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Depositional environment and microfacies analysis: An example of the Asmari Formation in West Zagros Basin, Lorestan province (Iran)

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Abstract

The carbonate sequence of the Asmari Formation is the most important oil reservoir formed in the Zagros Basin, southwestern Iran. In order to interpret the sedimentary environment, the Makhmal-Kuh and Kaka-Reza sections in the Lorestan province were investigated. These sections were compared with some other outcrops in the Zagros Basin. Twenty one genera and species were identified in the Makhmal-Kuh section, and 20 genera and species in the Kaka-Reza section. Among foraminifera, *Miogypsina* sp., *Amphistegina* sp., *Elphidium* sp., *Operculina* sp., *Nephrolepidina* sp., *Eulepidina* sp., *Heterostegina* sp., *Nummulites fichtelli*, *Nummulites vascus* and *Nummulites intermedius* are the most important species. Based on the identification of co-occurrence taxa, two assemblage zones are introduced in the Makhmal-Kuh section, and one faunal assemblage zone in the Kaka-Reza section. Petrographic analysis also led to the recognition of twelve microfacies types in the Makhmal-Kuh section and five microfacial types in the Kaka-Reza section. Based on these microfacial types, three sub-environments were determined in the Makhmal-Kuh section and two settings in the Kaka-Reza section: Outer ramp, in the aphotic zone, dominated by planktic foraminifera, bryozoan, and echinoids; the mid ramp, in the oligophotic zone, characterized with benthic foraminifera and planktic foraminifera; the shallower waters of the mesophotic-euphotic zone dominated by benthic foraminifera and coralline red algae in the inner ramp. Therefore, the depositional sub-environments along with biotic assemblages represent warm waters of tropical regions under photic variable conditions in a homoclinal ramp. Based on the distribution of co-occurrence fossils, the Asmari Formation is dated as Rupelian to the Aquitanian.

Keywords: *Asmari Formation, Biostratigraphy, Lorestan, Microfacies, Zagros.*

1. Introduction

The Zagros basin was associated with the Gondwana super continent during the Paleozoic era. Subsequently, this basin became a region of passive margin in the Mesozoic and Cenozoic eras (Motiei 1994; Heydari 2008). Following the Upper Cretaceous deposits and the compressive phase, from the middle Eocene to early Miocene, which led to the closure of the Neo-Tethys Ocean, the Zagros belt was developed in the northeastern margin of the Arabian Plate. The Zagros Basin extends from Turkey and northeast Iraq to southeast Iran. A foreland basin was formed in this area during the Paleogene period (Motiei 1994; Aghanabati 2004; Lacombe et al. 2011a, b). Afterwards, an intrashelf basin was created throughout the Oligo-Miocene in the Zagros Basin (van Buchem et al. 2010). In fact, the area was formed of large intra-shelf basins surrounded by deep water basin. The Asmari Formation was deposited on the deeper margins of a carbonate platform with overlap configuration at the top of the Pabdeh Formation (Ziegler 2001; van Buchem et al. 2010). Thus, the Cenozoic deposits in this basin include deep shale sediments and shallow water carbonates belonging to the Pabdeh and Asmari formations, respectively (James and Wynd 1965; Sherkati and Letouzey 2004). In fact, the deposits of carbonate platforms are potentially carbonate reservoirs that are often associated with excellent source rocks such as the shale facies of the Pabdeh Formation, so that they can form petroleum systems. Hence, the Tertiary carbonate reservoir platforms are widely observed worldwide and especially throughout the Zagros Basin (namely the Asmari Formation) (Pomar et al. 2014). They have a large volume of hydrocarbons (van Buchem et al. 2010; Shabafrooz et al. 2015). Therefore, the formation is an important hydrocarbon reservoir in the Zagros Basin, which is thereafter overlain by the Gachsaran Formation during the middle Miocene. Based on biostratigraphic data, the Asmari Formation was deposited during the Oligocene–Miocene in Khuzestan, Fars and Lorestan (James and Wynd 1965). Its type section consists of 314 m of limestones, dolomitic limestones and argillaceous limestones (Motiei 1994). In recent decades, extensive studies have mostly addressed the determination of age, depositional environment and its geometry, as well as the biostratigraphic criteria and sequence stratigraphy of the Asmari Formation (e.g., James and Wynd 1965; Adams and Bourgeois 1967; Ehrenberg et al. 2007;

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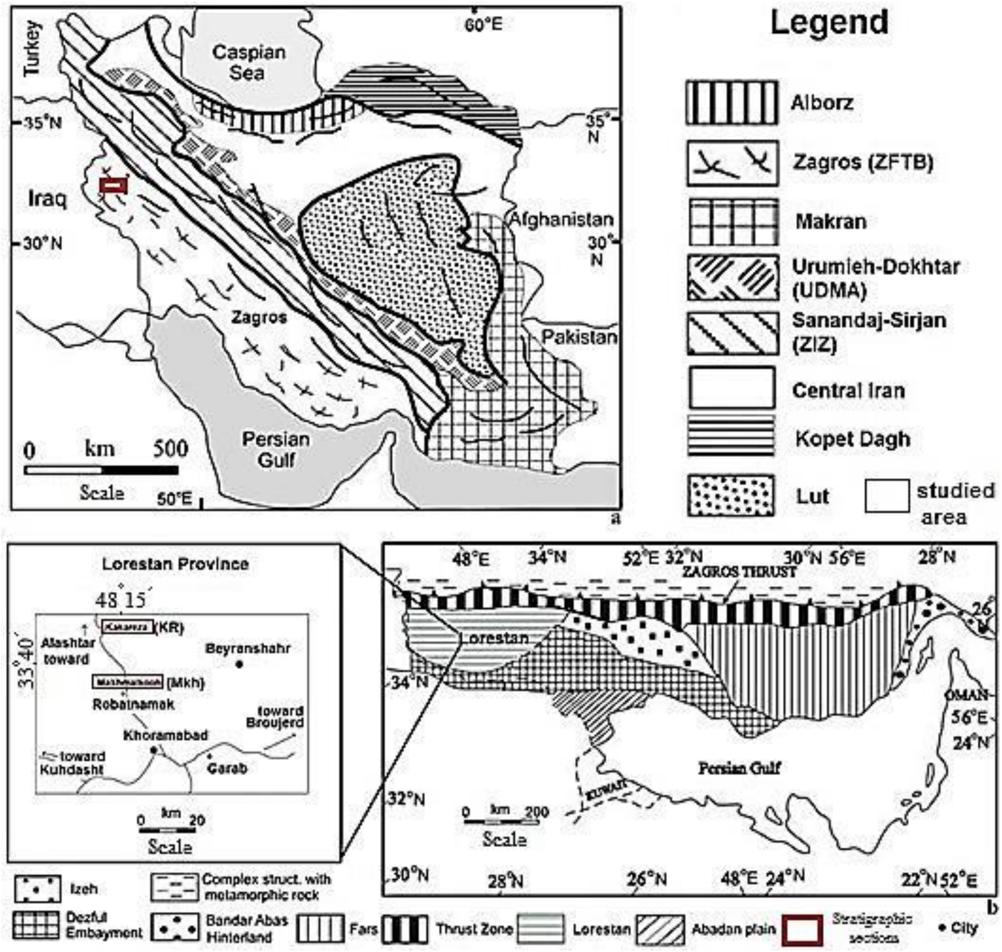

Fig 1. a General map of Iran showing the eight geological provinces (from Heydari et al. 2003). Abbreviations of the Zagros Basin: UDMA, Urumieh-Dokhtar magmatic arc; ZFTB, Zagros fold-thrust belt; ZIZ, Zagros imbricate zone (from Alavi 2004). b Geological setting of the simplyfolded Zagros belt with its structural provinces (modified after Falcon 1961; Sherkati and Letouzey 2004). The left rectangular shows the location of the studied area (Mkh: Makhmal-Kuh, KR: Kaka-Reza).

Rahmani et al. 2009; van Buchem et al. 2010; Vaziri-Moghaddam et al. 2010; Seyrafian et al. 2011; GhasemShirazi et al. 2014; Shabafrooz et al. 2015; Taheri et al. 2017; Yazdi et al. 2017; Poorbehzadi et al. 2019; Baratian et al. 2020). Recently, Laursen et al. (2009) and van Buchem et al. (2010), based on the foraminiferal assemblages calibrated with strontium isotopic evidence, introduced a new biozonation for this formation. Therefore, the main goals of this study are to evaluate the stratigraphic changes and microfacies analysis, to determine the age of the Asmari Formation carbonates and to reconstruct the sedimentary environment in order to provide a consistent model for the study section.

1.1. Geological setting and study area

The Zagros Basin is divided into three tectono-stratigraphic units including the Zagros fold–thrust belt (ZFTB), the Zagros imbricated zone (ZIZ) and the Urumieh–Dokhtar magmatic arc (UDMA) (Stöcklin 1968; Alavi 2004). The Zagros fold–thrust Zone includes the Fars Province (southern part), the Khuzestan Province with the Dezful Embayment (central part), and the Lorestan Province in the northwestern part of Zagros (Motiei 1995; Sherkati et al. 2006). The studied sections are located in the ZFT zone of the Zagros Basin, Lorestan Province. These are the Makhmal-Kuh (Mkh) and the Kaka-Reza (KR) sections near the Khoram Abad city, all located in northwestern Iran. The Makhmal-Kuh section, is situated about 15 km north-east of Khoram Abad at the Tang-e Shabikhon, west of Iran (coordinates 33 36' 9" N, 48 17' 22" E) (Fig 1). The Kaka-Reza section (coordinates 33 43 '18 "N and E 48 16' 03") is located about 25 km northeast of Khoram Abad and 15 km from Alashtar. Geological map of studied area shows in Figure 2.

2. Materials and Methods

This study deals with regional stratigraphic sections of the Asmari Formation throughout the Lorestan province in the Zagros Basin. The studied sections include two outcrops with northern trend.

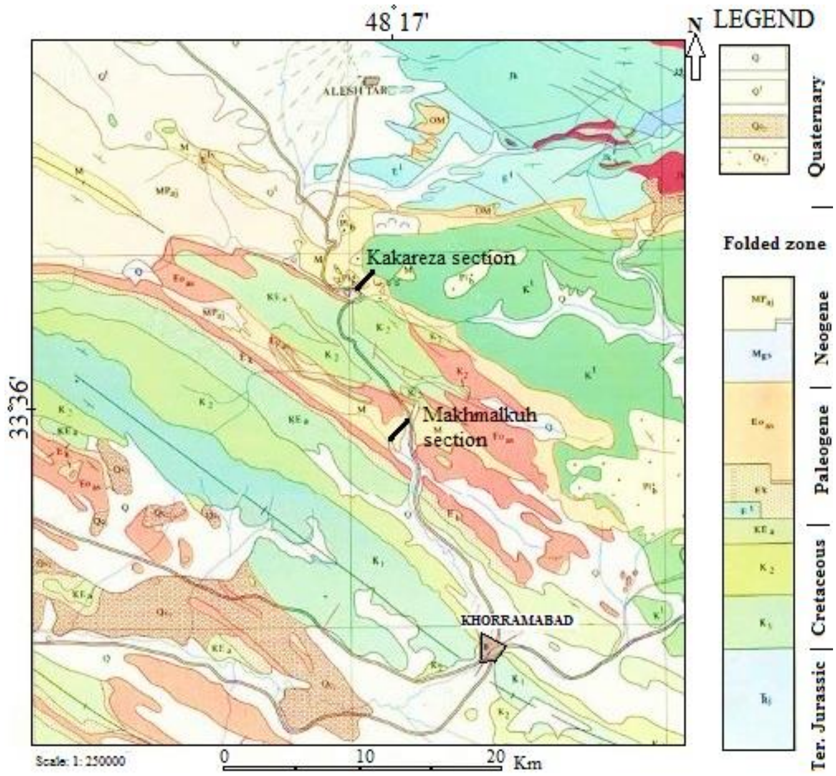

Fig 2. Geological map of Khorramabad (1:250000) (NIOC 1992) and studied sections, Lorestan Province.

