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Larger Foraminiferal Biostratigraphy and Facies Analysis of the Oligocene–Miocene Asmari Formation in the Western Fars Sub-basin, Zagros Mountains, Iran

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Abstract: The Oligocene–Miocene carbonate record of the Zagros Mountains, known as the Asmari Formation, constitutes an important hydrocarbon reservoir in southern Iran. This marine carbonate succession, which developed under tropical conditions, is explored in terms of larger foraminiferal biostratigraphy, facies analysis and sequence stratigraphy in a new section at Papoon cropping out in the western Fars sub-basin, in the south-east of the Zagros belt. Facies analysis shows evidence of re-working and transport of skeletal components throughout the depositional system, interpreted here as a carbonate ramp. The foraminifera-based biozones identified include the *Globigerina–Turborotalia cerroazulensis–Hantkenina* Zone and *Nummulites vascus–Nummulites fichteli* Zone, both of Rupelian age, the *Archaias asmaricus–Archaias hensoni–Miogypsinoides complanatus* Zone of Chattian age and the 'Indeterminate' Zone of Aquitanian age. The vertical sedimentary evolution of the formation exhibits a progressive shallowing of the facies belts and thus the succession is interpreted as a high-rank low-order regressive systems tract. This long-lasting Rupelian–Aquitanian regressive event is in accordance with accepted global long-term eustatic curves. Accordingly, long-term eustatic trends would have been a factor controlling accommodation during the deposition of the Asmari Formation studied in the western Fars sub-basin.

Key words: larger foraminifera, biostratigraphy, sequence stratigraphy, carbonate platform, Oligocene, Zagros Basin, Iran

1 Introduction

Larger foraminifera were prolific carbonate producers in the worldwide tropical to sub-tropical platform belts during the Paleogene (e.g., Buxton, 1988; Cahuzac and Poignant, 1997; Geel, 2000; Romero et al., 2002; Bassi, 2005; Scheibner and Speijer, 2008; Brandano et al., 2009; Höntzsch et al., 2013; Jaramillo-Vogel et al., 2016; Tomassetti et al., 2016; Albert-Villanueva et al., 2017; Bover-Arnal et al., 2017). Such benthic carbonate-producing biota are sensitive to changing environmental conditions (e.g., Hallock 1988, 2000; Scheibner and Speijer, 2008) and thus have had a rich and complex evolutionary diversity since the Cambrian (e.g., BouDagher-Fadel, 2008). Due to high diversification and extinction rates of the larger foraminiferal genera and species throughout the Eocene and Oligocene, these organisms are key biostratigraphic markers for this time period (e.g., Cahuzac and Poignant, 1997; Serra-Kiel et al., 1998; Bassi et al. 2007; Boukhary et al., 2010; Habibi, 2016a, b, 2017; Ferràndez-Cañadell and Bover-Arnal, 2017). In addition, a major extinction and turnover of larger foraminifera, and other organisms such as scleractinian corals, occurred at the Oligocene–Miocene boundary (e.g., Brasier, 1988; Edinger and Risk, 1994; Cahuzac and Poignant, 1997).

In the Middle East, a thick (hundreds of meters) and extensive (plate-scale) Oligo-Miocene carbonate sedimentary record occurs and is rich in larger foraminifera. This stratigraphic interval developed under marine tropical conditions and is known as the Asmari Formation (Fm.); it has long been known as a prosperous stratigraphic interval for oil extraction (e.g., Hull and

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Warman, 1970; Ala, 1982). Oil in the fractured reservoirs of the Asmari Fm. is mainly trapped in the Zagros Mountains along wide and gentle antiform structures (e.g., Hull and Warman, 1970; McQuillan, 1973, 1974). The economic interest of this locally dolomitic limestone unit (with sandstone and anhydrite members), makes the Asmari Fm. one of the world's most studied ancient carbonate system in terms of chronostratigraphy and sedimentology (e.g., Van Buchem et al., 2010; Vaziri-Moghaddam et al., 2006, 2010; Saleh and Seyrafian, 2013; Shabafrooz et al., 2015; Allahkarampour Dill et al., 2018). The chronostratigraphy of the Asmari Fm. is mainly based on Sr-isotope data (Ehrenberg et al., 2007) and larger foraminiferal biostratigraphy (e.g., Laursen et al., 2009; Van Buchem et al., 2010; Habibi, 2016a, b, 2017). However, given the plate-scale extension of the Asmari Form Fm., there are still areas in the Middle East where this sedimentary record remains underexplored.

In this regard, the main purpose of this paper is to provide overall analyses of a previously uninvestigated Oligo-Miocene carbonate succession belonging to the Asmari Fm. that crops out in the environs of the village of Papoon, western Fars sub-basin in the southeastern Zagros Mountains (Fig. 1). The study includes sedimentological and sequence-stratigraphic analyses and a larger foraminiferal biostratigraphic framework for this sedimentary succession. The results fill a gap in the geological and paleontological knowledge of the Asmari Fm. in this western marginal part of the Fars sub-basin, and thus are of significance for Oligocene–Miocene paleobiogeographic reconstructions of the Tethyan Seaway (see Boukhary et al., 2008, Kuss and Boukhary, 2008), which connected the Indo-Pacific and Mediterranean–Atlantic sides of Tethys through the Iranian Plate.

2 Geological Setting

The Zagros is a Miocene–Pliocene fold-thrust mountain belt located along the northeastern margin of the Arabian plate (Fig. 1). It extends in a NW–SE direction from southeastern Turkey to the Strait of Hormuz in southern Iran. This mountain belt resulted from the tectonic inversion of the Zagros foreland basin, an infra-Cambrian to Neogene intra-shelf basin that developed owing to the collision between the Afro-Arabian and Iranian plates (e.g., Stöcklin, 1968; Alavi, 2007; Bahroudi and Talbot, 2003). During the Oligocene–Miocene period, the margin of the Zagros Basin was characterized by carbonate-dominated marine environments (e.g., Van Buchem et al., 2010). The carbonate sedimentary successions characterized by the presence of benthic foraminifera, corals and coralline red algae constitute the Asmari Fm. (e.g., James and Wyndt, 1965; Ala, 1982; Davoudzadeh et al., 1997; Seyrafian, 2000; Vaziri-Moghaddam et al., 2010; Avarjani et al., 2015; Shabafrooz et al., 2015; Adabi et al., 2016; Kakemem et al., 2016; Habibi, 2016a, b; Allahkarampour Dill et al., 2018).

The Zagros fold and thrust belt can be subdivided into five zones based on their structural style and sedimentary history namely High Zagros, Dezful Embayment, Izeh, Lurestan and Fars (e.g., Falcon, 1974; Heydari, 2008; Fig. 1c). In addition, the Fars structural province (Fars sub-basin) can be as well subdivided into Interior Fars and Coastal Fars (e.g., James and Wyndt, 1965; Ala, 1982; Fig. 1c). The carbonate succession studied herein is located in the southeastern part of the Zagros Mountains in the Coastal Fars sub-basin (Figs. 1a, 1c).

The general stratigraphic architecture of the study area includes the Cretaceous carbonates and marls of the Sarvak and Gurpi formations, which are the oldest units outcropping in the area, the overlying evaporates of the Paleocene–Eocene Sachun Fm., the shallow-water carbonates of the Eocene Jahrum Fm., the Eocene–Oligocene deeper water marls of the Pabdeh Fm., the Oligo-Miocene larger foraminifera-bearing carbonates of the Asmari Fm. here analyzed, and the overlying evaporitic unit of the Gachsaran Fm. (e.g., James and Wyndt, 1965; Ala, 1982; Fig. 2).

3 Materials and Methods

The study section is located near the village of Papoon, about 80 km northwest of Shiraz City (Fig. 1). The stratigraphic section was logged about 3 km west of Papoon, along a creek that cuts the mountain range in a SW–NE direction (Fig. 1a). Sedimentological and stratigraphic field observations were complemented with the petrographic examination of thin sections for textural characterization, recognition of skeletal components and microfacies analysis. A total of 227 thin sections were made from 218 samples taken every 1 to 3 m along the sedimentary succession analyzed. Microfacies textures were classified following Dunham (1962) and Embry and Klovan (1971). Nine facies were characterized on the basis of lithology, texture and types of skeletal components present.

The first larger foraminiferal biostratigraphy of the Asmari Fm. was established by Wynd (1965) and later reviewed by Adams and Bourgeois (1967). More recently, Laursen et al. (2009) and Van Buchem et al. (2010) combined these early biostratigraphic frameworks together with Sr-isotope stratigraphy (Ehrenberg et al. 2007), and re-established the chronostratigraphy of the Asmari Fm. into seven biozones of Rupelian to Burdigalian age. The

