



# The regional facies analysis and depositional environments of the Oligocene and Lower Miocene deposits; Zagros Basin, SW of Iran

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## Abstract

A regional transect is selected to study the paleoenvironment of the Oligocene and Lower Miocene deposits in the Zagros Basin (Persian Gulf Foreland Basin to the High Zagros). This study rebuilds the sedimentary environments and paleogeography of the Zagros basin deposits in the Oligocene and the Lower Miocene. A transect consists of two stratigraphic subsurface sections at the Persian Gulf Foreland Basin, five stratigraphic subsurface sections at the Dezful Embayment, two stratigraphic outcrop sections at the Zagros Simply Folded and one exposure section at the High Zagros. The sediments are included Asmari Formation and the Pabdeh Formation. Lithostratigraphy studies show that the Pabdeh Formation has been composed of an alternation of marls and medium-bedded argillaceous limestone. The Asmari Formation is generally composed of medium- to thick-bedded limestone. Micropaleontology studies offer Early Oligocene for Pabdeh Formation and Early–Late Oligocene to Early Miocene age for Asmari Formation. Variety in fabrics, textures and fauna features has produced 13 microfacies and based on geometry, lateral and vertical facies relationships, the homoclinal ramp is proposed for the Oligocene and Lower Miocene deposits. Hence, corresponding to this research, the Rupelian sedimentation has occurred in the Dezful Embayment and Zagros Simply Folded, so that a systematic progradation suggests from Zagros Simply Folded (N/NE) (Asmari/Pabdeh Formation) to the Dezful Embayment (S/SW) (Asmari carbonate system). Following a regression system during the Late Oligocene to the Early Miocene, continuing sedimentation uniformly has been felt out in the shallow water system throughout the study area.

**Keywords** Oligocene · Miocene · Asmari · Pabdeh · Zagros

## Introduction

An important point to realize this study is the presence of hydrocarbon resources in the Oligocene and Miocene deposits which are extended through the Zagros basin from west to southeast of Iran. The Pabdeh and Asmari Formations were studied in detail and formally defined by James and Wynd (1965) (Fig. 1). The Asmari Formation deposited in the flanking shelves of the Zagros foredeep is composed of light-colored, well-jointed, micritic and foraminiferal limestones (Ziegler 2001). Previous studies have been often focused on biostratigraphy, lithostratigraphy, and paleoenvironment of the Asmari Formation such as Wynd (1965), Adams and Bourgeois (1967), Vaziri-Moghaddam et al. (2006), Ehrenberg et al. (2007), Laursen et al. (2009), Van Buchem et al. 2010; Seyrafian et al. (2011), Hoseinzadeh et al. (2015), Roozpeykar and Moghadam (2015), Adabi et al. (2016) and

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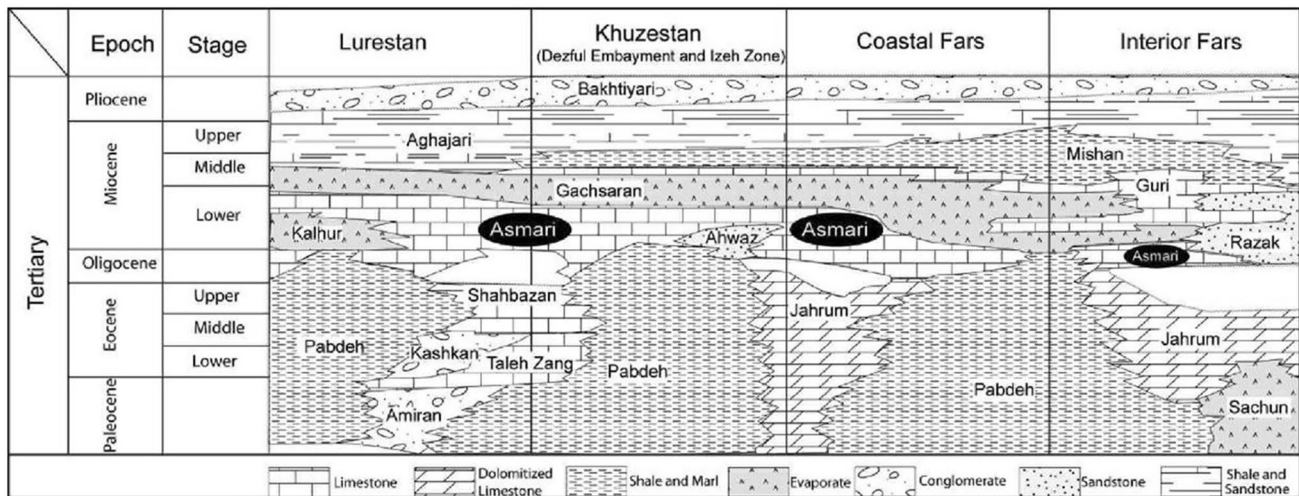
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**Fig. 1** Cenozoic stratigraphic correlation chart of the Iranian sector of the Zagros Basin. Adapted from James and Wynd (1965)

Sadeghi et al. (2018). In this study, the depositional setting of the Pabdeh and the Asmari Formation (Oligocene and Lower Miocene deposits) is the main target for the rebuilding of the sedimentary model.

## Geological setting

The geological and geographical location of the surface and subsurface stratigraphic sections is shown in Fig. 2. Ten stratigraphic sections include: the Binalud-1 (BB-1), Kharg-2 (KG-2) (Persian Gulf Foreland Basin), Binak-4 (BK-4), Golkhary-2 (GL-2), Kilorkarim-4 (KK-4), Bibi-Hakimeh-2 (BH-2), Gachsaran-55 (GS-55) (Dezful Embayment), Mish and the Anneh (Zagros Simply Folded Belt) and Semirum (High Zagros) (Fig. 3).

The Zagros fold-and-thrust belt is a part of the Alpine–Himalayan system which formed along the Arabia–Eurasia collision zone (Golonka 2004), following the closure of the Neotethys ocean (Barrier and Vrielynck 2008). This fold-and-thrust belt can be subdivided into several zones based on their structural style and sedimentary history (Lurestan, Izeh, Dezful Embayment, Fars and High Zagros) (Shabafrooz 2015). The Oligocene–Miocene deposits (Pabdeh and Asmari Formations) have not outcropped in Dezful Embayment but their outcrops expose near the Mountains Front Fault (MFF) in the Zagros Simply Folded Belt.

## Materials and methods

In this research, more than 1800 samples collected from 10 outcrops and cores in the Persian Gulf, Boushehr, Kohkilooye and Esfahan provinces have been studied. The

subsurface stratigraphic sections (55% core) were sampled at the National Iranian Oil company (NIOC) repository. The petrographic analysis was conducted by a polarizing microscope. The main references used for the identification of foraminifera and facies belts are included: Wilson (1975), Flugel (2004, 2010), Buxton and Pedley (1989), Loeblich and Tappan (1988) and Laursen et al. (2009), Geel (2000), Romero et al. (2002), Corado and Brandano (2003), Cosovic et al. (2004), Rasser et al. (2005), Beavington-Penney and Racey (2004), Nebelsick et al. (2005), Renema (2006), Bassi et al. (2007), Barattolo et al. (2007), Daniel et al. (2008), Brandano et al. (2009a, b), Rahmani et al. (2009), Van Buchem et al. (2010), Habibi (2014), Shabafrooz et al. (2015), Kakemem et al. (2016) and Sadeghi et al. (2018).

## Stratigraphy

The stratigraphic structure of the study area is included: the shallow-water carbonates of the Jahrum and Shahbazan Formations (Eocene); the deeper-water marls and muddy limestone of the Pabdeh Formation (Oligocene); the shallow-water carbonates of the Asmari Formation (Oligo-Miocene) and the alternation of evaporites (gypsum and anhydrite), carbonates and marls of the Gachsaran and Razak Formations (Miocene) (Fig. 4).

The Asmari Formation limestone is covered the shallow-water carbonates of the Jahrum Formation (Eocene) in the Persian Gulf Foreland Basin to the Dezful Embayment (Kilorkarim-4). The Jahrum Formation is the lateral equivalent of the Pabdeh Formation (BH-2 to Anneh) in the Folded Zagros; this architecture has occurred in Eocene and Early Oligocene. The Shahbazan Formation (dolomitic limestone)