Sampling was done with one sample per 1 m for about 85 m of the Makhmal-Kuh section and per 1-2 m with 90 samples from 120 m of the Kaka-Reza section. A total of 175 slides were examined with an optical microscope for semi-quantitative microfacies analysis, and distribution of faunal assemblages. The terminology used for facies textural description follows the classification schemes of Dunham (1962) and Embry and Klovan (1971). For biostratigraphic studies were used the concepts provided by many researchers (e.g., Bolli 1966; Caron 1985; Kalantari 1986; Postuma 1971; Loeblich and Tappan 1988; Premoli Silva and Verga 2004; Amiri Bakhtiar et al. 2010). In general, the microfacies characteristics were done based on fossil content, depositional texture, grain composition and grain size. The two studied sections were compared with other sections of Lorestan and Gachsaran areas, respectively. The selected sections namely the Mamulan section in Central Lorestan Province, the Kabir Kuh section in South Lorestan Province, and the Tang-e Gurgoda section in the Dezful Embayment in Gachsaran city were studied by Vaziri-Moghaddam et al. (2010) and van Buchem et al. (2010), which have been used for better understanding of the sedimentary environment and correlation in this study.

3. Results

3.1. Lithostratigraphy

Usually, in the carbonate depositional environments, the content of sediment with skeletal fragments produced by marine biotic assemblages effect under specific ecological conditions (Mateu-Vicens et al. 2008). In the present study, the Asmari Formation attains a thickness of 85 m in the Makhmal-Kuh section. It consists of thick to medium bedded limestone, thin limestone and dolomitic limestone dominated by benthic foraminifera and coralline red algae. The Asmari Formation in the Kaka-Reza section is composed of rock units with thin to medium bedded limestone and sometimes thick-bedded limestone. The thickness of this formation in Kaka-Reza is 120 m. According to the lithological study, the rock units have the texture of wackestone, packstone and grainstone. In both sections, the Asmari Formation at the base overlies the dolomite of the Shahbazan Formation and to the top the formation is overlain by anhydrite and gypsum of the Gachsaran Formation (Figs 3, 4). The occurrence of gypsum and anhydrite of the Gachsaran Formation indicates climate changes. According to Miller et al. (2005), during the early Miocene, there is evidence for a cooling event. This climate change, accompanied by a drop in sea level during the Aquitanian to Burdigalian, caused anhydrite deposition from seawater through evaporation.

3.2. Biostratigraphy

The carbonate platforms are characterized by active producers (biotic organisms) such as marine small and large benthic biotic communities during the Oligocene to early Miocene (Prothero 2003; Hallock et al. 2006). Biostratigraphic criteria of the Asmari Formation were studied by Wynd (1965) using foraminiferal markers.

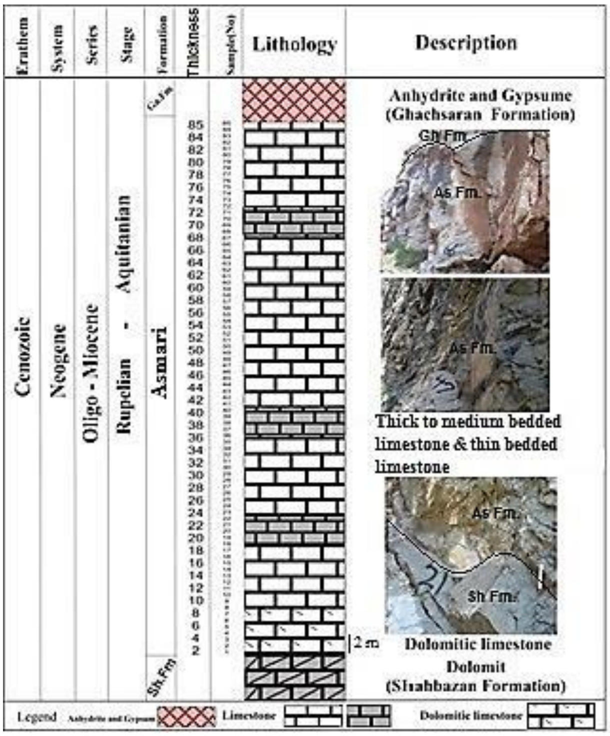

Fig 3. Lithostratigraphic column of the Asmari Formation, Makhmal-Kuh section, Lorestan Province.

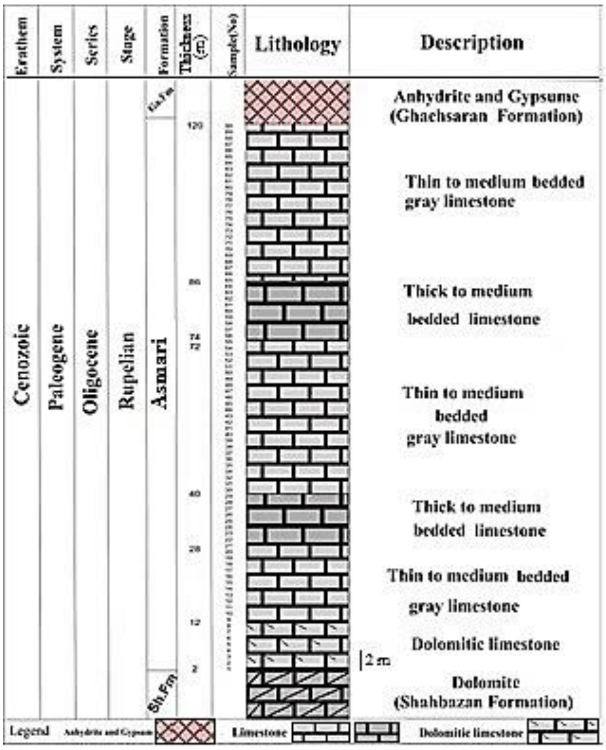

Fig 4. Lithostratigraphic column of the Asmari Formation, Kaka-Reza section, Lorestan province.

Accordingly, Wynd (1965) introduced the 55-61 biozones of the Asmari Formation as follows: Zone 55 (*Globigerina* spp.), Zone 56 (*Lepidocyclina*–-*Operculina*–*Ditrupa*), Zone 57 (*Nummulites intermedius* – *Nummulites vascus* Assemblage Zone), Zone 58 (*Archaias operculiniformis*) and Zone 59 (*Austrotrillina howchini*–*Peneroplis evolutus* Assemblage Zone) for the Oligocene, and Zone 61 (*Borelis melocurdica*) for the Miocene (Burdigalian) (Fig 5). Subsequently, Adams and Bourgeois (1967) modified the previous biostratigraphic studies and proposed biozones which includes *Eulepidina*–*Nephrolepidina* –*Nummulites* assemblage zone for the Oligocene and *Miogypsinoides*-–*Archaias*–*Valvulinid* assemblage zone for the Miocene (Aquitanian). Also, two subzones (*Archaias asmaricus*–*Archaias hensoni* and *Elphidium* sp. 14–*Miogypsina*) for Aquitanian and the *Borelis melo* group–*Meandropsina iranica* assemblage zone for the Burdigalian (Fig 5). Afterward, Ehrenberg et al. (2007) modified previous studies based on information obtained from the Sr isotope stratigraphy. They introduced 5 bioevents based on index fossils of the *Nummulites, Miogypsina, Archaias,* as well as *Spiroclypeus blankenhorni* and *Borelis melo curdica*. According to Ehrenberg et al. (2007), the extinction of the *Nummulites* occurred near the Rupelian/Chattian boundary. Then, Laursen et al. (2009) and van Buchem et al. (2010) presented a new biozonation by using the strontium isotope. Here, biostratigraphic studies are performed based on previous research and information obtained from the studied sections. Accordingly, a total of 21 foraminifera genera and species were identified in the Makhmal-Kuh section, and 20 genera and species in the Kaka-Reza section for which the distributions have been determined and drawn (Figs 6, 7). In the present study, all the lithostratigraphic correlation charts of the Asmari Formation are presented in the Figure 12. Some selected benthic foraminifera from the studied sections are illustrated in Plates. In the present study, the zoning scheme presented in the Makhmal-Kuh and the Kaka-Reza sections includes several zones based on the stratigraphic distribution of foraminifera, which is as follows:

3.2.1. Foraminifera assemblage in the Makhmal-Kuh section

In the Makhmal-Kuh section, a total of 21 genera and species of foraminifera were identified (Plates MK). This led to the identification of two assemblage zones (Fig 6):

***Eulepidina* – *Nephrolepidina* – *Nummulites* Assemblage Zone**

This zone is up to 58 m thick at the lower part of the Asmari Formation. The most important foraminifera taxa are *Eulepidina elephantina, Eulepidina dilatata, Nephrolepidina tournoueri, Nummulites* sp., *Nummulites vascus, Nummulites fichteli, Nummulites intermedius, Assilina* sp., *Operculina complanata, Operculina* sp., *Pyrgo* sp., *Amphistegina lessonii,* *Amphistegina* sp., *Triloculina tricarinata* and *Triloculina trigonula*. In this zone, among benthic foraminifers, intact specimens such as *Nephrolepidina*, *Amphistegina*, and *Nummulites* are the most important components which indicate the mesophotic zone (Pomar et al. 2014). In addition, large foraminifera are the most important components of the Oligocene-early Miocene transition.

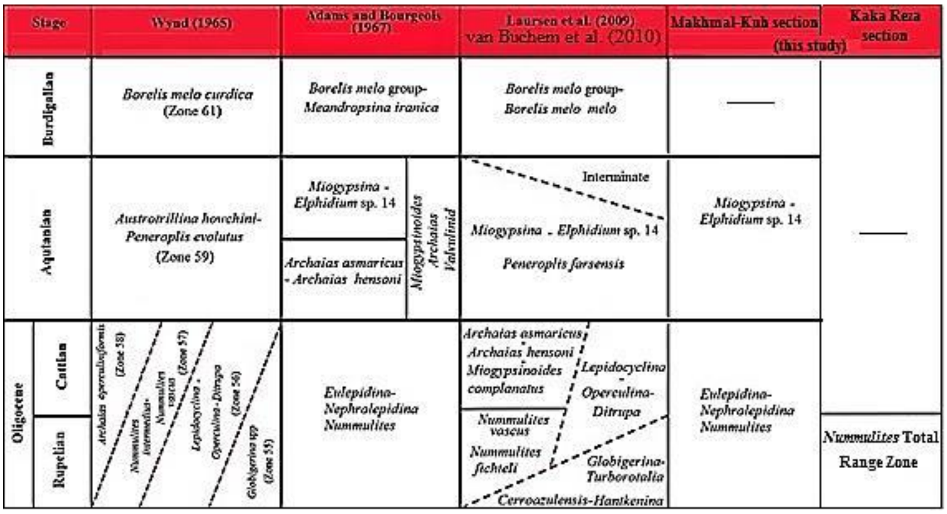

Fig 5. Biozonation of the Oligo-Miocene Asmari Formation carbonates in the Zagros Basin (from Wynd 1965; Adams & Bourgeois 1967; Laursen et al. 2009) and the studied sections.