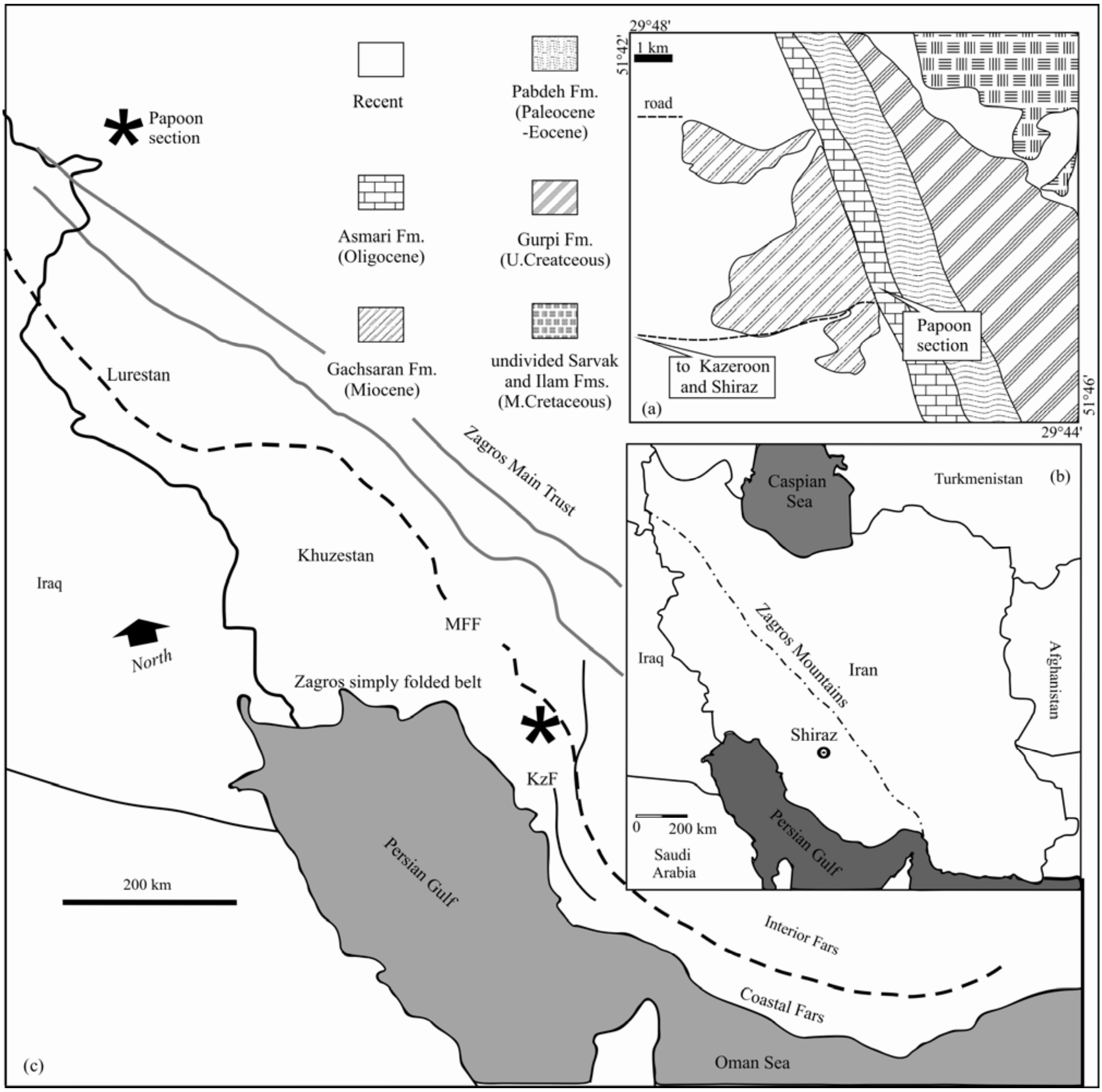

Fig. 1. Geological map of the study area, Zagros Mountains, SW Iran.
(a) (modified from MacLeod and Majedi 1972); (b) location in the Coastal Fars structural subdivision; (c) western Fars sub-basin. KzF: Kazerun Fault, MFF: Mountain Front Fault.

larger foraminiferal biostratigraphy presented herein is based on this latter foraminiferal zonation. Owing to the limestone lithology of the studied samples, it was not possible to obtain isolated specimens and the study was carried out by means of thin sections. Accordingly, taxonomic identification of foraminifera for biostratigraphical and paleoenvironmental purposes was performed on not strictly centered axial or equatorial sections showing the nepionic apparatus. Previous works such as Adams and Bourgeois (1967), Sirel (2003), Sirel et al. (2013) and Habibi (2017) also helped in the identification of larger foraminifera. The thin sections used in this study are deposited in the Museum of Paleontology at Shiraz University, Shiraz, Iran (bearing P perfix).

A transgressive-regressive (T-R) sequence stratigraphic interpretation (see Catuneanu et al., 2011) was carried out to identify the changes in accommodation that occurred during the deposition of the carbonate succession analyzed. The T-R sequence analysis was founded on the recognition of a maximum flooding surface located at the base of the Asmari Fm., which marks a low-order change

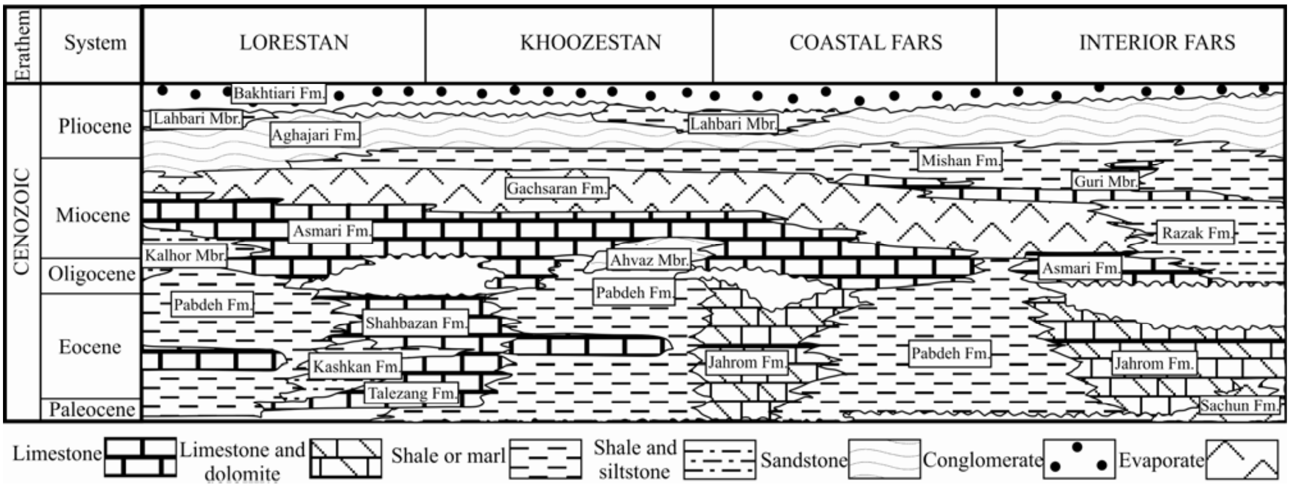

Fig. 2. Cenozoic chronostratigraphic chart of the Zagros Mountains (based on James and Wynd 1965, and Ala, 1982).
Fm.: Formation, Mbr: Member.

in facies trend from deepening- to shallowing-upwards.

4 The Papoon Section

The Asmari Fm. carbonates bearing larger foraminifera studied in the Papoon section (Figs. 1a, 3) are encased between an underlying marly unit corresponding to the Pabdeh Fm. (Figs. 3a–b), and an overlying stratigraphic interval of conglomerates, marls, limestones and evaporites that belongs to the Gachsaran Fm. (Fig. 3c). In the Papoon section, the Asmari Fm. is 338 m thick, whereas the whole of the succession logged, including the uppermost and lowermost parts of the Pabdeh and Gachsaran formations, respectively, is 351 m thick (Fig. 4).

Above the marl deposits of the Pabdeh Fm., the first 156 m of the Asmari Fm. are formed by an alternation of marls, marly-limestones and limestones, which evolve upwards in the succession to thicker-bedded and massive limestones (182 m thick) (Fig. 4). As noted above, the limestones of the Asmari Fm. are locally dolomitic.

4.1 Facies analysis

Nine distinct facies (FA) are characterized based on macroscopic and microscopic observations of lithologies, textures, and components and their pre-burial taphonomic signatures throughout the carbonate succession studied.

FA1 Planktonic foraminiferal marls: Marl deposits belonging to the Pabdeh Fm. underlie the analyzed platform carbonates of the Asmari Fm. (Figs. 3b, 4). The marls contain abundant planktonic foraminifera, calcareous nannoplankton, sponge spicules, molluscs and echinoids.

FA2 Planktonic foraminiferal wackestone-packstone: This facies occurs in the lowermost part of the Asmari Fm., and overlies the marls of the Pabdeh Fm. (Figs. 3b, 4). It is characterized by marls, and limestones and marly-limestones with wackestone and packstone textures containing abundant planktonic foraminifera (Fig. 5a). Planktonic foraminifera mainly correspond to globigerinids with poor to moderate preservation. Small benthic foraminifera, fragments of echinoids and bryozoan colonies, and non-skeletal components such as peloids and glauconite are present as well.

FA3 *Operculina* wackestone-packstone: Marly-limestones with wackestone and packstone textures with thin and small tests of *Operculina* characterize this facies (Figs. 4, 5b). The identified specimens of *Operculina* mainly correspond to A-form individuals. Planktonic foraminifera such as *Globigerina* spp. are also common constituents of the facies. However, the visually estimated abundance of planktonic foraminifera is clearly reduced with respect to FA2. *Heterostegina*, echinoids, bivalves and bryozoans, as well as peloids, also occur.

FA4 Larger foraminiferal and coralline algae packstone-grainstone: This facies is mainly characterized by grain-supported textures of abraded and fragmented skeletal components of larger foraminifera and coralline algae (Figs. 4, 5c). Locally, wackestone textures occur. The most abundant larger foraminifera identified are *Operculina*, *Heterostegina* and *Neorotalia*. Other hyaline perforate foraminifera such as *Amphistegina* and *Nephrolepidina* are common as well. Encrusting foraminifera and tests of *Archaias*, valvulinids, *Austrotrillina*, *Sphaerogypsina*, *Planurboulinoides*, *Elphidium*, *Reusella*, *Triloculina* and other miliolids are also present. Coralline algae mainly occur as fragments of non-geniculate specimens. *Ditrupa* and fragments of echinoids, gastropods, dasycladaceans, bryozoans, corals, oysters and of other bivalves are also present. Ooid grains

