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Facies and paleoenvironmental reconstruction of Early–Middle Miocene deposits in the north-west of the Zagros Basin, Iran

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Abstract: Facies analysis and paleoenvironmental reconstruction of the Burdigalian to Langhian Asmari Formation, outcropping in the Khorram Abad Anticline, in the north-west of the Zagros Basin allow us to interpret the carbonate ramp history during the Early–Middle Miocene time span. The biota producing sediments in this system are dominated by the rhodalgal and echinofor skeletal-grain associations. Based on the facies distribution and paleoecology of the biotic content, the ramp is divided into three parts: inner, middle and outer ramp. The inner ramp is further subdivided into an inner zone where the main components include imperforate benthic foraminifera and molluscs associated with subordinate coral patch reefs, and an outer shallow-water zone dominated by wackestones–packstones with benthic foraminifera and coralline red algae facies. A shoal belt dominated by coralline red algae, benthic foraminifera, and coral fragments occurs in a distal inner ramp position. The middle ramp is characterized by rhodoliths, crustose red algal wackestone and thinly branching corals associated with encrusting foraminifera in proximal parts, and coralline red algal with larger benthic foraminifera and bryozoan colonies in the deeper oligophotic zone. The outer ramp includes proximal parts dominated by bryozoans, echinoids and molluscs with subordinate planktonic foraminifera and the distal part characterized by planktonic foraminifera and deep epifauna and infauna benthic foraminifera. Changes in trophic conditions and sea-level fluctuations, which are related to tectonic activities, seem to be the important factors in skeletal production and the spatial distribution of carbonate factories.

Keywords: facies, Burdigalian–Langhian, Asmari Formation, Zagros Basin, carbonate ramp, euphotic, oligophotic.

Introduction

Coralline red algae are common components during the Early and Middle Miocene (Halfar & Mutti 2005). Their peak in abundance, replacing corals as dominant reef builders from the Burdigalian to Early Tortonian, paralleled the increased extinction rates of planktonic foraminifera, radiolarian, corals and larger foraminifera (Halfar & Mutti 2005). The taxonomic components of living coralline algal assemblages are distinct in different geographical regions, and vary along environmental gradients within a given region (Adey & Macintyre 1973; Adey 1979; Braga et al. 2010; Aguirre et al. 2017). Coralline algae thrive in a wide range of trophic conditions, from oligotrophic reef environments, such as reef crests where they can be the major builders (Bosence 1984) to mesotrophic waters on marine platforms in diverse latitudes (Adey & Macintyre 1973; Aguirre et al. 2017). In addition to light and temperature as predominant factors limiting the distribution of coralline algae, hydrodynamic energy is considered to be most important in affecting rhodolith shape, structure, and distribution (e.g., Bosence 1983a, b; Basso 1998; Aguirre et al. 2017). Coralline algae growth morphology is also strongly related to environmental parameters, in particular to water conditions and depth (Peña & Bárbara 2008; Braga et al. 2010; Aguirre et al. 2017). Highly branched thalli may form in slow moving (Peña & Bárbara 2008) or shallow waters (Steller et al. 2003). Discoidal (i.e. flat) forms may be more abundant in deep waters where downward growth is unfavourable, whilst spherical and ellipsoidal forms may occur in shallower water (Peña & Bárbara 2008). Consequently rhodolith morphology and their taxonomic assemblage have been used for paleoecological and paleoenvironment reconstructions (Bosence & Pedley 1982; Bosence 1983a, b; Bassi 1995, 2005; Rasser & Piller 2004; Checconi et al. 2010; Brandano & Ronca 2014; Coletti et al. 2015, 2018). Larger Benthic Foraminifera (LBF) have arisen many times in the geological record from ordinary-sized ancestors (e.g., Hottinger 1997). Their appearance is often related to periods of global warming, relative drought, raised sea levels, expansion of tropical and subtropical habitats, and reduced oceanic circulation (Hallock & Glenn 1986). The main factor limiting the latitudinal distribution of symbiont-bearing foraminifera is temperature (e.g., Hottinger 1983; Langer & Hottinger 2000) because persistent temperatures below 14 °C in the winter months seem to hinder their survival. Larger foraminifera are thus restricted to the tropics apart from a few species that can also survive in the warm temperate zone (e.g., Betzler et al. 1997; Hohenegger et al. 2000; Langer & Hottinger 2000). Further factors influencing the distribution of larger foraminifera are light intensity, water energy and substrate conditions (Hottinger 1983; Bassi et al. 2007).

This study focuses on the Asmari Formation, a thick carbonate sequence of the Oligocene–Miocene in the foreland Zagros Basin, south-west Iran. This Formation is the most prolific Iranian oil reservoir (51 oil reservoir which produce near 90 % of Iranian oil; Amirshahkarami et al. 2007) and one of the biggest in the world (31 billion barrels of oil in place; Roehl & Choquette 1985). These limestones are highly fossiliferous, and non-skeletal grains are also common. Biogenic components include diverse benthic foraminifera, coralline red algae, corals, molluscs, echinoids, bryozoans, and serpulids. Non-skeletal grains, larger benthic foraminifera, and zooxanthellate corals suggest deposition in warm tropical waters (Roozpeykar & Maghfouri Moghaddam 2016). The paleoecological reconstruction suggests the present-day Persian Gulf as the most appropriate model for the Asmari Fm. (Amirshahkarami et al. 2007). The aim of the present work are: (1) to identify foraminiferal associations and their stratigraphical position; (2) to characterize the facies and paleoenvironments of the Asmari Formation and (3) describe and interpret the sequence stratigraphic model.

Geological settings

The NW–SE-trending Zagros orogenic belt extends over 2000 km from Turkey to southeastern Iran, and it represents a large segment of the Alpine–Himalayan collisional system (e.g., Berberian & King 1981; Golonka 2004). Its formation results from the long-standing convergence between Eurasia and Gondwanian-derived fragments, as underlined by ophiolite belts and present-day GPS vectors (Agard et al. 2011). The mountain belt has been divided into NW–SE trending structural zones (imbricated and simply folded belt) parallel to the plate margin and separated by major fault zones such as the High Zagros and Mountain front faults (Sepehr & Cosgrove 2004). The imbricated belt situated between the high Zagros and Zagros main reverse faults and simply folded belt lies to the south west of the High Zagros (Sepehr & Cosgrove 2004). The sedimentary column of the Zagros fold-thrust belt comprises a 12-km-thick section of Lower Cambrian through Pliocene strata without significant angular unconformities (Falcon 1961; Stocklin 1968; Colman-Sadd 1978). In addition to the tectonic divisions parallel to the mountain belt, the belt has also been divided laterally to the Lurestan, Dezful Embayment and Fars regions from northwest to southeast. These were all part of the continental margin of the Arabian platform and are now separated from each other by N–S and E–W trending fault zones. These fault zones played, and still play, an important role in controlling sedimentation of the basin and as a result these regions have different sedimentary successions (Sepehr & Cosgrove 2004). The study area is located in Tange-Shabikhon about 12 km North West of Khorram Abad City (Lurestan subzone of Zagros fold-thrust zone). The studied stratigraphic section was measured in detail at 33°36’10” N and 48°17’56” E (Fig. 1).

The studied section is up to 120 m in thickness, consisting of thick bedded and massive limestones in the lower and middle parts, and of marl and nodular anhydrite in the upper part. The strata disconformably overlie the dolomitic Shahbazan Formation.

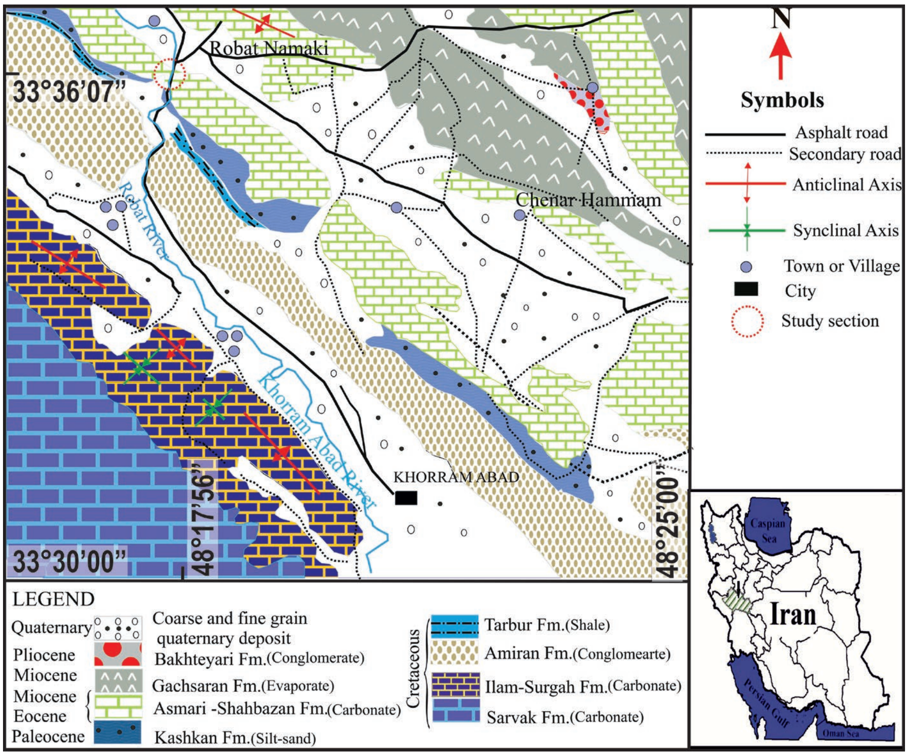

Fig. 1. Locality and geological map of the studied area.

Materials and methods

For this study, one stratigraphic section was measured in the field and its lithologies and sedimentary patterns were described. Field observations were complemented with the petrographic examination of 50 thin sections and 16 washing samples for identification of biogenic components and facies characteristics (skeletal components, depositional texture, and grain size). The textural classification follows the classifications of Embry & Klovan (1971) and Dunham (1962). For paleoenvironmental reconstructions, the relative abundance of calcareous algae, benthic foraminifera and other skeletal components (i.e., the green alga *Halimeda*, echinoids, molluscs, bryozoans, corals and so on); were estimated in thin-section by image analysis and measuring the proportional area occupied by each taxon relative to the total biogenic population (Perrin et al. 1995). As a result, our suggestions with regard to the paleoenvironmental conditions are primarily based on the dominant genera and taxa displaying >40 % abundance, while the subsidiary taxa are less regarded. Additionally, the changes in relative abundance of coralline red algal assemblages counted by this method, were used to constrain the bathymetry of the depositional setting (see Supplementary Table S2). Paleodepth has been interpreted following works on recent and fossil examples (Adey 1979, 1986; Lund et al. 2000; Aguirre et al. 2000; Brandano et al. 2005). Following this method, the distribution of taxa suggests that Corallinales lived in the shallower water accompanied by corals and thick-walled LBF (10–20 m), while Hapalidiales are more typical for deeper-water conditions, associated with thin-walled LBF (40–80 m). The preservation level of large benthic foraminiferal tests was used to determine allochthonous fossils related to sediment transport. For marls, about 100 g of washed residue from every sample were checked under the stereomicroscope to pick up the main fossil groups. The benthic foraminifera were identified to species-level (as far as possible), sorted, and counted. The identification of genera and species largely follows Loeblich & Tappan (1988) and Cicha et al. (1998) publications. Planktonic foraminifera were specified as one group and counted in order to obtain P/B ratios, meaning the percentages of planktonic foraminifera in the total foraminiferal assemblages (% P=P/(P+B)×100).

