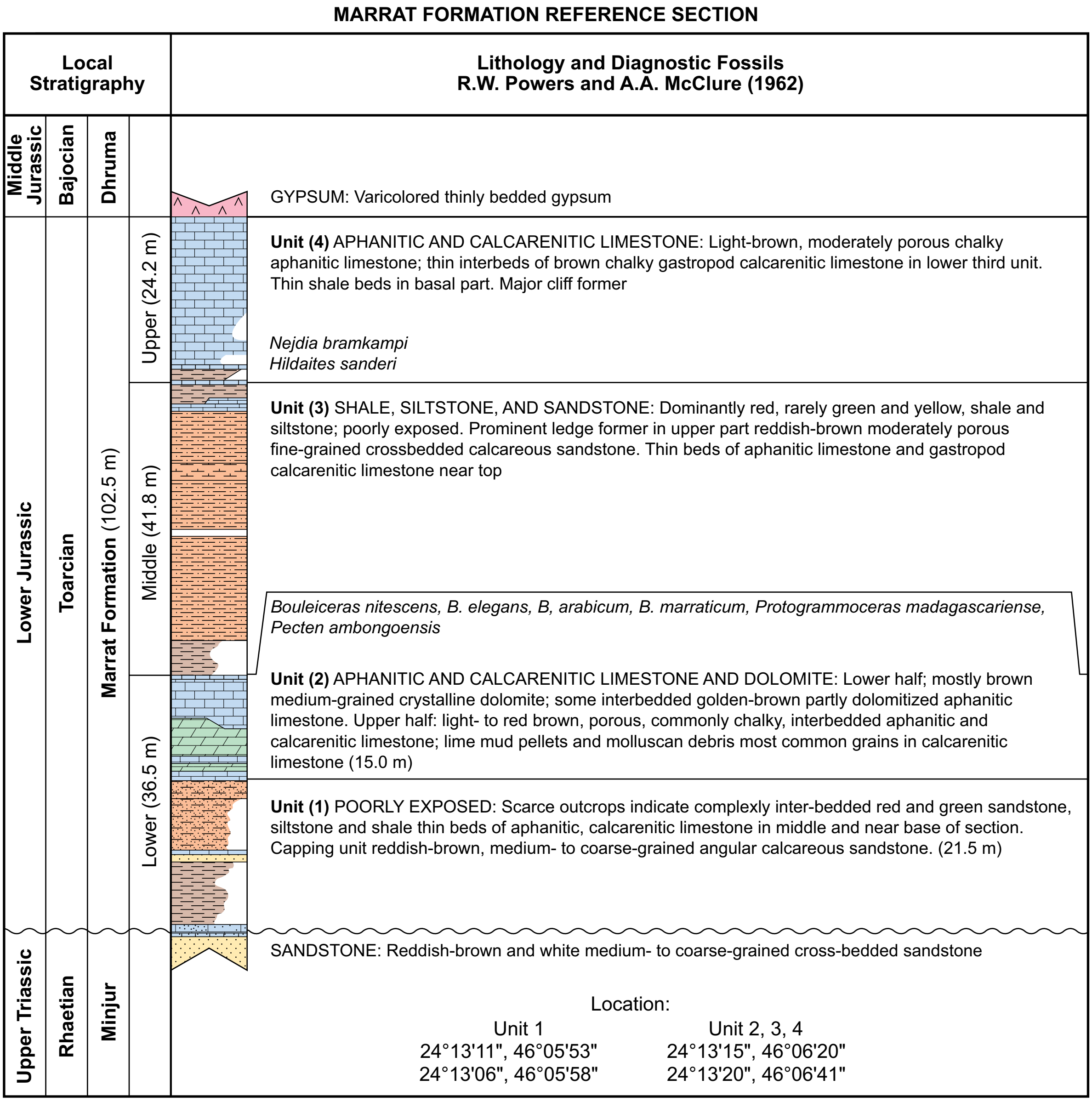


Figure 3: Marrat Formation in Khashm adh Dhibi reference section as measured and described by R.W. Powers and H.A. McClure and published in Powers et al. (1966).

2.3 Sequence Stratigraphy (1990 to Present-day)

Le Nindre et al. (1990a, b) were the first authors to interpret Saudi Arabia's Jurassic and Cretaceous formations as T-R sequences, and to correlate them to the global sequence and eustatic framework of Haq et al. (1987, 1988). They dated the Bouleiceras horizon as Early Toarcian (*falciferum* zone = *serpentinum* zone) and the Nejdia horizon as Middle Toarcian (*bifrons* zone), which in the chart of Haq et al. (1988) implied the Marrat corresponds to the lower part of global Toarcian Sequence UAB-4.3. Regional correlations of the Marrat Formation to units in other Arabian Plate countries and the global framework were presented by other authors (e.g., Grabowski and Norton, 1995; Al-Husseini, 1997).

2.4 Maximum Flooding Surface MFS J10 (2001 to Present-day)

At the turn of the century, Sharland et al. (2001) presented a chrono- and sequence-stratigraphic framework for the Arabian Plate consisting of 63 timelines represented by isochronous maximum flooding surfaces (MFS). The type section of each MFS was defined by three variables with supporting figures, tables and references:

- the position of the MFS in a section or borehole based on local lithostratigraphic definitions;
- age-diagnostic fauna and its relative age in a Stage (i.e., early, middle, late);
- numerical age according to the geologic time scale GTS 1996 (Gradstein and Ogg, 1996), and the global framework of Haq et al. (1988).

In the entire Early Jurassic Sharland et al. (2001) defined just one MFS, named J10, with its type section in the Upper Marrat in Central Saudi Arabia. They positioned Toarcian MFS J10 in the Nejdia horizon that yielded the ammonites *Nejdia bramkampi* and *Parahildaites sanderi* dated in the *bifrons* zone (Enay et al., 1987, 1994; Enay and Mangold, 1994; Fischer et al., 2001).

Sharland et al. (2001) also identified candidates for MFS J10 in formations in ten other Arabian Plate countries, and estimated its age as 185.0 Ma in GTS 1996 (Gradstein and Ogg, 1996). Several authors adopted the Middle Toarcian *bifrons* zone for MFS J10 (e.g., Haq and Al-Qahtani, 2005; Al-Mojel et al., 2017, 2019). According to GTS 2020 (Hesselbo et al., 2020) the age of base *bifrons* zone is c. 181.0 Ma.

Higher up in the succession, Sharland et al. (2001) positioned Lower Bajocian MFS J20 in the lower part of the Middle Jurassic Dhruma Formation. They intentionally left MFS J01 to J09 and MFS J11 to MFS J19 open so that they could be used for MFSs that may be recognized in future studies.

The significance of the integer ‘10’ in MFS J10, however, has been mis-interpreted by some authors to imply it should be positioned in the most open-marine interval with abundant and diverse Toarcian faunas. In the absence of a formal procedure for naming a new MFS or revising the definition of a named MFSs, some authors repositioned MFS J10 in the Bouleiceras horizon (instead of the Nejdia horizon) and assigned it to the Lower Toarcian *serpentinum* zone (Kadar et al., 2015, Simmons and Davies, 2018).

Choosing the precise stratigraphic position of an MFS in a stratigraphic section can be problematic. According to the schematic eustatic cycle in Figure 1 the MFS occurs near the end of the rapid RSL rise (i.e., top of transgressive systems tract, TST, transgression, T); however, this position is generally difficult to determine without regional traverses and seismic data. Furthermore, some authors assign MFS J10 to Lower Marrat while others to Middle Marrat without specifying whether they are using the lithostratigraphic scheme of Powers et al. (1966) or Vaslet et al. (1983).

Currently several sources of confusion occur in regards to MFS J10. These are summarized below, together with our proposed clarifications and further discussed in more detail in this study.

Is the Bouleiceras horizon in Lower or Middle Marrat? We propose the three Marrat subdivisions as defined by Vaslet et al. (1983), and adopted in this study, be raised to formal Members. As such, the Bouleiceras horizon occurs in lowermost Middle Marrat Member.

Should MFS J10 be positioned near the Bouleiceras or Nejdia horizon? We propose retaining MFS J10 as defined by Sharland et al. (2001) in Saudi Arabia near the Nejdia horizon. We follow Al-Mojel et al. (2019) and name the MFS at base Bouleiceras horizon MFS J09. As discussed in Chapter 5 our chosen positions for MFS J09 and MFS J10 differ from those of Al-Mojel et al. (2019).

Is the *bifrons* zone (Nejdia horizon) Middle or Upper Toarcian? According to GTS 2020 (Hesselbo et al., 2020), “There is no agreement on the number of substages of the Toarcian.” We adopt the three-substage division (e.g., Groupe Français d’Étude du Jurassique, 1997), which groups the *tenuicostatum* and *serpentiunm* zones in Early Toarcian, the *bifrons* and *variabilis* zones into Middle Toarcian, and places the limit of the Upper Toarcian at the base of the *thouarsense* zone.

What is the stratigraphic position of MFS J10 in the Khashm adh Dhibi section? We position MFS J10 at the top of the Nejdia horizon.

In which global T-R sequence does MFS J10 occur? If MFS J10 is positioned at the top of the Nejdia horizon, which is dated as basal *bifrons* zone, then according to the most recent compilation of Jurassic T-R sequences (Haq, 2018) it would occur in Sequence JTo3.

Should the numerical age of MFS J10 be revised from 185 (Sharland et al., 2001) to 181 Ma according to GTS 2020? If MFS J10 is positioned in basal *bifrons* zone, then its age should be younger than c. 181 Ma. The *serpentinum-bifrons* zonal boundary is estimated by cyclostratigraphy at c. 180.4 Ma in GTS 2016 (Ogg et al., 2016), 181.17 Ma in GTS 2020 (Hesselbo et al., 2020), and 180.9 Ma (Ruebsam and Al-Husseini, 2021). The zonal boundary is constrained by U-Pb dating at 180.9 ± 0.5 Ma (Mazzini et al., 2010; corrected by Corfu et al., 2016).

2.5 High-resolution Marrat Sequences (2018 and 2019)

The high-resolution sequence architecture of the Marrat reference section at Khashm adh Dhibi was recently interpreted in two articles. In the first article, Farouk et al. (2018) characterize the formation in terms of three sequences and fourteen 'small cycle sets'; however, a comparison of the lithofacies descriptions, positions and thicknesses of key units differ significantly from the field observations documented in the present study. In the second article, Al-Mojel et al. (2019) characterize the formation in terms of two 'composite sequences', each consisting of five 'high-frequency sequences' (HFS). Both studies chose positions for sequence stratigraphic surfaces (SB, MFS) that are significantly different.

2.6 Scope of the Present Study

In Chapter 3 of this study the Khashm adh Dhibi reference section is described in detail and presented side-by-side with a panoramic photo of the nearly vertical Dhibi Escarpment in order to accurately identify its members, units and subunits in the measured reference section (Figures 4 and 5, Photo 1). The positions and ages of the Bouleiceras and Nejdia horizons are pinpointed in the reference section. In Chapter 4 the Marrat lithofacies, depositional environments and T-R sequences are interpreted together with the results of the laboratory analyses of samples (prefixed by JMA-82, and their stratigraphic positions are shown in Figures 5 and 6). Chapter 5 discusses several pitfalls largely caused by the ambiguous terminology and concepts of sequence stratigraphy as evident in the conflicting interpretations of the Marrat reference section.

3. MARRAT REFERENCE SECTION AT KHASHM ADH DHIBI

The Khashm adh Dhibi locality not only provides the best-exposed and one of the most representative Marrat sections, but also it is the most extensively studied Toarcian section. Between December 1981 and February 1982, Y.M. Le Nindre, C. Cavelier, J. Manivit, D. Vaslet and J.M. Brosse measured and described in great detail the Marrat reference section (Figures 4 and 5, Photos 1 to 5), and their observations are summarized in the Explanatory Notes of the 1:250,000-scale geological map of the Darmā Quadrangle (Manivit et al., 1985a; Figure 2).

3.1 Lithostratigraphy and Biostratigraphy

In the following discussion the three informal divisions of the Marrat Formation as defined by Vaslet et al. (1983) are referred to as 'Members'. Besides the Bouleiceras and Nejdia horizons, other subdivisions are referred to as Units, Subunits and beds. Throughout this article the positions of surfaces are cited to the nearest meter above the base of the Marrat Formation, and thicknesses of members, units and subunits are cited to a resolution of better than one meter.

3.1.1 Lower Marrat Member

The 47 meter-thick Lower Marrat Member lies on the Minjur Sandstone and is subdivided into Units (1) to (4) (Figures 4 and 5a; Photos 1 and 2). Powers et al. (1966) placed its upper boundary at the base of their Middle Marrat Unit (4) at 36.5 m in their measured section (Figure 3), which corresponds to the base of the 'Red Claystone' at 51 m [Middle Marrat Unit (2a,), Figure 5a, Photo 1).

