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Article

Biostratigraphy, microfacies and paleoecology of the Asmari Formation, Interior Fars province, Zagros Basin, Iran

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With 9 figures and 3 tables

Abstract: The Pir-Sabz Section of the Asmari Formation is located in the Interior Fars province, Zagros Basin (Iran). The Asmari Formation at the study area is 312 m in thickness and formed by massive bedded limestone. According to the identified index microfossils, three Oligocene assemblage biozones were recorded: 1) *Globigerina* spp., 2) *Lepidocyclina – Operculina – Ditrupa*, and 3) *Archaias asmaricus – Archaias hensoni*. Twelve facies types were recognized according to their texture, occurrence and abundance of foraminifera, scleractinian corals and other skeletal grains: F1 Bioclastic planktonic foraminiferal wackestone–packstone, F2 Bioclastic planktonic foraminiferal echinoid packstone, F3 Bioclastic *Operculina* packstone, F4 Bioclastic Lepidocyclinidae packstone–rudstone, F5 Bioclastic coralline algal Lepidocyclinidae packstone–rudstone, F6 Bioclastic Lepidocyclinidae – Nummulitidae wackestone–packstone–grainstone, F7 Bioclastic Lepidocyclinidae – *Neorotalia* – coral packstone–rudstone, F8 Coral boundstone, F9 Bioclastic porcellaneous foraminifera – coral packstone, F10 Bioclastic coralline algal bryozoan wackestone–packstone, F11 Bioclastic benthic foraminifera (perforate and imperforate) wackestone–packstone, and F12 Bioclastic benthic foraminifera (imperforate) wackestone–packstone. From the base to the top of the section the facies types indicate: F1 aphotic zone and outer shelf; F2 aphotic to oligophotic zones on the outer and middle shelf (distal); F3 and F4 oligophotic zone and distal middle shelf; F5, F6 and F7 mesophotic zone situated on the middle shelf (proximal); F8, F9, F10 and F11 euphotic zone and inner shelf (open marine), F12 euphotic zone and inner shelf (slightly restricted). The Pir-Sabz coral fauna has a clear Mediterranean affinity and is represented by at least six different scleractinian species which formed a non-reefal coral community on the proximal middle-shelf.

Key words: Asmari Formation, Oligocene, benthic foraminifera, scleractinian corals, microfacies.

1. Introduction

The Asmari Formation (Oligocene – Miocene) in the Zagros sedimentary basin is widespread and is of economic interest due to its high reservoir potential for hydrocarbon accumulations. The formation mainly consists of limestone but also dolomitic limestone, dolomite, anhydrite (Kalhur anhydrite) and sandstone (Ahwaz sandstone; Motiei 2001; Fig. 1). The aim of this paper is to present a detailed description of the Asmari Formation from a 312 meter thick section outcropping in the Interior Fars province (Zagros Basin). This section, hereafter called the Pir-Sabz Section, has been studied in terms of biostratigraphy, microfacies, depositional environment and depositional model, with a special focus on benthic foraminifera and scleractinian corals.

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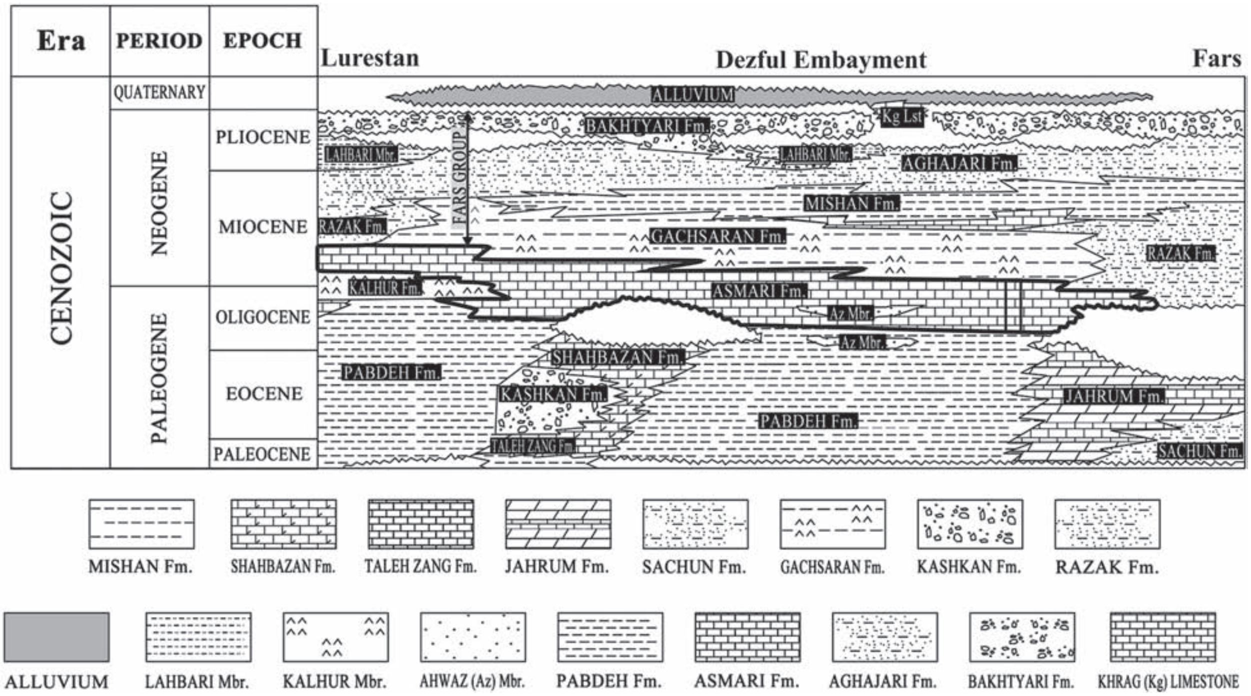

Fig. 1. Cenozoic lithostratigraphy in the Zagros Basin (after Motiei 2001). The location of the study section is marked by a rectangle.

2. Geological setting and location of the Pir-Sabz Section

Based on the sedimentary successions, magmatism, metamorphic processes and plate tectonic units, Iran is subdivided into eight units and include Zagros, Sanandaj-Sirjan, Urumieh-Dokhtar, Central Iran, Kopeh Dagh, Lut and Makran (Berberian & King 1981; Heydari et al. 2003). The Asmari Formation sediments were deposited on a carbonate platform at the margin of the northwestern Zagros sedimentary basin. The sedimentary and structural characteristics subdivide the Zagros Basin into the following units: Lurestan, Fars (Interior and Coastal), High Zagros, Dezful Embayment and Izeh (Falcon 1974; Farzipour-Saein et al. 2009; Fig. 3). With regard to the Zagros sedimentary basin classification, the study area is located in the Interior Fars (Fig. 3a, c).

The first studies on the Asmari Formation have been conducted by Busk & Mayo (1918), Richardson (1924) and Thomas (1948). Further studies include the works of Wynd (1965), James & Wynd (1965), Adams & Bourgeois (1967), Kalantari (1986) and Motiei (1993). Recent studies have improved our knowledge on the biostratigraphy of the Asmari Formation (Sadeghi et al. 2010; Seyrafian et al. 2011; Saleh & Seyrafian 2013) and the use of strontium isotopes shed new light on the stratigraphical framework (Ehrenberg et al. 2007; Laursen et al. 2009; van Buchem et al. 2010). Recent research on the microfacies, depositional environments and paleoecology of the Asmari Formation have been conducted by Fakhari et al. (2008), Rahmani et al. (2009), Mossadegh et al. (2009), Vaziri-Moghaddam et al. (2010), Avarjani et al. (2015), Shabafrooz et al. (2015), and Taheri et al. (2017).

The study area is located at the northeastern flank of the Dashtak anticline, 38 km north of Kazerun. The Pir-Sabz Section is situated in the Tang-e Chogan area and has the following coordinates: N 29°47’09”, E 51°38’03”. The study section is next to the Pir-Sabz village (Fig. 3b), where the Asmari Formation is well-exposed. It gradually replaces shales of the Pabdeh Formation. Despite the widespread exposure of the overlying evaporitic Gachsaran Formation, the top of the study formation is slightly covered by alluvium (Fig. 2). This section comprises greyish thin, medium and thick massive bedded limestones.