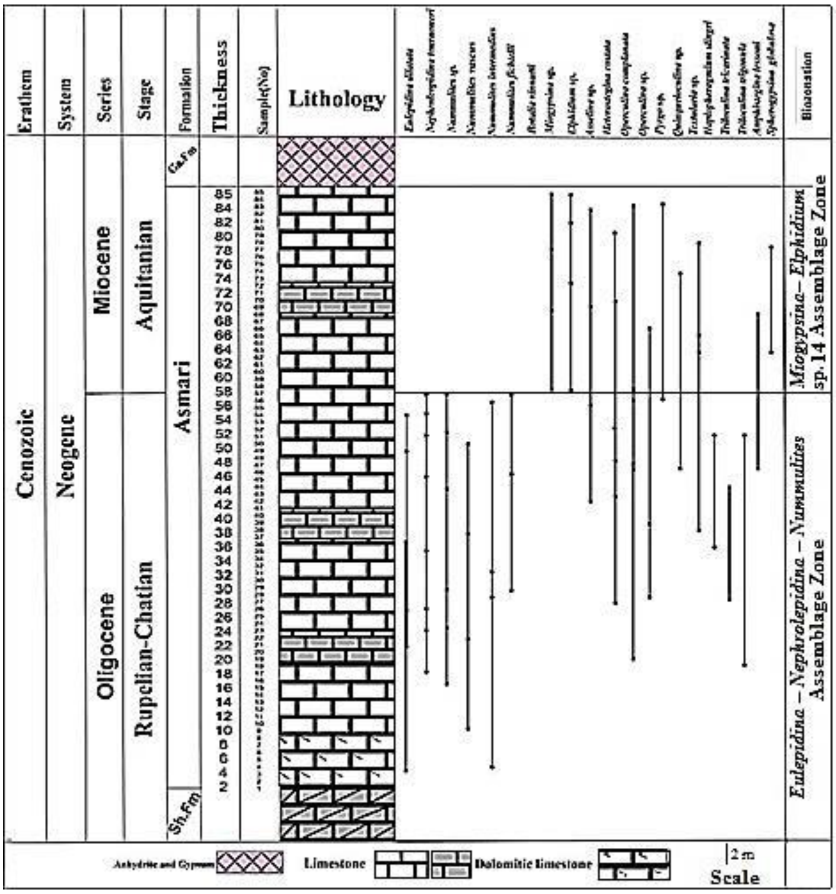

Fig 6. Vertical distribution of the biotic assemblages in the Asmari Formation, Makhmal-Kuh section, Lorestan Province.

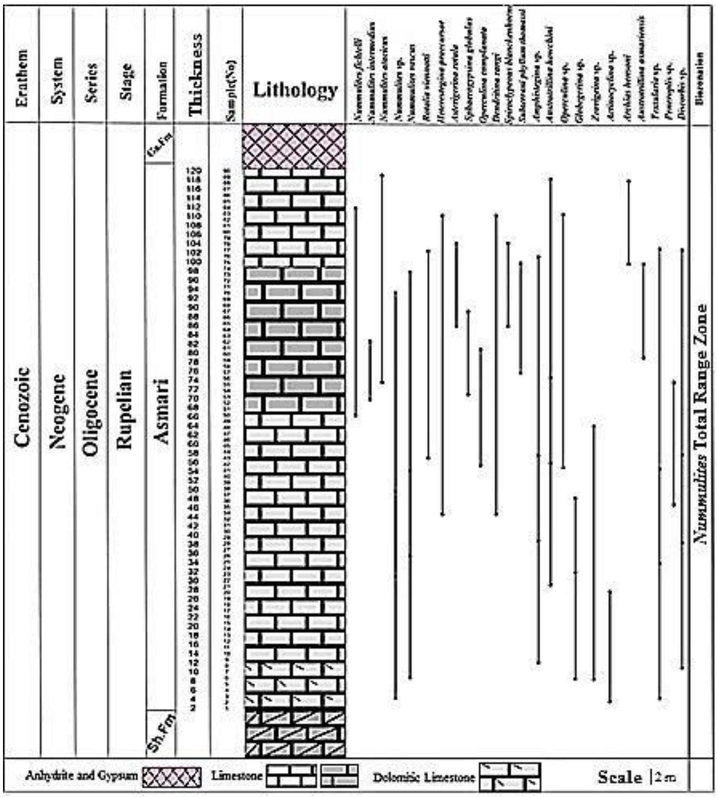

Fig 7. Vertical distribution of the biotic assemblages in the Asmari Formation Kaka-Reza section, Lorestan Province.

They allow the subdivision of biostratigraphic chart of the sequence. Both species *Eulepidina dilatata* and *Eulepidina elephantina* were identified from the studied section within the Rupelian and Chattian. *Eulepidina dilatata* is distinct from *Eulepidina elephantina* by its large size and the absence of pillars which penetrate to the surface. Adams and Bourgeois (1967), as well as Laursen et al. (2009) reported both two species of *Eulepidina* from the Asmari Formation. The presence of *Eulepidina* indicates the Oligocene age. *Nephrolepidina tournoueri* and *Operculina complanata* are also recorded from the late Rupelian and Chattian from this formation in Zagros Basin (Laursen et al. 2009). The species *Operculina complanata* from northeastern Italy in the late Oligocene has been reported, in the Chattian deposits (Bassi et al. 2007). As mentioned above, *Nummulites vascus* and *Nummulites fichteli* were recorded in this assemblage zone. The appearance of *N. vascus* and *N. fichteli* indicates late Rupelian and early Chattian age which is in accordance with SB22 zone in the Mediterranean basin from the zoning of Cahuzac and Poignant (1997). These species were reported from the sediments of Rupelian and Chattian in northeastern Italy (Venetian area) as well as the Zagros Basin in southwestern Iran by Bassi et al. (2007) and Laursen et al. (2009). Of course, the last occurrence of the *Nummulites* (*N. bouillei*) was recorded in the Mediterranean basin in the late Oligocene, late Chattian (biozone SB23) (Cahuzac and Poignant 1997), but not recorded in this biozone. According to Ehrenberg et al. (2007), the last appearance of the *Nummulites*, occurred in the late Rupelian. BouDagher-Fadel (2008) also believe that the extinction of *Nummulites* is related to the Rupelian stage. The presence of *Nummulites, Eulepidina* together with *Nephrolepidina*, indicates Rupelian-Chattian interval in many regions of Iran such as Sabzevar, Kashan, Qom (Rahaghi 1980) and Garmsar (Daneshian and Ramezani Dana 2007). This assemblage zone is also introduced by Adams and Bourgeois (1967) and attributed to the Rupelian-Chattian interval. Moreover, the introduced zone is in accordance to the zone of *Nummulites vascus-Nummulites fichteli* of Laursen et al. (2009), which is Rupelian in age (Fig. 5).

***Miogypsina– Elphidium* sp. 14 Assemblage Zone**

This Assemblage Zone is recorded in the upper part of the Asmari Formation and its thickness is 27 m. Some of the species identified in the study section include: *Miogypsina* sp., *Operculina* sp., *Elphidium* sp., *Assilina* sp., *Planorbolina* spp., *Heterostegina costata, Amphistegina lessoni, Operculina complanata, Pyrgo* sp., *Quinqueloculina* sp., and *Spherogypsina globulosa*. This assemblage zone is in accordance to the zone of *Miogypsina– Elphidium* sp. 14 of Adams and Bourgeois (1967) that is early Miocene (Aquitanian) in age. Adams and Bourgeois (1967) subdivided *Elphidium* into *Elphidium* sp. 1 and *Elphidium* sp. 14 based on wall characteristics. In their view, *Elphidium* sp. 14, with a thick wall, has stratigraphic value and occurs in

Aquitanian. Therefore, due to the presence of *Elphidium* sp. 14, this biozone coincides to the Aquitanian stage. The presence of *Operculina complanata* along with *Nephrolepidina*is indicates the late Chattian and it is correlated with SB23. Also, compared with the standard bio-zone of Laursen et al. (2009) (=*Miogypsina–Elphidium* sp. 14, *Peneroplis farsensis* Assemblage Zone), this faunal assemblage corresponds to the Aquitanian due to the presence of *Miogypsina* and *Elphidium* sp. A genus like *Miogypsina* has stratigraphic value because it is considered an indicator of the early Miocene (Aquitanian) (Adams et al. 1983; Maghfouri Moghaddam et al. 2019). This species has been reported in many parts of Iran including Fars and Embayment Dezful (the first appearance in the late Chattian) (Amirshahkarami et al. 2007; Sadeghi et al. 2009). This assemblage zone is in accordance to the middle Asmari Formation as introduced by Thomas (1948). Due to the fossil assemblages, it corresponds to the SB24 zone in the Mediterranean region (Cahuzac and Poignant 1997). Therefore, based on the location of this assemblage over the assemblage zone No. 1, the age of this zone can be attributed to Aquitanian. Hence, based on the distribution of identified fossils in both zones (1 and 2), the age of the Asmari Formation from Oligocene (Rupelian-Chattian) to early Miocene (Aquitanian) in the Makhmal-Kuh section is suggested (Fig. 5).

3.2.2. Assemblage in the Kaka-Reza section

In Kaka-Reza section, a total of 20 genera and species of foraminifera were identified (Plate KR). This allows us to identify the following assemblage zone (Fig 7):

***Nummulites* Total Range Zone**

The only zone identified in the Kaka-Reza section is the *Nummulites* Total Range Zone, which is up to 120 m thick. Species in the studied section include the following: *Nummulites fichteli-intermedius* group, *Nummulites vascus, Nummulites* aff. *atacicus, Operculina complanata*, *Nummulites* sp., *Amphistegina* sp., *Heterostegina* sp., *Operculina* sp. This biozone is defined based on a range of *Nummulites*. According to Racey (1994) in northern Oman, the presence of *Nummulites* without the genus *Eulipidina* indicates lower Oligocene (Rupelian). Also the results of the strontium isotope studies of Ehrenberg et al. (2007) show that the last *Nummulites* occurrences is about 1 Ma before the end of the Rupelian. Therefore, since *Nummulites* in the studied section extends from the base upwards without *Eulipidina*, the age of the Asmari Formation can be considered as Rupelian (early Oligocene).

3.3. Microfacies analysis

3.3.1. Microfacies types in the Makhmal-Kuh section

Semi-quantitative analysis by microscopic observations and petrographic studies (study of textures, allochems and skeletal components in thin sections) led to the recognition of several microfacies types in the Makhmal-Kuh sedimentary environment. Microfossils in thin sections have been studied based on some biostratigraphic aspects. These reflect different positions in sedimentary environment such as inner ramp, mid ramp, outer ramp (Fig 8).

Facies related to the inner ramp (lagoon)

This facies association includes four microfacies types (C):

Microfacies C1 (Bioclastic coral floatstone / rudstone)

The most important elements of sub-facies C1 are generally coral fragments along with benthic foraminifera (*Elphidium, Miogypsina, Amphistegina, Borelis* and miliolids), and bioclast fragments. Corals indicate the euphotic zone. Also, coral colonies are able to spread in seagrass environments. In addition, *Elphidium*, *Borelis Amphistegina* and *Miogypsina* species have been widely reported from shallow marine environments. These fauna, along with small miliolids suggest the high-energy conditions around of coral adjacent to the seagrass meadows (euphotic zone). The abundance of calcite microcrystalline (lime mud) in this sub-facies indicates shallow environments. This facies represents the inner ramp environment in the euphotic zone colonized by sea-grass (Brandano et al. 2009; Pomar et al. 2014). The inner ramp lithofacies consists of horizontal beds with very abundant porcellaneous foraminifera, *Borelis* and miliolids as stated above.