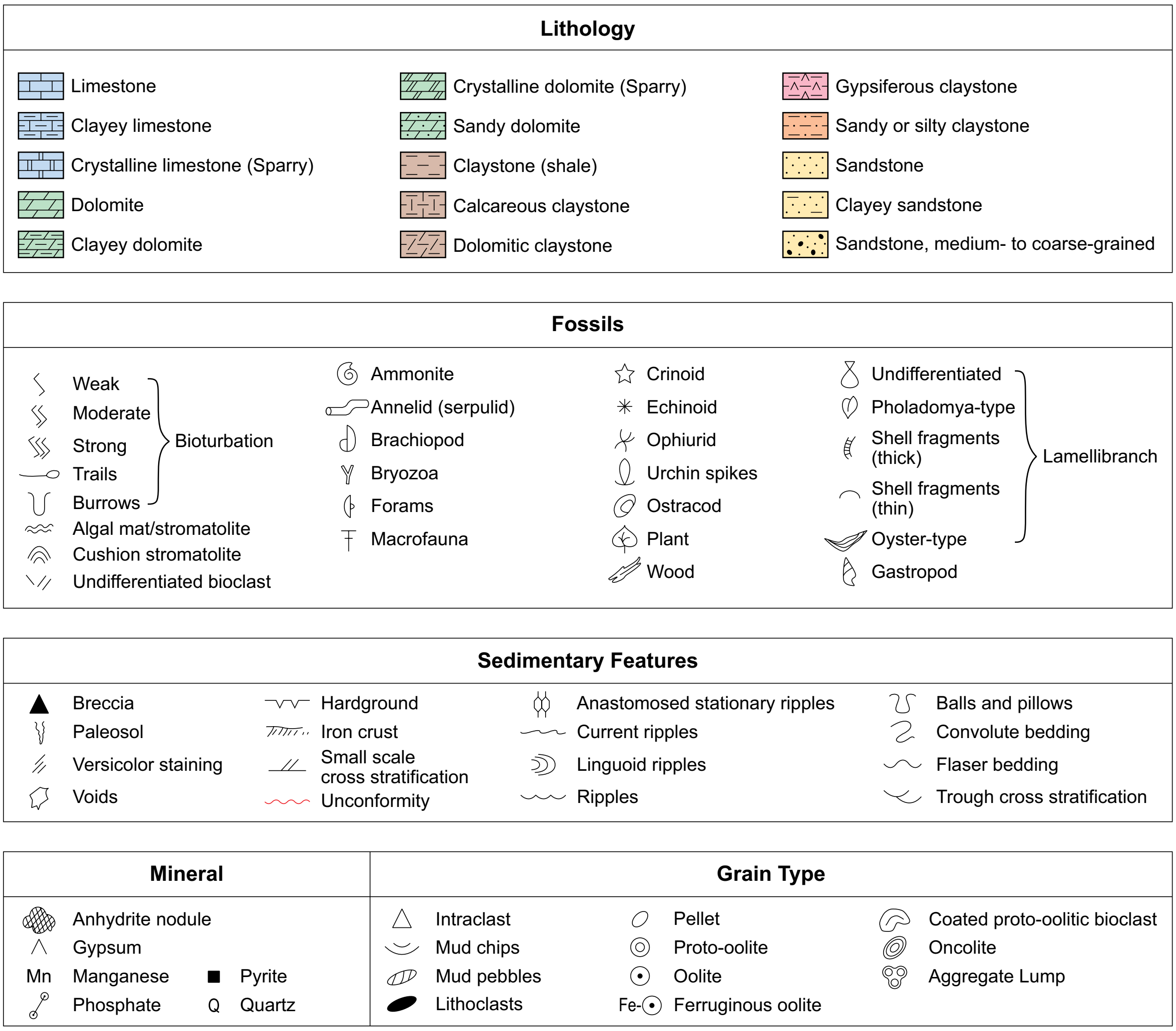


Figure 4: Legend showing lithofacies, and symbols representing fossils, sedimentary features, minerals and grain type in Figure 5. Symbols in parenthesis indicate less frequent occurrence.

Table 2: Ammonite Zonation

		Northwest Europe		Mediterranean		Saudi Arabia		
		Zone	Subzone	Zone	Subzone	Fauna	Zone-Subzone	
Toarcian Stage	Middle (part)	*Hildoceras bifrons*	*Hildoceras bifrons*	*Hildoceras bifrons*	*Hildoceras bifrons*			
			Hildoceras sublevisoni		*Hildoceras sublevisoni*	*Nejdia Parahildaites*	*Bramkampi*	
	Lower	*Harpoceras serpentinum*	*Harpoceras falciferum*	*Hildaites levisoni*	*Harpoceras falciferum ?*		*Nitescens*	
			Eleganticeras elegantulum (exaratum)		*Hildaites levisoni*	Protogrammoceras Bouleiceras		*Madagascariense*
		Dactylioceras tenuicostatum	*Dactylioceras semicelatum*	*Dactylioceras polymorphum*	*Dactylioceras semicelatum*	?		
			Paltarpites paltus		*Eodactylites mirabile*			

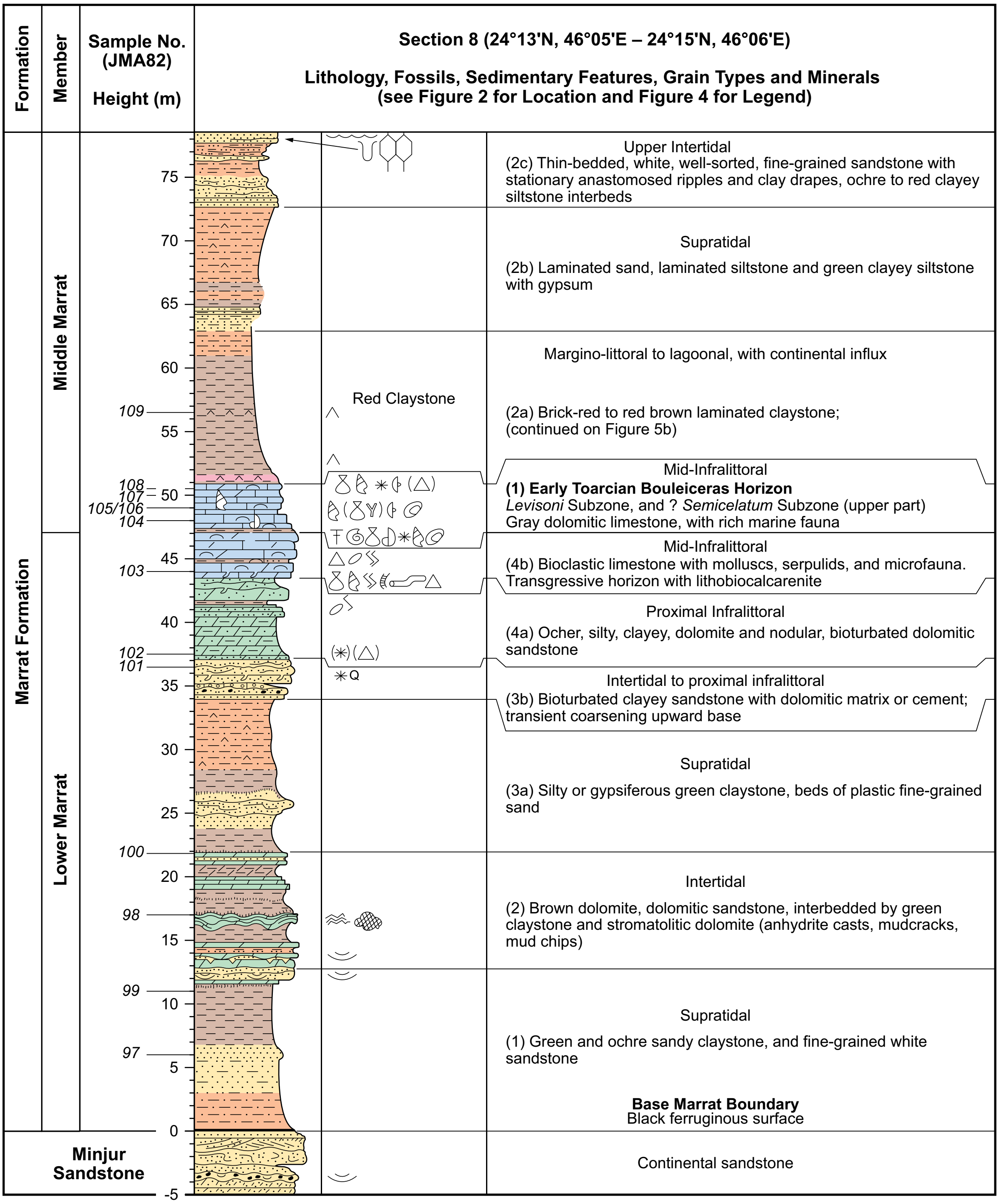


Figure 5a: Lower Marrat Member and lower part of Middle Marrat Member in Khashm adh Dhibi reference section as measured and described between December 1981 and February 1982 by Y.M. Le Nindre, C. Cavelier, J. Manivit, D. Vaslet and J.M. Brosse (BRGM authors). Sample numbers shown in left-side column are prefixed 'JMA82' in Chapter 3.

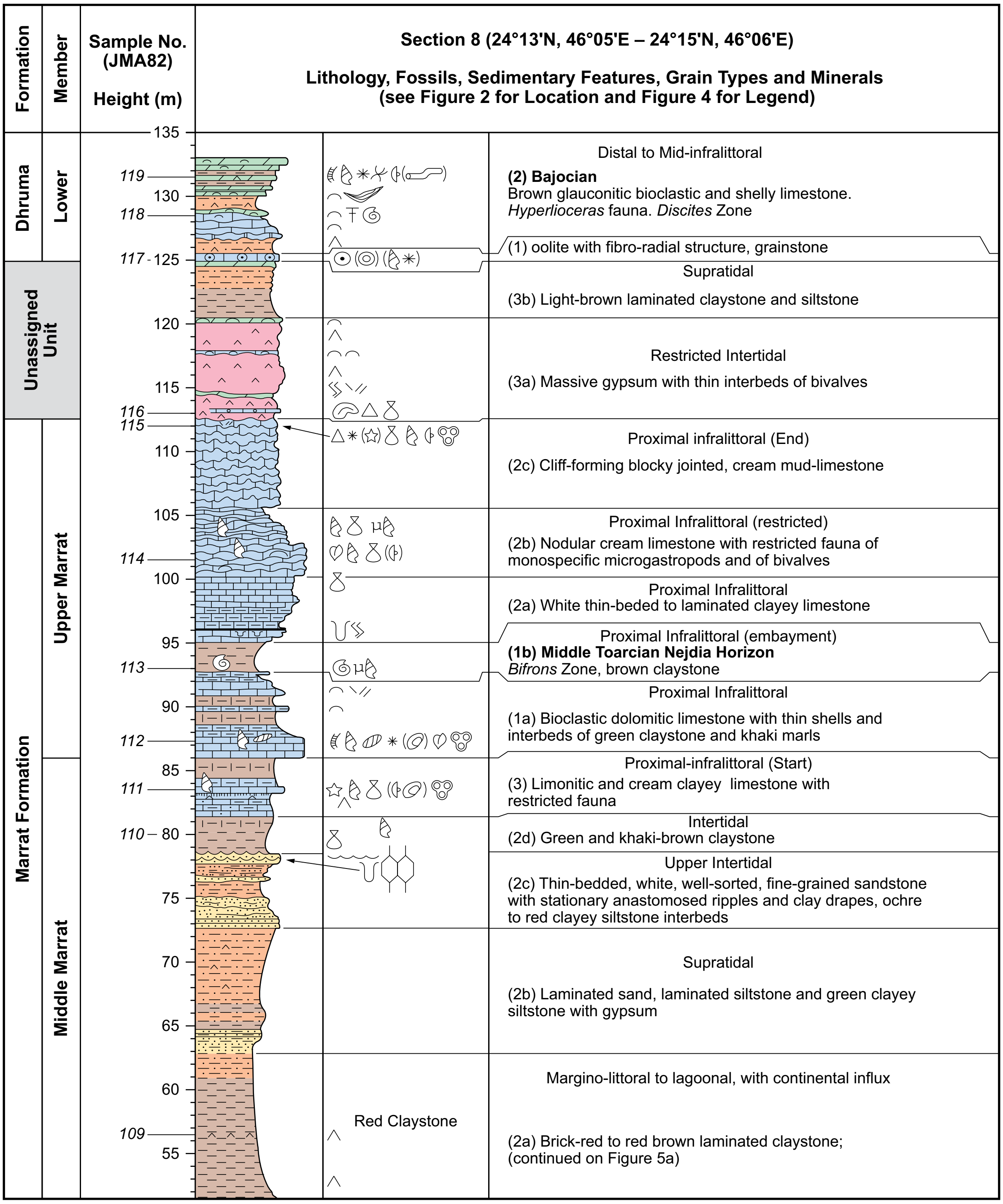


Figure 5b: Upper part of Middle Marrat and Upper Marrat Members in Khashm adh Dhibi reference section as measured and described between December 1981 and February 1982 by Y.M. Le Nindre, C. Cavelier, J. Manivit, D. Vaslet and J.M. Brosse.

