Chapter

Paleoecology and Sedimentary Environments of the Oligo-Miocene Deposits of the Asmari Formation (Qeshm Island, SE Persian Gulf)

Seyed Hadi Sajadi and Roya Fanati Rashidi

Abstract

The Asmari Formation is composed of limestones, marly limestones, and marls, whose subsurface thickness in this region is about 148 m. Two assemblage zones have been recognized through the distribution of large foraminifera in the study area, indicating a Late Oligocene (Chattian)-Early Miocene (Aquitanian) age. The gradual facies changes and the lacking of turbiditic deposits show that the Asmari Formation was deposited in a carbonate ramp environment. Based on the depositional textures and petrographical studies, characterizing gradual shallowing upward trends of an open marine carbonate ramp, three distinct depositional settings have been recognized: lagoon, barrier, and open marine. MF1 was characterized by the occurrence of hyaline benthic and planktonic foraminifera representing distal middle ramp and below the storm wave base of other ramp. Paleolatitudinal reconstructions based on skeletal grains suggest that carbonate sedimentation of the Asmari Formation took place in tropical waters within the photic zone.

Keywords: Asmari Formation, microfacies, paleoecology, benthic foraminifera, Oligocene-Miocene, Qeshm Island

1. Introduction

This chapter deals with the Asmari Formation (one of the best known carbonate reservoirs in the world) [1], an Oligocene-Miocene carbonates succession cropping out in the south-eastern Zagros basin, southern Iran (**Figure 1**). At the type section outcropping in Tang-e Gel-e Tursh (Valley of Sour Earth), which is located on the south-western flank of the Kuh-e Asmari anticline, the Asmari Formation mainly consists of limestones, dolomitic limestones, and argillaceous limestones [3, 4], having an average thickness of 314 m. In the Qeshm Island, the Asmari shallow marine limestone is located in the subsurface and was deposited over the Pabdeh Formation with a gradational stratigraphic contact. The contact with the overlying Gachsaran Formation (i.e., evaporitic rocks) is conformable and gradual (**Figure 2**). This formation is present in the most part of the Zagros basin, and its lithology is characterized by limestones, dolomitic limestones, dolomites, and

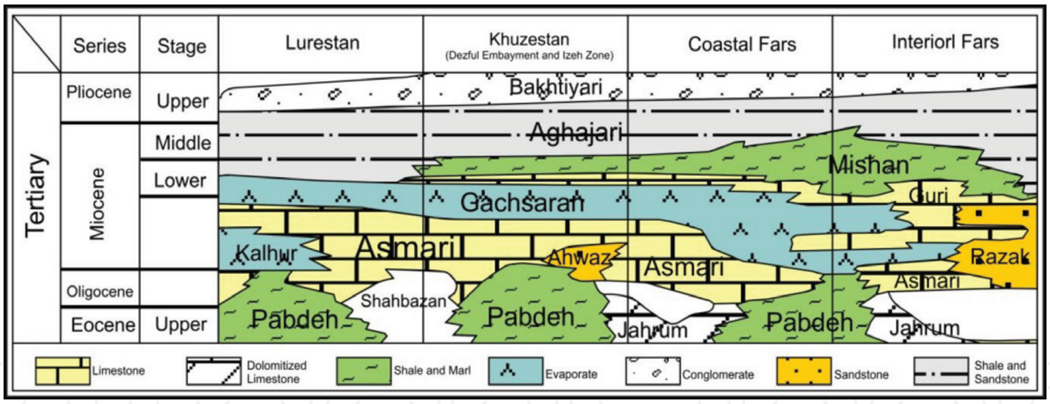

Figure 1.
Cenozoic stratigraphic correlation chart of the Iranian sector of the Zagros Basin, after James and Wynd [2].

marly limestones. Some anhydrite (Kalhur Member) and lithic and limy sandstones (Ahwaz Member) also occur within the Asmari Formation [3, 4]. Previous studies have focused on biostratigraphy and lithostratigraphy of the Asmari Formation and were originally defined in primary works [5–8]. Later, other researchers have introduced the microfaunal characteristics and the assemblage zones for the Asmari Formation [2, 9, 10]. More recent studies of the Asmari Formation have been conducted on facies and sedimentary environment [8, 11–17]. Referring to the biostratigraphy of the Asmari Formation, it was earlier outlined in the 1960s based on unpublished reports [18]. The application of the isotopic stratigraphy has later proved that the sediments ascribed to the Miocene "Aquitanian" are in fact Late Oligocene, Chattian in age. This was proved by the application of Sr-isotope stratigraphy to cored sections from 10 Iranian oil fields and 14 outcrop sections, within the framework of a high-resolution sequence stratigraphic study down to fourth order cycles. The Chattian/Aquitanian boundary is marked by a major faunal turnover, with the general extinction of *Archaias* species and *Miogypsinoides complanatus*. Main insights on the stratigraphic setting of the Asmari Formation have been given from the strontium isotopic stratigraphy [19]. The Asmari Formation

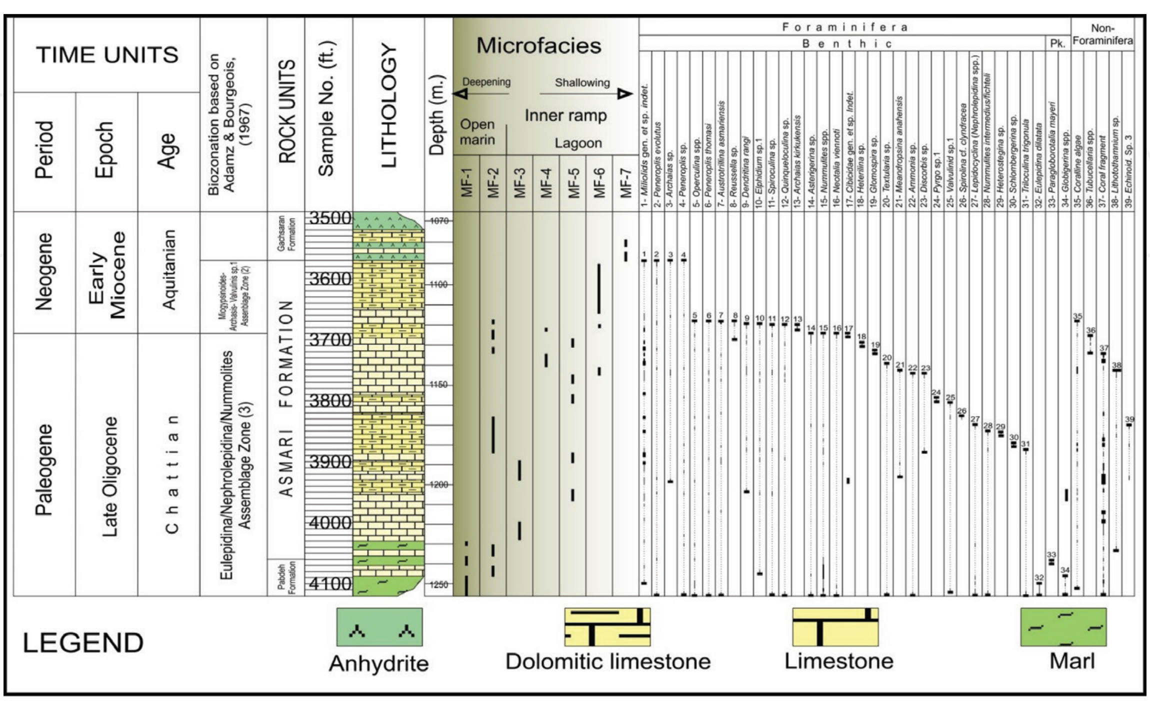

Figure 2.
Lithostratigraphy column, microfacies, benthic and planktonic foraminifers' distribution and biozonation of the Asmari Formation at Qeshm Island (well no. 2).