Microfacies C2 (Bryozoan wackestone- packstone)

The most important feature of this facies is the abundance of light-independent fauna such as Bryozoa. The abundance of delicate Bryozoan reflects low-energy conditions in deep offshore habitats. Bryozoan include the Cyclostomata and Cheilostomata orders. Benthic foraminifera such as *Elphidium* represents other biological constituents of these facies.

Microfacies C3

This facies contains marl beds and the benthic foraminifera have very little variation. In this facies *Ammonia* sp. *Ammonia tepida*, *Ammonia beccarii*, and *Elphidium granosum* are present. Planktic foraminifera are abundant and the ratio of planktic foraminifera to benthic is about 70%. *Ammonia beccarii* is a euryhaline taxon and can exist from marine to brackish environments, but is particularly predominant in marginal marine environments. *Ammonia tepida* and *Elphidium granosum* are also associated with environments such as lagoon. *Elphidium granulosum* is hypersensitive to oxygen variation. Therefore, the *Ammonia* predominance indicates that in addition to salinity fluctuations, oxygen stress may have a large impact on the environment of these facies (Lintner et al. 2020).

Microfacies C4

This facies is composed of thin to medium bedded anhydrite, which is located between pelagic facies. The deposition of anhydrite among the pelagic facies indicates sedimentation in a relatively deep hypersaline marine basin with unstable and stressful conditions.

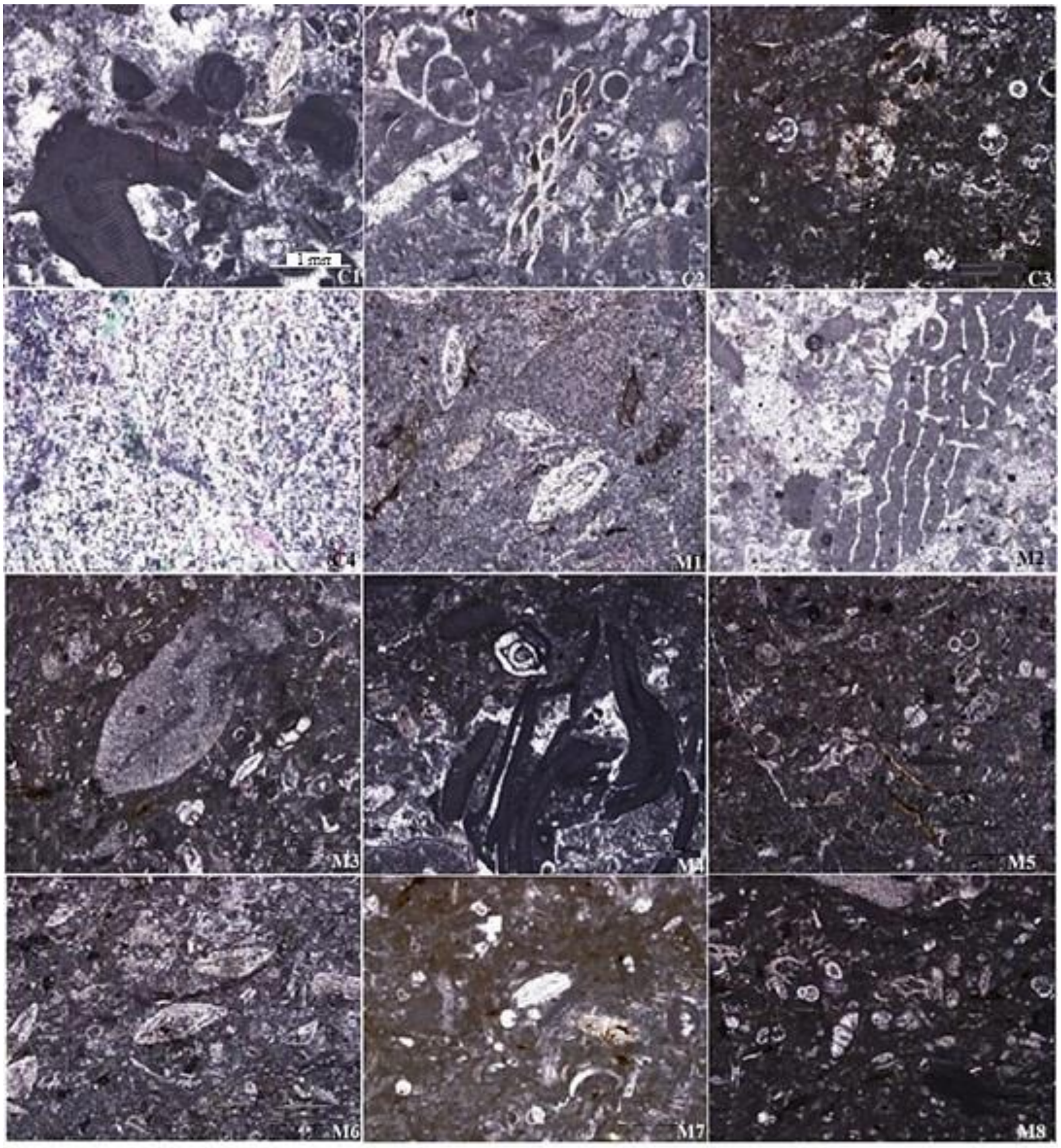

Fig 8. Microfacies in the Asmari Formation (Makhmal-Kuh section): MF C1 (Sample MK. 25), MF C2 (Bryozoan wackestone-packstone) (Sample MK. 40), MF C3 (Sample MK. 85), MF C4 (Sample MK. 83), MF M1 (Bioclastic imperforate foraminiferal wackestone- packstone) (Sample MK.17), MF M2 (Foraminiferal/corallinacean floatstone-rudstone) (Sample MK. 55), MF M3 (Bioclastic perforate foraminiferal wackestone- packstone) (Sample MK. 62), MF M4 (Bioclastic corallinacean algal floatstone-rudstone) (Sample MK. 11), MF M5 (Pelagic foraminiferal-Nummulitidae-bryozoan wackestone-packstone) (Sample MK. 84), MF M6 (Sample MK. 49), MF M7 (Sample MK.79), MF M8 (Sample MK. 80).

Facies related to the outer ramp-mid ramp (open marine)

Facies analysis, allows the recognition of eight microfacies types (M):

Microfacies M1 (Bioclastic imperforate foraminiferal wackestone- packstone)

The major components of this microfacies type are skeletal grains of imperforate benthic foraminifera such as *Dendritina, Peneroplis, Meandropsina, Spirolina, Borelis* and miliolids with a wackestone– packstone texture. The larger benthic foraminifera with hyaline walls include *Amphistegina* and *Elphidium*. Minor components are small benthic foraminifera, *Discorbis, Textularia,* and *Ammonia*, fragments of echinoids, molluscs and corallinacean algae such as *Lithoporella*. The accumulation of imperforate benthic foraminifera indicates deposition in a shallow environment with low turbulence. This indicates mesotrophic to oligotrophic conditions at low depths. The occurance of thick-shelled *Amphistegina* with seagrass also indicate life in the photic zone and shallow water conditions (Romero et al. 2002).

Microfacies M2 (Foraminiferal/corallinacean floatstone-rudstone)

This microfacies type is characterised by nodules and branches of red algae. The benthic foraminifera include both perforate (*Amphistegina, Miogypsina*) and imperforate forms (*Meandropsina,* miliolids). Minor components are fragments of molluscs, bryozoa, echinoids, coral and red algae (genus *Lithothamnion*). Perforated foraminifera, such as *Amphistegina* and *Miogypsina* closely contact with seagrass. Also, the microcrystalline abundant matrix with seagrass indicates shallow water conditions. The skeletal compound (dominance of red corallinacean with the composition of perforate and imperforate foraminifera), and the stratigraphic position indicate sedimentation in the initial zone of mid ramp setting.

Microfacies M3 (Bioclastic perforate foraminiferal wackestone- packstone)

The major components of this microfacies type are heterotrophic forms such as molluscs, bryozoa, echinoids with a wackestone–packstone texture. Other components are corallinacean red algae, *Lithothamnion*, *Mesophyllum* and perforate benthic foraminifera. The larger benthic foraminifera include both *Amphistegina* and *Operculina*. The occurrence of large foraminifers is often attributed to light intensity, water energy, rising sea levels due to global warming, and development of tropical habitats (Hallock and Glenn 1986; Hohenegger 2000; Bassi et al. 2007). In this facies, there are also small benthic foraminifera such as *Cibicides*, *Lobatula*, *Elphidium* and *Textularids*. Red algae with green algae and coral fragments are other examples of this microfacies type. The co-exsistence of large foraminifera belonging to the deep areas such as *Amphistegina* and Nummulitidae along with smaller foraminifera and Melobesioidae algae are characteristic of the middle ramp environment and the oligophotic zone. According to Hottinger (1997), *Nummulites* inhabit the deepest environments among the observed components. Other components, such as bryozoa, mollusc shell fragments with echinoids crustaceans also confirm this interpretation.

Microfacies M4 (Bioclastic corallinacean algal floatstone-rudstone)

This microfacies type is mainly characterised of corallinacean algae colonies (*Lithothamnion*, *Sporolithon*) and Rhodolite. The texture is floatstone-rudstone. Rhodolites were mainly branch-shaped. Other components can be found, such as coral, bivalve shell fragments with echinoids. Among the large foraminifera, *Amphistegina* and *Operculina* have been identified. *Elphidium*, *Sphaerogypsina, Lobatula, Acervulinid* and *Textularids* are also present. The presence of species such as *Operculina*, *Amphistegina* together with algal components, Melobesioidae and Sporolithacea suggest an oligotrophic environment within middle ramp setting. The presence of shallow-water fauna along with debris bioclasts and deep-sea organisms indicates that sedimentation in the shallow waters of euphotic, is caused by marine currents.

Microfacies M5 (Planktic foraminiferal-Nummulitidae-bryozoan wackestone-packstone)

The main skeletal grains consist of bryozoa, grain debris of planktic foraminifera and fragments of benthic foraminifera (*Cibicides*, *Amphistegina*, *Elphidium*, *Buliminids*, *Operculina* and *Textularids*). Common biota are molluscs and echinoids. The major components of this microfacies type are bryozoans while light-dependent organisms are present in low percentages. This facies is characterized by deep-water benthic foraminifera such as *Operculina* and *Amphistegina*. Also, the presence of deeper foraminifera such as *Nummulites* suggests sedimentation in the oligophotic zone. The small Nummulitidae were reported from open marine conditions by Romero et al. (2002). The decrease in the number of foraminifera and the increase in bryozoa are probably related to an increase in food levels (mesotrophic conditions).

Microfacies M6

This microfacies type is characterised by benthic and planktic foraminifera in the marl sedimentary unit. Echinoid fragments and spines, bryozoan and gastropods are also present in some samples. *Globigerina* and *Globigerinoides* are the most important planktic foraminifera. The benthic foraminifera include *Eponides* sp., *Elphidium crispum*, *E. maculleum*, *E. granusom*, *E. fichtellaneum*, *Heterolepa dutemplei, Cibicides* sp., *Cibicides lobatulus* and *Cibicidoides* sp. The fine-grained composition and the high abundance of planktic foraminifera in marl sediment reflect sedimentation in a low-energy open marine environment, down of storm waves. Also, the presence of benthic taxa such as *Heterolepa*, *Cibicides* and *Cibicidoides* represents a stable environment with good ventilation, adequate oxygen level, water currents and oligomesotrophic nutrient conditions.