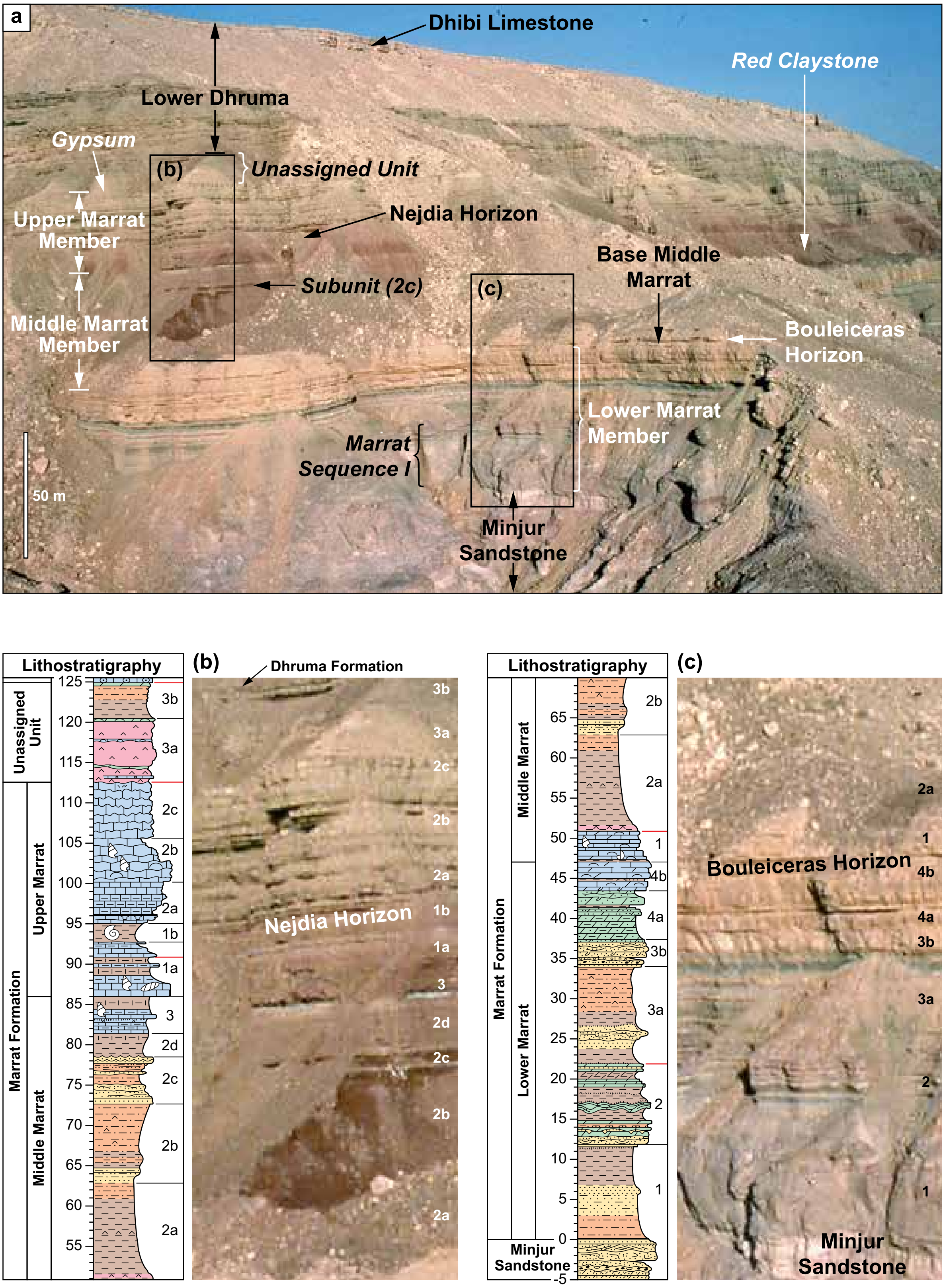


Photo 1: (a) Panoramic photo of the Dhibi Escarpment taken from a helicopter showing the upper Minjur Sandstone, Marrat Formation and Lower Dhruma. The Middle Dhruma crops out in the overlying plateau and hills, and farther west the Upper Dhruma and Tuwaiq Mountain Limestone form the Tuwaiq Mountain Escarpment. The Dhibi Escarpment is most prominent in the Darma', Wadi ar Rayn and Wadi al Mulayh Quadrangles; south of 21°45'N in the Sulayyimiyah Quadrangle it merges with the Tuwaiq Mountain Escarpment (Figure 2). **(b and c)** Comparison between the reference section measured at Khashm adh Dhibi locality and two extracts from Photo (a).

The 14.5-meter difference for the Marrat thickness beneath the Red Claystone (51 m *versus* 36.5 m) is due to the poor exposure of the outcrop (Figure 3, Powers et al., 1966; Photos 1 and 2).

3.1.2 Middle Marrat Member

The Middle Marrat Member *sensu* Vaslet et al. (1983) is 39 m thick and subdivided into Units (1) to (3) (Figure 5a; Photos 1 to 4). Powers et al. (1966) included the 4-meter thick Middle Marrat Unit (1) in uppermost Lower Marrat, and estimated their Middle Marrat thickness as 41.8 m (Figure 2). Middle Marrat Unit (1) is the Bouleiceras horizon, which yielded the rich marine Bouleiceras fauna (Arkell, 1952; Powers et al., 1966; Énay and Mangold, 1985, 1994, 2021; Énay et al., 1987; Figures 3 and 5a, Table 2).

In the reference section the Bouleiceras horizon yielded *Protogrammoceras madagascariense* Thevenin, and in the more fossiliferous Khashm al Jufayr Section (Section 9, Figure 2) the Bouleiceras fauna includes *Bouleiceras elegans* Arkell (16 specimens), *B. nitescens* (1 specimen), *B. arabicum* (5 specimens), *B.* cf. *rochi* (1 specimen), *B.* sp. ind. (32 specimens), and *Protogrammoceras madagascariense* Thevenin (41 specimens) (Énay et al., 1987; Énay and Mangold, 2021). In the Khashm al Jufayr and in other sections, the horizon also contains a rich marine fauna with bryozoans, echinoids, and the brachiopod *Liospiriferina undulata* (Seguenza, 1985). Abundant sea urchins and brachiopods are visible at the surface of the grey limestone. The concentration of this fauna may have preceded an extinction event marked at the base of the Red Claystone.

According to biostratigraphic studies (Énay and Mangold, 1985, 1994, 2021; Énay et al., 1987; Howarth, 2013; Table 2) the Bouleiceras fauna is correlated to the lower *H. levisoni* subzone of the *H. levisoni* zone, and possibly to the upper part of the *D. semicelatum* subzone of the *D. polymorphum* zone in the Mediterranean region. In Northwestern Europe, the Bouleiceras fauna is correlated to the *E. elegantulum* subzone of the *H. serpentinum* zone and possibly to the upper part of *D. semicelatum* subzone of the *D. tenuicostatum* zone.

The carbonates of the Lower Marrat Subunit (4b) and Middle Marrat Unit (1) contain a marker microfauna of characteristic foraminifers: *Glomospira, Pseudocyclamina liassica, Epistomina*, and other species. *P. liassica* is not found above Middle Marrat Unit (1) and is reminiscent of the Lower and Middle Liassic in the Neo-Tethyan realm (Bassoulet et al., 1985) and characteristic of the Pliensbachian (Septfontaine, 1981). The association of *P. liassica* with the Bouleiceras fauna indicates it extends to the Lower Toarcian in Saudi Arabia.

Beneath the Bouleiceras horizon, the Lower Marrat Member was assigned to the Lower Toarcian (e.g., Powers, 1968; Manivit et al., 1985a), however the Pliensbachian/Toarcian Boundary is not constrained by biostratigraphy in Saudi Arabia and may occur in lowermost Marrat Formation.

Above the Bouleiceras horizon, the Middle Member consists of the monotonous and laminated Red Claystone [Subunit (2a), Red Shale], the most readily recognized Marrat subunit in the outcrop belt (Photos 1 to 4). Unit (2) is 32 m thick in the reference section; in the Darmā Quadrangle it ranges between 32 and 42 m, and in the subsurface between 25 and 60 m ('Marrat Marker' *sensu* Saudi Aramco). The upper boundary of the Middle Marrat Member is positioned beneath a 2 meter-thick dolomite bed at 86 m.

3.1.3 Upper Marrat Member

The Upper Marrat Member *sensu* Powers et al. (1966) is about 26.5 m thick (Figures 3 and 5b; Photos 1 and 4); it includes the Nejdia horizon, which is characterized as a brown, or brown and green claystone [Subunit (1b)] between 93 and 95 m. From this interval the first four authors of this study collected the ammonites *Nejdia bramkampi* Arkell (200 specimens including fragments), and *Parahildaites sanderi* Arkell (27 specimens, associated with abundant microgastropods; Figure 5b).

The Nejdia fauna is correlated to the early Middle Toarcian *H. sublevisoni* subzone of the *H. bifrons* zone (Arkell, 1952; Powers et al., 1966; Énay and Mangold, 1985, 1994, 2021; Énay et al., 1987; Howarth 2013; Table 2). Above the Nejdia horizon, Unit (2) is c. 17.5 m thick (between 95 and 112.5

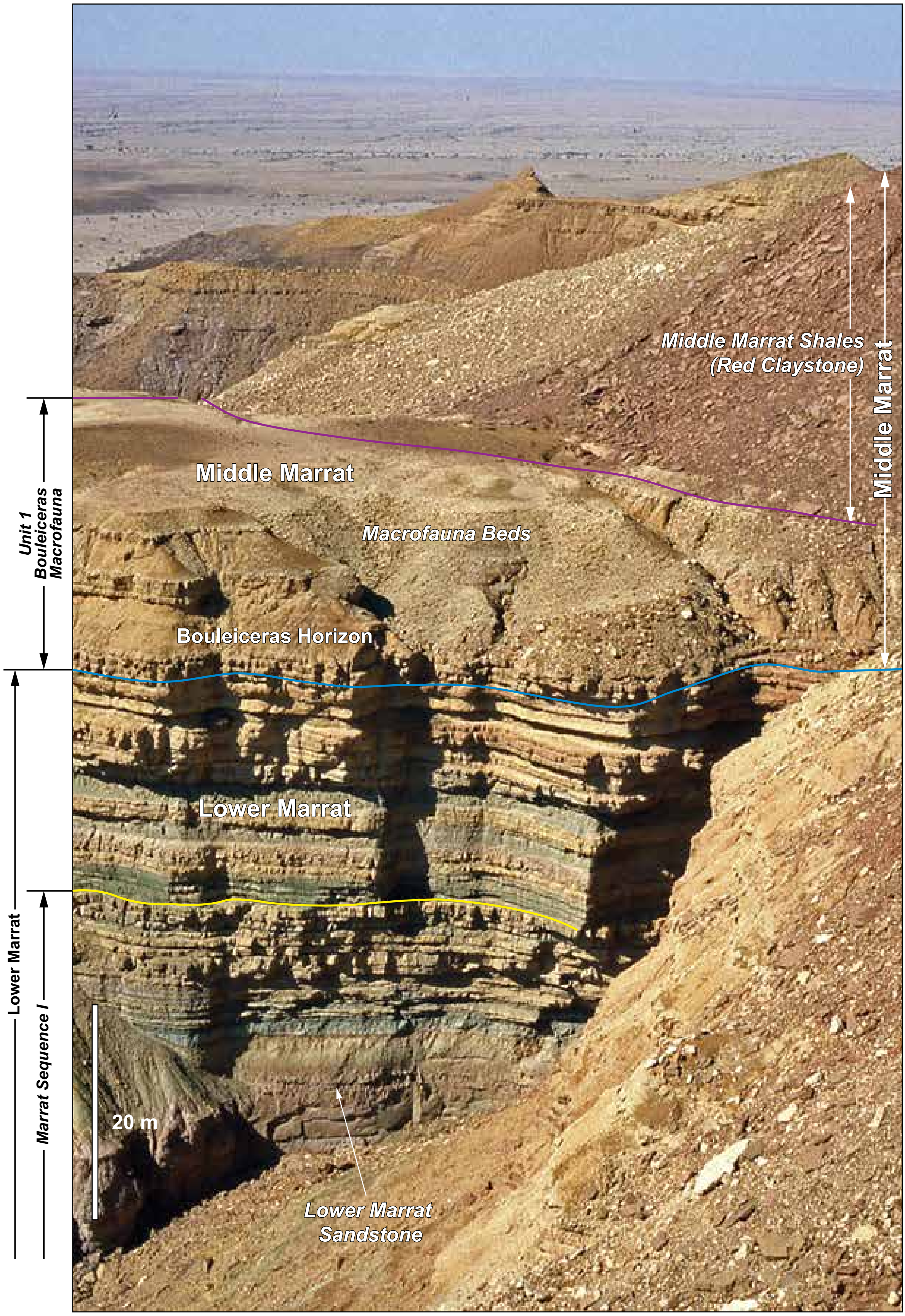


Photo 2: Lower Marrat Member, South Khashm adh Dhibi area, Darma' Quadrangle (photo by Y.M. Le Nindre). The top of transgressive Marrat Sequence I (sandstone to carbonate) is marked by widespread stromatolitic horizons.

m) and consists of clayey limestone, and cream limestone containing a restricted fauna of molluscs, rare foraminifers that inhabited a shallow protected lagoon (*Textulariideae, Ataxophramiideae, Ophtalmiideae*) and bioclasts: common echinoderms and shell debris (Figure 5b).

Unit (3) occurs between 112.5 and 125 m and is here referred to as the **Unassigned Unit** (Figure 5b; Photos 1 and 5)**.** Its lower part consists of 7.5 m of massive gypsum with thin bivalves interbeds **[Subunit (3a)]**. Its upper part consists of 5 m of light-brown laminated siltstone and claystone **[Subunit (3b)]** containing continental microflora in the subsurface. Powers (1968) included the Unassigned Unit in the Dhruma Formation (see Chapter 3.2.2).

3.2 Boundaries of the Marrat Formation

3.2.1 Lower Boundary of the Marrat Formation

At outcrop the boundary between the Marrat Formation and underlying Minjur Sandstone is marked by a black ferruginous surface. Powers (1968) interpreted the base of the Marrat Formation as follows:

> "an unconformity of regional scope although little or no section appears to be cut out in the area of outcrop north of 22°30′N nor in adjacent subsurface sections. The maximum effect is shown at Al Haddar in Well ST-21 (21°53′N, 47°58′E) and east of Ghawar, Abqaiq and Dammam fields, where Marrat rests directly on the Jilh Formation (Lower–Middle Triassic) with no intervening Minjur Sandstone (Upper Triassic-Lower Jurassic)".

As described by Powers (1968) the boundary does not appear to represent an erosional unconformity, but rather an onlap surface of regional extent. More recent subsurface data has confirmed that over paleohighs, such as the Qatar Arch, the Minjur and/or older formations are apparently missing by non-deposition (Stewart et al., 2016).

