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ORIGINAL PAPER

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# Depositional environment and sequence stratigraphy of the Oligo-Miocene Asmari Formation in SW Iran

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**Abstract** The Asmari Formation, a thick carbonate succession of the Oligo-Miocene in Zagros Mountains (southwest Iran), has been studied to determine its microfacies, paleoenvironments and sedimentary sequences. Detailed petrographic analysis of the deposits led to the recognition of 10 microfacies types. In addition, five major depositional environments were identified in the Asmari Formation. These include tidal flat, shelf lagoon, shoal, slope and basin environmental settings and are interpreted as a carbonate platform developed in an open shelf situation but without effective barriers separating the platform from the open ocean. The Asmari carbonate succession consists of four, thick shallowing-upward sequences (third-order cycles). No major hiatuses were recognized between these cycles. Therefore, the contacts are interpreted as SB2 sequence boundary types. The Pabdeh Formation, the deeper marine facies equivalent of the Asmari Limestone is interpreted to be deposited in an outer slope-basin environment. The microfacies of the Pabdeh Formation shows similarities to the Asmari Formation.

**Keywords** Asmari Formation · Larger foraminifera · Microfacies · Sequence stratigraphy · Oligo-Miocene

## Introduction

The Asmari Formation, a thick carbonate sequence of the Oligo-Miocene, is the main petroleum reservoir in southwest Iran. It was deposited on a carbonate platform developed across the Zagros Basin (Fig. 1). The Asmari Formation is present throughout the Zagros Basin, but it is best developed in the Dezful Embayment (Fig. 1). Lithologically, the Asmari Formation is characterized by limestones, dolomitic limestones and argillaceous limestones (Motiei 1993).

In the northwestern part of the Zagros Basin, the evaporate Kalhur Member interfingers with limestones of the middle Asmari Formation, whereas in the southeast a sandy facies, the Ahwaz Member replaces the limestones. Little work has been done on the effects of relative sea-level changes during deposition of the Oligo-Miocene carbonate sediments in the Zagros Basin. The objectives of this study are: (1) to provide a facies analysis and recognition of the depositional environments of the Asmari Formation and (2) to develop a sequence stratigraphic model. In this article one stratigraphic section was chosen and subjected to detailed microfacies analysis, based mainly on the distribution of Oligo-Miocene foraminiferal assemblages.

## Methods and study area

More than 300 samples from the Asmari Formation were studied. Some samples from the underlying Pabdeh Formation (see Fig. 1) were also analysed for comparison.

Field and petrographic studies were carried out for facies analysis and paleoenvironmental reconstruction of the Asmari Formation. Facies were determined for each paleoenvironment according to carbonate grain types, textures and interpretation of functional morphology of larger foraminifers. The lithologies and the microfacies types were described according to Dunham (1962).

The study area is located about 141 km north of Ahwaz and 60 km northeast of Lali (Fig. 2). The section was measured in detail at 32° 30′N and 49° 11′E.

### Previous work

The Asmari Formation was named after the Kuh-e Asmari in Khuzestan Province by Busk and Mayo (1918)

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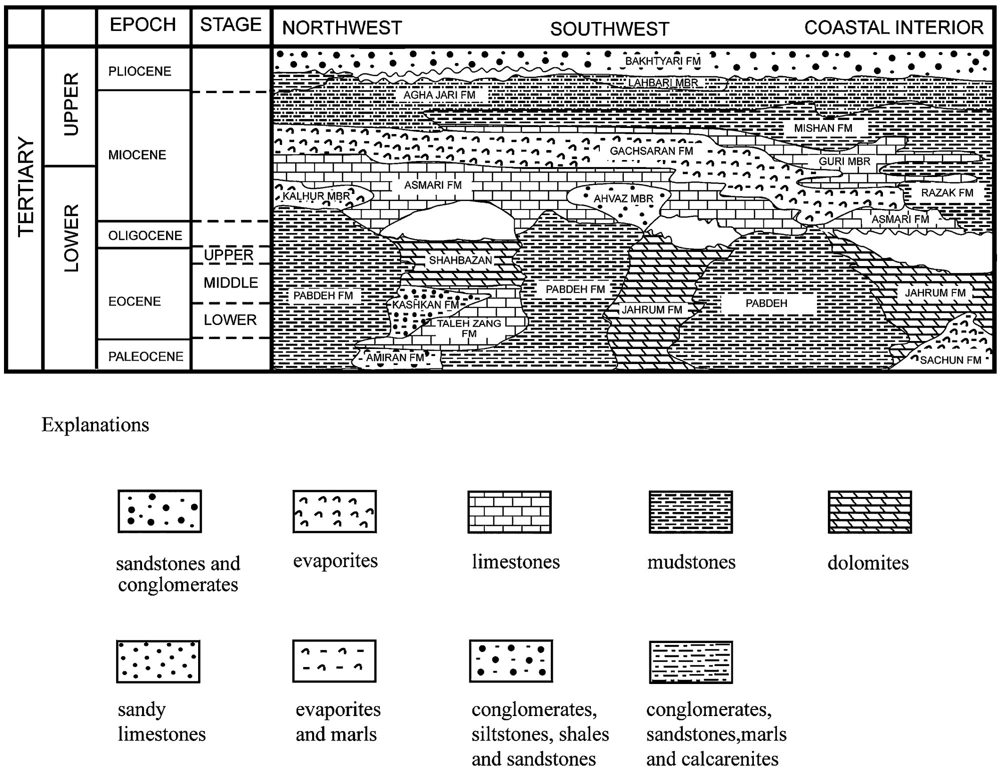



**Fig. 1** Correlation chart of the tertiary of southwest Iran (adopted from Ala 1982)

and referred to a sequence of Cretaceous-Eocene age. The Asmari Formation was also studied by Richardson (1924) and Van Boecha et al. (1929). Lees (1933) revised the previous works and considered the Asmari Formation to be Oligo-Miocene in age. Thomas (1948) dated the Asmari Formation as Oligocene-Burdigalian. The Formation was studied in detail and formally defined by James and Wynd (1965).