Microfacies M7 (Planktic foraminiferal packstone)

This facies is characterized by a very low diversity of benthic foraminifera. The most abundant benthic fauna are *Uvigerina* and *Pappina*. Pelagic foraminifera are relatively abundant (planktonic/ benthic ratio is 21.5 to 70%), including *Globigerinoides* and *Globigerina*. The very low diversity of benthic foraminifera and the dominance of a particular group such as *Uvigerina* reflect low oxygen content at the sediment-water contacts surface. When the inlet flow of organic carbon dominates the environment, it tends to increase population and exhibit opportunistic behavior and is able to withstand dioxic conditions. *Reticulophragmium* is a species able to withstand stressful environmental conditions such as low oxygen and high levels of nutrients. Therefore, this facies represents an unstable and stressful environment with low oxygen levels that can be caused by taphonomic processes or some factors affecting living communities.

Microfacies M8 (Planktic foraminiferal wackestone)

This facies is characterized by abundant planktic foraminifera. *Rectuvigerina* is a well-known species of endemic foraminifera. In addition, *Uvigerina, Bulimina, Bolivina* and *Nonion* are also present. This microfacies type is characterised by abundant and diverse planktic foraminifera (planktonic/ benthic ratio is 90-72%). In addition to *Globigerina* and *Globigerinoides, Globorotalia* is also present. The abundance of endogenous taxa compared to surface taxa may represent mesotrophic conditions. The high ratio of planktonic/ benthic and benthic foraminifer assemblages represents the deep outer neritic environment.

3.3.2. Microfacies types in the Kaka-Reza section

Microfacies study of the Asmari Formation at the Kaka-Reza section indicates sedimentation in a carbonate ramp environment (Fig 9). The inner ramp is characterized by lagoonal microfacies, low diversity of fauna and presence of perforate benthic foraminifera. In addition, the proximal middle ramp microfacies are present in the studied section, but distal middle ramp and outer ramp facies are not present in the studied section.

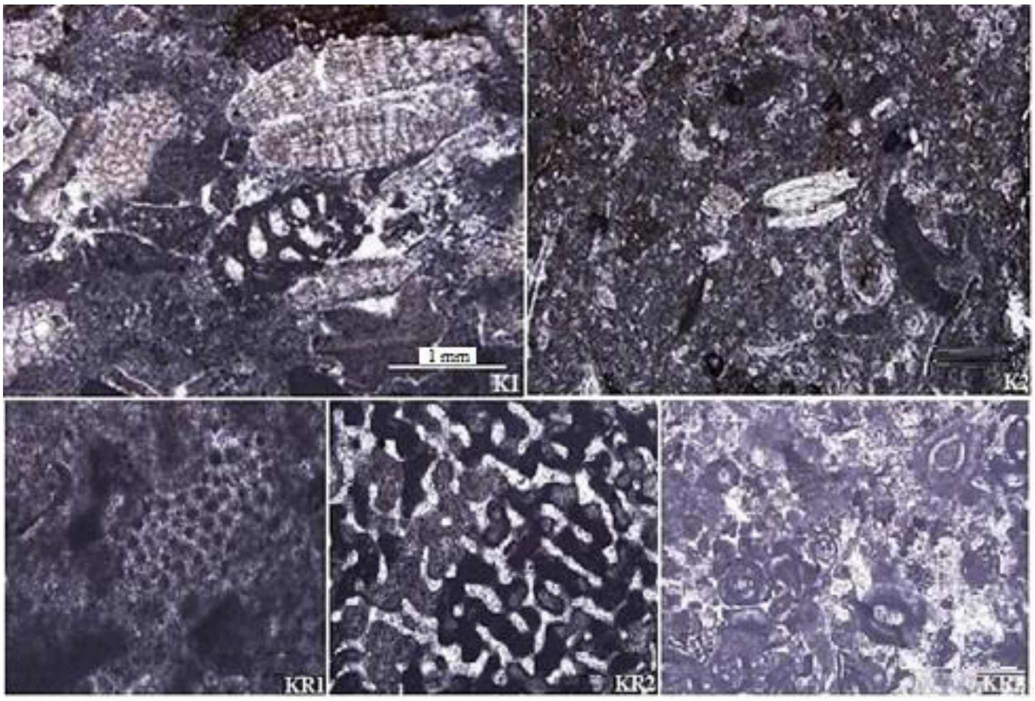

Fig 9. Microfacies types of the Asmari Formation (Kaka-Reza section): MF K1 (Bioclastic miogypsinid packstone-grainstone) (Sample. 2), MF K2 (Bioclastic packstone-grainstone) (Sample. 45), MF KR1 (Peloidal packstone-grainstone) (Sample. 36), MF KR2 (Algal coral boundstone) (Sample. 28), MF KR3 (Bioclastic imperforate foraminiferal wackestone- packstone) (Sample. 48).

Facies related to the inner ramp (lagoon)

Facies analysis, allows the recognition of three microfacies (KR):

Microfacies KR1 (Peloidal packstone-grainstone)

In this microfacies type, the peloids make up 40 to 50 percent of the main components. The peloids have different shapes from sub-angular to relatively round, do not show sorting and texture ranges from micritic to sparite. The minor components of this microfacies type are small foraminifera, with an amount of 3 to 4 percent. The restricted conditions are characterized by the absence of normal marine biota, abundance of peloids and very rare skeletal fauna (Geel 2000; Romero et al. 2002). This microfacies type has also been recognised in other sections of the Asmari Formation (Amirshahkarami et al. 2007; Rahmani et al. 2009; Vaziri-Moghaddam et al. 2010).

Microfacies KR2 (Algal coral boundstone)

The bulk of this facies consists of massive limestone that is formed by abundant coral and algae. In other words, this facies mainly consists of coral colonies, which usually are trapped by algae. The facies is associated with algal boundstone and is formed in the lagoon. In addition, the facies is also in patchy form or Patch reefs. These form in the inner ramp (Baceta et al. 2005).

Microfacies KR3 (Bioclastic imperforate foraminifera wackestone-packstone-grainstone)

The main components of this microfacies type are benthic foraminifera with imperforate walls such as *Austrotrillina, Dendritina, Meandropsina,* and miliolids. Their texture is represented by wackestone-packstone-grainstone. Other bioclasts are crinoids, echinoidsspines and bivalve fragments.In this facies, grains are poorly sorted and medium size, as well as round to sub-angular in shape. The existence of abundant imperforate benthic foraminifera indicates deposition in a restricted shelf lagoon with high salinity conditions (Geel 2000; Romero et al. 2002). This microfacies type has also been reported in other sections (Amirshahkarami et al. 2007; Rahmani et al. 2009; Vaziri-Moghaddam et al. 2010). The presence of foraminifera such as *Borelis* in many environments indicates warm conditions (Halfar et al. 2004).

Facies related to the mid ramp (Open marine)

Facies analysis, allows the recognition of two microfacies types (K):

Microfacies K4 (Bioclastic packstone-grainstone)

This microfacies type is characterised by bioclasts of small benthic foraminifera, crinoids, corallinacean red algae, bivalve fragments and echinoids spines in a packstone-grainstone depositional texture. The grains have good sorting and low micrite content. The depositional texture is predominantly grainstone, and at some samples is packstone-grainstone. These facies is formed in a middle ramp environment. Here, the middle ramp is characterised by bioclasts in a skeletal packstone-grainstone texture. This evidence suggests a shallow water depositional setting above the wave base (Flügel 2004 and 2010).

Microfacies K5 (Bioclastic miogypsinids packstone-grainstone)

The microfacies is characterized by the perforate benthic foraminifera that are located in a packstone-grainstone texture. The main skeletal grains mainly consist of *Miogypsina*, but there are benthic foraminifer such as *Elphidium* and *Nummulites*. Other skeletal components are crinoids, bryozoans and echinoids. The minor elements in this microfacies type are imperforate foraminifera such as miliolids and *Peneroplis* less than 10%. Due to the fossil contents of this facies, its sedimentary environment is in the upper slope (offshore) with a low to medium energy (Beavington-Penney and Racey 2004). Recent studies by Halfar et al. (2004) and Seyrafian et al. (2011) show that benthic foraminifera such as *Nummulites*, *Peneroplis* and miliolids are formed in warm climates. The presence of foraminifera such as *Miogypsina* indicates proximal mid ramp environment (Bassi et al. 2007).

3.4. Depositional models

The faunal data and petrographic studies obtained from the studied sections allow biostratigraphic studies and microfacies types to be used to interpret environmental conditions. The interaction of various factors including carbonate producing biotas, relative sea level changes and the sediment distribution processes extensively influence the carbonate platform establishment (Einsele 2000; Pomar et al. 2004; Allahkarampour Dill et al. 2017). The Asmari carbonate platform was formed in the studied sections on dolomitic limestone of Shahbazan Formation. In fact, progressive infilling of the basin led to the prograding of the Asmari platform over the Shahbazan Formation. In this regard, the recognition of microfacies types and their position in the carbonate sequence, together with the analysis of skeletal components, allows each facies to be attributed to a specific depositional setting. In the Makhmal-Kuh section, carbonate platform is usually characterized by uniform carbonate production by large benthic foraminifera and red algae above the optical zone as well as planktic foraminifera below the optical zone. In other words, based on the detailed facies analysis as well as the dependence of the creatures on light, the ramp is divided into three parts: inner ramp, middle ramp and outer ramp. Accordingly, microfacies analysis has determined several sedimentary environments including open marine and lagoon setting in the Asmari Formation at the Makhmal-Kuh section. Therefore, the sedimentary model of Asmari Formation which is formed from Rupelian to Aquitanian in this area is as follows: 1) inner ramp/euphotic and mesophotic zones, 2) mid ramp/oligophotic zone, 3) outer ramp/aphotic zone or deep zone (Figs 10, 11).

1) The inner ramp is characterized by a wackestone-packstone facies containing foraminiferal assemblages. On the inner ramp there are two facies areas, the inner shallow part and the deeper outer area. The internal shallow area is characterized by the presence of abundant imperforate benthic foraminifera, and mollusc from shallow depths with sufficient energy. The deeper parts of the inner ramp have a large accumulation of coralline red algae (e.g., *Lithothamnion*) as well as benthic foraminifera such as *Elphidium* and *Amphistegina*. Coralline red algae exhibit their greatest species richness during the Oligocene with increasing diversity and become the dominant carbonate producers during the early Miocene (Aguirre et al. 2000; Rasser and Piller 2004; Halfar and Mutti 2005). These assemblages represent deposition in shallow waters of the euphotic-mesophotic zone. Large foraminifera can live only in shallow sea floors and oligotrophic environments (Hottinger 1983; Hallock 1985; Langer and Hottinger 2000). The predominance of larger foraminifera in all facies, indicates sedimentation in warm water and oligotrophic conditions in the euphotic zone. From the inner ramp to the mid ramp ormore depth, red algal communities show a gradual decline. Moreover, the presence of species such as *Lepidocyclina, Borelis, Amphistegina, Elphidium* and *Miogypsina* together with corals in all of the fauna assemblages indicates a euphotic to mesotrphic environment in the tropical realm.

2) Oligophotic conditions are caused by a decrease in the amount of light entering the basin in the middle ramp. Coralline red algae and benthic foraminifera with thin and elongated tests such as *Operculina, Amphistegina*, with echinoid, bryozoan fragments and molluscs form middle ramp facies assemblages.

