

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

Tahereh HABIBI^{1, *}, Telm BOVER-ARNAL²

¹ Department of Earth Sciences, College of Sciences, Shiraz University, 71454 Shiraz, Iran

² Departament de Mineralogia, Petrologia i Geologia Aplicada, Facultat de Ciències de la Terra, Universitat de Barcelona, Martí i Franquès s/n, 08028 Barcelona, Spain

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–Miogypsinoidea 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.

Keywords: Foraminifera; biostratigraphy; sequence stratigraphy; carbonate platform; Oligocene; Zagros Basin; Iran

* corresponding author Email: thabibi@shirazu.ac.ir;

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), coming to prominence during the late Paleozoic. 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; Ferrández-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 Warman 1970; Ala 1982). Oil in the fractured reservoirs of the Asmari Fm. is mainly trapped in the Zagros Mountains along wide and gentle antiformal 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 systems in terms of chronostratigraphy and sedimentology (e.g., van Buchem et al. 2010; Vaziri-Moghaddam et al. 2006, 2010; Adabi et al. 2016; 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 intra-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, C).

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 evaporites 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 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 (P numbers).

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 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.

4.1.1 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.

4.1.2 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.

4.1.3 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.

4.1.4 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, *Austrorillina*, *Sphaerogypsina*, *Planorboulinoidea*, *Elphidium*, *Reusella*, *Triloculina* and other miliolids are also present. Coralline algae mainly occur as fragments of non-geniculate specimens. *Ditrupe* and fragments of echinoids, gastropods, dasycladaceans, bryozoans, corals, oysters and of other bivalves are also present. Ooid grains occur locally.

4.1.5 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 foraminifera 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 *Ditrupe*.

4.1.6 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).

4.1.7 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 *Austrorillina*, *Meandropsina*, valvulinids, *Archaias*, *Borelis*, *Peneroplis*, *Sorites*, *Triloculina*, *Biloculina*, *Sivasina* and other undetermined miliolids. Perforate foraminifera are less abundant and represented by robust tests of *Neorotalia*, *Heterostegina*, *Amphistegina*, *Nephrolepidina*, *Ammonia*, *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 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.

4.1.8 FA8: Mudstone

This facies is composed of dense micritic textures with scarce fragments of skeletal components (Figs 4, 5F). Bioturbation features, peloids and quartz grains occur scattered in these micrite deposits.

4.1.9 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* (Figs. 7D-E), *Operculina complanata* (Figs. 7G, I), *Heterostegina assilinoidea* (Figs. 7B-C), *H. praecursor* (Figs. 7 L, N), *Nephrolepidina praemarginata*, *N. morgani* (Figs. 8E-F), *N. turneri*, *N. partita* (Fig. 8B), *Nephrolepidina* sp. (Fig. 8J), *Eulepidina elephantina* (Figs. 8D, G), *E. dilatata* (Fig. 8C), *E. raulini* (Fig. 8A), *Neorotalia viennoti*, *Amphistegina mammilla* (Figs. 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 foraminifera determined are *Miogyssinoides complanatus* (Figs. 8H-I, K), *Spirochlopeus blanckenhorni* (Fig. 7H), *Archaias kirkukensis* (Figs. 9D, G, J), *Ar. asmaricus* (Fig. 9C), *Ar. hensoni*, *Peneroplis flabelliformis* (Fig. 9E), *P. evolutus*, *P. thomasi*, *P. sp.*, *Neorotalia viennoti* (Figs. 7F, J), *Sorites* sp. (Fig. 9A), *Miogyssinoides* 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 the *Globigerina* spp.–*Turborotalia cerroazulensis*–*Hantkenina* Assemblage Zone (Laursen et al., 2009).

Meter 42.9 is characterized by the first occurrence of *Operculina complanata* and *Amphistegina* sp. (Fig. 6). Above this level and until meter 150.8, the foraminiferal assemblage includes species such as *Heterostegina assilinoidea*, *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*, *Miogypsinoidea complanatus*, *Miogypsinoidea* sp., *Spiroclypeus blanckenhorni*, *Peneroplis flabelliformis*, *P. evolutus*, *P. thomasi*, *P. sp.*, *Neorotalia viennoti*, *Sorites* sp., *Sphaerogypsina globulosa*, *Elphidium* sp., *Discorbis* sp., *Austrotrillina howchini*, *A. asmariensis*, *Triloculina trigonula*, other unidentified miliolids and undetermined planktonic foraminifera (Fig. 6). The concurrence of *Spiroclypeus blanckenhorni*, *Miogypsinoidea complanatus*, *Archaias asmaricus* and *Ar. hensoni* defines the *Archaias asmaricus*–*Archaias hensoni*–*Miogypsinoidea complanatus* Assemblage Zone of Chattian age (Laursen et al. 2009; van Buchem et al. 2010). This assemblage zone would then correlate with the Chattian SB zones 22B and 23 of Cahuzac and Poignant (1997). However, according to Cahuzac and Poignant (1997), *Miogypsinoidea* is absent in SB zone 22B (early Chattian) and its occurrence is restricted to SB zone 23 (late Chattian; see also Ferrández-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 *Miogypsinoidea 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. Allahkrampour 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).

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 evaporites 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; Adabi et al. 2016; 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–Miogypsionoides 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.

Acknowledgements

The authors are grateful to Shiraz University for providing financial support during field work. Carles Ferràndez-Cañadell, Laura Tomassetti, Mohamed Boukhary and an anonymous reviewer are sincerely thanked for improving the manuscript. This work was supported by the I + D + i research project CGL2015-60805-P (BIOGEOEVENTS) and by the Grup de Recerca Reconegut per la Generalitat de Catalunya 2017 SGR 824 “Geologia Sedimentària”.

References

- Adabi, M.H., Kakemem, U., Sadeghi, A., 2016. Sedimentary facies, depositional environment, and sequence stratigraphy of Oligocene-Miocene shallow water carbonate from the Rig Mountain, Zagros basin (SW Iran). *Carbonates Evaporites*, 31, 69–85.
- Adams, C.G., 1968. A revision of the foraminifera genus *Austrotrillina* PARR. *Bull. Br. Museum (Nat. Hist.), Geol. (Palaeont.) Ser.*, 16(2), 71–97. – is this the ref for the taxon in Fig. 9
- Adams, T.D., Bourgeois, F., 1967. Asmari biostratigraphy. Place?: Iranian Oil Operating Companies. Geological and Exploration Division, Rep. No. 1074.
- Ala, M.A., 1982. Chronology of trap formation and migration of hydrocarbons in Zagros sector of Southwest Iran. *AAPG Bulletin*, 66, 1535-1541.
- Alavi, M., 2007. Structures of the Zagros fold-thrust belt in Iran. *American Journal of Science*, 307, 1064-1095.
- Albert-Villanueva, E., González, L., Bover-Arnal, T., Ferràndez-Cañadell, C., Esteban, M., Fernández-Carmona, J., Calvo, R., Salas, R., 2017. Geology of the Falcón Basin (NW Venezuela). *Journal of Maps*, 13, 491–501.