Adams and Bourgeois (1967), Wells (1967), Kalantari (1986) and Jalali (1987) reviewed previous investigations and described the lithological characteristics and microfaunal assemblages of the Asmari Formation.

More recent studies based on subsurface data and outcrops of the Asmari Formation were carried out by Seyrafian (1981), Seyrafian et al. (1996), Hamedani et al. (1997), Seyrafian and Hamedani (1998, 2003), Seyrafian (2000).

## Geological setting

The Iranian plateau extends over a number of continental fragments welded together along suture zones of oceanic character. The fragments are delineated by major boundary faults, which appear to be inherited from older geological periods. Each fragment differs in its sedimentary sequence, nature and age of magmatism and metamorphism, and its structural character and intensity of deformation (Berberian and King 1981). These fragments are the following provinces: (1) Zagros, (2) Sanandaj-Sirjan, (3) Urumieh-Dokhtar, (4) Central Iran, (5) Alborz, (6) Kopeh Dagh, (7) Lut and (8) Makran (Fig. 3).

The study area (Lali section) is located in the Zagros Basin. The Zagros Basin was a continental margin attached to the eastern edge of Africa throughout the Phanerozoic. During the Permian, detachment of Iran plate (comprising Alborz, Central-East-Iran microcontinent, and Sanandaj-Sirjan) from the Arabian plate caused the formation of Neotethys Ocean.

Individual microcontinents were later detached from this assemblage and followed their northward path. The various fragments were sutured to Eurasia before and during Miocene time when Africa collided with Eurasia. The Alpidic-Himalayan orogeny caused major deformation in all Iranian fragments and amalgamated them into their present-day configuration (Berberian and King 1981; Alavi 1994; Golonka 2000).

## Biostratigraphy

Biostratigraphic criteria of the Asmari Formation were established by Wynd (1965) and reviewed by Adams and Bourgeois (1967), however in unpublished reports only. The Asmari Formation is divided into lower, middle and upper units, based on the presence of foraminiferal assemblages (Table 1).

From base to top four foraminiferal assemblages were determined in the study area (Fig. 7).

1. Assemblage 1 consists of: *Nummulites* spp., *Eulepidina dilatata*, *Eulepidina elephantina*, *Nephrolepidina tournoueri*, *Heterostegina* sp., *Austrotrillina* sp., Amphistegina sp. and miliolids. This microfauna corresponds to the *Eulepidina-Nephrolepidina-Nummulites*