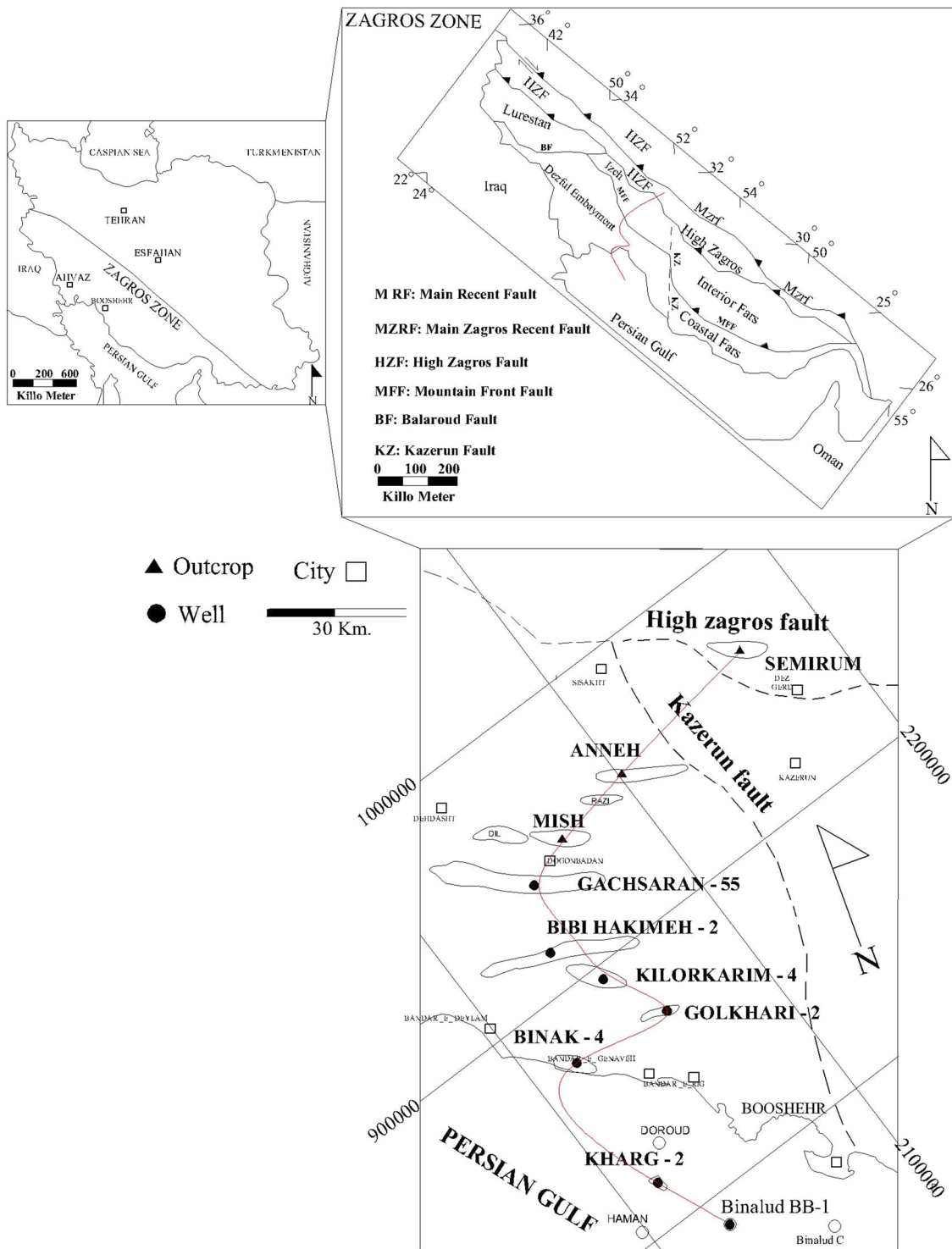
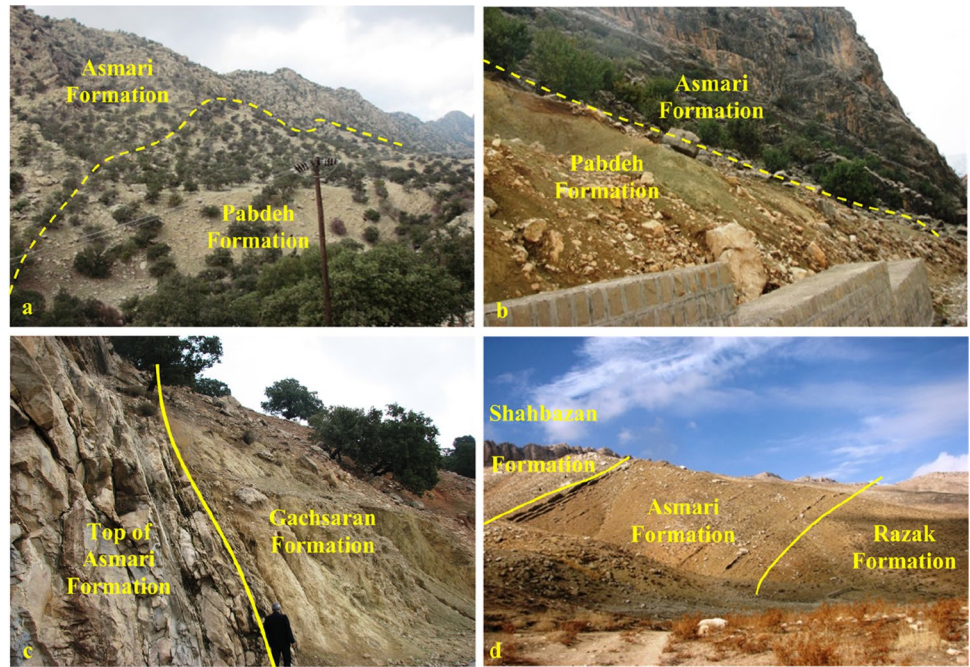


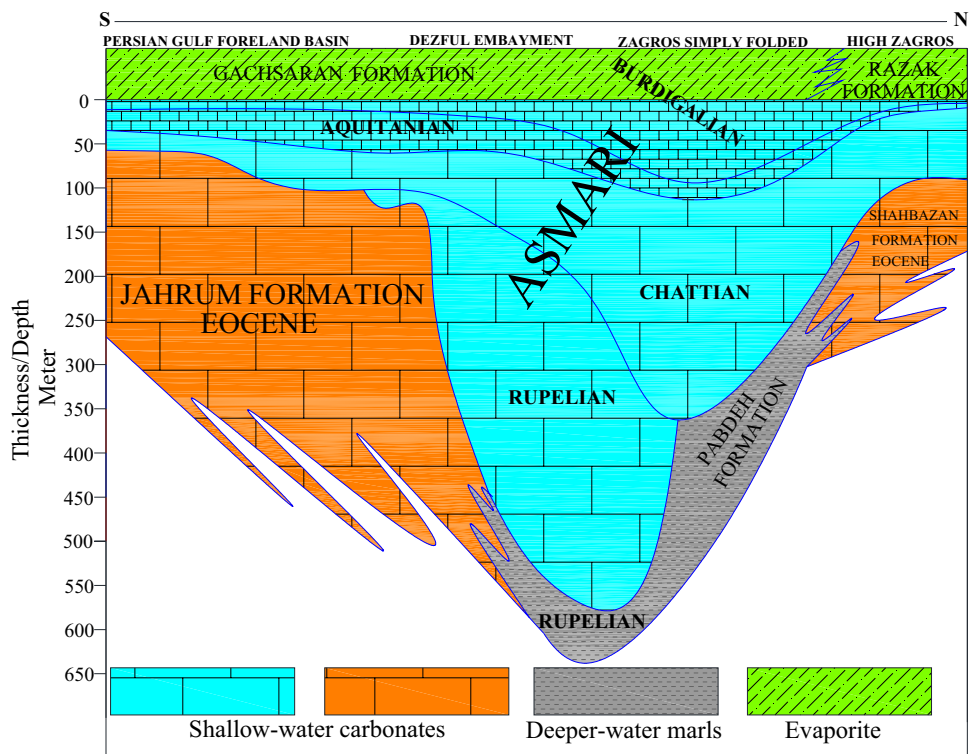
Fig. 2 The geological and geographical setting of the study area (Retrieved from Sepehr and Cosgrove 2004)



**Fig. 3** Field photographs of the outcrop sections, **a** Mish section, **b** and **c** Anneh (Folded Zagros) and **d** Semirum section (High Zagros)



**Fig. 4** Schematic regional stratigraphic architecture design; lateral relations between the Asmari, Pabdeh, Jahrum, Shahbazan, Gachsaran and Razak Formations in the study area



exposed at Semirum stratigraphic section in the High Zagros and it is better developed in Semirum city. The shallow-water carbonates of the Shahbazan Formation (Eocene) are located at the base of the Asmai Formation.

The Oligocene and Lower Miocene deposits in the Persian Gulf Foreland Basin have included the Asmari Formation which is composed of calcareous sandstone, dolostone, dolomitic limestone, and limestone; Reduction lateral

thickness of the dolomites bedded has occurred from Persian Gulf Foreland Basin to the High Zagros.

Across the study area, thick-bedded limestones are well developed in the Rupelian (Lower Asmari, Numulitidae, Lepidocyclinidae, Miogypsinidae packstone) and the Chattian (middle Asmari, imperforate foraminifera packstone).

The Ahvaz sandstone Member deposits (imperforate foraminifera wackestone) of the Asmari Formation are located only at the Persian Gulf Foreland Basin during the Early Miocene.

Medium-bedded limestones generally composed of porcelaneous foraminifera wackestone are well developed in the Early Miocene (Aquitanian to Burdigalian) at the Zagros Simply Folded Belt and High Zagros.

The Asmari Formation is capped by Alternation of evaporites (gypsum and anhydrite), carbonates and marls deposits of the Gachsaran and the Razak Formations (Miocene). The Razak Formation (composed of evaporites and clastics deposits such as microconglomerate bedded) is located at the Semirum stratigraphic section in the High Zagros. Some stratigraphic data from outcrops and subsurface sections are shown in Table 1.