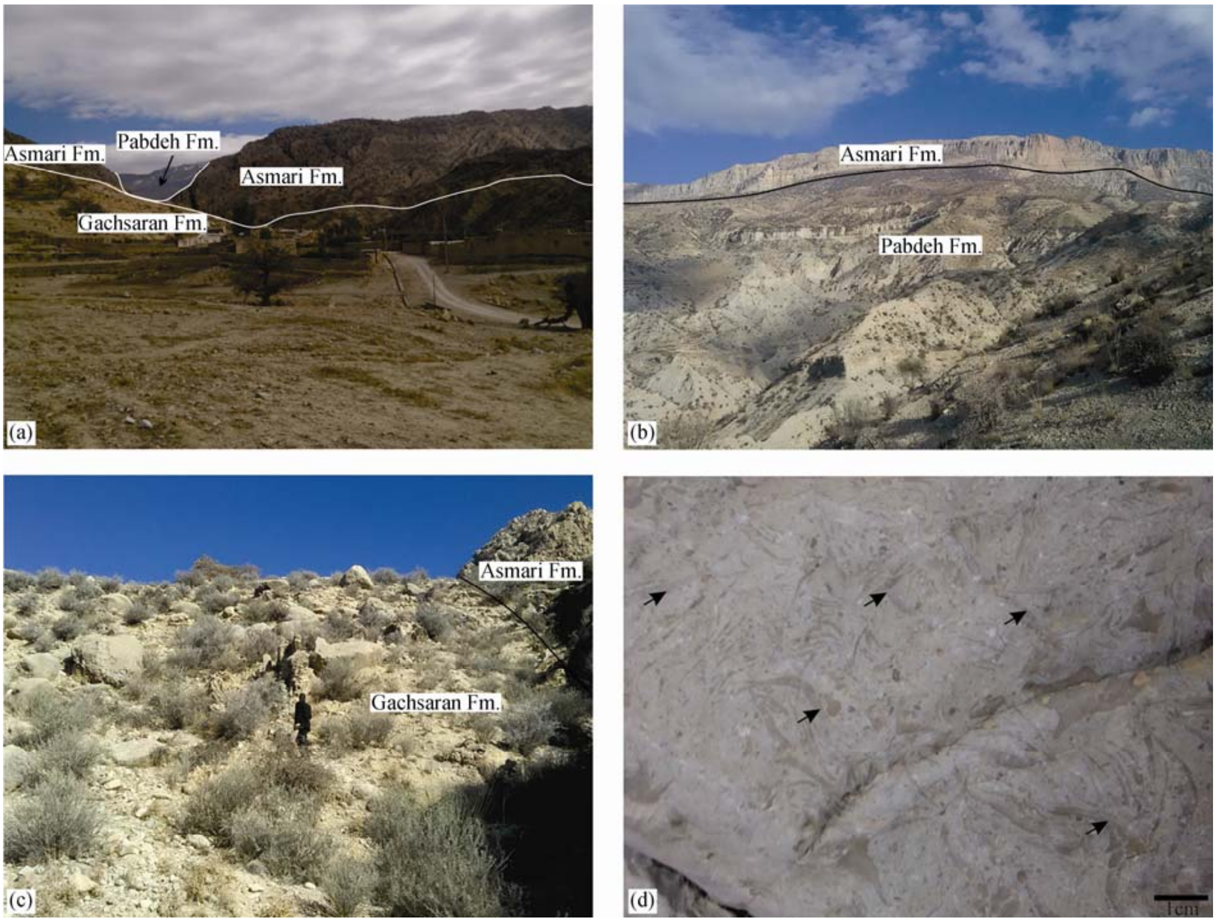

Fig. 3. Outcrop-scale photographs of the Asmari Formation in the Papoon section.
(a), view of the Papoon section; (b), boundary between the Pabdeh and Asmari Formations; (c), boundary between the Asmari and Gachsaran Formations; (d), *Lepidocyclina*-bearing beds in the Asmari Formation. Black arrows point to lepidocyclinid tests.

occur locally.

FA5 Lepidocyclinid floatstone-rudstone: The coarse-grained limestones of this facies are located at the transition between the marly-limestone deposits of the lower part of the analyzed succession and the thick and massive limestone beds of its upper part (Fig. 4). The facies is characterized by floatstone to rudstone textures with large and flat tests of *Eulepidina* (Figs. 3d, 5d). *Nephrolepidina*, *Heterostegina* and *Operculina* are also common constituents. B-form larger foraminfera tests are dominant. *Eulepidina*, *Operculina* and *Heterostegina* occur slightly abraded and fragmented. Well-preserved tests of *Neorotalia*, *Amphistegina* and *Sphaerogypsina* also occur and can be locally dominant. Minor fragmented tests of planktonic foraminifera are also present. Subordinate components include fragments of coralline algae, echinoids, brachiopods, bivalves and large and well-preserved tubes of *Ditrupa*.

FA6 Coral-bearing carbonates: This facies is characterized by the occurrence of isolated colonies of scleractinian corals found in growth position. The matrix between the coral colonies is made up of a micritic texture with scarce skeletal components such as fragments of molluscs or foraminifera. Colonies are commonly encrusted by coralline algae. The corals are not building a framework with a topographic relief, i.e., a coral reef, but are level-bottom communities. This facies presence is restricted to the middle-upper part of the study section and occurs interbedded with FA4 and 7 (Fig. 4).

FA7 Imperforate foraminiferal packstone-grainstone: Poorly sorted packstone and grainstone textures dominated by a high diversity of imperforate foraminifera characterize this facies (Figs. 4, 5e). Locally, wackestone textures also occur. Imperforate foraminifera are represented by *Austrotrillina*, valvulinids, *Archaias*, *Borelis*, *Peneroplis*, *Sorites*, *Triloculina*, *Biloculina*, and other undetermined miliolids. Perforate foraminifera are less abundant and represented by robust tests of *Neorotalia*, *Heterostegina*, *Amphistegina*, *Nephrolepidina*, *Discorbis* and *Reusella*. Other bioclastic components present comprise bivalves, bryozoans, echinoids, and fragments of coralline algae, rhodoliths, gastropods, green algae, brachiopods and corals. These latter skeletal components together with perforate foraminifera

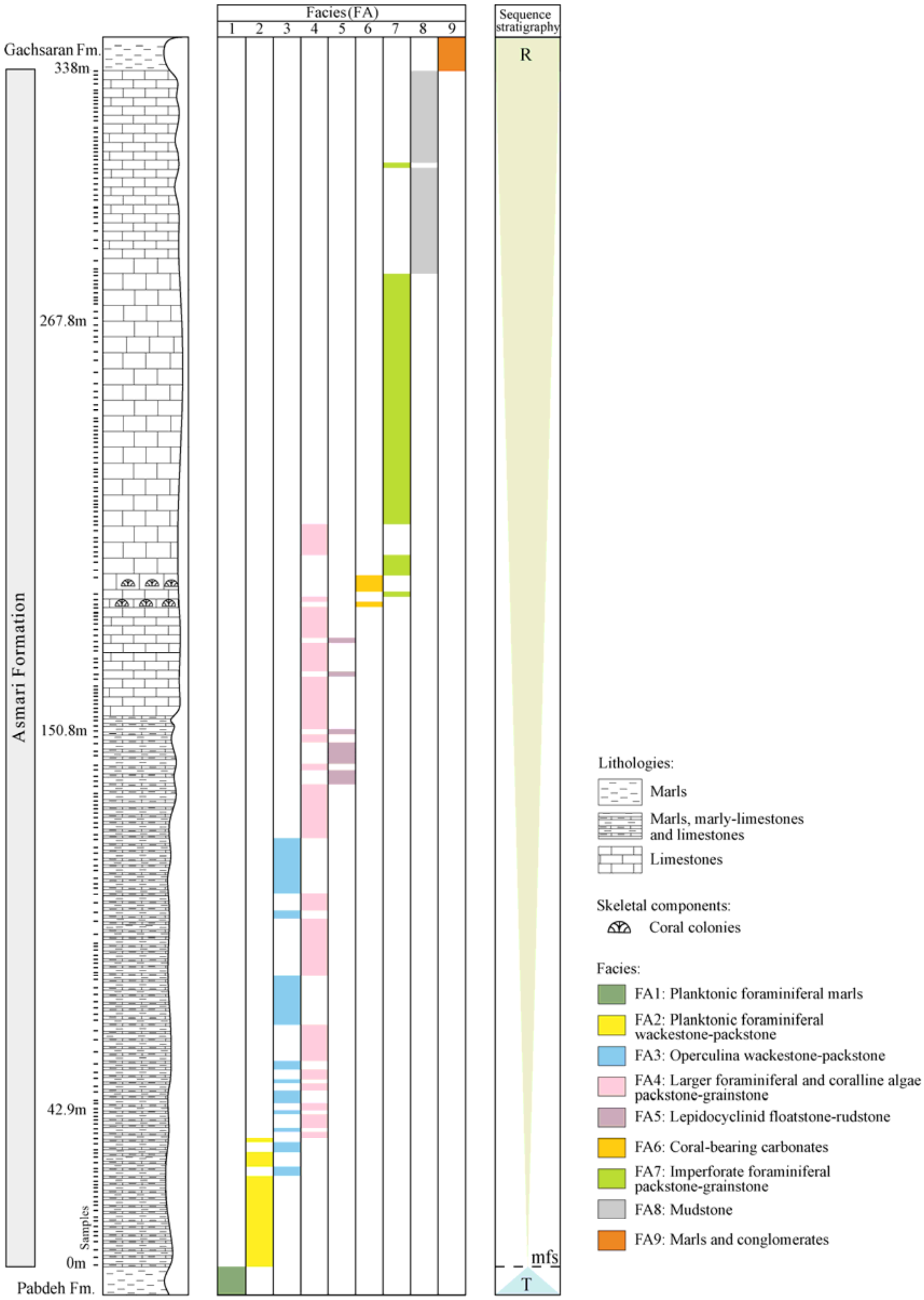

Fig. 4. The Papoon stratigraphic section including the distribution of the facies characterized, the T-R sequence -stratigraphic interpretation and the larger foraminiferal biozones based on those established by Laursen et al. (2009). T: Transgressive deposits, R: Regressive deposits, mfs: maximum-flooding surface.

commonly occur bioeroded, abraded and fragmented. Larger foraminifera tests are also locally encrusted by coralline algae. Micritization is a common diagenetic alteration in this facies. In some samples, peloids are present as a major constituent. Locally, sections of charophyte thalli and gyrogonites occur.