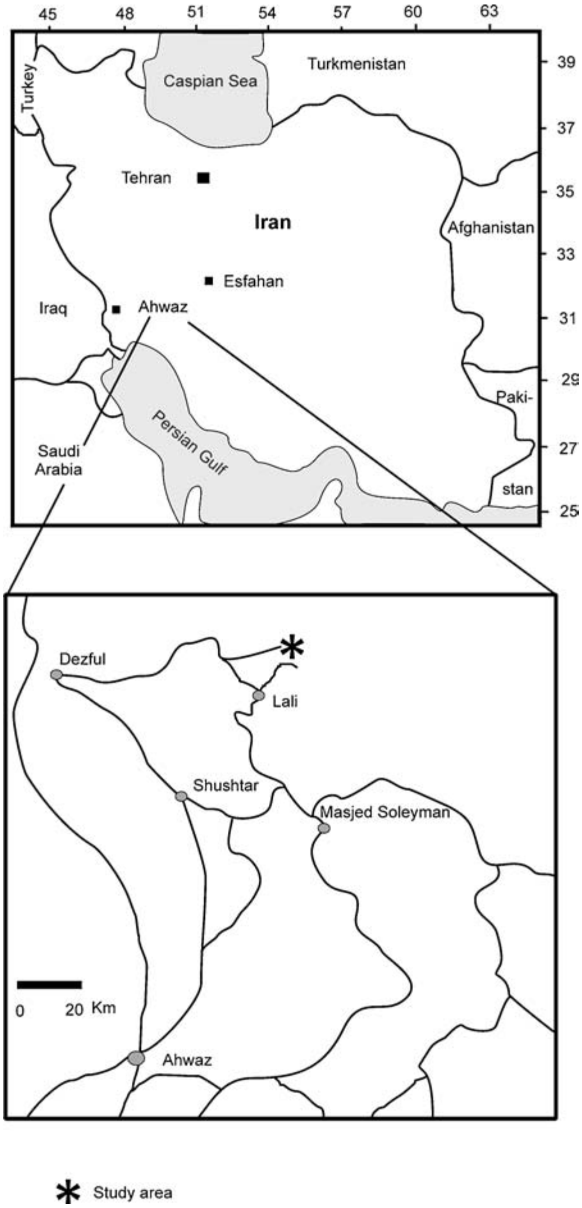



**Fig. 2** Location of the study area in southwest of Iran

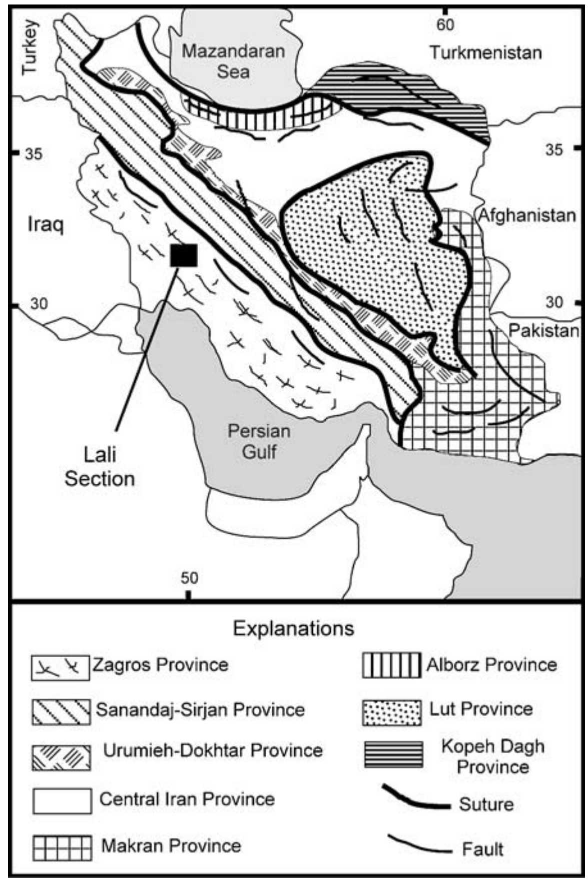



**Fig. 3** General map of Iran showing the eight geologic provinces. The Lali area is located in Zagros province (adopted from Heydari et al. 2003)

assemblage zone of Adams and Bourgeois (1967). Therefore, the assemblage is placed into the lower part of the Asmari Formation (Table 1) and is attributed to the Oligocene based on the content of large foraminifers.

Schuster and Wielandt (1999) demonstrated in contemporaneously deposited sediments of the Qom Formation of Central Iran, that extinction of the *Nummulites* representatives roughly corresponds to the boundary between the planktonic foraminiferal zones P21 and P22 which, according to Berggren et al. (1995), is within the Chattian (see Seyrafian and Hamedani 2003: 166).

2. Assemblage 2 consists of *Austrotrillina howchini*, *Archaias hensoni*, *Peneroplis thomasi*, *Miogypsinoides complanatus*, *Borelis pygmaea* and miliolids and represent the *Archaias asmaricus-Archaias hensoni* subzone of the Early Miocene (Early Aquitanian) age (Adams and Bourgeois 1967).
3. Foraminifera of assemblage 3 include *Peneroplis* sp., *Austrotrillina howchini*, *Borelis* sp., *Borelis pygmaea*, *Miogypsina* sp., *Elphidium* sp. and miliolids.

   These foraminifera are correlated with "*Miogypsina-Elphidium* sp. 14" assemblage subzone of Adams and Bourgeois (1967) and are attributed to the late Aquitanian.

   Assemblages 2 and 3 are placed in the middle part of the Asmari Formation.

**Table 1** Biozonation of the Asmari Formation modified after Adams and Bourgeois (1967)

| Biozones | Rock units | Age |
|---|---|---|
| *Borelis melo-Meandropsina iranica* | Upper Asmari | Burdigalian |
| *Elphidium* sp. *14-Miogypsina* | Upper middle Asmari | Late Aquitanian |
| *Archaias asmaricus-Archaias hensoni* | Lower middle Asmari | Early Aquitanian |
| *Eulepidina Nephrolepidina Nummulites* | Lower Asmari | Oligocene |

4. Assemblage 4 consists of *Borelis melo-curdica*, *Borelis* sp., *Dendritina rangi*, *Peneroplis farsensis*, *Meandropsina iranica*, *Meandropsina anahensis*, *Archaias* sp. and miliolids.

This assemblage is found in the upper part of the Asmari Formation. The foraminifera correspond to *Borelis melo-Meandropsina iranica* assemblage zone of Adams and Bourgeois (1967), and indicate a Burdigalian age.

A *Globigerina* assemblage is also present in the middle part of the Upper Asmari Formation (within *Borelis melo-Meandropsina iranica* zone of Adams and Bourgeois 1967) in the study area (Fig. 7). This assemblage is equivalent to biozone-55 of Wynd (1965).

### Assemblages of Oligo-Miocene foraminifers as paleoenvironmental indicators

In the Oligo-Miocene succession at the study area the most dominant benthic foraminifera are represented by the genera *Nummulites*, *Operculina*, *Heterostegina*, *Lepidocyclina*, *Borelis*, *Archaias*, *Peneroplis* and planktonic foraminifera.

Benthic skeletal components are the most conspicuous constituents of carbonate platforms, while significant carbonate production occurs in open oceans mainly from planktonic production. Carbonate production directly or indirectly depends on photosynthesis and consequently on light penetration into water column. The foraminiferal assemblages of the Asmari Formation consist predominantly of various imperforate and perforate forms with a complex inner morphology. Both groups of larger foraminifera often were supported by endosymbiotic relationships with unicellular algae.

Larger symbiont-bearing foraminifera are also light-dependent although they can be found in relative deep settings (Hohenegger et al. 1999). Shallow marine carbonate sediments of Oligo-Miocene succession at the study area exhibit a great diversity and abundance of larger foraminifers, which occupied most niches in the photic zone of tropical to subtropical oceans. Consequently larger foraminifera provide a useful tool for reconstructing paleoenvironments (Frost and Langenheim 1974; Fermont 1982; Setiawan 1983; Geel 2000).

The Oligo-Miocene foraminifera studied have been compared with the depth range of Recent foraminifera, foraminifera-bearing Early Oligocene carbonates from the Lower Inn Valley of Austria (Nebelsick et al. 2001), and Eocene foraminiferal limestones of the Adriatic carbonate platform (Cosovic et al. 2004). Such a comparison permits determination of distribution of larger and planktonic foraminifers along the depth gradient. The foraminiferal assemblages of the basin environment are characterized by planktonic foraminifera. Planktonic foraminifera are indicative of open marine biotope. The absence of photosymbiont-bearing taxa suggests that this assemblage was deposited below the photic zone.

The simultaneous occurrence of the large perforated foraminiferal tests such as large and flat symbiont-bearing nummulitids, i.e. *Operculina* and *Heterostegina* with planktonic foraminifera represents the deepest environments of the lower limit of the photic zone, most likely in a slope environment (Geel 2000; Romero et al. 2002). Whereas the occurrence of small to medium-sized nummulitids with imperforated foraminiferal tests (miliolids and borelisids) suggests an inner shelf environment (Geel 2000; Brandano and Corda 2002).