- Albert-Villanueva, E., Bover-Arnal, T., Ferrández-Cañadell, C., Salas, R., 2018 in press. Comment on “Tectonic and environmental factors controlling on the evolution of Oligo-Miocene shallow marine carbonate factories along a tropical SE Circum-Caribbean” by Silva-Tamayo et al. (2017). *Journal of South American Earth Sciences*, doi: 10.1016/j.jsames.2017.08.023
- Allahkarampour Dill, M., Vaziri-Moghaddam, H., Seyrafian, A., Behdad (Ghabeishavi), A., 2018. Oligo-Miocene carbonate platform evolution in the northern margin of the Asmari intra-shelf basin, SW Iran. *Marine and Petroleum Geology*, 92, 437–461. doi: 10.1016/j.marpetgeo.2017.11.008
- Amorosi, A., 1997. Detecting compositional, spatial, and temporal attributes of glaucony: a tool for provenance research. *Sedimentary Geology*, 109, 135–153.
- Avarjani, S., Mahboubi, A., Moussavi-Harami, R., Amiri-Bakhtiar, H., Brenner, R.L., 2015. Facies, depositional sequences, and biostratigraphy of the Oligo-Miocene Asmari Formation in Marun oilfield, North Dezful Embayment, Zagros Basin, SW Iran. *Palaeoworld*, 24, 336–358.
- Bahrudi, A., Talbot, C.J., 2003. The configuration of the basement beneath the Zagros Basin. *Journal of Petroleum Geology*, 26, 257–282.
- Bassi, D., 2005. Larger foraminiferal and coralline algal facies in an Upper Eocene storm-influenced, shallow-water carbonate platform (Colli Berici, north-eastern Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 226, 17–35.
- Bassi, D., Hottinger, L., Nebelsick, J.H., 2007. Larger foraminifera from the Upper Oligocene of the Venetian area, north-east Italy. *Palaeontology*, 50, 845–868.
- Bassi, D., Nebelsick, J.H., 2010. Components, facies and ramps: Redefining Upper Oligocene shallow water carbonates using coralline red algae and larger foraminifera (Venetian area, northeast Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 295, 258–280.
- Beavington-Penney, S.J., 2004. Analysis of the effects of abrasion on the test of *Palaeonummulites venosus*: Implications for the origin of nummulithoclastic sediments. *Palaios*, 19, 143–155.
- Beavington-Penney, S.J., Racey, A., 2004. Ecology of extant nummulitids and other larger benthic foraminifera: applications in palaeoenvironmental analysis. *Earth-Science Reviews*, 67, 219–265.
- Bieda, F., 1936. Miocen Brzozowej I Gromnika I jego fauna otwornicowa (Le Miocène de Brzozowa et de Gromniket sa fauna des Foraminifères). *Rocz Pol Towarz Geol.*, 12, 255–275.
- Blanckenhorn, H., 1890. Das Eocän in Syrien, mit besonderer Berücksichtigung Nord-Syriens. Ein Beitrag zur Geologie Syriens. *Zeitschrift deutschen geologischen Gesellschaft*, 42, 318–360.
- BouDagher-Fadel, M.K., 2008. Evolution and geological significance of larger benthic foraminifera. Oxford: *Developments in Palaeontology and Stratigraphy*, Elsevier, 21, 540 pp.
- Boukhary, M., Abdelghany, O., Hussein-Kamel, Y., Bahr, S., Alsayigh, A., Abdelraouf, M., 2010. Oligocene larger foraminifera from United Arab Emirates, Oman and Western Desert of Egypt. *Historical Biology*, 22, 348–366.
- Boukhary, M., Kuss, J., Abdelraouf, M., 2008. Chattian larger foraminifera from Risan Aneiza, northern Sinai, Egypt, and implications for Tethyan paleogeography. *Stratigraphy*, 5, 179–192.
- Bover-Arnal, T., Ferrández-Cañadell, C., Aguirre, J., Esteban, M., Fernández-Carmona, J., Albert-Villanueva, E., Salas, R., 2017. Late Chattian platform carbonates with benthic foraminifera and coralline algae from the SE Iberian Plate. *Palaios*, 32, 61–82.
- Brandano, M., Frezza, V., Tomassetti, L., Pedley, M., Matteucci, R., 2009. Facies analysis and palaeoenvironmental interpretation of the Late Oligocene Attard Member (Lower Coralline Limestone Formation), Malta. *Sedimentology*, 56, 1138–1158.
- Brandano, M., Lippardini, L., Campagnoni, V., Tomassetti, L., 2012. Downslope-migrating large dunes in the Chattian carbonate ramp of the Majella Mountains (Central Apennines, Italy). *Sedimentary Geology*, 255–256, 29–41.
- Brandano, M., 2016. Oligocene Rhodolith beds in the Central Mediterranean area. In: Riosmena-Rodríguez, R., Nelson, W., and Aguirre, J., eds., *Rhodolith/Maërl Beds: A global perspective*. Berlin: Springer-Verlag, pp. 195–219.
- Brandano, M., Cornacchia, I., Raffi, I., Tomassetti, L., 2016. The Oligocene–Miocene stratigraphic evolution of the Majella carbonate platform (Central Apennines, Italy). *Sedimentary Geology*, 333, 1–14.
- Brandano, M., Cornacchia, I., Tomassetti, L., 2017. Global versus regional influence on the carbonate factories of Oligocene-Miocene carbonate platforms in the Mediterranean area. *Marine and Petroleum Geology*, 87, 188–202.
- Brasier, M., 1988. Foraminiferid extinction and ecological collapse during global biological events, In: Larwood, G. (ed.), *Extinction and survival in the fossil record*. Systematics Association Special, 34, 37–64.
- Buchem, F.S.P. van, Allan, T.L., Laursen, G.V., Lotfpour, M., Moallemi, A., Monibi, S., Motiei, H., Pickard, N.A.H., Tahmasbi, A.R., Vedrenne, V., Vincent, B., 2010. In: van Buchem, F.S.P., Gerdes, K.D., Esteban, M. (Eds.), *Mesozoic and Cenozoic carbonate systems of the Mediterranean and the Middle East: Stratigraphic and diagenetic reference models*. Geological Society, London, Special Publications, 329, 219–263.