FA8 Mudstone: This facies is composed of dense micritic textures with scarce fragments of skeletal

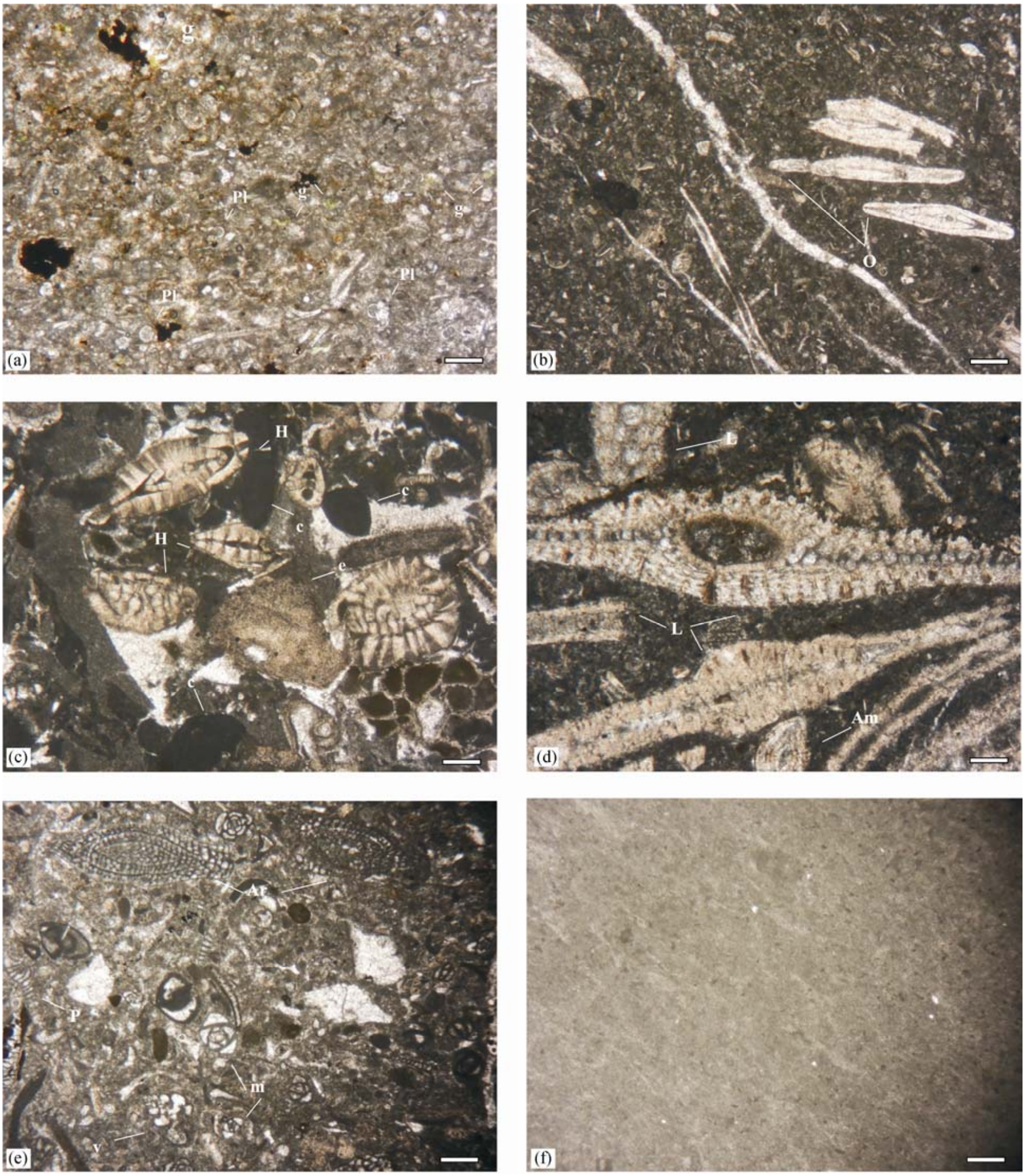

Fig. 5. Thin-section photomicrographs of facies characterized in the Papoon section.
(a), Facies FA2: Planktonic foraminiferal wackestone-packstone. Pl: planktonic foraminifera, g: glauconite; (b), FA3: *operculina* wackestone-packstone. O: *Operculina*; (c), FA4: larger foraminiferal and coralline algae packstone-grainstone. H: *Heterostegina*, c: coralline alga, e: echinoid; (d), FA5: lepidocyclinid floatstone-rudstone. L: lepidocyclinid, Am: *Amphistegina*; (e), FA7: imperforate foraminifera packstone-grainstone. Ar: *Archaias*, m: miliolid, v: valvulinid, P: *Peneroplis*; (f), FA8: mudstone.

components (Figs. 4, 5f). Bioturbation features, peloids and quartz grains occur scattered in these micrite deposits.

FA9 Marls and conglomerates: Marl deposits with interbedded conglomerates form this facies, which makes up the uppermost part of the succession studied (Fig. 4). These marls and conglomerates belong to the base of the Gachsaran Fm. (Fig. 3c). Upwards in the succession of the Gachsaran Fm., the marls occur interbedded with carbonates and anhydrite and gypsum layers (e.g., Van Buchem et al., 2010; Vaziri-Moghaddam et al., 2010; Habibi and Ruban, 2017).

4.2 Foraminiferal assemblage

The foraminiferal assemblage of the uppermost part of the Pabdeh Fm. and the first 42.9 m of the Asmari Fm. consists of small and commonly broken tests of *Globigerina* spp. (Fig. 6). Rare tests of *Textularia* sp. are observed as well. From meter 42.9 to meter 150.8 of the section logged (Fig. 6), the foraminifera species identified correspond to *Nummulites vascus* (Fig. 7d–e), *Operculina complanata* (Figs. 7g, i), *Heterostegina assilinoides* (Fig. 7b–c), *H. praecursor* (Fig. 7l, n), *Nephrolepidina praemarginata*, *N. morgani* (Figs. 8e–f), *N. tourneri*, *N. partita* (Fig. 8b), *Nephrolepidina* sp. (Fig. 8j), *Eulepidina elephantina* (Fig. 8d, g), *E. dilatata* (Fig. 8c), *E. raulini* (Fig. 8a), *Neorotalia viennoti*, *Amphistegina mammilla* (Fig. 7a, k), *Am. bohdanowiczi* (Fig. 7m), *Am. conoides*, *Planorbulinoides retinaculata*, *Discorbis* sp., *Reusella* sp. and *Globigerina* spp. (Fig. 6).

Between meters 150.8 and 267.8, the foraminifers determined are *Miogypsinoides complanatus* (Fig. 8h–i, k), *Spiroclypeus blanckenhorni*, *Archaias kirkukensis* (Fig. 9d, h, k), *Ar. asmaricus* (Fig. 9c), *Ar. hensoni*, *Peneroplis flabelliformis* (Fig. 9e), *P. evolutus*, *P. thomasi*, *P.* sp., *Neorotalia viennoti* (Fig. 7f, j), *Sorites* sp. (Fig. 9a), *Miogypsinoides* sp., *Sphaerogypsina globulus* (Fig. 7o), *Elphidium* sp., *Discorbis* sp., *Austrotrillina howchini* (Fig. 9i), *A. asmariensis* (Fig. 9f), *Triloculina trigonula* (Fig. 9j), *Planorbulinella larvata* (Fig. 9b), valvulinids (Fig. 9g) and *Globigerina* spp. Above meter 267.8, only rare specimens of *Peneroplis*, *Sorites* and *Elphidium* were determined at genus level (Fig. 6).

5 Discussion

5.1 Biostratigraphic considerations

The age calibration of proximal platform carbonates by means of the standard planktonic zonation is often difficult because of the scarcity of planktonic foraminifera in such shallow-water settings. Identification of planktonic foraminifera is also problematic in thin section. On the other hand, the study area samples examined contain prolific skeletons of larger foraminifera, which show high diversity and generally occur well preserved (Figs. 6–9).

The uppermost part of the Pabdeh Fm. and the lowermost part of the Asmari Fm., until meter 42.9 of the section logged, are characterized by the presence of *Globigerina* spp. (Fig. 6). Laursen et al. (2009) defined the *Globigerina* spp.–*Turborotalia cerroazulensis*–*Hantkenina* Assemblage Zone as a stratigraphic interval dominated by *Globigerina* spp. where the extinction of *Turborotalia cerroazulensis* and *Hantkenina* occurs. When *Hantkenina* is present the age is Eocene, whereas when it is absent, the age is Early Oligocene (Rupelian). Given the absence of *Hantkenina* spp. and *T. cerroazulensis* in this stratigraphic interval characterized, the lowermost part of the Asmari Fm. is considered to be of Rupelian age and ascribed to Laursen et al.'s (2009) Assemblage Zone.

Meter 42.9 to 150.8 is characterized by the occurrence of *Operculina complanata*, *Amphistegina* sp. *Heterostegina assilinoides*, *Neorotalia viennoti*, *Eulepidina elephantina*, *Eulepidina dilatata*, *Nephrolepidina praemarginata*, as well as *Nummulites vascus* (Fig. 6). This latter species defines the *Nummulites vascus*–*N. fichteli* Assemblage Zone of Laursen et al. (2009) and indicates a Rupelian age. Laursen et al. (2009) also reported the occurrence of *Heterostegina* spp., *Neorotalia viennoti*, *Eulepidina elephantina*, *Eulepidina dilatata* and *Nephrolepidina praemarginata* in the *Nummulites vascus*–*N. fichteli* Assemblage Zone. This Rupelian biozone correlates with the shallow benthic (SB) zones 21 and 22A of Cahuzac and Poignant (1997). In this regard, the stratigraphic ranges of *Nummulites vascus*, *Eulepidina dilatata* and *Nephrolepidina praemarginata* in the Papoon section are consistent with the presence of the SB zone 22A of Cahuzac and Poignant (1997) between meters 126.4 and 150.8, and so, at least, the uppermost part of the *Nummulites vascus*–*N. fichteli* Assemblage Zone is characterized. Nevertheless, according to Cahuzac and Poignant (1997), the occurrence of *Nummulites vascus*, *Eulepidina dilatata* and *Nephrolepidina praemarginata* could also be indicative of an early Chattian age (SB zone 22B).

The *Nummulites vascus*–*N. fichteli* Assemblage Zone has been also characterized in the interior Fars sub-basin (Habibi 2016a,b, 2017), where both *N. vascus* and *N. fichteli* are present. However, in the Papoon section, *Nummulites fichteli* was not recognized. This fact might probably be related to a facies control of the larger foraminifera species occurrences.