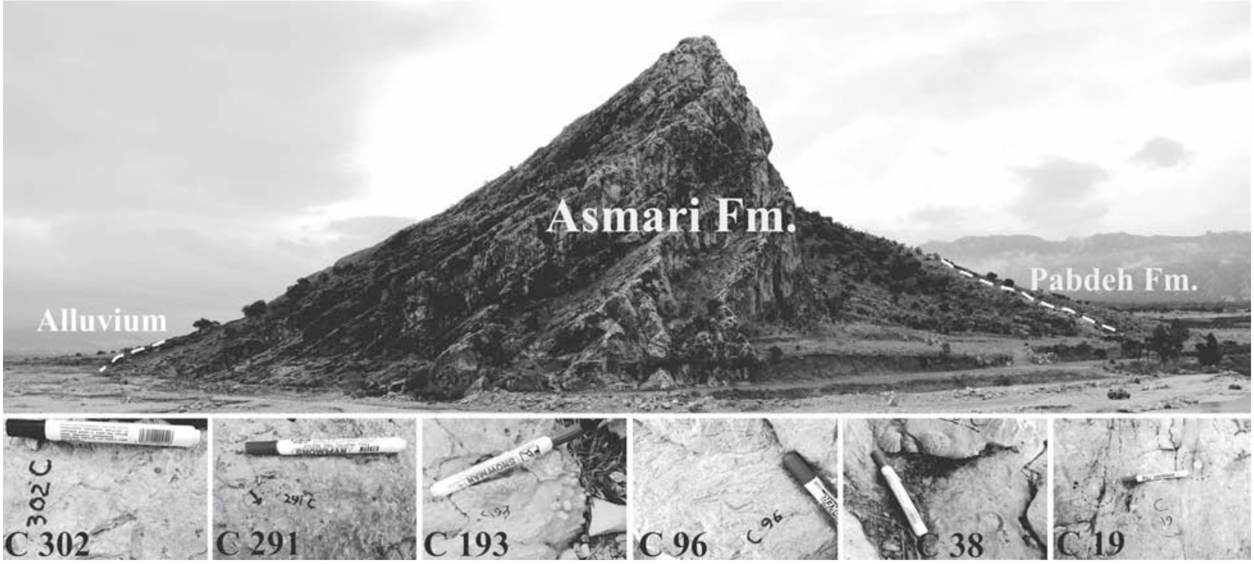

Fig. 2. General view of the Asmari Formation at the study area and the underlying Pabdeh Formation (northeastern flank of the Dashtak anticline, north of Kazerun; view to the southeast).

3. Methods

In addition to section logging, field work included detailed analysis of fossil and facies change studies. Samples were taken in 1 to 2 meter intervals. In the laboratory, about 200 thin sections were prepared and studied with an optical microscope. Identification of microfossils, genera and species are based on Adams & Bourgeois (1967), Loeblich & Tappan (1988) and Sirel (2003). Facies textures were identified following the classification of Dunham (1962) and Embry and Klovan (1971). Facies descriptions follow the nomenclature of Wilson (1975) and Flügel (2010). Paleoecological and paleoenvironmental interpretations of foraminiferal assemblages follow Beavington-Penney & Racey (2004), Boudagher-Fadal (2008), and Boukhary et al. (2008), among others.

3. Results

3.1. Revised biostratigraphy

The biostratigraphy of the Asmari Formation was first studied by Thomas (1948) using larger benthic foraminifera as index markers. Wynd (1965) introduced and referred the following biozones (zones 55-61) to the Asmari Formation: 55 (*Globigerina* spp.), 56 (*Lepidocyclina – Operculina – Ditrupa*), 57 (*Nummulites intermedius – Nummulites vascus*), 58 (*Archaias operculiniformis*) and 59 (*Austrotrillina howchini – Peneroplis evolutus*) for the Oligocene and zone 61 (*Borelis melo curdica*) for the Miocene (Burdigalian). Adams & Bourgeois (1967) later revised previous studies and presented the following biozonation: *Eulepidina – Nephrolepidina – Nummulites* assemblage zone for the Oligocene, *Miogypsinoides – Archaias – Valvulinid* assemblage zone for the Miocene (Aquitanian), with consideration of two sub-assemblage zones (*Archaias asmaricus – Archaias hensoni and Elphidium* sp. 14 – *Miogypsina*) for the early to middle and middle to Late Aquitanian, respectively, and the *Borelis melo* group – *Meandropsina iranica* assemblage zone for the Burdigalian. The biozones, in association with assemblage zones (Cahuzac & Poignant 1997; Table 1), were based on biostratigraphic studies conducted through the Zagros (Asmari Formation) and Central Iranian basins (Qom Formation). Ehrenberg et al. (2007) again modified previous studies on the basis of information obtained from strontium isotope stratigraphy for the Asmari Formation and presented 5 biostratigraphy events based on index fossils (*Nummulites*, *Spiroclypeus blanckenhorni*, *Miogypsina*, *Archaias* and *Borelis melo curdica*). Later, Laursen et al. (2009) and van Buchem et al. (2010) presented a new biozonation for the Asmari Formation by using the strontium isotope and absolute age dating method (Table 2). In the Pir-Sabz Section of the Asmari Formation, a total of 34 genera of foraminifera were identified. Twenty five taxa were

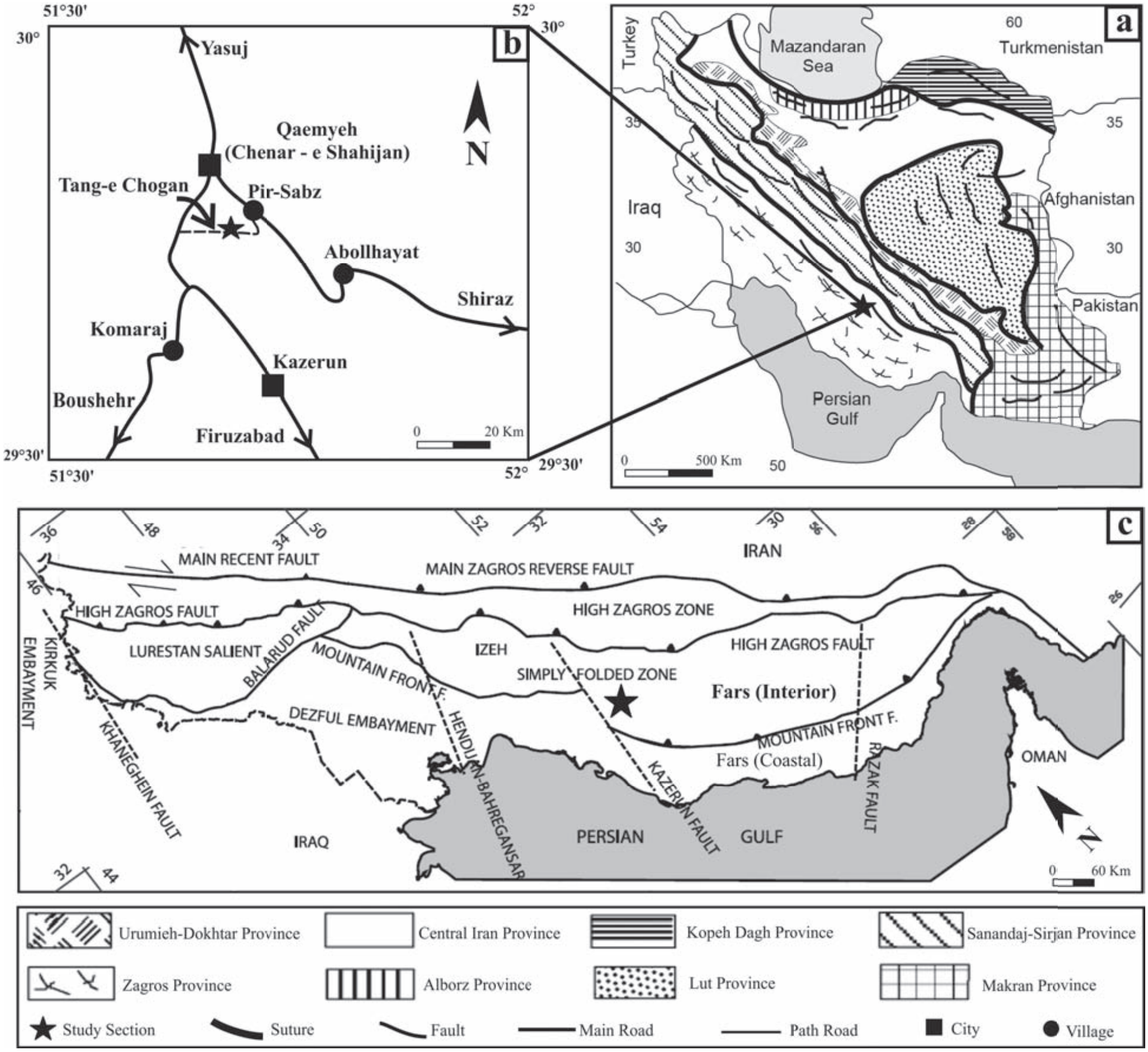

Fig. 3. Geological setting and status of the study section. **a** – Geological units of Iran (after Heydari et al. 2003); **b** – Map of access roads to the study section and **c** – Structural geology of the Zagros Basin (after Farzipour-Saein et al. 2009); The location of the study area is indicated by an asterisk.

identified to species level. This allowed the identification of 3 assemblage zones.

3.1.1. Assemblage zone 1

Assemblage zone 1 occurs at the base of the Pir-Sabz Section, from the top of the Pabdeh Formation and 14 meters into the Asmari Formation. This zone is characterized by the presence of abundant specimens of *Globigerina* spp. Other microfossils include *Globigerina* spp., *Ditrupa* spp., *Elphidium* sp. 1, *Elphidium* sp., *Discorbis* sp., *Paragloborotalia* cf. *P. nana*, *Paragloborotalia* cf. *P. siakensis*, *Globoturborotalia* cf. *G. ciperoensi*, *Haplophragmium slingeri*, *Haplophragmium* sp., and *Lenticulina* sp.