has been studied in the subsurface at the Bibi Hakimeh, Marun, and Ahwaz oilfields and in an outcrop section from the Khaviz anticline. It consists of approximately 400 m of cyclic platform limestones and dolostones with subordinate intervals of sandstone and shale. The method of Sr-isotope stratigraphy is well suited for dating these strata because of the rapid rate of change of marine strontium ratio during Asmari deposition (roughly 32–18 Ma) and the common presence of well-preserved macrofossils. Profiles of age against depth in the four areas show a decrease from higher stratigraphic accumulation rates in the lower Asmari to lower rates in the middle to upper part of the formation. There is also a trend toward less open marine depositional conditions and increasing early dolomitization and anhydrite abundance above the lower part of the formation. These changes reflect the dynamics of platform progradation across the areas studied, from early deposition along relatively high accommodation margin to slope settings to later conditions of lower accommodation on the shelf top. Ages of sequence boundaries have been estimated from the age-depth profiles at each locality, providing a framework for stratigraphic correlation. The Asmari deposition began in early Rupelian time (34–33 Ma) in the Bibi Hakimeh area, when basinal marly facies accumulated in the north-western sector of the study areas. The depositional sequences have durations of 13 Ma, whereas the component cycles represent average time intervals of 100–300 Ky. This chapter reports on the subsurface sedimentological study of the Asmari Formation, whose results have been correlated and compared for a better geologic comprehension of the outcrops of the Asmari Formation in the adjacent areas. The objectives of this study are (1) a description of the facies and their distribution on the Oligocene-Miocene carbonate platform and (2) an interpretation of the paleoenvironmental features based on the assemblages of benthic hyaline and imperforate foraminifera.

2. Geological setting

The Zagros Basin is the second largest basin in the Middle East and is defined by a 7–14-km thick succession of coverage sediments deposited over a region located along the north-northeast edge of the Arabian plate. This basin was part of the stable Gondwana supercontinent in the Paleozoic era and of a passive margin in the Mesozoic era, and it became a site of plate convergence and formation of thrust belts in the Cenozoic era [20]. The Zagros Fold-and-Thrust Belt of Iran is a result of the Alpine orogenic events [21, 22] in the Alpine-Himalayan mountain range. It extends in a NW-SE direction from eastern Turkey to the strait of Hormoz in southern Iran. The tectonic activity of this area was entirely due to the convergence of the Arabian and Eurasian continents. After the closure of the Neo-Tethys basin, during late Oligocene-early Miocene times, the Zagros basin was gradually narrowed and the Asmari Formation was deposited with a lithology including lithic sandstone (Ahwaz Member) and evaporites (Kalhur Member) [1, 23]. The maximum thickness of the Asmari Formation is found in the north-eastern corner of the Dezful Embayment. On the basis of the lateral facies variations, the Iranian Zagros fold-thrust belt is divided into different tectono-stratigraphic domains, which are from SE to NW: the Fars Province or eastern Zagros, the Khuzestan province or Central Zagros, and finally the Lurestan Province or Western Zagros [3, 4] (**Figure 3b**). Also, from south-west to north-east of the Zagros basin, there are the Zagros folded belt, folded and thrusted belt, and High Zagros and crush zone [25–28]. The Hormozgan Province is located in southern Iran and is part of Zagros Folded belt. This region is accompanied by NW-SE, W-E, and N-S trending simple anticlines and synclines with very great thickness of Fars Group deposits (Gachsaran, Mishan, Aghajari, and Bakhtiari Formations) and presence of 118 salt plugs. So, for these specific features, Motiei [3, 4] called this area as the “Bandar Abbas Hinterland” (**Figure 3**).

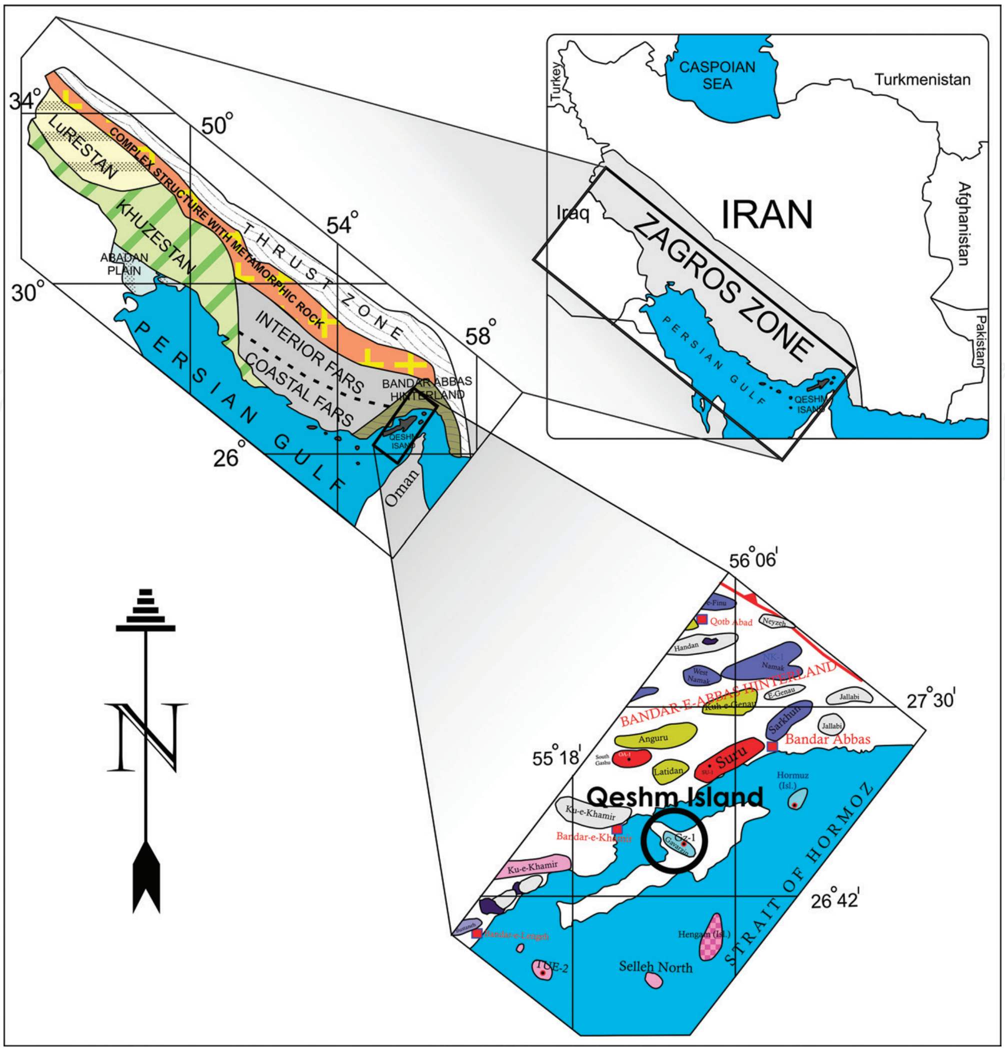

Figure 3.
Geological location and geological map of the studied section, modified after geological map [24].

