

Sedimentary facies, depositional environment, and sequence stratigraphy of Oligocene–Miocene shallow water carbonate from the Rig Mountain, Zagros basin (SW Iran)

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Abstract This study investigates the depositional environment and sequence stratigraphy of the Asmari Formation that is exposed at the Rig anticline in the Izeh zone of the Zagros foreland basin with a thickness of 374 m as a sequence of thin, medium, thick, and massive carbonate rocks. The Asmari Formation is Oligocene–Early Miocene (Burdigalian) in age at the study area. In this area 12 microfacies are distinguished on the basis of their depositional texture, petrographic analysis, and fauna. These facies deposited in four major depositional environment including tidal flat, lagoon, shoal, and basin. The Asmari Formation represents sedimentation on a homoclinal carbonate ramp system. Based on the microfacies analysis, sequence stratigraphic studies, and distribution of planktonic and benthic foraminifera, six third-order sequences, three in Oligocene (Rupelian, Early Chattian, and Late Chattian in age) and three in Miocene (Early Aquitanian, Late Aquitanian, and Early Burdigalian in age), in Rig mountain section were identified.

Keywords Asmari Formation · Oligo-Miocene · Zagros basin · Microfacies · Depositional environment · Sequence stratigraphy

Introduction

Carbonate platform deposits of the Asmari Formation, Iran, contain some of the largest oil reservoirs in the world (Alavi 2004). At its type section in Tang-e Gel Tursh on the southwestern flank of the Kuh-e Asmari anticline, this formation consists mainly of a 314-m-thick succession of indurated skeletal limestone (Thomas 1950). The thickness of the Asmari Formation varies from 90 to 594 m.

An Oligocene (Rupelian) to Early Miocene (Burdigalian) age has been determined for the unit based mainly on foraminiferal zones and strontium isotope stratigraphy (Lees 1933; Thomas 1950; James and Wynd 1965; Wynd 1965; Adams and Bourgeois 1967; Ehrenberg et al. 2007; Laursen et al. 2009; Van Buchem et al. 2010). However, the base of the Asmari Formation varies in age. Deposition took place on a carbonate platform at the margin of a NW-trending basin in the foreland of the Zagros orogenic belt as the tectonic front caused by the collision of the Arabian Plate and Eurasia progressively moved southwestward (Sephehr and Cosgrove 2004). Deposits on the platform (Fig. 1), including the Asmari Formation, show a general shallowing upward trend.

More recent publications on the Asmari formation are the outcrop and subsurface work on microfacies, depositional environment and sequence stratigraphy (such as Seyrafian and Hamedani 2003; Vaziri-Moghaddam et al. 2006; Amirshahkarami et al. 2007a, b; Van Buchem et al. 2010) and the Sr isotope work by Ehrenberg et al. (2007) and Mossadegh et al. (2009) and biostratigraphic work by Laursen et al. (2009) and Seyrafian et al. (2011). The purpose of these studies are microfacies analysis, reconstruction of sedimentary environment, and to describe and interpret the sequence stratigraphy that developed in the study area. This study is based on one outcrop section in Rig anticline at

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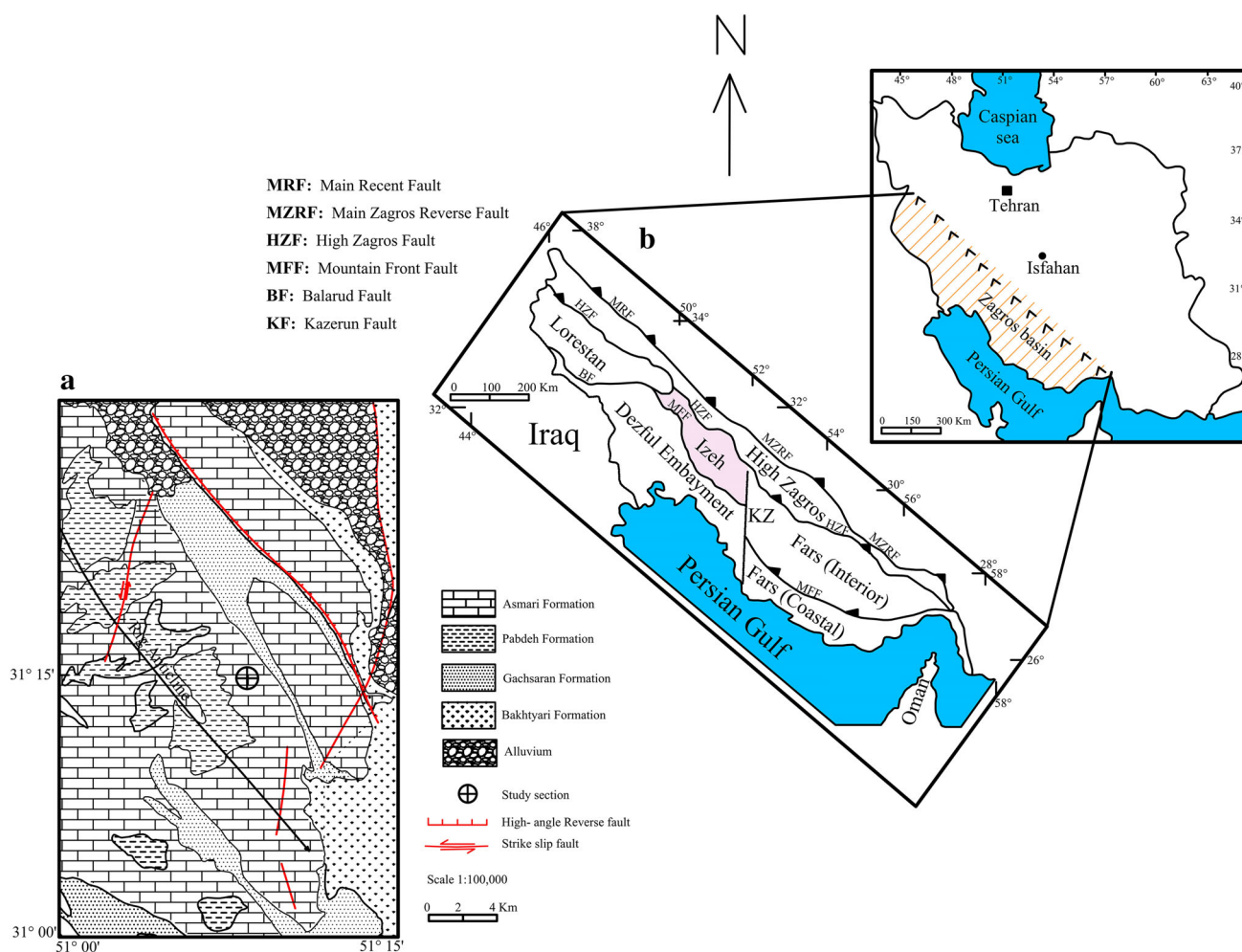


Fig. 1 **a** Location and geological map of the study area at Rig anticline, southwest Iran. **b** Six major tectonostratigraphic domains of the Zagros basin (adapted from Motiei 1993). The study area located in Izeh and High Zagros zones

Aman valley close to the cities of Boroujen and Lordegan in Charmahal va Bakhtiari Province (Figs. 1, 2). In the Rig anticline, the lower contact of the Asmari Formation with the Pabdeh Formation is gradational, but its contact with the above Gachsaran Formation is disconformable (Fig. 1).

Geological setting

The Zagros sedimentary basin extends over the northeastern (present coordinates) Afro-Arabian continental margin and was affected by the Early Cretaceous to present day Zagros orogeny (Alavi 2007). This formed the Zagros fold–thrust belt, which is one of the important tectonic units of Iran and has a length of more than 1500 km, and width between 100 and 300 km (Motiei 1993; Alavi 2004).

The Zagros fold–thrust belt is divided into several zones (Lurestan, Izeh, Dezful Embayment, Fars, High Zagros) (Fig. 1) that differ according to their structural style and

sedimentary history (Berberian and King 1981; Motiei 1993). The study area is located in NE part of the Izeh zone and SE of the Rig mountain oil field (SW Iran) (Fig. 1). The Izeh zone and Dezful Embayment are separated from Lurestan and Fars by the Balarud and Kazerun faults, respectively (Falcon 1974; Motiei 1993). The Izeh Zone is part of the Zagros simply folded belt, and is characterized by numerous outcrops of the Asmari Formation.

Ice covered the South Pole but not the North Pole, during the Oligocene. Warm temperate forests covered northern Eurasia and North America. The climate during the Miocene was similar to today's climate, but to some extent warmer. Well-defined climatic belts stretched from Pole to Equator. At that time, the Asmari Formation was deposited in subtropical low latitudes, around thirty degrees north (Heydari 2008; Ehrenberg et al. 2007). A transition from normal marine to hypersaline conditions took place during the Oligo-Miocene (Mossadegh et al. 2009).