- Buxton, M.W.N., 1988. Morphology and habitat of Upper Oligocene lepidocyclinids from the Maltese Islands. *Revue de Paléobiologie*, Vol. Spéc. 2, 631–632.
- Cahuzac, B., Poignant, A., 1997. An attempt of biozonation of the European basin, by means of larger neritic foraminifera. *Bull Soc Geol France*, 168, 2, 155–169.
- Castillo, V., Benkovics, L., Cobos, C., Demuro, D., Franco, A., 2017. Perla field: the largest discovery ever in Latin America. In: R. K., Merrill and C. A., Sternbach (eds.), *Giant fields of the decade 2000–2010*. AAPG Memoir, 113, pp. 141–152.
- Catuneanu, O., Abreu, V., Bhattacharya, J.P., Blum, M.D., Dalrymple, R.W., Eriksson, P.G., Fielding, C.R., Fisher, W.L., Galloway, W.E., Gibling, M.R., Giles, K.A., Holbrook, J.M., Jordan, R., Kendall, C.G.St.C., Macurda, B., Martinsen, O.J., Miall, A.D., Neal, J.E., Nummedal, D., Pomar, L., Posamentier, H.W., Pratt, B.R., Sarg, J.F., Shanley, K.W., Steel, R.J., Strasser, A., Tucker, M.E., Winker, C., 2009. Towards the standardization of sequence stratigraphy. *Earth-Science Reviews*, 92, 1–33.
- Catuneanu, O., Galloway, W.E., Kendall, C.G.St.C., Miall, A.D., Posamentier, H. W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. *Newsletters on Stratigraphy*, 44, 173–245.
- Davoudzadeh, M., Lammerer, B., Weber-Diefenbach, K., 1997. Paleogeography, stratigraphy, and tectonics of the tertiary of Iran. *Neues Jahrb. Geol. Palaontol. -Abh.*, 205, 33–67.
- Defrance, M.J.L., 1822. *Lenticulites*, In: Cuvier, M.F., (Ed.), *Dictionnaire des Sciences naturelles*. Paris: Levrault F.G. Strasbourg et Le Normant, 25(1aa–1eo). pp. 425–453.
- Dunham R.J., 1962. Classification of carbonate rocks according to depositional texture. *American Association of Petroleum Geologists Bulletin*, 1, 108–121.
- Edinger, E.N., Risk, M.J., 1994. Oligocene-Miocene extinction and geographic restriction of Caribbean corals: roles of turbidity, temperature, and nutrients. *Palaios*, 9, 576–598.
- Ehrenberg, S.N., Pickard, N.A.H., Laursen, G.V., Monibi, S., Mossadegh, Z.K., Svana, T.A., Aqrawi, A.A.M., McArthur, J.M., Thirlwall, M.F., 2007. Strontium isotope stratigraphy of the Asmari Formation (Oligocene-Miocene), SW Iran. *Journal of Petroleum Geology*, 30, 107–128.
- Embry, A.F., Klován, J.E., 1971. A Late Devonian reef tract on Northeastern Banks Island, NWT. *Canadian Petroleum Geology Bulletin*, 19, 730–781.
- Embry, A.F., Johannessen, E.P., 1992. T–R sequence stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic- Lower Jurassic succession, western Sverdrup basin, Arctic Canada, In: Vorren, T.O., Bergsager, E., Dahl-Stamnes, O.A., Holter, E., Johansen, B., Lie, E., Lund, T.B. (Eds.), *Arctic Geology and Petroleum Potential*, vol. 2 (Special Publication). Norwegian Petroleum Society (NPF), pp. 121–146.
- Falcon, N.L., 1974. Southern Iran: Zagros Mountains. *Geological Society, London, Special Publications*, 4, 199–211.
- Ferrández-Cañadell, C., Bover-Arnal, T., 2017. Late Chattian larger foraminifera from the Prebetic Domain (SE Spain): new data on Shallow Benthic Zone 23. *Palaios*, 32, 83–109.
- Fichtel, L. von, Moll, J.P.C. von, 1798. *Testacea microscopica aliaque minuta ex generibus Argonauta et Nautilus ad naturam picta et descripta* (Microscopische und andere kleine Schalthiere aus den Geschlechtern Argonaute und Schiffer). Vienna: Anton Pichler, xii+123 pp.
- Geel, T., 2000. Recognition of stratigraphic sequences in carbonate platform and slope deposits: empirical models based on microfacies analysis of Palaeogene deposits in southeastern Spain. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 155, 211–238.
- Greig, D.A., 1935. *Rotalia viennotti*, an important foraminiferal species from Asia Minor and Western Asia. *J. Paleontol.*, 9, 523–526.
- Habibi, T., 2016a. Bio- and sequence stratigraphy and microfacies analysis of the Oligocene Asmari Formation at Sepidar Anticline, Interior Fars sub-Basin, SW Iran. *Historical Biology* 28(4), 519–532.
- Habibi, T., 2016b. Biostratigraphy, paleoenvironment and foraminiferal associations of the Rupelian–Chattian sediments in Zagros Basin, SW Iran. *Journal of African Earth Sciences*, 323:370–380.
- Habibi, T., 2017. Biostratigraphy and Systematic Paleontology of the Oligocene Larger Benthic Foraminifera from Fars Province, Zaros Basin, SW Iran. *Iran J Sci Technol Trans Sci.*, DOI 10.1007/s40995-017-0155-7.
- Habibi, T., Ruban, D.A., 2017. Outstanding diversity of heritage features in large geological bodies: The Gachsaran Formation in southwest Iran. *Journal of African Earth Sciences*, 133, 1–6.
- Hallock, P., 1988. Diversification in algal symbiont-bearing Foraminifera: a response to oligotrophy?. *Revue Paléobiol. Genève Vol. Spec.*, 2, 789–797.
- Hallock, P., 2000. Symbiont-bearing foraminifera: harbingers of global change? *Micropaleontology*, 46 (supplement 1), 95–104.
- Hallock, P., Glenn, E.C., 1986. Larger foraminifera: a tool for paleoenvironmental analysis of Cenozoic carbonate depositional facies: *Palaios*, 1, 55–64.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, 235, 1156–1166.

- Hardie, L.A., 1977. Sedimentation on the modern carbonate tidal flats of northwest Andros Island, Bahamas. Baltimore: The Johns Hopkins University Press, 202 pp.
- Henson, F.R.S., 1950. Middle eastern Tertiary Peneroplidae (Foraminifera) with remarks on the phylogeny and taxonomy of the family. Ph.D. thesis, Leiden University, 70 pp.
- Heydari, E., 2008. Tectonics versus eustatic control on supersequences of the Zagros Mountains of Iran. *Tectonophysics*, 451(1–4), 28, 56–70.
- Hohenegger, J., Yordanova, E., and Hatta, A., 2000. Remarks on West Pacific Nummulitidae (Foraminifera). *Journal of Foraminiferal Research*, 30, 3–28.
- Höntzsch, S., Scheibner, C., Brock, J.P., Kuss, J., 2013. Circum-Tethyan carbonate platform evolution during the Palaeogene: the Prebetic platform as a test for climatically controlled facies shifts. *Turkish Journal of Earth Sciences*, 22, 891–918.
- Hottinger, L., 1997. Shallow benthic foraminiferal assemblages as signals for depth of their deposition and their limitations. *Bull. Soc. Géol. France*, 168, 491–505.
- Hull, C.E., Warman, H.R., 1970. Asmari oil fields of Iran. In: Halbouty, M.T., (ed.), *Geology of giant petroleum fields*. American Association of Petroleum Geologists, Memoir 14, 428–437.
- James, G.A., Wynd, J.G., 1965. Stratigraphic nomenclature of Iranian Oil Consortium Agreement area. *American Association of Petroleum Geologists Bulletin*, 49, 2182–2245.
- Janson, X., van Buchem, F.S.P., Dromart, G., Eichenseher, H.T., Dellamonica, X., Boichard, R., Bonnaffe, F., Eberli, G., 2010. Architecture and facies differentiation within a Middle Miocene carbonate platform, Ermenek, Mut Basin, southern Turkey, In: van Buchem, F.S.P., Gerdes, K.D., Esteban, M. (Eds.), *Mesozoic and Cenozoic carbonate systems of the Mediterranean and the Middle East: Stratigraphic and diagenetic reference models*. Geological Society, London, Special Publications, 329, 265–290.
- Jaramillo-Vogel, D., Bover-Arnal, T., Strasser, A., 2016. Bryozoan beds in northern Italy as a shallow-water expression of environmental changes during the Oligocene isotope event 1. *Sedimentary Geology*, 331, 148–161.
- Joly, N., Leymerie, A., 1848. Mémoire sur les Nummulites considérées zoologiquement et géologiquement. *Mém. Acad. Sci. Toulouse*, (3), 4, 1–70.
- Kakemem, U., Adabi, M.H., Sadeghi, A., Kazemzadeh, M.H., 2016. Biostratigraphy, paleoecology, and paleoenvironmental reconstruction of the Asmari Formation in Zagros Basin, southwest Iran. *Arab. J. Geosci.*, 9, 1–15.
- Kuss, J., Boukhary, M., 2008. A new Upper Oligocene marine record from northern Sinai (Egypt) and its paleogeographic context. *Geo Arabia*, 13, 59–84.
- Lamarck, J.B., 1801. Suite des mémoires sur les fossils des environs de Paris. *Anal. Mus. Nat. d’Hist. Nat.*, 5, 237–245.
- Laursen, G.V., Monibi, S., Allan, T.L., Pickard, N.A., Hosseiney, A., Vincent, B., Hamon, Y., Van-Buchem, F.S.P., Moallemi, A., Druillion, G., 2009. The Asmari Formation revisited: changed stratigraphic allocation and new biozonation. European Association of Geoscientists & Engineers. First International Petroleum Conference & Exhibition, Shiraz, Iran. Extended abstract, pp. B29, DOI 10.3997/2214-4609.20145919.
- Lemoine, P., Douville, R., 1904. Sur le genre *Lepidocyclina* Gumbel. *Mém. Soc. géol. France*, 12/2(32), 5–41.
- Leutenegger, S., 1977. Symbiosis between larger foraminifera and unicellular algae in the Gulf of Elat, Red Sea. *Utrecht Micropaleontological Bulletin*, 15, 241–244.
- MacLeod, J.H., Majedi, M., 1972. Geological Map of Kazerron, 1:100.000 Scale. [Place?]: Iranian Oil Operating Companies.
- McQuillan, H., 1973. Small-scale fracture density in Asmari Formation of southwest Iran and its relation to bed thickness and structural settings. *Am. Ass. Pet. Geol. Bull.*, 57, 2367–2385.
- McQuillan, H., 1974. Fracture patterns on Kuh-e Asmari Anticline, southwestern Iran. *Am. Assoc. Pet. Geol. Bull.*, 58, 236–246.
- Michelotti, G., 1841. Saggio storico dei Rizopodi caratteristici dei terreni supracretacei. *Mem. Fis. Soc. Ital. Sci. Modena*, 22, 296p.
- Nebelsick, J.H., Rasser, M.W., Bassi, D., 2005. Facies dynamics in Eocene to Oligocene circumalpine carbonates. *Facies*, 51, 197–216.
- Parker, W.K., Jones, T.R., 1865. On some foraminifera from the North Atlantic and Arctic Oceans, including Davis Straits and Baffin’s Bay. *Philos. Trans. R. Soc.*, 155, 325–441.
- Pirouz, M., Simpson, G., Bahroudi, A., Azhdari, A., 2011. Neogene sediments and modern depositional environments of the Zagros foreland basin system. *Geological Magazine*, 148, 838–853.
- Pomar, L., Mateu-Vicens, G., Morsili, M., Brandano, M., 2014. Carbonate ramp evolution during the Late Oligocene (Chattian), Salento Peninsula, southern Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 404, 109–132.
- Pomar, L., Esteban, M., Martinez, W., Espino, D., Castillo De Ott, V., Benkovics, L., Castro Leyva, T., 2015. Oligocene-Miocene carbonates of the Perla Field, Offshore Venezuela: Depositional model and facies architecture. *AAPG Special Publication*, 108, 647–674.