Results and discussion

Facies description and interpretation

Based on biogenic composition, textural and lithological characteristics, twelve facies were identified in the limestone and three facies were identified in the marls. These facies are related to different environments of the carbonate ramp:

FC1 (porcellaneous foraminiferal wackestone packstone): This facies is characterized by abundant larger and small porcellaneous foraminifera (45 %). Porcellaneous foraminifera are dominated by *Borelis melo curdica*, *Dendritina rangi* and miliolids. Soritids, *Peneroplis evolutus* are also common. Perforate foraminifera (genera *Ammonia*, *Discorbis* and *Elphidium*) (15 %), encrusting coralline red algae (8 %), fragments of *Porites* sp. (15 %), echinoid spines (13 %), molluscs (5 %) and quartz grains are occasionally present (Fig. 2A,B).

The dominance of porcellaneous foraminifera points to a well-lit and shallow portion of the photic zone in a proximal inner ramp setting (Romero et al. 2002; Bassi et al. 2007; Reuter et al. 2007; Bassi & Nebelsick 2010). Low turbidity is indicated by the high diversity of the porcellaneous foraminiferal fauna, which develops in meso- to oligotrophic settings at shallow depths (e.g., Hallock 1984, 1988; Reiss & Hottinger

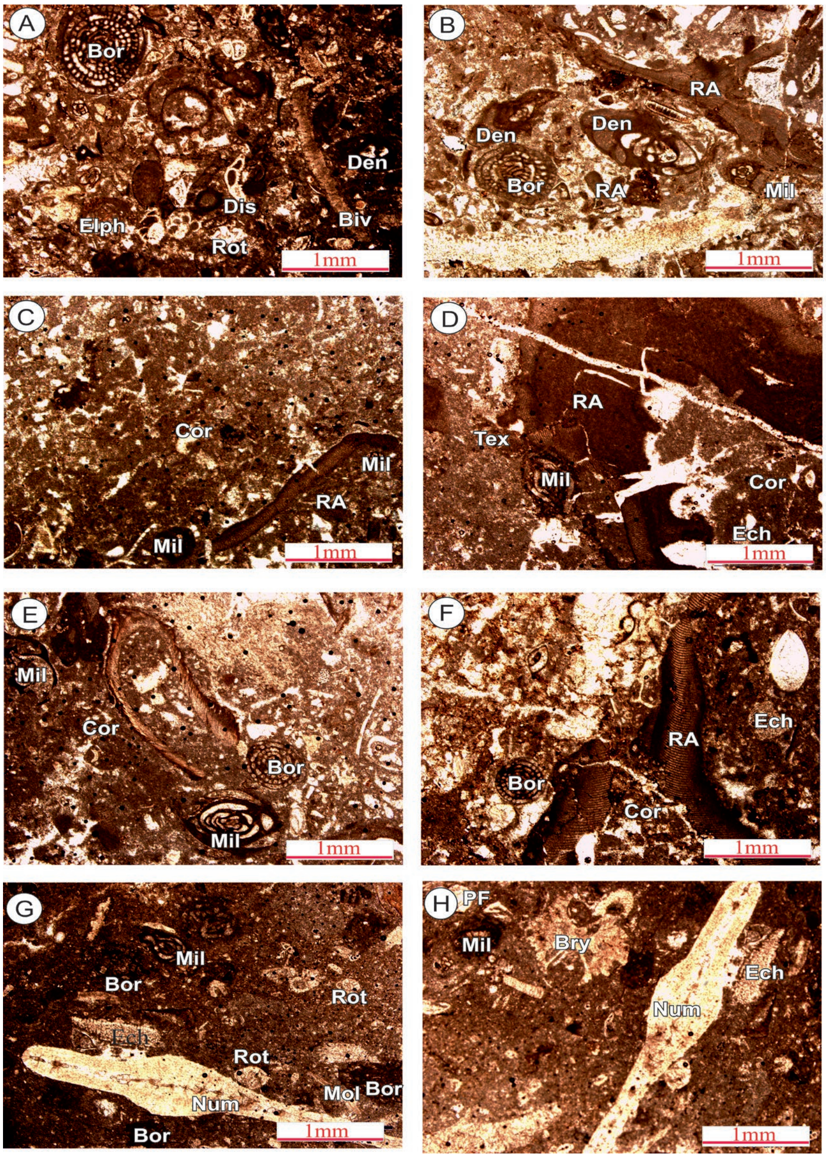

Fig. 2. Photomicrographs of the microfacies recognized within the Asmari Formation. **A, B** — FC1, porcellaneous foraminiferal wackestone packstone; **C–F** — FC2, corallinacea, coral boundstone/rudstone; **G, H** — FC3, perforate-imperforate foraminifera wackestone. Biv: Bivalve, Ech: Echinoid, Cor: Coral, Bry: Bryozoan, RA: Red Algae, Den: Dendritina, Sor: Soritids, Sph: Sphaerogypsina, Amp: Amphistegina, Num: Nummulitids, Elp: Elphidium, EF: Encrusting Foraminifera, PF: Planktonic Foraminifera.

1984; Buxton & Pedley 1989). The presence of discorbids and small miliolids, along with large porcellaneous taxa, indicates the occurrence of extensive seagrass meadows in euphotic conditions (Pomar et al. 2014). The high amount of micrite reflects a relatively low-turbulence environment (Barattolo et al. 2007).

FC2 (bioclast-coral boundstone/rudstone): This facies is characterized by the dominance of corals (76 %) (mainly of genus *Porites*). The benthic foraminifera (6 %) are also present and represented by thick LBF tests (*Miogypsina globulina*, *Amphistegina* sp., *Borelis melo curdica* and Soritids), small miliolids, *Elphidium* sp., discorbids and textulariids. Other components are coralline red algae (14 %), molluscs (1 %), echinoids (2 %) and bryozoans (1 %). The coralline assemblage is dominated by the encrusting thalli of *Neogoniolithon* sp. and *Lithothamnion* cf. *valens* (Fig. 2C–F).

Neogoniolithon is actually one of the most important framework-forming coralline algae in Eocene carbonate factories (Nebelsick et al. 2005), since it can develop directly over a soft substrate (Fravega & Vannucci 1989; Rasser 2000; Rasser & Piller 2004; Nebelsick et al. 2005; Quaranta et al. 2007). Eocene coralline-algal bindstones, are thought to develop at depths comparable or slightly greater than those of the rhodolith facies, although with lower energy and higher substrate stability (Rasser & Piller 2004; Bassi 2005; Nebelsick et al. 2005). This is also consistent with models of distribution of coralline-algal growth-form in modern oceans, which state that coralline-algal framework develops preferentially in environments with a stable substrate, moderate to low hydrodynamic energy and low sedimentation rate (e.g., Basso 1998). The foraminiferal (*Borelis*, *Miogypsina*, *Amphistegina* and miliolid) assemblage suggests deposition in the inner shelf habitats, where sea-grass meadows interfinger with adjacent unvegetated areas (Schuster & Wielandt 1999; Brandano et al. 2009a, b). The presence of molluscs, echinoids, bryozoans and encrusting forms of corallinacean red algae confirm the occurrence of extensive sea-grass meadows over the inner shelf (Hoffman 1979; Ivany et al. 1990; Astibia et al. 2004; Beavington-Penney et al. 2004). This facies is therefore thought to have been deposited in an inner-shelf environment largely colonized by sparse scleractinian and coralline-algal bioconstructions, within or close to seagrass meadows (Maurizot et al. 2015).

FC3 (bioclastic perforate and imperforate foraminifera wackestone): The main components are mixed perforate and imperforate benthic foraminifera (40 %). The perforate foraminifera assemblage is represented by well-preserved thick and flat tests of *Operculina complanata*, *Operculina* sp., *Amphistegina* sp., *Elphidium* sp., and small rotaliids. Porcellaneous foraminifera include preserved and abraded tests of *Borelis melo curdica, Dendritina rangi* and miliolids. Other common components are bryozoans (19 %), bivalves (3 %), corallinacea (8 %), corals (9 %), echinoids (13 %), small rotaliids (2 %), encrusting foraminifera (4 %) (acervulinids and *Haddonia*) and planktonic foraminifera (2 %). Corallines are represented by hooked and encrusting thalli of *Neogoniolithon* sp (Fig. 2G, H).

Operculina spp. are epifaunal, herbivorous taxa possessing diatoms as endosymbiontic algae. They live in warm water from the shallow shelf (e.g., in lagoons) down to the base of the photic zone (Murray 1991) depending on the specific species. The modern *Operculina* (i.e. *Operculina complanata*) can occur in medium light conditions in somewhat deeper part of the photic zone (Bassi et al. 2007). Recent *O. ammonoides* live on fine sandy substrates from the FWWB down to the storm wave base at 100 m (Hohenegger et al. 1999; Hohenegger 2004). The associated foraminiferal assemblage, on the other hand, suggest a different setting (Wielandt-Schuster et al. 2004). Imperforate foraminifera are most abundant making them characteristic of the assemblages. However, imperforate foraminifera (*Borelis* and *Dendritina*) and epiphytic assemblages suggest euphotic condition with extensive sea-grass meadows on inner shelf areas (Brandano et al. 2012; Brandano et al. 2009a, b; Mateu-Vicens et al. 2008). Rotaliids and amphisteginids are also common in modern sea-grass environments (Sen Gupta 1999). The sea-grass meadow interpretation is also supported by the presence of red-algal crusts with hooked forms (Beavington-Penney et al. 2004). Accordingly, this assemblage might be related to a vegetated substrate which offers shaded habitats to oligophotic elements (i.e. *O. complanata*) in a distal inner ramp setting.

FC4 (branching coralline floatstone/rudstone): This facies is dominated by free-living coralline branches and rhodoliths (72 %). Other components are represented by coralline algal debris (2 %), fragments of echinoids (6 %), molluscs (2.5 %), bryozoans (0.5 %), LBF (10 %), small benthic (2 %), planktonic (1 %) and encrusting foraminifera (4 %). Hapalidiales dominate coralline-algal assemblage in this facies. Corallinales are common to rare and are represented only by *Lithoporella melobesioides*. Among recognizable Hapalidiales the genus *Lithothamnion* cf. *valens* is the most abundant species of the association. *Mesophyllum* cf. *roveretoi* is another common Hapalidiales. *Phymatolithon calcareum* is rare and is the only recognized species of *Phymatolithon*. The LBF assemblage is characterized by thick-walled dominating with thin-walled, flat-lenticular subordinate *Amphistegina* sp., and rare flat and thin tests of *Operculina complanata.* In some samples, rare *Borelis* sp. also occur. Small benthic foraminifera are represented by cibicidids*, Elphidium,* textulariids and rare miliolids (Fig. 3A–C).

This facies can be compared to maërl facies which are characteristically composed of coralline algal branches, rhodoliths, and their detritus (e.g., Bosence 1984; Adey 1986; Freiwald et al. 1991; Freiwald 1995; Pivko et al. 2017). In modern tropical environments, maërl occurs in a very shallow zone commonly associated with sea-grass meadows (Bosence 1985; Steneck 1986). In the present-day Mediterranean Sea, maërl deposits occupy the upper part of the circa-littoral zone, just below the deepest occurrence of *Posidonia* meadows (Canals & Ballesteros 1997). The maërl facies is also reported in fossil deposits (Brandano 2003; Brandano et al. 2010, 2016; Bassi & Nebelsick 2010; Nebelsick et al. 2013) from the inner and middle ramp deposits in the Oligocene and Miocene carbonates of the Mediterranean realm. The biotic composition indicates a depositional environment ranging from the distal part of the inner ramp to the middle ramp settings. The inner ramp environment is indicated by the co-occurrence of thick perforate forms of *Amphistegina* and imperforate *Borelis* and miliolids. Deposition in the middle ramp is indicated by the presence of deep-living LBF (*Amphistegina* and *Operculina*), planktonic foraminifera and by the absence of *in-situ* shallow imperforate fauna such as *Borelis* and miliolids (Brandano et al. 2012, 2016): this would imply that the tests of foraminifera of shallow-water affinity were resedimented at greater depth (Brandano et al. 2010). The increasing depth of deposition from inner ramp to middle ramp is also inferred from the coralline taxonomic assemblages. The taxonomic trend can be summarized as follows: inner ramp assemblage characterized by Hapalidiales (*Lithothamnion*) and Corallinales (common *Lithoporella*); middle ramp, dominated by Hapalidiales (*Lithothamnion* and *Mesophyllum*) with rare Corallinales. A similar increase in Hapalidiales with depth together with a relative decrease in Corallinales has been widely documented in modern settings (e.g., Adey 1979; Adey et al. 1982; Lund et al. 2000) and fossil paleoenvironments (Bassi 1995, 1998, 2005; Perrin et al. 1995; Bassi et al. 2006; Barattolo et al. 2007; Checconi et al. 2007, 2010). The abundance of free-living coralline branches suggests low substrate-stability (Barattolo et al. 2007).