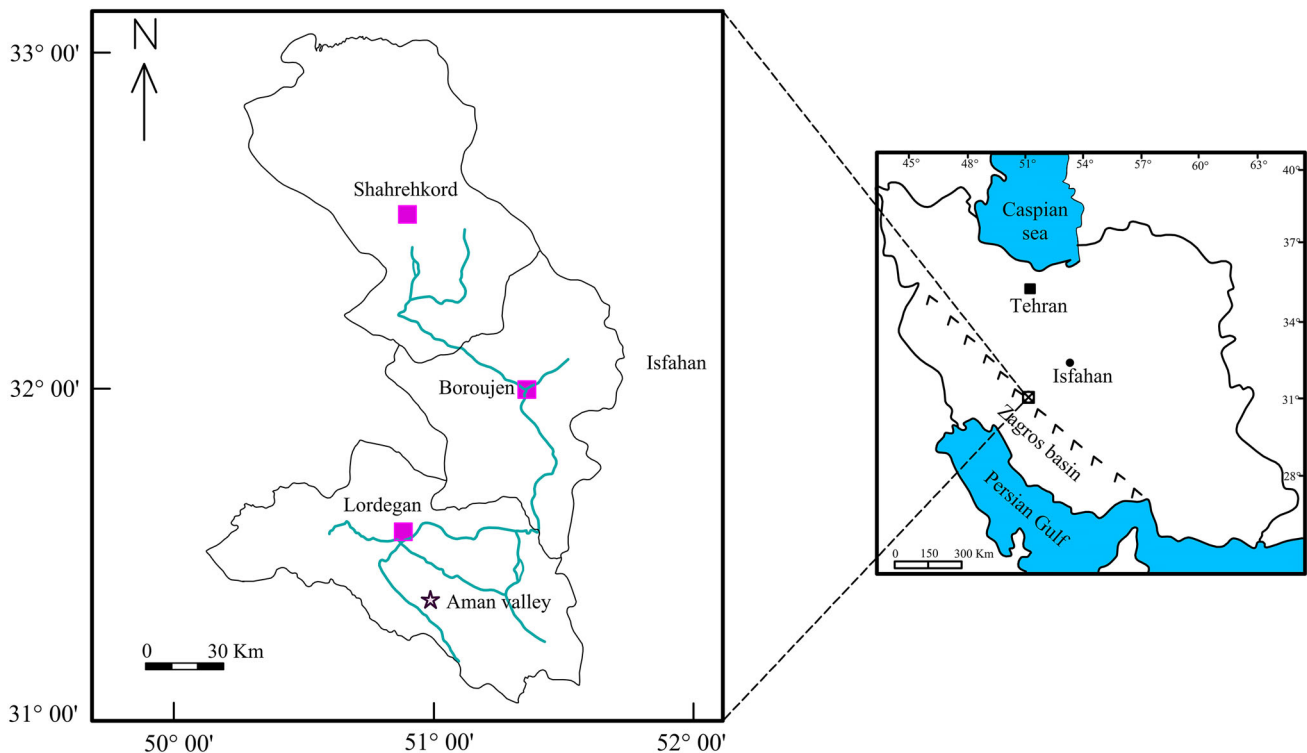


Fig. 2 Location map of the study area in Aman valley, Izeh zone

Map of Fig. 3 showing palaeogeography of Asmari deposition at two stages: (a) Shallow water carbonate facies of the Asmari Formation pass laterally into basinal marl facies of the Pabdeh Formation (Early Oligocene). (b) From mid-Oligocene time, major influxes of siliciclastic took place from the west, and the Asmari platform margins prograded, reducing the area of Pabdeh basinal deposition.

Methods of study

The section was measured and logged at the Aman valley section. Two hundred and forty-two samples were taken bed by bed from the 364-m-thick Asmari Formation. Some samples in massive beds were taken at less than 1 m intervals. Thin sections were stained by potassium ferricyanide and alizarin-red S solution (Dickson 1965). Facies analysis and paleoenvironmental reconstruction were based on microfacies characteristics including depositional texture (Dunham 1962), grain size, grain composition and fossil content. Wilson (1975) and Flügel (2010) facies belts and sedimentary models were used to develop the sedimentary model and sequence framework.

Biostratigraphy

From base to the top of the Asmari Formation sequence, six foraminiferal assemblages were determined in the study area on the basis of the Asmari Formation biozones described by Laursen et al. (2009) (Fig. 4). These assemblages are:

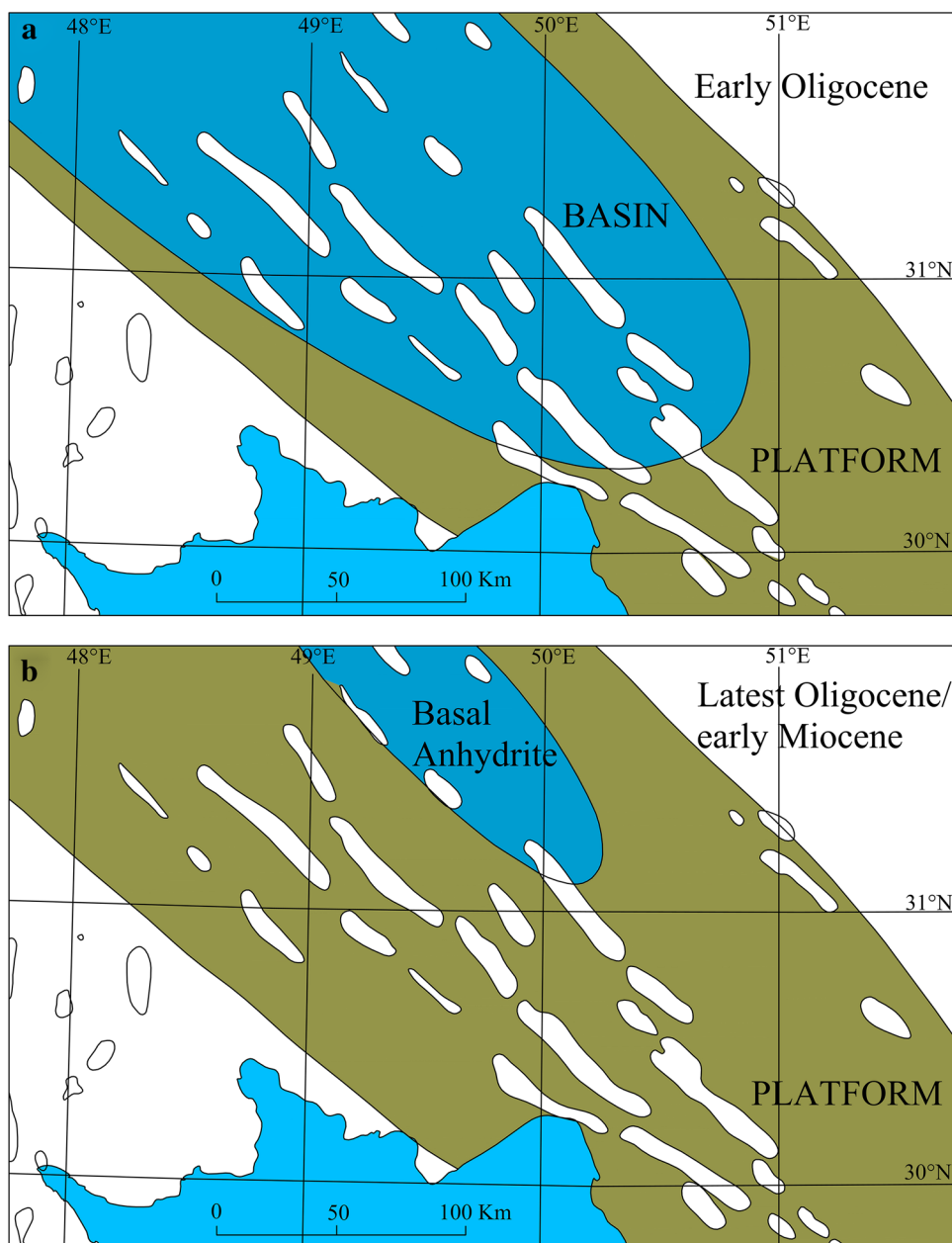
Assemblage zone I From the base to 14 m thickness, *Globigerina* sp. and *Globorotalia* sp. are present. This assemblage is correlated with *Globigerina–Tuborotalia cerroazulensis–Hantkenina* assemblage zone of the Rupelian time.

Assemblage zone II From 14 to 80 m, *Nummulites vascus*, *Nummulites fichteli*, *Nephrolepidina* sp., *Neorotalia viennotti*, *Amphistegina lessoni* and *Discorbis* sp. are mainly present and correspond to *Nummulites vascus–Nummulites fichteli* assemblage zone of Rupelian age.