- Reich, S., Di Martino, E., Todd, J.A., Wesselingh, F.P., Renema, W., 2015. Indirect paleo-seagrass indicators (IPSIs): A review. *Earth-Science Reviews*, 143, 161–186.
- Reuss, A. E., 1848. Die fossilen Plyparien des Wiener Tertiärbeckens. *Haidengers Naturwissenschaftliche Abhandlungen*, Wien, 2, 1–109.
- Rezaee, P., Salari, S.H., 2016. Petrography and mineralogy of Gachsaran Formation in west of Bandar-e-Abbas, Kuh-e-Namakikhamir Section, south of Iran. *J. Fundam. Appl. Sci.*, 8, 956–969.
- Romero, J., Caus, E., Rosell, J., 2002. A model for the palaeoenvironmental distribution of larger foraminifera based on late Middle Eocene deposits on the margin of the South Pyrenean basin (NE Spain). *Palaeogeography Palaeoclimatology Palaeoecology*, 179, 43–56.
- Shabafrooz, R., Mahboubi, A., Vaziri-Moghaddam, H., Ghabeishavi, A., Moussavi-Harami, R., 2015. Depositional architecture and sequence stratigraphy of the Oligo-Miocene Asmari platform; southeastern Izeh zone, Zagros Basin, Iran. *Facies*, 61, 1–32.
- Scheibner, C., Speijer, R.P., 2008. Late Paleocene–early Eocene Tethyan carbonate platform evolution — A response to long- and short-term paleoclimatic change. *Earth-Science Reviews*, 90, 71–102.
- Schiavinotto, F., Verrubbi, V., 1994. *Nephrolepidina* in the Oligo-Miocene section of the Gran Sasso (Central Apennines): environment-evolution relations: *Bollettino della Società Paleontologica Italiana*, 33, 375–406.
- Schlumberger, C., 1900. Note sur le genre *Miogypsina*. *Soc. géol. France., Ser. 3(28)*, 327–333.
- Serra-Kiel, J., Hottinger, L., Caus, E., Drobne, K., Ferrandez, C., Jauhri, A.K., Less, G., Pavlovec, R., Pignatti, J., Samso, J.M., Schaub, H., Sirel, E., Strougo, A., Tambareau, Y., Tosquella, J., Zakrevskaya, E., 1998. Larger foraminiferal biostratigraphy of the Tethyan Paleocene and Eocene. *Bulletin de la Société géologique de France*, 169, 281–299.
- Seyrafian, A., 2000. Microfacies and depositional environments of Asmari Formation at Dehdez area (a correlation across central Zagros Basin). *Carbonates Evaporites*, 15, 22–48.
- Sirel, E., 2003. Foraminiferal description and biostratigraphy of the Bartonian, Priabonian and Oligocene shallow-water sediments of the southern and eastern Turkey. *Revue de paléobiologie, Genève*, 22(1), 269–339.
- Sirel, E., Özgen-Erdem, N., Kangal, Ö., 2013. Systematics and biostratigraphy of Oligocene (Rupelian-Early Chattian) foraminifera from lagoonal-very shallow water limestone in the eastern Sivas Basin (central Turkey). *Geologia Croatica, Zagreb*, 66/2, 83–109.
- Smout, A., Eames, F.E., 1958. The genus *Archaias* (Foraminifera) its stratigraphical distribution. *Palaeontology*, 1(3), 207–225.
- Stöcklin, J., 1968. Structural history and tectonics of Iran, A review. *American Association of Petroleum Geologists, Bulletin*, 52, 1229–1258.
- Tan Sin Hok, 1930. Over cycloclypeus; vooloopige resultaten einer biostratigraphische studie. *Mijnningenieur Bandoeng Java*, 11, 233–242.
- Tomassetti, L., Benedetti, A., Brandano, M., 2016. Middle Eocene seagrass facies from Apennine carbonate platforms (Italy). *Sedimentary Geology*, 335, 136–149.
- Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G. St. C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), *Sea Level Changes – An Integrated Approach*. SEPM Special Publication, 42, 39–45.
- Vaziri-Moghaddam, H., Kimiagari, M., Taheri, A., 2006. Depositional environment and sequence stratigraphy of the Oligo-Miocene Asmari Formation in SW Iran. *Facies*, 52, 41–51.
- Vaziri-Moghaddam, H., Seyrafian, A., Taheri, A., Motiei, H., 2010. Oligocene-Miocene ramp system (Asmari Formation) in the NW of the Zagros basin, Iran: Microfacies, paleoenvironment and depositional sequence. *Revista Mexicana de Ciencias Geológicas*, 27, 56–71.
- Wynd, J., 1965. Biofacies of Iranian Oil Consortium Agreement Area. Place?: Iranian Oil Offshore Company, Report 1082 [Unpublished].

About the first author:

Fig. 1. Geological map of the study area, Fars Province, 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.

Fig. 2. Cenozoic chronostratigraphic chart of the Zagros Mountains (based on James and Wynd 1965 and Ala 1982). Fm. [this is the normal abbreviation – check figure and change if necessary]: Formation, Mbr [this is the normal abbreviation – check figure and change if necessary]: Member.

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.

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.

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.