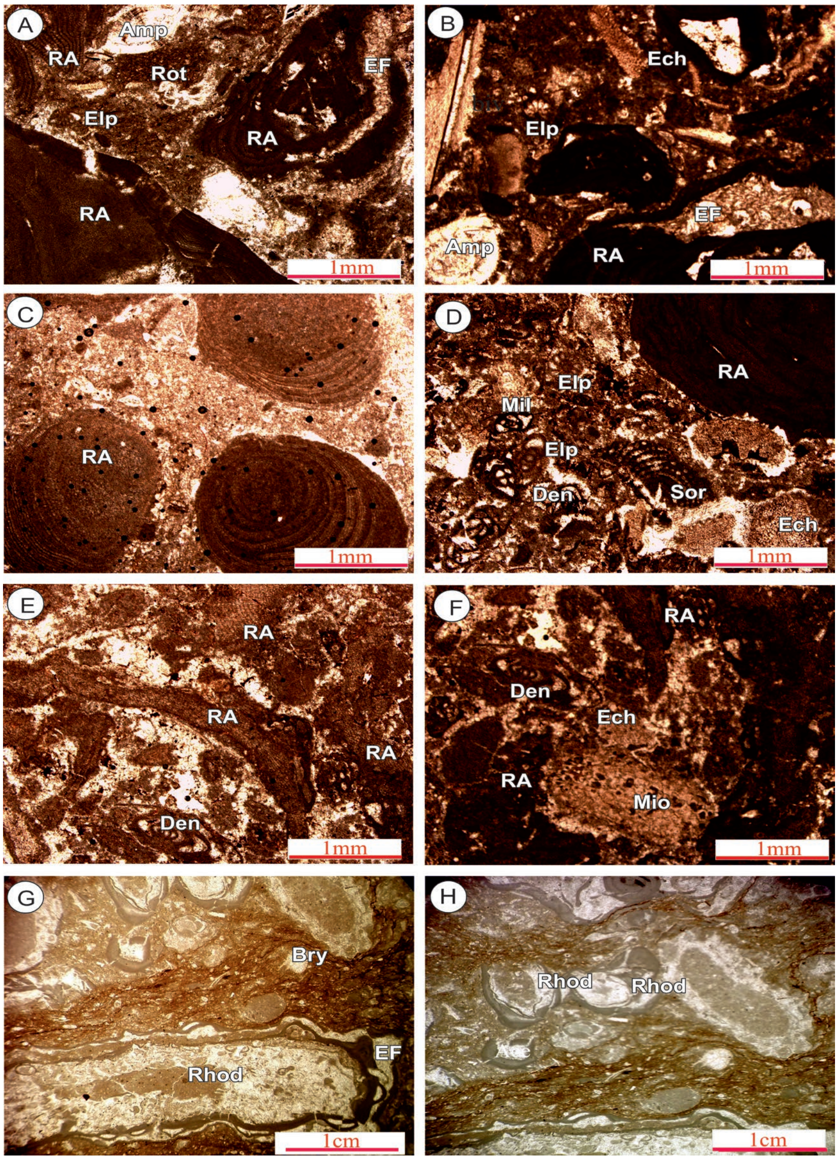

Fig. 3. Photomicrographs of the microfacies recognized within the Asmari Formation. **A–C** — FC4, branching red algal floatstone-rudstone. **D–F** — FC5, foralgal grainstone; **G, H** — FC6, Rhodalgal floatstone/rudstone; Biv: Bivalve, Ech: Echinoid, Cor: Coral, Bry: Bryozoan, RA: Red Algae, Den: Dendritina, Sor: Soritids, Sph: Sphaerogypsina, Amp: Amphistegina, Num: Nummulitids, Elp: Elphidium, Mio: Miogypsina, Mil: Miliolid, Bor: Borelis, EF: Encrusting Foraminifera.

FC5 (foralgal grainstone): This facies consists of dominating coralline algae (60 %) (mainly lumpy and encrusting growth forms) and subordinate foraminifera (33 %). Further subordinate components are molluscs (1 %), echinoderms (5 %) and bryozoans (1 %). The most abundant LBF are represented by robust and thick-walled *Amphistegina* sp., *Sphaerogypsina* sp., *Miogypsina globulina, Borelis melo curdica* and *Dendritina rangi*. Other common foraminifera are small rotaliids, miliolids, soritid, *Peneroplis evolutus* and *Sphaerogypsina* sp. (Fig. 3D–F).

The absence of micrite is regarded as indicative of moderate to high bottom current conditions, an interpretation that is further supported by coralline growth-forms and by the abundance of robust benthic foraminifera such as Miogypsinids, *Rotalia*, *Sphaerogypsina* and amphisteginids (Hallock & Glenn 1986; Fournier et al. 2004). It is interpreted as a shoal developed above fair weather wave-base, within the distal inner ramp.

FC6 (Rhodalgal floatstone/rudstone): This facies comprises floatstone/rudstone characterized by the abundance of ellipsoidal, laminar to branched rhodoliths (88 %). Rhodoliths range between 2 and 5 cm and are mainly composed of *Neogoniolithon* sp. Nuclei consist of corals and bryozoans. *Lithothamnion* cf. *valens* (4 %) is also present, forming free-living branches. Other components are benthic foraminifera (2.5 %), bivalves (0.5 %), bryozoans (2 %) and echinoids (2 %). Planktonic foraminifera (1 %) are also present. Benthic foraminifera are represented by flat *Amphistegina* sp., *Elphidium* sp., textulariids and encrusting foraminifera (*Miniacina* sp.) (Fig. 3G, H; Fig. 2A).

A shallow marine environment is indicated by the dominance of Corallinales, which tend to predominate in shallow-water settings of modern seas (Lund et al. 2000; Braga & Aguirre 2004; Flamand et al. 2008). Shallow-water Corallinales-dominated rhodoliths are also documented in the fossil records from the Tethyan realm (e.g., Bassi 1998, 2005; Brandano et al. 2005, 2010; Bassi et al. 2006, 2008; Benisek et al. 2009; Bassi & Nebelsick 2010; Braga et al. 2010). Bassi & Nebelsick (2010) suggesting an environment within the FWWB in a proximal middle ramp setting. Ellipsoidal rhodoliths are usually considered characteristic of high-energy conditions (e.g., Bassi 1995, 1998; Bassi & Nebelsick 2010; Checconi et al. 2010). Nonetheless, rhodolith shape is not directly correlated with water energy (e.g., Brandano et al. 2005; Bassi et al. 2006). The occurrence of thin laminar thalli and foraminiferal crusts on the rhodolith surface may reflect relative stabilization and only occasional movement in calm water prior to burial (e.g., Pisera & Studencki 1989; Aguirre et al. 1993). Alternatively, it is also possible that rhodoliths formed in a low energy environment when overturning was provided by the activity of organisms.

FC7 (Crustose coralline algal wackestone): This facies is characterized by the abundance of usually well-preserved, thin delicate coralline-algal crusts (40 %). The dominating coralline alga is *Mesophyllum* cf. *roveretoi*. Other components are thinly branching corals (14 %), green algae (28 %), fragments of molluscs (14 %), echinoids (2 %) and small benthic foraminifera (2 %) such as *Elphidium* sp., *Textularia* sp. and *Bigenerina* sp (Fig. 4B–D).

The coralline alga *Mesophyllum* is reported from low-light environments and is commonly found in clear waters at a depth of 20–80+ m (Adey 1979; Perrin et al. 1992). The dominance of thin delicate crusts suggests low hydrodynamic, low light intensity and low sedimentation rate (e.g., Lund et al. 2000; Bassi 2005). The high amount of fine-grained sediment between the crusts, also supports low hydrodynamic energy (Rasser 2000).

FC8 (acervulinid coral floatstone/rudstone): In this facies, thinly branching corals (78 %) together with acervulinids (8 %) and coralline algae (7 %) are the main components. Coralline algal assemblage is represented by thin encrusting thalli which envelope the coral colonies or float within the muddy matrix. The coralline assemblage is dominated by *Mesophyllum*. Rare *Lithothamnion* cf. *valens* is also present. Benthic foraminifera (3 %), *Ditrupa* sp. (0.5 %), echinoids (2 %), bryozoans (0.7 %) and bivalves (0.7 %) are subordinate. The foraminifera association is characterized by encrusting foraminifera (*Gypsina* and *Miniacina*), flat *Amphistegina* sp., flat-thin walled nummulitids, *Elphidium* sp., textulariids, rare *Borelis melo curdica* and *Sphaerogypsina* sp. Bioerosion is common (Fig. 4E–H).

Recent acervulinids are common in very shallow water, as cryptobionts, up to the lower limit of the photic zone, likely due to the disappearance with depth of benthic diatoms, their food source (Reiss & Hottinger 1984). They are an indicator of reduced competition for substrate encrustation, which could

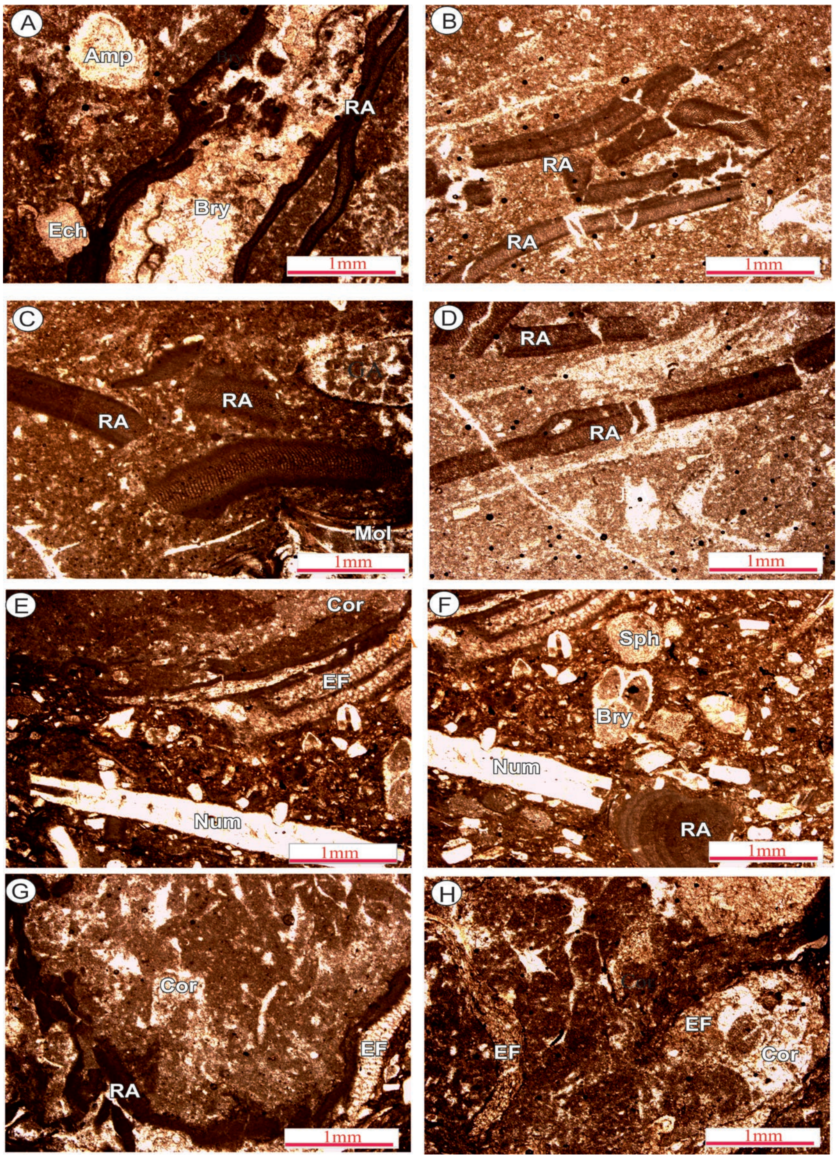

Fig. 4. Photomicrographs of the microfacies recognized within the Asmari Formation. **A** — FC 9, Rhodalgal floatstone, rudstone. **B–D** — FC10, Crustose coralline algal wackestone–packestone.; **E–H** — FC11, branching coral rudstone. Biv: Bivalve, Ech: Echinoid, Bry: Bryozoan, RA: Red Algae, Cor: Coral, Amp: *Amphistegina*, Num: Nummulitids, PF: Planktonic Foraminifera.