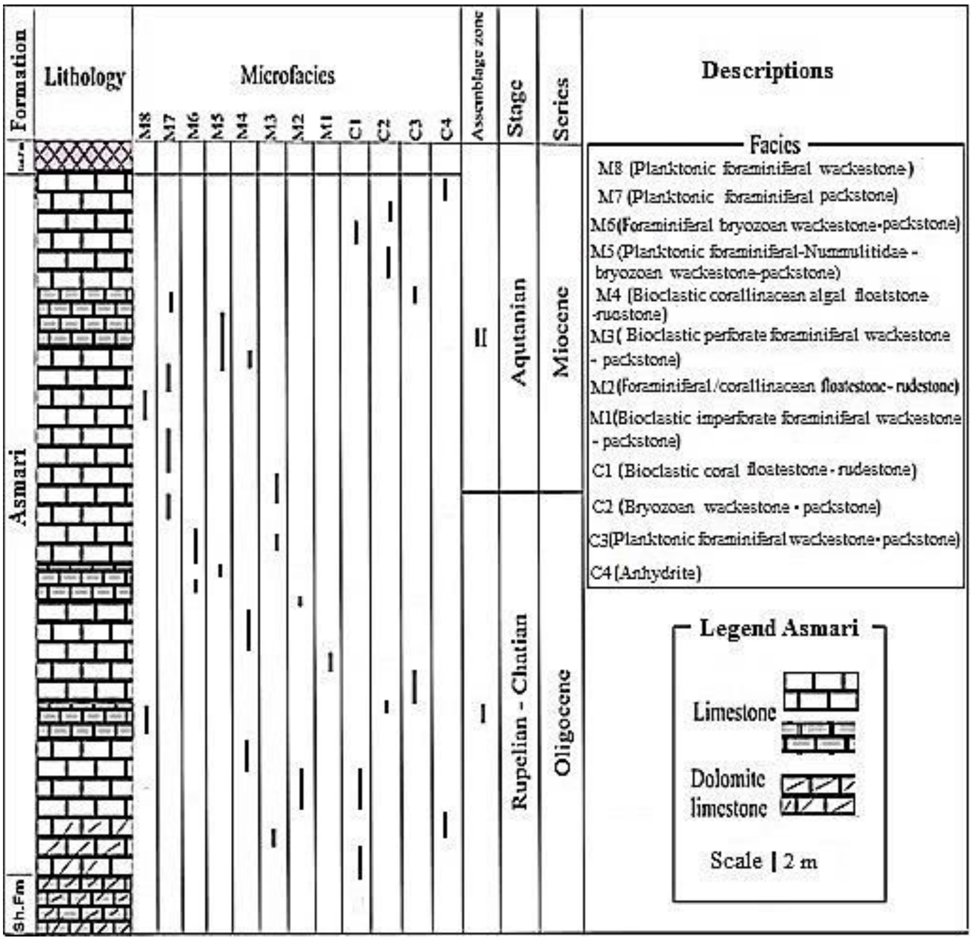

Fig 10. Vertical facies distribution of the Oligo-Miocene sediments, Makhmal-Kuh section, Zagros Basin.

In the middle ramp, large perforate foraminifera (*Amphistegina, Operculina, Heterostegina*), red algae, echinoids and bivalve fragments, along with a high percentages of clay, represent a sedimentary environment below the wave base and oligophotics conditions.

Towards the deeper parts, the facies is altered by small perforate benthic foraminifera, increasing the amount of molluscs and bryozoans, and increasing abundance of planktic foraminifera. Simultaneous occurrence of *Nummulites* and planktic foraminifera indicates the deepest environments below the photic zone, most likely in a slope environment. Since, according to Hottinger (1997), *Nummulites* inhabit in the deepest environment among the observed components. Thus, *Nummulites* packstone–wackestone texture was deposited below the FWWB. The abundance of deeper foraminifera such as *Nummulites* suggests sedimentation in the oligophotic zone of the middle ramp, which depends on the amount of nutrients entering the basin.

3) The outer ramp environment is characterized by the predominance of light-independent fauna (Bryozoa) and planktic foraminifera. The environment is divided into two parts: a) the shallower environment in the outer ramp, which is affected by bryozoans and has a lesser amount of the planktic foraminifera, b) facies belonging to a deeper environment, which includes sediments dominated by planktic foraminifera (*Globigerinoides*), echinoid, and deep benthic foraminifera. These are the most important components of the outer ramp. The presence of *Uvigerina* and *Bulimina*, especially in the sub-facies M6-M8 indicates low oxygen conditions in the deeper part (Bahr et al. 2014). Therefore, the absence of light-dependent biota such as corallinacea as well as the species *Borelis*, *Lepidocyclina (Eulepidina, Nephrolepidina)*, *Miogypsina*, indicates that depositional environment was developed under aphotic conditions in an outer ramp. The study of assemblage zones in the studied section indicates that the Zagros Basin was low latitude during the Oligo-Miocene.

Also, in the Kaka-Reza section, accurate facies analysis allows the interpretation of the carbonate environment, including the inner and mid ramps in the Asmari Formation (Figs 11, 12). The paleoenvironment is interpreted as the environment of hemoclinal ramp, which includes mid ramp dominated by *Miogypsina*, *Nummulites*, *Elphidium*, and *Peneroplis* with low-to medium energy and with packstone and grainstone textures at the upper slope up to the inner ramp dominated by peloids, patch reefs, miliolids, imperforate foraminifera (such as *Borelis, Austrotrillina, Dendritina*) along with wackestone, packstone and grainstone textures that indicate the lagoon setting. Therefore, in this section, the inner ramp is characterized by lagoonal microfacies which include benthic foraminifera and low fauna diversity. Also, the mid ramp microfacies are observed, but the outer ramp facies were not recorded in the studied section. Hence, the depositional model of Asmari Formation formed in the Rupelian interval is a homoclinal ramp that includes inner ramp and mid ramp. In fact, the sedimentation of the Asmari Formation in the Kaka-Reza section started with a mid ramp, which then turned into an inner ramp by reducing the depth of the basin.

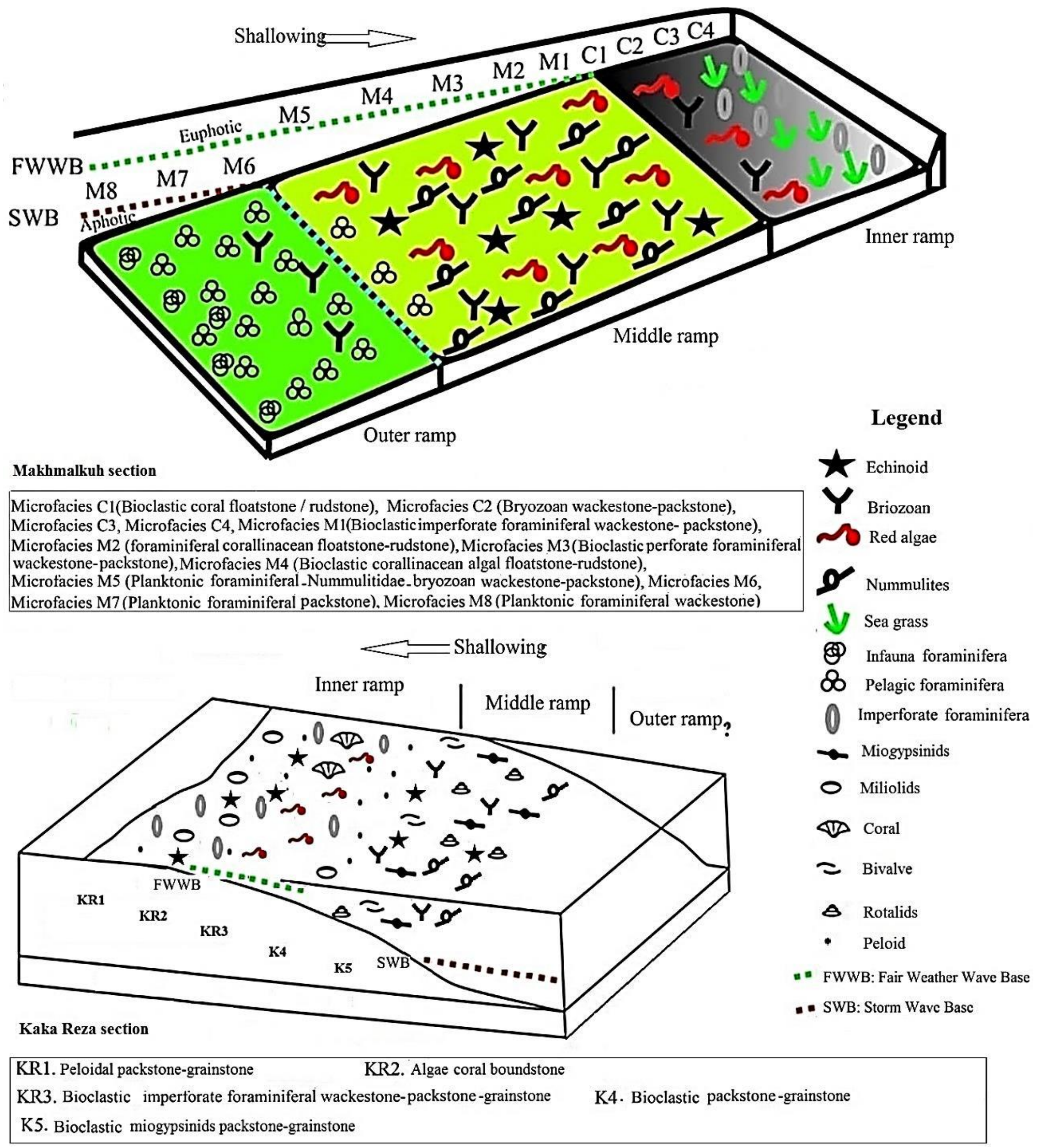

Fig 11. Depositional sub-environments of the Asmari Formation, Makhmal-Kuh and Kaka-Reza sections (Lorestan Province).

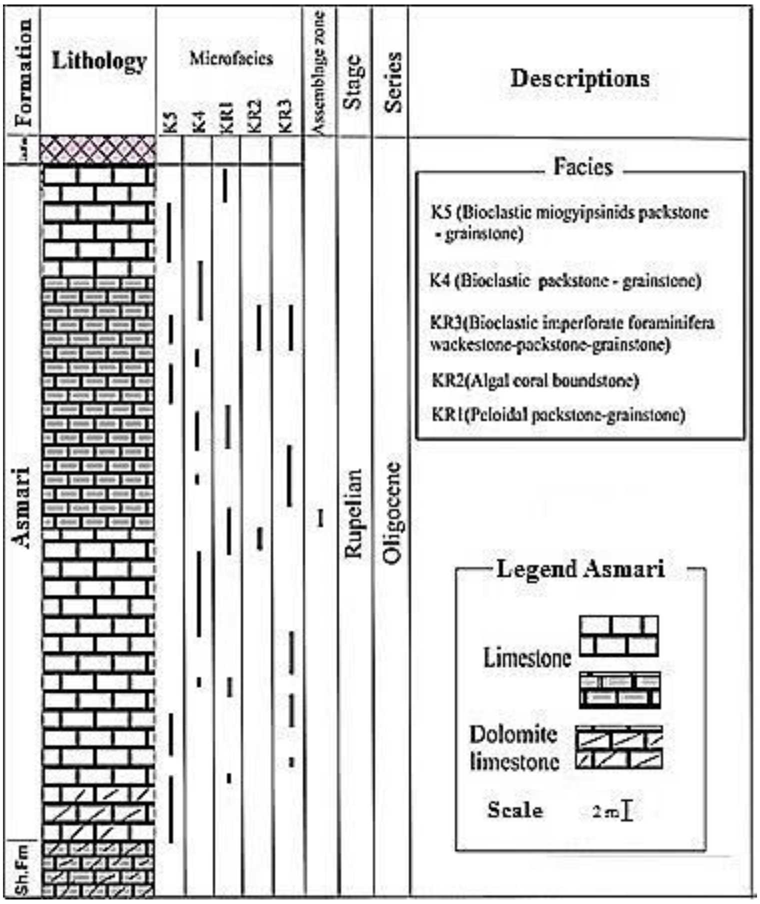

Fig 12. Vertical facies distribution of the Oligo-Miocene sediments, Kaka-Reza section (Zagros Basin).