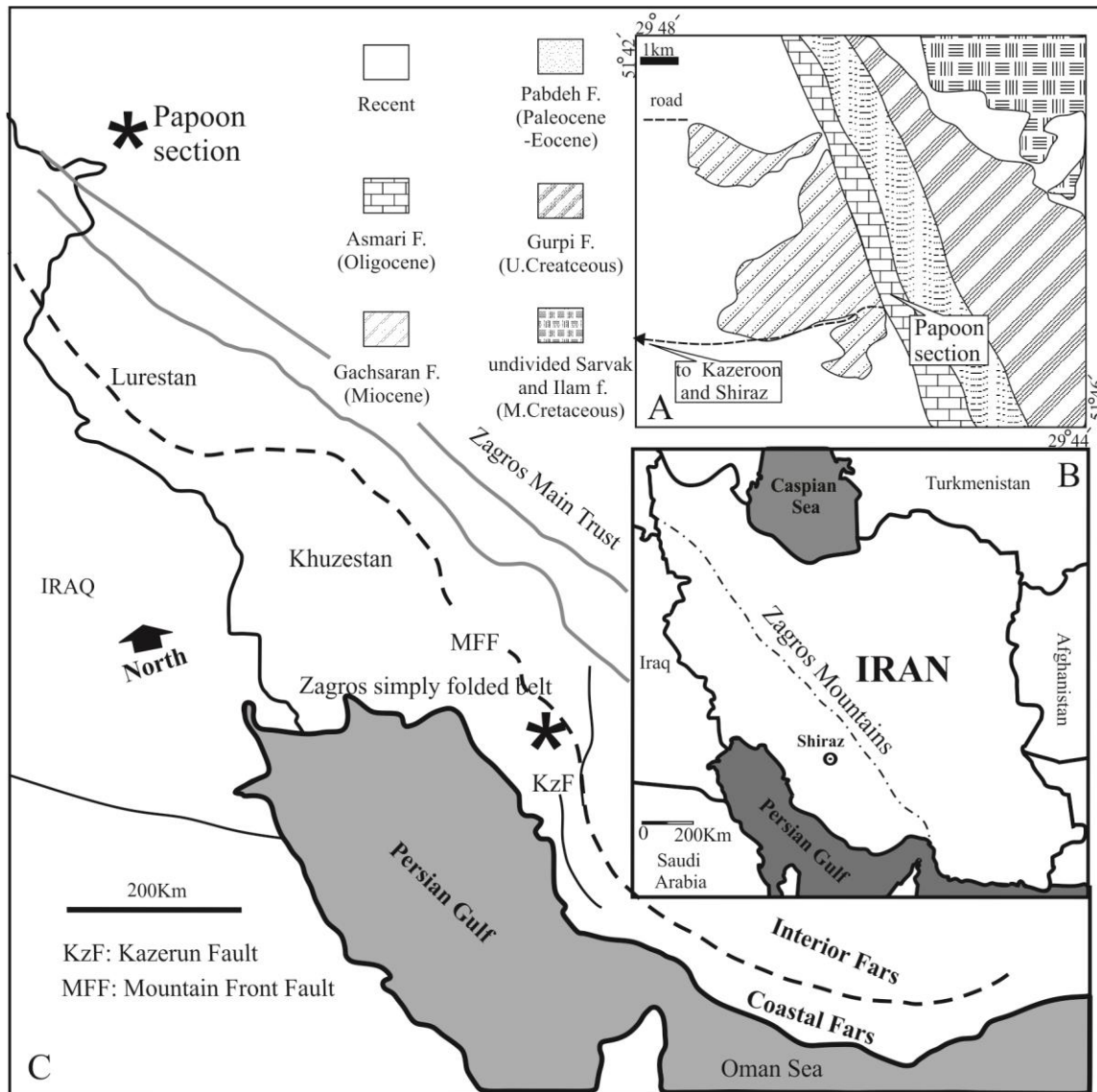
Fig. 6. Stratigraphic distribution of larger foraminifera species in the Papoon section including the biostratigraphic zonation based on Laursen et al. (2009). Key to Facies (FA) color codes, lithologies and skeletal components is shown in Figure 4.

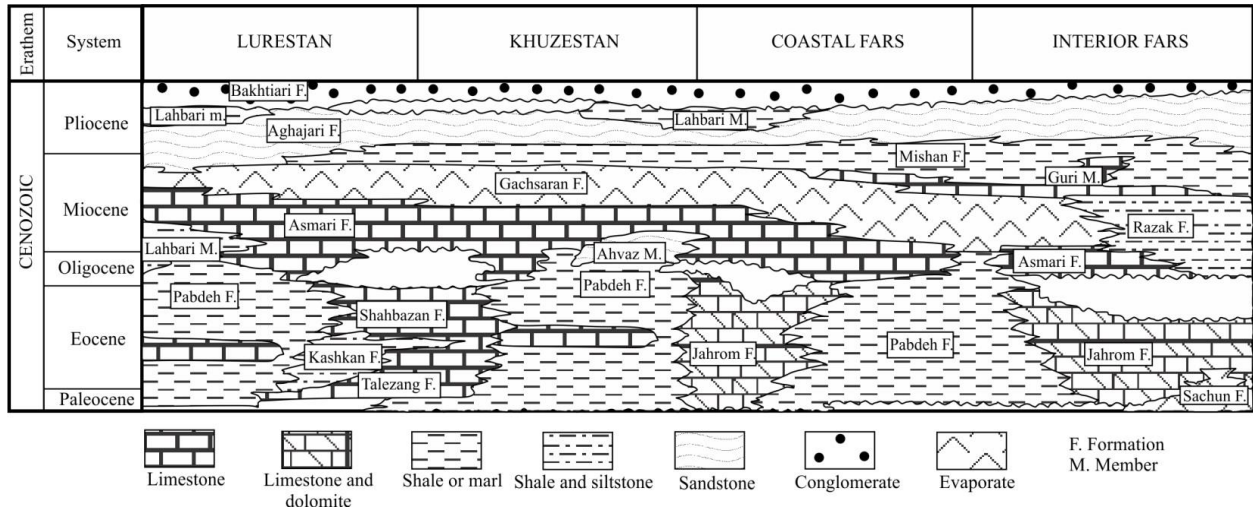
Fig. 7. Representative benthic foraminifera from the Asmari Formation in the Papoon section: (a) *Amphistegina mammilla* (Fitchel and Moll, 1798), Oligocene; Axial section, Sample no. P293; (b) *Heterostegina* cf. *assilinoidea* Blanckenhorn, 1890, Oligocene; Tangential Section, Sample no. P272; (c) *Heterostegina assilinoidea* Blanckenhorn, 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* (Greig, 1935), Oligocene; f, Equatorial section, Sample no. P305; j, Axial section, Sample no. P303. (g, i) *Operculina complanata* (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* Bieda, 1936, Oligocene, Axial section, Sample no. P300; (o) *Sphaerogypsina globulus* (Reuss, 1848), Oligocene, Equatorial section, Sample no. P294.

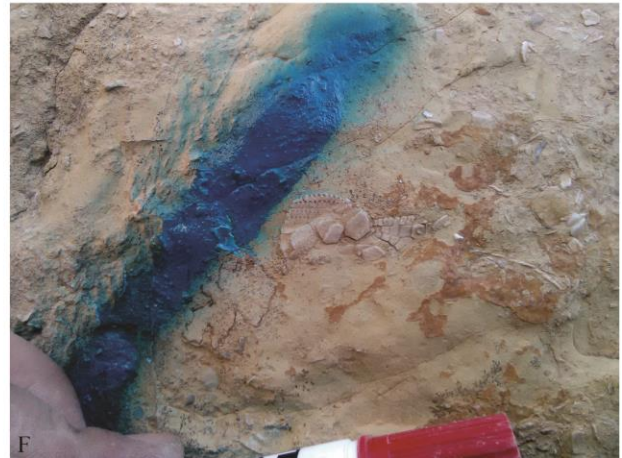
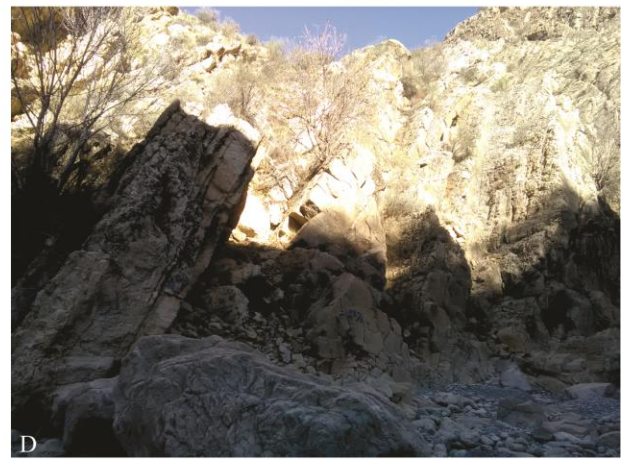
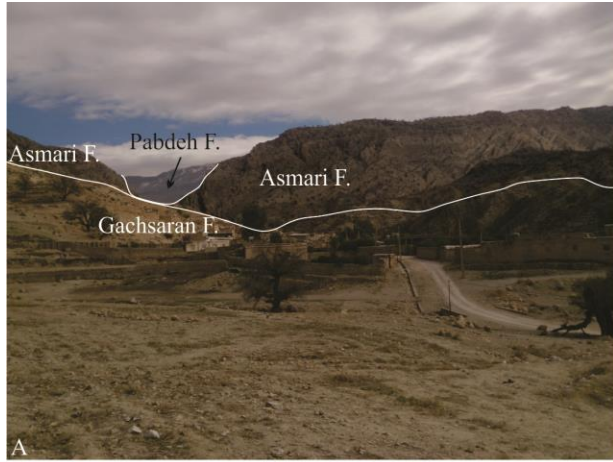
Fig. 8. Representative benthic foraminifera from the Asmari Formation in the Papoon section. (a) *Eulepidina raulini* (Lemoine and Douvillé, 1904), Rupelian, Axial section, Sample no. P297; (b) *Nephrolepidina partita* Douvillé, Rupelian, Axial section, Sample no. P290; (c) *Eulepidina dilatata* (Michelotti,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