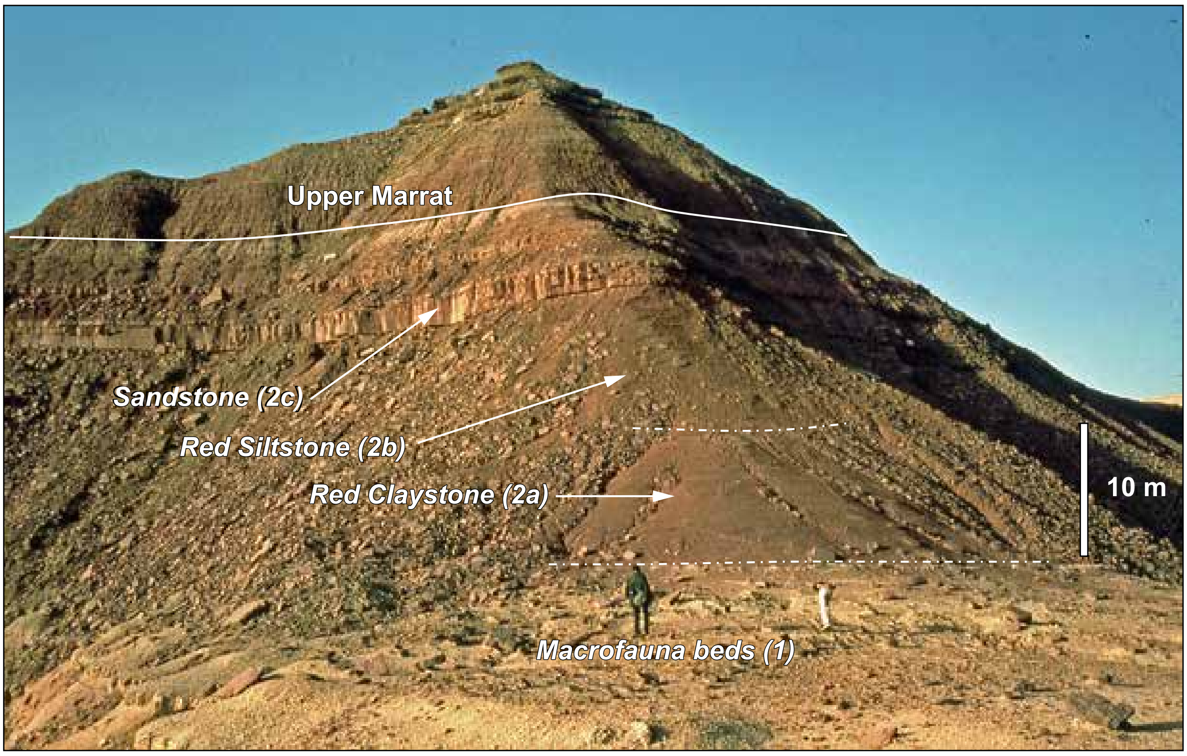


Photo 3: Middle and Upper Marrat Members, South Khashm adh Dhibi area, Darma' Quadrangle (photo by Y.M. Le Nindre). Geologist standing on top of Bouleiceras horizon [Middle Marrat Unit (1)] searching for fossils. Base of Upper Marrat Member is on top of white carbonated bed.

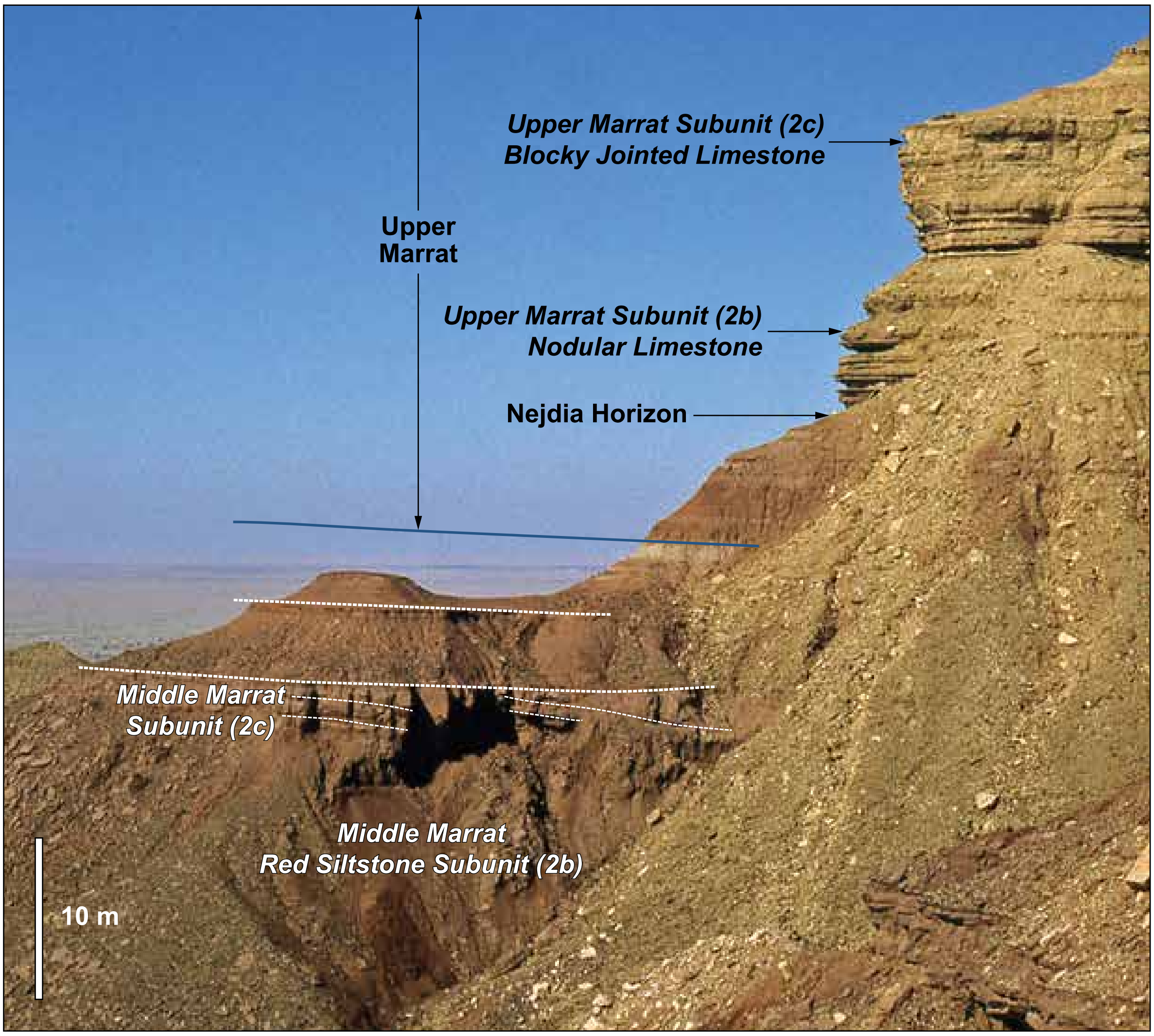


Photo 4: Middle and Upper Marrat Members, South Khashm adh Dhibi area, Darma' Quadrangle (photo by Y.M. Le Nindre). The base of Middle Marrat Subunit (2c) shows small-scale channeling, whereas the top is flat and rippled.

The Bouleiceras fauna in basal Middle Marrat Member is dated as Early Toarcian; i.e., lower *levisoni* subzone (= lower *serpentinum zone*) to latest *semicelatum* subzone (= upper *tenuicostatum zone*). This age indicates the lowermost Marrat probably occurs in Lower Toarcian *tenuicostatum* zone (not identified) or possibly late Pliensbachian from foraminifers. Other studies have considered the underlying Minjur Sandstone as Triassic implying an Early Jurassic hiatus spans the Hettangian, Sinemurian and lower Pliensbachian in Saudi Arabia (e.g., Al-Husseini, 2007; Farouk et al., 2018; Al-Mojel et al., 2019).

An Early Jurassic hiatus, however, is not supported by more recent dating of the uppermost Minjur Sandstone as late Triassic–Pliensbachian based on the recognition of the T0-J Palynozone (N.P. Hooker, *in* Issautier et al., 2019). N.P. Hooker reported the T0-J Palynozone is characterized by pollen and spores including superabundant *Corollina* spp., rare-common *Araucariacites australis*, rare *Callialasporites dampieri*, oldest rare *Callialasporites turbatus*, and persistent and often frequent *Gleicheniidites* spp. throughout.

N.P. Hooker further reported that last down hole occurrence (LDO) of the rare dinocyst *Nannoceratopsis gracilis* in the upper part indicates marginal marine environments, no older than late Pliensbachian (Bucefalo Palliani and Riding, 2003). First down hole occurrence (FDO) of rare-frequent *Dapcodinium priscus* in the middle-lower part indicates marginal-nearshore

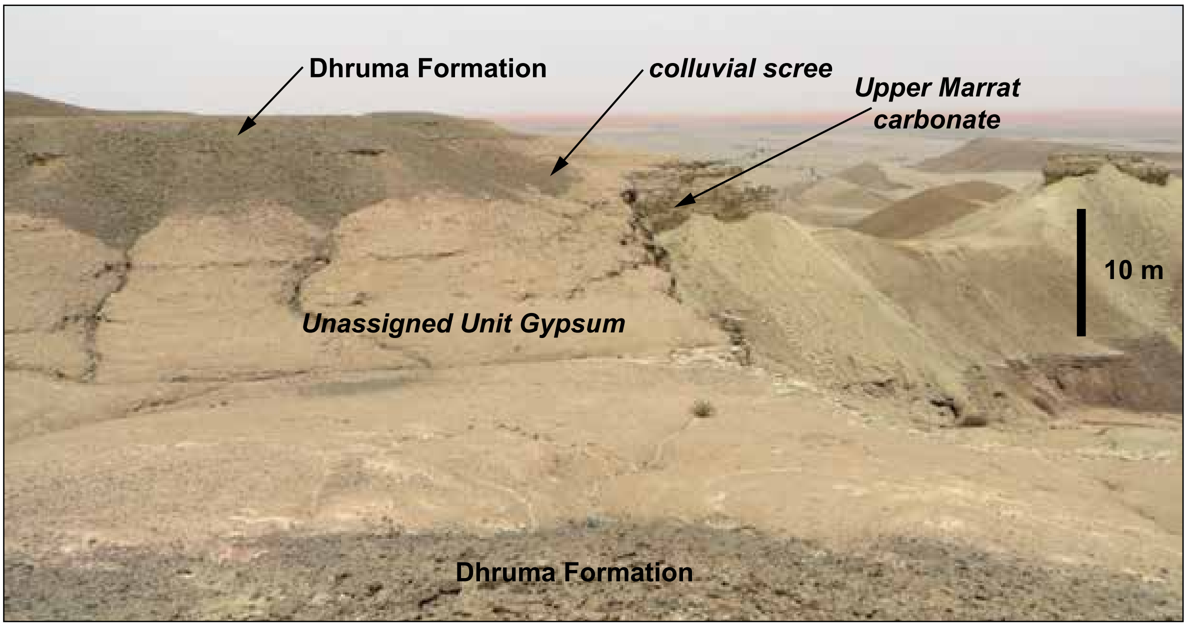


Photo 5: Gypsum of the 'Unassigned Unit' (white) above the Upper Marrat carbonate, Khasm adh Dhibi, Darma' Quadrangle (photo by Y.M. Le Nindre). The upper part of the 'Unassigned Unit' is partially covered by colluvial scree of the Lower Dhruma (grey). The cream interbeds within the gypsum correspond to intermediate coquina beds as shown on the section in Figure 5b.

marine environments, and an age in the range latest Rhaetian–-Pliensbachian. Occurring in this palynozone in central Saudi Arabia is the spore *Kekryphalospora distincta*, which ranges in Europe and Australia as no older than Pliensbachian (Fenton and Riding, 1987; Riding et al., 2010). However, it cannot be totally discounted that the spore *K. distincta* could have been derived from the overlying Marrat Formation.

3.2.2 *Upper Boundary of the Marrat Formation and Unassigned Unit*

The Unassigned Unit (between 112.5 and 125 m, Figure 5b, Photos 1 and 5) represents the transition between of the Marrat and overlying Dhruma Formation in the reference section. It was considered part of the Bajocian Dhruma Formation by Powers et al. (1966, Figure 3) and Al-Mojel et al. (2017, 2019); however, Vaslet et al. (1983) and Manivit et al. (1985a) considered it Upper Marrat Unit (3). In the absence of biostratigraphic indicators this unit was tentatively assigned to an Aalenian regression (Le Nindre, 1990b). The likelihood that the Unassigned Unit is part of the Marrat Formation (followed by a late Toarcian and Aalenian hiatus) is supported by regional correlations in northern Arabia (Sharland et al., 2001, 2004; Haq and Al-Qahtani, 2005).

The Unassigned Unit is overlain by a 10-cm thick grainstone bed characterized by very abundant oolites (diameter of about 250 micrometer) and bioclasts as oolite nuclei. It is referred to as Dhruma Unit (1) because it passes conformably to Dhruma Unit (2), which yielded the Lower Bajocian *Hyperlioceras* fauna. The Dhruma oolitic bed is widely recognized in the Marrat and Dhruma outcrops, whereas the underlying Unassigned Unit only occurs in Khashm adh Dhibi and the nearby Khashm al Jufayr sections. In the latter section nodular chicken mesh (former anhydrite) gypsum beds occur just below the Dhruma oolitic bed. The Khashm al Jufayr gypsum beds are considered the lateral equivalents of the 7.5 m-thick, massive gypsum in the lower part of the Unassigned Unit in Khashm adh Dhibi.