## Biostratigraphy

Biostratigraphy of the Pabdeh and Asmari Formations was established by Wynd (1965) and reviewed by Adams and Bourgeois (1967); however, these studies have not been published. Adams and Bourgeois (1967) assigned four assemblage zones for the Asmari Formation. Ehrenberg et al. (2007) applied a method of strontium isotope stratigraphy to date the Asmari Formation in some locations in the

southwest of Iran. Their data were used by Laursen et al. (2009) in establishing a new biozonation which revised the Oligocene and Miocene chronostratigraphic boundary for the Asmari Formation (Fig. 5). In this research, six biozones have been identified for Pabdeh and Asmari Formation.

### Assemblage zone 1

The biozone includes limestones and muddy limestones bedded of the Pabdeh Formation. Increased lateral of biozone's thickness occurred from Dezful Embayment to the Zagros Simply Folded gradually (Fig. 6). The lower boundary of this biozone is beginning with the disappearance of the *Globorotalia cerroazulensis* and *Hantkenina* sp. and appearance of the *Globigerina* spp., *Globorotalia ciperoensis*, *Bolivina* sp., *Globigerina praebulloide*, *Globorotalia kugleri*, and *Cibicides* sp.

According to the Assemblage zone #55 wynd (1965), Ehrenberg et al. (2007), Laursen et al. (2009) and Van Buchem et al. (2010) studies, the Assemblage is attributed to Rupelian.

### Assemblage zone 2

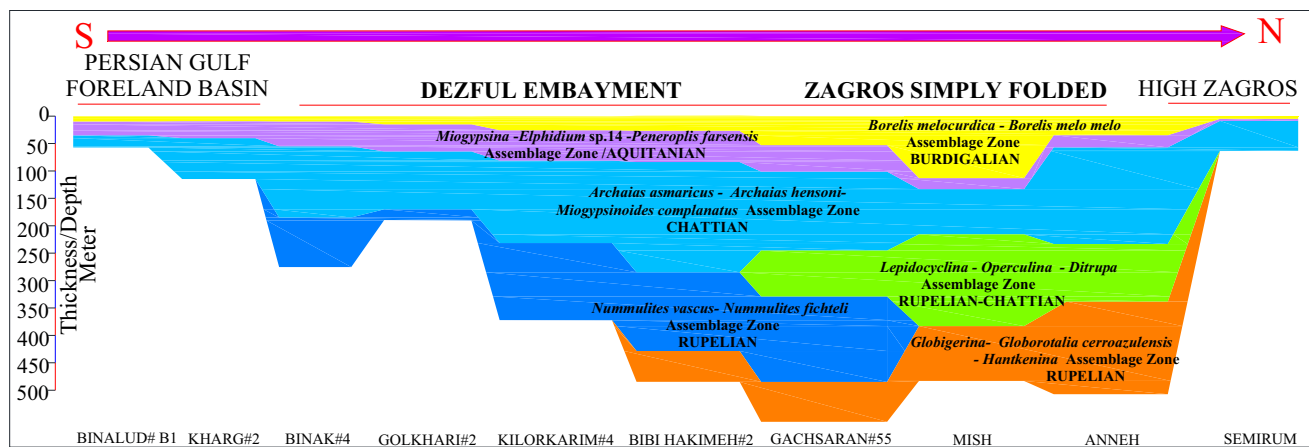
The zone is developed in the Zagros Simply Folded (Fig. 6) and according to the Laursen et al. (2009) and Van Buchem et al. (2010) studies, the Assemblage is attributed to the Late Oligocene (Rupelian–Chattian). The main lithology consists of thick-bedded limestone with intercalation of muddy limestone and dolomitic limestone. The *Ditrupea* is the main fauna at the base of the Asmari Formation and the other foraminifera are included: *Lepidocyclina* sp., *Operculina* sp., *Eulepidina dilatata*, *Heterostegina* sp.,

**Table 1** Sections stratigraphic data

Section	Asmari F. Thickness (m.)	Pabdeh F. Thickness (m.)	Ahvaz Member. Thickness (m.)	Lithology (Asmari)	Lithology (Pabdeh)
BB-1	57	–	32	Dolostone and sandstone	–
KG-2	113	–	48	Dolomitic limestone, dolo sandstone and sandstone	–
BK-4	275	–	23	Limestone, dolomitic limestone, sandstone and sandy limestone	–
GL-2	188	–	–	Dolostone and dolomitic limestone	–
KK-4	372	–	–	Dolo limestone and limestone with intercalation of muddy limestone	–
BH-2	528	57	–	Dolomitic limestone and limestone with intercalation of muddy limestone	Muddy limestone
GS-55	530	73	–	Limestone with intercalation of muddy limestone	Muddy limestone
Mish	383	100	–	Limestone with Dolostone	Marl and muddy limestone
Anneh	345	180	–	Limestone with dolomitic limestone	Marl and muddy limestone
Semirum	66	–	–	Limestone	–

Age interpretation		Previous studies				Standard Chronostratigraphy	
SERIE	STAGE	Wynd (1965)	Adams & Bourgeois (1967)	Laursen et al., (2009)	This study	STAGE	SERIE
		Age interpretation					
MIOCENE		Borelis melo cordica Zone #61	Borelis melo cordica - Meandropolina iranica Assemblage Zone Elphidium sp.14 - Miogypsinina Assemblage Subzone Archaius asmaricus - Archaius bensoni - Assemblage Subzone	Borelis melocordica - Borelis melo melo Assemblage Zone Miogypsinina - Elphidium sp.14 - Peneroplis jursensis - Assemblage Zone	Borelis melocordica - Borelis melo melo Assemblage Zone Miogypsinina - Elphidium sp.14 - Peneroplis jursensis - Assemblage Zone	BURDIGALIAN	MIOCENE
AQUITANIAN		Austrotritina howelini - Peneroplis evolutus Assemblage Zone #59	Miogypsinina - Archaius - Valentinid Assemblage Zone Mioyprasinid - Archaius - Valentinid Assemblage Zone Trifarina - Nummulites Assemblage Zone			20.43 AQUITANIAN	23.03
OLIGOCENE UNDIVIDED		Archaius operculiformis Zone # 58 Lepidocyclina - Operculina - Ditrupa Assemblage Zone #56 Nummulites intermedium - Nummulites vaseus Assemblage Zone # 57 Globigerina sp. IV Assemblage Zone # 55				CHATTIAN 28.4	OLIGOCENE
OLIGOCENE						RUPELLIAN	33.9

Fig. 5 Biozonation of the Asmari and upper deposits of the Pabdeh Formations., Important note: Fossils assemblages in the study area well correspond to Laursen et al. (2009) biozonation



**Fig. 6** Regional biostratigraphic correlation; the lateral relationship between the Asmari and Pabdeh Formation (orange color)

*Nephrolepidina tourneuri*, *Rotalia viennotti*, and *Planorbulina* sp. This biozone is equivalent to the *Nummulites vascus*–*N. fichteli*–*Eulepidina* Zone (SB22B) of Cahuzac and Poignant (1997) in Europe and it is comparable to #58 Assemblage zone of wynd (1965) and *Eulepidina*–*Nephrolepidina*–*Nemmulites* Assemblage Zone (No.3) of Adams and Bourgeois (1967) in the Zagros Basin.

### Assemblage zone 3

The strontium isotope dating method by Ehrenberg et al. (2007) showed that the last *Nummulites* occurrence to be roughly 1 Mio. years before the end of Rupelian time. Hence, based on the presence of *Nummulites vascus* and *Nummulites fichteli*, the zone is attributed to Rupelian. Thickly bedded limestones with intercalation of muddy limestones are the main lithology of the zone. The associated fauna includes *Operculina complanata*, *Heterostegina* spp, *Rotalia viennotti*, *Eulepidina dilatata*, and *Ditrupa*. This zone has extended only in the Dezful Embayment (Fig. 6).

### Assemblage zone 4

The biozone is increased in thickness from the Dezful Embayment to the Zagros Simply Folded (Fig. 6). The occurrence of *Archaias* (*A. kirkukensis* and *A. hensoni*), and the presence of *Miogypsinoides complanatus*, *Borelis pygmae*, and *Asterogerina rotula* indicate that the zone belongs to the Chattian. The zone has corresponded to the “*Archaias asmaricus*–*A. hensoni*–*Miogypsinoides complanatus*” Assemblage Zone Laursen et al. (2009), and the *Miogypsinoides*–*Eulepidina* zone (SB 23) of Cahuzac and Poignant (1997) in Europe. The biozone also is equivalent

to the *Aichaias operculiniformis* zone (#58) of wynd (1965) and the *Archaias asmaricus*–*A. hensoni* Assemblage sub-zone (No. 2b) of Adams and Bourgeois (1967) in the Zagros Basin.

### Assemblage zone 5

The occurrence of *Miogypsina* and *Borelis melo curdica*, and also the disappearance of the *Archaias* indicate that the zone corresponds to the early Miocene (Ehrenberg et al. 2007; Laursen et al. 2009; Van Buchem et al. 2010). According to the Ehrenberg et al. (2007) studies, the interval between the last appearance of the *Archaias* and the first appearance of the *Borelis melo curdica* can be considered as Aquitanian (The SBZ 24 of Cahuzac and Poignant 1997) (Joudaki and Baghbani 2018). The biozone in thickness is uniform throughout the study area, but it is increased considerably in the Mish section (Fig. 6). Main deposits consist of medium- to thick-bedded limestone with intercalation of muddy limestone and dolomitic limestone.