3. Methods and study area

This study involves one stratigraphic subsurface section from the Asmari Formation. The study area is located at Qeshm Island, southern Iran (**Figure 3c**). The lithologies and the microfacies types were classified and described according to Dunham [29]. Some samples from the underlying Pabdeh and overlying Gachsaran Formations were also analyzed for boundaries distinction. A total of 60 thin sections of the cores and cuttings have been analyzed under the microscope for biostratigraphy and facies. Petrographic studies were carried out for facies analysis and paleoenvironmental reconstruction of the Asmari Formation. Facies have been determined for each paleoenvironment according to carbonate grain types, textures, and interpretation of functional morphology of small and larger foraminifers. Biostratigraphy has been determined based on the well-known benthic foraminifera biozones of Adams and Bourgeois [30].

4. Result

4.1 Biostratigraphy

Biostratigraphic criteria of the Asmari Formation were established by Wynd [10] and reviewed by Adams and Bourgeois [30] in unpublished reports only. Biozonation and age determinations in the study area are based on benthic foraminifera biozonation of Adams and Bourgeois [30]. From the base to the top, two foraminiferal assemblages have been recognized and were discussed as it follows:

Assemblage I. This assemblage corresponds to the *Eulepidina-Nephrolepidina-Nummulites* Assemblage Zone (3) [30]. The assemblage is considered to be Chattian in age. The most diagnostic species include Miliolids gen. et sp. Indet., *Peneroplis evolutus*, *Archaias* sp., *Peneroplis* sp., *Operculina* spp., *Peneroplis thomasi*, *Austrollina asmariensis*, *Reussella* sp., *Dendritina rangi*, *Elphidium* sp. 1, *Spiroculina* sp., *Quinqueloculina* sp., *Asterigerina* sp., *Nummulites* spp., *Neorotalia viennoti*, Cibicidae gen. et sp. Indet, *Archaias kirkukensis*, *Hetererilina* sp., *Glomospira* sp., *Textularia* sp., *Meandropsina anahensis*, *Ammonia* sp., *Discorbis* sp., *Pyrgo* sp. 1, *Valvulinid* sp. 1, *Spirolina* cf. *clyndracea*, *Lepidocyclina* (*Nephrolepidina* spp.), *Nummulites intermedius/fichteli*, *Heterostegina* sp., *Schlombergerina* sp., *Triloculina trigonula*, *Eulepidina dilatata*, *Rotalia* sp., *Bolivina* sp., *Paragloborotalia mayeri*, and *Globigerina* spp.

Assemblage II. This assemblage corresponds to the *Miogypsinoides-Archaias-Valvulinid* sp. 1 Assemblage Zone (2) [30]. The assemblage is considered to be Aquitanian in age. The most important foraminifera in this assemblage are *Miliolids* gen. et sp. Indet., *Peneroplis evolutus*, *Archaias* sp., *Peneroplis* sp., *Operculina* spp., *Peneroplis thomasi*, *Austrollina asmariensis*, *Reussella* sp., *Dendritina rangi*, *Elphidium* sp. 1, *Spiroculina* sp., *Quinqueloculina* sp., and *Archaias kirkukensis*.

4.2 Microfacies analysis

The microfacies analysis of the Asmari Formation in the study area has resulted in the definition of seven types of facies, which characterize the platform development. Each microfacies exhibits typical skeletal and non-skeletal components and related sedimentary textures. These facies are related to the three depositional settings (lagoon, barrier, and open marine) of inner, middle, and outer portions of a carbonate platform (**Figure 4**). Since the Asmari Formation overlies the Pabdeh Formation and conformably underlies the Gachsaran Formation, some samples from the Pabdeh and Gachsaran Formations have also been studied. The general environmental interpretation of the microfacies is discussed in the following paragraphs.

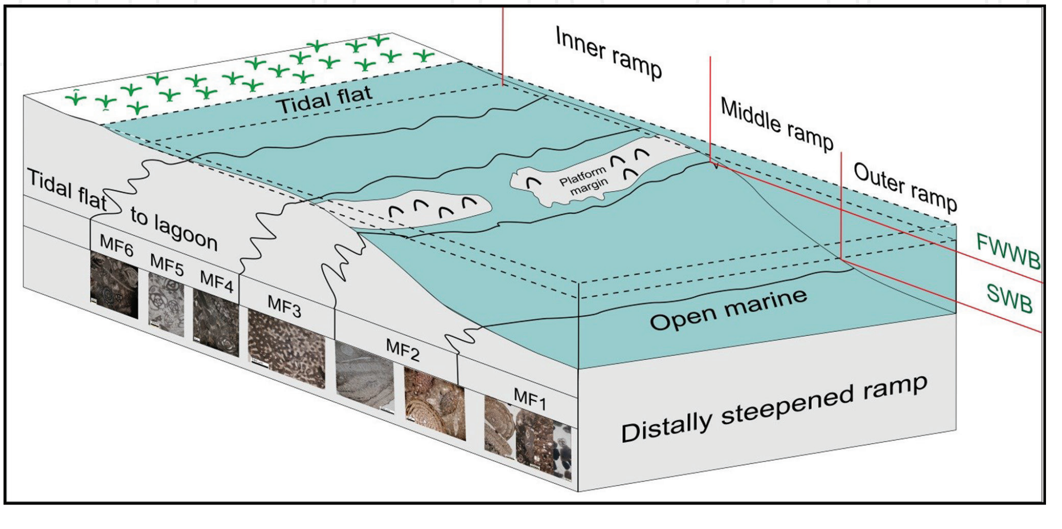

Figure 4.
Depositional model for the carbonate platform of the Asmari Formation at the southeast of Zagros basin, Qeshm Island [31].

4.2.1 MF1 marl facies

There are intercalations of marl across the section, but this facies mainly occurs in the lower part of the succession (**Figure 5A**–**D**). They are gray to green marl and contain benthic (miliolids, *Nummulites*, *Neorotalia*, *Elphidium*, *Operculina*, *Amphistegina* and textularids) and planktonic (*Paragloborotalia mayeri* and *Globigerina* spp.) foraminifera. The planktonic foraminifera occur at the base of the succession, where the boundary between the Pabdeh and Asmari Formations is located [32].

