Oligocene-Miocene ramp system (Asmari Formation) in the NW of the Zagros basin, Iran: Microfacies, paleoenvironment and depositional sequence

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ABSTRACT

The Asmari Formation deposited in the Zagros foreland basin during the Oligocene-Miocene. Four different measured sections were studied in this area in order to interpret the facies, depositional environment and sequence stratigraphy of the Asmari Formation. In this study, thirteen different microfacies types have been recognized, which can be grouped into six depositional environments: tidal flat, restricted lagoon, open lagoon, shoal, slope and basin. The Asmari Formation represents sedimentation on a carbonate ramp. Four third-order sequences are identified, on the basis of deepening and shallowing patterns in the microfacies and the distribution of the Oligocene-Miocene foraminifers. The depositional sequences 1, 2 and 3 were observed in Dehluran and Kabirkuh-Darrehshahr areas, and are synchronous with a period of either erosion or non-deposition represented by unconformities in Mamulan and Sepid Dasht areas.

Key words: microfacies, paleoenvironment, ramp, Asmari Formation, Zagros basin, Iran.

RESUMEN

La Formación Asmari se depositó en el antepaís de la cuenca Zagros durante el Oligoceno-Mioceno. Se estudiaron y midieron cuatro secciones diferentes en esta área para interpretar las facies, ambiente de depósito y la secuencia estratigráfica de la Formación Asmari. En este estudio, trece tipos diferentes de microfacies han sido reconocidos, los cuales pueden ser agrupados en seis ambientes de depósito: planicie de marea, laguna restringida, laguna abierta, mar somero (bancos de arena), pendiente marina y cuenca. La Formación Asmari representa sedimentación en una rampa carbonatada. Cuatro secuencias de tercer orden se identificaron, según patrones de profundidad y superficialidad de las microfacies y la distribución de los foraminíferos del Oligoceno-Mioceno. Las secuencias de depósito 1, 2 y 3 se observaron en las áreas de Dehluran y Kabirkuh-Darrehshahr, y son sincrónicas con un período de erosión o bien de no depósito, representado por discordancias en las áreas de Mamulan y Sepid Dasht.

Palabras clave: microfacies, paleoambiente, rampa, Formación Asmari, cuenca Zagros, Irán.

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INTRODUCTION

This paper deals with the Asmari Formation, an Oligocene-Miocene carbonate succession in the northwestern Zagros basin, southwest Iran (Figure 1). The area is excellent to establish the geometrical relationship between sedimentary facies and sequence stratigraphy of a carbonate platform.

The Asmari Formation, a thick carbonate sequence of the Oligocene-Miocene, is one of the best known carbonate reservoirs in the world. It is present in most of the Zagros basin. Lithologically, the Asmari Formation consists of limestone, dolomitic limestone, dolomite and marly limestone. Some anhydrite (Kalhur Member) and lithic and limy sandstones (Ahwaz Member) also occur within the Asmari Formation (Motiei, 1993).

The Asmari Formation was originally defined in primary works by Busk and Mayo (1918), Richardson (1924), Van Boeck *et al.* (1929), and Thomas (1948). Later, James and Wynd (1965), Wynd (1965), Adams and Bourgeois (1967), Kalantary (1986), and Jalali (1987) introduced the microfaunal characteristics and assemblage zones for the Asmari Formation. More recent studies of the Asmari Formation have been conducted on biostratigraphic criteria (Seyrafian *et al*., 1996; Seyrafian and Mojikhalifeh, 2005; Hakimzadeh and Seyrafian, 2008; Laursen *et al*., 2009), microfacies and depositional environments (Seyrafian and Hamedani, 1998, 2003; Seyrafian, 2000) and depositional environment and sequence stratigraphy (Vaziri-Moghaddam *et al*., 2006; Amirshahkarami *et al*., 2007a, 2007b; Ehrenberg *et al*., 2007).