4. MARRAT DEPOSITIONAL SEQUENCES

In this chapter the lithofacies, depositional environments and sequence architecture of the Marrat Formation in the Khashm adh Dhibi reference section are interpreted based on field observations,

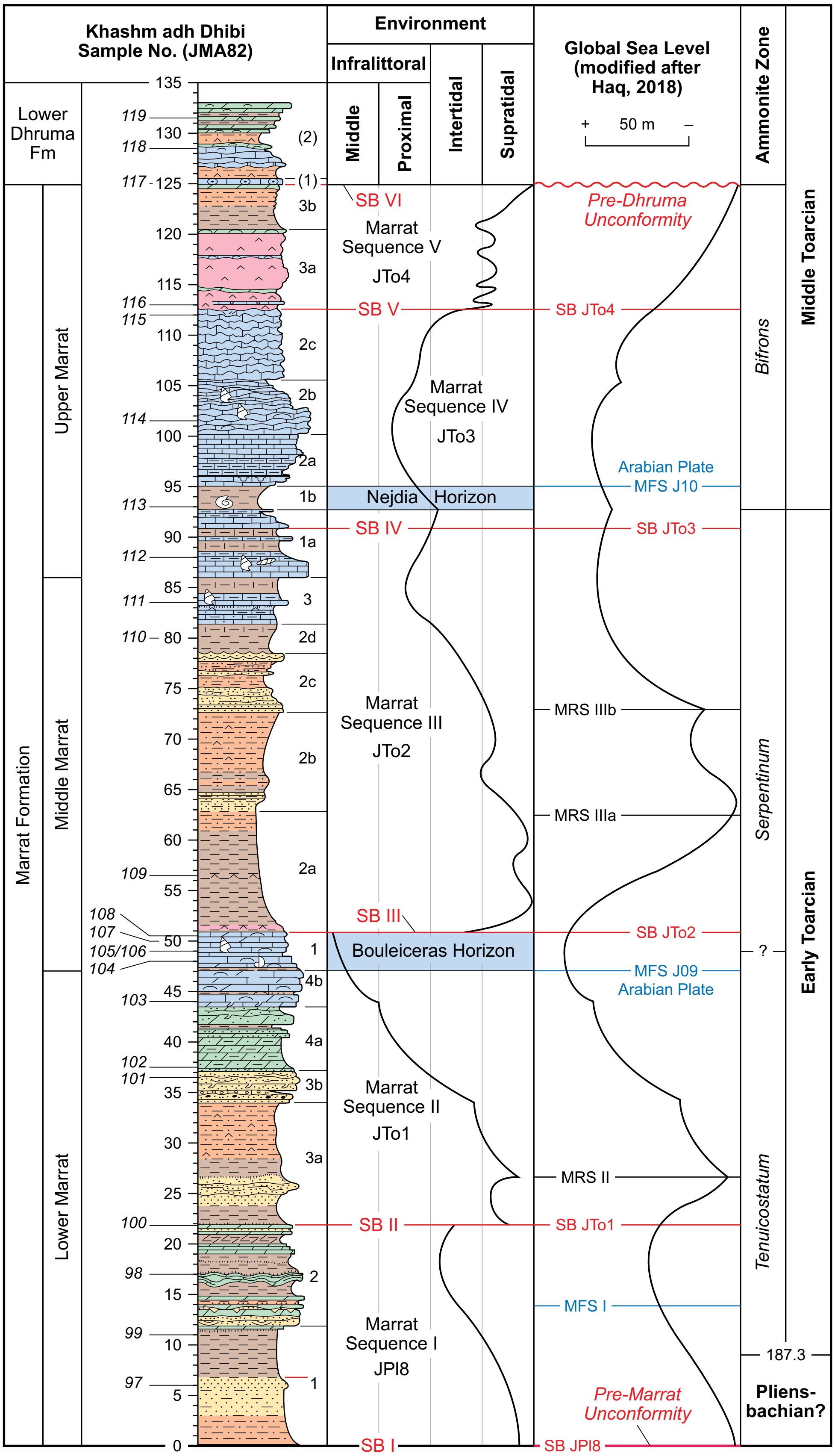


Figure 6: Depositional settings of the Marrat Formation reveal five sequences designated Marrat Sequence I to V that correlate closely to global Sequences JPl8 to JTo4 (Haq, 2018). The Unassigned Unit is interpreted as Marrat Sequence V and the start of a long-term sea level fall that resulted in a late Toarcian and Aalenian hiatus (pre-Dhruma Unconformity). Red lines indicate sequence boundaries SB I to SB VI, blue lines represent maximum flooding surfaces (MFS) and black line maximum regression surfaces (MRS).

as well as on the results of laboratory analyses of samples (prefixed by JMA-82, shown in Figures 5 and 6). Based on sedimentological and lithofacies descriptions the depositional settings of the formation fluctuated between supratidal, intertidal, proximal and middle infralittoral, thus revealing five Marrat sequences and three main eustatic cycles, punctuated by several sequence boundaries (SB), maximum flooding surfaces (MFS) and maximum regressive surfaces (MRS) (Figure 6).

4.1 Marrat Sequence I

In the reference section Marrat Sequence I (c. 22 m thick) consists of Lower Marrat Units (1) and (2) (Figures 5a and 6, Photos 1 and 2). Its lower sequence boundary (SB I) is placed at the pre-Marrat Unconformity between the Minjur Sandstone and Marrat Formation, and its upper sequence boundary (SB II) beneath Lower Marrat Unit (3). **Unit (1)** (c. 12 m thick) consists of green to ochre sandy claystone (siltstone), fine-grained sandstone and claystone deposited in supratidal settings.

Unit (2) (c. 9 m thick, Figures 5a and 6) was sampled at 6 m (Sample JMA82-97) and is azoic with abundant gypsum and quartz. A second sample taken at 17 m (JMA82-98) consists of a former dolomicrosparite, dedolomitized with Fe dolomite and dedolomite in fractures. A sample from 21.8 m (JMA82-100) is a bioturbated mudstone of micrite and dolomicrite with floating quartz grains corroded by the carbonate. Limonitic speck may be former pyrite crystals. Unit (2) includes beds of stromatolitic dolomites, dolomitic sandstones with anhydrite casts, mudcracks, and mudstones with algal laminae, indicating it was deposited in low-energy, brackish intertidal settings.

We interpret Unit (1) as representing a transgression and Unit (2) a high stand, and position MFS I at 12 m between the two units. Marrat MFS I probably occurs in the *tenuicostataum* zone but is not identified or named in the Arabian Plate MFS framework of Sharland et at al. (2001). The eustatic cycle encompassing Sequence I ends in lower Sequence II at maximum regressive surface MRS II (Figure 6).

4.1.1 Stromatolites in Saudi Arabia

Unit (2) contains various types of stromatolites that formed in intertidal to subtidal settings. Logan et al. (1964, 1974) classified stromatolites according to their shapes, colonies and vertical development: (1) laterally linked hemispheroids (LLH); (2) discrete spheroids, either as randomly stacked hemispheroids or concentrically arranged spheroids (SS); and (3) discrete, vertically stacked hemispheroids (SH). Monty (1981, 1994) and more recent authors have complemented this initial classification and discussed its environmental significance. In general, the vertical development is related to tidal range or to water depth and wave energy.

The finest form is internal cryptalgal lamination in mud. In the upper to supratidal domain, thin planar algal mats are intercalated with gypsum or anhydrite, which form 'evaporitic sandwiches' and may give way to 'tepee' deformations by desiccation and crystallization (Plate 1a, b). By further dissolution, algal and mud beds can be fragmented into microbreccia. In other climate settings, the Cyanophyceae can form coatings around plant stems of the salt marsh (Arcachon Bay), or thin mats on the sediment. In the upper-middle intertidal domain, algal mats can develop as planar or undulating stromatolites. If growth and tidal range conditions allow, particularly in the middle-lower intertidal domain, the stromatolite may have a vertical development with bulbous (Plate 1c), or hemispheroid, domal, ball (Plate 1d – LLH, hemispheroid, tending to SS, oncolite), or columnar shapes.

In Saudi Arabia, these shapes are common at the base (columnar SH) and on top (thrombolites) of the Permian-Triassic Khuff Formation, in the Triassic Jilh Formation, Lower Marrat Member, and Bajocian Lower Dhruma Unit D1. In the Jilh, Lower Marrat and in the Lower Dhruma, besides algal mats, other types of stromatolites are mainly of the small LLH form (noted in the legend under the generic term of 'cushion stromatolite', Figure 4), space-linked, or close-linked hemispheroids. They can be close-linked to form colonies in shape of a cushion up to a metric size in the Lower Marrat Mamber (Plate 1e, f) and in the Miocene Dam Formation.

Plate 1: Marrat Sequence I

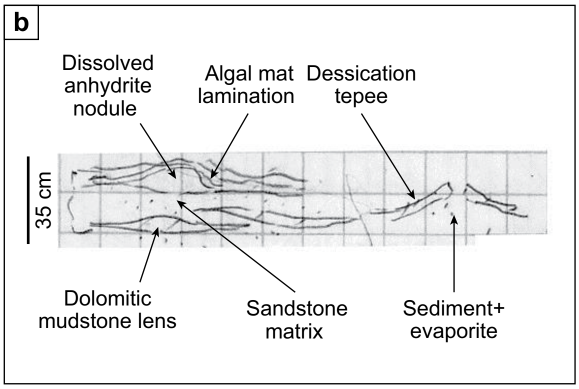


Plate 1: (a) Fine-grained sandstone with dissolved anhydrite nodules and dolomitic mudstone with algal laminae deposited in an upper intertidal setting, near top Marrat Sequence I; **(b)** Field drawing by Y.M. Le Nindre at 26 m above base Marrat Formation Graben Awsat section , Darma' Quadrangle.

Plate 1: (c) Example of bulbous stromatolite, and **(d)** ball stromatolite developed in upper Marrat Sequence I, Darma' Quadrangle.

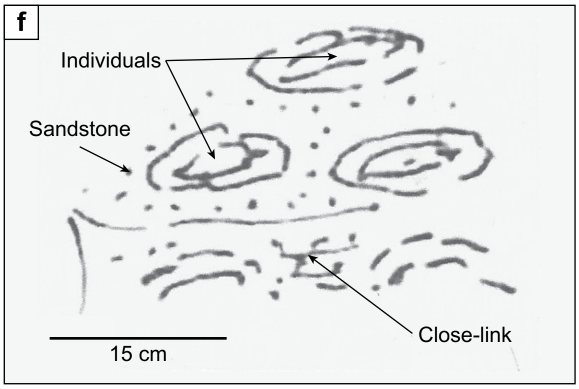


Plate 1: (e) Close-linked stromatolites in cushion emerging from sandstone, top Marrat Sequence I; **(f)** original field drawing by Paul Le Strat (1983), Khashm an Numayrah section, Shaqra' Quadrangle.

Larger-sized stromatolites colonize the lower intertidal and the subtidal domain with metric vertical development, and become real algal mounds involving various types of algae and associated organisms. These latter forms are more common in Paleozoic (algal mound of the Qasr Member of the Devonian Jauf Formation, Dawmat al Jandal) and in the Proterozoic (stromatolites of the Mayghabat Formation (Donzeau and Le Nindre, 1982).

Oncolites are a particular type of spherical stromatolite of various sizes; mostly pisolithic, they can be much larger. The modern opinion gives a larger contribution to more general algal-microbial associations and diagenetic processes in addition to classical blue-green algae (Cyanophyceae/ Cyanobacteria, e.g., Frantz et al., 2015) or other epoch-specific algal developments (e.g. Devonian Renalcis, Pratt, 1984).

4.2 Marrat Sequence II

Marrat Sequence II (c. 29 m thick, between c. 22 and 51 m) consists of Lower Marrat Units (3) and (4) and Middle Marrat Unit (1) (Figures 5a and 6). **Subunit (3a)** (c. 12 m thick, between c. 22 and 34 m, Photo 1) consists of terrestrial clastics and gypsiferous siltstones deposited in supratidal settings. **Subunit (3b)** lies sharply on Subunit (3a) and is about 3 m thick (between c. 34 and 37 m). Its basal part consists of coarse-grained sandstones. Observations made in a nearby pipeline trench show sigmoidal megaripples typically occurring in sandstones deposited in intertidal settings (Plate 2a, b). Based on the analyses of two samples the upper part of Subunit (3b) was deposited in proximal infralittoral settings:

- Sample JMA82-101 (36.5 m) consists of laminated dolosparite and dolomicrosparite with remnants of dolomicrite and ghosts of echinoid debris with syntaxic cement. Quartz (100 to 500 μm) is frequent.

- Sample JMA82-102 (37.5 m) consists of zoned dolosparite with voids partially cemented by geodic euhedral Fe-dolosparite.

Lower Marrat Subunit (4a) (c. 6.5 m thick, between c. 37 and 43.5 m, Figures 5a and 6) consists mainly of dolomite and dolomitic sandstone with rare debris of echinoderms and weak bioturbation. It was deposited in proximal infralittoral settings.

Lower Marrat Subunit (4b) (c. 3.5 m thick, between c. 43.5 and 47 m, Figures 5a and 6) consists of a moderately bioturbated, bioclastic limestone. Sample JMA82-103 (44 m) consists of wackestone with microgastropods and thin lamellibranches with rare echinoids (Plate 2c). Numerous brachiopod shells are encrusted by serpulids; lamellibranches and gastropods shells are often dissolved. Spicles of sponges, skeletal plates of echinoids, and ostracods are also observed. This horizon marks the first upward occurrence of characteristic foraminifers population: *Pseudocyclammina* cf. *liassica*, *Labyrinthina*, *Glomospira*, *Lenticulina*, *Lingulina*, and others. The sediment contains also micritic intraclastes. Subunit (4b) was deposited in mid- infralittoral settings.

Middle Marrat Unit 1 (c. 4 m thick, between c. 47 and 51 m) corresponds to the Bouleiceras horizon, which contains one of the richest fauna in the formation characterized, in particular, by abundant brachiopods and echinoids. Five samples were collected and analyzed from this unit, of which three were for petrographic studies.

- Sample JMA82-104 (48 m) consists of mudstone-wackestone with echinoids: skeletal plates, *Diadema*-type echinoid spines; small debris of brachiopods, hyaline and agglutinating foraminifers, which although not frequent, include *Pseudocyclammina liassica*, *Lenticulina*, *Glomospira*. Ostracods are present.

- Sample JMA82-107 (50 m) consists of wackestone with bryozoans (Plate 2d) abundant microgastropods, dissolved thin lamellibranches, several hyaline foraminifers, *Glomospira* (Plate 2e), *Lenticulina*, and *Pseudocyclammina liassica* and other foraminifers. Brachiopods are also identified.

- Sample JMA82-108 (50.5 m) immediately predates deposition of Red Claystone [Subunit Unit (2a)] and characterizes the abrupt transition from carbonates to the sienna-red kaolinitic claystones. It consists of zoned dolosparite with many lamellibranches ghosts (Plate 2f). It shows a change from wackestone to a euhedral crystalline dolomite and a less diversified content mainly of undetermined shells and debris of shells (incl. gastropods) and of echinoderms. Probable *Lenticulina* were recognized among the preserved bioclasts.

Plate 2: Marrat Sequence II

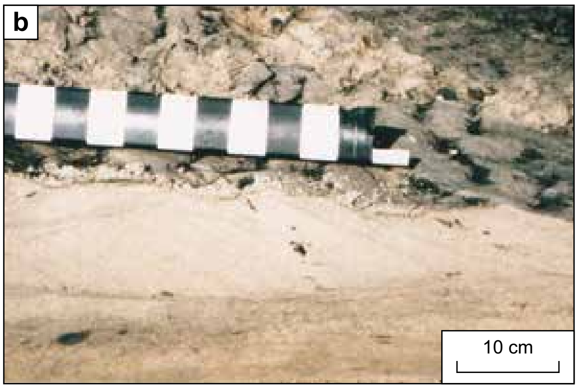


Plate 2: (a) Sigmoidal megaripple (Lower Marrat, Yanbu-Abqaiq pipeline trench in Wadi ash Shams, Darma' Quadrangle); and **(b)** present-day analog in a tidal channel (mesotidal regime), Arcachon Bay (Photo by Y.M. Le Nindre; courtesy ASF 1986, H. Feniès). This bedform and internal bundles are determined by variation of current velocity during a neap tide–spring tide cycle.