Assemblage zone III From 80 to 113 m, *Eulepidina elephantina*, *Eulepidina dilitata*, *Lepidocyclina* sp., *Ditrupea* sp. and textularids are present. This faunal assemblage is time equivalent to *Lepidocyclina–Operculina–Ditrupea* assemblage zone of Rupelian–Chattian in age.

Assemblage zone IV From 113 to 148 m, *Borelis* sp., *Peneroplis evolutus*, *Archaias asmaricus*, *Austrotrillina howchini*, and miliolids are mainly present. These for-

Fig. 3 Palaeogeographic map showing two stages of Asmari deposition (from Ehrenberg et al. 2007). The blue area at the south is the present location of the Persian Gulf shows location of studied section



aminifera are correlated with *Archaias asmaricus*–*Archaias hensoni*–*Miogypsinoidea complanatus* assemblage zone of Chattian age.

Assemblage zone V From 148 to 249 m, *Borelis* sp., *Elphidium* sp. 14, *Elphidium* sp., *Miogypsina* sp., *Peneropolis thomasi* are mainly present and correspond to *Miogypsina*–*Elphidium* sp. 14, *Peneropolis farsenensis* assemblage zone of Aquitanian age.

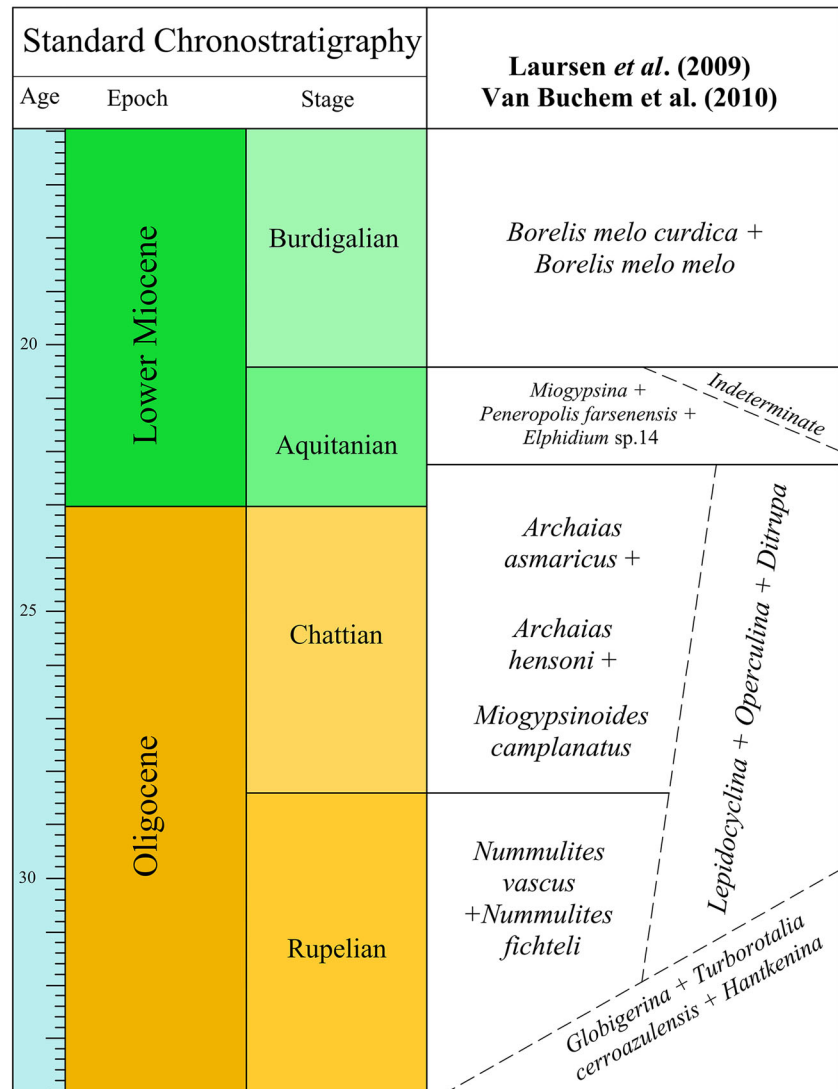
Assemblage zone VI From 264 to 364 m, *Borelis melo curdica*, *Dendritina rangi*, *Borelis* sp., *Peneropolis* sp. and miliolids are present. These foraminifera correspond to *Borelis melo curdica*–*Borelis melo melo* assemblage zone of Burdigalian age.

As a result of this study, the Asmari Formation in Rig anticline is Oligocene (Rupelian) to Early Miocene (Burdigalian) in age.

Microfacies analysis and depositional environment

Based on the study of the textures, allochems and skeletal components in thin sections of the outcrop, twelve microfacies were identified, which are indicative of tidal flat, lagoon, shoal and open marine environments (Fig. 8). The preferred depositional model for the succession is a ramp model (Purser and Seibold 1973; Read 1985; Tucker and

Fig. 4 Biozonation of the Oligocene–Miocene carbonates for the Zagros basin (after Laursen et al. 2009; Van Buchem et al. 2010)



Wright 1990; Burchette and Wright 1992; Gischler and Lomando 2005; Flügel 2010) shown in Fig. 5.

Tidal flat facies

Mf 1, fenestral mudstone

This facies consists of fine-grained microcrystalline lime–dolomite mudstone that lacks bioclasts. Fenestral fabrics are well developed. Evaporites and their moulds are absent in this facies (Fig. 6a). Sedimentary structures are minor, but millimetre laminae of 0.5–2 mm thick are present in some beds. Microkarstic features are also present.

Interpretation

The fine-grained nature of this facies, lack of fauna, and presence of fenestral fabric suggest that deposition

occurred in a tidal flat environment. These bird’s-eye structures are typical of a tidal flat zone and are product of shrinkage and expansion or gas scape from micritic sediments (Ginsburg and Hardie 1975; Shinn 1983; Adabi and Asadi Mehmandosti 2008). Lamination is probably due to microbial binding. The dolomitization may be the result of early diagenesis (e.g. Tucker 1991).

Mf 2, quartz dolo-mudstone

This microfacies is lime–dolomite mudstone with silt size grains of detrital quartz. There is no evidence of subaerial exposure (such as a vesicular fabric, bird’s-eye or fenestral fabric) in this facies (Fig. 6b). The sedimentary structures observed in this facies include parallel lamination and bioturbation.