4.2.1.1 Interpretation

The features of benthic faunas and the stratigraphic relationships with the other microfacies suggest that the marly facies was deposited in an open lagoon

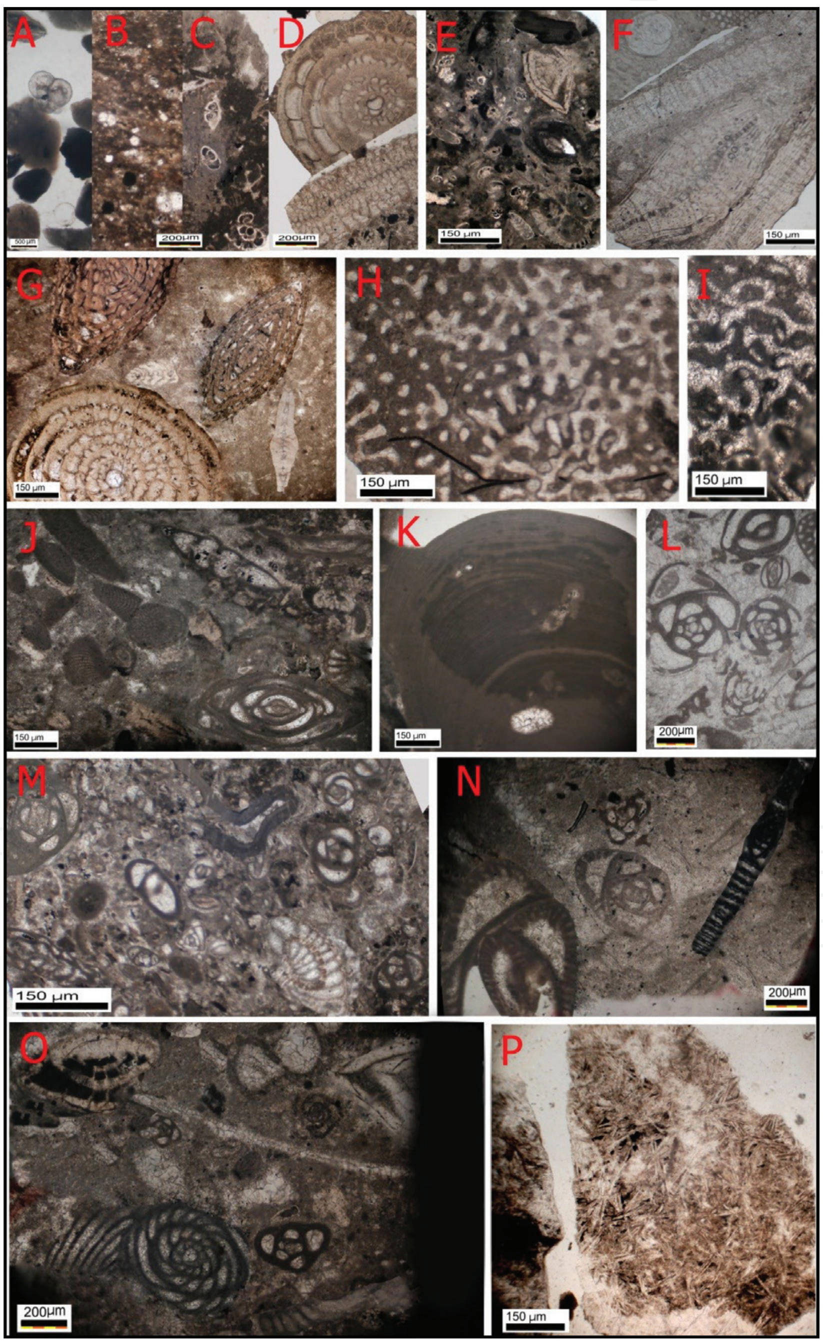

Figure 5.
Microfacies types of the Asmari Formation. (A–D) MF1, Marl facies. (E–G) MF2, bioclastic Lepidocyclinidae, Nummulitidae, Neorotalia, Wackestone-packstone. (H and I) MF3, coral boundstone. (J and K) MF4, miliolids corallinacea bioclastic wackestone. (L and M) MF5, miliolids bioclastic wackestone. (N and O) MF6, imperforate foraminifera bioclast wackestone-packstone. (P) MF7, evaporite.

with a normal-salinity water, but the coexistence of planktonic and some benthic (Nummulitidae) foraminifera in the base of the Asmari marls and marly limestones has suggested that this facies was deposited in calm, low-energy hydrodynamic, and deep normal-salinity water, which indicates a deposition below the storm wave base [33–36].

4.2.2 MF2 bioclastic wackestone-packstone with Lepidocyclinidae, Nummulitidae, and Neorotalia

This microfacies is composed of grain-supported texture with abundant large benthic foraminifera (**Figure 5E–G**). The foraminiferal assemblage is represented by numerous large benthic perforate foraminifera such as Lepidocyclinidae and Nummulitidae (*Nummulites* and *Operculina*). Other components such as *Astigerina* and red algae are rare. Due to changes in the type of fauna in some samples, the name of this facies changes to bioclastic wackestone-packstone with Lepidocyclinidae, Nummulitidae and Neorotalia. The biostratigraphic distribution and paleoenvironmental model of the Asmari Formation in this stratigraphic interval are most prominent in the lower parts of the Asmari Formation [37].

4.2.2.1 Interpretation

It consists of gray marly limestone beds. The combination of micritic matrix and abundance of typical open marine fauna including large Nummulitidae, Lepidocyclinidae and Neorotalia suggest a low-medium energy, open marine environment. Other bioclasts such as red algae and shell fragments are rare. This microfacies shows an environment between the storm wave base and fair-weather wave base (FWWB) [35, 36]. The presence of large *Nummulites* and lepidocyclinids suggests that this microfacies took place in relatively deep water and was formed in the lower photic/oligophotic zone in a distal middle ramp [22, 38–50].

4.2.3 MF3 coral boundstone

This facies is characterized by the abundance of scleractinian and massive coral colonies (**Figure 5H** and **I**).

4.2.3.1 Interpretation

This microfacies is interpreted to be formed by in situ organisms as an organic reef (Bioherm) in margin of platform and was located above the fair-weather wave base (FWWB) [36].

4.2.4 MF4 miliolids corallinacea bioclastic wackestone

Miliolids, coralline red algae and coral are dominating components in this microfacies (**Figure 5J** and **K**). Other bioclasts are rare but include *Peneroplis* and dendritic fragments. The textures are wackestones.

4.2.4.1 Interpretation

The MF5 represent low- to medium-energy open lagoon shallow subtidal environments, but there is different from MF4 by their texture and grain composition.

Depositional textures, fauna and stratigraphic position took place in warm, euphotic and shallow water, with low to moderate energy conditions, in a semi-restricted lagoon. This area is located within inner carbonate platform setting [32].

The presence of well-preserved coralline algae indicates a relatively quiet-water environment with a stable substrate and low sedimentation rates [51]. The associations of miliolids within this facies support the additional interpretation of a relatively protected environment, probably the inner part of a platform [52].

4.2.5 MF5 miliolids bioclastic wackestone

This facies is characterized by the dominant presence of small benthic foraminifera (miliolids) (**Figure 5L** and **M**). Other components such as *Peneroplis*, *Elphidium*, bryozoan and extraclasts are rare. The matrix is fine-grained micrite.