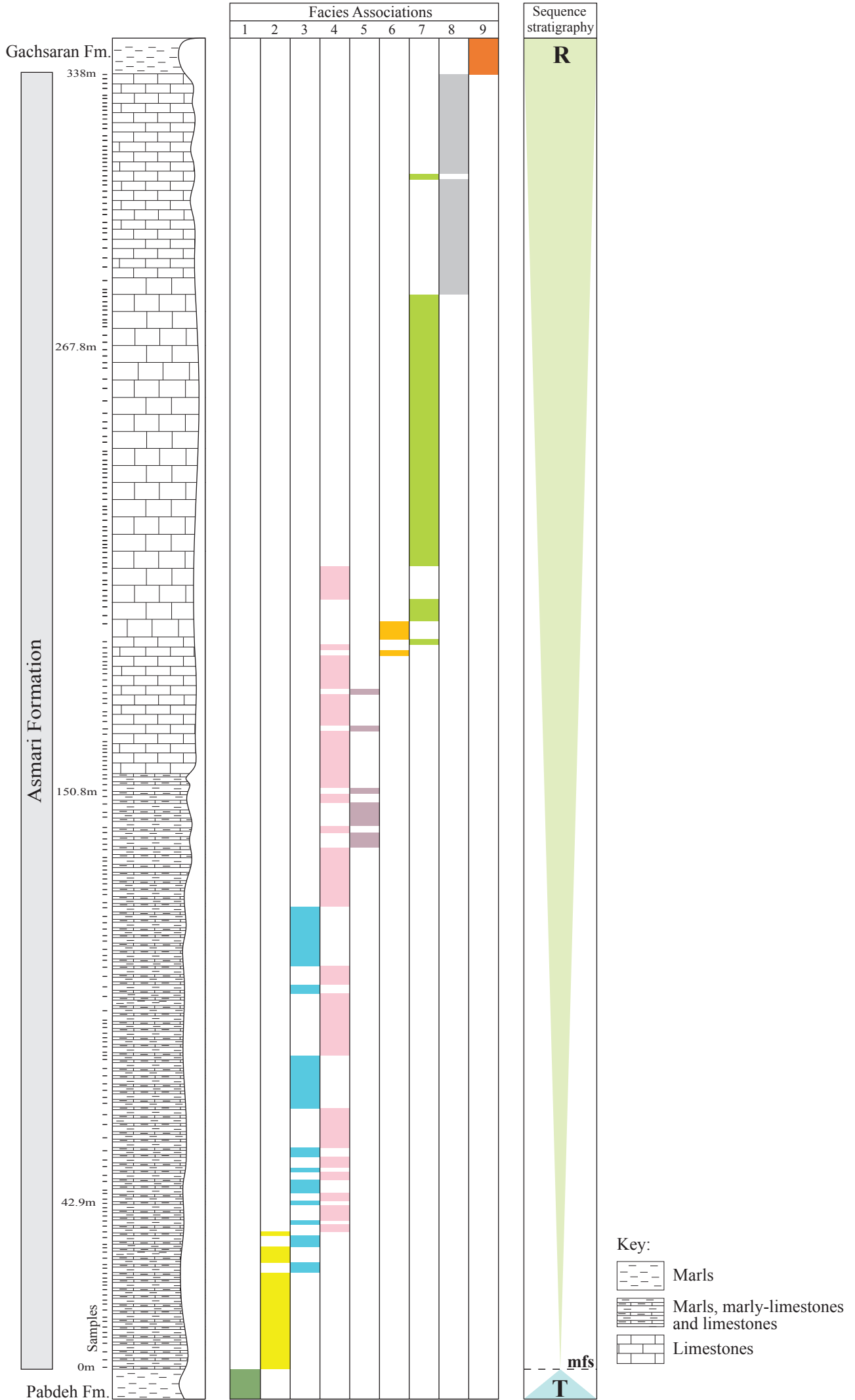
Fig. 9. Representative benthic foraminifera from the Asmari Formation in the Papoon section. (a) *Sorites* sp., Chattian, Axial section, Sample no. P96; (b) *Planorbulinella larvata* (Parker and Jones, 1865), Oligocene, Axial section, Sample no. P292; (c) *Archaias asmaricus* Smout and Eames, 1958, Chattian,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

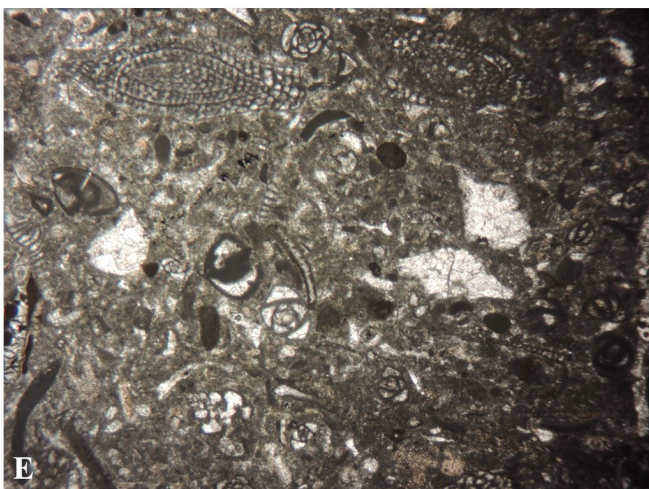
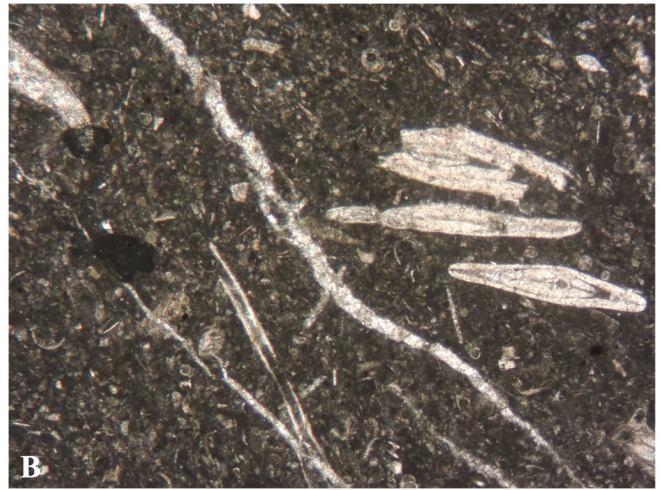
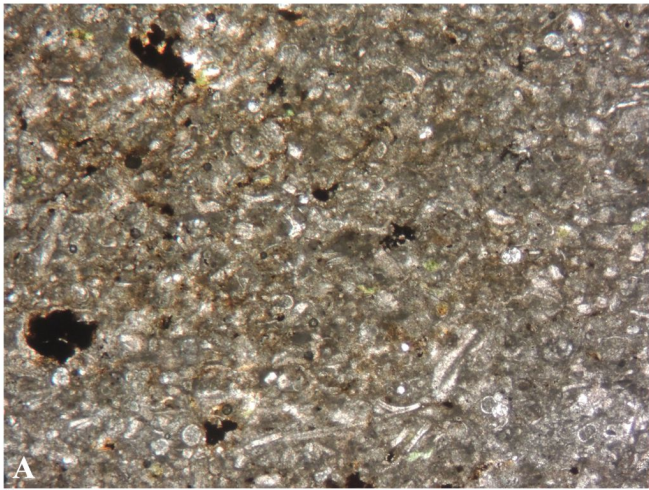
Fig. 10. Schematic reconstruction of facies spatial distribution along a carbonate ramp depositional profile during the long-term regression recorded by the Asmari Formation in the Papoon section. Not to scale. The depositional model results from the application of Walter's Law of Facies.