*Operculina* lives on soft sediments whereas *Heterostegina* prefers firm substrates (Reiss and Hottinger 1984; Hohenegger et al. 1999). Large and flat *Lepidocyclina* are indicative for normal marine salinity conditions. They lived freely on the seafloor or were attached to hardsubstrates within the euphotic zone (Geel 2000). *Sphaerogypsina globulus* is generally common in Oligocene and Miocene shallow-water sediments (Nebelsick et al. 2001). The dominating genus *Amphistegina* in the sediments studied, is a typical representative of tropical (Reiss and Hottinger 1984) to warm-temperate modern environments (Betzler et al. 1997).

The lower photic zone is dominated by large, flat and perforated foraminifera (such as lepidocyclinids and nummulitids) associated with symbiont-bearing diatoms (Leutenegger 1984; Romero et al. 2002), whereas the shelf lagoon is characterized by a high abundance of imperforate foraminifera (miliolids, borelisids, peneroplids) (Geel 2000).

Generally the upper photic zone is dominated by porcellaneous larger foraminifera (such as peneroplids and borelisids) predominantly living in symbiosis with dinophyceans, chlorophyceans, or rhodophyceans (Leutenegger 1984; Romero et al. 2002).

Borelisids live on all kinds of substrate in relatively shallow clear waters in wave-protected settings, whereas soritids (e.g., *Archaias*) prefer leaves of seagrass (Geel 2000). Peneroplids also are epiphytes and generally live in shallow restricted hypersaline lagoons (Romero et al. 2002).

Miliolids have imperforate tests without symbionts. They can be found in a variety of very shallow-water environments from subhaline to hypersaline conditions (Geel 2000).

## Microfacies analysis

Systematic sampling and field observations at the study area show that the lowermost Asmari Formation interfingers with the uppermost exposed layers of the Pabdeh Formation (Oligocene). The Asmari Formation is composed of thin to medium and thick-bedded limestones and marly limestones. The Pabdeh Formation is composed of marly limestones, green to cream marls and shales. For comparison, some samples from the uppermost Pabdeh Formation have been studied as well. Microfacies A1 and A2 (see below) are common both in the Pabdeh and Asmari Formations.

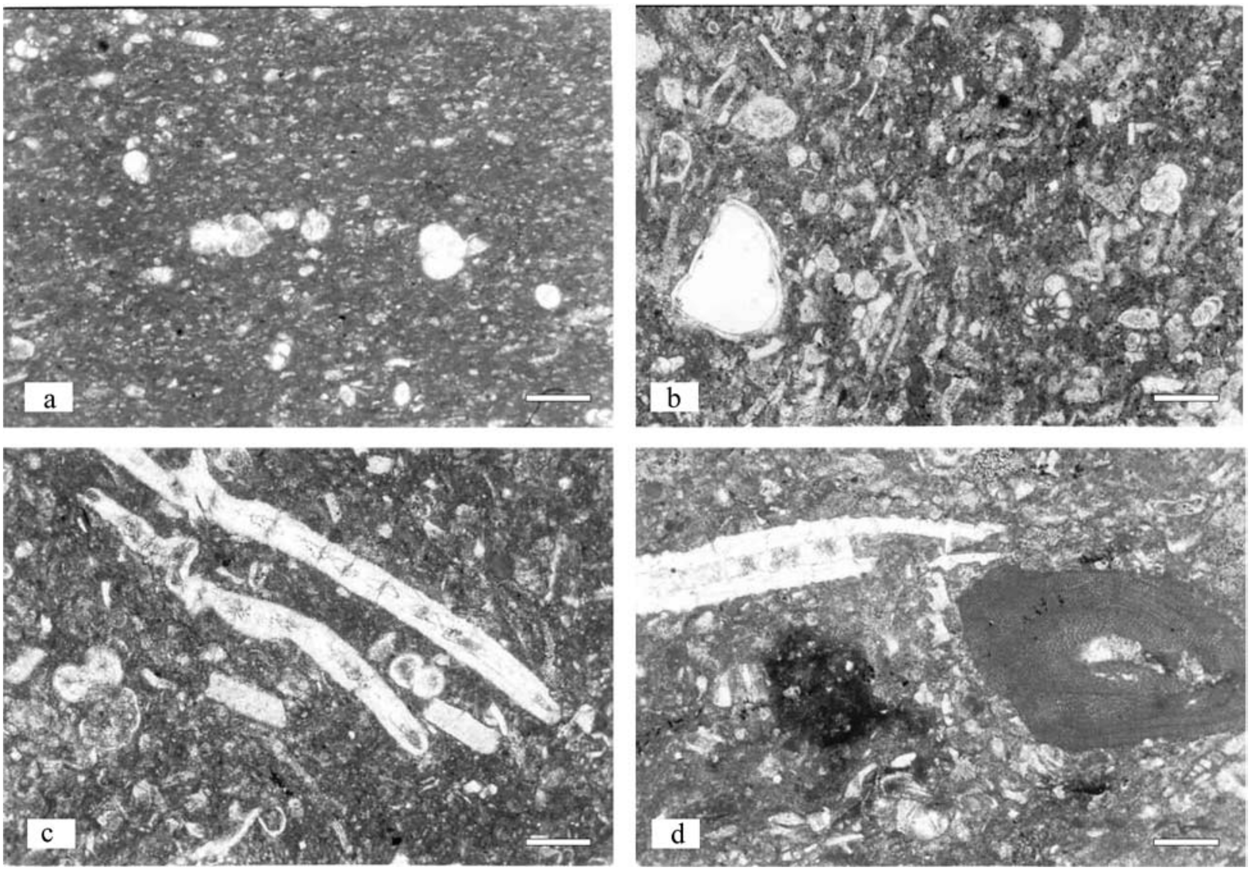



**Fig. 4** General view of open-marine microfacies. **a** Planktonic foraminifer mud-/wackestone. **b** Bioclastic-planktonic foraminifer wacke-/packstone. **c** Planktonic foraminifer-bioclastic-nummulitid wacke-/packstone. **d** Nummulitid-bioclastic-corallinacean wacke-/packstone. Scale bars: 0.5 mm

1. *Planktonic foraminifer mud-/wackestone*: The predominant skeletal grains are planktonic foraminifera (globigerinids and globorotalids). Subordinate taxa belong to the smaller benthic foraminifers (textularids and nodosarids; Fig. 4a). This microfacies is lime mud-dominated and lacks a shallow-water neritic fauna. No sedimentary features that are indicative of shallow-water and high-energy sedimentation were observed.