From meter 150.8 to meter 267.8, the foraminiferal assemblage identified includes *Archaias kirkukensis*, *Ar. asmaricus*, *Ar. hensoni*, *Miogypsinoides complanatus*, *Miogypsinoides* sp., *Spiroclypeus blanckenhorni*, *Peneroplis flabelliformis*, *P. evolutus*, *P. thomasi*, *P.* sp., *Neorotalia viennoti*, *Sorites sp.*, *Sphaerogypsina globulusa*, *Elphidium* sp., *Discorbis* sp., *Austrotrillina howchini*, *A. asmariensis*, *Triloculina trigonula*, other unidentified miliolids and undetermined planktonic foraminifera (Fig. 6). The concurrence of *Spiroclypeus blanckenhorni*, *Miogypsinoides complanatus*, *Archaias asmaricus* and *Ar. hensoni* defines the *Archaias asmaricus* –*Archaias hensoni*–*Miogypsinoides complanatus* Assemblage Zone of Chattian age (Laursen et al., 2009; Van Buchem et al., 2010). This assemblage zone would

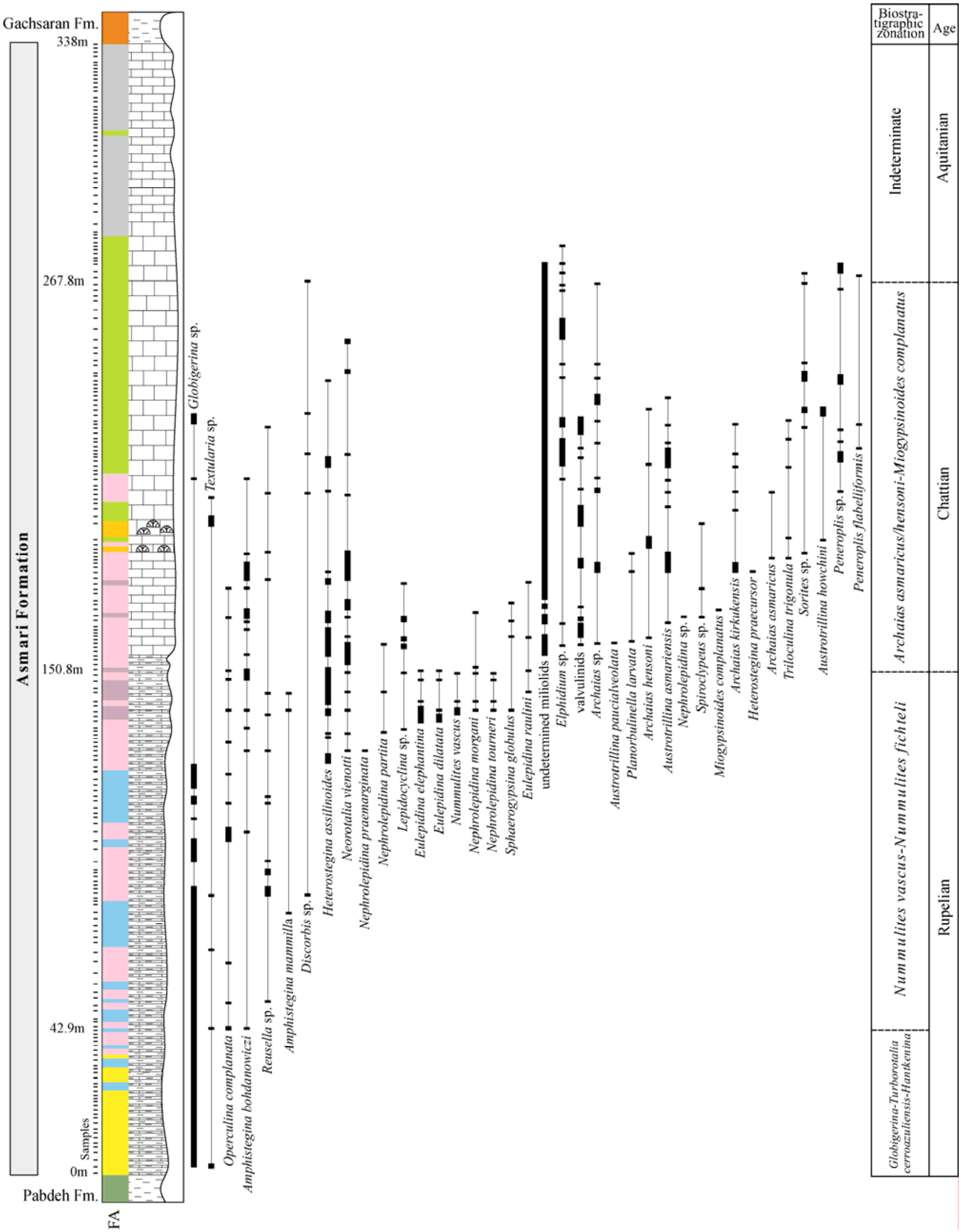

Fig. 6. Stratigraphic distribution of larger foraminifera species in the Papoon section including the biostratigraphic zonation based on Laursen et al. (2009). Key to Facies (FA) color codes, lithologies and skeletal components is shown in Figure 4.

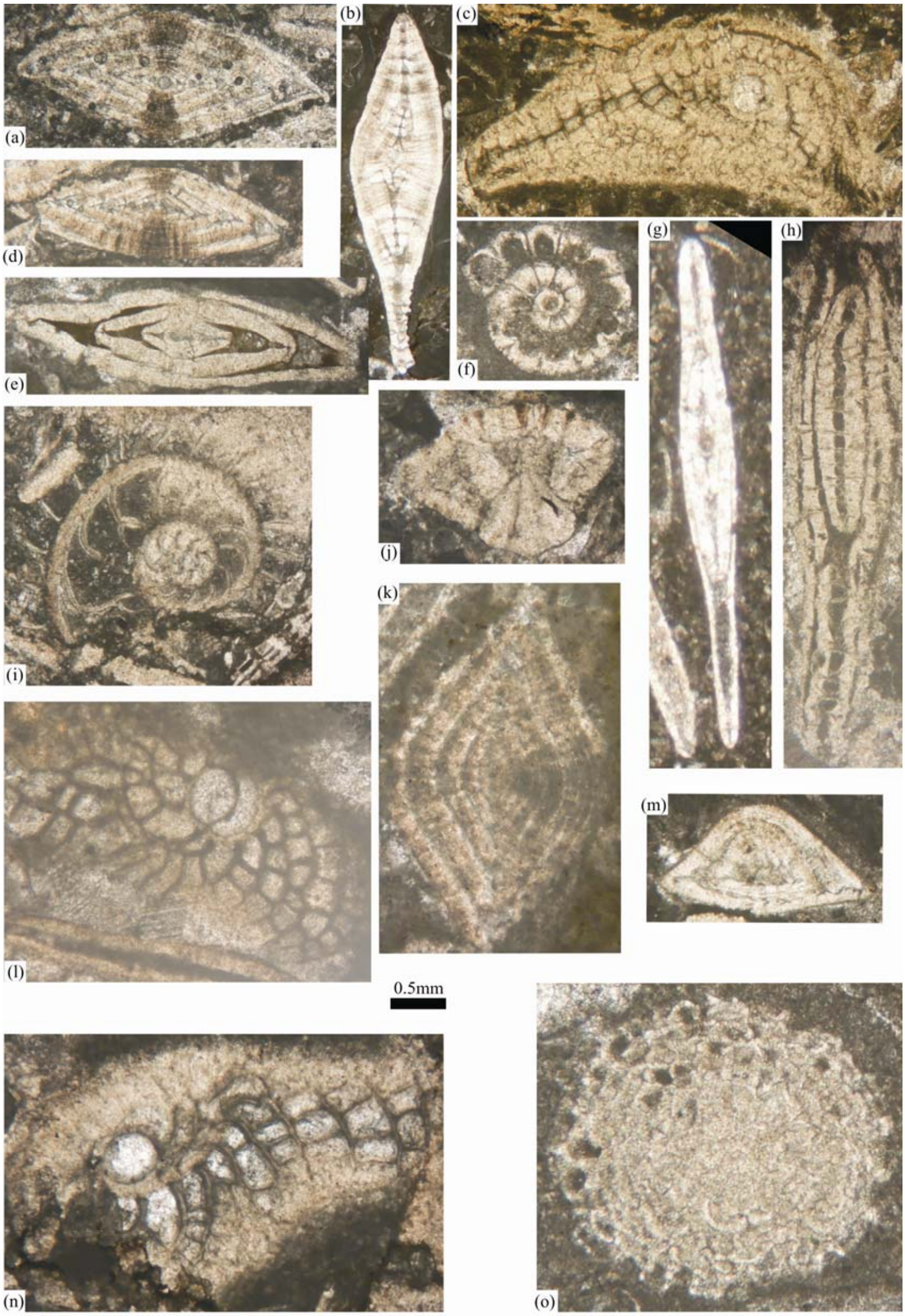

Fig. 7. Representative benthic foraminifera from the Asmari Formation in the Papoon section.

(a), *Amphistegina mammilla* (after Fitchel and Moll, 1798), Oligocene; Axial section, Sample no. P293; (b), *Heterostegina* cf. *assilinoides* Blanckenhorn, 1890, Oligocene; Tangential Section, Sample no. P272; (c), *Heterostegina assilinoides* Blankenhorn, Oligocene; Equatorial section, Sample no. P291. (d), *Nummulites vascus* Joly and Leymerie, 1848, Rupelian; Axial section, Sample no. P292; (e), *Nummulites* cf. *vascus*, Tangential section, Sample no. P295. (f, j), *Neorotalia viennoti* (after Greig, 1935), Oligocene; f, Equatorial section, Sample no. P305; j, Axial section, Sample no. P303. (g, i), *Operculina complanata* (after Defrance, 1822), Rupelian; g, Axial section, Sample no. P260; i, Sub-equatorial section, Sample no. P268; (h), *Spiroclypeus* sp., Oligocene, Sub axial section, Sample no. P319. (k), *Amphistegina* cf. *mammilla*, Oligocene, Sub axial section, Sample no. P246; (l, n), *Heterostegina praecursor* Tan Sin Hok, 1930, Oligocene; l, Equatorial section, Sample no. P306; n, Equatorial section, Sample no. P300; (m), *Amphistegina bohdanowiczi* (after Bieda, 1936), Oligocene, Axial section, Sample no. P300; (o) *Sphaerogypsina globulus* (after Reuss, 1848), Oligocene, Equatorial section, Sample no. P294.