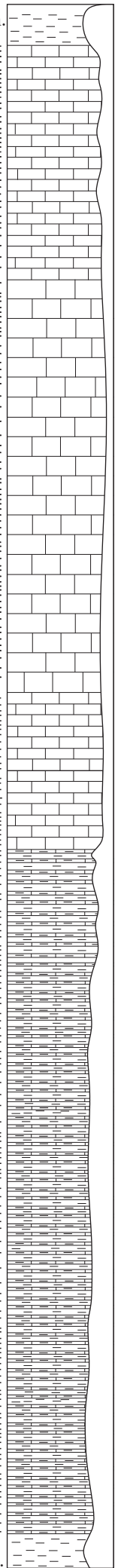






Gachsaran Fm.

Asmari Formation



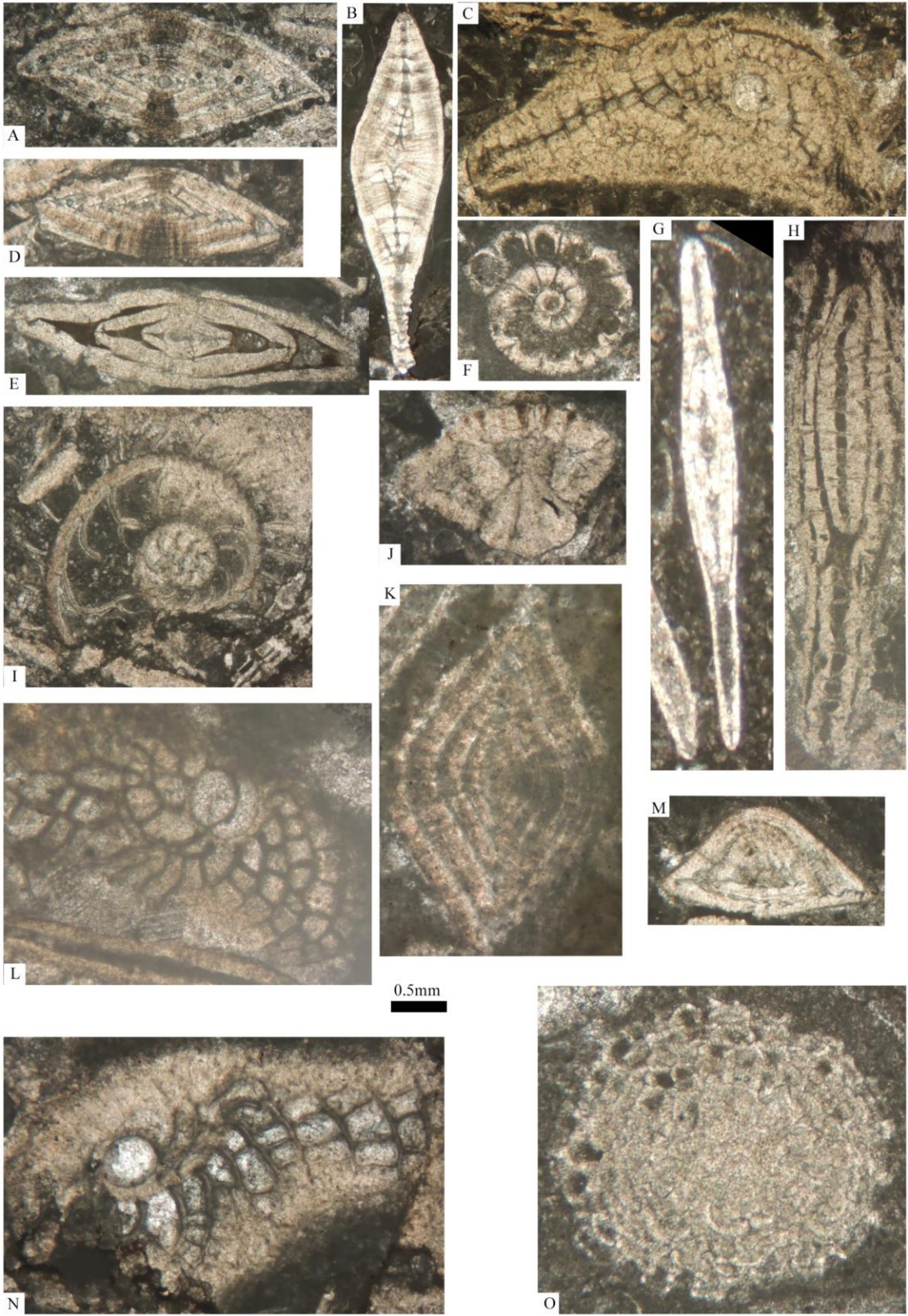
Key:

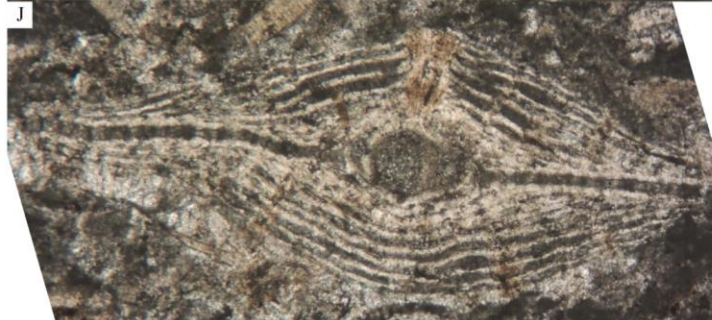
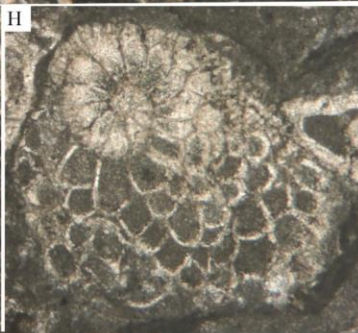
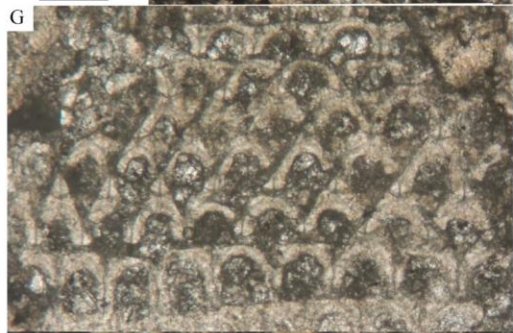
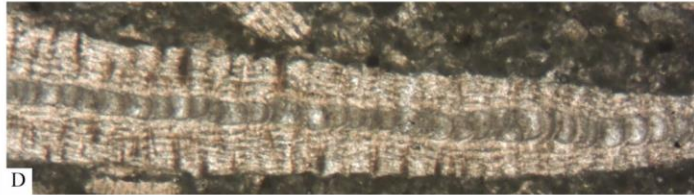
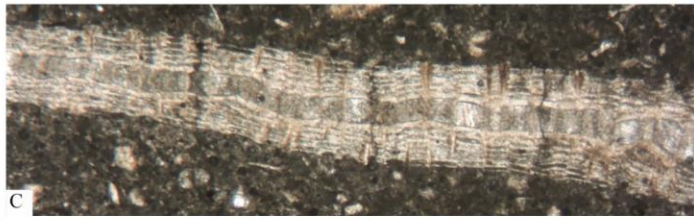