The assemblage zone 1 in the Pir-Sabz Section corresponds to the *Globigerina* spp. assemblage zone introduced by Wynd (1965) and Adams & Bourgeois (1967) and to the *Globigerina* spp. – *Turborotalia cerroazulensis* – *Hantkenina* zone of Laursen et al. (2009),

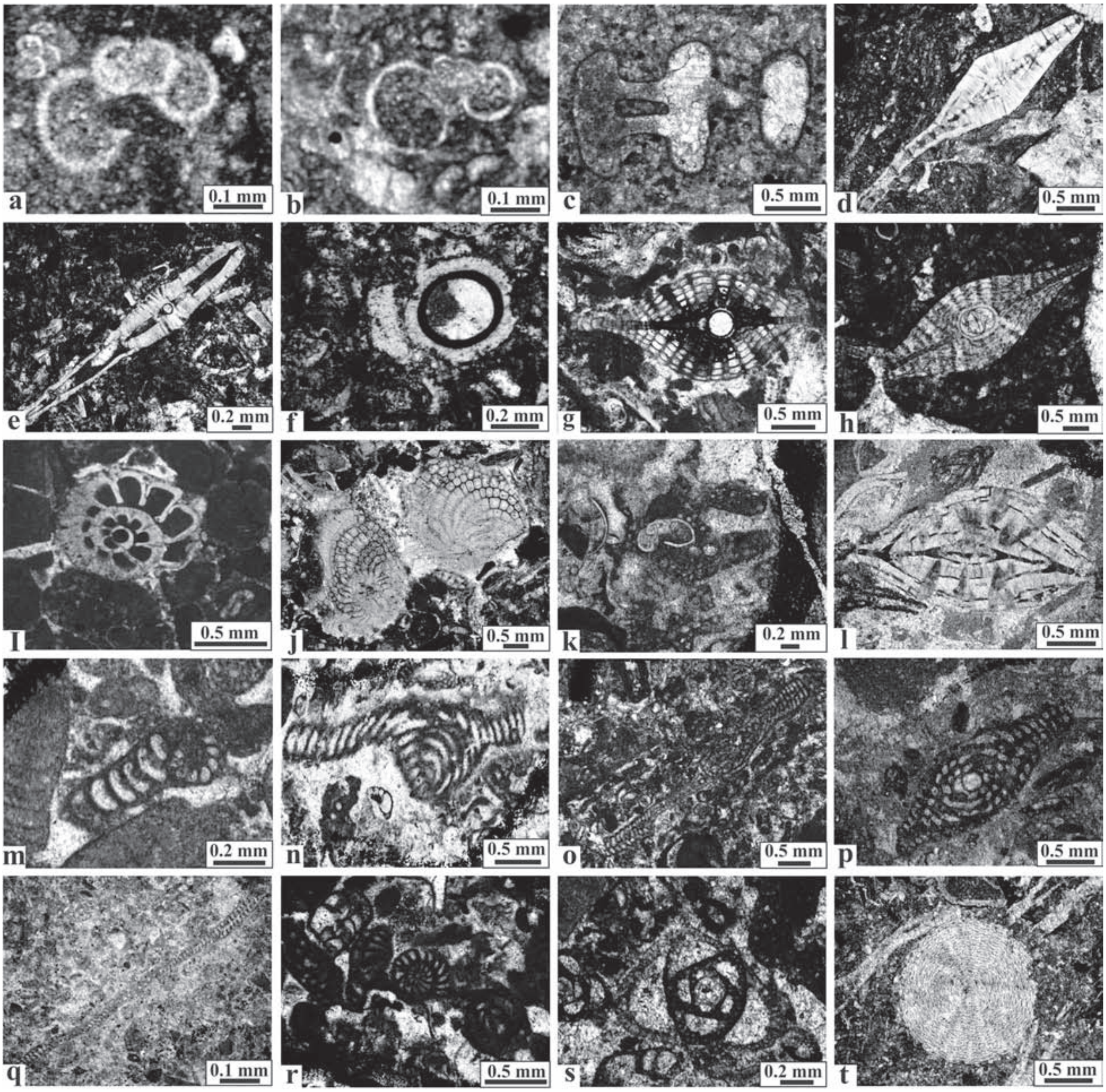

Fig. 4. Microfossils in the Asmari Formation in the Interior Fars area, Zagros Basin, **a** – *Globoturborotalia* cf. *G. ciperoensi*, axial section, sample No. 13C; **b** – *Paragloborotalia* cf. *P. siakensis*, axial section, sample No. 18C; **c** – *Haplophragmium slingeri*, axial section, sample No. 1C; **d** – *Heterostegina* sp., subaxial section, sample No. 193C; **e** – *Operculina complanata*, axial section, sample No. 92C; **f** – *Ditrupa* sp., transverse section, sample No. 92C; **g** – *Nephrolepidina tournoueri*, axial section, sample No. 134C; **h** – *Nephrolepidina* sp., axial section, sample No. 193C; **i** – *Neorotalia viennoti*, equatorial section, sample No. 292C; **j** – left view, *Heterostegina* sp., parallel section, right view, *Heterostegina* cf. *H. praecursor*, equatorial section, sample No. 118C; **k** – *Discorbis* sp., axial section, sample No. 202C; **l** – *Spiroclypeus* sp., subaxial section, sample No. 288C; **m** – *Spirolina* cf. *S. cylindracea*, transverse section, sample No. 252C; **n** – *Peneroplis* cf. *P. thomasi*, oblique section, sample No. 248C; **o, p** – *Archaias* sp., subaxial section, sample No. 278C; **q** – *Meandropsina* cf. *M. iranica*, axial section, sample No. 284C; **r** – *Peneroplis farsensis*, transverse section, sample No. 286C; **s** – *Austrotrillina* cf. *A. howchini*, transverse section, sample No. 212C; **t** – *Sphaerogypsina globulus*, equatorial section, sample No. 274C.

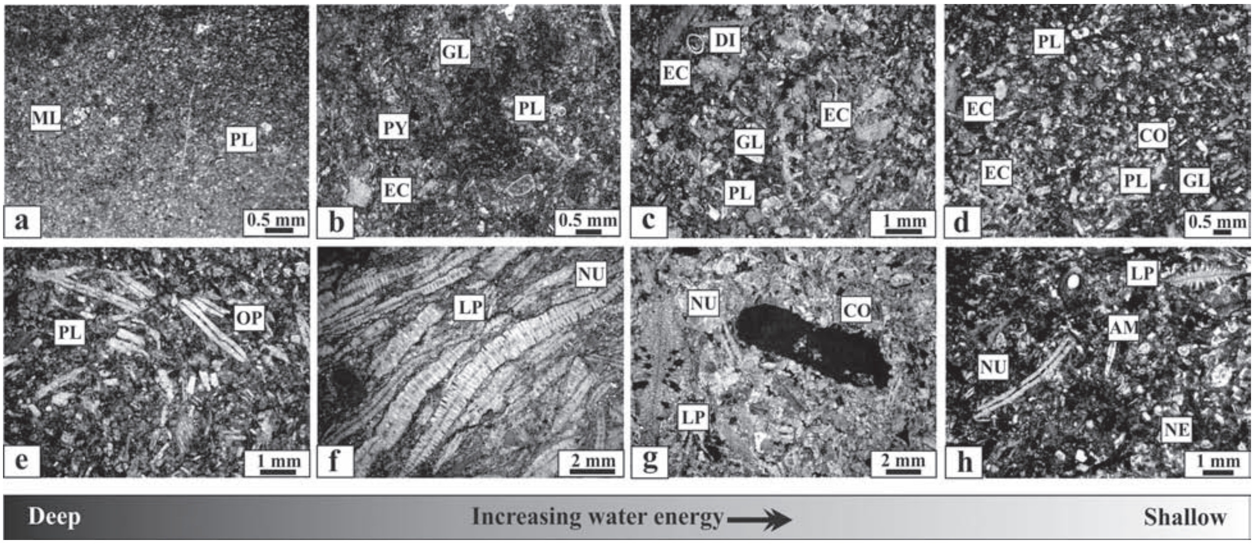

Fig. 5. Microfacies of the Asmari Formation in the studied section: **a, b** – F1, Bioclastic planktonic foraminifera wackestone–packstone, sample No. C3 and C11; **c, d** – F2, Bioclastic planktonic foraminifera echinoid packstone, samples No. C32 and C34; **e** – F3, Bioclastic *Operculina* packstone, sample No. C30; **f** – F4, Bioclastic Lepidocyclinidae packstone/rudstone, sample No. C96A; **g** – F5, Bioclastic corallinacean Lepidocyclinidae packstone–rudstone, sample No. C109; **h** – F6, Bioclastic Lepidocyclinidae Nummulitidae wackestone–packstone–grainstone, sample No. C92A; (ML: miliolids, PL: planktonic foraminifera, GL: glauconite, PY: pyrite, EC: echinoid, DI: *Ditrupa*, CO: coralline algae, OP: *Operculina*, NU: Nummulitidae, LP: Lepidocyclindae, AM: *Amphistegina*, NE: *Neorotalia*, CR: coral, CR: bryozoan, GA: gasteropod, PN: *Peneroplis*, AR: *Archaias*, BI: bivalve).

and is of Oligocene age (Tables 1, 2). The presence of *Paragloborotalia* cf. *P. siakensis* in assemblage 1 is indicative for a Late Chattian age (Boudagher-Fadel 2012).