This paper reports on a sedimentological study of Asmari Fm. outcrops, whose results could contribute to a better understanding of the subsurface Asmari Formation in adjacent oilfield areas. The main objectives of this reseach were foused on (1) a description of the facies and their distribution on the Oligocene-Miocene carbonate platform, (2) the palaeoenvironmental reconstruction of the carbonate platform, and (3) the origin of sequences that developed in the study area mainly based on the distribution of the foraminifera.

GEOLOGICAL SETTING

Based on the sedimentary sequence, magmatism, metamorphism, structural setting and intensity of deformation, the Iranian Plateau has been subdivided into eight continental fragments, including Zagros, Sanandaj-Syrjan, Urumieh-Dokhtar, Central Iran, Alborz, Kopeh-Dagh, Lut, and Makran (Heydari *et al*, 2003; Figure 2). The study area is located in the northwestern part of the Zagros basin and include four sections: 1) Dehluran, 2) Kabirkuh-Darrehshahr, 3) Mamulam and 4) Sepid Dasht (Figure 1).

The Zagros basin is composed of a thick sedimentary sequence that covers the Precambrian basement formed during the Pan-African orogeny (Al-Husseini, 2000). The total thickness of the sedimentary column deposited above the Neoproterozoic Hormuz salt before the Neogene Zagros folding can reach over 8 to 10 km (Alavi, 2004; Sherkati and Letouzey, 2004). The Zagros basin has evolved through a number of different tectonic settings since the end of Precambrian. The basin was part of the stable Gondwana supercontinent in the Paleozoic, a passive margin in the Mesozoic, and became a convergent orogen in the Cenozoic.

During the Palaeozoic, Iran, Turkey and the Arabian plate (which now has the Zagros belt situated along its northeastern border) together with Afghanistan and India, made up the long, very wide and stable passive margin of Gondwana, which borderered the Paleo-Tethys Ocean to the north (Berberian and King, 1981).

By the Late Triassic, the Neo-Tethys ocean had opened up between Arabia (which included the present Zagros region as its northeastern margin) and Iran, with two different sedimentary basins on both sides of the ocean (Berberian and King, 1981).

The closure of the Neo-Tethys basin, mostly during

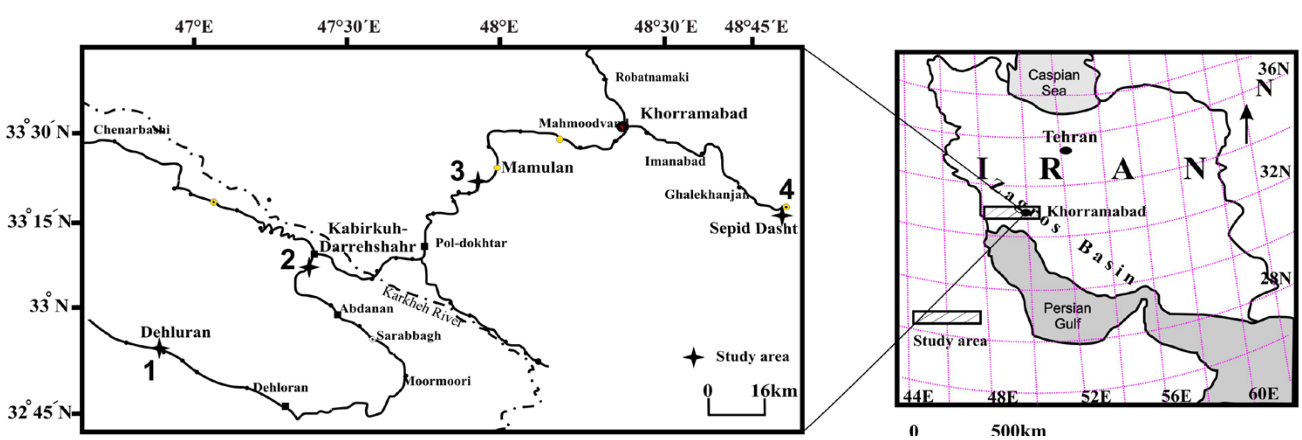

Figure 1. Map showing the location of the study areas in northwest Zagros. Dehluran (Section 1), Kabirkuh-Darrehshahr (Section 2), Mamulan (Section 3) and Sepid Dasht (Section 4).