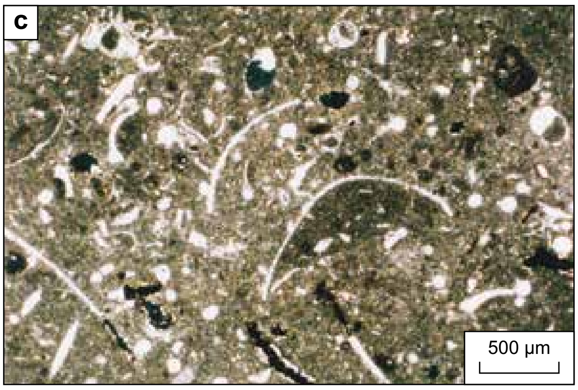


Plate 2: (c) Photomicrograph of wackestone with thin-valve lamellibranches and rare echinoderms, near top Lower Marrat (Sample JMA82-103, natural light), Khashm adh Dhibi, Darma' Quadrangle.

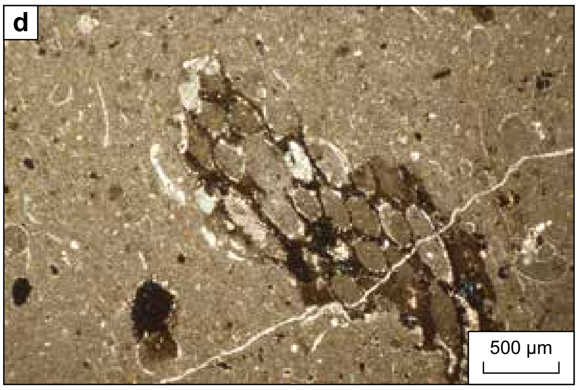


Plate 2: (d) Photomicrograph of bryozoa fragment with thin-shell lamellibranches and gastropods, basal Middle Marrat (Sample JMA82-107, natural light), Khashm adh Dhibi, Darma' Quadrangle.

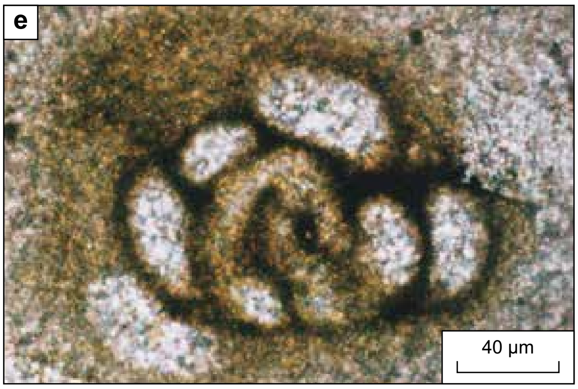


Plate 2: (e) Foraminifer *Glomospira* is characteristic of uppermost Marrat Sequence II (Samples JMA82-103, 104 and 107); photo-micrograph from Sample VD80-332, polarized and reflected light), Khashm al Jufayr, Wadi ar Rayn Quadrangle).

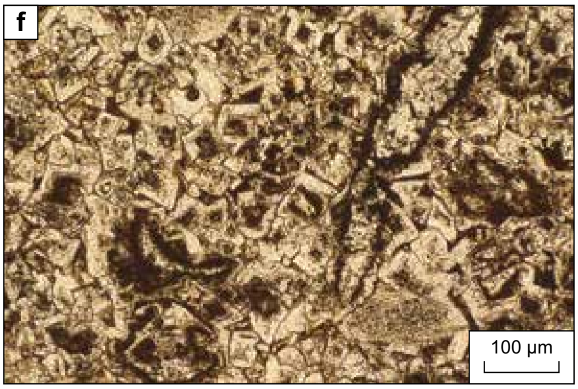


Plate 2: (f) Photomicrograph of zoned dolosparite with ghosts of bioclasts (bivalves, echinoids), basal Middle Marrat beneath Red Claystone (Sample JMA82-108 – B40323, natural light), Khashm adh Dhibi, Darma' Quadrangle.

Middle Marrat Unit (1) (Bouleiceras horizon) contains the rich Bouleiceras faunal association described in Chapter 2, and its microfacies indicate it was deposited in a middle infralittoral setting. Unit (1) corresponds to the most open-marine setting observed within the formation and together with Lower Marrat Subunit (4b) is interpreted as the highest relative sea level represented in the formation.

The transgression of Marrat Sequence II spans the interval between MRS II and MFS II at base of the Bouleiceras horizon at 47 m. We follow Al-Mojel et al. (2019) and correlate Marrat MFS II to Arabian Plate MFS J09 (Figure 6). The eustatic cycle accompanying Marrat Sequence II starts to fall at SB III and reaches a minimum level at MRS IIIa and/or MRS IIIb in Sequence III.

4.3 Marrat Sequence III

Marrat Sequence III (c. 40 m thick, between 51 and 91 m) consists of Middle Marrat Units (2) and (3) and the lower part of Upper Marrat Subunit (1a) (Figures 5 and 6). **Subunit (2a)** (c. 12 m thick, between 51 and 63 m) is referred to as the **'Red Claystone'** (Photos 1 to 3). Sample JMA82-109 (56.5 m) from the Red Claystone is barren of fauna and contains abundant iron oxides, some gypsum and quartz. X-ray mineralogical and chemical analyses show an association with notable content of Li, B, Sr, Ba and other elements reflecting an evaporitic influence. Well-crystallized kaolinite is the main clay mineral (70%), with subordinate illite (20%) and interstratified illite-smectite (10%) suggesting brackish waters.

Subunit (2b) (c. 9.5 m thick, between 63 and 72.5 m, Photos 1 to 4) consists of laminated sandstone and siltstone, and green clayey siltstone with gypsum. Middle Marrat Subunits (2a) and (2b) are separated by a thin sandstone bed (at c. 63 m, Figures 5b and 6). By stratigraphic position it correlates to a bed in Khashm al Jufayr (Section 9, Figure 2) consisting of 1 m-thick, foliaceous intercalations of fine-grained dolomitic siltstone with gypsum veins and hematite. The bed in the Al Jufayr Section is overlain by laminated, stratified or cross-bedded (flat), very silty to fine-grained, well-sorted limonitic sandstone with foresets.

The boundary between subunits (2a) and (2b) marks a maximum regressive surface (MRS IIIa, Figure 6), which is interpreted as a third-order sequence boundary by Al-Mojel et al. (2017, 2019; see Chapter 5). Higher up at c. 70 m another surface may represent MRS IIIb, or a fourth-order sequence boundary, or a transgressive surface (TS). The choice of the sequence stratigraphic term (SB, MRS) for surfaces IIIa and IIIb can lead to confusion in defining T-R sequences (Figure 1).

Subunit (2c) (c. 6 m thick, between 72.5 and 78.5 m) consists from base-up:

- 2 meters of white, fine-grained, very rounded sandstone intercalated with undulated clayey films in its upper part; at macroscopic scale, small progradational channels are observed in this unit (Photo 4);
- 3 meters of ochre clayey siltstone and very fine-grained sandstone; and
- one meter of white, fine-grained, well-sorted sandstone capped by a perforated surface with anastomosed stationary ripples (Plate 3a, b).

Subunit (2c) is interpreted as a sand flat deposited in upper intertidal settings with salt marsh creeks at the base.

Subunit (2d) (c. 3 m thick, between 78.5 and 81.5 m) consists of green to khaki brown claystone deposited in intertidal settings. Sample JMA82-110 (80 m) contains rare gastropods but not any microfauna. Residues show frequent iron oxides and rare quartz.

4.3.1 Depositional setting of the Red Claystone

The abrupt passage at SB III from the carbonates of the Bouleiceras horizon to the Red Claystone implies a significant climate change and depositional setting. This claystone was explored for industrial minerals by Laurent and Al-Habshi (BRGM) in 1976 in an area extending from north

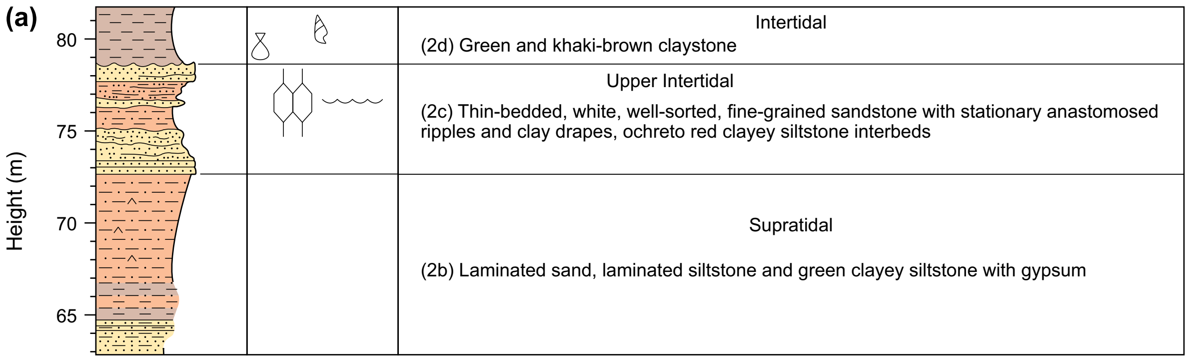
Darmā up the type locality of Marrah (24°30′N to 25°03′N), thus providing a good knowledge of its chemical and mineralogical composition.

The deposition of the Red Claystone may have occurred in a lower deltaic plain with meandering fluvial channels or in an ephemeral lake as suggested by Al-Mojel et al. (2017, 2019). Alternatively, the setting may have been a large confined brackish bay lacking an effective drainage system. The water level may have been uniform with minimum accommodation space, but sufficient for decantation. The analyses of Sample JMA82-109 (56.5 m) indicates a discrete evaporitic influence, consistent with the presence of interstratified illite-smectite, and the occurrence of gypsum suggests brackish waters. The red clastics are weathered laterites apparently sourced from the Proterozoic basement and deposited in a tropical humid climate (Abed, 1979; Manivit et al., 1990). Manivit et al. mention a notable content in illite and interstratified illite-smectite in closed basin setting, whereas kaolinite is only present in coastal setting.

Based on palynological analysis N.P. Hooker (written communication, 2017) suggested sedimentation in a continental setting with swamp flora on the one hand, and a tidal trend, on the other. N.P. Hooker reported [brackets added here for clarity]:

> "the Middle Marrat Shale [corresponding to all of Unit (2), 'Marrat Marker'] in subsurface contains chitinous microforam test linings and is apparently marine, but the degree of marine influence is difficult to judge. There is an influx of terrestrial debris, including spores derived from a swamp flora [e.g. *Deltoidospora* ferns, Majmah boreholes, Manivit et al., 1990]. This almost

Plate 3: Marrat Sequence III



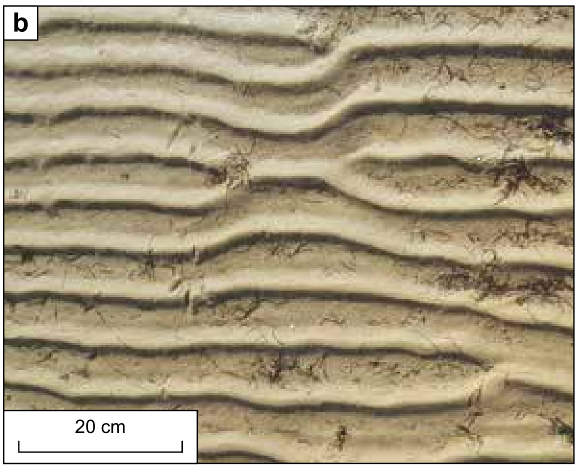


Plate 3: (a) Anastomosed stationary ripples in Middle Marrat Subunit (2c), and **(b)** in present-day upper intertidal flat. Microgastropods (*Peringia ulvae*) are frequently trapped between two ripples.

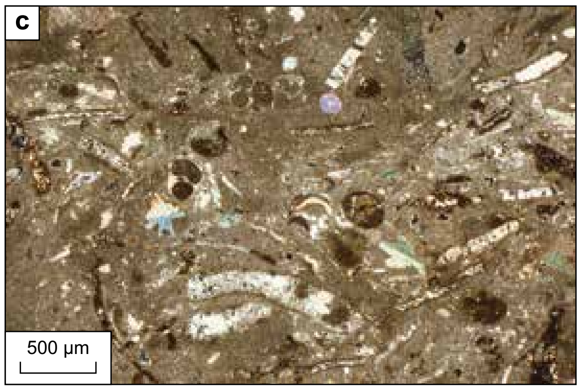


Plate 3: (c) Photomicrograph of bioturbated bioclastic wackestone with recrystalized lamellibranches, limonitic gastropods with internal sediment, echinoderms and aggregates. (Samples JMA82-111–B40324, polarized light) upper Middle Marrat, Khashm adh Dhibi, Darma' Quadrangle.

certainly reflects a brief period of increased humidity and moist climatic interlude, amongst the otherwise highly arid Lower Marrat and Upper Marrat. The influx of terrestrial debris probably results from increased run-off due to higher rainfall (hence the swamp flora), but could also relate to a drop in sea level."

4.3.2 Transition between Marrat Sequences III and IV

Al-Mojel et al. (2017, 2019) interpreted four high-frequency sequences (HFS-2.2 to HFS-2.5) in cores extracted from the Dhibi-1 borehole (N24°12′, E46°15′) situated about 15 km east of the Khashm adh Dhibi section (Figure 2). Based on a bed-for-bed correlation between the reference section and the borehole we recognize the Marrat interval spanning uppermost Middle Marrat to the gypsum interval [Unassigned Subunit (3a)] (Figures 6 and 7). We correlate SB IV in the reference section to the boundary between HFS-2.2 and HFS-2.3.