3.1.2. Assemblage zone 2

Assemblage zone 2 covers the range from 14 to 276 meters of the Asmari Formation. The zone is characterized by the occurrence of *Globigerina* spp., *Paragloborotalia* cf. *P. siakensis*, *Ditrupa* spp., *Eulepidina dilatata*, *Eulepidina elephantina*, *Eulepidina* sp., *Nephrolepidina tournoueri*, *Nephrolepidina* sp., *Lepidocyclina* sp., *Heterostegina assilinoides*, *Heterostegina costata*, *Heterostegina* cf. *H. praecursor*, *Heterostegina* sp., *Operculina complanata*, *Operculina* sp., *Neorotalia viennoti*, *Neorotalia* sp., *Elphidium* sp. 1, *Elphidium* sp., a valvulinid taxon, *Haplophragmium slingeri*, *Haplophragmium* sp., *Lenticulina* sp., *Planorbulina* sp., textulariids, *Amphistegina* sp., *Discorbis* sp., *Onychocella* sp., *Pyrgo* sp., *Borelis* sp., *Subterranophyllum thomasi*, and *Triloculina* sp. Assemblage zone 2 corresponds to the *Lepidocyclina – Operculina – Ditrupa* assemblage zone of Wynd (1965) and the *Lepidocyclina – Operculina – Ditrupa* assemblage zone of Laursen et al. (2009) and is of Oligocene age (Rupelian–Chattian; Tables 1, 2). As mentioned above, the occurrence of *Paragloborotalia* cf. *P. siakensis* is indicative for a Late Chattian age (Boudagher-Fadal 2012). Therefore, assemblage 2 is also considered to be of Late Chattian age.

3.1.3. Assemblage zone 3

Assemblage zone 3 corresponds to the remaining upper part of the Pir-Sabz Section (from 276 to 312 meters). This zone was determined by the occurrence of *Heterostegina* sp., *Austrotrillina asmariensis*, *Austrotrillina howchini*, *Austrotrillina* sp., *Archaias asmaricus*, *Archaias kirkukensis*, *Archaias* sp., *Peneroplis evolutus*, *Peneroplis farsensis*, *Peneroplis thomasi*, *Peneroplis* sp., *Neorotalia viennoti*, *Neorotalia* sp., *Elphidium* sp. 1, a valvulinid taxon, *Triloculina trigonula*, *Triloculina* sp., *Borelis haueri*, *Borelis* sp., *Discorbis* sp., *Meandropsina iranica*, *Meandropsina anahensis*, *Meandropsina* sp., textulariids, *Bigenerina* sp., *Amphistegina* sp., *Planorbulina* sp., *Pyrgo* sp., Gastropoda, *Spiroclypeus* sp., *Spirolina* cf. *cylindracea*, *Spirolina* sp., *Tubucellaria* sp., and *Sphaerogypsina globulus*. Assemblage zone 3 corresponds to the *Archaias operculiniformis* subzone of Wynd (1965) and to the *Archaias asmaricus – A. hensoni – Miogypsinoides complanatus*

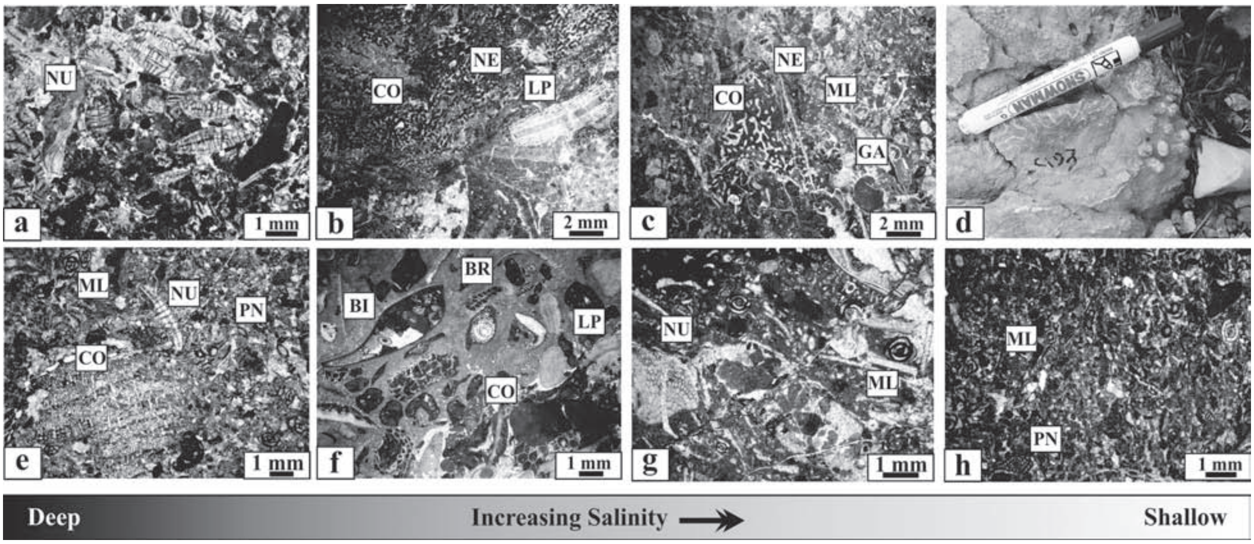

Fig. 6. Microfacies of the Asmari Formation in the studied section; **a** – F6, Bioclastic Nummulitidae packstone–grainstone; sample No. C118, **b** – F7, Bioclastic Lepidocyclinidae *Neorotalia* coral packstone/rudstone, sample No. C113; **c** – F7, Bioclastic *Neorotalia* coral packstone–rudstone, sample No. C236A; **d** – F8, Coral boundstone, sample No. C193; **e** – F9, Bioclastic foraminifera (imperforate) coral packstone, sample No. C212; **f** – F10, Bioclastic coralline algal bryozoan wackestone–packstone, sample No. C294; **g** – F11, Bioclastic benthic foraminifera (perforate and imperforate) wackestone–packstone, sample No. C280; **h** – F12, Bioclastic benthic foraminifera (imperforate) wackestone–packstone, sample No. C248B.

assemblage zone of Laursen et al. (2007) and is of Oligocene age (Chattian; Tables 1, 2). As a result of this study, the Asmari Formation in the Pir-Sabz Section of the Interior Fars province (Zagros Basin) is of Oligocene age (Late Chattian; Figs. 4, 7).

3.2. Facies types and depositional environments

Based on the study of 200 thin sections in association with field observations, 12 facies types were recognized in the Asmari Formation at the Pir-Sabz Section. These facies types (F1-F12) were named according to sedimentary texture, assemblages of foraminifera and other skeletal components recorded in thin sections (Dunham 1962; Embry & Klovan 1971; Wilson 1975; Flügel 2010).

F1 Bioclastic planktonic foraminiferal wackestone–packstone

F1 is characterized by fine grained and muddy material and a grain-supported texture. Major elements of this facies are planktonic foraminifera (*Globigerina* and globorotalids without spines). Debris of echinoids, bryozoans, *Neorotalia*, *Haplophragmium*, *Lenticulina*, small miliolids and textulariids are minor elements. Non-skeletal components are represented by very fine quartz, rounded glauconite grains and pyrite in small quantities (Fig. 5a, b).

The presence of abundant planktonic foraminifera and the fine-grained texture reflects a depositional setting in normal marine, deep and low-energy waters in an outer shelf environment (Wilson 1975; Buxton & Pedley 1989; Cosovic et al. 2004; Geel 2000; Flügel 2010). The occurrence of planktonic foraminifera, the lack of benthic symbiont-bearing foraminifers such as Nummulitidae or Lepidocyclinidae, and the absence of coralline algae suggest a deposition below the photic zone (Cosovic et al. 2004; Langer & Hottinger 2000; Fajemila et al. 2015). An autochthonous origin is suggested for rare fragments of smaller miliolid foraminifera. The presence of planktonic foraminifera, a fine-grained sediment texture and the lack of turbidite structures are characteristic for low energy stable environmental conditions (Buxton & Pedley 1989; Cosovic et al. 2004; Flügel 2004).

Petrographical observations of glauconite elements have shown that they occur as individual grains and minute aggregates of green glauconite with an amorphous to hypidiomorphic structure (Harris & Whiting 2000; Chang et al. 2008). Similar glauconite grains occurring on outer shelf environments have been reported from different areas of the Zagros sedimentary basin, where a transitional facies from the Pabdeh to the Asmari formations exists (Lali area: Vaziri-Moghaddam et al. 2006; Chamanbolbol area: Amirshahkarami et al. 2007; Khaviz anticline: Rahmani et al. 2009; northwest of the Zagros sedimentary basin: Vaziri-Moghaddam et al. 2010; Naura anticline: Sooltanian et al. 2011).