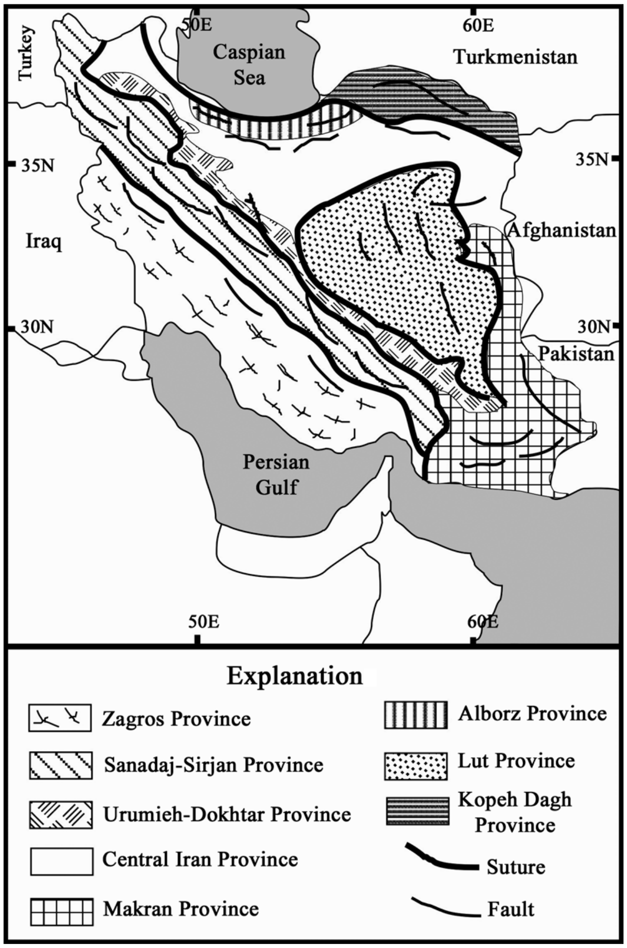

Figure 2. Subdivisions of the Zagros orogenic belt (adopted from Heydari *et al*., 2003).

the Late Cretaceous, was due to the convergence and northeast subduction of the Arabian plate beneath the Iranian sub-plate (Berberian and King, 1981; Stoneley, 1981; Beydoun *et al*., 1992; Berberian, 1995). The closure led to the emplacement of pieces of the Neo-Tethyan oceanic lithosphere (i.e., ophiolites) onto the northeastern margin of the Afro-Arabian plate (e.g., Babaie *et al*., 2001; Babaei *et al*., 2005; Babaie *et al*., 2006).

Continent-continent collision starting in the Cenozoic has led to the formation of the Zagros fold-and-thrust belt, continued shortening of the mountain range, and creation of the Zagros foreland basin. The Late Cretaceous to Miocene rocks represent deposits of the foreland basin prior to the Zagros orogeny, and subsequent incorporation into the colliding rock sequences. This sequence unconformably overlies Jurassic to Upper Cretaceous rocks.

Compressional folding began during or soon after the deposition of the Oligocene-Miocene Asmari Formation (Mapstone, 1978; Sepehr and Cosgrove, 2004).

During the Palaeocene and Eocene, the Pabdeh (pelagic marls and argillaceous limestones) and the Jahrum (shallow marine carbonates) formations were, respectively, deposited in the middle part and on both sides of the Zagros basin axis (Motiei, 1993). During the Oligocene-Miocene this basin was gradually narrowed and the Asmari Formation was deposited. Different facies, including lithic sandstone (Ahwaz Member) and evaporites (Kalhur Member) were deposited during late Oligocene-early Miocene times (Ahmadhadi *et al*., 2007). In the southwestern part of the Zagros basin, the Asmari Formation overlies the Pabdeh Formation, whereas in the Fars and Lurestan regions it covers the Jahrum and Shahbazan formations (Figure 3). Although the lower part of the Asmari Formation interfingers with the Pabdeh Formation in the Dezful Embayment (Motiei, 1993), its upper part covers the entire Zagros basin. The maximum thickness of the Asmari Formation is found in the northeastern corner of the Dezful Embayment.