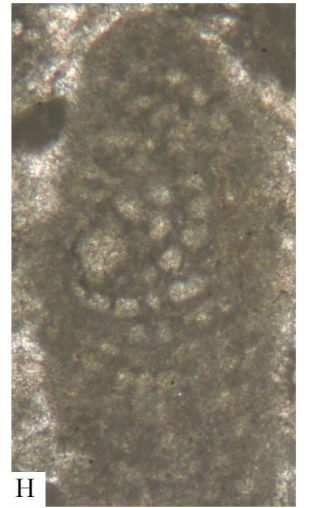
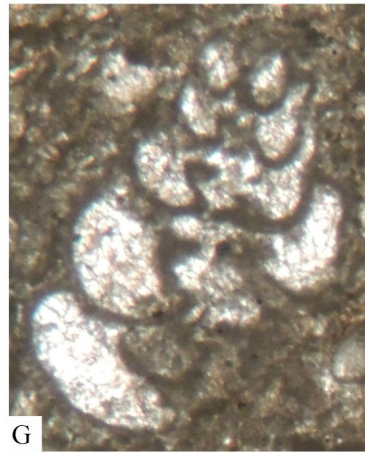
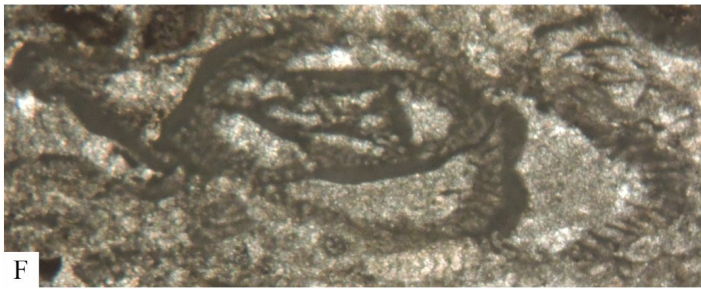
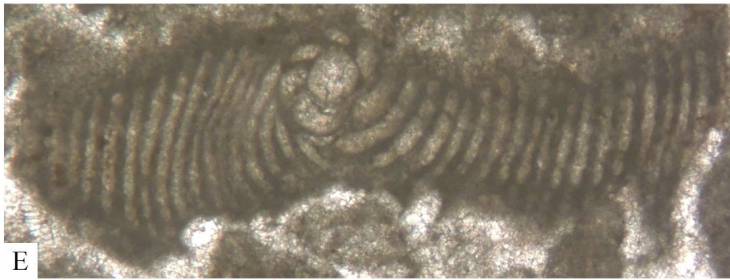
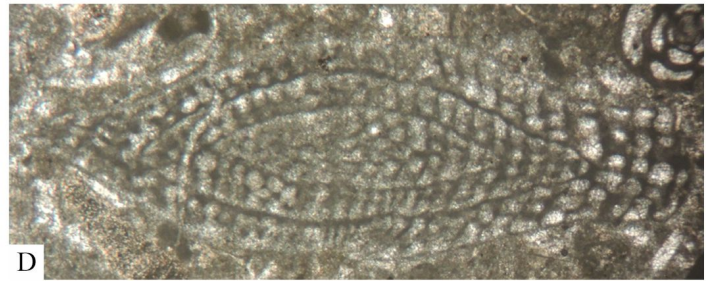
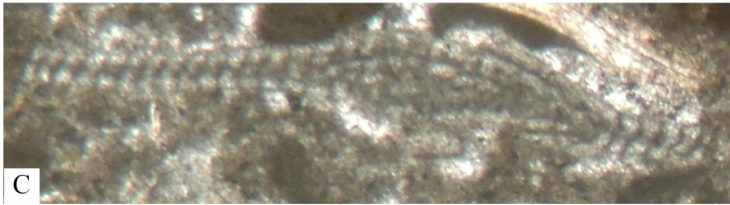
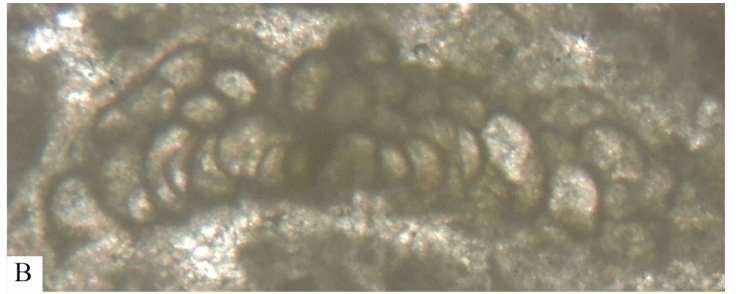
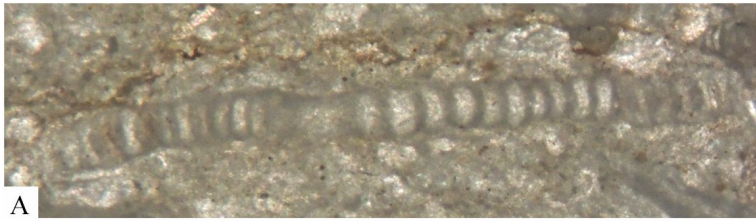
Marls
Marls, marly-limestones and limestones
Limestones

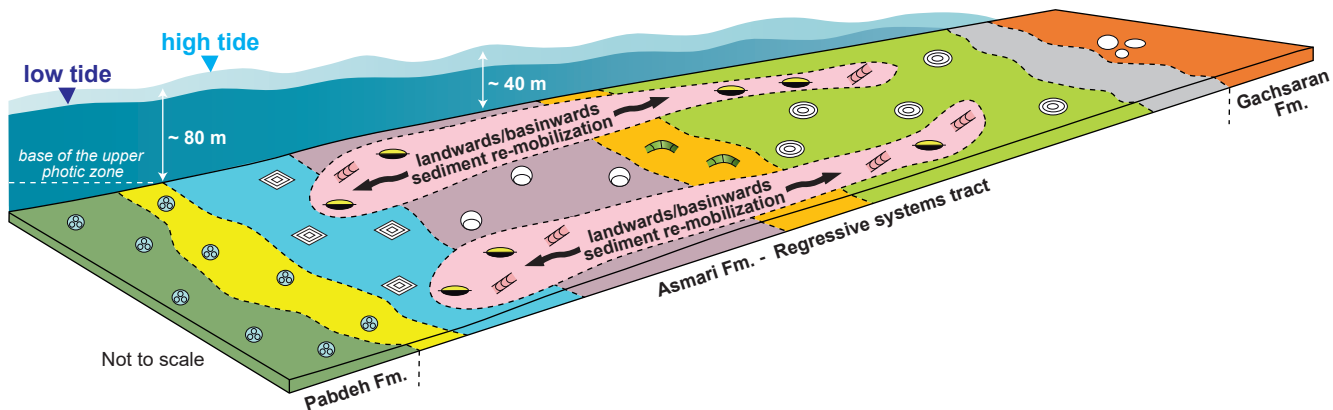
Biostratigraphic zonation	Age
<i>Globigerina-Turborotalia cerruzziensis-Hantkenina</i>	
Nummulites vascus-Nummulites fichteli	Rupelian
<i>Archaias asmaricus/hensoni-Miogypsinoidea complanatus</i>	Chatthian
Indeterminate	Aquitanian

Pabdeh Fm.









Key

- Cobbles and pebbles
- Imperforate foraminifera
- Colonial corals
- Lepidocyclinids
- Perforate foraminifera
- Coralline algae
- Operculina
- Planktonic foraminifera

Facies Associations

- FA1: Marls with planktonic foraminifera
- FA2: Planktonic foraminifera wackestone-packstone
- FA3: Operculina wackestone-packstone
- FA4: Larger foraminifera and coralline algae packstone-grainstone
- FA5: Lepidocyclinid floatstone-rudstone
- FA6: Coral-bearing carbonates
- FA7: Imperforate foraminifera packstone-grainstone
- FA8: Mudstone
- FA9: Marls and conglomerates