4.2.5.1 Interpretation

This facies is characterized by low diversity skeletal fauna and was deposited in a restricted low-energy lagoonal environment. There is a low biotic diversity of fauna, which shows a high-stressed habitat in very shallow restricted areas, where great fluctuations in salinity and temperature probably occurred [52].

4.2.6 MF6 imperforate foraminifera bioclast wackestone-packstone

The main elements of this microfacies are skeletal and non-skeletal components (**Figure 5N** and **O**). The skeletal components include a high diversity of imperforate foraminifera in grain-supported textures and several genera of benthic foraminifera (*Austrotrillina*, *Archaias*, *Peneroplis*, *Meandropsina*, *Elphidium*, *Dendritina* and miliolids). Peloids are rare, and other minor biota consists of particles of bryozoans and corals.

4.2.6.1 Interpretation

The occurrence of large number of porcelain imperforate foraminiferal tests may point to the depositional environment being slightly hypersaline [15]. These deposits include different textures ranging from wackestone to packstone. Some porcelain imperforate foraminifera (*Peneroplis* and *Archaias*) live in recent tropical and subtropical shallow water environments [53]. Textural characteristics and prolific porcelain foraminifera suggest that a medium-to-high energy portion of a restricted lagoon with a nearby tidal flat sedimentary environment prevailed [17]. Such an assemblage can be associated with an inner ramp environment [1, 17, 35, 36, 53, 54].

4.2.7 MF7 evaporite

Anhydrite and gypsum facies have been observed in the upper part of the Asmari Formation, which represents the beginning of the Gachsaran Formation (**Figure 5P**). The first anhydrite has been deposited above the marly limestones with a sharp contact.

4.2.7.1 Interpretation

Considering the deposition of anhydrite implies that the depositional environment became isolated from the open marine at that time, which has allowed for the concentration and submarine precipitation of salt. The thickness of the evaporate deposits indicates that they are submarine deposits formed in an isolated saline basin. A eustatic sea level fall is one of the most likely causes. This event took place around the early Miocene (Aquitanian), and its stratigraphic expression was recorded at the boundary of the Asmari and Gachsaran Formations. Based on Ehrenberg et al. [19], this anhydrite is exposed at the top of the Asmari Formation and indicates the Oligocene-Miocene boundary. Ehrenberg et al. [19] noted that strontium dates got from anhydrite formed as an evaporate rather than as a later diagenetic product.

5. Discussion

5.1 Sedimentary development of the Oligocene-Miocene Fars sub-basin

Planktonic and benthic foraminifera and non-foraminifera distribution of the Oligocene deposits can represent the type of sedimentary environment, adopted from joint project of French and Iran Oil Company [55] (**Figure 6**). During the Paleogene, Pabdeh (basinal marls and argillaceous limestones) Formation was deposited in the middle and on both sides of the Zagros basinal axis [3] (**Figure 1**). The shallow marine limestones of the Asmari Formation were deposited above the Pabdeh Formation in the section of this study (**Figure 1**). During the Rupelian and early Chattian, outer ramp facies (Pabdeh

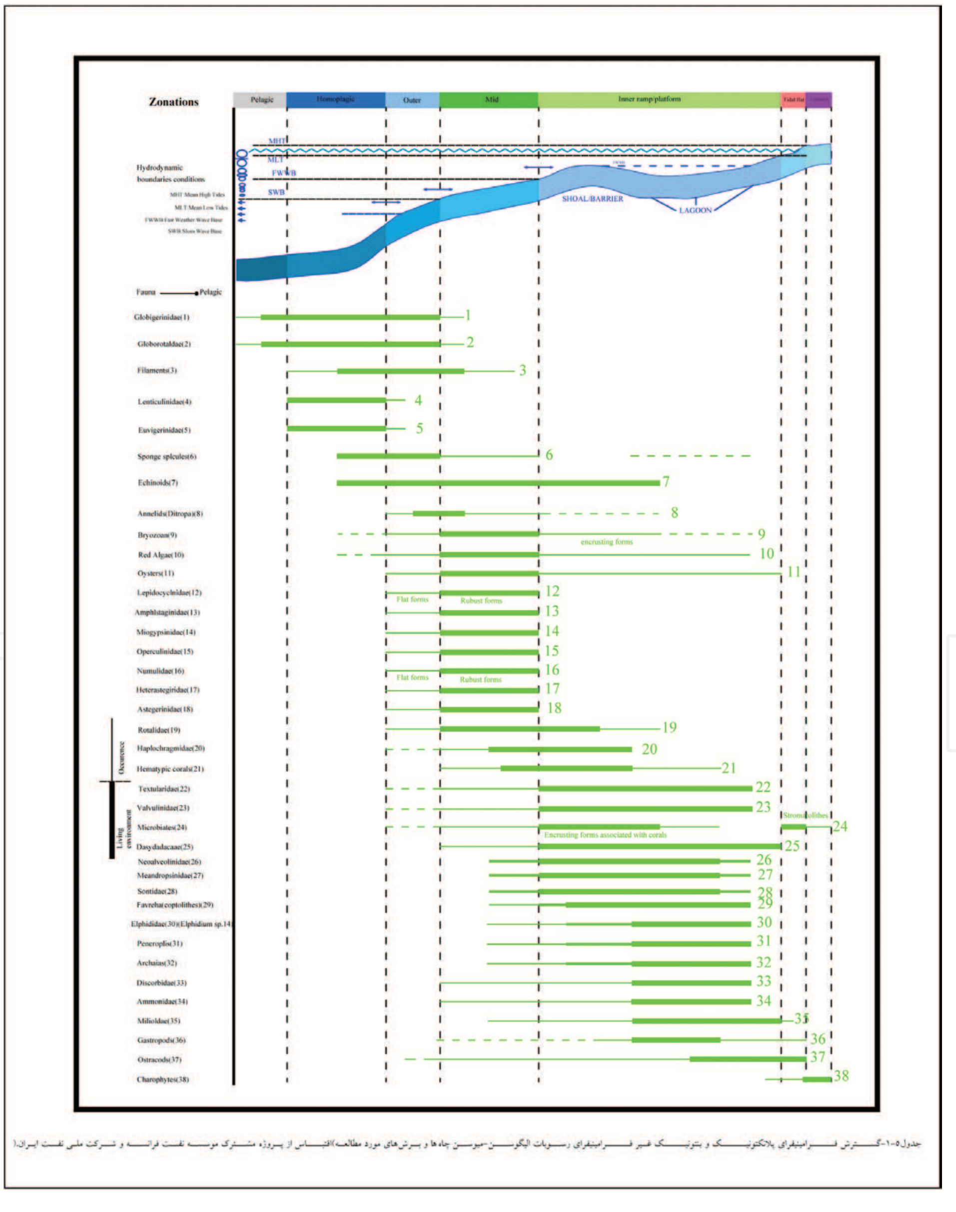

Figure 6.
Foraminifera and non-foraminifera distribution of the Oligocene deposits, adopted from joint project of French and Iran Oil Company [55].