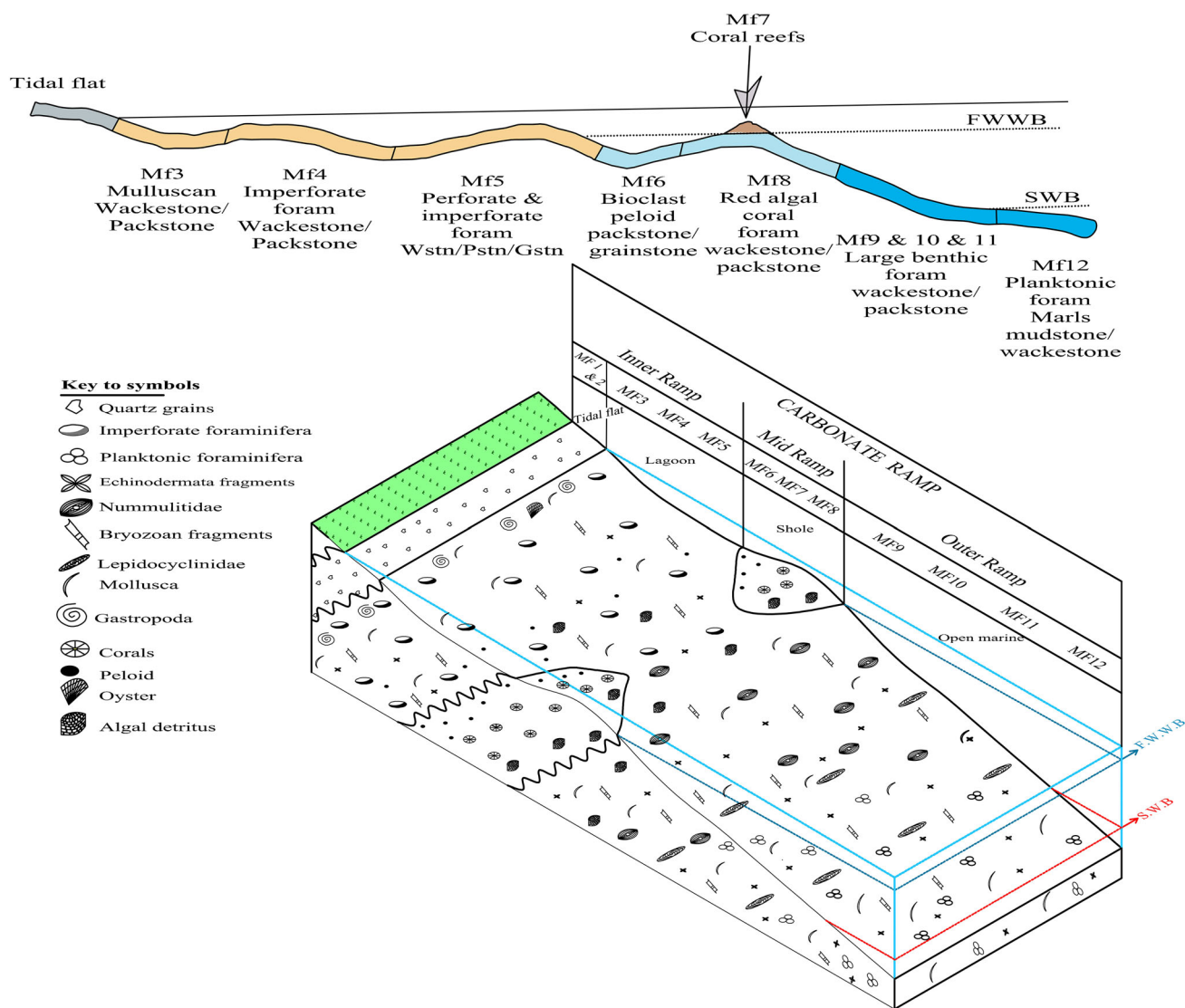


Fig. 5 Depositional model for the carbonate ramp system of the Asmari Formation showing the main depositional settings and principal facies associations in the Rig anticline, Zagros Basin

Interpretation

Sediments composed of a mixture of carbonate and siliciclastic material are common in nearshore and inner-shelf settings (Flügel 2010). The input of terrigenous materials into the carbonate environment could take place by erosion of the underlying sediments in a tidal zone (Flügel 2010) or by wind-blown silt. Furthermore, vertical relationship with lagoon facies and low diversity of fauna, mud-rich texture and the lack of subaerial exposure features in this facies are indicators of a sedimentary environment from the lower part of the intertidal setting.

Lagoonal facies

Restricted lagoonal facies

Mf 3, bivalve benthic foraminifera gastropod wackestone–packstone These packstone–wackestone facies are composed of lime mud with intact gastropods, bivalves, ostra, and benthic foraminifera (such as miliolids and *Clavulina*). Other bioclasts such as bryozoan, and textularid are rare. Some grains have been partially micritized (Fig. 6c).

Interpretation

Abundance of lime mud, low diversity of organisms, and intact gastropod fossils indicate a low-energy environment. In stressful environments (such as hypersaline or fresh water) gastropods can be the main component of deposits (Scholle and Scholle Dana 2006). Paucity of fauna in diversity and abundance, and a stratigraphic position below tidal flat facies are evidence for deposition of this facies in nearshore lagoonal settings (Wilson and Evans 2002). In comparison with analogue in Holocene sediments of the Persian Gulf, gastropods are abundant in shallow subtidal, particularly in lagoonal environment, where both salinity and temperatures are extreme (Purser and Seibold 1973).

Mf 4, bioclast imperforate foraminifera wackestone–packstone

This wackestone–packstone facies consists of abundant benthic imperforate foraminifera that include: *Archaias*, *Peneroplis*, *Dendritina*, *Meandropsina*, *Borelis*, *Austrotrillina* and miliolids. Other biota is discorbis, textularia, *elphidium*, bryozoa and other shell fragments (Fig. 6d).

Interpretation

Some porcelaneous imperforate foraminifera (*Peneroplis* and *Archaias*) live in recent tropical and subtropical shallow water environments (Holzmann et al. 2001). Restricted conditions are suggested by the rare to absent normal marine biota and abundant imperforate foraminifera. The occurrence of a large number of porcelaneous imperforate foraminiferal tests and the muddy textures suggest the depositional environment was a slightly hypersaline, low-energy lagoon environment (Wilson 1975; Geel 2000; Vaziri-Moghaddam et al. 2006; Brandano and Corda (2002); Flügel 2010).

Open lagoon facies

Mf 5, bioclast perforate and imperforate foraminifera wackestone–packstone

This wackestone–packstone microfacies contains benthic foraminifera and micritized bioclasts. The larger benthic foraminifera include both perforate and imperforate forms. Common foraminifera with perforate walls are small–medium-sized *Nummulitidae*, *Miogypsinidae*, *Operculina*, *Neorotalia*, *Ammonia* and *Amphistegina*. Imperforate forms are miliolids (*Triloculina*, *Quinqueloculina*, *Pyrgo*, *Sigmoilina*), *borelis* and *Austrotrillina*. Minor components are *dendritina*, fragments of molluscs and bryozoa,

echinoids, coral and fragment of corallinacea red algae (Fig. 6e).

Interpretation

Microfacies Mf5 has also been reported in other sections of the Asmari Formation by Vaziri-Moghaddam et al. (2010); Amirshahkarami et al. (2007a, b); Amirshahkarami (2012). The benthic assemblage together with red algal debris characterizes an inner-shelf to open lagoon setting (Corda and Brandano 2003). Miogypsinoids lived in shallow waters of normal salinity (Geel 2000) and recent *Amphistegina* and *Neorotalia* live in the photic shallow water (Romero et al. 2002). The occurrence of the imperforate foraminifera was reported from restricted lagoon conditions by Geel (2000) and Romero et al. (2002). Therefore, the occurrence of perforate and imperforate benthic foraminifera reflects that deposition took place in an open shelf lagoon with normal circulation and well-oxygenated waters (Romero et al. 2002; Renema 2006).

Shoal facies

Mf 6, bioclast peloid grainstone

Bioclast peloid grainstone contains common miliolids and peloids as well as fragments of *Operculina*, *Asterigerina*, *rotalia*, *Amphistegina*, corallinacea, bivalve, and echinoid. The grains are medium sorted to well sorted, fine to medium sand size and vary from sub-angular to rounded (Fig. 6f).

Interpretation

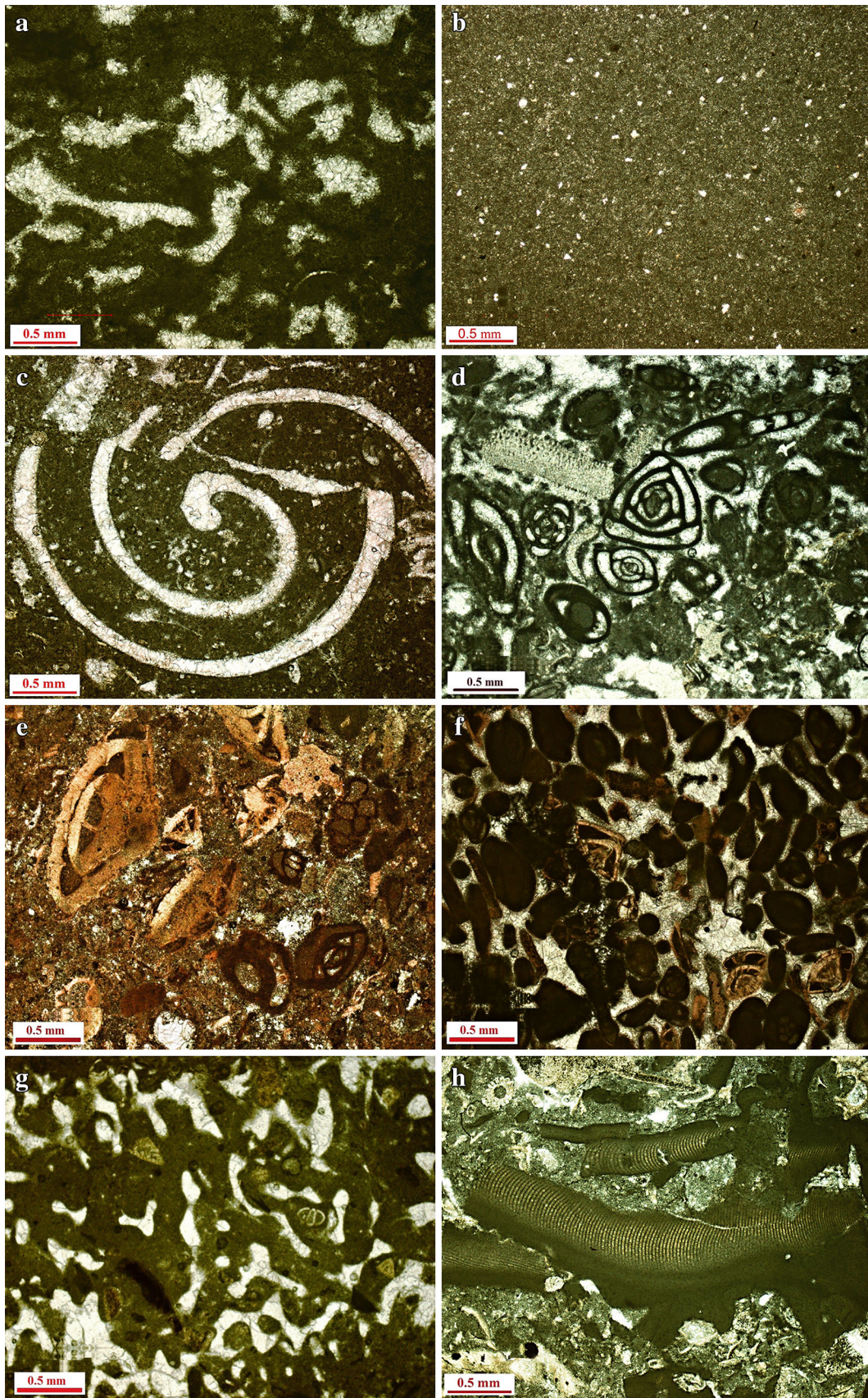
The fragmented fauna, well-sorted components, and grainy texture suggests a high-energy shoal environment above the fair-weather wave base, separating the open marine from more restricted marine environment (Flügel 2010; Khatibi Mehr and Adabi 2013).