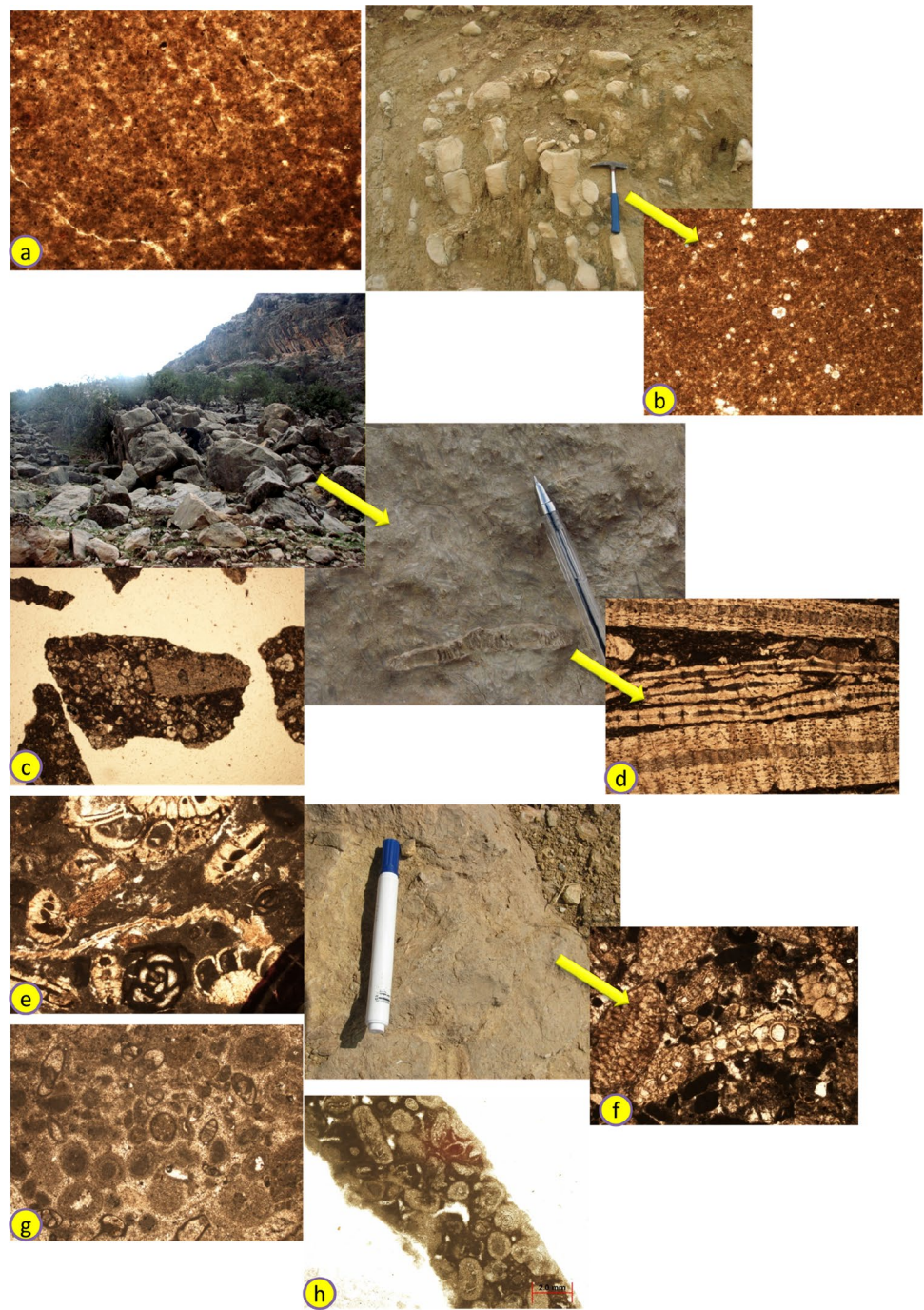
### Assemblage zone 6

The biozone in thickness is uniform throughout the study area, but it is reduced gradually from the Zagros Simply Folded to the High Zagros (Fig. 6). The total range of the *Borelis melo curdica* within the Asmari Formation is attributed to the Burdigalian (Ehrenberg et al. 2007; Laursen et al. 2009; Van Buchem et al. 2010).

The associated fauna are *Meandropsina iranica*, *Valvulina* sp.2, *Discorbis* sp. and *Ammonia* sp. The main lithology is consist of medium-bedded limestone with intercalation of sandy and dolomitic limestone.



**Fig. 7** Field photograph and micro-photograph of the facies in the study area (Mf1–Mf5); **a** Mf 1, Argillaceous mudstone, Anneh section, Pabdeh Formation. **b** Mf 2, Planctonic foraminifera wackestone, Anneh section, Pabdeh Formation. **c** Mf 2, Planctonic foraminifera packstone, BiBi Hakimeh-2, Pabdeh Formation. **d** Mf 3, Bioclastic Numulitidae Lepidocyclinidae packstone, Anneh section, Asmari Formation. **e** Mf 4, Perforate foraminifera corallinacea packstone, Anneh section, Asmari Formation. **f** Mf 4, Perforate foraminifera corallinacea packstone, Semirum section, Asmari Formation. **g** and **h** Mf 5, Oolitic packstone–grainstone, Binak#4, Asmari Formation



## Facies

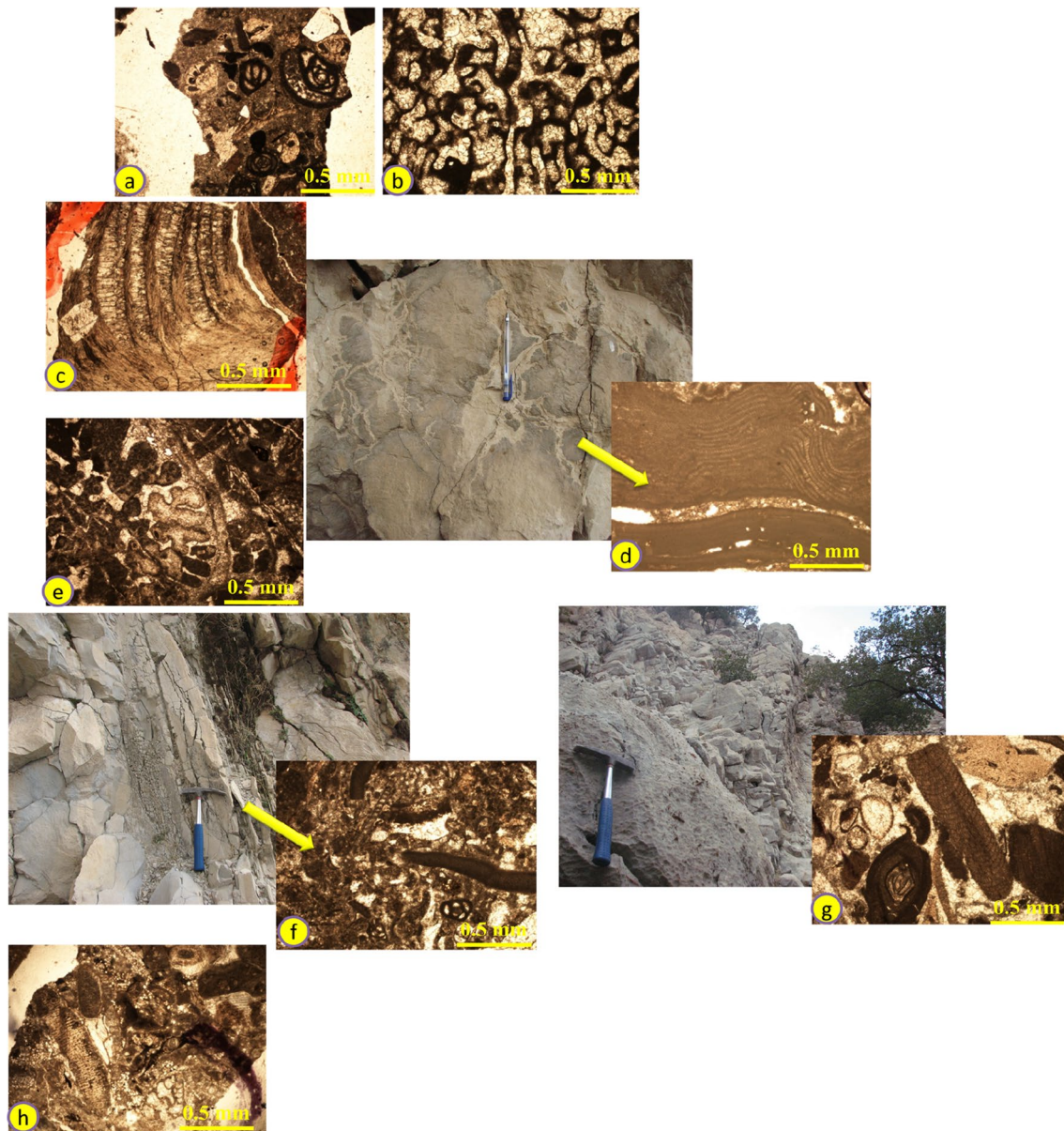
Microscopic studies led to the identification of 13 microfacies for the Oligocene and Lower Miocene deposits. Identification of skeletal and non-skeletal components and determination of the rock texture was done according to the Dunham classification as the process. These facies associations reflect different bathymetric, hydrodynamic and trophic conditions (Shabafrooz et al. 2015). The facies defined here and their distribution along the depositional

profile including the environments characterized are similar to those described by Vaziri-Moghaddam et al. (2006), Rahmani et al. (2009), Allahkarampour Dill et al. (2010), Shabafrooz et al. (2015), Sadeghi et al. (2018) and Shu Gao (2019).