be related to a decrease not only in light intensity (Perrin 1992), but also in sedimentation rate and water turbulence (Bassi et al. 2012). The widespread occurrence of these heterotrophic encrusters also indicates suitable conditions in terms of food availability (Zamagni et al. 2009). The coral assemblage is dominated by branched forms. These coral forms are observed in reef environments subjected to low light levels and/or relatively high nutrients (Dryer & Logan 1978; Sanders & Baron-Szabo 2005) that are highly resistant to sedimentation, and that feed largely or entirely heterotrophically (Dryer & Logan 1978). Among the microfaunal components, the larger benthic foraminifera are few and represented by *Operculina complanata* and *Amphistegina* sp. At present, *Operculina complanata* thrives in the lower photic zone on fine sandy bottoms and is able to tolerate elevated nutrients and sediment influx (e.g., Hohenegger 2000; Langer & Hottinger 2000). Increased nutrient availability may be the explanation for the positive correlation between increased organic matter, degree of bioerosion and encrustation by algae and infaunal suspension feeders (Hallock & Schlager 1986; Perrin et al. 1995; Edinger et al. 2000). Accordingly, a low energy middle-ramp environment, likely characterized by enhanced nutrient level (mesotrophic) and reduced light-level is conceivable for the studied acervulinid-coral facies.

FC9 (bioclastic nummulitid wackestone/packstone): The main components are thin-walled and flat shelled large benthic foraminifera (50 %). The LBF skeletons are dominated by *Heterostegina* sp., *Operculina complanata* and *Amphistegina* sp. Coralline red algae (10 %) are also common and they are dominated by Hapalidiales. Echinoids (11 %), molluscs (2 %) and bryozoans (23 %) (mainly erect rigid bilaminar adeoniform cheilostomatid and vinculariiform cyclostomatid *Onychocella* sp., *Tubucellaria* sp. and *Celeporaria* sp.) are also abundant. Small benthic foraminifers (4 %) also occur. The assemblage includes textulariids, rare miliolids, *Cibicides* sp. and rare encrusting forms *Gypsina* sp. and *Miniacina* sp (Fig. 5A–C).

The abundance of Hapalidiales and thin-shelled, flat nummulitids suggest that the accumulation of biota occurred in the oligophotic zone (Hohenegger 1996; Brandano & Corda 2002; Brandano et al. 2010; Novak et al. 2013). Erect, rigid bryozoans suggest moderate water turbulence and sedimentation rates (Lagaaij & Gautier 1965; Moissette et al. 2007).

FC10 (pelagic foraminifera bioclastic wackestone–packstone): This facies consists of fine to coarse fragments and tests of larger benthic foraminifera (32 %) associated with planktonic foraminifera (12.5 %). Nummulitids and amphisteginids are represented as predominantly flat and thin walled forms. Small benthic foraminifera (3 %) are rare and include textulariids, *Elphidium crispum* and miliolids. Other important components are *Ditrupa* sp. (1 %), bryozoans (11 %), echinoid plates and spines (24 %), coralline red algae (14.5 %) and bivalve shell fragments (1 %) (Fig. 5D–F).

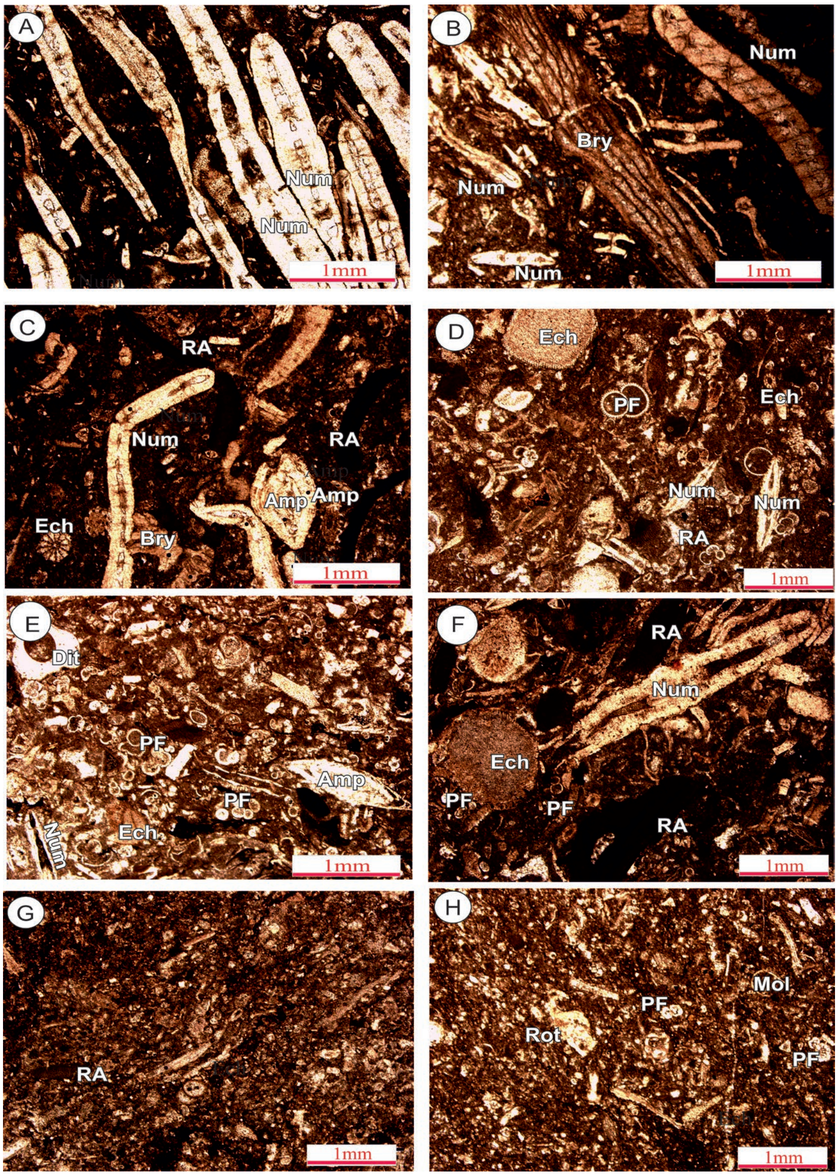

Fig. 5. Photomicrographs of the microfacies recognized within the Asmari Formation. **A–C** — FC12, bioclast nummulitidae wackestone packstone. **D–F** — FC13, pelagic foraminifera bioclastic packstone; **G, H** — MF14, fine bioclastic wackestone Biv: Bivalve, Ech: Echinoid, Bry: Bryozoan, RA: Red Algae, Amp: *Amphistegina*, Num: Nummulitids, Dit: Ditrupa, PF: Planktonic Foraminifera, Qg: Quartz Grain, Rhod: Rhodolith, EF: Encrusting Foraminifera.

The co-occurrence of planktonic foraminifera and thin, flat nummulitids point to deposition at the dysphotic lower middle ramp (Höntzsch et al. 2010). The occurrence of shallow water dwellers such as epiphytic foraminifers and thick *Amphistegina* specimens, reflect active downslope sediment transport processes (Mateu-Vicens et al. 2008).

FC11 (fine bioclastic wackestone): This microfacies consists of fine-grained bioclastic wackestone with highly abraded biogenic components, dominated by echinoid plates and spines (61 %), bryozoans (9 %) and foraminifera (20 %). Foraminifera are dominated by *Elphidium* sp. and planktonic foraminifera. Coralline algae (6 %) and bivalves (4 %) are present in minor percentages. In some samples, bioturbation is high. Fine quartz grains are also present (Fig. 5G, H).

The combination of micritic matrix and a relatively high degree of fragmentation points to textural inversion (Folk 1962) that can be explained by a low-energy environment affected by occasional storm events (Rasser et al. 2005). The absence of LBF and occurrence of planktonic taxa indicate outer-ramp setting (Mateu-Vicens et al. 2008). The sediment-producing biota (echinoids, bryozoans and bivalves) together with an absence of larger foraminifera such as *Heterostegina* and *Operculina* suggest a depositional environment located at the transition between the oligophotic and aphotic zone (Brandano et al. 2010). Bryozoans, together with molluscs and echinoids, are heterotrophic organisms that do not require much light to live and proliferate (Brandano & Corda 2002). Thus, their occurrence could suggest a high nutrient supply that could have limited the development of euphotic biota, favouring the bloom of photo independent biota such as planktonic foraminifera and suspension feeders (Brandano et al. 2016).

Marly facies

The marly deposits are dominated by planktonic and small benthic foraminifera, including both infaunal and epifaunal taxa. Three facies are recognized based on the relative abundance of infaunal/epifaunal benthic foraminifera and planktonic foraminifera.

FM1: This facies developed in the lower parts of the marly deposits. Planktonic foraminifera such as *Globigerinoides* and *Globigerina* are the dominant components. Echinoid spines and benthic foraminifera are also present. The assemblage is characterized by *Cibicidoides* sp. and *Heterolepa dutemplei*. Planktonic/benthic ratio of 90–100 % has been recorded for this facies (Supplementary Fig. S4).

The fine-grained composition and planktonic foraminifera abundance suggest hemipelagic deposition in an open-marine, low energy environment situated below storm wave base (Peyros et al. 2010). The presence of the *Cibicidoides* and *Heterolepa* species indicate a well oxygenated substrate and the presence of bottom water currents (Székely & Filipescu 2016).

FM2: This facies is characterized by the co-occurrence of epifaunal and infaunal benthic foraminifera. The most abundant species are *Bulimina inflata*, *Nonion fabum* and *Uvigerina* sp. Epifaunal taxa also occur (mainly *Neoeponides* sp., *Eponides* sp. and *Siphoninoides* cf. *echinata*). Planktonic taxa are present and represented by *Globigerina*, *Globigerinoides* and *Globorotalia* (Supplementary Fig. S4).

The benthic foraminiferal assemblages (*Neoeponides*, *Siphoninoides* and *Bulimina*) indicate that the deposition of this succession took place in a relatively deep sedimentary basin, consistent with the outer shelf-slope environment (Murray 1991; Schmiedl et al. 2003). The co-existence of *Siphoninoides* with *Bulimina* spp., which is assumed to tolerate increased nutrient supply, are indicative of oxygen depleted, mesotrophic to eutrophic seafloor environments (García-Gallardo et al. 2017).

FM3: This facies is composed of anhydrite nodules and occurs in the upper part of the marl deposits. Planktonic and benthic foraminifera are abundant. The benthic assemblage is dominated by *Bulimina* spp., while the planktonic assemblage is constituted by *Orbulina* and *Globigerinoides*. The P/B ratio reach up to 40 % (Supplementary Fig. S4).