3.5. Comparison and evaluation

The biostratigraphic study of the Asmari Formation has been performed by different geologists in several parts of the Zagros Basin, which has led to the offer of different age ranges (e.g., Kimiagari 2006; Amirshahkarami et al. 2007; Rahmani et al. 2009; van Buchem et al. 2010; Vaziri-Moghaddam et al. 2010; Parvaneh nejad Shirazi et al. 2012; Taheri et al. 2017; Monjezi et al. 2019). In the present study, the Asmari Formation in the Kaka-Reza and Makhmal-Kuh sections, along with the Mamulan and Kabir Kuh sections in the west of Khoram Abad, as well as Tang-e Gurgoda section in the Dezful Embayment are compared (van Buchem et al. 2010; Vaziri-Moghaddam et al. 2010) (Fig 13). In the Makhmal-Kuh section, the Asmari Formation has been deposited from the early Oligocene (Rupelian) to early Miocene (Aquitanian). Also, in the Kaka-Reza section, this formation was deposited only in the Rupelian age. According to Vaziri-Moghaddam et al. (2010), the Asmari Formation is deposited in the Kabir Kuh section in the late Oligocene (Chattian)-early Miocene (Burdigalian) and in the Mamulan section in the Burdigalian (early Miocene). Van Buchem et al. (2010) also reported that the Asmari Formation was deposited in the Tang-e Gurgoda section in the Rupelian-Burdigalian (early Oligocene-early Miocene). Therefore, results show that the age range of the Asmari Formation varies in different sections from early Oligocene (Rupelian) to early Miocene (Burdigalian). Here, the results of the study show that the age of the Asmari Formation from Kaka-Reza section to Makhmal-Kuh and then Mamulan section in the central Lorestan becomes younger. In fact, the age changes in deposits of the Asmari Formation in northwestern Zagros (central Lorestan) may reflect changes in the environmental conditions of the area. Also, while the deposition of the Asmari Formation has continued during Rupelian (Kaka-Reza, Makhmal-Kuh and Gurgoda), the section of Mamulan and Kabir Kuh were still site of deposition of the Shahbazan and Pabdeh formations, respectively. Lack of Chattian to Burdigalian sediments in the Kaka-Reza section and Burdigalian deposits at the Makhmal-Kuh section may be due to erosion or non-deposition. Therefore, during the Paleocene-Eocene interval, the pelagic Pabdeh Formation was deposited in the Fars and Khuzestan (southern and central parts). Then, during the middle Eocene, a shallow platform was created due to the global sea level decline. The sea level fall continued to the early Oligocene, until in this areas of the Zagros Basin, the Asmari Formation was replaced by the Pabdeh Formation (Motiei 1994; Alavi 2004). In the central part of the Zagros (Khuzestan Province/Tang-e Gurgoda section) the Asmari Formation was formed in the Oligocene (Rupelian) and extends to the early Miocene. These conditions started with delay in the northwestern part of the Zagros Basin (parts of Lorestan province/ Kabir Kuh and Mamulan sections) and continued up to the end of the Burdigalian age.

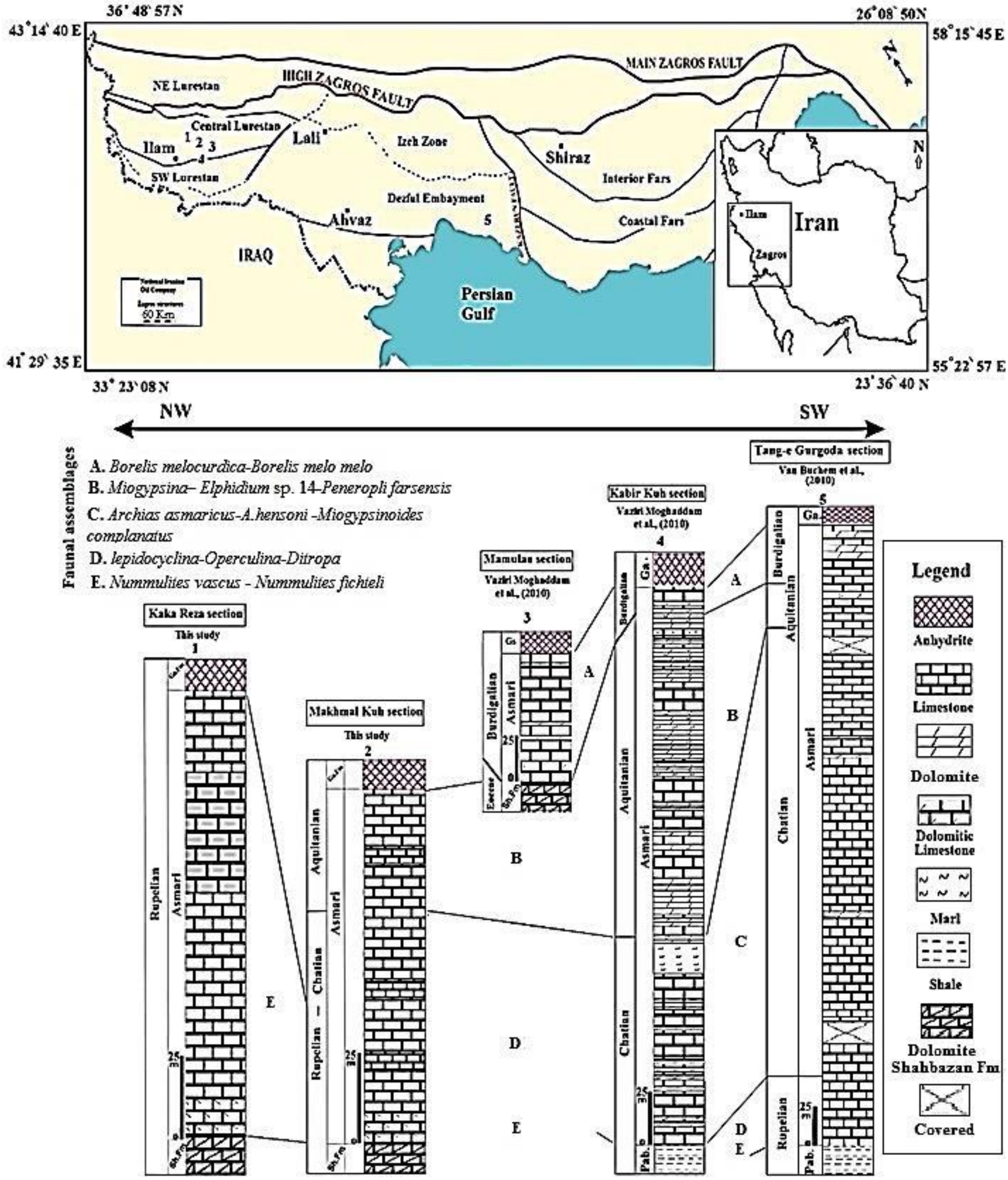

Fig 13. Correlation of the Asmari Formation at the Makhmal-Kuh and Kaka-Reza sections with some others in the Zagros Basin.

4. Conclusion

The Asmari Formation was studied in the stratigraphic sections of Makhmal-Kuh and Kaka-Reza to determine the exact age and characteristics of their sedimentary environment in the Lorestan province. Based on biostratigraphic data, two assemblage zones were recorded in the Makhmal-Kuh section. The first assemblage is *Eulepidina – Nephrolepidina – Nummulites*, which is considered to be Oligocene in age. The presence of *Nummulites, Eulepidina* along with *Nephrolepidina*, indicates Rupelian to Chattian interval. The presence of *Nummulites* species indicates the age of Rupelian. The second assemblage is *Miogypsina–Elphidium* sp. 14, which indicates the early Miocene (Aquitanian) age. These faunal assemblages are correlated with the SB22, SB23 and SB24 zones in the Mediterranean basin. In this study, two different environments in the Makhmal-Kuh section were identified based on microfacies type analysis, which include the lagoon and the open marine. Based on the evaluation of the microfacies types and their comparison with the standard microfacies belts, it was found that the Asmari carbonate system is composed in the homoclinal ramp, which includes the inner, mid and outer ramps. These environments were under euphotic-mesophotic, oligophotic and aphotic conditions. In the Kaka-Reza section, the only zonal assemblage identified is the *Nummulites* Total Range Zone, which is early Oligocene (Rupelian) in age. In this section, microfacies type analysis allows the interpretation of carbonate environments including the middle and inner ramps in the Asmari Formation. So that, sedimentation begins with the middle ramp, and subsequently becomes an inner ramp with reducing basin depth. Here, considering the time of sedimentation of the Kaka-Reza and Makhmal-Kuh sections, it seems that the Kaka-Reza section was out of water throughout Chattian to Aquitanian, while the Makhmal-Kuh section was still being deposited at this time. Moreover, the presence of *Lepidocyclina, Miogypsina, Heterostegina,* and *Operculina* with Corallinacea in the Asmari Formation is the most important biotic assemblage that suggests tropical realm in this basin.

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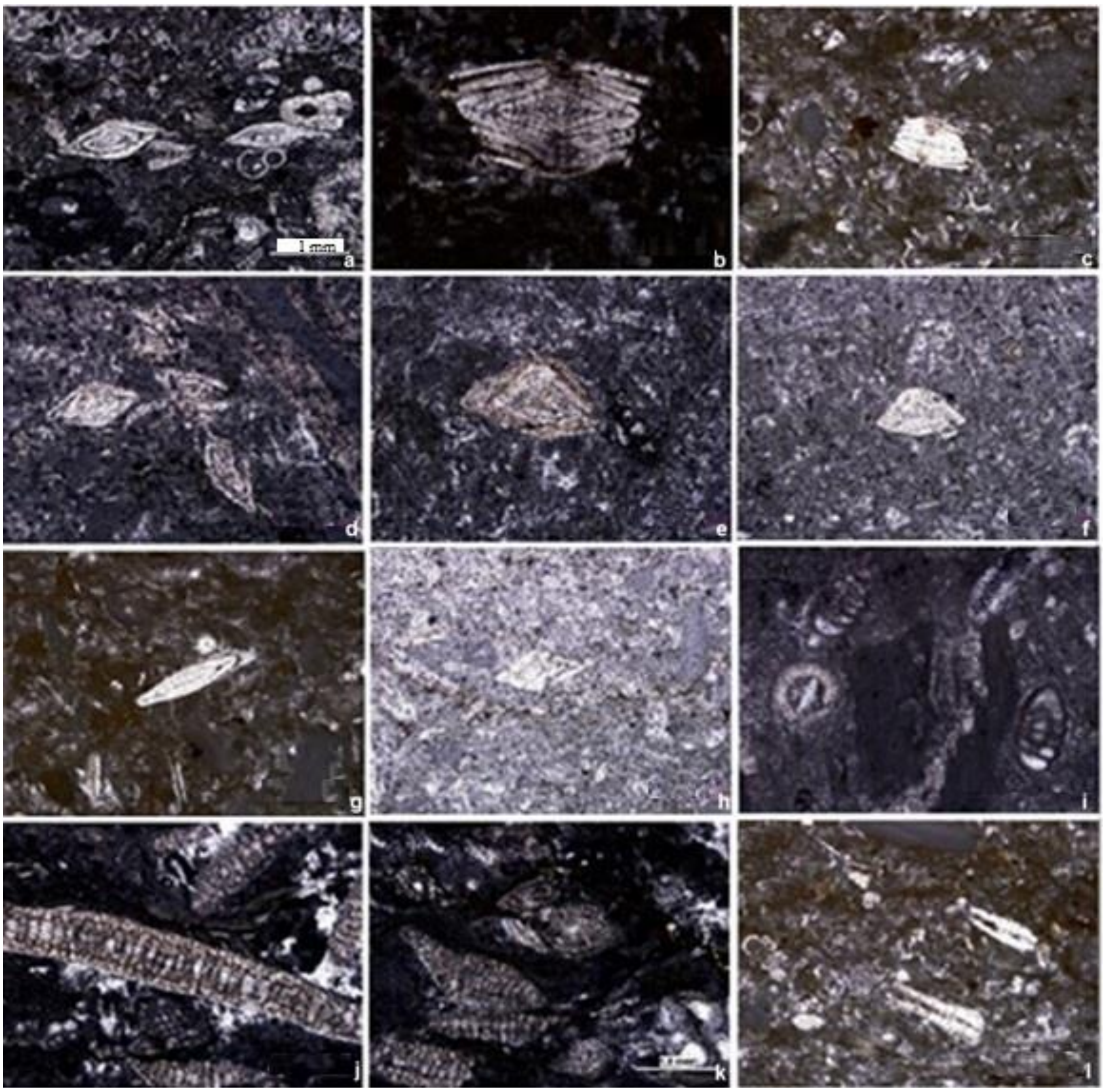