   *Environmental interpretation*: The abundance of planktonic foraminifera, the occurrence of smaller benthic foraminifera and the fine-grained matrix suggest a lower part of an outer slope-toward-basin environment. The low energy hydrodynamic regime indicates a deposition below the normal wave base (Wilson 1975; Flügel 1982; Geel 2000). The disappearance of both symbiont-bearing larger foraminifera and red algae indicate the lower limit of the photic zone (Cosovic et al. 2004).
2. *Bioclast-planktonic foraminifer wacke-/packstone*: This microfacies is poor in large skeletal fragments and mainly contains mm-sized debris of bryozoans, molluscs and echinoids. Planktonic foraminifers (globigerinids and globorotalids) are the main components. The smaller benthic foraminifera such as textularids are also present. This microfacies has a fine-grained matrix (Fig. 4b).

   *Environmental interpretation*: Microfacies A2 reflects a pelagic marine environment (Scholle et al. 1983) with particles transported from adjacent shallow-water areas. The depositional environment is interpreted as an outer slope environment. A similar microfacies was reported from the outer slope environment of the Maltese Tortonian ramp by Pedley (1996).
3. *Planktonic foraminifer-bioclastic-nummulitid wacke-/packstone*: This microfacies is characterized by the simultaneous occurrence of large benthic and planktonic foraminifers. Benthic foraminifers include large *Operculina*, and *Lepidocyclina*. Among these foraminifera, the lepidocyclinids are represented by predominantly thin and strongly flattened tests. Operculinids are elongated and thin-walled forms. Planktonic foraminifers (globigerinids and globorotalids; Fig. 4c) are also present. The bioclastic component of this microfacies is shell fragments of echinoderms, bryozoans and corallinaceans.

   *Environmental interpretation*: This facies is similar to A2 microfacies, but is characterized by less planktonic foraminifers and generally abundant larger benthic foraminifers. The composition of the biota shows that this microfacies changes transitionally into an outer slope assemblage. The depositional environment was situated at the platform slope between the normal wave base and the storm wave base. Similar sediments were reported from the deeper shelf by Geel (2000) from southeastern Spain.

4. *Nummulitid-bioclastic-corallinacean wacke-/packstone* : Skeletal grains consist of benthic foraminifera, corallinaceans, fragments of echinoderms and bryozoans. The benthic foraminifera include large *Operculina*, *Heterostegina*, *Lepidocyclina*, *Miogypsina*, and *Amphistegina*. Rare planktonic foraminifera are also present (Fig. 4d).

   *Environmental interpretation*: The faunal association (nummulitids, corallinaceans and rare planktonic foraminifers) of this microfacies indicates shallower environments at the platform slope, probably near high-energy shoals. The presence of corallinaceans and larger foraminifera such as *Heterostegina*, *Operculina*, *Lepidocyclina* and *Amphistegina* suggest a middle ramp position and point to oligotrophic conditions (Pedley 1996; Pomar 2001).

5. *Bioclastic grainstone*: This microfacies is characterized by a high abundance of shell fragments (mainly mollusk debris). The bioclasts show micritic envelopes. Subordinate biota include benthic foraminifers (*Operculina* and *Lepidocyclina*; Fig. 5a).

   *Environmental interpretation*: The good sorting of grains and the absence of a fine matrix indicates high-energy conditions for deposition of this microfacies. In accordance to the standard microfacies types described by Wilson (1975) and Flügel (1982), microfacies A5 is interpreted as a shoal environment above the normal wave base which was located at the platform margin, separating the open-marine from the more restricted-marine environments.

6. *Foraminifer-corallinacean-bioclastic pack-/grainstone*: This microfacies is characterized by a high diversity of benthic biota, including foraminifers (small to medium-sized *Operculina*, *Heterostegina* and *Lepidocyclina*, neoalveolinids, miliolids, rotalids and Amphistegina), bryozoans, echinoderms and coralline