METHODS AND STUDY AREA

Four sections of the Asmari Formation were measured bed by bed, and sampled in four areas (Dehluran, 180; Kabirkuh-Darrehshahr, 260; Mamulan, 69/5; and Sepid Dasht, 82/5 m thick; Figures 1 and 4), and sedimentologically investigated. The sections were described in the field, including their weathering profiles, facies and bedding surfaces. Fossils and facies characteristics were described in thin sections from 408 samples. Test shapes of the largest benthic foraminifera were taken into account for the facies interpretation, as their differences depend on the environment (Hottinger, 1980, 1983; Reiss and Hottinger,1984; Leutenegger, 1984; Hohenegger, 1996; Hallock, 1999; Hohenegger *et al*., 1999; Geel, 2000; Brandano and Corda, 2002; Corda and Brandano, 2003; Barattolo *et al*., 2007). The lithology and the microfacies types were described according to the schemes porposed by Dunham (1962) and Embry and Klovan (1971). Also, the same 408 samples were used for sequence stratigraphy analyses.

BIOSTRATIGRAPHY

Biozonation and age determinations are based on strontium isotope stratigraphy recently established for the Asmari Formation by Laursen *et al*. (2009). Results from the foraminifera data are summarized in Table 1.

Three assemblages of foraminifera were recognized in the studied areas and were discussed in ascending stratigraphic order as follows:

Assemblage 1. This assemblage occurs only at Kabirkuh-Darrehshahr area (Section 2). The most important foraminifera are: *Eulepidina* sp*., Eulepidina dilatata, Eulepidina elephantine, Lepidocyclina* sp*., Nephrolepidina* sp*., Operculina* sp., *Operculina complanata, Austrotrillina howchini, Austrotrillina asmaricus, Peneroplis* sp., *Triloculina trigonula*, *Spiroclypeus blanckenhorni*, miliolids and globigerinids. This assemblage is correlated with *Lepidocyclina*-*Operculina*-*Ditrupa* assemblage zone