## Outer ramp microfacies association

Two facies types have been identified for the outer ramp environment.





**Fig. 8** Field photograph and micro-photograph of the facies in the study area in the study area (Mf6–Mf8); **a** Mf 6, Bioclastic perforate and imperforate foraminifera packstone, BiBi Hakimeh-2., Asmari F. **b** Mf 7, Bioclastic corallinacea coral packstone–boundstone, Anneh section, Asmari F. **c** and **d** Mf 7, Bioclastic corallinacea coral packstone–boundstone, Semirum section, Asmari F. **e** Mf 7, Bioclastic

corallinacea coral packstone–boundstone, BiBi Hakimeh-2, Asmari F. **f** Mf 8, Bioclastic imperforate foraminifera corallinacea packstone, Anneh section, Asmari F. **g** Mf 8, Bioclastic imperforate foraminifera corallinacea packstone Semirum section, Asmari F. **h** Mf 8, Bioclastic imperforate foraminifera corallinacea packstone BiBi Hakimeh-2, Asmari F

### Mf 1—Argillaceous mudstone

This facies generally consists of fine-grained muddy limestone of the Pabdeh Formation with interbedded green marl. This facies is interpreted as normal sea salinity below of the fair-weather wave base (FWWB) and storm wave base

(SWB). The facies is considered as being deposited in a relatively deep basinal environment, as suggested by the dominant marl and the faunal content (introduced by Flugel (2004) as RMF2). The facies included light-gray medium-bedded muddy limestone (centimeter scale, up to 20 cm) geometry from a limited geological zone (only in Pabdeh

Formation of the Anneh outcrop/Zagros Simply Folded) (Fig. 7a).

### **Mf 2—Planctonic foraminifera wackestone/packstone**

The facies is related to the Pabdeh Formation and it is distributed from Dezful Embayment to the Zagros Simply Folded. The main components are included planktonic foraminifera (*Globorotalia*, *Globigerina* and ...), Echinoid fragments within a homogenous micrite. The increased amount of components in this facies is clear in the Zagros Simply Folded (packstone/poor sorting). The beds are centimeter-scale medium (up to 20 cm). This facies deposited in a relatively deep environment, as suggested by the dominant marls and muddy limestones (Wilson 1975; Flugel 2004, 2010; Buxton and Pedley 1989; Geel 2000; Cosovic et al. 2004) (Fig. 7b and c).

### **Middle ramp microfacies association**

#### **Mf 3—Bioclastic Numulitidae Lepidocyclinidae packstone**

The main components consist of large foraminifera (Numulitidae and Lepidocyclinidae) along with Echinoid fragments, red Algae, Bryozoans and *Ditrupea* trace fossil, with silt- to medium sand-sized nummulithoclastic matrix (poor sorting/coarse grained). Often, the association of components has been seen in a floatstone form. The high diversity of large perforate foraminifera indicates that the sedimentation has been taking place in the distal part of middle ramp along with low to medium energies system and below the fair-weather wave base (FWWB) of open marine environment (Buxton and Pedley 1989; Geel 2000; Beavington-Penney and Racey 2004; Bassi et al. 2007; Brandano et al. 2009a, b) (Fig. 7d). The beds are meter-scale thick (up to 2 m). The facies is identified in the transitional zone between Asmari and Pabdeh Formations from the Dezful Embayment to the Zagros Simply Folded. The lateral facies changes indicate that the facies distribution has well developed to the Zagros Simply Folded during the Oligocene.

#### **Mf 4—Bioclastic perforate foraminifera packstone**

The facies components included are: Numulitidae, Lepidocyclinidae, Miogypsinidae, Rotallidae, Corallinacea, Coral, Bryozoans and Echinoid fragments (Fig. 7e and

f). Their size ranges generally are between 0.1 and 1 mm; some measured 5 mm or more. This facies consists of meter-scale thick (up to 2 m), light-gray, slightly argillaceous limestone (sheet bedded geometry/moderate sorting) with a packstone matrix. Diversity and abundance of lens-shaped perforate foraminifera along with the red algae indicate that the sedimentation has been taken place in the low to moderate energy system of proximal middle ramp (Corado and Brandano 2003; Beavington-Penney and Racey 2004; Rasser et al. 2005; Bassi et al. 2007; Barattolo et al. 2007; Shabafrooz et al. 2015; Kakemem et al. 2016). Facies distribution in the Asmari Formation is located from Dezful Embayment to the High Zagros. However, the reduction lateral distribution of this facies has occurred to the High Zagros (Chattian).

### **Inner ramp microfacies association**

In this study, seven facies types have been identified for the inner ramp environment.

#### **Mf 5—Oolitic packstone/grainstone**

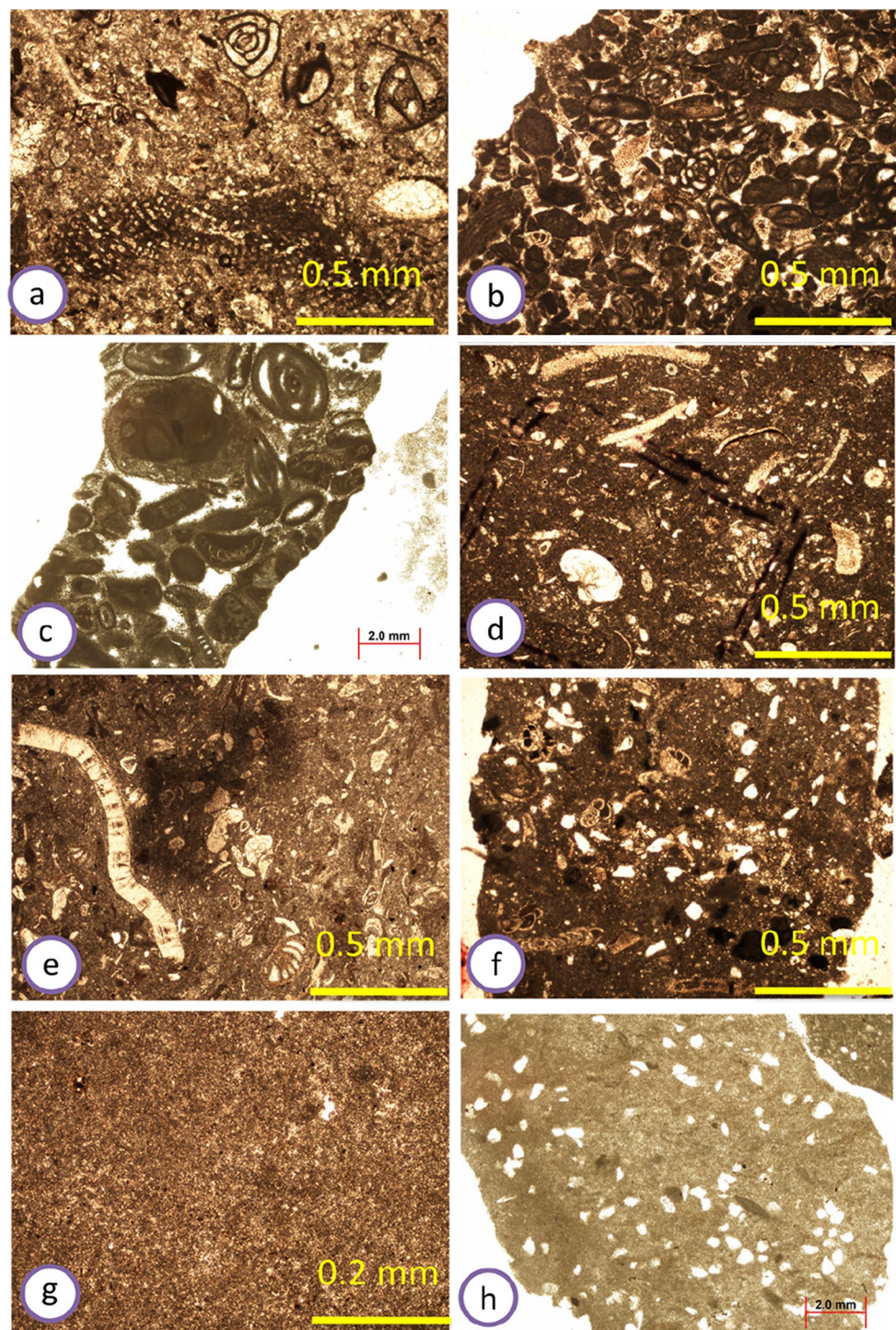
The main components are ooids (up to 0.2 mm diameter/well rounded) and the associated grains are included Peloids, *Miliolids*, Intraclast fragments, Echinoids, and corals. The matrix is a mixture of carbonate mud and sparry calcite cement and the dissolution porosity within ooids has been generally created (Moldic porosity) (Fig. 7g and h). The Ooids grainstone has been developed on a high-energy carbonate ramp as a barrier islands system (Wilson 1975). The facies distribution is expanded from Dezful Embayment (BK-4) to the Zagros Simply Folded (Mish stratigraphic section).