Formation) was predominant at the Qeshm section (well no. 3) (**Figure 2**). This is visible in the lower part of the Asmari Formation. So, the Chattian sediments of the Asmari Formation in this section gradationally overlie the Pabdeh Formation. Indeed, Chattian basin in this time restricted by shallow subtidal environments.

5.2 Paleoecology

Large benthic foraminifera (such as Nummulitidae) produced great amount of carbonates during the Early and Middle Paleogene. In the Oligocene, euphotic conditions prevailed and carbonate production related to these foraminifers (especially *Nummulites*) declined [56]. Larger perforate forms are represented by *Amphistegina*, nummulitids and lepidocyclinids. Perforate foraminifera that live in shallow waters are characterized by hyaline walls and so protect themselves from ultraviolet light by producing very thick, lamellate test walls to prevent photo inhibition of symbiotic algae within the test in bright sunlight. These large forms are the most important indicators for constructing paleoenvironmental models in the warm, shallow marine environments [42]. The presence of these large and flat forms (Lepidocyclinidae and Nummulitidae) in the lower part of Asmari Formation, in comparison with analogues in the modern platform, allowed interpreting these sediments as having been deposited in the lower photic zone [41–45, 48]. In contrast, coralline red algae communities become dominant, as most phototrophic carbonate producers thrive in shallow marine environments [56], especially through Early Miocene to Tortonian [57]. Coralline red algae and large benthic foraminifera (*Nummulites*, *Operculina*, *Lepidocyclina*, *Archaias*, *Peneroplis* and *Dendritina*) are the most significant and dominant biota in the Asmari Formation at the study area. Other components such as corals, bryozoan and echinoderms are present within the matrix. The distribution of larger foraminifera and coralline red algae are largely dependent on the salinity, depth, light, temperature and climate, nutrients, effect of hydrodynamic energy and flow substrate on the biostrate and dispersion of taxa [13, 58]. Small benthonic foraminifera are common locally and include porcellaneous (miliolids) and perforated (rotaliids) forms. Rotaliids are dominated by *Neorotalia viennoti* specimens. Larger foraminifera represented by the porcellaneous imperforate tests such as *Archaias* and *Peneroplis* may point to the depositional environment being within the photic zone in tropical carbonate platforms and slightly hypersaline [17, 35, 37, 54]. Flatter tests and thinner test walls with increasing water depth reflect decreased light levels at greater depths or perhaps poor water transparency in shallow waters [40]. These test shapes reflect adaptation to low hydrodynamic energy. Some biogenic components such as miliolids indicate stress conditions within restricted environments. Miliolids-dominated benthic foraminiferal assemblages reflect a decreased circulation and probably a reduced oxygen contents or euryhaline conditions. Miliolids are found in a variety of very shallow, hyposaline to hypersaline environments or are even common in the sand shoal environments of normal salinities [59, 60] and are generally taken as evidence of restricted lagoon [53].

5.3 Depositional environments

Three depositional environments have been identified in the Oligocene-Miocene succession of the Qeshm Island, on the basis of the biostratigraphic content and of the facies relationships (**Figure 6**). These include lagoon, barrier and open marine (**Figure 4**). These three environments are represented by seven microfacies types (MF1: distal middle ramp and below the storm wave base of other ramp, MF2: deeper fair water wave base of a middle ramp setting and MF 3–6: shallow water setting of an inner ramp influenced by wave and tide processes). Carbonate ramp environments are characterized by (1) the inner ramp, between the upper shore face and fair weather wave base, (2) the middle ramp, between fair weather wave base and storm wave base and (3) the outer ramp, below normal storm wave base down to the basin plain [61]. Inner ramp deposits represent marginal marine deposits indicative of open lagoon and protected lagoon. In the restricted lagoon environment, faunal diversity is low and normal marine faunae are lacking, except for imperforate benthic foraminifera such as miliolids and *Dendritina*, which indicate quite conditions. A large number of porcellaneous imperforates points to somewhat hypersaline waters [33, 52]. The presence of imperforate foraminifera that include *Archaias*, *Peneroplis*, *Dendritina*, *Meandropsina*, *Austrotrillina* and miliolids indicates a low-energy, upper photic, shallow lagoonal depositional environment. The large porcellaneous foraminifera types such as *Archaias*, *Peneroplis* and *Dendritina* are present in MF 6. The occurrence of *Archaias* and *Peneroplis* is typical of recent tropical and subtropical shallow water environments [46, 62] and are characteristics of the upper part of the upper photic zone (inner ramp). Furthermore, these large porcellaneous foraminifera are also common fossils in the Mesozoic and Cenozoic neritic sediments [57]. And also, inner ramp deposits represent a wider spectrum of marginal marine deposits, indicative of a high-energy reef (MF 3). The middle ramp setting is represented by the medium to fine grained foraminiferal bioclastic wackestones-packstones, dominated by assemblages of larger foraminifera with perforate walls such as *Amphistegina*, *Operculina*, and *Nummulites* (**Figure 5**). The faunal association suggests that the depositional environment was situated in the mesophotic to oligophotic zone [48, 63]. Open lagoon shallow subtidal environments are characterized by microfacies types that include mixed open marine bioclasts (such as red algae, echinoids and corals) and protected environment bioclasts (such as miliolids). The diversity association of skeletal components represents a shallow subtidal environment, with optimal conditions as regards salinity and water circulation. The change in larger foraminiferal fauna from porcellaneous imperforated to hyaline perforated forms points to a decrease in water transparency [38]. The microfacies 1 and 2 are subject to an open marine environment of a proximal outer ramp and middle ramp, respectively. More common components of the microfacies 1 is biota association, such as large benthic foraminifera (Lepidocyclinidae, *Nummulites* and *Operculina*), small benthic foraminifera (*Neorotalia*), coralline red algae, which is dominated in lower photic zone. Moreover, the red algae association with these larger foraminifera places the middle ramp in an oligophotic to mesophotic zone [48, 53, 57, 63, 64].

6. Conclusions

The Oligo-Miocene Asmari Formation is a thick sequence of shallow water carbonates and is widespread in the Zagros basin. The subsurface section of the Asmari Formation in the south-eastern part of the Zagros and Qeshm Islands has allowed to recognize different depositional environments based on the sedimentological analysis, on the distribution of the foraminifera and on the microfacies studies. The occurrence of large foraminifera (*Nummulites*, *Operculina*, *Lepidocyclina*, *Archaias*, and *Peneroplis*), coralline red algae, coral debris and fragments of Echinoderms, Mollusks and Bryozoans has evidenced that a high nutrient stability in an oligothrophic to mesothrophic condition existed during the deposition of the Asmari Formation. Based on the occurrence of these fossils, two assemblage zones (*Eulepidina-Nephrolepidina-Nummulites* Assemblage Zone and

Miogypsinoides-Archaias-Valvulinid sp. 1 Assemblage Zone) have been recognized, and the Asmari carbonate in the study area is Chattian-Aquitanian in age. Based on the occurrence of skeletal (large benthic foraminifera and coralline red algae) and non-skeletal components, the following environmental and palaeoecological implications have been defined for the Asmari depositional environment at the Qeshm Island, southern Bandar Abbas Hinterland. Based on components and texture, seven microfacies types have been recognised and grouped into three depositional environments, corresponding to inner, middle and outer carbonate ramp. The microfacies 1 and 2 were deposited in an open marine environment of a proximal outer ramp and middle ramp, respectively. The microfacies 3–6 belong to an inner ramp/platform environment. These assemblages of the Asmari Formation suggest that the carbonate sedimentation took place in tropical waters in oligotrophic to slightly mesotrophic conditions.