Low diversity assemblages, dominated by one or few species, tend to occur in stressed environments (Drinia et al. 2004). The presence of infaunal benthic foraminifera (*Bulimina*) indicates an unstable, stressed environment, probably linked to the presence of low oxygen concentration (Jorissen et al. 1992; Kaiho 1994) and high salinity on the seafloor (Van der Zwaan 1982; Verhallen 1991; Drinia et al. 2007; Di Stefano et al. 2010).

Depositional model

The facies distribution represents a gradual shift from a shallow lagoonal setting to a basin environment (Fig. 6 and Supplementary Fig. S5). Slide deposits and breaks on the slope angle were not observed. Coral reefs are not developed, but small scattered patch reefs occur. This suggest a ramp morphology for the carbonate system. This interpretation is also supported by the absence of oncoids, pisoids and aggregate grains that have been found in shelf carbonates and are rarely present in a ramp system (Flügel 2004). The general facies pattern indicates a progressive deepening upward from inner ramp to middle ramp and finally to outer ramp environment

Two facies zones have been defined among the inner ramp sediments: proximal and distal shallow water zones. The proximal shallow water zone is dominated by porcellaneous foraminiferal wackestone/packstone comprising *Borelis*, miliolids, *Dendritina,* soritids and molluscs. Subordinate biota includes encrusting coralline red algae, small fragments of coral, echinoids and small rotalids. In general, porcellaneous larger foraminifers (such as peneropelids and soritids) predominantly live in symbiosis with dinophyceans, chlorophyceans or rhodophyceans (Romero et al. 2002). Today, larger porcellaneous foraminifera thrive in tropical carbonate platforms within the upper part of the photic zone (e.g., Reiss & Hottinger 1984; Hohenegger 2000). The abundant occurrence of this foraminifera group reflects environments with very limited

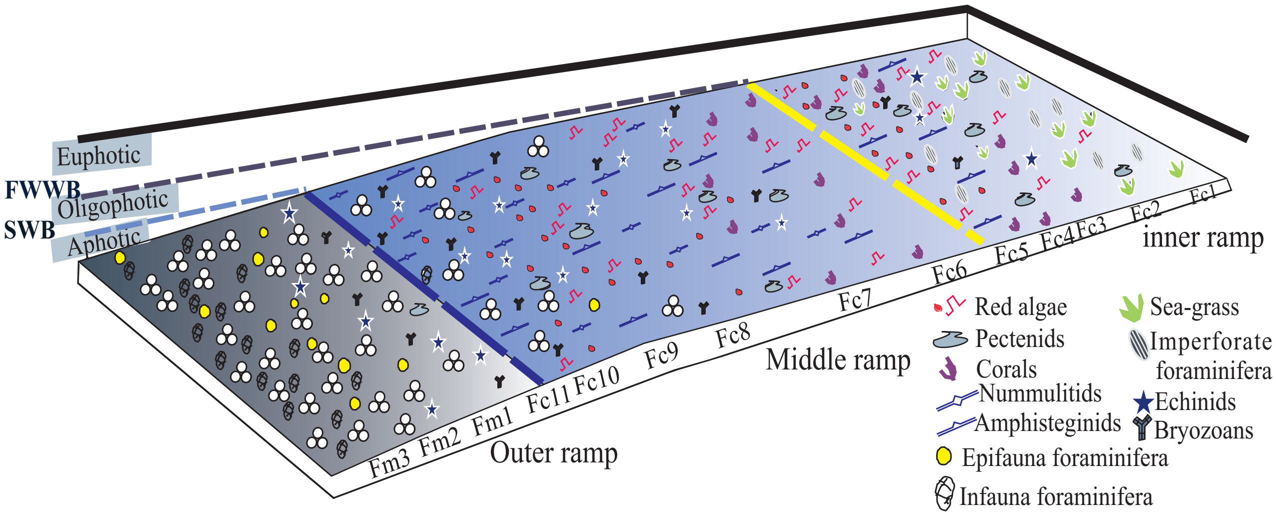

Fig. 6. Depositional model for the platform carbonate of the Asmari Formation in the Tang-e-Shabikhon area, Zagros Basin, south-west Iran. FWWB: Fair weather wave base; SWB: Storm wave base (see text for further details).

circulation and relatively hypersaline (Geel 2000) and suggests the presence of sea-grass meadows (Sen Gupta 1999; Brandano et al. 2009a, b; Bassi & Nebelsick 2010). In the deeper parts of the inner zone, coral colonies (*Porites*) form small-patches associated with miliolids, small rotaliids, *Borelis*, miogypsinids and amphisteginids. The distal shallow-water zone is characterized by an increase in the coralline-red algal contents of sediments. It consists of mixed foraminifera wackestone and branching red algae floatstone/rudstone. The mixed foraminifera wackestone, comprises a highly diverse assemblage of large perforate and imperforate foraminifera, small benthic foraminifera (miliolids, textularids, small rotaliids), encrusting red algae, molluscs, echinoids and bryozoans. Branching red-algae floatstones/rudstones contain abundant red algal nodules and branches with rare miliolids and large foraminifera. A shoal belt of grainstone occurs in the transitional part of inner to middle ramp deposits. In the shoal deposits, skeletal grains usually display a high degree of fragmentation and abrasion. Robust benthic foraminifera and corallinacean fragments were the predominant biotic components. The coralline association (*Lithothamnion*, *Neogoniolithon* and *Spongites*) and larger foraminifera assemblage (*Amphistegina*, *Miogypsina, Operculina*) place the inner ramp in the euphotic–mesophotic shallow-water zone (Pomar 2001). The absence of sedimentary structures together with the presence of foraminiferal assemblage, characterized by abundant epiphytic taxa, indicates deposition into a seaweed or sea-grass dominated environment (Brandano et al. 2009a, b).

Based on the biota, the middle ramp can also be subdivided into two distinct facies belts: proximal and distal middle ramp. The proximal middle ramp facies, are represented by rhodalgal facies, comprising thin encrusting *Neogoniolithon* associated with bryozoans, corals and rare to common LBF and encrusting foraminifera.

Toward deeper water, this facies is replaced by crustose red algal floatstone/rudstone and acervulinid coral floatstone/rudstone. The presence of crustuse coralline algae in a middle ramp setting can be related to suitable substrates and low turbulence conditions (Bassi 1995; Rasser & Piller 2004). The profusion of encrusting foraminifera suggests enhanced trophic levels (i.e. mesotrophic conditions), with competition for the substrate as the main limiting factor (Mutti & Hallock 2003).

The distal sector is characterized by the dominance of coralline red algal and larger hyaline foraminifers, and the disappearance of hermatypic corals. The inner facies is represented by coralline algal floatstone/rudstone dominated by *Lithothamnion* and *Mesophyllum*. Associated taxa include flat *Amphistegina* and some encrusting foraminifera. In deeper parts, this facies is replaced by larger foraminifera facies. The faunal assemblage includes mostly thin LBF (*Operculina*, *Heterostegina*, *Amphistegina*), rare to common branching bryozoans, echinoids, molluscs, coralline red algae, *Ditrupa*, encrusting benthic foraminifera and planktonic foraminifera. A low sedimentation rate is presumably responsible for the very dense foraminiferal accumulation (Bassi 2005). In the upper part of the section, this facies exhibits a grain-size decrease and an increased percentage of planktonic foraminifera. The muddy sediments of the middle ramp setting reflect low-energy conditions. The absence of wave-related structures and the abundance of coralline algae and LBF such as *Heterostegina*, *Operculina* and *Amphistegina*, place the middle ramp setting in the oligophotic zone, below the fair weather wave base (Pomar et al. 2012).

The sediments from outer ramp are characterized by the predominance of photo-independent biota. The main sediment-producing biota in the shallower facies are primarily represented by bryozoans and echinoids and to a lesser extent by small benthic foraminifera and bivalves. All the skeletal grains are embedded in a fine micritic matrix. In rare cases some reworked elements from the oligophotic zone, such as fragmented coralline red algae, are present. Deeper facies are dominated by planktonic foraminifera together with benthic foraminifera lacking photosynthetic organisms.

Conclusions

The skeletal assemblage of the studied mixed carbonate–evaporitic units is mainly composed of foraminifera and coralline algae. Corals, bryozoans and molluscs are subordinated. Based on the benthic and planktonic foraminifera distribution, the studied section is Burdigalian–Langhian in age. Based on the facies analysis and the faunal constituents, the study section was deposited on a homoclinal ramp. The ramp is divided into three parts: an inner ramp, a middle ramp and an outer ramp. The inner ramp is characterized by wackestone–packstone with a diverse assemblage of imperforated foraminifera in shallow protected areas, and bioclast imperforate foraminifera wackestone with branching red algae floatstone/rudstone in the deeper part. The shoal facies is marked by foraminifera, corals as well as coralline red algal grainstone. The shallower parts of the middle ramp are characterized by the occurrence of acervulinid, coral boundstone and floatstone, branching coral rudstone and rhodolith wackestone-packstone. The distal middle ramp is dominated by coralline algal floatstone/rudstone and bioclastic nummulitic wackestone/packstone. The shallower parts of the outer ramp are characterized by bryozoans, echinoids, rare benthic foraminifera and mollusc fragments. Planktonic foraminifera together with epifaunal and infaunal deep benthic foraminifera are the most important components of distal outer ramp to basin facies. The benthic foraminifera association in a distal outer ramp setting indicates a shift from a stable environment with well-oxygenated bottom-waters and oligotrophic conditions to an unstable environment with eutrophic and dysoxic conditions.

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Supplement

Biogenic components

Biogenic components are dominated by coralline red algae and foraminifera (including benthic and planktonic foraminifera) (Tables S1 and S2). Corals, bryozoans, mollusks, barnacles, echinoids and *Ditrupa* are subordinate. Benthic Foraminifera are represented by both perforate and imperforate forms. The calcareous red algae are dominated by species of the Hapalidiales and Corallinales. Rare geniculate coralline red algae are also present. Six genera were identified: The Corallinales is represented by *Lithoporella melobesiodes, Neogoniolithon* sp. and *Spongites* sp. Hapalidiales are represented by *Lithothamnion* cf. *valens*, *Phymatolithon* cf. *calcareum* and *Mesophyllum* cf. *roveretoi*. *Corallina* sp. is the only geniculate coralline red alga.

Mollusks are represented by pectinids, oysters and gastropods. Echinoderms are recognized mostly as spine cross sections or test fragments. Among them, *Clypeaster* is present. Bryozoans are mostly represented by erect delicate branching and erect bilaminar growth forms belonging to cyclostomate and cheilostomate families. Among them, *Onychocella* sp., *Tubucellaria* sp. and *Celeporaria* sp. were recognized. Zooxanthellate corals are mainly dominated by poritids.

Biostratigraphy

Both planktonic and benthic fossil foraminifera were used to determine the age (Figs. S1 and S2). In the lower and middle parts of this section, the planktonic foraminifera are rare, thus the biostratigraphic setting of the assemblages, in the absence of planktonic data, is based on the benthic foraminifera.

Among the benthic foraminifera, *Miogypsina globulina* is important. The *Miogypsina globulina* is a common worldwide marker species for the Burdigalian (Özcan & Less 2009). The occurrence of it indicates SBZ 25 of Cahuzac & Poignant (1997). In the upper part of the section, planktonic foraminifera are common. Based on the distribution, three biozones were recognized: The first recognized zone corresponds to the *Trilobatus trilobus* Zone (M4 of Berggren et al. 1995) and dated late Burdigalian. It is considered that the interval between 75–93 m belongs to this biozone, because of the First Occurrence (FO) *Trilobatus trilobus* at the base and of *Praeorbulina glomerosa* at the top. The next interval that was recognized corresponds to the *Praeorbulina glomerosa* Zone (M5 of Berggren et al. 1995) that extends from 93 to 103 m, between the FO of *Praeorbulina glomerosa* and that of *Orbulina suturalis.* This zone is assigned to Langhian age. The last zone recognized corresponds to the *Orbulina suturalis* Zone (M6 of Berggren et al. 1995), which is defined by the range of *Orbulina suturalis*. This zone occupies the upper part of the section (from 103–120 m) and dated Langhian. The biozones recognized in study section are shown in Fig. S1.