#### **Mf 6—Bioclastic perforate and imperforate foraminifera packstone**

The bioclastic packstone facies included perforated, imperforate foraminifera and echinoids fragments (Fig. 8a) and an increased amount of components in the facies is clear in the Zagros Simply Folded (packstone/poor sorting). The beds are meter-scale thick (up to 2 m). The presence of perforated and imperforate foraminifera indicates the semi-restricted lagoon (Romero et al. 2002; Corado and Brandano 2003).



**Fig. 9** Microphotographs of the facies in the study area (Mf9–Mf11); **a** Mf 9, Imperforate foraminifera wackstone, Semirum section., Asmari Formation. **b** Mf 9, Imperforate foraminifera packstone, Anneh section, Asmari Formation. **c** Mf 9, Imperforate foraminifera grainstone, Binak-4., Asmari Formation. **d** and **e** Mf 10, Bioclastic rotallids echinoides wackstone, Anneh section, Asmari Formation. **f** Mf 10, Bioclastic rotallids echinoides wackstone, Binak-4, Asmari Formation. **g** Mf 11, Mudstone, Anneh section, Asmari Formation. **h** Mf 11, Mudstone, Kharg-2, Asmari Formation



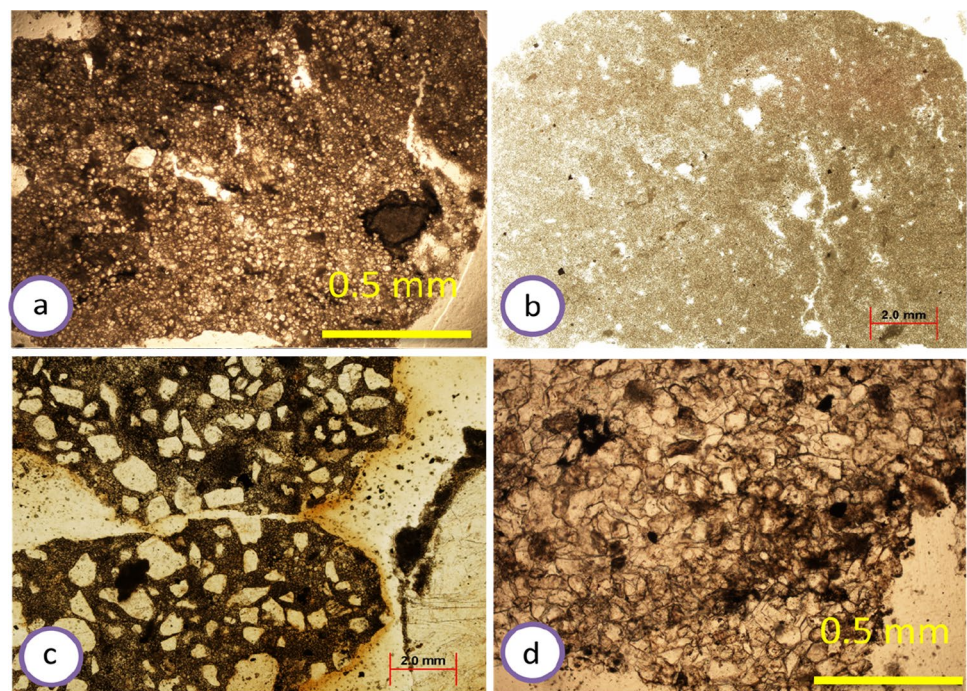
#### Mf 7—Bioclastic corallinacea coral packstone/boundstone

The beds are meter-scale thick (up to 2 m). The main allochems of the facies are Corals, red Algae, along with Bryozoers, Bivalve bioclasts and some *Miliolids* packstone to

boundstone. The angularity of Corals and Corallinacea fragments (Poor rounded) represent the individual patch reefs (isolated outcroppings of coral) (Reef core, buildup geometry). The well-preserved corallinacea indicates the low sedimentation rates by a low-energy system on a stable bed



**Fig. 10** Microphotographs of the facies in the study area (Mf12–Mf13); **a** Mf 12, Dolomudstone, Binak-4., Asmari Formation. **b** Mf 12, Dolomudstone, Kharg-2., Asmari Formation. **c** Mf 13, Calcareous sandstone, Kharg-2., Asmari Formation. **d** Mf 13, Calcareous sandstone, Binak-4., Asmari Formation



surface (Nebelsick and Bassi 2005). Porcelaneous foraminifera with Coral fragments (branched and scattered forms) characterize the fairly enclosed environment by low-water energy system in the lower part of the photic zone. Similar to this facies have been reported as a lagoon to the reef by Corado and Brandano (2003), Nebelsick et al. (2005) and Brandano et al. (2009a, b) (Fig. 8b–e). Facies distribution in the Asmari Formation is located from Dezful Embayment to the High Zagros. However, the reduction lateral distribution of this facies has occurred to the Zagros Simply Folded and the High Zagros.

#### **Mf 8—Bioclastic imperforate foraminifera corallinacea packstone**

The beds are meter-scale thick (up to 2 m) (bedding geometry). The main components included are: Corallinacea and imperforate foraminifera (*Spiroloculina* sp., *Quinqueloculina* sp., *pyrgo* sp. 1) along with Bivalves, Echinoides and Bryozoers fragments (moderate sorting) (Fig. 8f and g). The red algae and imperforate foraminifera association indicate that the sedimentation has been taking place in a lagoon environment (Romero et al. 2002; Corado and Brandano 2003). The facies distribution had developed during the Rupelian to the Burdigalian at the Dezful Embayment but it had particularly

expanded in the Chattian at the Zagros Simply Folded and High Zagros.

#### **Mf 9—Imperforate foraminifera wackestone/packstone**

The facies is composed of low to high diversity of imperforate foraminifera (grain-supported texture/moderate sorting) including *Archaias*, *Peneroplis*, *Austrorillina*, *Meandropsina*, *Denderitina*, and *Borellis*. Other associated fauna are included: echinoids, Bivalves bioclasts with *Ploides* (Fig. 9a–c). The beds are meter-scale thick (up to 2 m) (planar bedding). The vertical facies distribution shows that expanding has happened during the Chattian–Burdigalian. The lagoon index microfossils indicate that the sedimentation has been taken place in the shallow water system and intense light conditions of the inner ramp system (Geel 2000; Corado and Brandano 2003; Bassi et al. 2007; Brandano et al. 2009a, b).

#### **Mf 10—Bioclastic rotallids echinoides wackestone**

The beds are centimeter-scale medium (up to 30 cm) (nodular limestone). The main components included are: Echinoides fragments and small *Rotallids* along with ostracods, Bivalve bioclasts, and some foraminifera such as *Discorbis* and *miliolids* (poor sorting/mud-supported) (Fig. 9d–f).

**Table 2** Distribution of facies in the studied sections

Facies	Binalud #1	Kharg #2	Binak #4	Golkhari #2	Kilor karim #4	BiBi Hakime #2	Gachsaran #55	Mish	Anneh	Semirum
Argillaceous mudstone									•	
Undeterminate										
Planctonic foraminifera wackstone–packstone						•	•	•	•	
Bioclastic Numulitidae Lepidocyclinidae packstone				•		•	•	•	•	
Perforate foraminifera corallinacea packstone						•	•	•	•	•
Oolitic packstone–grainstone		•								
Bioclastic perforate and imperforate foraminifera packstone			•		•					•
Bioclastic corallinacea coral packstone–boundstone					•					•
Bioclastic imperforate foraminifera corallinacea packstone				•	•		•			•
Imperforate foraminifera wackstone–packstone			•		•					•
Bioclastic rotallids echinoides wackstone			•		•					•
Mudstone										
Dolomudstone		•								•
Calcareous sandstone		•								•

Facies distribution is located from Dezful Embayment to the Zagros Simply Folded. However, the reduction lateral distribution of this facies has occurred to the Zagros Simply Folded during the Aquitanian—Burdigalian.

**Mf 11—Mudstone**

The facies is composed of a low percentage of benthic foraminifera and ostracods shells (poor sorting), authigenic quartz, fenestral fabric within fine-grain micrite (Fig. 9g and h). The field observations reveal that facies geometry is thin to medium nodular-bedded limestone. This facies has been deposited in the shallow lagoon water by low-energy system (The proximal inner ramp) Flugel (2004), Buxton and Pedley (1989), Van Buchem et al.(2010), Habibi (2014), Shabafrooz et al. (2015), and Kakemem et al. (2016). The facies has been identified in the geological zones of Persian Gulf Foreland Basin and Zagros Simply Folded. The vertical changes indicate that the facies has been deposited during the Late Oligocene to the Early Miocene.

**Tidal flat facies (Coastal plain)**

The tidal flats zones are formed in areas where there is a sufficient supply of fine-grained deposits and tides dominate over other hydrodynamic forces (Shu Gao 2019). In this research, two facies types are identified for the tidal zone.