Mf 7, bioclast coral boundstone

This bioclast coral boundstone facies is from 0.2 to 0.9 m thick, and characterized by the abundance of scleractinian coral colonies that are mostly in growth position (Fig. 6g), in a matrix of lime mud.

Interpretation

This microfacies is interpreted to be formed by in situ organisms as an organic reef (bioherm) located above the fair-weather wave base (Wilson 1975). The boundstones



◀ **Fig. 6** **a** Mf 1: Fenestral mudstone. **b** Mf 2: Quartz dolo-mudstone. **c** Mf 3: Bivalve benthic foraminifera gastropod wackestone–packstone. **d** Mf 4: Bioclast imperforate foraminifera wackestone–packstone. **e** Mf 5: Bioclast perforate and imperforate foraminifera wackestone–packstone. **f** Mf 6: Bioclast peloid grainstone. **g** Mf 7: Bioclast coral boundstone. **h** Mf 8: Bioclast, coral corallinean wackestone–packstone

probably formed on the middle ramp associated with shoals.

Mf 8, bioclast coral corallinean wackestone–packstone

This dominantly wackestone–packstone and less common grainstone facies is characterized by abundant corallinean red algae and corals (Fig. 6h). Other biota is fragment of rotalia, discorbis, bryozoa, echinoid, and mollusca.

Interpretation

This facies with its millimeter size debris of reef-derived particles, in particular corallinean red algae and corals probably formed as debris sheets peripheral to reefs. This microfacies is distinguished from the reef facies by an abundance of angular chips of coralline red algae and shell debris, and the absence of in-place boundstone fabrics. In comparison with analogues in modern day Persian Gulf facies, the above microfacies fauna in this study occur at all depths that are most prolific near the coast, where they help to build patch or shoal reefs at depths less than 15 m (Purser and Seibold 1973; Gischler and Lomando 2005).

Open marine facies

Mf 9, bioclast operculina wackestone–packstone

The *Bioclast operculina wackestone–packstone* facies consist dominantly of *operculinid* and *heterosteginid forams* in a fine-grained lime mudstone and is common in the lower Asmari Formation. Planktonic foraminifera (such as *globigerinids*) are also present with minor amounts. Operculinids are elongated and include thin- to thick-walled forms. The bioclastic components of this facies are tubucellaria, and fragments of echinoderms, bivalves and bryozoans. Fragmentation of larger foraminifera is rare (Fig. 7a).

Interpretation

Planktonic foraminifers with minor amounts, and high abundance of large and flat benthic foraminifers indicate that sedimentation took place in relatively deep water, under oligophotic conditions (Geel 2000; Romero et al.

2002; Bassi et al. 2007). Flatter and thinner walls of larger benthic forams reflect decreased light levels at greater depths (Nebelsick et al. 2005; Bassi et al. 2007; Khatibi Mehr and Adabi 2013). Packstone and wackestone fabrics are compatible with deposition in a low–medium energy open marine environment on the deeper ramp slope between the normal wave base and storm wave base. Depth to storm wave base by comparison with modern Persian Gulf would be 30–50 m (Purser and Seibold 1973).

Mf 10, bioclast nummulitid lepidocyclinid wackestone–packstone

The bioclastic nummulitid lepidocyclinid wackestone–packstone is common in the lower Asmari and contains abundant flat larger benthic foraminifera of the Nummulitidea (*nummulites*, *operculina*, *heterostegina*) and Lepidocyclinidae (*eulepidina*, *nephrolepidina*). Less abundant bioclasts include red algae, echinoid, bryozoan, bivalve, and small benthic foraminifera (Fig. 7b). Because *nummulites* disappear above the Rupelian–Chatian boundary, this facies becomes bioclastic lepidocyclinid wackestone–packstone.

Interpretation

The abundance of typical open marine skeletal fauna including large and flat Nummulitidea, Lepidocyclinidea, echinoids, and bryozoan, along with mud-rich to mud-poor packstone and wackestone indicates that facies Mf 10 was deposited in a medium- to low-energy open marine ramp slope between fair-weather wave base and storm wave base (Wilson 1975; Romero et al. 2002; Flügel 2010; Khatibi Mehr and Adabi 2013).

Mf 11, bioclast nummulitids wackestone–packstone

This bioclast nummulitid wackestone–packstone facies is characterized by gravel-sized large benthic foraminifera dominantly of lens-shaped Nummulitidea and its fragments. Other bioclasts include echinoderms, bivalves, rotalia and the foram *Ammonia*. This facies occurs in the base of the Asmari Formation (Fig. 7c).

Interpretation

The presence of stenohaline fauna such as perforate foraminifera and echinoids and stratigraphic position below open marine facies, both suggest that sedimentation took place in an open marine environment. Micritic mud and wackestone–packstone fabrics with whole larger foram sand the fragmented fauna in the matrix suggesting a relatively low- to moderate-energy deeper ramp environment, probably near storm wave base (Scholle and Scholle

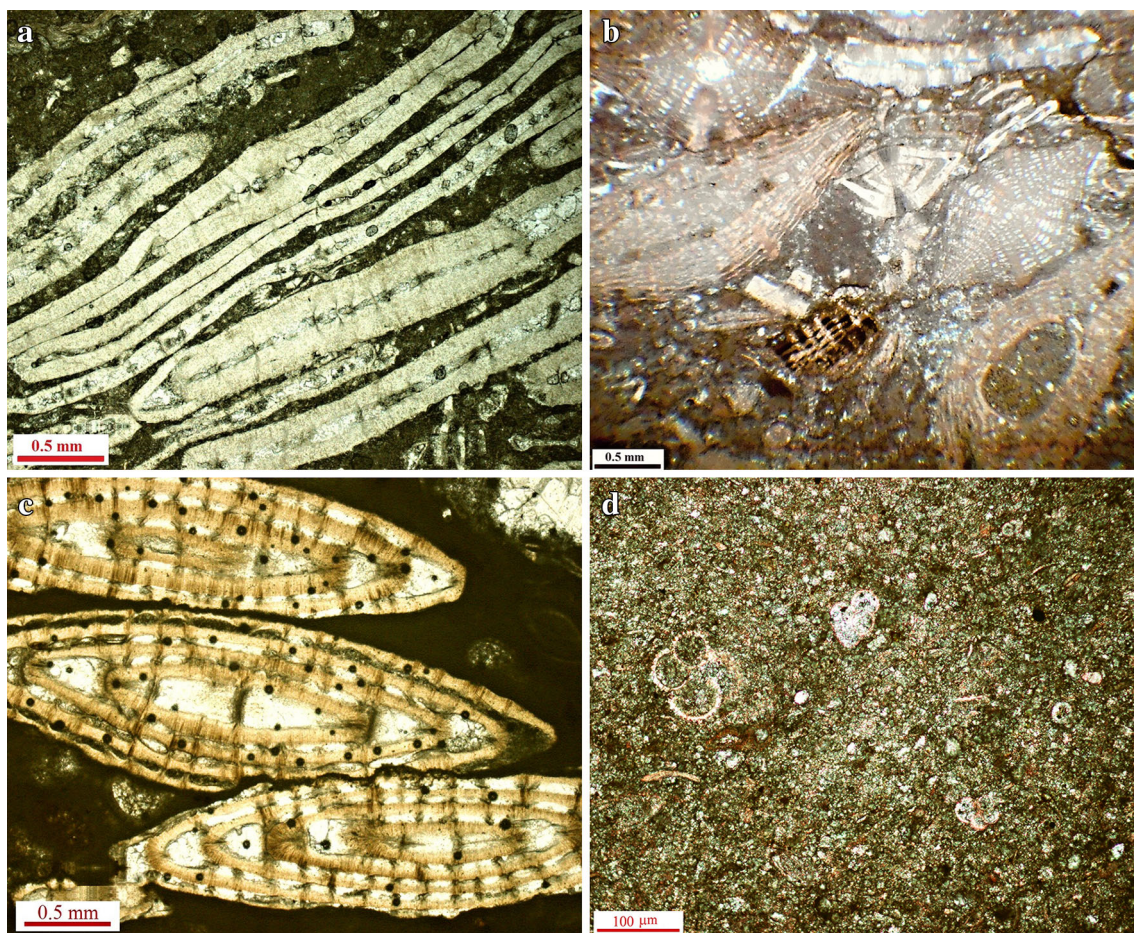


Fig. 7 **a** Mf 9: Bioclast, operculina wackestone–packstone. **b** Mf 10: Bioclast, nummulitids, lepidocyclinids wackestone–packstone. **c** Mf 11: Bioclast, nummulitids wackestone–packstone. **d** Mf 12: Planktonic foraminifera mudstone–wackestone