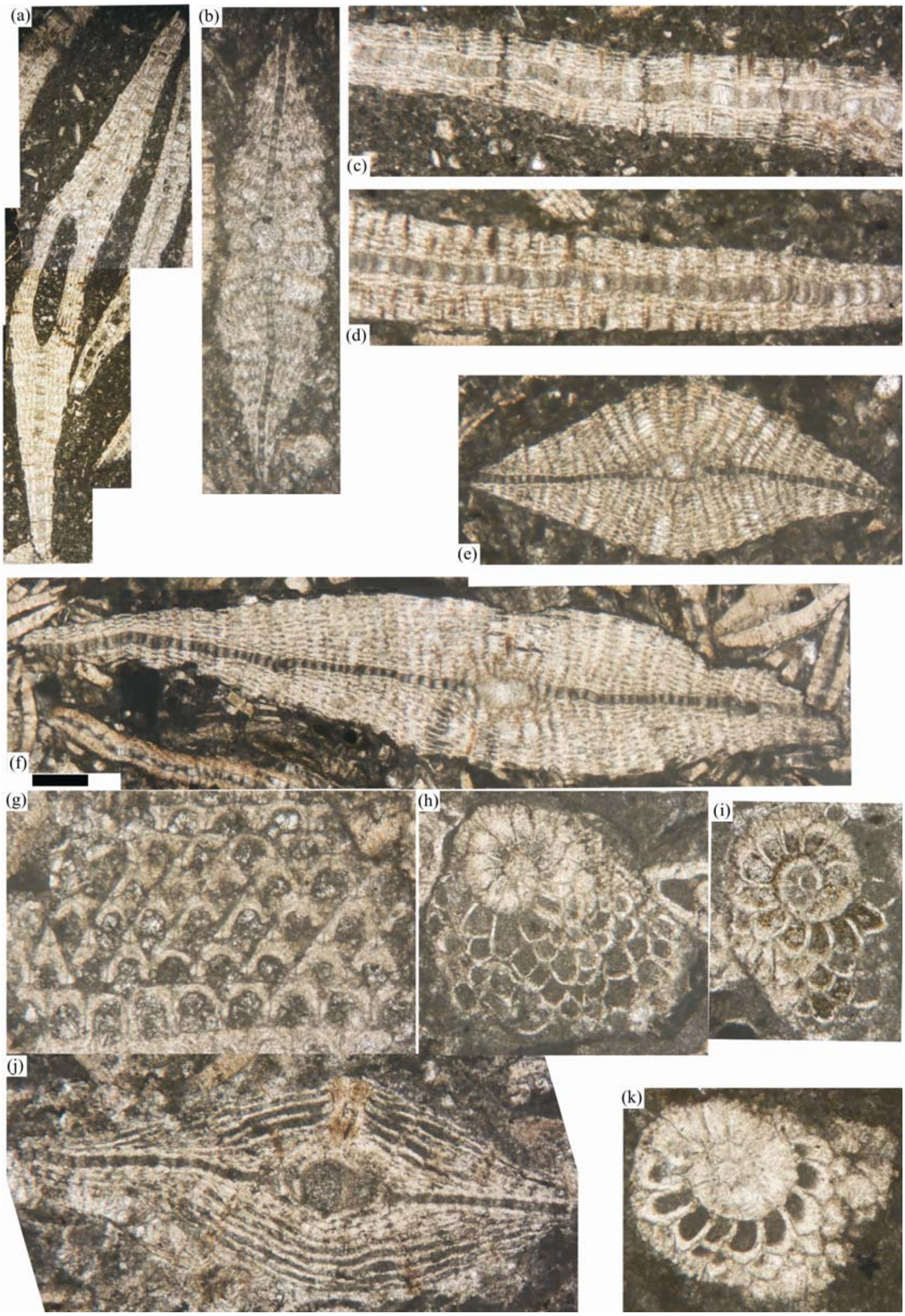

Fig. 8. Representative benthic foraminifera from the Asmari Formation in the Papoon section.
(a), *Eulepidina raulini* (after Lemoine and Douvillé, 1904), Rupelian, Axial section, Sample no. P297; (b), *Nephrolepidina partita* Douvillé, Rupelian, Axial section, Sample no. P290; (c), *Eulepidina dilatata* (after Michelotti, 1841), Rupelian, Axial section, Sample no. P293; (d, g), *Eulepidina elephantina* (after Lemoine and Douvillé, 1904), Rupelian; d, Axial section, Sample no. P301; g, Equatorial section, Sample no. P299; (e, f), *Nephrolepidina morgani* (after Lemoine and Douvillé, 1904), Rupelian, Axial sections, Sample no. P293; (h, i, k), *Miogypsinoides complanatus* (after Schlumberger, 1900), Chattian, Equatorial sections, Sample no. P312; (j), *Nephrolepidina* sp., Rupelian, Axial section, Sample no. 312.

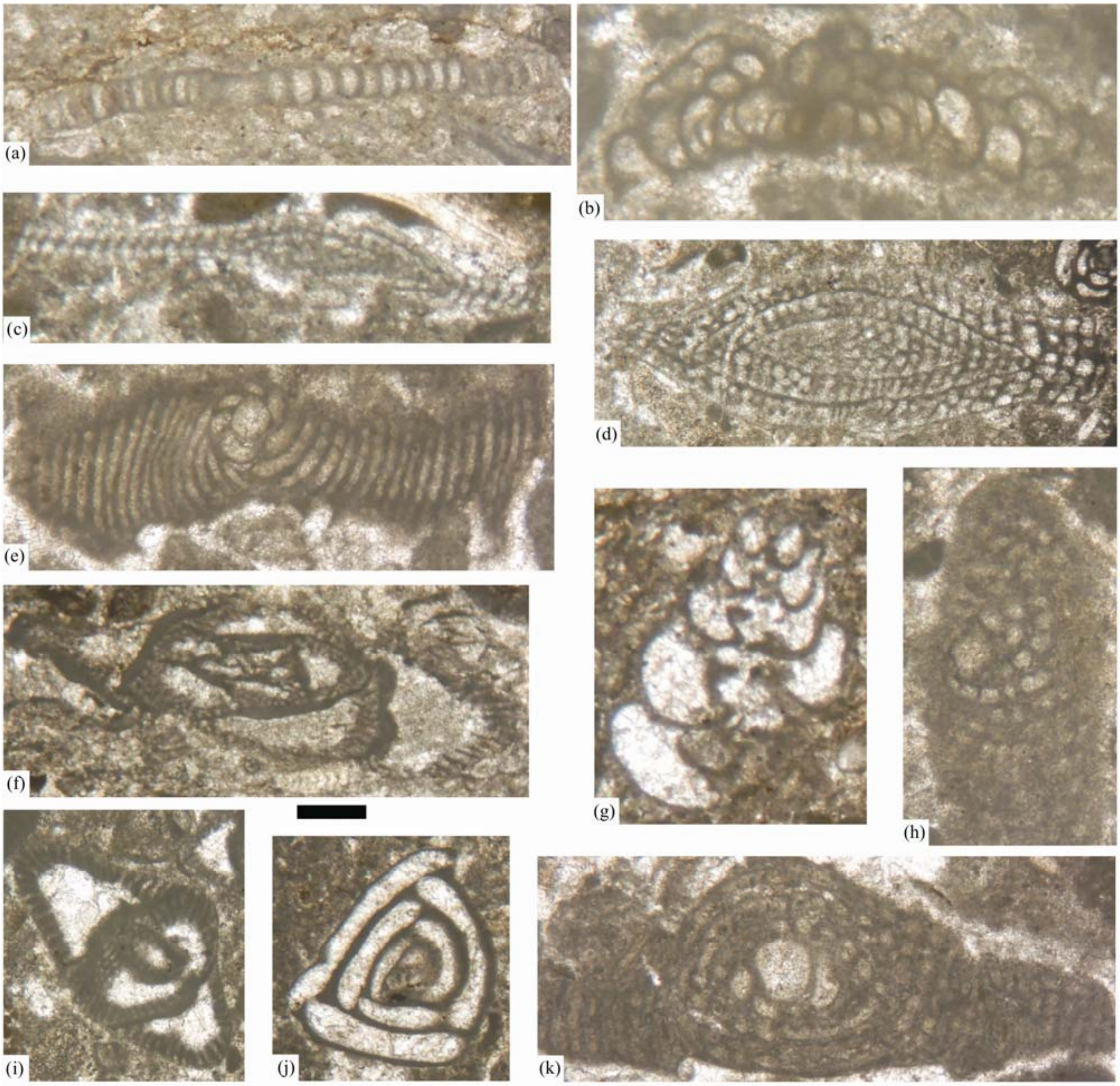

Fig. 9. Representative benthic foraminifera from the Asmari Formation in the Papoon section.
(a), *Sorites* sp., Chattian, Axial section, Sample no. P96; (b), *Planorbulinella larvata* (after Parker and Jones, 1865), Oligocene, Axial section, Sample no. P292; (c), *Archaias asmaricus* (after Smout and Eames, 1958), Chattian, Sub-axial section, Sample no. P324; (d, h, k), *Archaias kirkukensis* (after Henson, 1950), Chattian; (d), Subaxial section, Sample no. 323; (h), equatorial section, Sample no. P323; (k), equatorial section, Sample no. P104; (e) *Peneroplis flabelliformis* Sirel and Özgen-Erdem, Oligocene, Equatorial section, Sample no. P93; (f) *Austrotrillina asmariensis* (after Adams, 1968), Oligocene, Equatorial section, Sample no. P95; (g), valvulinid, Oligocene, Axial section, Sample no. P310; (i) *Austrotrillina howchini* (after Schlumberger, 1900), Oligocene, Equatorial section, Sample no. P83; (j), *Triloculina trigonula* (after Lamarck, 1801), Oligocene, Equatorial section, Sample no. P98.

then correlate with the Chattian SB zones 22B and 23 of Cahuzac and Poignant (1997). However, according to Cahuzac and Poignant (1997), *Miogypsinoides* is absent in SB zone 22B (early Chattian) and its occurrence is restricted to SB zone 23 (late Chattian; see also Ferràndez-Cañadell and Bover-Arnal 2017). Therefore, the SB zone 22B of Cahuzac and Poignant (1997) is either not represented in the Papoon section, or it is restricted between meter 150.8 and the first occurrence of *Miogypsinoides complanatus*, or it can even include or comprise the uppermost part of the *Nummulites vascus–N. fichteli* Assemblage Zone. In this respect, the correlation between the current larger foraminiferal biostratigraphic framework of the Asmari Fm. (Laursen et al. 2009; Van Buchem et al. 2010) and the larger foraminiferal biozonation of western European basins (Cahuzac and Poignant 1997) is not so straightforward.