F2 Bioclastic planktonic foraminiferal echinoid packstone

The main elements of F2 are echinoids associated with debris of planktonic foraminifera. Minor elements are porcellaneous foraminifera (*Pyrgo* and *Triloculina*), bryozoans, *Ditrupa*, crushed coralline algae, *Haplophragmium*, *Neorotalia* and textulariids. The texture in the F2 packstone is grain-supported. Quartz, glauconite and pyrite, although not frequent, are visible (Fig. 5c, d).

Reduced numbers of planktonic foraminifera and the appearance of small hyaline foraminifera reflect a slight decrease in water depth. The association of planktonic foraminifera and echinoids reveals that the deposition took place in normal marine waters with moderate wave energy (Pedley 1996; Geel 2000; Pomar 2001; Flügel 2010). The absence of larger symbiont-bearing foraminifera suggests a deposition below the photic zone (Cosovic et al. 2004) in the deeper part of a middle-to-outer shelf environment below the influence of storm waves (Romero et al. 2002; Corda & Brandano 2003) on a soft fine-grained and muddy sea-floor (Geel 2000; Cosovic et al. 2004; Bassi et al. 2007).

F3 Bioclastic *Operculina* packstone

The F3 facies shows a grain-supported fabric and the major skeletal component is *Operculina*, a larger symbiont-bearing foraminifer. The hyaline tests of *Operculina* are either long and thin and well-preserved, or thick and crushed. The crushed *Operculina* shells are fractured and eroded. Secondary skeletal components include debris of echinoids, coralline algae, bryozoans, *Neorotalia*, *Ditrupa*, *Lepidocyclina*, *Heterostegina*, planktonic foraminifera and textulariids. Crushed shells of miliolids and unbroken shells of textulariids are also present (Fig. 5e).

The presence of symbiont-bearing larger foraminifera (*Operculina* and *Heterostegina*), coralline algae, echinoids and bryozoans indicate that the F3 facies has been formed in normal saline warm waters (Geel 2000; Bassi et al. 2007; Flügel 2010; Langer et al. 2013) in the lower part of the photic zone (oligophotic). Under low light conditions, symbiont-bearing foraminifera increase their shells to absorb the maximum light (Hallock & Glenn 1986; Cosovic et al. 2004). Operculinids with elongated shells are typically deposited in middle shelf habitats (Hohenegger 1996, 2004; Hallock 1999; Geel 2000; Beavington-Penney & Racey 2004; Bassi et al. 2007; Hottinger 2007; Brandano et al. 2009; Bassi & Nebelsick 2010; Thissen & Langer 2017).

F4 Bioclastic Lepidocyclinidae packstone–rudstone

The basic elements of this microfacies are hyaline elongated shells (>2 mm) of Lepidocyclinidae (*Nephrolepidina* and *Eulepidina*). Minor skeletal components comprise *Amphistegina*, *Neorotalia*, bryozoans, echinoids, coralline algal fragments, and oyster debris (Fig. 5f).

The dominance of Lepidocyclinidae in F4 suggests a deposition in the lower photic zone in distal position of a distal middle shelf (Pedley 1996; Pomar 2001; Corda & Brandano 2003). The well-preserved Lepidocyclinidae with elongated shells are an indication of open marine water with low to moderate wave energy. The association of Lepidocyclinidae with echinoids and coralline algae suggests a deposition in an oligophotic middle shelf setting (Barattolo et al. 2007; Bassi et al. 2007; Brandano et al. 2009). Well-preserved elongated and thinner *Lepidocyclina* shells indicate low water energy conditions (Leutenegger 1984; Hallock 1988), soft and stable substrates (Hallock & Glenn 1986; Reiss & Hottinger 1984; Geel 2000; Romero et al. 2002) and low light conditions (Beavington-Penney & Racey 2004).

F5 Bioclastic coralline algal Lepidocyclinidae packstone–rudstone

Coralline algae (*Lithophyllum* and *Lithothamnion*) and Lepidocyclinidae (*Nephrolepidina* and *Eulepidina*) are the main constituents of F5. *Neorotalia*, *Amphistegina*, textulariids, echinoid debris, *Planorbulina*, *Ditrupa* and peloids are minor associated elements. Some porcellaneous foraminifera, such as *Pyrgo*, *Borelis* and miliolids, were also recorded (Fig. 5g).

The abundance of coralline algae suggests photic zone conditions (Pedley 1996; Geel 2000; Pomar 2001; Flügel 2010). The presence of hyaline rounded and robust shells of Lepidocyclinidae and Nummulitidae indicate an increase in light intensity and wave energy conditions in waters of a middle shelf environment

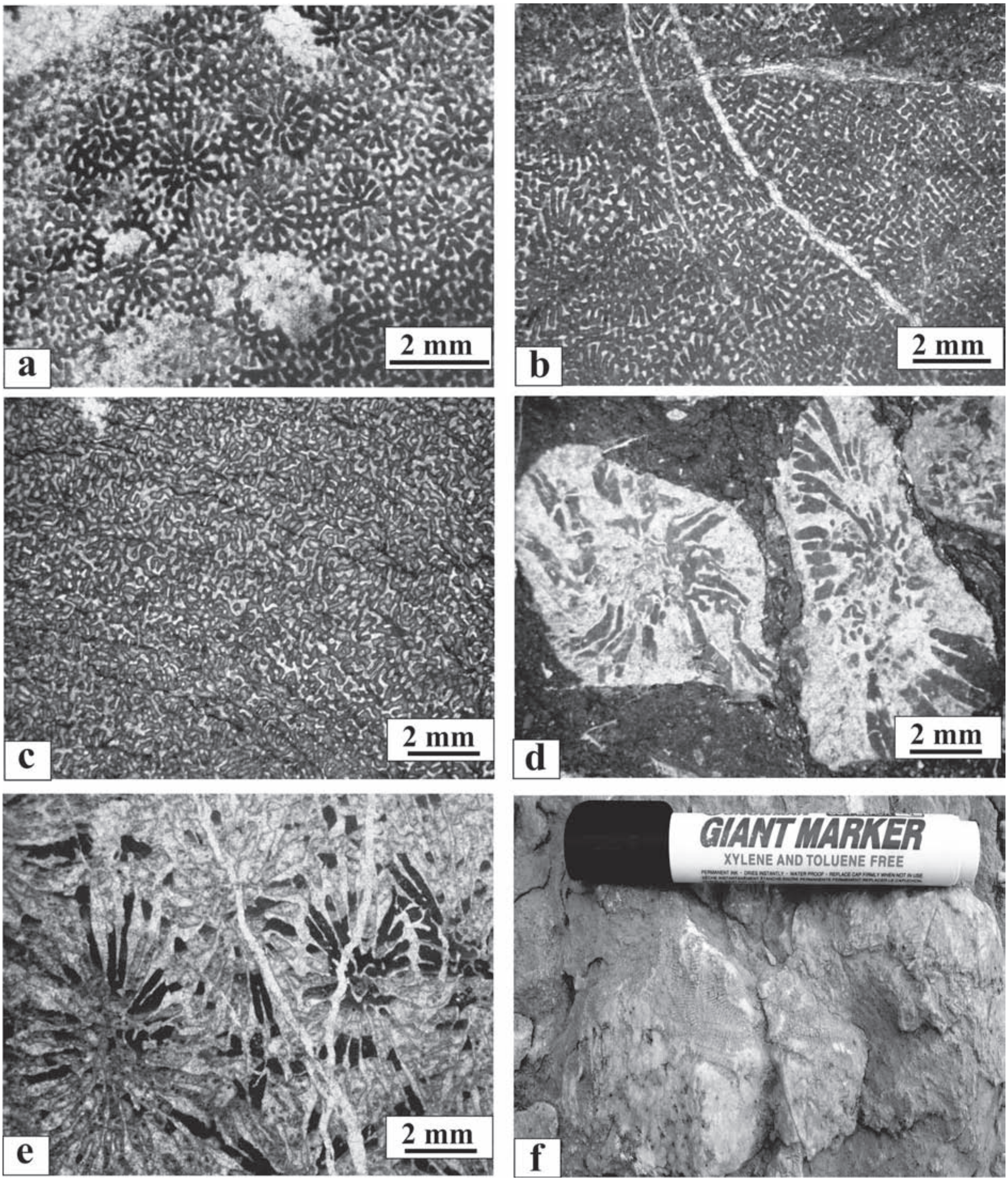

Fig. 7. Scleractinian corals of the Asmari Formation; **a** – *Actinacis rollei*; transverse section; **b, c** – *Porites* sp., sub-transverse and oblique sections; respectively; **d** – *Caulastraea farsis*, transverse section; **e** – *Favia* sp. 2 *sensu* SCHUSTER 2002b, **f** – *Leptoria bithecata*; transverse section, field outcrop.

(Beavington-Penney & Racey 2004; Barattolo et al. 2007; Nebelsick et al. 2001; Rasser & Piller 2004; Braga & Bassi 2011; Nebelsick et al. 2013).

F6 Bioclastic Lepidocyclinidae – Nummulitidae wackestone–packstone–grainstone

Hyaline foraminifera (Lepidocyclinidae and Nummulitidae) are major elements of this facies type and coralline algae, *Amphistegina*, *Neorotalia*, echinoids, oyster debris, and corals fragments are secondary components of F6. The tests of Lepidocyclinidae and nummulitids decrease in size but test walls become thicker (Fig. 5h). In F6, the size of coralline algal particles decreases. A number of thin sections show a variant of facies F6. This grain-supported subfacies is characterized by abundant, robust lens-shaped tests of *Heterostegina* (Bioclastic Nummulitidae packstone–grainstone; Fig. 6a).