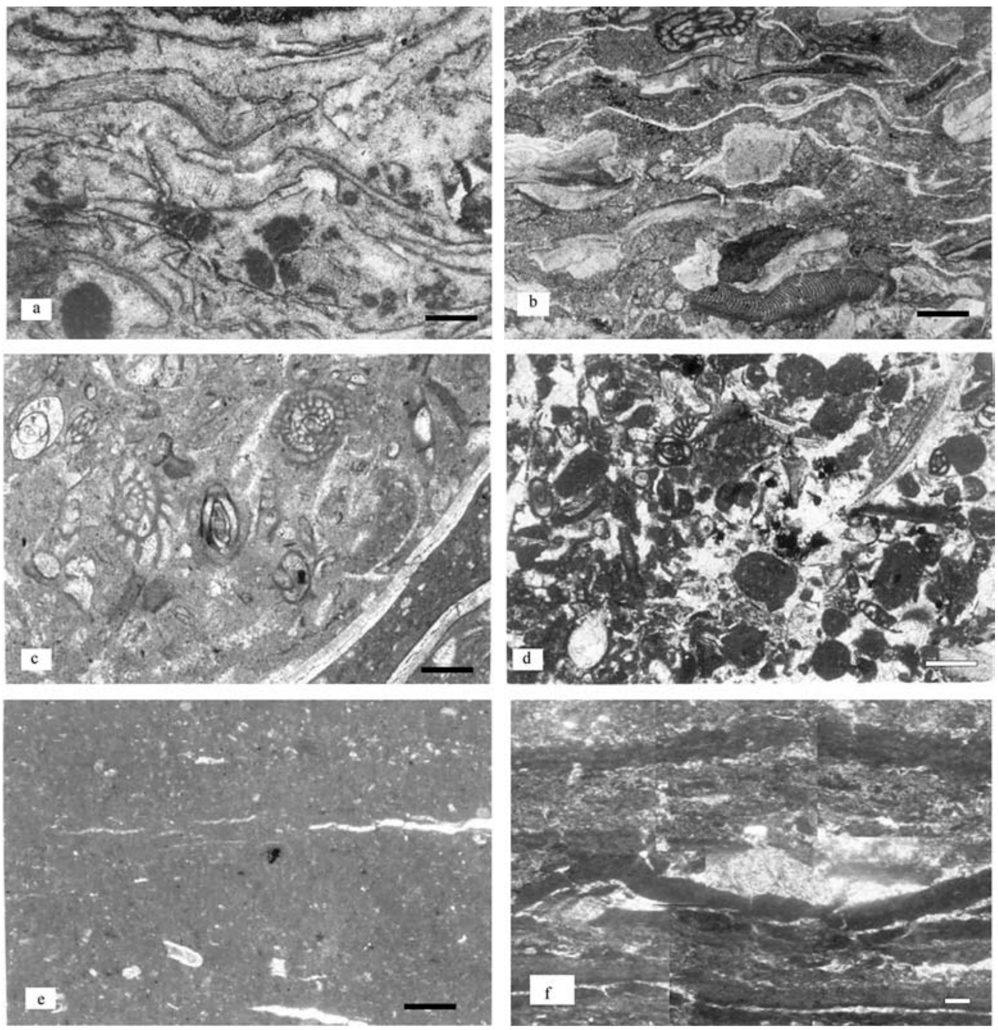


**Fig. 5** General view of shoal, lagoon and tidal flat microfacies. **a** Bioclastic grainstone. **b** Foraminifer-corallinacean-bioclastic pack-/grainstone. **c** Bioclastic-miliolid-borelisid wacke-/packstone. **d** Miliolid-intraclastic-bioclastic pack-/grainstone. **e** Mudstone with shell fragments. **f** Stromatolitic boundstone. Scale bars: 0.5 mm

algae, particularly *Lithophyllum* and *Lithothamnion* and corals. Occasionally, A6 occurs as a wackestone textural rock type (Fig. 5b).

*Environmental interpretation*: Small to medium-sized nummulitids in association with smaller miliolids indicate that sedimentation took place in a shelf lagoon. A similar facies with imperforated foraminifers, perforated foraminifers (*Operculina*, *Heterostegina*, *Amphistegina*) and corallinaceans was reported from inner ramp of the Miocene sediments of the central Apennines (Corda and Brandano 2003) and from Early Oligocene deposits of the Lower Inn Valley (Nebelsick et al. 2001).

7. *Bioclastic-miliolid-borelisid wacke-/packstone*: The abundant components of this microfacies type are benthic foraminifers, borelisids, miliolids and *Archaias*. Associated foraminifers are *Meandropsina*, *Dendritina*, *Austrotrillina*, *Peneroplis* and *Amphistegina*. Other components are echinoderm fragments and coralline algae (Fig. 5c).

   *Environmental interpretation*: The occurrence of a large number of porcellaneous imperforate foraminifer tests points to a slightly hyperhaline environment. Such an assemblage and the similarity with the standard microfacies types described by Wilson (1975) and Flügel (1982) indicate a shelf lagoon environment. A similar microfacies was reported from shelf lagoon environment of the Miocene, Central Basin, Iran (Okhravi and Amini 1998).

8. *Miliolid-intraclast-bioclast pack-/grainstone*: The components of this microfacies are mainly benthic foraminifers (miliolids), bioclasts (fragments of echinoderms and mollusc shells) and more or less rounded intraclasts (Fig. 5d).

   *Environmental interpretation*: The textural characteristics and abundance of miliolids and intraclasts suggest that the sedimentary environment is a restricted lagoon toward with a nearby tidal flat.

9. *Mudstone with shell fragments*: These deposits are represented by mud-supported lithotypes sometimes formed by mm-thick laminae, generally with shell fragments (Fig. 5e). The subtidal origin of this microfacies is supported by the lack of subaerial exposure features and by the fact that the facies A9 overlies the restricted lagoon facies (A8).

10. *Stromatolitic boundstone*: This microfacies is formed by stromatolitic laminae, locally showing a fenestral fabric (Fig. 5f).

    *Environmental interpretation*: The stromatolitic texture, locally showing early diagenetic structures of fenestral type, suggests depositional processes in environments varying from low-intertidal to supratidal.

## Depositional environment

Five major depositional environments identified in the Oligo-Miocene succession in the Lali area, on the basis of the distribution of the foraminifera and vertical facies relationships (Fig. 6). These include tidal flat, shelf lagoon, shoal, slope and basin environments. These five environments are represented by 10 microfacies types (MF-A1: outer slope to basin; MF-A2: outer slope; MF-A3: slope; MF-A4: upper slope; MF-A5: shoal, platform margin; MF-A6: platform margin toward lagoon; MF-A7: shelf lagoon; MF-A8 and MF-A9: restricted lagoon; MF-A10: low intertidal to supratidal).