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References

[1] Vaziri-Moghaddam H, Seyrafian A, Taheri A, Motiei H. Oligocene-Miocene ramp system (Asmari Formation) in the NW of the Zagros basin, Iran: Microfacies, paleoenvironment and depositional sequence. Revista Mexicana de Ciencias Geológicas. 2010;**27**:56-71

[2] James GA, Wynd JG. Stratigraphic nomenclature of Iranian Oil Consurtium agreement area. AAPG Bulletin. 1965;**49**:2182-2245

[3] Motiei H. Stratigraphy of Zagros. Treatise on the Geology of Iran. Ministry of Mines and Metals. Tehran: Geological Survey of Iran; 1993. p. 1

[4] Motiei H. Zagros Stratigraphy. In: Plan for Codifying Book. State Geology Organization, National Iranian Oil Company (NIOC); 1993

[5] Busk HG, Mayo HT. Some notes on the geology of the Persian oilfields. Journal Institute Petroleum Technology. 1918;**5**(17):5-26

[6] Richardson RK. The geology and oil measures of Southwest Persia. Journal of the Institute Petroleum Technology. 1924;**10**(43):256-296

[7] Van Boeckh HDE, Lees GM, Richardson FDS. Contribution to the stratigraphy and tectonics of the Iranian ranges. In: Gregory JW, editor. The Structure of Asia. London: Methuen and Co.; 1929. pp. 58-177

[8] Thomas NA. The Asmari Limestone of southwest Iran. National Iranian Oil Company; 1948. Report 706, unpublished

[9] Jalali MR.Stratigraphy of Zagros Basin. National Iranian Oil Company, Exploration and Production Division; 1987

[10] Wynd JG. Biofacies of the Iranian Oil Consortium Agreement area. In: Unpublished Report. Iranian Oil Operating Companies, Geological and Exploration Division; 1965

[11] Rahmani Z, Vaziri-Moghaddam H, Taheri A, Ghabeishavi A. A model for the paleoenvironmental distribution of larger foraminifera of Oligocene–Miocene carbonate rocks at Khaviz Anticline, Zagros Basin, SW Iran. Historical Biology. 2009;**21**(3-4):215-227

[12] Sadeghi R, Vaziri-Moghaddam H, Taheri A. Microfacies and sedimentary environment of the Oligocene sequence (Asmari Formation) in Fars sub-basin, Zagros Mountains, Southwest Iran. Facies. 2011;**57**(3):431-446

[13] Sooltanian N, Seyrafian A, vaziri-Moghaddam H. Biostratigraphy and paleo-ecological implications in microfacies of the Asmari Formation (Oligocene), Naura anticline (interior Fars of the Zagros Basin), Iran. Carbonates and Evaporites. 2011;**26**:167-180

[14] Taheri A, Vaziri-Moghaddam H, Seyrafian A. Relationships between foraminiferal assemblages and depositional sequences in Jahrum Formation, Ardal area (Zagros Basin, SW Iran). Historical Biology. 2008;**20**(3):191-201

[15] Vaziri-Moghaddam H, Kalanat B, Taheri A. Sequence stratigraphy and depositional environment of the Oligocene deposits at Firozabad section, southwest of Iran based on microfacies analysis. JGeope (Geopersia). 2011;**1**(1):71-82

[16] Vaziri-Moghaddam H, Kimiagari M, Taheri A. Depositional environment and sequence stratigraphy of the Oligo-Miocene Asmari Formation in SW Iran. Facies. 2005:1-11

[17] Vaziri-Moghaddam H, Kimiagari M, Taheri A. Depositional environment and sequence stratigraphy of the Oligocene—Miocene Asmari formation in SW Iran. Facies. 2006;**52**:4151

[18] Laursen GV, Monibi S, Allan TL, Pickard NAH, Hosseiney A, Vincent B, et al. The Asmari Formation revisited: Changed stratigraphic allocation and new biozonation. In: First International Petroleum Conference and Exhibition, Shiraz, Iran. 2009

[19] Ehrenberg SN, Pickard NAH, Laursen GV, Monibi S, Mossadegh ZK, Svånå TA, et al. Strontium isotope stratigraphy of the Asmari Formation (Oligocene–Lower Miocene), SW Iran. Journal of Petroleum Geology. 2007;**30**:107-128

[20] Bahroudi A, Koyi Hemin A. Tectono-sedimentary framework of the Gachsaran Formation in the Zagros foreland basin. Marine and Petroleum Geology. 2004;**21**:1295-1310

[21] Ricou LE, Braud J, Brunn JH. Le Zagros Mem Hors. Ser Soc Geol. 1977;**8**:33-52

[22] Sadeghi A, Vaziri-Moghaddam H, Taheri A. Biostratigraphy and paleoecology of the OligoMiocene succession in Fars and Khuzestan areas (Zagros Basin, SW Iran). Historical Biology. 2009;**21**(1-2):17-31

[23] Ahmadhadi F, Lacombe O, Marc Daniel J. Early reactivation of basement faults in central Zagros (SW Iran), evidence from pre-folding fracture populations in Asmari Formation and lower tertiary paleogeography. In: Lacombe O, Lave J, Roure F, Verges J, editors. Thrust Belts and Foreland Basins. Berlin: Springer; 2007. pp. 205-228

[24] Geological Division. Zagros Structures. National Iranian Oil Company (NIOC), Exploration Directorate; 2004

[25] Falcon NL. Southern Iran: Zagros mountains. In: Spencer A, editors. Mesozoic–Cenozoic Orogenic Belts. Geological Society, London, Special Publication. 1974;**41**:99-211

[26] Sepehr M, Cosgrove JW. Structural framework of the Zagros fold thrust belt, Iran. Marine and Petroleum Geology. 2004;**21**:829-843

[27] Sherkati S, Letouzey J. Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran. Marine and Petroleum Geology. 2004;**21**:535-554

[28] Fakhari MD, Axen GJ, Horton BK, Hassanzadeh J, Amini A. Revised age of proximal deposits in the Zagros foreland basin and implications for Cenozoic evolution of the high Zagros. Techtonophysics. 2008;**451**:170-185

[29] Dunham RJ. Classification of carbonate rocks according to their depositional texture. In: Ham WE, editor. Classification of Carbonate Rocks. A Symposium: AAPG Bulletin. 1962. pp. 108-121

[30] Adams CG, Bourgeois E. Asmari biostratigraphy. In: Unpublished Report. Geological and Exploration Division, Iranian Oil Offshore Company; 1967

[31] Read JF. Carbonate margins of passive (extensional) continental margins: Types, characteristics and evolution. Tectonophysics. 1982;**81**:195-212