The TST of HFS-2.2 in Dhibi-1 (Al-Mojel et al., 2019) approximately correlates to **Middle Marrat Unit (3)** in Khashm adh Dhibi (c. 4.5 m thick, between c. 81.5 and 86 m; Figure 7)**.** The morphologically prominent solid carbonate slabs at 83.5 m consist of bioturbated wackestone, bioclastic limestone, with fauna epigenized by limonite: aggregates, lamellibranches (some recrystallized) and gastropods with internal sediment (Sample JMA82-111 at 83.5 m; Plate 3c); the slabs represent deposition in a proximal infra-littoral setting during a marine flooding pulse. The upper part of the TST of HFS-2-2 was deposited during a stillstand characterized by the calcareous claystones above the limestone slabs in upper Unit (3) in the reference section (83.5 to 86 m).

Upper Marrat Unit (1) (c. 9 m thick, between c. 86 and 95 m, Figure 7) corresponds to a fairly homogenous lithological assemblage representing deposition in a confined medio- to proximal infralittoral setting in the area from Khashm al Jufayr to Khashm Numayrah (Figure 2). **Upper Marrat Subunit (1a)** is about 7 m thick (between c. 86 and 93 m) and consists of bioclastic dolomitic limestone with thin shells interbedded with green claystone and khaki marls. Sample JMA82-112 (87.5 m) contains lamellibranches, recrystallized with a micritic layer, more-or-less epignenized by limonite, as well as very abundant debris and aggregates with rare echinoids; the texture evolves from wackestone to grainstone following the bedding.

The lower part of Subunit (1a) between about 86 and 88.5 m was deposited during a second marine pulse and contains the MFS of HFS-2.2 (Figure 7). The pulse was followed by a smooth sea level rise with low accommodation space and a constant sedimentary response. The MFS and HST of HFS-2.2 in Dhibi-1 correlate to the interval between about 86 and 91 m in Upper Marrat Subunit (1a). Marrat SB IV is positioned at 91 m at the base of a 1.6 m-thick (between 91 and 92.6 m), brownish-grey limestone, mudstone-wackestone, which becomes increasingly more clayey upwards, with rare shells and limonitic clasts. It is correlated to the upper SB of HFS-2.2.

A thin carbonate bed (c. 70 cm thick at about 92.5 m) typically bears microgastropods and immediately underlies the Nejdia horizon (Sample JMA82-113). The MFS of Marrat Sequence IV occurs in the top of the Nejdia horizon [Subunit (1b)] at 95 m in Khashm adh Dhibi and correlates to the MFS of HFS-2.3 in Dhibi-1. We follow Al-Mojel et al. (2019) and name the Nejdia MFS as Arabian Plate MFS J10, as originally defined by Sharland et al. (2001) (Figure 6).

The Nejdia horizon contains thin microgastropod grainstones and mudstones, and yielded a high number of *Nejdia* specimens demonstrating coastal accumulation. From the uppermost Nejdia horizon, sedimentation evolved to cream nodular, more carbonated limestone forming the main Upper Marrat Unit (2) carbonates. The Nejdia horizon, and its lateral equivalents, provide a recognizable fossiliferous interval marking the turning point from the transgressive Marrat Sequence III to the high stand Marrat Sequence IV.

4.4 Marrat Sequence IV

Marrat Sequence IV is about 21.5 m thick (between 91 and 112.5 m) in the reference section and corresponds to HFS-2.3 to HFS-2.5 in Dhibi-1 (about 18.5 m thick, between 152 and 133.5 m, Figures

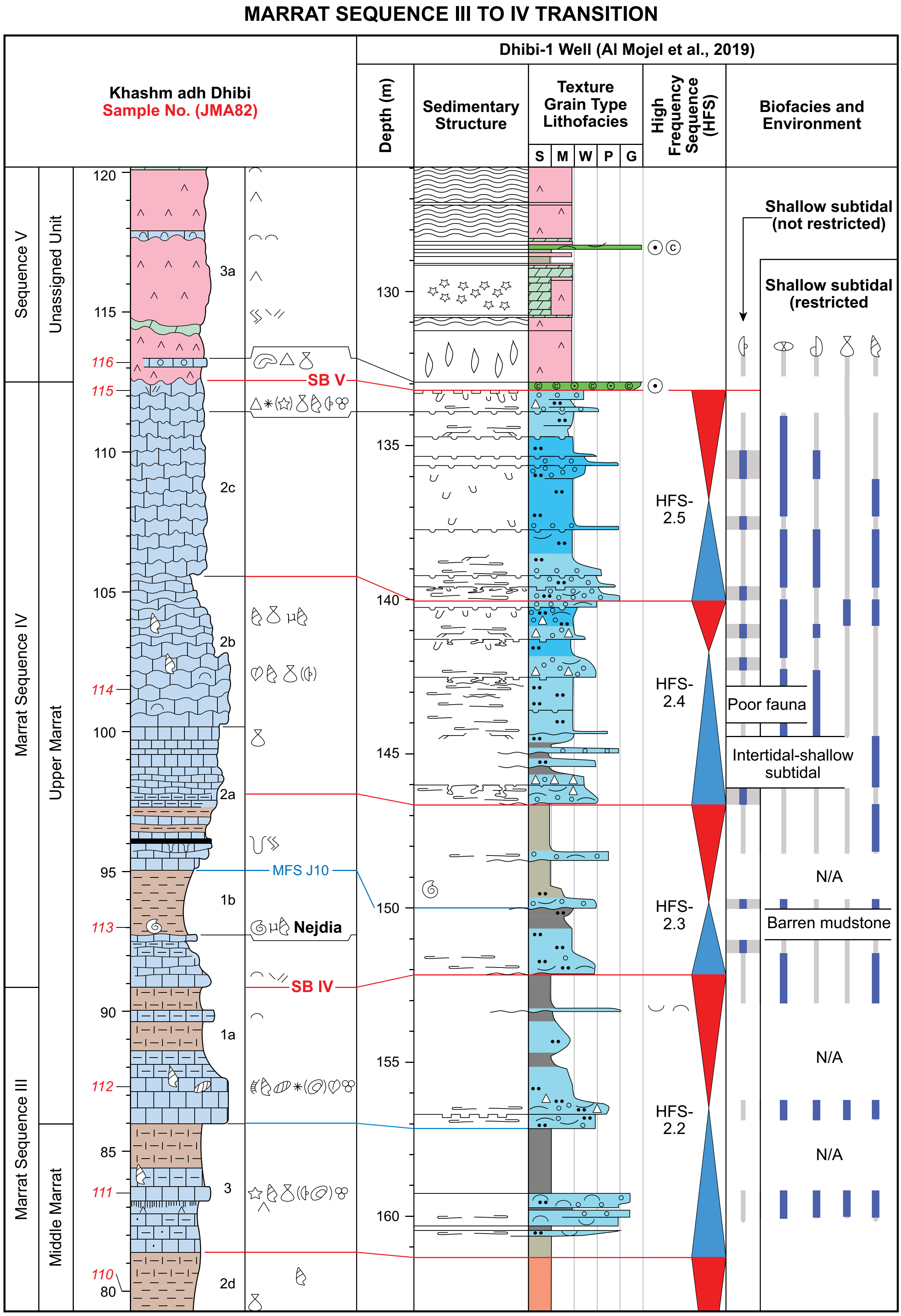


Figure 7: (a) *For caption and legend see facing page.*

6 and 7). As explained in Chapter 4.3, SB IV is placed at 91 m in the upper part of Subunit (1a) and MFS J10 at 95 m at top of the Nejdia horizon [Subunit (1b)]. **Subunit (2a)** (c. 5.0 m thick, between 95 and 100 m) consists of white thin-bedded to laminated clayey limestone deposited in proximal infralittoral settings.

Subunit (2b) (c. 5.5 m thick, between 100 and 105.5 m) consists mainly of nodular cream limestone. It contains intercalations of barren mudstone with minor fractures and cemented voids indicating a lagoonal to subaerial domain (Sample JMA82-114 at 101.5 m, Figures 6 and 7). This subunit was deposited in restricted proximal infralittoral settings as evident by the limited fauna of molluscs, and in particular, by the abundance of monospecific microgastropods comparable to the present-day *Peringia (Hydrobia) ulvae* (Pennant, 1777) (Le Nindre, 1971, pl. 1, and field observations, Arcachon Bay 2018; Wikipedia '*Peringia ulvae*') (Plate 4a,b). Other bioclasts are essentially small echinoderms debris.

Subunit (2c) (c. 7 m thick, between 105.5 and 112.5 m, Figures 6 and 7) is a blocky jointed mud-limestone. Sample JMA82-115 (112.3 m) taken from the uppermost part of Upper Marrat limestone Subunit (2c) is a marine reworked horizon characterized by abundant micritic intraclastes, frequent foraminifers Ataxophramiideae (rare Ophtalmiideae and ostracods), frequent echinoderm debris and lamellibranches. Gastropods are less frequent, and sponge spicules are rare. This bed matches an equivalent bed in Dhibi-1 at 133.5 m. Both beds are considered by the authors as the top of the Marrat limestone, beneath the anhydrite interval ('Unassigned Unit').

Sample JMA82-116 (113.3 m; Figures 6 and 7, Plate 4c) was taken from the oolitic grainstone in the lowermost part of gypsum of the Unassigned Unit and matches the oolitic grainstone at 133 m in Dhibi-1. The alizarine red coloration emphasizes the contrast between a dolomitic matrix and calcitic constituents. Fibrous-radial oolite of calcite (former aragonite) with nucleus of micrite, are partially recrystallized in Fe dolo(micro)-sparite. The nuclei are sometimes made of micritized or recrystallized mollusca debris (lamellibranches). Not all debris are oolitized; some remain free

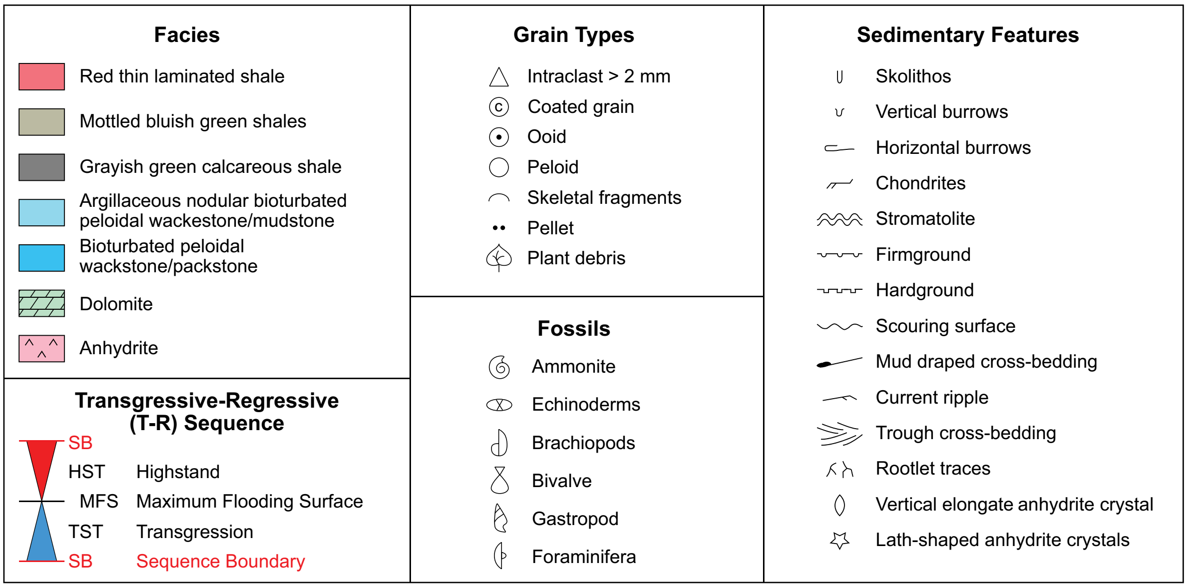


Figure 7 (*continued*): (a) In the Dhibi-1 borehole, situated about 15 km east of the reference section, Al-Mojel et al. (2019) interpreted four high-frequency sequences (HFS-2.2 to HFS-2.5) in the upper part of the Marrat Formation (below the anhydrite interval of the Unassigned Unit). A bed-for-bed correlation indicates SB IV in the reference section at 91 m is a minor SB and passes to base HFS-2.3 in Dhibi-1. MFS IV corresponds to Arabian Plate MFS J10 (Sharland et al., 2001) and occurs at 95.0 m at top Nejdia horizon (*bifrons* zone). **(b)** Legend for Dhibi-1 Well (Al-Mojel et al., 2019) with some symbols redrawn to better resemble those in Figure 4.

Plate 4: Marrat Sequence IV

Plate 4: (a) Present-day analog of micro-gastropod *Peringia ulvae* Pennant with its trail in the intertidal domain, Arcachon Bay (Le Nindre, 1971) and **(b)** specimens collected in December 2018. This microgastropod forms specific facies in the upper intertidal domain and may be accumulated in the millions.

Plate 4: (c) Photomicrograph of wackestone-packstone with fibrous-radial oolites on micritised bioclast nuclei, top carbonate of Upper Marrat Member (Sample JMA82-116, natural light), Khashm adh Dhibi, Darma' Quadrangle.

in the wackestone-packstone. The remnant mud matrix indicates these oolites were not deposited (but perhaps formed) in active shoals.

The restricted fauna in Upper Marrat Subunit (2c) does not indicate a new marine diversification, but rather the confinement, which is in a phase of degradation and reworking. Subunit (2c) represents deposition in a proximal infralittoral setting culminating in a regression abruptly terminated at SB V. Subunit (2c) correlates closely to HFS-2.5 in the Dhibi-1 Well (Al-Mojel et al., 2019), which was deposited in an inner lagoonal setting, similar to that at Khashm adh Dhibi.

In Dhibi-1, rare agglutinating forams were found in the interval from about 142 to 135 m (Figure 7; *Ammodiscus*, and other textulariideae, and *Trochammina*), which are typical of restricted conditions (Nagy et al., 2010). Al-Mojel et al. (2019) however, indicate brachiopods are common in HFS-2.4 and HFS-2.5 between 145.5 and 136.5 m, which would imply open-marine rather than restricted conditions. Traces of brachiopods were not found at outcrop in Subunits (2b) and (2c), corresponding HFS-2.3 and HFS-2.4, nor in thin sections from Sample 114 (Figure 7). It seems possible that the bivalves were confused with brachiopods in thin sections in Dhibi-1, as evident by their rare occurrence in this interval.