Plate MK1. Some benthic foraminifers identified in the Makhmal-Kuh section. a. *Nummulites* cf. *vascus* (Sample No. 2), b. *Nummulites intermedius* (Sample No. 3), c. *Nummulites* cf. *fichtelli* (Sample No. 3), d. *Nummulites* sp. (Sample No. 28), e. *Amphistegina* sp. (Sample No. 29), f. *Amphistegina* sp. (Sample No. 43), g. *Assilina* sp. (Sample No. 3), h. *Nummulites* sp. (Sample No. 51), i. *Elphidium* sp. (Sample No. 51), j. *Eulepidina* sp. (Sample No. 8), k. *Nephrolepidina* sp. (Sample No. 8), l. *Heterostegina* sp. (Sample No. 3).

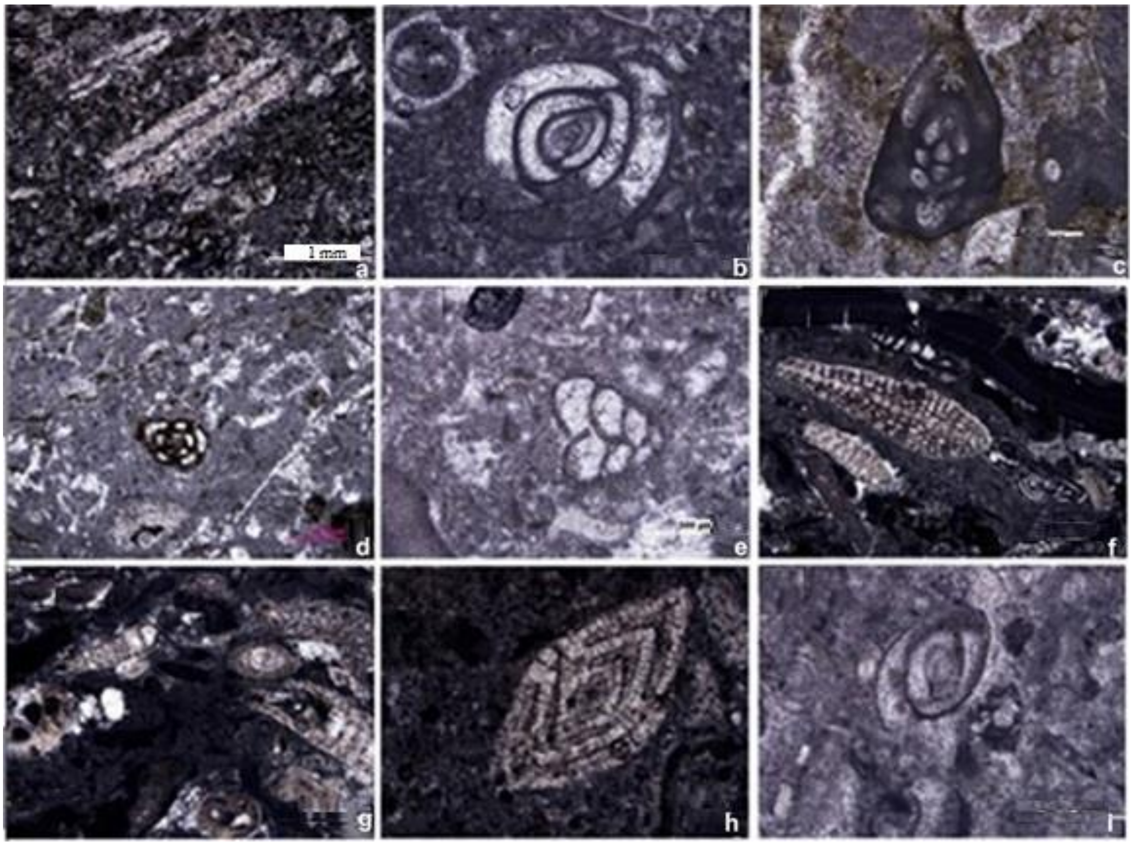

Plate MK2. Some benthic foraminifers identified in the Makhmal-Kuh section. a. *Operculina* sp. (Sample No. 49), b. *Pyrgo* sp. (Sample No. 35), c. *Quinqueloculina* sp. (Sample No. 43), d. *Quinqueloculina* sp. (Sample No. 33), e. *Textularia* sp. (Sample No. 47), f. *Miogypsina* sp. (Sample No. 9), g. *Miogypsina* sp. (Sample No. 8), h. *Nummulites* sp. (Sample No. 51), i. Polymorphinidae indet. (Sample No. 33).

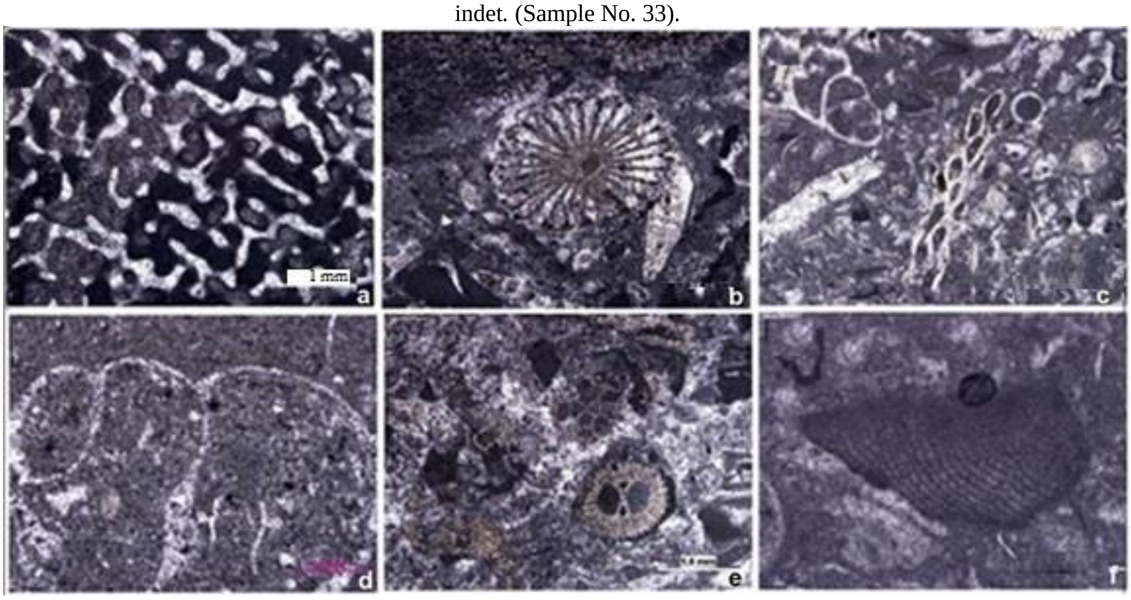

Plate MK3. Some microfossils identified in the Makhmal-Kuh section. a. Coral (Sample No. 28), b. Echinoid (Sample No. 9), c. Bryozoa (Sample No.40), d. Gastropod (Sample No. 22), e. *Tubicellaria* sp. (Sample No. 25), f. Red algae (Sample No. 32).

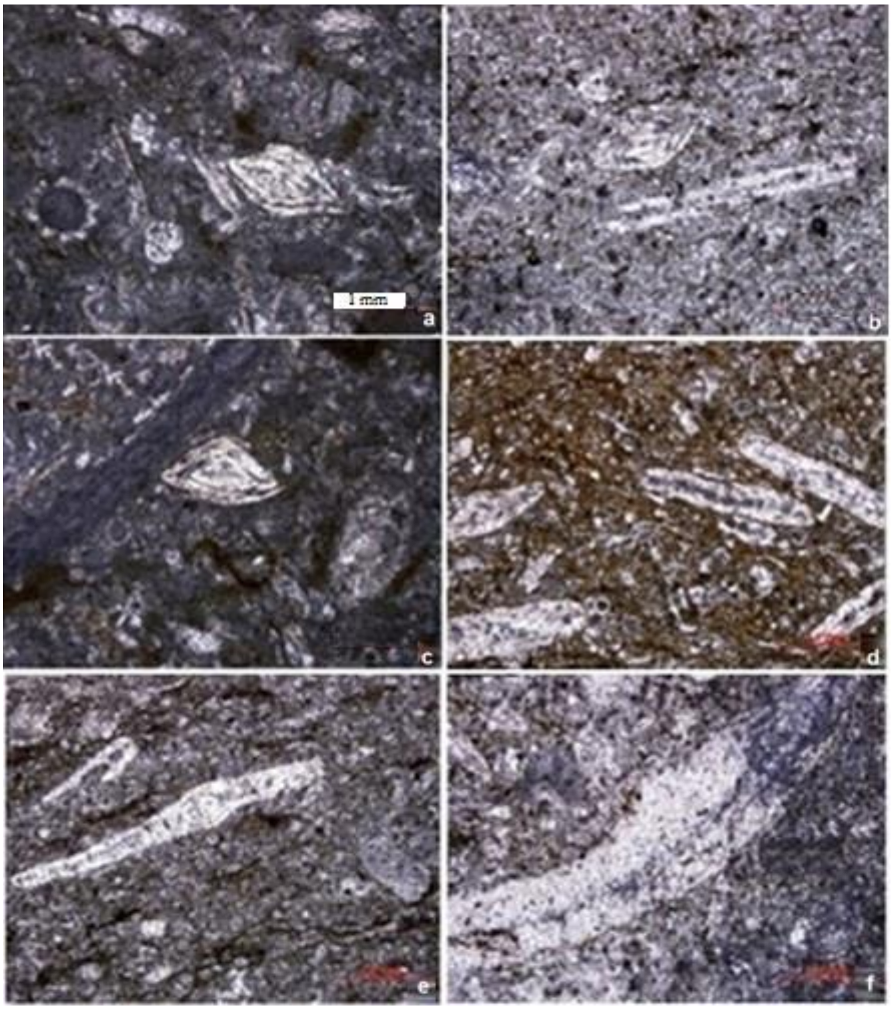

Plate KR. Some microfossils identified in the Kaka-Reza section. a. *Nummulites* cf. *fichtelli* (Sample No. 84), b. *Nummulites* aff. *atacicus* (Sample No. 62), c. *Amphistegina* sp. (Sample No. 84), d. *Heterostegina* sp. and *Operculina* sp. (Sample No. 74), e. *Operculina* sp. (Sample No. 63), f. *Operculina* sp. (Sample No.77).