Dana 2006; Bassi et al. 2007; Flügel 2010; Payros et al. 2010). The Oligocene shallow water facies shows a change in the Rupelian stage. In the latest Rupelian, the *Nummulites* disappeared, and *Eulepidina* and *Lepidocyclina* become a dominated fauna (Assemblage zone III). The disappearance of the Nummulites is an age sign, while the presence or absence of *Eulepidina* is an environmental indicator (Laursen et al. 2006; Van Buchem et al. 2010).

Mf 12, planktonic foraminifera mudstone–wackestone

The main components of the planktonic forma mudstone–wackestone facies are planktonic foraminifera (such as *Globigerina*, *Globorotalia*), less common skeletal bioclasts of echinoids and bivalves along with moderate to abundant lime mud (Fig. 7d).

Interpretation

The high amounts of lime mud, lack of mechanical sedimentary structures, and presence of planktonic

foraminifera suggest that this facies was deposited in calm, low-energy deep ramp or basin settings with normal salinity (Wilson 1975; Romero et al. 2002; Cosovic et al. 2004; Flügel 2010). The absence of photo symbiont-bearing taxa suggests that this microfacies was deposited below the photic zone (Cosovic et al. 2004) which by analogy with the modern day Persian Gulf would be below 30 m water depth, while the abundant mud would suggest water depths of 50–80 m.

Sedimentary model

Microfacies analysis have allowed the interpretation of several carbonate marine environments including open marine, shoal, open lagoon, restricted lagoon, and tidal flat in the Asmari Formation in the Rig mountain oil field. These environments are represented by twelve facies types including: two tidal flat facies (Mf 1–2), two restricted lagoon facies (Mf 3–4), one open lagoon facies (Mf 5), three shoal facies (Mf 6–8), and four open marine, storm influenced deeper ramp facies (Mf 9–12).

The palaeoenvironments of the Asmari Formation can be reconstructed by the arrangement of the facies belt and the distribution of the larger benthic foraminifera assemblages. The accumulation of the studied carbonate deposits took place during a transgressive–regressive cycle, indicated by an upward-shallowing trend recorded in the Aman Valley section. On the basis of the facies, stratigraphy, gradual shallowing trend from the basin into the shallow ramp, absence of oncoids, pisoids, and aggregate grains that have been found in the shelf carbonate or rarely present at carbonate ramp systems (Flügel 2010), the homoclinal ramp depositional profile is suggested for the deposition of the Asmari Formation at the study area (Fig. 5). Given the presence of scattered reefs, but absence of foreslope breccias, turbidites and slumps, this was not a rimmed shelf, but a homoclinal ramp (cf Read 1985; Burchette and Wright 1992). The thick lagoonal facies shows that the inner ramp depositional setting was dominant in the study area. Larger benthic foraminifera are important for recognition of the Cenozoic carbonate ramp (Flügel 2010).

In the section of the Rig Anticline, tidal flat environments are characterized by fenestral lime–dolomite mudstone (Mf 1) and mixed siliciclastic–carbonate sediments [quartz dolomudstone (Mf 2)]. The most common facies of the inner ramp is imperforate foraminifera, bioclastic wackestone–packstone (Mf 4–5). The restricted shallow marine environment or restricted lagoon is commonly dominated by imperforate foraminifera (Romero et al. 2002) such as miliolid, borelis, peneroplis, and archaias. The coexistence of perforate and imperforate foraminifera indicates that the depositional setting was a semi-restricted lagoon (Mf 5).

The mid-ramp shoal complex is represented by coral boundstone, corallinacean red algae and bioclast grainstone (Mf 6–8). Good sorting and the lack of carbonate mud indicate constant reworking by waves (Mf 6). The main site of reef carbonate production (Mf 7) was located above the fair-weather wave base probably in about 5–10 m of water (Purser and Seibold 1973; Wilson 1975, Gischler and Lomando 2005).

Four facies types suggested that open marine environment occur in outer ramp settings. The outer ramp is identified by the foraminiferal assemblage with perforate walls including *Nummulitidae*, *Lepidocyclonidae*, and small benthic foraminifera (Mf 9–11). The facies of the outer ramp–basin floor environment in the Asmari Formation is planktonic foraminifera mudstone–wackestone characterized by marly limestone lithologies. The presence of mud supported textures and the apparent absence of wave and current structures suggest a low-energy environment below the storm wave base (Wilson 1975; Burchette and Wright 1992).

Sequence stratigraphic framework

Sequence and seismic stratigraphy has provided a means of relating the geologic record of continental margins to changes in accommodation that are related to changes in ice volume, and tectonic subsidence or uplift (Vail et al. 1977; Haq et al. 1987) and subsidence. Sea-level history is deduced by the recognition of unconformity bounded units (i.e. depositional sequences) deposited in response to a cycle of falling and rising sea level. The sequence stratigraphic model defines depositional sequences as genetically related chronostratigraphic units representative of a single cycle of relative sea-level rise and fall, bounded by discontinuity surfaces (e.g. Vail et al. 1977; Posamentier and Vail 1988; Van Wagoner et al. 1990; Posamentier and James 1993). Retrogradational, aggradational and progradational stacking patterns are developed due to eustatic sea-level fluctuations. A sequence stratigraphic interpretation proposed for the Asmari Formation is based on the biozonation and the broad palaeoenvironmental inferences revealed by microfacies analysis and stacking patterns of facies (Fig. 8).

In this section, between the underlying Pabdeh Formation and the topmost unconformity, at the base of the Gachsaran Formation, the Asmari limestone succession is divided into six third-order depositional sequences that were deposited through Oligocene to early Miocene time (Fig. 8); the thickness of the sequences varies from 24 to 95 m.

In the Rig Anticline section, the authors have distinguished three Oligocene (Rupelian, Early Chattian, and Late Chattian in age) and three Miocene (Early Aquitanian, Late Aquitanian, and Early Burdigalian in age) sequences.

Depositional sequence 1 (Rupelian)

Sequence 1 includes uppermost part of the Pabdeh Formation and lower part of the Lower Asmari Formation in the study area. The TST and lower boundary of sequence 1 (the Pabdeh Formation) are not studied. The Mfs of sequence 1 consist of shale and open marine limestones with *Nummulites fichteli* as an index fossil and is close to the base of the Asmari Formation (Sharland et al. 2001). The HST of sequence 1 consists of lagoonal and shallow open marine limestones with evidence of shallowing upward, which is characterized by large benthic perforate foraminifera (such as *Eulepidina*, *Nephrolepidina*, *Nummulites*). The boundary between sequence 1 and sequence 2 is a type 2 of sequence boundary (SB2) and characterized by bioclast, imperforate foraminifera wackestone–packstone.