4.5 Marrat Sequence V

The Unassigned Unit between the Marrat and Dhruma Formations is about 12.5 m thick (between c. 112.5 and 125 m, Figures 5b and 6, Photos 1 and 5), and in the present study we interpret it as Marrat Sequence V. **Subunit (3a)** (c. 7.5 m thick, between 112.5 and 120 m) consists mainly of massive gypsum with interbeds of bivalves deposited in a sabkha or salina. Sequence Boundary SB V is positioned at the base of the gypsum interval at the top of the thin reworked horizon with intraclasts and fauna from which Sample 115 was taken at 113.3 m. Subunit (3a) correlates to the anhydrite interval between 133.2 and 126 m in Dhibi-1 (Figure 7).

Subunit (3b) (c. 5 m thick, between 120 and 125 m, Figures 5b and 6) consists of claystone and siltstone deposited in terrestrial settings. Unit (3b) is capped by SB VI below the thin oolitic grainstone [Dhruma Unit (1)] deposited in a proximal infralittoral setting. In the outcrop sections Dhruma Unit (1) is interpreted as the basal part of the Bajocian Dhruma transgression following a late Toarcian–Aalenian hiatus; i.e., pre-Dhruma Unconformity, SB VI).

5. COMPARISON OF MARRAT SEQUENCES

5.1 Marrat Sequence Architecture

Al-Mojel et al. (2017, 2019) defined the members of the Marrat Formation in the reference section following the lithostratigraphic scheme of BRGM; however, they considered the Minjur Sandstone as upper Triassic and the early Jurassic (pre-Toarcian) as a hiatus. They assigned the upper Unidentified Unit (gypsum layer) to the lower part of the Bajocian Dhruma Formation (Figure 8). They described the lithofacies and their associations, depositional settings, and the sequence architecture of the Marrat Formation in the reference and eight more sections situated further south, as well as the Upper Marrat in the Dhibi-1 borehole (Figure 7).

Al-Mojel et al. (2019) interpreted the Marrat reference section in terms of Composite Sequence MCS-1 consisting of high-frequency sequences HFS-1.1 to HFS-1.5, and Composite Sequence MCS-2 consisting of HFS-2.1 to HFS-2.5 (Figure 8). Sequence MCS-1 occurs between SB I (pre-Marrat Unconformity) and MRS IIIa, and its MFS J09 is positioned at the top of the Bouleiceras horizon, where we position SB III. Sequence MCS-2 occurs between MRS IIIa and SB V, and its MFS J10 is positioned in HFS-2.5 (Figures 7 and 8). Marrat Sequence I (this study) closely corresponds to HFS-1.1, HFS-1.2 and lower HFS-1.3, but it is not considered a separate T-R sequence by Al-Mojel et al. (2019).

Farouk et al. (2018, Figure 8) interpreted lithofacies and their associations, depositional settings, relative sea level and the high-resolution sequence architecture of the Marrat Formation in the Marrat reference section, and a second section situated approximately 10 km further to the southeast. They also assigned the Minjur Sandstone exclusively to the Upper Triassic, and interpreted three Marrat T-R sequences. Their description of the reference section is significantly different from that of Powers et al. (1966, Figure 3), Al-Mojel et al. (2019) and the one described in our study (Figure 5). In particular, the stratigraphic positions of key units such as the Bouleiceras and Nejdia horizons, and the Red Claystone are incorrectly shown, rendering most of our attempts to draw correlations speculative at best.

5.2 Maximum Flooding Surfaces

In Figure 1 the maximum flooding surface (MFS) is positioned near the end of the rapid RSL rise (i.e., top of the transgressive systems tract, TST, transgression, T) and not at the highest relative sea level (RSL). In the Marrat Formation, we interpret MFS I at 12.0 m in the presumed *tenuicostatum* zone in lower Unit (2) (Figure 6). The position of Arabian Plate MFS J09 at 47.0 m marks the end of transgression at the base of Middle Marrat Unit 1 (Bouleiceras horizon) near the *tenuicostatum*/*serpentinum* zonal boundary. The top of the Bouleiceras horizon is Marrat SB III; however, it is designated MFS J09 (Al-Mojel et al., 2019), and apparently the MFS of a small cycle set (Figure 8, Farouk et al., 2018). MFS J10 occurs in the bifrons zone at 95 m at the top of the Nejdia horizon in Marrat Sequence IV. Marrat Sequence V is a low stand and does not contain an MFS. From a biostratigraphic viewpoint, MFS J09 and MFS J10 occur at horizons containing age-indicative correlative markers that can be traced at regional and global scales.

5.3 Correlation of the Marrat and Global Sequences

The Marrat is marked by six SBs that can be approximately correlated to those of Haq (2018) (Figure 6). The pre-Marrat Unconformity (Marrat SB I) occurs above the upper Triassic–Pliensbachian Minjur Sandstone and represents a hiatus that on paleohighs can span the early Jurassic up to approximately the Plienbachian/Toarcian Boundary. In the absence of a significant hiatus the pre-Marrat Unconformity passes to Marrat SB I and would correlate to SB JPl8.

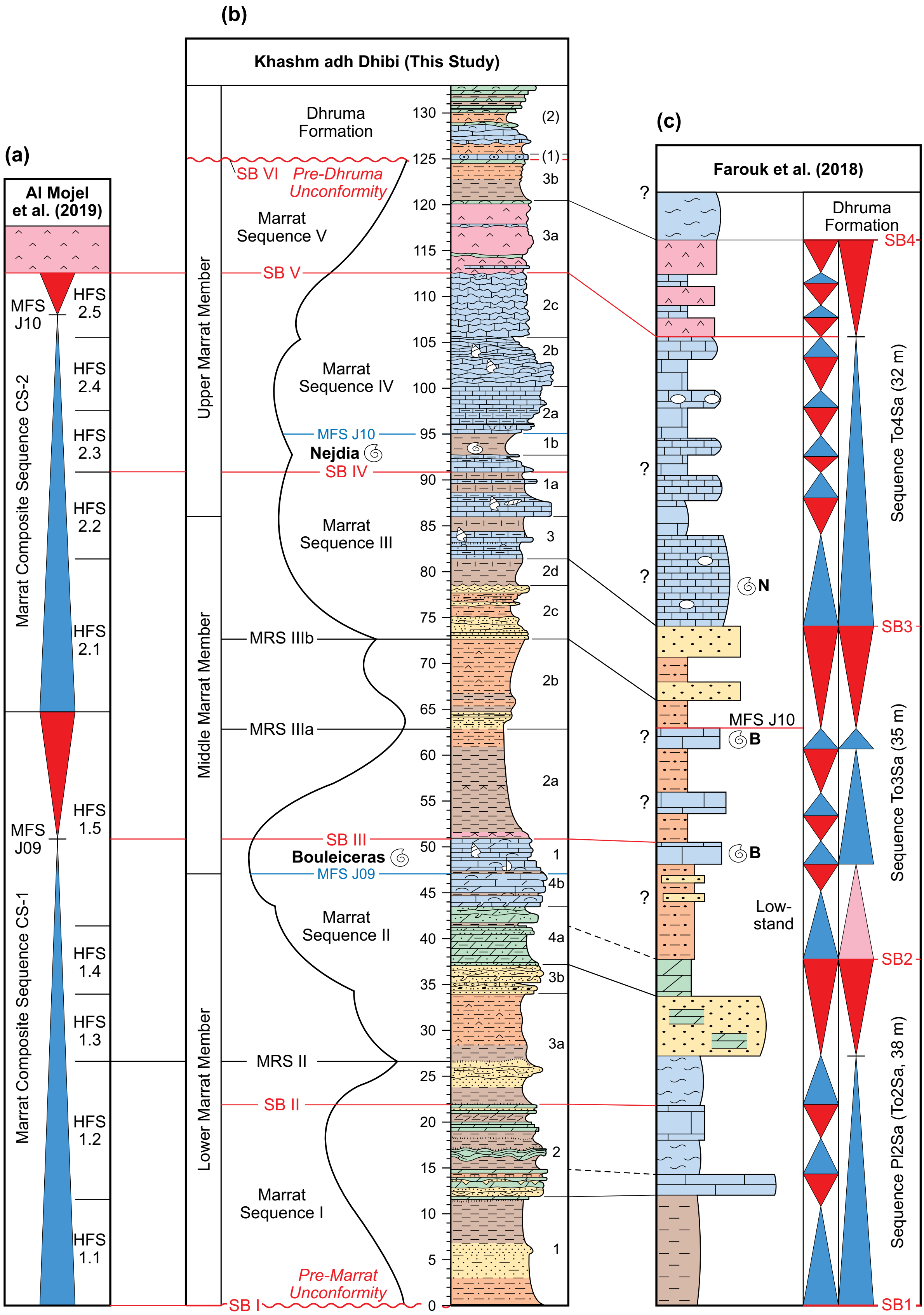


Figure 8: Marrat Sequences I to V in the Khashm adh Dibi reference section (This study, Figure 6) and eustatic cycles (modified after Haq, 2018) compared to alternative interpretations of T-R sequences. Confusing sequence stratigraphic nomenclature results in sequence boundary SB III passing to MFS J09 (Al-Mojel et al., 2019). The Marrat reference section in Farouk et al. (2018) is misrepresented in intervals punctuated by questiona marks (?), rendering most correlations speculative.

Marrat Sequence I is dated as older than *serpentinum* zone by the overlying Bouleiceras horizon suggesting it correlates, in part or completely, to global Sequence JPl8 of late Pliensbachian-early Toarcian age. In this scenario Marrat SB II correlates to global SB JTo1 in *tenuicostatum* zone, and Marrat SB III to global SB JTo2 in lower *serpentinum* zone (Figure 6).

Haq (2018) considered SB JTo3 as a significant sequence boundary immediately below the *bifrons* zone; it correlates to Marrat SB IV below the Nejdia horizon. However, evidence for a marked, sharp sedimentary discontinuity or break is not observed in the reference section, nor in other sections. Instead, the evolution of Marrat Sequence III indicates it is a transgression, which extends almost continuously into a high stand corresponding to Marrat Sequence IV. It seems likely that SB JTo3 is a minor sequence boundary separating high-frequency sequences (HFS) or fourth-order sequences. The top of the Nejdia horizon at 95 m corresponds to Arabian Plate MFS J10 in Marrat Sequence IV; it correlates to the MFS of HFS-2.3 in Dhibi-1 and not to that in HFS-2.5 (Al-Mojel et al., 2019).

Haq (2018, their figure 1; Figure 6) depicted Sequences JTo4 to JTo6 with dashed lines to emphasize they are provisional and subject to further evidence. He interpreted these three sequences to occur in a long-term sea-level fall that started in the late *bifrons* zone and continued into the Aalenian. The long-term fall is consistent with SB V as the start of a low stand, and the late Toarcian and Aalenian in Saudi Arabia a hiatus represented by the pre-Dhruma Unconformity (SB VI).

Farouk et al. (2018) correlated their SB 1 to SB 4 to global SB JTo1 to SB JTo4 implying the late Pliensbachian–early Toarcian global Sequence JPl8 is not represented in the reference section.

Al-Mojel et al. (2019, their figure 14) assigned Sequence MCS-1 to the mid-*serpentinum* and early *bifrons* zones, and assumed the *tenuicostatum* and early *serpentinum* zones as a hiatus. They considered Sequence MCS-2 as middle *bifrons* zone. Their age assignments imply the Marrat Formation correlates to global Sequences JTo2 and JTo3 and that late Pliensbachian-early Toarcian Sequence JPl8 and early Toarcian Sequence JTo1 are not represented in the reference sections.

CONCLUSIONS AND RECOMMENDATIONS

The description and interpretation of the Marrat reference section in terms of T-R sequences (this study) vary significantly from those in two recent articles (Farouk et al., 2018; Al-Mojel et al., 2019). Major differences occur even after normalizing for lithostratigraphic conventions, facies and their associations, depositional settings and measured thicknesses (Figure 8). In particular, the positions and names for key isochronous surfaces (e.g., MFS J09, SB III, MFS J10, SB VI) are conflictingly defined in the same section. A solution to this problem remains unresolved as explained by Catuneanu and his 19 coauthors (2009) in their conclusion (Figure 1):

> "In spite of its popularity among geoscientists in academia, industry, and government organizations, sequence stratigraphy remains a stratigraphic method that is not formalized in stratigraphic guides or codes. This reflects the existence of different approaches for applying sequence stratigraphy to the rock record".

We believe a more definitive approach should be advocated. We recommend that local T-R sequences and depositional settings be used to refine or confirm global T-R sequences and sea level curves (Figure 6). This practice would allow stratigraphers to better understand how sequence stratigraphic terms are used in relation to local and regional relative sea level and global sea level. We also recommend that global and Arabian Plate sequences be formally named and defined in type sections, and compiled and updated in web-based sequence-stratigraphic lexicons.

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MEMORIUM

We sadly report that one of our coauthors, Jacques Manivit (1932–2020), passed away in June 2020. Jacques was a good friend and senior mentor to his younger colleagues. His expertise, good temperament and laughter cemented the success of the team, and he is greatly missed by his family, friends and professional colleagues.

Jacques began his career as a Petroleum Geologist with France's S.N REPAL in the Algerian Sahara, followed by a long career with France's Geological Survey, Bureau de Recherches Géologiques et Minières (BRGM) as mapping geologist and stratigrapher. Principally contributing to the Geological Map of France, he was involved in the Cover Rocks mapping project of the Saudi Arabian Deputy Ministry for Mineral Resources from 1980 to 1988. Jacques received his Doctorate of Sciences on the biostratigraphy of Permian to Late Jurassic rocks of central Arabia, from the University of Paris in 1987, with D. Vaslet and Y.M. Le Nindre. He is author or co-author of key publications on the Middle East, and especially of the memoir "le Jurassique d'Arabie Centrale", 1990, 559 p. After his retirement in December 1992, Jacques continued an activity of mapping geologist from 1994 to 2003.

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