Continued of depositional environment

These marly sediments show major differences in abundance, diversity and composition of benthic foraminifera assemblages (Fig. S3). These differences mostly represent different paleoecological conditions such as substrate, sedimentation rate, salinity, oxygen concentration and trophic conditions. In the lower parts of sediments, planktonic foraminifera show a high species diversity and benthic foraminifera assemblages are characterized by epifaunal species. Planktonic foraminifera assemblages are dominated by shallow-surface dwelling forms such as *T. trilobus, Gs. diminutus, Gs. altiaperturus, Gs. subquardatus, T. immaturus, G. bulloides, Globigerinella obesa* and *G. falcoensis.* The co-occurrence of the planktonic species *Globigerina bulloides-praebulloides* and *Globigerinoides* spp. suggests a seasonal succession of assemblages characterized by the alternation of warm seasons with a stratified oligotrophic water and cool seasons with a mixed upper water column (e.g., Reynolds & Thunell 1985; Rigual-Hernández et al. 2012; Kuhnt et al. 2013; Salmon et al. 2014). The seafloor protists are characterized by epifaunal *Cibicidoides* spp., which are widespread in well-ventilated (Schmiedl et al. 2003), and, in general, they are tolerant to continues influx and low quality organic matter (Venturelli et al. 2014; Gottschalk et al. 2016). Therefore, the co-occurrence of *Cibicidoides* spp., and high-nutrient marker planktonic *G. praebulloides-bulloides* group, might indicate seasonal influx of phytodetritus, corresponding to continental nutrient input by rivers. In the middle part of deposits, a marked increase in diversity of both benthic and planktonic foraminifera was observed. Benthic foraminifera are mainly represented by *Bulimina inflata*, *Bolivina spathulata*, *Uvigerina* sp. and *Nonion fabum*. The occasional presence in some samples of *Siphoninoides* cf. *echinata* and *Neoeponides* sp. is observed. Planktonic taxa are constituted by *Trilobatus trilobus, T. diminutus, T. immaturus, Gs. altiaperturus, Gs. subquardatus, G. brazieri, O. bilobata, O. suturalis, Gt. scitula, Gt. obesa,* and *Gt. mayeri.* The simultaneous presence of surface-dwellers (*Globigerinoides* spp., and *Gt. mayeri*) indicative of oligotrophic, stratified waters and cold/eutrophic deep-dwellers as *Gt. scitula* indicative of mixing water suggest a seasonal succession of assemblages (Drinia et al. 2007). Abundant *Uvigerina*, *Bulimina*, *Bolivina* and *Nonion* typify regions of high organic productivity and a sustained flux of organic matter to the seafloor (Thomas et al. 1995). Based on the high abundance of dysoxic and suboxic taxa and the lack of oxyphylic taxa, a bottom water with relatively low-oxygen content, can also be assumed for this group (Pippèrr & Reichenbacher 2010). A marked decrease in species diversity of foraminifera was observed in the uppermost layers. Planktonic foraminifera associations are typified by shallow, surface-dwelling such as *O. suturalis, O. bilobata* and small forms of *Globigerinoides* spp. The sparse benthic

Table S1: Relative abundance of coralline algal components in the eleven facies.

Facies	**Hapalidiales**			**Corallinales**					
	Lithothamniom	*Mesophyllum*	*Phymatolithon*	*Neogoniolithon*	*Lithoporella*	*Spongites*	*Corallina*	unidentified	**Paleodepth (m)**
C1								100	10–15 (Mateu-Vicens et al. 2008)
C2	21			77			2		10–20 (Brandano et al. 2005)
C3				100					10–20 (Aguirre et al. 2000)
C4	86	1	4		6			3	10–25 (Adey 1986)
C5						66		34	10–20 (Brandano et al. 2005)
C6	5			95					20 (Riegl & Piller 1997; 1999)
C7		100							25 (Riegl & Piller 1997; 1999)
C8	8	92							25 (Riegl & Piller 1997; 1999)
C9	7	15						8	30–50 (Martindale 1992)
C10	31	65						4	40–80 (Adey 1979)
C11		100							>80

Table S2: Foraminifera assemblage in the Asmari Formation at the studied area.

Planktonic foraminifers:

Trilobatus trilobus (Reuss), *Trilobatus immaturus* (LeRoy), *Trilobatus bisphericus* (Todd)*, Trilobatus quadrilobatus* (d'Orbigny), *Globigerinoides altiaperturus* Bolli*, Globigerinoides diminutus* Bolli*, Globigerinoides parawoodi* Keller*, Globigerinoides sacculifer* (Brady)*, Globigerinoides conglobatus* (Brady)*, Globoturborotalita nepenthes* (Todd), *Globoturborotalita connecta* (Jenkins), *Globoquadrina tapuriensis* Blow & Banner, 1962, *Globoquadrina dehiscens* (Chapman, Parr & Collinns), *Dentoglobigerina pseudovenezuelana* (Blow & Banner), *Globigerina bulloides* d`Orbigny*, Cassigerinella chipolensis* (Cashman & Ponton), *Globigerinella obesa* (Bolli), *Hastigerina aequilateralis* (Brady), *Globigerina calida* (Parker), *Globigerina ruber* (d'Orbigny), *Globigerina brazieri* Jenkins*, Globigerina falconensis* Blow, *Globigerina eamesi* Blow*, Globorotalia obesa* Bolli, *Globorotalia mayeri* Cushman & ellisor*, Globorotalia scitula* (Brady), *Praeorbulina sicana* Di Stefani*, Praeorbulina glomerosa* (Blow), *Orbulina bilobata* (d'Orbigny), *Orbulina suturalis* Bronnimann*.*

Larger benthic foraminifers:

1. perforate

Amphistegina sp., *Miogypsina globulina* (Michelotti), *Heterostegina* sp., *Operculina complanata* (Defrance)*, Neorotalia* sp.,

2. imperforate

Peneroplis evolutus Henson, *Dendritina rangi* (d'Orbigny), *Sorites* sp., *Meandropsina anahensis* Henson*, Meandropsina iranica* Henson*, Borelis melo* (Fichtel & Moll) *curdica* Reichel*, Borelis melo* (Fichtel & Moll, 1798).

Smaller benthic foraminifers:

1. perforate

Nonion fabum (Fichtel & Moll), *Bulimina inflata* Seguenza*, Bulimina costata* d'Orbigny*, Bolivina spathulata* (Williamson), *Uvigerina* sp., *Eponides* sp.*, Cibicidoides* sp., *Cibicides* sp., *Heterolepa dutemplei* (d'Orbigny), *Textularia* sp., *Bigenerina* sp., *Haddonia* sp., *Miniacina* sp., *Planorbulina* sp., *Ammonia beccarii* (Linne), *Discorbis* sp., *Sphaerogypsina* sp., *Gypsina* sp., *Elphidium crispum* (Linne)

2. imperforate
Triloculina tricarinata d'Orbigny*, Triloculina trigonula* (Lamarck)*, Pyrgo* sp., *Quincueloculina* sp.

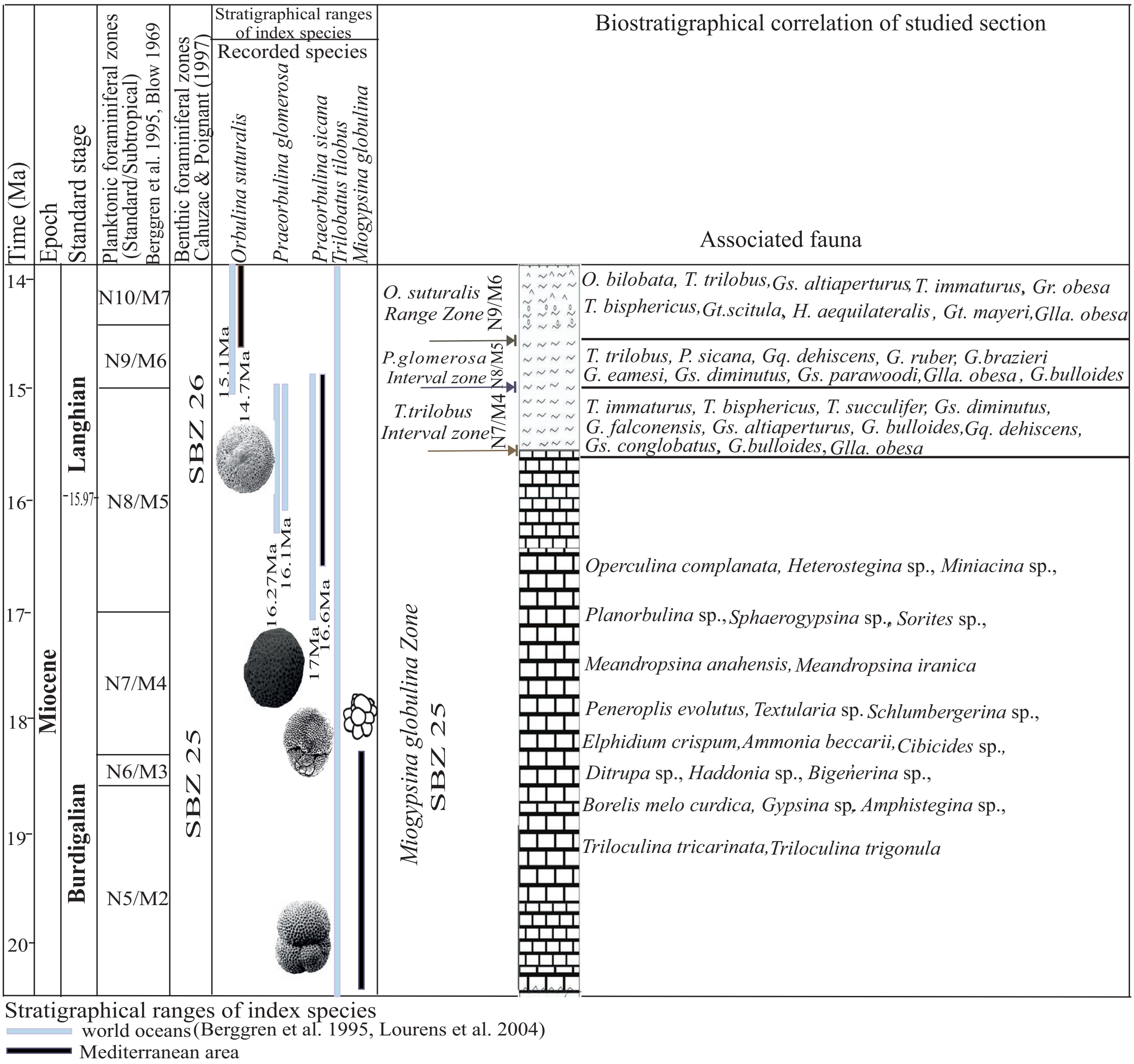

Fig. S1. Biostratigrapic correlation of the Asmari Formation at the studied area

community is dominated by *Bulimina* spp. reflecting an unstable, stressed environment. The presence of infaunal and low oxygen tolerant species such as *Bulimina* spp. points to high nutrient supply and decrease of the oxygen content in to the deepest sediment levels inhabited by the infaunal benthic foraminifera (Drinia et al. 2004). *Orbulina* spp. which thrive in relatively warm and oligotrophic surface waters (Bé & Tolderlund 1971; Hemleben et al. 1989), were found to tolerate high salinity conditions (Bijma et al. 1990), and are common, often dominant taxon in pre-evaporitic assemblages (e.g., Sprovieri et al. 1996; Blanc-Valleron et al. 2002; Sierro et al. 2003). Small forms of *Globigerinoides* spp. also indicate warm oligotrophic season with variable salinity (e.g., Schmuker 2000; Di Stefano et al. 2010; Holcová 2017). Therefore, the dominance of *Orbulina* spp. and *Globigerinoides* spp. throughout this interval provides evidence for the development of hypersaline conditions also in the near-surface waters. These changes in foraminifera association and environmental conditions would be related to limited bottom circulation caused by progressive isolation of the bottom-waters of basin. The isolation of basin could have been caused by the presence of a sill and or by internal basement uplifts, which divided the foreland into a series of isolated to semi-connected, fault-bounded basins (e.g., Rodgers 1987). This caused a slowdown of the vertical circulation, favouring stratification of surface and intermediate waters and stagnation at depth (Di Stefano et al. 2010; Kováč et al. 2017a, b). As a result, the proportional abundances of epifaunal and oxyphylic forms abruptly decreased whereas infaunal taxa became more abundant. With enhanced stratification of water column, deep-water stagnation associated to