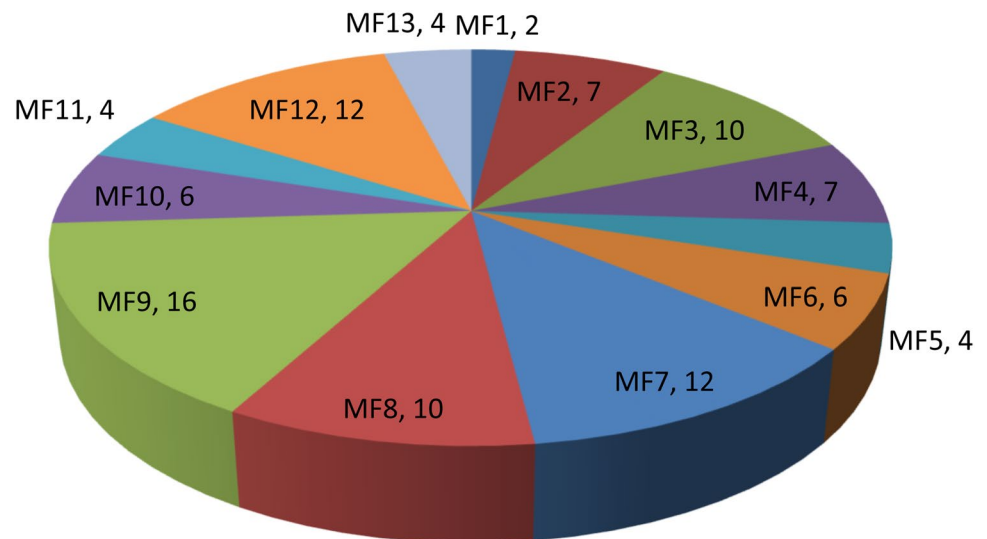
**Mf 12—Dolomudstone**

The facies is composed of fine-grain crystalline dolomite and fenestral fabric in the centimeter/meter-scale medium- to thick-bedded dolomitized mudstone (poor sorting) (Fig. 10a and b). Probably dolomites are formed primarily when sea-water is lowered (Flugel 2004). The vertical and lateral changes indicate that the facies has been deposited during the Late Oligocene at the Dezful Embayment, while facies distribution has happened in the Early Miocene at the Zagros Simply Folded.

**Mf 13—Calcareous sandstone**

The facies consists of quartz grains in the centimeter/meter-scale medium- to thick-bedded sandy limestone from Ahwaz Sandstone Member (Upper Asmari Formation) at the Persian Gulf Foreland Basin. The quartz grains are generally slightly rounded and poorly sorted form (Fig. 10c and d). The proximal tidal flat is proposed for this facies, so that sediments were composed of mixtures of siliciclastic and carbonate material during the Early Miocene (Flugel 2004; Van Buchem et al. 2010; Wilson1975).

**Fig. 11** Pie diagram of facies percentage in the study area



### Interpretation and depositional setting model

Interpretation and depositional settings depend on carbonate factories during the time. In other words, the depositional setting is controlled by change in the carbonate factories' production. Hence, in this research, the outer ramp depositional settings (production of marls and muddy limestones) are characterized by the planktonic foraminifera's association along with the echinoids fragments in the Pabdeh Formation. The middle ramp (production of a thick sequence of calcium carbonate) is introduced by coarse-grained packstone and it is interpreted by the presence of the large *Lepidocyclina*, *Heterostegina*, and *Operculina* (Distal mid ramp). The proximal mid ramp is determined by small perforate foraminifera such as *Asterogerina*, *Lepidocyclina*, *Heterostegina*, *Operculina*, *Amphistegina* and *rotalia* along with red algae, bivalves, and bryozoers fragments.

The presence of ooides and ploidies within grainstone sparite texture as well as large coral and corallinacea fragments boundstone indicates the patch reef islands system as a bioclastic dam. The inner ramp/lagoon depositional setting (production of a thick sequences of calcium carbonates) is characterized by the imperforate foraminifera association of Miliolidae, Alveolinidae, Spiroloculinidae, Peneropelidae, Soritidae along with red algae, echinoids, bivalves and bryozoers fragments within the fine- to coarse-grained wackestone to packstone texture.

The association of small *Rotallids*, echinoids in the microcrystalline mudstone confirms the shallow water

system of the inner ramp (tidal flat to the lagoon). The coastal plain or tidal zone (production of a medium sequences of sandstones, dolomites, and calcium carbonate) is distinguished by the dolomitic limestone and calcareous sandstone facies. Facies distribution and Pie diagram of microfacies percentage are shown in Table 2 and Fig. 11. Also, the facies logs distribution from ten measured stratigraphic sections and the sedimentary model are shown in Figs. 12 and 13.

### Early Oligocene (Rupelian) depositional setting

The Rupelian sedimentation has occurred in the Dezful Embayment and Zagros Simply Folded in the study area. The facies interpretations indicate that a homoclinal ramp with a gentle depth gradient has been dominant from Dezful Embayment (Lagoon/Inner ramp/Euphotic zone) to the Zagros Simply Folded (Mid Ramp/Outer ramp). Depositional models (Fig. 14) show a systematic progradation from Zagros Simply Folded (N/NE) (Asmari/Pabdeh Formation) to the Dezful Embayment (S/SW) (Asmari carbonate system).

### Late Oligocene (Rupelian/Chattian) depositional setting

The Chattian sedimentation has occurred throughout the study area. The depositional trend offers the continued progradation system that shows the sedimentation took place in a shallow sedimentary environment (Platform/Mid ramp) from the homoclinal ramp during the Chattian. The Asmari



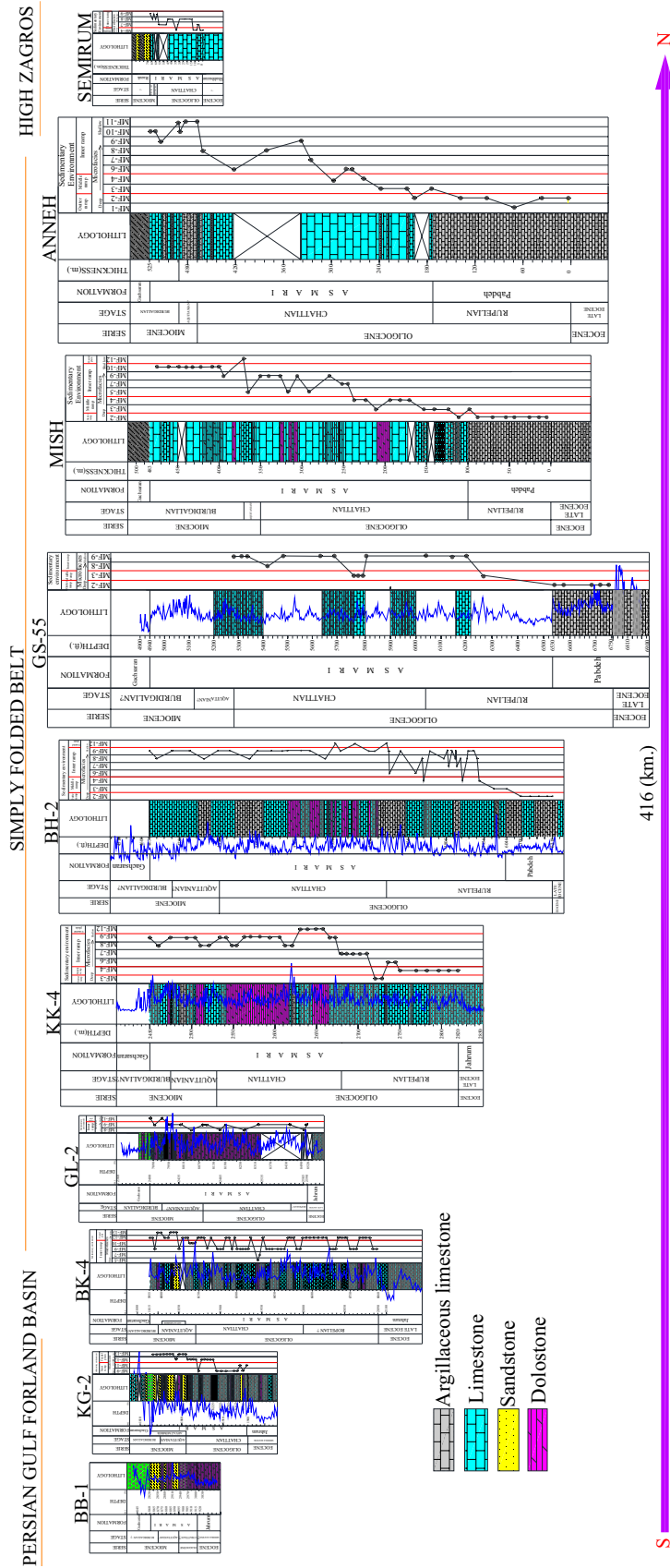


Fig. 12 Log of facies distribution from ten measured stratigraphic sections in the study area; the blue line shows the gamma wave chart and the black line on the sedimentary environment shows facies vertical distribution diagram