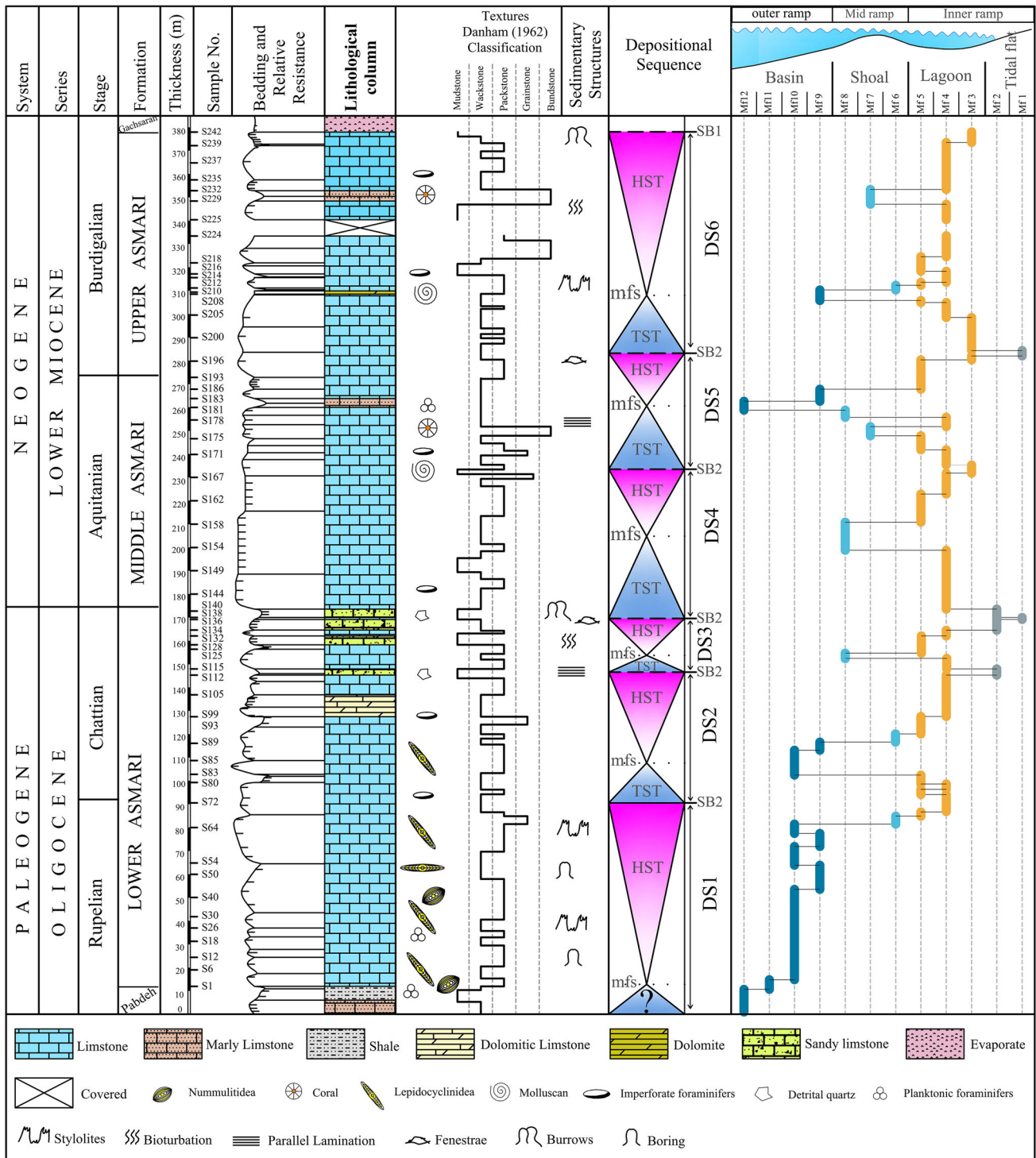


Fig. 8 Vertical facies distribution showing paleoenvironmental and sequence stratigraphic characteristics of the Asmari Formation at Rig anticline in Zagros basin

Depositional sequence 2 (early Chattian)

Sequence 2 is nearly 70 m thick. The TST has a deepening upward facies trend passing vertically from restricted lagoon and open lagoon facies with imperforate foraminifera

to open marine carbonates with large benthic perorate foraminifera. The mfs lies beneath the shallow open marine limestones with lepidocyclinids (Sharland et al. 2004) and Van Buchem et al. 2010). The HST of sequence 2 is characterized by gradual facies change from open marine

facies to open lagoon facies and then restricted facies. The boundary between sequence 2 and sequence 3 is characterized by quartzose dolo-mudstone and is a type 2 sequence boundary (SB2) that shows no clear evidence of subaerial exposure.

Depositional sequence 3 (late Chattian)

Sequence 3 is nearly 24 m thick. The TST consists of restricted lagoon deposits with imperforate foraminifera. The HST of sequence 3 is composed of open to restricted lagoonal facies that are mostly characterized by co-occurrence of perforated and imperforated foraminifera. The boundary between sequence 2 and sequence 3 is characterized by tidal flat, fenestral mudstone and is a type 2 sequence boundary. The composition of the sediments changed around the Rupelian–Chattian boundary. During the Rupelian the sedimentary system was carbonate dominated, with marls in the basin, while from the early Chattian onwards significant amounts of sand and silts were brought into the basin (Fig. 8).

Depositional sequence 4 (early Aquitanian)

Sequence 4 is 63 m thick, and is composed of lagoonal facies with perforate and imperforate foraminifera in the TST and HST. The mfs of sequence 4 is beneath shoal facies containing open marine fossils such as echinoid,

corallinean, and coral within shoal facies. The boundary between sequence 4 and sequence 5 is a type 2 sequence boundary and characterized by lagoonal bivalve, benthic foraminifera, gastropod wackestone–packstone.

Depositional sequence 5 (late Aquitanian)

Sequence 5 is nearly 50 m. The TST is an overall upward deepening succession of lagoonal facies to shoal facies with coral, corallinean, perforate, and imperforate foraminifera, and is punctuated by a thin lagoonal phase. The mfs is within or at base of deeper marine slope and basin facies with planktonic foraminifera. The HST is markedly upward shallowing. The early HST consists of slope and basinal upward-shallowing wackestone and packstone with perforate large benthic foraminifera (*Operculina*, *Heterostegina*). Late HST deposits consist of upward-shallowing lagoonal sediments with abundant perforate and imperforate benthic foraminifera. The boundary between sequence 5 and sequence 6 is characterized by fenestral mudstone (SB2).

Depositional sequence 6 (early Burdigalian)

This sequence is 63 m thick. The TST of sequence 6 consists of a deepening upward succession of restricted and semi-restricted facies passing up into near open marine facies. The mfs is at the base of a packstone with perforate large benthic foraminifera. The HST in addition to the thin