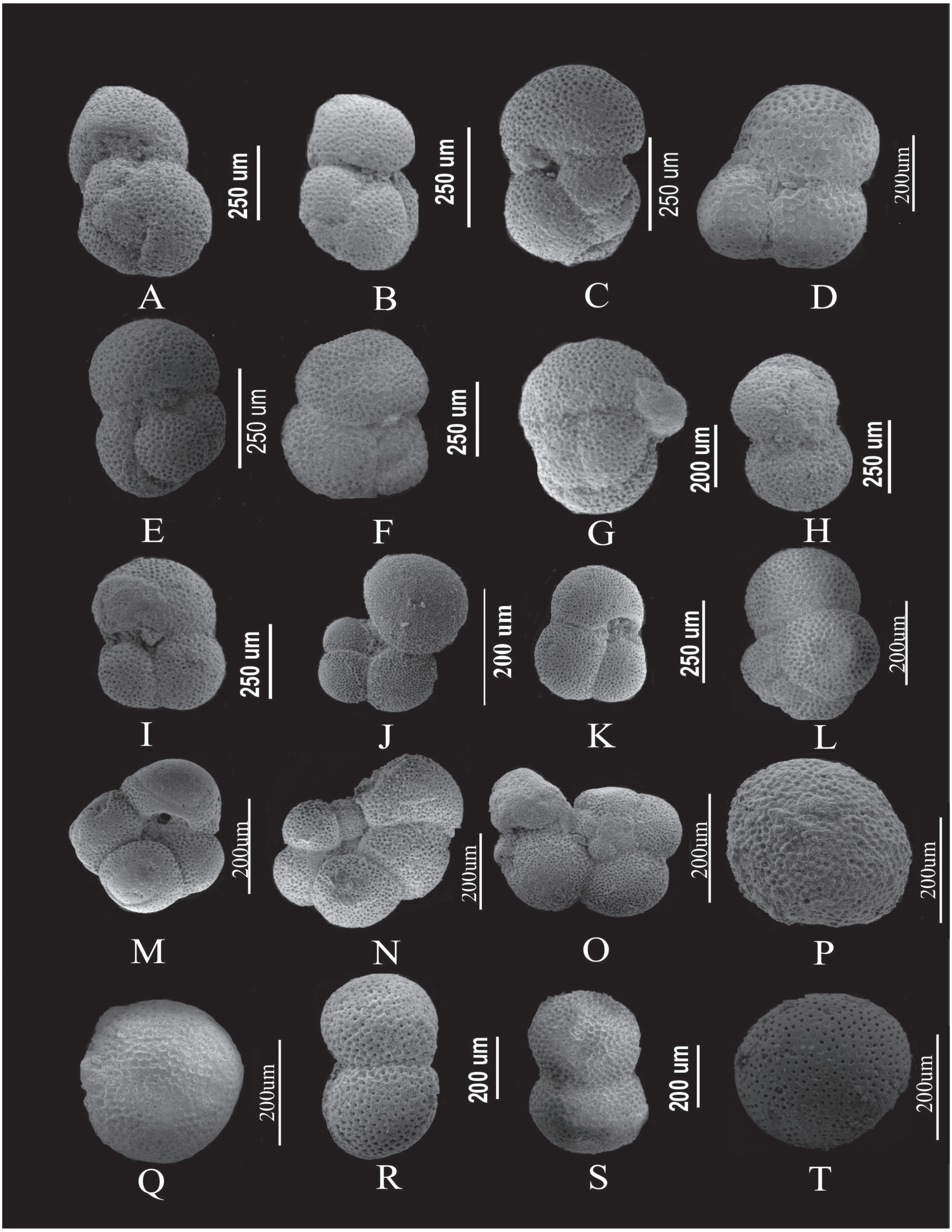

Fig. S2. Photomicrograph of some selected planktonic foraminifera of the Asmari Formation. **A, B** — *Trilobatus quadrilobatus* (d'Orbigny); **C, D** — *Globigerinoides altiaperturus* Bolli; **E, F** — *Trilobatus trilobus* (Reuss); **G, H** — *Trilobatus immaturus* (LeRoy); **I** — *Globoquadrina tapuriensis* Blow & Banner; **J, K** — *Globigerinella obesa* (Bolli); **L, M** — *Globoquadrina dehiscens* (Chapman, Parr, & Collinns); **N, O** — *Hastigerina* sp.; **P, Q** — *Praeorbulina glomerosa* (Blow); **R, S** — *Orbulina bilobata* (d'Orbigny); **T** — *Orbulina suturalis* Bronnimann.

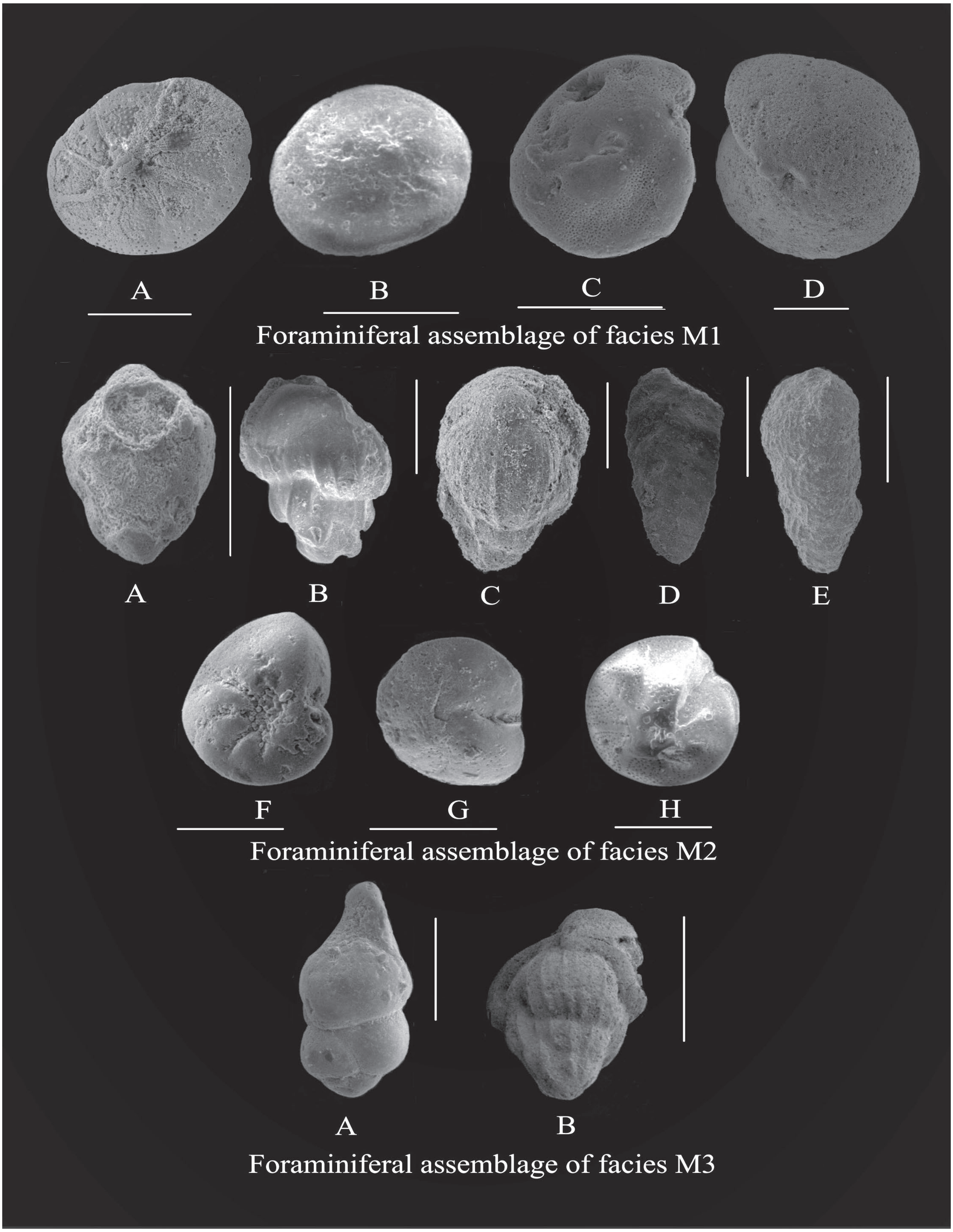

Fig. S3. Foraminiferal assemblage of MF1: **A, B** — *Cibicidoides* sp.; **C, D** — *Heterolepa dutemplei* (d'Orbigny). Foraminiferal assemblage of MF2: **A** — *Siphoninoides* cf. *echinata* (Brady); **B** — *Uvigerina* sp.1; **C** — *Bulimina inflata* Seguenza; **D** — *Bolivina spathulata* (Williamson); **E** — *Uvigerina* sp. 2; **F** — *Nonion fabum* (Fichtel & Moll); **G** — *Neoeponides* sp.; **H** — *Eponides* sp.. Foraminiferal assemblage of MF3: **A** — *Praeglobobulimina* sp.; **B** — *Bulimina costata* d'Orbigny. Scale bars=200 µm.

oxygen depletion and salinity increased, reaching intermediate depth, resulting in the dominance of stress-tolerant benthic species and the disapparence of intermediate-dweller planktonic foraminifers. This increased salinity also caused the precipitation of evaporitic deposits intercalated with marly deposits contain opportunistic foraminifera.

Sequence stratigraphy

One deepening upward third-order sequence was recognized (Figs. S4 and S5). Considering the facies and depositional geometries, this sequence can be grouped into transgressive system tract and lowstand system tract. The lower boundary of this sequence is defined by sedimentation of Asmari Formation over dolomitic Shahbazan Formation. The sequence boundary reflects a large hiatus between the middle Eocene and early Burdigalian (SB1). The basal part of the sequence predominantly consists of lagoonal and shoal microfacies. These facies constituted the early TST. The late TST represents a dominance of middle and outer ramp facies and a deepening upward trend. The mfs is marked by hemipelagic grey marls with dominance of deep dwellers of planktonic foraminifera (e.g., *Globorotalia scitula, Gt. obesa* and *Hastigerina* spp.) and infauna–epifauna benthic foraminifera (e.g., *Bulimina*, *Uvigerina* and *Cibicidoies*). LST reveals a relative sea-level fall and a prevailing restricted and stressful environment. LST is characterized by nodular anhydrite rich in deep infaunal benthic foraminifera (e.g., *Bulimina*). The studied section record a transgressive event which coincides with the global sea level curve of Haq et al. 1987 (Fig. S5). This transgressive event might be also related to a tectonic influence. During the early Burdigalian in response to the eastward developing of Asmari foredeep system, an increase of tectonic subsidence caused new flooding of the platform (e.g., Vaziri-Moghaddam et al. 2010; Kavoosi & Sherkati 2012). As the result of this tectonic event, the northeastern region rapidly subsided and was flooded by the sea.