From meter 267.8, which records the last occurrence of

Archaias, to the top of the Asmari Fm. logged, the succession contains rare specimens of *Peneroplis*, *Sorites*, *Elphidium* and miliolids (Fig. 6). The overlying *Miogypsina–Elphidium* sp. 14–*Peneroplis farsenensis* Assemblage Zone of Aquitanian age (Laursen et al. 2009; Van Buchem et al. 2010) was not recognized in the section studied owing to the absence of the index species *Miogypsina*. The absent *Miogypsina* might be related to the upwards-shallowing trend of the sedimentary succession recorded at Papoon (Fig. 4). Today, *Miogypsina* inhabits the lower part of the upper photic zone, between *ca*. 40 and 80 m (Hottinger, 1997). Accordingly, this latter stratigraphic interval at Papoon is ascribed to what Laursen et al. (2009) termed the 'Indeterminate Zone'. This Indeterminate Zone encompasses most of the Aquitanian stage (Laursen et al., 2009; Van Buchem et al., 2010).

5.2 Changes in accommodation

The Oligo-Miocene carbonates of the Asmari Fm. have previously been analysed by means of sequence stratigraphy in different areas of the Zagros Mountains by numerous authors. The published studies highlight differences, or distinct interpretations by the different authors, in the sequential arrangement and age of the Asmari limestones throughout Iran. In the Interior Fars sub-province, southeastern Zagros Mountains, Habibi (2016a, b) arranged different Asmari exposures into two depositional sequences of Rupelian age, and an aggrading transgressive unit of late Rupelian–Chattian age.

In the Dezful Embayment, northwestern Zagros Mountains, Ehrenberg et al. (2007) recognized nine surfaces with sequence-stratigraphic significance that bound eight depositional sequences of late Rupelian to early Burdigalian age. Also in this area, Van Buchem et al. (2010) interpreted up to six transgressive-regressive sequences, which comprise the Rupelian–early Burdigalian time interval and give rise to the Asmari Fm. in this province. In the same structural zone, Vaziri-Moghaddam et al. (2010) recognized for the Asmari Fm. four depositional sequences of Chattian to Burdigalian age.

Adabi et al. (2016) interpreted the Asmari Fm. of the northeastern part of the Izeh Province, northeastern Zagros Mountains, as having recorded three depositional sequences of Oligocene age and three further depositional sequences that include the late Chattian–Burdigalian time interval. In the southeastern part of the same province, Shabafrooz et al. (2015) also subdivided the Asmari Fm. into six depositional sequences of Rupelian to Burdigalian age. Allahkrarampour Dill et al. (2018) recognized a total of six depositional units, three of Rupelian age and three of Chattian age in the Izeh and Fars provinces.

In the Asmari record studied in the Papoon section (Figs. 3–4), erosional truncations, stratal terminations or stacking patterns were not recognized. Accordingly, the arrangement of the Asmari Fm. into systems tracts and depositional sequences, *sensu* Van Wagoner et al. 1988, was not possible in this particular outcrop. However, the base of the studied Asmari Fm., which overlies the *Globigerina* marls of the Pabdeh Fm. (Fig. 3b), marks a lithological change and a large-scale facies shift from deepening- to shallowing-upwards (Fig. 4). In this regard, the regressive limestones of the Asmari Fm. are interpreted to downlap over the deeper-water marls of the Pabdeh Fm. In seismic stratigraphy, the surface downlapped by regressive strata above transgressive deeper deposits corresponds to a maximum-flooding surface (e.g., Catuneanu et al., 2011).

The vertical sedimentary evolution of the Asmari Fm. in Papoon marks a progressive long-term regression (Fig. 4). The facies characterized (Figs. 4–5) commence with an alternation of limestones, marly-limestones and marls rich in planktonic foraminifera (FA 2), and progressively shallow upwards recording six additional carbonate platform facies (FA3-FA8). The succession ends with coastal to supratidal deposits of marls, conglomerates and evaporites belonging to the Gachsaran Fm. (FA 9) (Fig. 4). Consequently, the succession studied including the top of the Pabdeh Fm., the entire Asmari Fm., and the base of the Gachsaran Fm. can be characterized as a low-order high-rank, *sensu* Catuneanu et al. 2009, transgressive-regressive sequence (Fig. 4).

There were, however, higher-order lower-rank changes of relative sea level that controlled accommodation during the deposition of the Asmari carbonates. These higher-frequency sea-level fluctuations are mainly highlighted between meters 24 and 205, from the *Globigerina* spp.–*Turborotalia cerroazulensis–Hantkenina* Assemblage Zone to *Archaias asmaricus–Archaias hensoni–Miogypsinoides complanatus* Assemblage Zone, by the alternation and repetition of facies (Fig. 4).

The resulting interpreted transgressive-regressive sequence (Fig. 4) does not coincide with previously reported sequence-stratigraphic analyses. Nevertheless, the lower-order higher-rank regression of relative sea level characterized, lasting from the Rupelian to the Aquitanian, is in agreement with Haq et al.'s (1987) long-term eustatic curve for this time period. Therefore, eustatism would have played a part in controlling the long-term changes in accommodation interpreted in the Papoon section.

In consequence, in the Papoon section, the Asmari Fm. can be seen as the result of long-term prograding carbonate platform growth and thus, as a regressive systems tract (*sensu* Embry and Johannessen 1992). In this regard, similar prograding Asmari carbonate bodies are shown in the schematic sequence-stratigraphic cross-sections found in Van Buchem et al. (2010), Shabafrooz et al. (2015) and Allahkarampour Dill et al. (2018).

5.3 Depositional model

Despite the one-dimensionality of the outcrop studied in the Papoon section, a depositional model for the facies examined is proposed herein (Fig. 10). The model results from the application of the Walter's Law of Facies along the long-term regression (regressive systems tract) recorded by the Asmari Fm. (Fig. 4), together with the ascription of lithologies, textures and fossil species determined to an interpreted paleoenvironmental/ paleoecological setting or water depth based on the facies analysis and the literature (e.g., Hardie, 1977; Hallock and Glenn, 1986; Hottinger, 1997; Hohenegger et al., 2000; Geel, 2000; Romero et al., 2002; Beavington-Penney, 2004; Beavington-Penny and Racey, 2004; Van Buchem et al., 2010; Brandano et al., 2017).

The facies rich in planktic foraminifera (FA1 and 2; Figs. 4, 5a) are interpreted to have been formed in the most distal platform settings (e.g., Van Buchem et al., 2010; Janson et al., 2010; Bover-Arnal et al., 2017; Brandano et al., 2017; Allahkarampour Dill et al., 2018), below the base of the upper photic zone (*sensu* Hottinger, 1997) (Fig. 10), which is marked by the occurrence of *Operculina complanata* (FA3, Fig. 5b) and was located at around 80 m water depth in Oligocene carbonate platforms. Moreover, the occurrence of glauconite in FA2 is indicative of low sedimentation rates (Amorosi, 1997).

The occurrence of A-form *Operculina* in FA3 (Figs. 4, 5b) indicates the lowermost euphotic zone (e.g., Hottinger, 1997; Nebelsick et al., 2005). *Operculina* is a symbiont-bearing genus and very low light levels inhibit photosynthesis and limit its sexual reproduction. (Hottinger, 1997; Leutenegger, 1977; Beavington-Penny and Racey, 2004). Accordingly, this microfacies was deposited in a distal platform setting, in a more proximal position than FA2 (Fig. 10).

Rudstone textures of FA4 (Figs. 4, 5c) contain larger foraminifera that thrived in the upper part of the upper photic zone, above ca. 40 m (Hottinger, 1997), such as *Archaias*, *Austrotrillina* and *Neorotalia*, as well as in the lower part of the upper photic zone, between ca. 40 and 80 m (Hottinger, 1997), such as lepidocyclinids, *Operculina* and *Heterostegina*. This fact indicates mixing of biota and thus, significant re-mobilization of skeletal components throughout the platform (e.g., Bover-Arnal et al., 2017: Fig. 10). Abrasion and fragmentation of larger foraminifera and other bioclastic components are also indicative of moderate and extensive re-working (e.g., Beavington-Penney, 2004).