[32] Rahmani Z, Vaziri-Moghaddam H, Taheri A. Facies diestribution and paleoecology of the Guri member of the Mishan Formation, in Lar area, Fars province, SW Iran. Iranian Journal of Science & Technology, Transaction A, Printed in the Islamic Republic of Iran. 2010;**34**(A3):257-266

[33] Buxton MWN, Pedley HM. A standardized model for Thethyan

tertiary carbonates ramps. Journal of Geological Society London. 1989;**146**:746-748

[34] Cosovic V, Drobne K, Moro A. Paleoenvironmental model for Eocene foraminiferal limestones of the Adriatic carbonate platform (Istrian Peninsula). Facies. 2004;**50**:61-75

[35] Flugel E. Microfacies Analysis of Limestones. Analysis, Interpretation and Application. Berlin: Springer; 2004. p. 976

[36] Wilson JL. Carbonate Facies in Geologic History. Berlin, Heidelberg, New York: Springer; 1975. p. 471

[37] Amirshahkarami M, Vaziri-Moghaddam H, Taheri A. Paleoenvironmental model and sequence stratigraphy of the Asmari Formation in Southwest Iran. Historical Biology. 2007;**19**(2):173-183

[38] Barattolo F, Bassi D, Romero R. Upper Eocene larger foraminiferal-coralline algal facies from the Klokova Mountain (south continental Greece). Facies. 2007;**53**:361-375

[39] Bassi D, Hottinger L, Nebelsick H. Larger foraminifera from the Upper Oligocene of the Venetian area, Northeast Italy. Palaeontology. 2007;**50**(4):845-868

[40] Beavington-Penney SJ, Racey A. Ecology of extant nummulitids and other larger benthic foraminifera: Applications in paleoenvironmental analysis. Earth-Science Reviews. 2004;**67**(2):19-265

[41] Geel T. Recognition of stratigraphic sequence in carbonate platform and slope: Empirical models based on microfacies analysis of Paleogene deposits in southeastern Spain. Palaeogeography Palaeoclimatology Palaeoecology. 2000;**155**:211-238

[42] Hallock P. Symbiont bearing foraminifera. In: Sen Gupta BK, editor. Modern Foraminifera. Dordrecht: Kluwer; 1999. pp. 123-139

[43] Hohenegger J. Remarks on the distribution of larger foraminifera (Protozoa) from Palau (western Carolines). In: Aoyama T, editor. The Progress Report of the 1995 Survey of the Research Project, Man and the Environment in Micronesia. Kagoshima University Research Center for the Pacific Islands, Occasional Papers. Vol. 32. 1996. pp. 19-45

[44] Hottinger L. Répartition comparée des grands foraminifères de la mer Rouge et de l'Océan Indien. Annali dell'Università di Ferrara; 1980;(6):35-51

[45] Hottinger L. Processes determining the distribution of larger foraminifera in space and time. Utrecht Micropaleontological Bulletins. 1983;**30**:239-253

[46] Leutenegger S. Symbiosis in benthic foraminifera, specificity and host adaptations. Journal of Foraminiferal Research. 1984;**14**:16-35

[47] Nebelsick JH, Rasswer M, Bassi D. Facies dynamic in Eocene to Oligocene Circumalpine carbonates. Facies. 2005;**51**:197-216

[48] Pomar L. Ecological control of sedimentary accommodation: Evolution from a carbonate ramp to rimmed shelf, Upper Miocene, Balearic Islands. Palaeogeography Palaeoclimatology Palaeoecology. 2001a;**175**:249-272

[49] Reiss Z, Hottinger L. The Gulf of Aqaba. In: Ecological Micropaleontology. Vol. 354. Berlin: Springer; 1984

[50] Romero J, Caus E, Rosell J. A model for the palaeoenvironmental distribution of larger foraminifera

based on late middle Eocene deposits on the margin of the south Pyrenean basin (NE Spain). Palaeogeography Palaeoclimatology Palaeoecology. 2002;**179**:43-56

[51] Nebelsick JH, Bassi D. Diversity, growth forms and taphonomy, key factors controlling the fabric of coralline algae dominated shelf carbonates. In: Insalaco E, Skelton PW, Palmer TJ, editors. Carbonate platform system: Components and interaction. Geological Society, London, Special Publications. 2000;**178**:89107

[52] Fournier F, Montaggioni L, Borgomano J. Paleoenvironments and high-frequency cyclicity from Cenozoic southeast Asian shallow-water carbonates, a case study from the Oligo-Miocene buildups of Malampaya (offshore Palawan, Philippines). Marine and Petroleum Geology. 2004;**21**:1-21

[53] Brandano M, Frezza V, Tomassetti L, Cuffaro M. Heterozoan carbonates in oligotrophic tropical waters: The Attard member of the lower coralline limestone formation (Upper Oligocene, Malta). Palaeogeography Palaeoclimatology Palaeoecology. 2008;**272**:110

[54] Flugel E. Microfacies Analysis of Limestone. Vol. 633. Berlin: Springer; 1982

[55] IFP-INOP. Sequence Stratigraphy of Oligocene in Dezful Area, Southwest Iran. In: Joint Project between French and Iranian Oil Company. Unpublished Report. 2006

[56] Pedley M, Carannante G. Cool-water carbonates ramps: A review. In: Pedley M, Caranante G, editors. Cool-water carbonates: Depositional systems and paleoenvironmental controls. Geological Society, London, Special Publications. 2006;**255**:1-9

[57] Brandano M, Frezza V, Tomassetti L, Cuffaro M. Heterozoan carbonates in oligotrophic tropical water, the Attard member of the lower coralline limestone formation (Upper Oligocene, Malta). Palaeogeography, Palaeoclimatology, Palaeoecology. 2009;**56**:1138-1158

[58] Murray JWL. Ecology and Paleoecology of Benthic Foraminifera. Vol. 397. Harlow: Longman; 1991

[59] Brasier MD. Ecology of recent sediment-dwelling and phytal foraminifera from the lagoons of Barbuda, West Indies. Journal of Foraminiferal Research. 1975a;**5**:42-46

[60] Brasier MD. The ecology and distribution of recent foraminifera from the reefs and shoals around Barbuda, West Indies. Journal of Foraminiferal Research. 1975b;**5**:193-210

[61] Burchette TP, Wright VP. Carbonate ramp depositional systems. Sedimentary Geology. 1992;**79**:3-57

[62] Lee JJ. Fine structure of the rhodophycean Porphyridium purpureum in situ in *Peneroplis pertusus* (Forskal) and *P. acicularis* (Batsch) and in axenic culture. Journal of Foraminiferal Research. 1990;**20**:162-169

[63] Hottinger L. Shallow benthic foraminiferal assemblages as signals for depth of their deposition and their limitations. Bulletin of the Geological Society of France. Société Géologique de France. 1997;**168**(4):491-505

[64] Brandano M, Corda L. Nutrients, sea level and tectonics: Constrains for the facies architecture of a Miocene carbonate ramp in Central Italy. Terra Nova. 2002;**14**:257-262