The size of the Lepidocyclinidae shells and the small size of red algal fragments suggest shallow waters conditions in an upper middle shelf environment (Corda & Brandano 2003; Rasser et al. 2005; Bassi et al. 2007). In F6, coarse grained substrates, *Lepidocyclina* and *Heterostegina* shells with thicker and lensed shaped morphology, reflect an increase in water energy (Geel 2000; Romero et al. 2002; Bassi et al. 2007; Brandano et al. 2009; Flügel 2010).

F7 Bioclastic Lepidocyclinidae – *Neorotalia* – coral packstone–rudstone

Coral fragments (mostly of Poritidae and *Porites* corals), *Neorotalia* and Lepidocyclinidae are the major constituents in F7. Minor elements include debris of coralline algae, small-sized hyaline foraminifera with *Amphistegina*, valvulinids, echinoids, bryozoans, peloids, oyster debris, porcellaneous foraminifera and crushed flakes of large hyaline foraminifera (Lepidocyclinidae, *Operculina*, and *Heterostegina*). The coral fragments are larger than 2 mm. In between the coral branches, debris of porcellaneous and hyaline foraminifera, peloids and other non-identifiable components were recorded (Fig. 6b). In some thin sections, fragments of corals along with small *Neorotalia* (without Lepidocyclinidae) were noted. This microfacies represents a variant of the F7 facies type (bioclastic *Neorotalia* coral packstone–rudstone; Fig. 6c).

The presence of angular fragments of fixed and light-dependent calcareous organisms such as corals, coralline algae and larger symbiont-bearing foraminifera suggest that deposition occurred in a photic zone environment subjected to high energy at shallow water-depths (Goldbeck & Langer 2009; Makled & Langer 2011). Facies type F7 reflects conditions of a shallow water setting of the middle shelf. Angular pieces of coralline algae next to hyaline shells and a lack of corals in growth position differentiate facies F7 from typical reef facies (Wilson 1975; Perrin et al. 1995; Corda & Brandano 2003; Flügel 2010). The association of red algae, coral fragments, and lens-shaped and rounded hyaline foraminifera suggests a deposition in the mesophotic zone in an environment with relatively high water energy (Pomar 2001).

F8 Coral boundstone

Facies type F8 represents a coral boundstone mainly formed by massive and branching coral colonies observed in growth position (Fig. 6d). The coral colonies do not constitute a continuous framework but rather occur as isolated colonies, small clusters, and coral patches. Coral growth forms include massive, branching, phaceloid, and meandroid colonies. Thin sections show that coral skeletons were subject to intense diagenesis involving dissolution and/or calcification. Although this prevents any microstructural study, some coral specimens display a rather good preservation of their morphological and micro-morphological characters, and have been identified at generic and species levels. The coral fauna is dominated by poritids and comprises at least 6 different genera and species. They include *Porites* sp., *Actinacis rollei*, *Leptoria bithecata*, *Caulastraea farsis*, *Astreopora* sp., and *Favia* sp. (Fig. 7; Table 3). The sediment between coral colonies contains bioclasts including tests of foraminifera (*Heterostegina*, *Lepidocyclina*, *Amphistegina* and *Neorotalia*, small miliolids: *Biloculina*, *Triloculina* and *Quinqueloculina*). Other components are coralline algae, bryozoans, echinoid fragments and mollusks.

The presence of zooxanthellate coral assemblages in growth position indicates that the development of this facies occurred in well-oxygenated clear waters on an open-marine platform. This coral community did not build a rigid wave-resistant framework capable to grow to sea-level. The coral framework density varies both laterally and vertically and there is a large spectrum of coral cover, from scattered coral colonies to dense frameworks (Perrin et al. 1995). However, most coral assemblages in carbonate ramp settings occur as isolated colonies, clusters of coral colonies or small-sized coral patches and represent non-reefal coral communities, like those observed in the Pir-Sabz Section of the Asmari Formation.

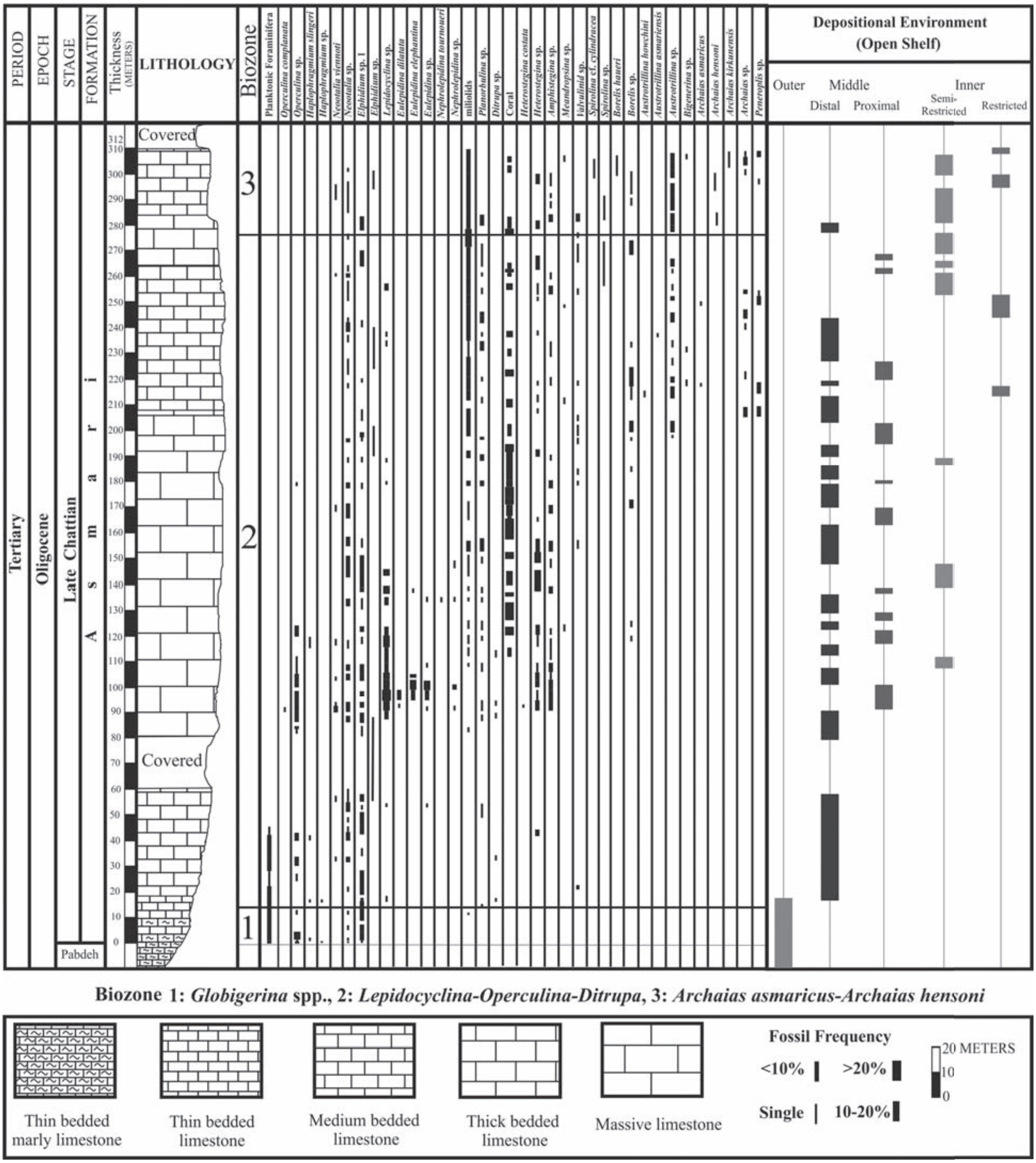

Fig. 8. Biostratigraphy and frequency of microfossils and types of sedimentary environments in the Asmari Formation in the Interior Fars province, Zagros Basin.