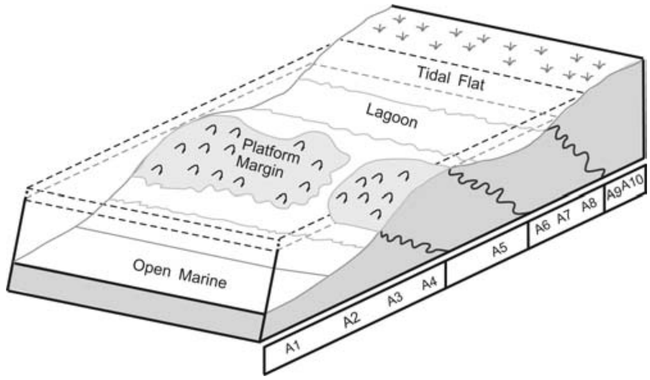


**Fig. 6** Depositional model for the platform carbonates of the Asmari Formation in Lali area, Zagros Basin, SW Iran

In the study area tidal flat facies are characterized by fenestral fabric, stromatolitic boundstone, and thin-bedding planes. The wavy or flat-laminated stromatolitic boundstones are formed by trapping and binding fine-grained carbonate sediments by cyanobacteria in the upper intertidal zone.

Shelf lagoon facies types are highly variable but contain abundant imperforated tests of foraminifera (miliolids, borelisids, *Archaias*, *Peneroplis*). Towards the shoal, imperforated foraminifers and perforated foraminifera (lens-shaped nummulitids, lepidocyclinids and rotalids) occur together. Shoal facies is characterized by bioclastic grainstone. Skeletal grains originate mainly from open-marine organisms living in the vicinity of the platform margin. Absence of mud and presence of sorted grains indicate high-energy conditions.

Slope facies contain abundant large perforated foraminiferal tests (large and flat nummulitids and lepidocyclinids). Basinwards, planktonic foraminifers and large foraminifers with perforated tests occur contemporaneously. Basin facies is marked by high planktonic foraminifera contents embedded in a mudstone–wackestone, thus representing quiet-water depositional environmental conditions. These five depositional environments of the Oligo-Miocene in the Lali area are similar to those found in many modern carbonate depositional settings (Read 1985; Jones and Desrochers 1992). Of these, the Persian Gulf is perhaps the best modern analogue for inferring ancient water depths because it shares many similarities with the Zagros Foreland Basin during Oligo-Miocene. Both settings represent peripheral foreland basins with similar basin geometries and comparably shallow depositional slopes.

Therefore, sedimentological and paleontological studies show that a ramp type carbonate platform sedimentary model can be fully applied to these ancient carbonate deposits (Read 1982; Tucker 1985; Tucker and Wright 1990).

## Sequence stratigraphy

Sequences are defined as a conformable succession of genetically related strata, bounded at the top and bottom by unconformities and/or their correlative conformities (Van Wagoner et al. 1988, 1990).

The unconformities are defined as surfaces of erosion or non-deposition and represent a significant time gap. The major control on deposition is relative sea-level change, determined by rates of eustatic sea-level variation and tectonic subsidence. Particular depositional system tracts are developed during specific phases of the sea-level change's curve: lowstand (LST), transgressive (TST), and highstand (HST) systems tracts. Sequences as defined above are generated by high amplitude sea-level changes with bounding unconformities produced during the relative sea level falls.

In marine shelf environments it is sometimes difficult to distinguish the different systems tracts of a depositional sequence (Vail et al. 1984; Posamentier and Vail 1988; Sarg 1988). This is particularly true when dealing with homogenous lithology, intermittent data irregular dating elements as no real isochrones can be depicted with certainty. Therefore, it is most helpful to use the various markers of high and low sea-level phases contained within strata to confirm interpretations. In this context, benthic foraminifera seem to provide particularly reliable data as they are very sensitive to any change in environment. The validity of this concept has been checked by studying the distribution of benthic foraminiferal associations in deposits where the cycles of eustatic rise and fall of sea-level were already well known (Cubaynes et al. 1989).

## Depositional sequences

Four depositional sequences were recognized in the Asmari Formation (Fig. 7), these include the following.

1. Sequence 1: The basal part of sequence 1 predominantly consists of basin and outer to middle slope community (pelagic and large perforated foraminiferal tests).

   In the upper part, a gradual shift from large perforate dominated tests toward imperforate dominated tests of the shelf lagoon can be observed. Above the lagoonal facies, mudstone facies with shell fragments succeed, which indicates a restricted lagoonal environment.

   The lower part is interpreted as a TST (because of deepening trend) and the upper part as the HST (due to a shallowing trend).
2. Sequence 2: The lower part of the sequence 2 (TST) consists of shelf lagoon deposits which are mostly characterized by imperforated foraminifera. The upper part of the TST is marked by the simultaneous occurrence of both perforated and imperforated foraminifera.

   The upper part of the sequence 2 (HST) is composed of limestone with numerous imperforated foraminifera. The boundary between sequence 2 and sequence 3 is characterized by stromatolitic boundstones (SB2).
3. Sequence 3: In the basal part of sequence 3 (TST), imperforated foraminifers (e.g., miliolids and borelisids) are common. Large perforated foraminifers (flat nummulitids and lepidocyclinids) and planktonic foraminifers are concentrated within the upper part.

   The HST of sequence 3 is characterized by a gradual shift from perforate-dominated fauna towards an imperforate-dominated foraminiferal fauna.

   The boundary between sequence 3 and sequence 4 is interpreted as a SB2 type, because this sequence boundary shows no clear evidence of subaerial exposure.
4. Sequence 4: The TST of sequence 4 is similar to the TST of sequence 3, but planktonic foraminifera are rare in this part.

   The HST of sequence 4 consists of limestone with numerous lagoonal imperforate foraminifers.

   The boundary between the TST and HST is marked by a gradual change in the foraminiferal assemblage. A limestone with a predominance of large perforate foraminifera is substituted by a limestone containing abundant borelisids and miliolids.