Comparison of the studied area with the Central Paratethys

The deposits studied here exhibit differences and similarities to the Early–Middle Miocene sediments from Central Paratethys. Hence, we compared the studied section with Robulus Schlier, Rzehakia Beds, Laa and Grund Formations of Austrian Molasse Basin (Spezzaferri & Ćorić 2002; Spezzaferri et al. 2002; Ćorić & Rögl 2004). Key differences between the Burdigalian of study area with Eggenburgian–Ottnangian (Robulus Schlier), Ottnangian (Rzehakia Beds) and Karpatian (Laa Formation) are the dominant biota, biostratigraphical markers and environmental conditions. The Burdigalian skeletal assemblage is dominantly composed of larger benthic foraminifera and coralline red algae, whereas mollusks, echinoids and scarce small benthic foraminifera characterize the lower part of the Ottnangian Robulus Schlier; fish remains are common in their upper part (Ćorić & Rögl 2004). The Rzehakia Beds are obviously contain reworked foraminifera and the stratigraphical position is not very clear (e.g., Holcová 2001). The biostratigraphical markers for Early–Middle Burdigalin are LBF (i.e. *Miogypsina globulina*), whereas the calcareous nannofossils are the most important for the Eggenburgian–Ottnangian Austrian Molasse Basin (Ćorić & Rögl 2004; Kováč et al. 2018). The biotic association in Early–Middle Burdigalian represents a dominance of inner–middle ramp settings with meso–oligotrophic conditions in studied section, whereas during the Early Ottnangian, paleoecological conditions were more eutrophic conditions that changed into intermediate between eutrophic and oligotrophic conditions (outer shelf) in Molasse Basin (Ćorić & Rögl 2004; Kováč et al. 2017a,b). During the Late Burdigalian, a distinct faunal change is observed in studied section, with an increase of planktonic foraminifera and appearance of deep epifana benthic foraminifera and disappearance of LBF. This indicates water depth of outer shelf with good oxygenated bottom-water. In Central paratethys, the Karpatian Laa Formation is dominated by Calcareous nanoplankton, planktonic and small benthic foraminifera (Spezzaferri et al. 2002; Ćorić & Rögl 2004; Schlögl et al. 2012). This assemblage indicates a greater depth (outer shelf to upper bathyal settings) with suboxic to dysoxic conditions, occurrence of high primary production and high surface water fertility (Spezzaferri et al. 2002). There is a hiatus between the Ottnangian and Karpatian deposits in Central Paratethys (Ćorić & Rögl 2004; Kováč et al. 2017b). A major sedimentation break also occurs between the Lower and Upper Burdigalian in the Zagros Basin, but not in the studied section, due to local tectonic activity and increased subsidence. The Langhian sediments from the studied area can be correlated with the Badenian sediments of the Lower and Upper Lagenidae zones, including the sediments of Grund Formation. The Early–Middle Miocene boundary in the Central Paratethys is characterized by a significant sea-level drop (Haq et al. 1987; Hardenbol et al. 1998, Kováč et al. 2017a,b), expressed as a hiatus traceable throughout the basin (frequently called the “Styrian unconformity”; Rögl et al. 2002; Latal & Piller 2003). After this gap, a first Badenian transgression was recorded within nannoplankton Zone NN4 with rare *Praeorbulina sicana* (Hohenegger et al. 2009). The main Badenian transgression covering all the Central Paratethys followed in the NN5 Zone. This transgression is also recorded in the studied area, with sediments containing *Praeorbulina* (conformably in this case) covering the Late Burdigalian deposits (Kováč et al. 2018). In both areas, the benthic assemblage is characteristic of outer shelf setting. In the studied area, the foraminiferal assemblages suggest a shift from more oxygenated bottom waters towards eutrophic conditions and oxygen depletion. Similarly, an increase in primary production and consequently a decrease in oxygen level also occurred during the Middle Badenian of the Austrian Molasse Basin (Ćorić & Rögl 2004). Formation of carbonate facies

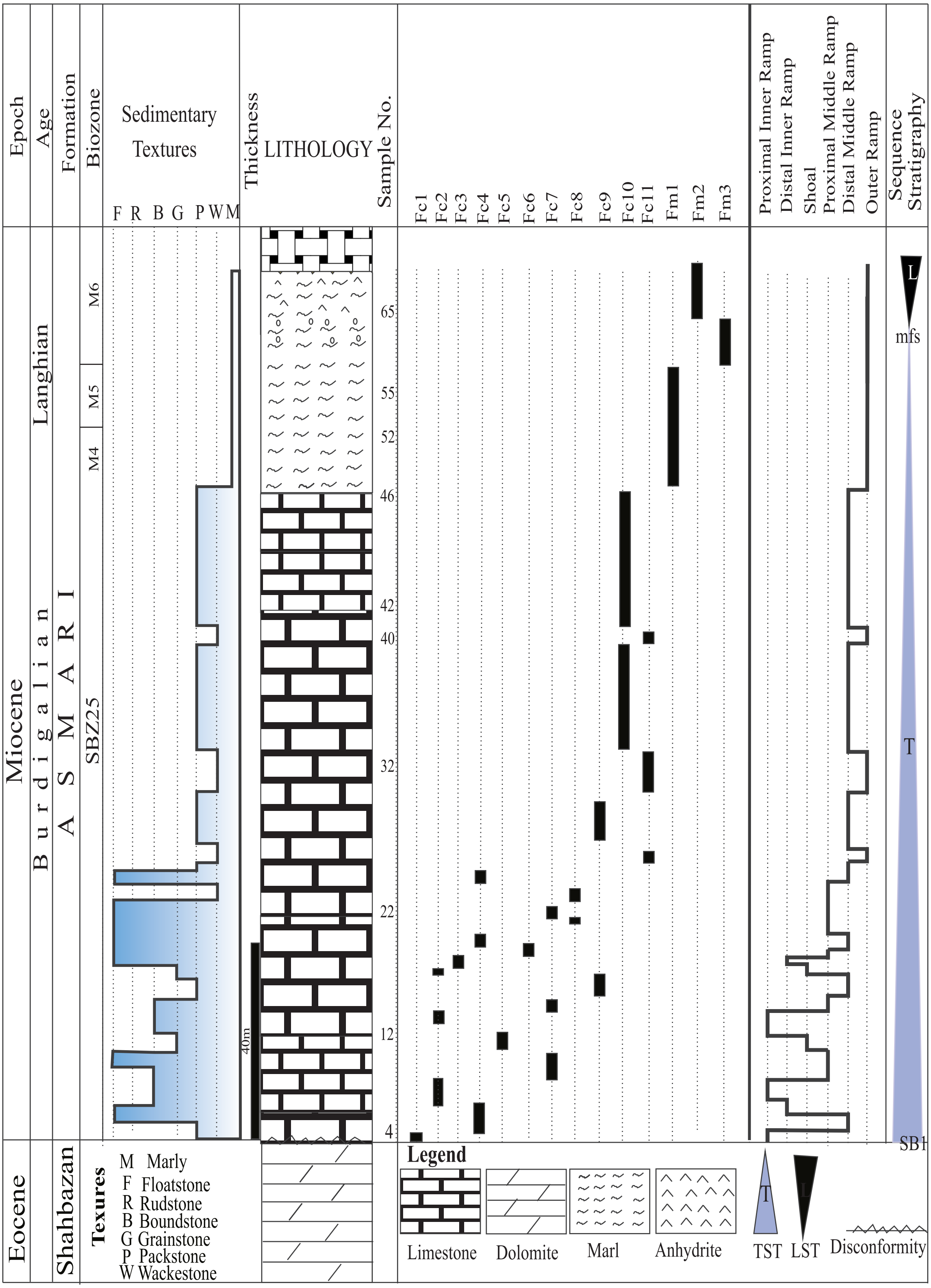

Fig. S4. Vertical facies distribution and sequence of the Asmari Formation at Tang-e-Shabikhon area, Zagros Basin. The vertical distributions of these facies indicate a deepening upward trend from the shallow water, euphotic, inner ramp to meso-oligophotic, middle ramp and into deep, aphotic, outer ramp.

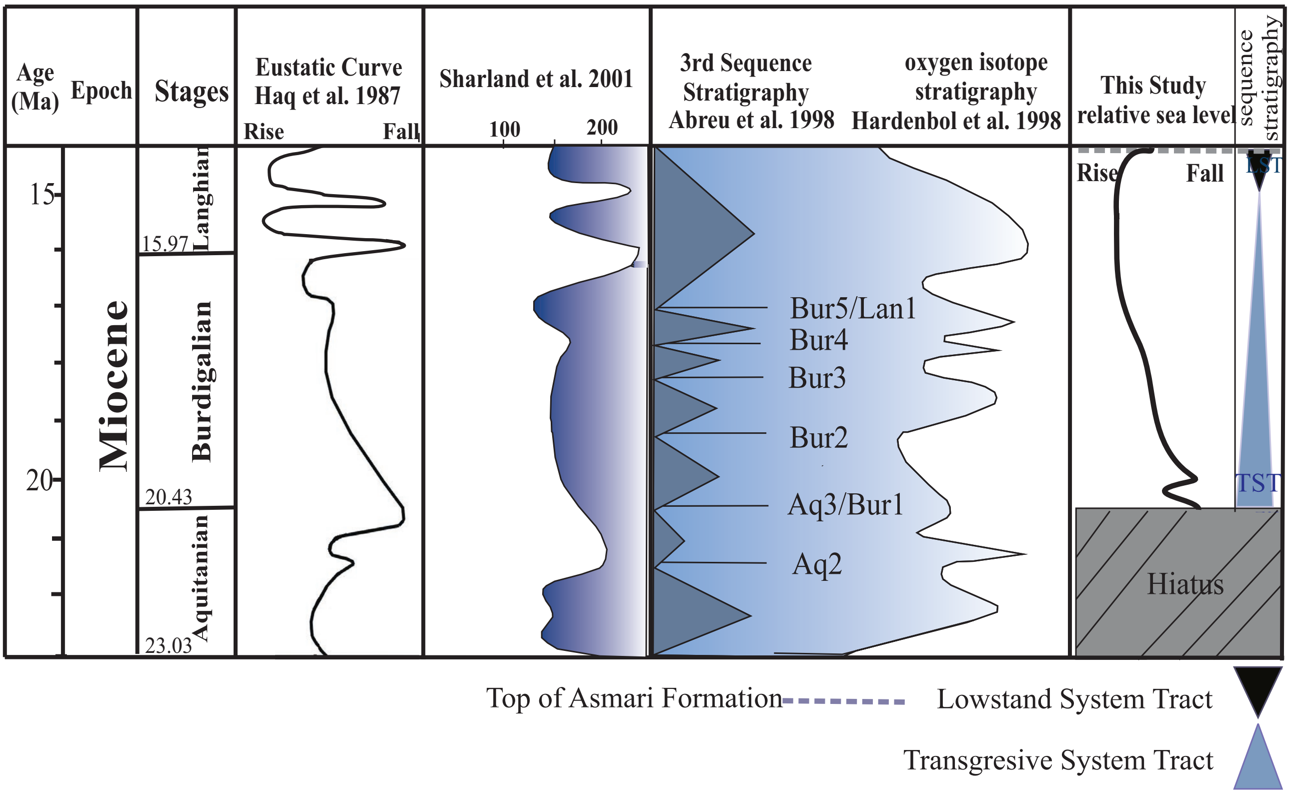

Fig. S5. Correlation chart of the global and regional eustatic curves with the studied section.

predominated with age reefs are recorded in the Carpathian Foredeep (Holcová et al. 2015) and later in the Central Paratethys (Pivko et al. 2017). The following evaporite event can also been observed in both areas. In the study area the evaporite deposition began in the deep part of the basin under dysoxic conditions gradually changing to shallow hyposaline environment (Gachsaran Formation). In the Carpathian Foredeep, mostly sulphate facies were deposited in shallow littoral parts of the foredeep, while chloride–sulphate facies developed in the deepest part of the basin, in front of the accretion wedge of the Outer Carpathians (Oszczypko & Ślączka 1989; Oszczypko 1997; Petrichenko et al. 1997; Andreyeva-Grigorovich et al. 2001, 2003; Bąbel 2004, 2005; Kováč et al. 2017a, b).

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