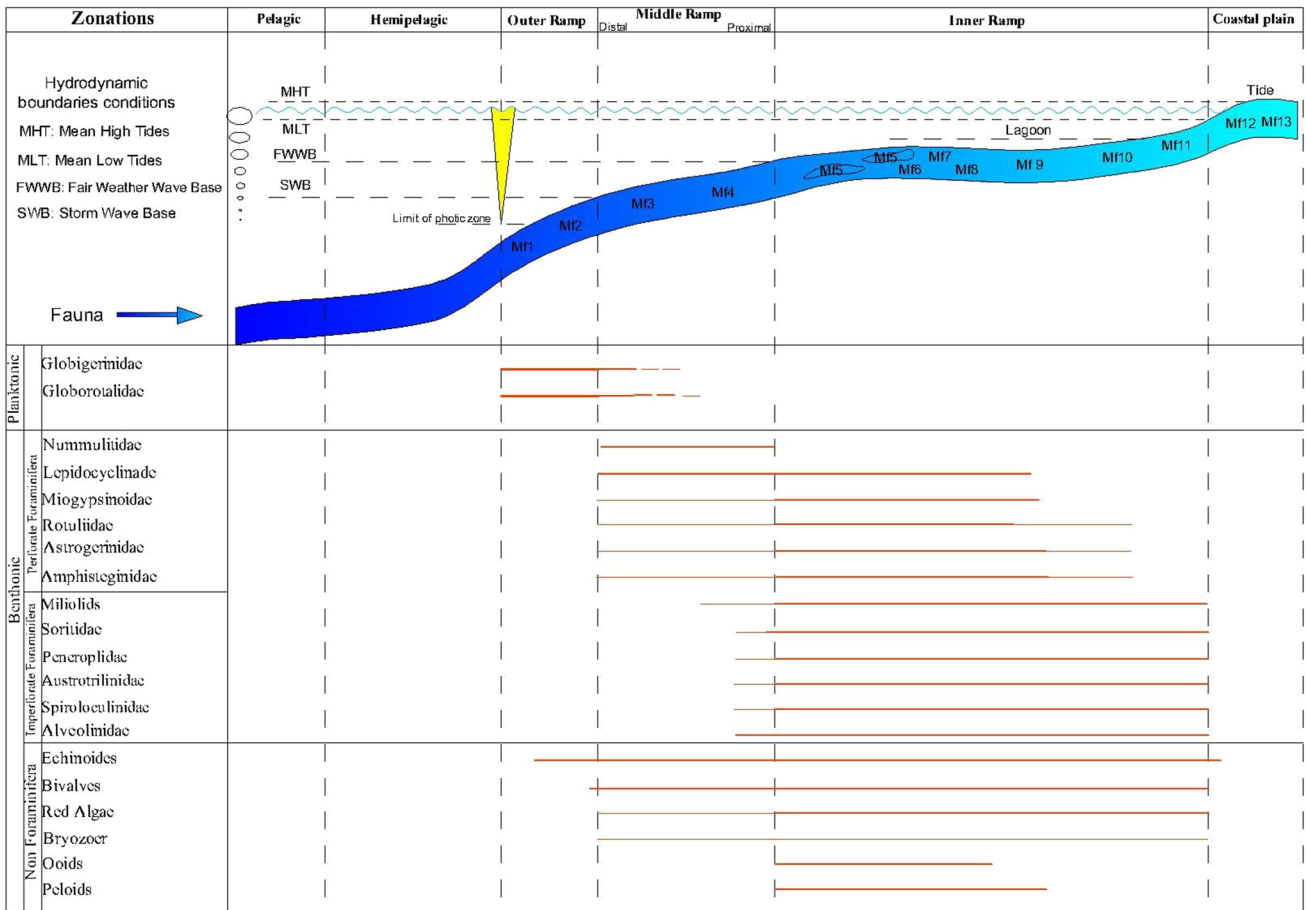


Fig. 13 Sedimentary model for the Oligocene and Lower Miocene deposits (based on studies by Van Buchem et al. 2010)

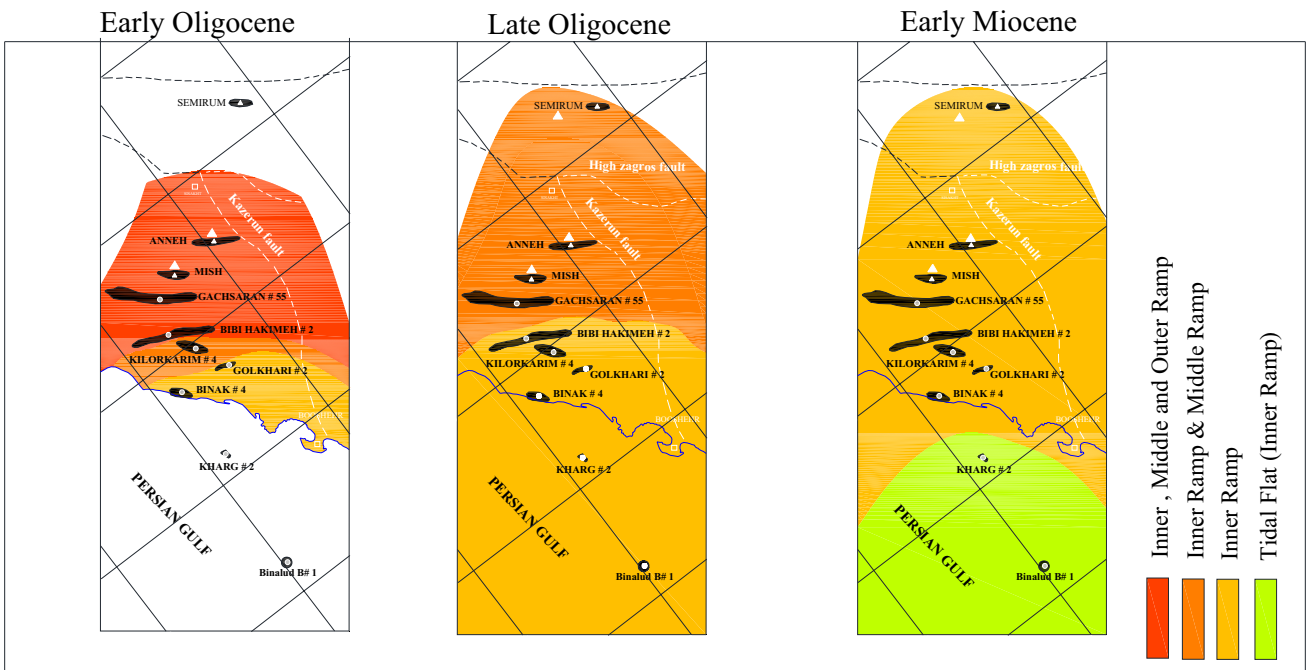


Fig. 14 Paleoenvironmental model for the Oligocene and Lower Miocene deposits in the study area

Formation has been deposited in a shallow-water system of the inner ramp (tidal zone/lagoon) exclusively in the Persian Gulf Foreland Basin and Dezful Embayment; furthermore, the Asmari carbonate sedimentation has been deposited in the mid ramp from the Zagros Simply Folded to the High Zagros.

### Early Miocene depositional setting

Following a regression system during the Late Oligocene to the Early Miocene, continuing sedimentation uniformly has been felt out in the shallow water system throughout the study area. The Asmari Sedimentation has been taken place in the tidal zone solely (dolomitization and siliciclastic deposits) at the Persian Gulf Foreland Basin (S/SW); while, the lagoon microfacies of the Asmari Formation including imperforate foraminifera (small miliolids, *Dendritina*, *Borelis*) wackestone to packstone beds has occupied at the Dezful Embayment, Zagros Simply Folded and the High Zagros (N/NE) (Fig. 14).

### Conclusion

To illustrate the depositional setting architecture, a regional transect was selected from Binalud oilfield (Persian Gulf Foreland Basin, S/SW) to the Semirum stratigraphic section at the High Zagros (N/NE) (416 km). The stratigraphic structure of the study area included: the shallow-water carbonates of the Jahrum and Shahbazan Formations (Eocene); the deeper-water marls and muddy limestone of the Pabdeh Formation (Oligocene); the shallow-water carbonates of the Asmari Formation (Oligo-Miocene) and the alternation of evaporites (gypsum and anhydrite), carbonates and marls of the Gachsaran and Razak Formations (Miocene). Facies distribution in the studied area confirms the sedimentary basin as a homoclinal carbonate ramp. The sedimentary basin geometric models showed that a systematic progradation system has been happened from the Zagros Simply Folded (N/NE) (Asmari/Pabdeh Formation) to the Dezful Embayment (S/SW) (Asmari carbonate system) in the Rupelian. The Lower Oligocene deposits have been eroded in the High Zagros. During the Late Oligocene (Chattian), the Asmari Formation has been deposited in a shallow-water system of the inner ramp and tidal zone exclusively in the Persian Gulf Foreland Basin and Dezful Embayment; furthermore, the Asmari carbonate sedimentation has been resided in the mid ramp from the Zagros Simply Folded to the High Zagros. During the Early Miocene (Aquitani and Burdigalian), continuous regressive system has caused that sedimentation takes place in a shallow water system uniformly throughout the study area.

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