There is a disconformity (SB1) developed between the Asmari Formation and the succeeding Gachsaran Formation (Middle Miocene).

## Conclusions

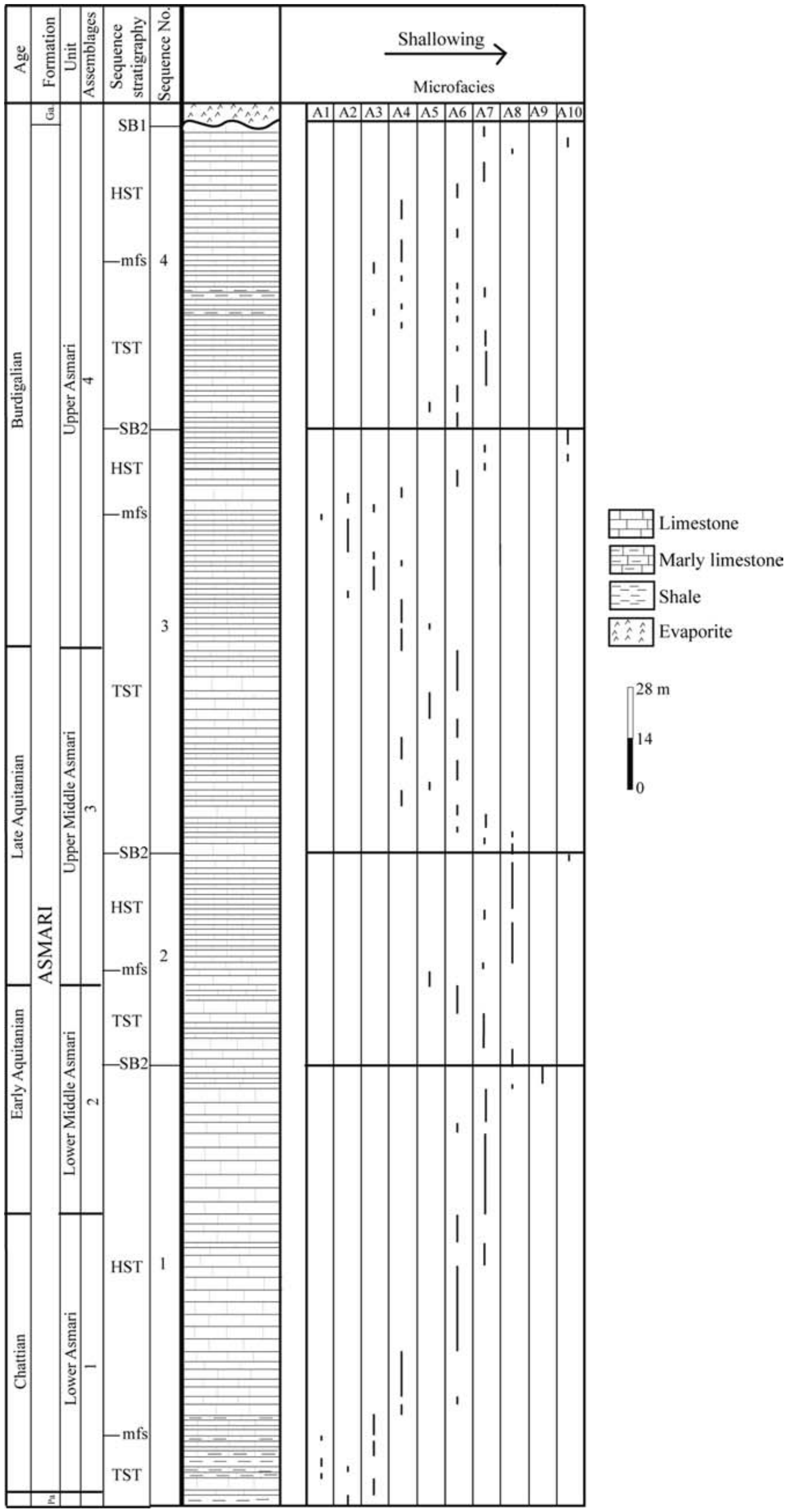
During the deposition of the Oligo-Miocene succession in the Lali area, 10 microfacies are recognized as following.

- MF A1 – Planktonic foraminifer mud-/wackestone
- MF A2 – Bioclast-planktonic foraminifer wacke-/packstone
- MF A3 – Planktonic foraminifer-bioclastic-nummulitid wacke-/packstone
- MF A4 – Nummulitid-bioclastic-corallinacean wacke-/packstone
- MF A5 – Bioclastic grainstone
- MF A6 – Foraminifer-corallinacean-bioclastic pack-/grainstone
- MF A7 – Bioclastic-miliolid-borelisid wacke-/packstone
- MF A8 – Miliolid-intraclast-bioclast pack-/grainstone
- MF A9 – Mudstone with shell fragments
- MF A10 – Stromatolitic boundstone

The microfacies studied were interpreted in terms of depositional environments as follows: MF-A1 (outer slope to basin); MF-A2 (outer slope); MF-A3 (slope); MF-A4 (upper slope); MF-A5 (shoal, platform margin); MF-A6 (platform margin toward lagoon); MF-A7 (shelf lagoon); MF-A8 and MF-A9 (restricted lagoon); MF-A10 (low intertidal to supratidal).

Carbonate deposition took place on a carbonate ramp. The slope and basin environment was separated from a

**Fig. 7** Vertical facies distribution and sequences of the Oligo-Miocene sediments in Lali area, Zagros. TST: transgressive systems tracts, HST: highstand systems tracts, mfs: maximum flooding surface, SB: sequence boundaries



shelf lagoon and a tidal flat by platform margin. The vertical sequence of the Asmari Formation indicates 4 major episodes of deepening and shallowing-upward.

TST are associated with planktonic and large perforated foraminifera. HST are characterized by predominantly imperforated foraminifera.

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