F9 Bioclastic porcellaneous foraminifera – coral packstone

The main components of facies F9 are represented by crushed coral fragments and a variety of porcellaneous foraminifera. The porcellaneous foraminiferal assemblage include miliolids (*Biloculina*, *Triloculina* and *Quinqueloculina*), *Meandropsina*, *Peneroplis*, *Archaias*, *Austrotrillina*, and *Pyrgo*. In this facies, porcel-

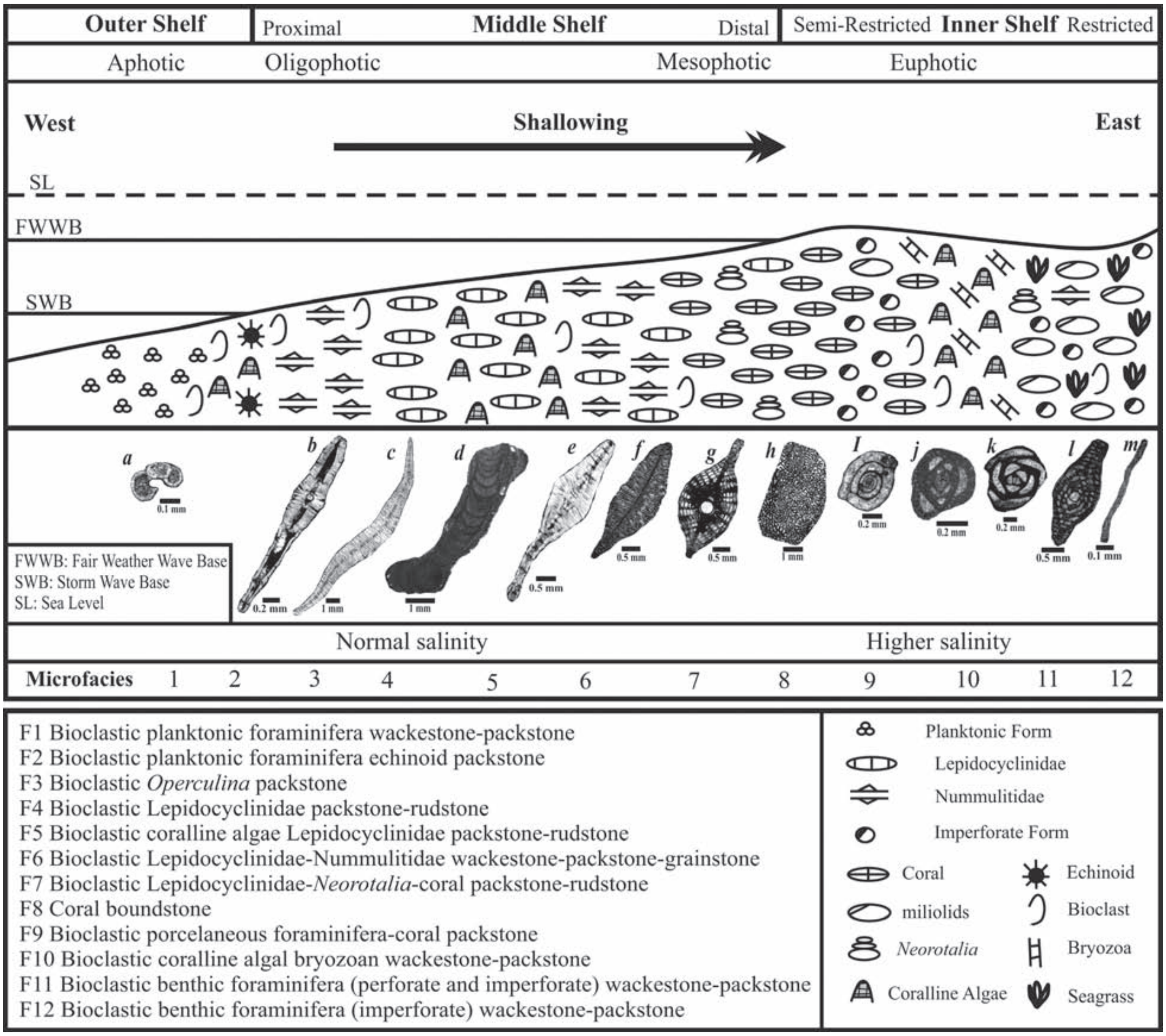

Fig. 9. Deposition model and distribution of foraminifera, corals and coralline algae in the carbonate shelf of the Asmari Formation with variations in depth, light intensity and water energy (Fars province, northeast flank of the Dashtak anticline, north of Kazerun); **a** – planktonic foraminifera; **b** – *Operculina complanata*; **c** – *Eulepidina elephantina*; **d** – Coralline algae; **e** – *Heterostegina* sp.; **f** – *Lepidocyclina* sp.; **g** – *Nephrolepidina tournoueri*; **h** – Coral; **i** – *Pyrgo* sp.; **j** – *Austrotrillina* sp.; **k** – miliolids; **l** – *Archaias* sp.; **m** – *Meandropsina* sp. (adapted from Flügel 2010).

laneous foraminifera more abundant and diverse than hyaline taxa. Less abundant constituents are small specimens of *Amphistegina*, *Neorotalia*, and lens-shaped *Heterostegina*, *Operculina* and Lepidocyclinidae. Gastropods, coralline algae, echinoids and bryozoan debris also occur as minor components. While corals in facies F8 were observed in growth position, these occur only as crushed fragments in facies type F9 (Fig. 6e).

The dominance of broken hyaline and porcellaneous foraminifera next to fragments of corals, suggests a deposition in a shallow inner shelf environment with high light intensity (Fournier et al. 2004; Flügel 2010).

F10 Bioclastic coralline algal bryozoan wackestone–packstone

The main components of this facies are bryozoans and coralline algae. Bivalves, echinoids, small individuals of *Neorotalia*, debris of Lepidocyclinidae, ultra-fine quartz particles, intraclasts and porcellaneous foraminifera (*Archaias* and *Peneroplis*) are secondary constituents of F10. Some coralline algal and bivalve fragments are larger than 2 mm. Within their shells, trapped echinoid fragments and other skeletal debris are visible. Eroded fragments of bryozoans and porcellaneous foraminifera (1 mm size) were also observed (Fig. 6f).

The co-occurrence of bryozoans, coralline algae, and porcellaneous foraminifera suggests a deposition in a sheltered inner shelf setting (Corda & Brandano 2003). Large skeletal grains in lime matrix indicate a quiet environment with limited water energy. The presence of bryozoans and coralline algae, indicates a permanent connection with the open marine environment (Flügel 2010). The large size (>2 mm) of skeletal components in a mud-supported matrix reflects low energy conditions (Geel 2000; Hohenegger 2000; Romero et al. 2002; Brandano et al. 2009; Bassi & Nebelsick 2010; Nebelsick et al. 2013).

F11 Bioclastic benthic foraminifera wackestone–packstone

The components of F11 are diverse and comprise hyaline foraminifera (*Amphistegina*, *Neorotalia*, and debris of Lepidocyclinidae, *Operculina* and *Heterostegina*) and porcellaneous taxa (miliolids, *Borelis*, *Archaias*, *Peneroplis*, *Meandropsina* and *Austrotrillina*). The minor elements include broken echinoid and bryozoan fragments, debris of coralline algae, gastropods and bivalves. The texture is mud-to-grain supported (Fig. 6g).

The co-occurrence of shallow lagoonal and open-marine foraminifera reveals a deposition in a shallow environment with high light intensity in an inner shelf setting (Geel 2000; Corda & Brandano, 2003; Bassi et al. 2007; Brandano et al. 2009). The presence of symbiont-bearing porcellaneous foraminifera (*Archaias*, *Peneroplis* and *Borelis*) in F11 reflect a shallow water environment with phytal substrates provided either by seagrasses or macroalgae (Langer 1988, 1993, 1998; Perry & Beavington-Penney 2005; Beavington-Penney et al. 2006; Tomás et al. 2016).

F12 Bioclastic benthic foraminifera (imperforate) wackestone–packstone

The main constituents of this facies are porcellaneous foraminifera which form a diverse assemblage. The assemblage includes individuals of *Archaias*, *Peneroplis*, *Austrotrillina*, *Pyrgo*, *Borelis* and *Meandropsina*. Less frequent components are small specimens of *Neorotalia*, gastropods and bivalve debris. Texture varies from mud- to grain-supported. Walls of most porcellaneous foraminifera appear to be thinner than in other facies types (Fig. 6h). Hyaline foraminifera are lacking. Gastropod and bivalve fragments increase in abundance relatively to facies F11.

Muddy texture and the presence of porcellaneous foraminifera in mud- to grain-supported matrix in F12 suggest a deposition in a shallow water environment with low water energy. The diverse porcellaneous biotas suggests lagoonal or inner shelf conditions in a shallow water environment. The presence of abundant specimens of *Archaias* indicates a water depth of less than 20 meters (Geel 2000; Corda & Brandano 2003; Vaziri-Moghaddam et al. 2006; Bassi et al. 2007; Brandano et al. 2009; Bassi & Nebelsick 2010, Langer & Hottinger 2000; Murray 1991; Hallock & Glenn 1986; Weinmann et al. 2013). Seagrass or algal substrates are indicated by the presence of ephiphytic foraminifera such as *Archaias* and *Peneroplis*.

4. Discussion

4.1. Deposition model

Microfacies analysis including the composition and distribution of foraminifera are used as key factors to determine the depositional environment of past habitats. At the Pir-Sabz Section, the Asmari Formation shows that the main components of sediments are larger symbiont-bearing benthic foraminifera, coralline algae and coral fragments. The composition and distribution of twelve facies types suggests a shallowing upward trend during the deposition of the Asmari Formation with a carbonate platform that is characterized by an inshore-offshore gradient (Flügel 2010). True coral reef structures and/or typical oolithic barriers are lacking and suggest that the sedimentation of the Asmari Formation in the Interior Fars province (north of Kazerun) has likely occurred on an open carbonate shelf. The twelve facies types identified reflect the facies zonation along the carbonate shelf transect from the outer (facies F1) and middle shelf (from F2 to F7) towards inner shelf habitats (F8 to F12; Figs. 8, 9).