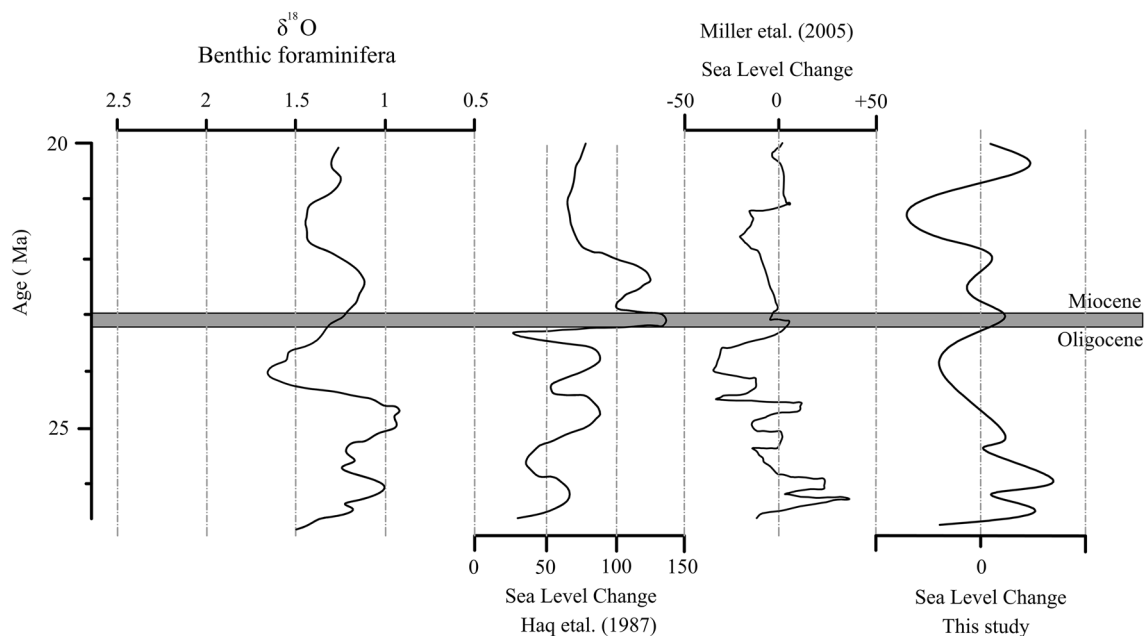
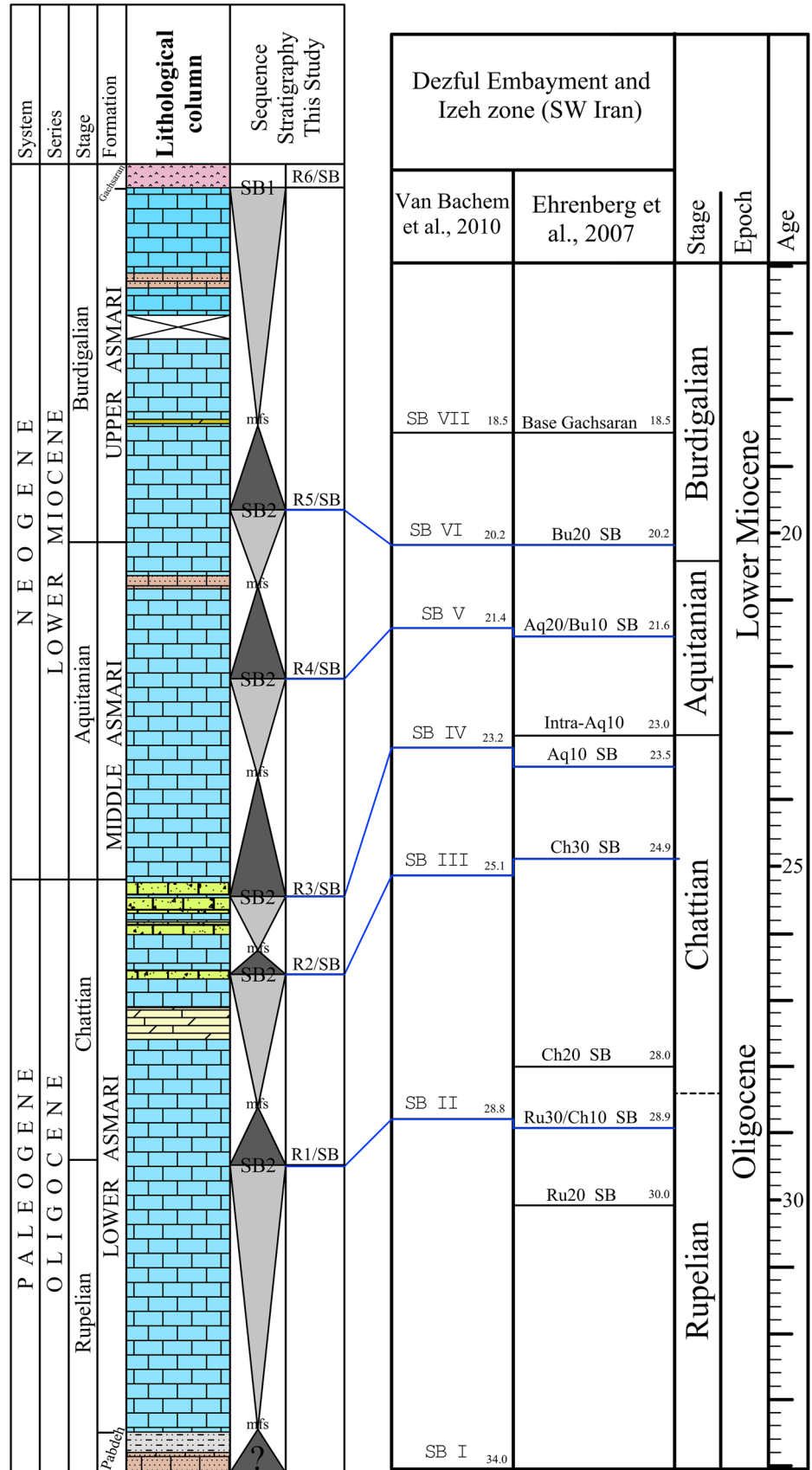


Fig. 9 Relative correlation exists between sea-level change curves of the study area, global oxygen isotopes (Miller 2009) and eustatic sea-level curves derived from coastal onlap patterns for the Oligocene–Miocene boundary interval from Haq et al. (1987) and Miller et al.

(2005). Calibration of Miller et al. (2005, 2009) curves is considered more realistic. Curves are adjusted to Astronomical Time Scale of Billups et al. (2004)

Fig. 10 Comparative scheme for sequences. Comparison of sequences for the Dezful Embayment and Izeh zone (Ehrenberg et al. (2007) and Van Buchem et al. (2010)) and this study



deep ramp packstone, consists of shoal to lagoonal facies, with imperforate foraminifera. There is a sharp and easily defined disconformity (type 1 sequence boundary) developed between the Asmari Formation and the following Gachsaran Formation (Middle Miocene). In the outcrop section, an anhydrite bed is found at the top of this sequence, marking the base of the Gachsaran Formation. This environmental change was coincident with the closure of the Neo-Tethys Ocean.

Discussion

Both subsidence and sedimentation rate are mostly related to the tectonic evolution of the belts that surrounded the Zagros proforeland system, influencing the lithosphere vertical motions and the precipitation of carbonate sediments through time. Sharland et al. (2001, 2004) in their study subdivide the Arabian Plate sedimentary succession into a series of Tectonostratigraphic Megasequences (TMS) that subdivided the geological history of the Arabian Plate from Precambrian to the Present. The Oligocene–Miocene age of the Asmari, Pabdeh and Gachsaran formations sit within the latest of the TMS, which is defined as the package of sediments lying between the unconformity marking both the onset of Red Sea Rifting and the first continental collision between Arabia and Eurasia and the present day topographic surface (Sharland et al. 2001). The subsidence rate of the Dezful embayment and Izeh zone from Oligocene to Miocene was between 13 and 14 cm/k.y (Barbieri et al. 2007).

Global climatic cooling and Antarctic glaciation influenced sedimentation worldwide during the middle Eocene to early Miocene (Van Buchem et al. 2010). This has been documented in marine and terrestrial faunal and floral changes, seismic data and oxygen and carbon isotope profiles (e.g. Miller et al. 2005; Abreu and Haddad 1998; Zachos et al. 2001). Three significant climatic cooling and glaciation events that predate the study interval are not particularly relevant in this study. The sequence subdivision proposed here and the associated lithological changes appear to coincide with global variations in climate and sea-level changes. The glacio-eustatic contribution to sea-level changes in the Oligocene and earliest Miocene of the US Atlantic continental margin was estimated by Kominz and Pekar 2001, who combined two-dimensional palaeoslope modelling of the foraminiferal biofacies and lithofacies with two-dimensional flexural back-stripping of the margin.

The Oligocene–Miocene relative sea-level change curve in the Rig anticline based on relative water depths of facies reflects several major transgressions and regressions, from the base to the top of the Asmari Formation. Eustatic sea-

level curves from coastal onlap patterns for the Oligocene–Miocene interval and shallowing and deepening trends were derived from Haq et al. (1987) and Miller et al. (2005) (Fig. 9). This could lead to eustatic sea-level changes that principally affected deposition at the Asmari Formation. Comparison of the Asmari Formation depositional sequence with the oxygen isotope curve provides a link between the Asmari Formation sea-level lowering and global sea-level changes for the Oligocene–Miocene boundary interval (Fig. 9). Increases in isotopic oxygen ($\delta^{18}\text{O}$) in deep-sea Atlantic cores correlate with the sea-level changes in the Asmari Formation (Fig. 9).

Ehrenberg et al. (2007) and Van Buchem et al. (2010), in their study of the Asmari Formation in the southwest of Iran, defined 7 sequence surfaces that were dated and correlated between several outcrops and subsurfaces. Five sequence boundaries of this study can be well matched with the proposed sequence boundaries by Ehrenberg et al. (2007) and Van Buchem et al. (2010) (Fig. 10). In increasing age they are: Bu20 Sequence Boundary of Ehrenberg et al. (2007) and SB VI Sequence Boundary of Van Buchem et al. (2010) equates with R5/SB, Aq20/Bu10 and SB V with R4/SB, Aq10 and SB IV with R3/SB, Ch30 and SB III with R2/SB, Ru30/Ch10 and SB II with R1/SB.

The sequence boundaries, in sequences 1, 2, 3, 4, 5 and 6 specified as type II sequence boundaries (basinward shift in facies), show no evidence of subaerial exposure. The upper boundary in sequence 6 is sharp and clearly defined as a type I sequence boundary, and is marked by presence of evaporites of the Gachsaran Formation. These six sequences vary in duration from 1.2 to 5.2 M.y, which classify as third-order cycles.

Conclusions

The Asmari Formation exposed at the Rig anticline part of the Izeh zone in the Zagros foreland basin was examined. Twelve microfacies types have been distinguished on the basis of depositional textures, petrographic analysis and fauna. These carbonate microfacies were deposited on a homoclinal carbonate ramp, and include four major subenvironments. These are tidal flat, lagoon, shoal, and open marine ramp slope and basin. The overall upward-shallowing trend recorded in the Aman valley section show that the studied carbonate deposits took place during a long-term (15.4 M.y) transgressive–regressive cycle. Relative sea-level change curves of the Asmari Formation in the Rig section were drawn and correlated with eustatic sea-level curves for the Oligocene–Miocene Boundary Interval from Haq et al. (1987) and Miller et al. (2005). Six third-order depositional sequences are identified from shallowing and deepening trends of depositional

sequences, and distribution of planktonic and benthic Oligocene–Miocene foraminifera.

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