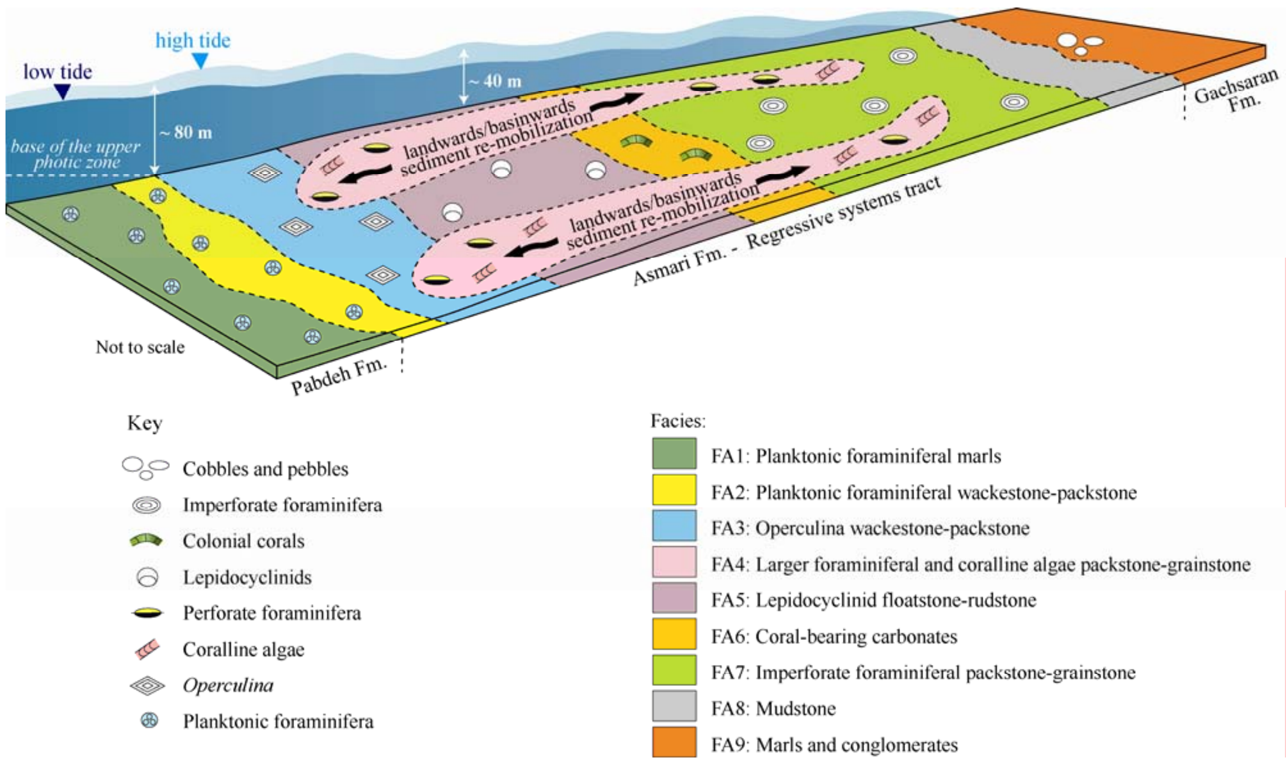

Fig. 10. Schematic reconstruction of facies spatial distribution along a carbonate ramp depositional profile during the long-term regression recorded by the Asmari Formation in the Papoon section. Not to scale. The depositional model results from the application of Walter's Law of Facies.

The lepidocyclinid-bearing limestones (FA5, Fig. 5d) were deposited mainly in the lower part of the upper photic zone (between *ca*. 40 and 80 m water depth, following Hottinger (1997) (Fig. 10) and thus, indicate mid to distal platform settings (e.g., Beavington-Penny and Racey, 2004; Bassi and Nebelsick, 2010; Brandano et al., 2012, 2016; Brandano, 2016). *Eulepidina*, which is the characteristic component of this facies, was a relatively deep-water foraminifera inhabiting the lower photic zone (e.g., Buxton, 1988; Schiavinotto and Verrubbi, 1994; Brandano et al., 2012, 2016). This interpretation is further reinforced by the presence of planktonic foraminifera and elongate *Operculina* and *Heterostegina*, which indicate low light conditions (e.g., Hohenegger et al., 2000; Beavington-Penny and Racey, 2004). In addition, the observed abraded and fragmented tests of foraminifera indicate sediment transport. Locally, fragmentation of *Eulepidina* tests corresponds to a post-depositional feature linked to sediment compaction.

The coral- and imperforate foraminifera-dominated facies (FA6 and 7; Fig. 5e) were situated in the upper part of the upper photic zone (*sensu* Hottinger, 1997), in proximal platform settings (Fig. 10; e.g., Geel, 2000; Romero et al., 2002; Van Buchem et al., 2010; Brandano et al., 2017). Coeval and similar non-reef-building coral communities have been interpreted to have flourished in a proximal to mid platform environment (e.g., Van Buchem et al., 2010; Pomar et al., 2014; Bover-Arnal et al., 2017; Allahkarampour Dill et al., 2018). The fact that most of the colonies are wholly encrusted by coralline algae is indicative of low sedimentation rates and at least moderate time of residence on the sea floor after death of the recognized colonial corals.

On the other hand, the abundance of imperforate foraminifera and low diversity of perforate foraminifera present in FA7 are commonly taken as evidence for restricted shallow-subtidal environments including lagoons (e.g., Geel, 2000; Romero et al., 2002; Habibi, 2016a, b). In this respect, symbiont-bearing porcellaneous imperforate foraminifera such as peneroplids and miliolids are nowadays adapted to phytal substrates and thus, indicative of sea grass meadows in proximal platform settings under euphotic conditions, between 0 and 30 m water depth (e.g., Hallock and Glenn, 1986; Hottinger, 1997; Beavington-Penny and Racey, 2004; Tomassetti et al., 2016; Reich et al., 2015). In such shallow-subtidal settings, wackestone textures indicate lower-energy conditions, whereas packstone and grainstone textures were formed under the influence of waves and tides. Bioerosion, abrasion, fragmentation and encrustation of skeletal components is indicative of low sedimentation rates. The rare presence of charophytes indicates sporadic re-working of skeletal components from nearby coastal brackish settings into shallow-subtidal environments during high-energy events such as storms.

The bioturbated mudstone textures of FA8 (Figs. 4, 5f) with scarce or absence of fossil content are interpreted as having been formed in proximal intertidal platform settings (Fig. 10) with a fluctuating salinity (i.e., lime mud tidal flats; Hardie, 1977; Van Buchem et al., 2010). The marls, conglomerates, carbonates and evaporates of the Gachsaran Fm. (FA 9) are commonly interpreted as shallow subtidal, intertidal and supratidal deposits (e.g., Pirouz et al., 2011; Habibi and Ruban, 2017). Marls and limestones were formed in very shallow subtidal settings, whereas evaporites would have originated in intertidal to supratidal sabkha environments (e.g., Pirouz et al., 2011; Rezaee and Salari, 2016). Therefore, the vertical evolution of the facies characterized (Fig. 4) indicates a progressive shallowing of the facies belts (Fig. 10).

The depositional profile of the Asmari Fm. in the Zagros Mountains has been mostly interpreted as a carbonate ramp (e.g., Vaziri-Moghaddam et al., 2010; Shabafrooz et al., 2015; Habibi, 2016a). On the other hand, Allahkarampour Dill et al. (2018) propose that the depositional profile of the Asmari Fm. from the Izeh, Dezful Embayment and Sub-Coastal Fars zones had four stages of evolution: i) a distally-steepened ramp (early Rupelian–early Chattian); ii) a flat-topped platform dominated by coral build ups (mid–late Chattian); iii) a homoclinal ramp (Aquitanian); and iv) a flat-topped platform (Burdigalian). Bulging of strata, step-like geometries and coral build-ups have also been reported in Asmari carbonates from the Izeh Province (e.g., Van Buchem et al., 2010; Shabafrooz et al., 2015).

Nevertheless, such geometrical features and bioconstructions have not been recognized in the Asmari Fm. examined near Papoon village. Although the absence of bulges, platform steps or coral frameworks could be related to the limited lateral extent of the outcrop analyzed, the depositional profile of the Asmari carbonates cropping out in the Papoon section during the characterized regressive systems tract is interpreted as a homoclinal ramp (Fig. 10). The absence of a barrier margin is in agreement with the widespread and recurrent occurrence of re-worked rudstone textures made up of skeletal components transported by hydrodynamic flows from diverse platform settings along the succession investigated (Figs. 4, 5c, 10). In this regard, coeval carbonate platform systems from the Tethys and Caribbean are mainly interpreted as ramps (e.g., Brandano et al., 2009, 2012, 2017; Bassi and Nebelsick, 2010; Pomar et al., 2014, 2015; Bover-Arnal et al., 2017; Castillo et al., 2017; Albert-Villanueva et al., 2018).

6 Conclusions

The newly examined section of the Asmari Fm. in the western Fars sub-basin shows a general picture in terms of facies very similar to other Asmari outcrops of the Zagros Mountains. Above the transgressive marls with planktonic foraminifera of the Pabdeh Fm., the lower part of the Asmari Fm. is made up of distal platform carbonates rich in planktonic foraminifera, *Operculina* and lepidocyclinids, whereas its upper part is dominated by deposits characterized by the presence of corals and imperforate foraminifera, and by peritidal mudstones. Coarse grain-supported textures formed by abraded and fragmented symbiont-bearing benthic foraminifera and coralline algae transported from distinct platform settings are recurrent throughout the studied Asmari succession, and mark episodes of re-working and sediment export throughout a depositional system lacking a barrier margin. In this regard, the carbonate rocks analyzed are interpreted to have been generated in a carbonate ramp system.

The taxonomic determination of larger foraminifera permitted the identification of index species such as *Nummulites vascus*, *Archaias asmaricus*, *Archaias hensoni*, *Spiroclypeus blanckenhorni* and *Miogypsionoides complanatus*. According to the most recent foraminifera-based biostratigraphic framework for the Asmari Fm. of the Zagros Mountains, the stratigraphic ranges of these fossils permitted the characterization of four biozones: the Rupelian *Globigerina–Turborotalia cerroazulensis–Hantkenina* Zone and *Nummulites vascus–Nummulites fichteli* zones, the Chattian *Archaias asmaricus–Archaias hensoni–Miogypsinoides complanatus* Zone; and the Aquitanian Indeterminate Zone. Therefore, the biostratigraphy of larger foraminifera carried out constrains the age of the Asmari Fm. in the environs of Papoon village as Rupelian to Aquitanian in age. However, the correlation of this biostratigraphic framework for the Asmari Fm. with the Oligo-Miocene larger foraminifera biozonation established for the European basins is problematic.

The vertical facies evolution recognized for the Asmari Fm. exhibits a progressive shallowing and thus, the succession is interpreted as having been deposited during a high-rank low-order regressive systems tract. The most regressive deposits correspond to the marls, conglomerates and evaporites of the Gachsaran Fm. This long-lasting Rupelian–Aquitanian regressive event is in accordance with published global long-term eustatic curves. Therefore, eustatism would have been an important factor controlling accommodation during the deposition of the Asmari Fm. in the western Fars sub-basin.

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