4.2. The coral fauna and its significance

Six coral taxa have been identified in our samples from the Pir-Sabz Section. All of them have to be considered as zooxanthellate-like (ZL) scleractinian corals according to criteria described in (Perrin & Bosellini 2012). Although evaluation of the taxonomical richness of the scleractinian fauna in the Pir-Sabz area is still preliminary, it should be noted that ZL coral faunas worldwide were typically of low to moderate diversity during the Early Oligocene and began to diversify from the middle to the Late Oligocene (Perrin 2002).

All six genera identified in the Pir-Sabz Section are known from the Oligocene of the circum-Mediterranean regions. Most of them originated in the Eocene of the Tethys or the Caribbean (Veron 2000), excepted *Actinacis* and a few doubtful records of *Favia* recorded from the Tethyan Cretaceous. One genus, *Actinacis*, is fossil and disappeared at the end of the Chattian. The five other genera are still extant taxa from the Indo-Pacific coral biogeographical province, with *Favia* and *Porites* belonging to both present-day Indo-Pacific and Western Atlantic Provinces. The four coral species identified in the Pir-Sabz Section are all Mediterranean taxa. With the exception of *Actinacis rollei*, which displays an extended spatial distribution within Mediterranean regions during the Oligocene, the three other species are known from the Oligocene of the Eastern Mediterranean area (*sensu* Perrin & Bosellini 2012), including *Caulastrea farsis*, which was only known from the Abadeh Section in Central Iran (Schuster 2002a). The coral fauna described by Schuster (Schuster & Wielandt 1999; Schuster 2002a) from the Oligocene of Abadeh (Qom Formation; Esfahan-Sirjan fore-arc basin, Iran) is a mixture between species of Mediterranean affinity and Indo-Pacific species. By contrast, the coral fauna of the Pir-Sabz Section appears to have no species in common with the nearest known Indo-Pacific Oligocene ZL-coral fauna of the Nari Series of Sind described by Duncan (1880), nor with the Early Miocene coral fauna of the Makran area (McCall et al. 1994). Therefore, the biogeographical affinity of the Pir-Sabz coral fauna is clearly Mediterranean, but due to the need of taxonomical revisions of the Sind corals and the preliminary information concerning the Asmari corals in the Interior Fars area, overlap of a few species with the Indo-Pacific fauna cannot be definitively ruled out (Table 3).

5. Conclusions

The Asmari Formation in the Interior Fars of the Zagros Basin consists of a 312 meters sequence of medium to massive greyish limestone. Based on the appearance and extinction of index microfossils, 3 assemblage zones were identified: 1 – *Globigerina* sp., 2 – *Lepidocyclina*, *Operculina*, *Ditrupa* and 3 – *Archaias asmaricus* – *Archaias hensoni*. All three assemblage zones are of Oligocene age (Late Chattian). Twelve facies types, characterized by mud-to-grain supported textures in association with the occurrence of hyaline and porcellaneous foraminifera, echinoids, coralline algae and corals, were deposited in an open shelf setting. The outer shelf is characterized by the presence of abundant planktonic foraminifera that were deposited below the storm wave base. An outer to distal middle shelf setting is suggested by the occurrence of echinoids and planktonic foraminifera. A distal middle shelf habitat is indicated by the occurrence of elongated and thin-walled hyaline foraminifera associated with coralline algae, echinoids and bryozoan debris. Proximal middle shelf conditions are reflected by the occurrence of robust and lens-shaped hyaline foraminifera in association with coral, coralline algae, echinoids and bryozoan fragments. A mixture of hyaline/porcellaneous foraminifera and corals and a gradual transition towards porcellaneous foraminiferal assemblages suggest an inner shelf setting. The proximal middle shelf assemblages contains non-reefal ZL-coral community assemblages that occur as isolated colonies or as small coral patches. The biogeographical affinity of this coral fauna is strictly Mediterranean, with a marked affinity to the eastern Mediterranean Oligocene coral fauna.

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Table 1. Assemblage zones for the Asmari Formation and Oligocene–Miocene basins in Europe.

Age		Wynd (1965)	Adams & Bourgeois (1967)		Cahuzac & Poignant (1997)
Miocene	Burdigalian	*Borelis melo curdica*	*Borelis* melo group *Meandropsina iranica*		*Borelis melo* group *Miogypsina*
Miocene	Aquitanian	*Austrotrillina howchini* *Peneroplis evolutus*	*Miogypsina* *Elphidium* sp. 14 — *Archaias asmaricus* *Archaias hensoni*	*Miogypsinoides* *Archaias* *Valvulinid*	*Austrotrillina howchini* *Miogypsina* *Miogypsinoides deharti*
Oligocene	Chattian	*Archaias operculiniformis* (zone 58) *Nummulites intermedius* *Nummulites vascus* (zone 57) *Lepidocyclina-Operculina* *Ditrupa* (zone 56) *Globigerina* spp. (zone 55)	*Eulepidina-Nephrolepidina* *Nummulites*		*Miogypsinoides-Eulepidina* *Nummulites vascus-Nummulites fichteli-Eulepidina*
Oligocene	Rupelian	(see above)	(see above)		*Eulepidina formosoides* *Nummulites vascus-Nummulites fichteli*

Table 2. Assemblage biozones in the Asmari Formation in the Interior Fars province, Zagros Basin (northeastern flank of the Dashtak anticline, north of Kazerun).

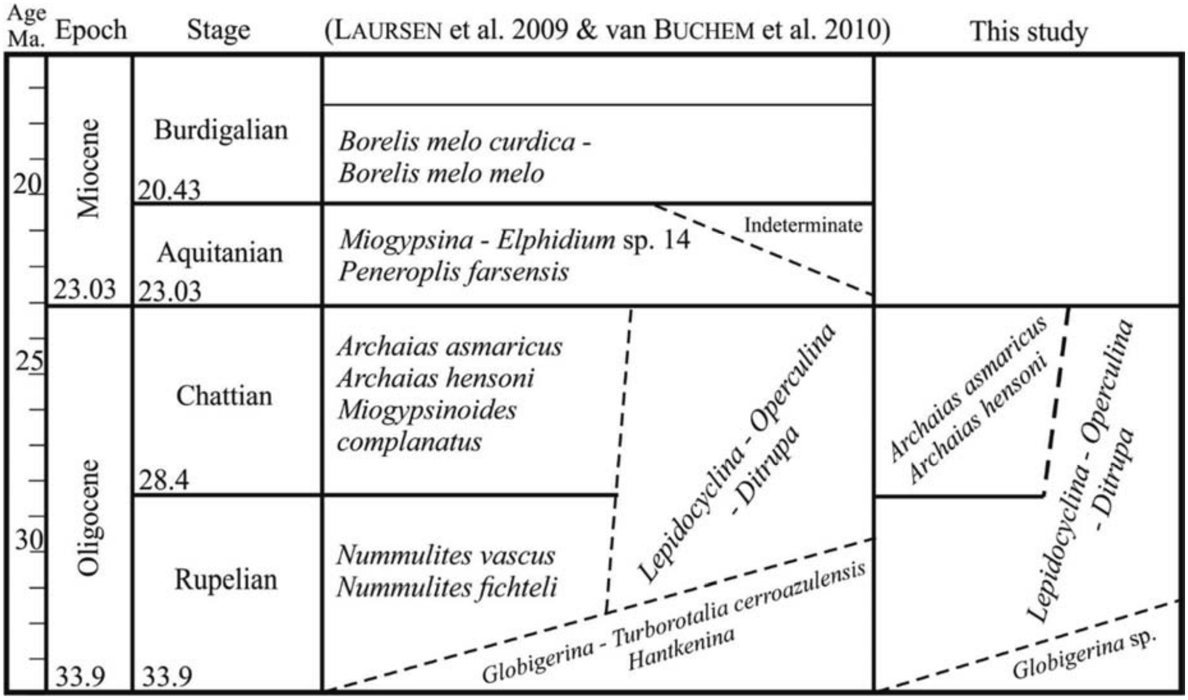

Table 3. Oligocene corals identified in the Pir-Sabz Section, Asmari Formation. Symbiotic status from PERRIN & BOSELLINI (2012).

Species	Symbiotic status	Regional distribution	Known distribution	Stratigraphical range
Family Acroporidae VERRILL (1902)				
Astreopora sp.	ZL			
Family Actinacididae VAUGHAN & WELLS (1943)				
Actinacis rollei REUSS (1864)	ZL	Tethys & Mediterranean	widespread	Late Eocene – Late Oligocene
Family Poritidae GRAY (1842)				
Porites sp.	ZL			
Family Faviidae GREGORY (1900)				
Caulastraea farsis SCHUSTER (2002a)	ZL	Mediterranean	Abadeh Section, Central Iran, E. Mediterranean	Late Oligocene
Favia sp. 2 sensu SCHUSTER (2002b)	ZL	Mediterranean	Doutsiko, Mesohellenic Basin, E. Mediterranean	Late Oligocene
Leptoria bithecata SCHUSTER (2002b)	ZL	Mediterranean	Doutsiko, Mesohellenic Basin, E. Mediterranean	Early and Late Oligocene