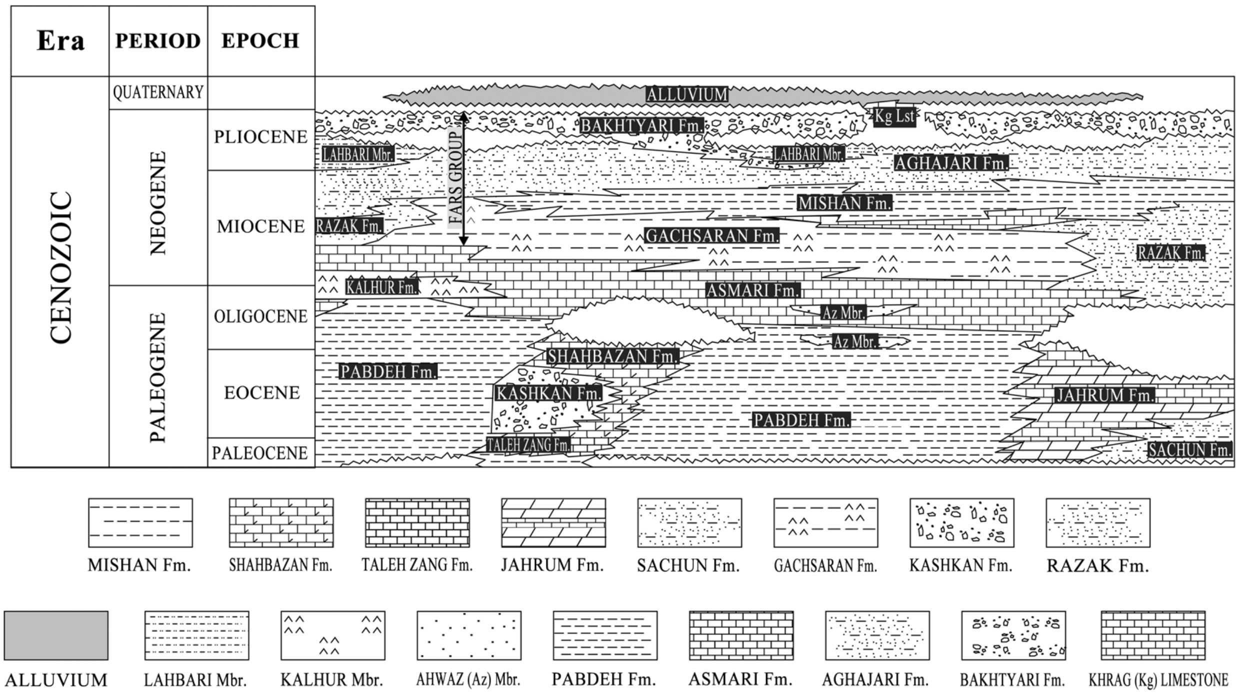

Figure 3. Schematic section showing the stratigraphic position of the Asmari Formation within the Cenozoic rocks of southwestern Iran (Motiei, 2001).

of Laursen *et al*. (2009) (Table 1) and is attributed to the Chattian time.

Assemblage 2. This assemblage is present in Dehluran (Section 1) and Kabirkuh-Darrehshahr (section 2) areas. The most diagnostic species in both studied sections include: *Miogypsina* sp., *Elphidium* sp. 14, *Lepidocyclina* sp., *Operculina complanata*, *Austrotrillina* sp., *Austrotrillina asmaricus, Peneroplis* sp., *Peneroplis thomasi*, *Triloculina trigonula, Miogypsinoides* sp., *Borelis* sp., *Meandropsina iranica, Meandropsina anahensis*, *Dendritina rangi*, *Amphistegina* sp., miliolids, *Discorbis* sp., *Valvulinid* sp. and *Neorotalia viennoti.* This assemblage corresponds to the *Miogypsina–Elphidium* sp. 14-*Peneroplis farsensis* assemblage zone of Laursen *et al*. (2009) (Table 1). The assemblage is considered to be Aquitanian in age.

Assemblage 3. This assemblage is recordable in all studied sections and consists of *Borelis melo curdica, Borelis* sp., *Peneroplis* sp., *Neorotalia* sp., *Elphidium* sp., *Meandropsina iranica*, *Dendritina rangi*, *Dendritina* sp., miliolids, *Discorbis* sp. and globigerinids. The assemblage represents the *Borelis melo curdica-Borelis melo melo* assemblage zone of Burdigalian age (Laursen *et al*., 2009).

MICROFACIES ANALYSIS

Facies analysis of the Asmari Formation in the study areas resulted in the definition of thirteen facies types (Figure 5), which characterize platform development. Each of the microfacies exhibits typical skeletal and non-skeletal components and textures. The general environmental interpretations of the microfacies are discussed in the following paragraphs.

Microfacies A. Stromatolitic boundstone (Figure 5.1)

This microfacies, with finely or moderately crinkled horizontal lamination, consists of alternating calcilutitic laminae and calcisiltic bioclastic laminae. Microfacies A is only present at Dehluran area (Section 1) and intercalates with mudstone facies.

Interpretation. This facies type is common in tidal flat sediments (Flügel, 2004; Hardie, 1986; Steinhauff and Walker, 1996; Lasemi, 1995; Hernández-Romano, 1999; Aguilera-Franco and Hernández-Romano, 2004). Today, flat laminated structures of microbial origin are found in intertidal settings. In regions with an arid climate (*e.g.*, Persian Gulf or Shark Bay) stromatolites with smooth mats are located in the lower intertidal zone (Davies, 1970a, 1970b; Kinsman and Park, 1976; Hoffman, 1976).

Microfacies B. Fenestrate mudstone (Figure 5.2)

This facies consists of fine grained microcrystalline limestone. Bioclasts are lacking and the fenestrate structures are well developed. Microfacies B was identified at Kabirkuh-Darrehshahr area (Section 2) and mostly occurs with quartz mudstone.

Interpretation. Fenestrate structures are typical prod-

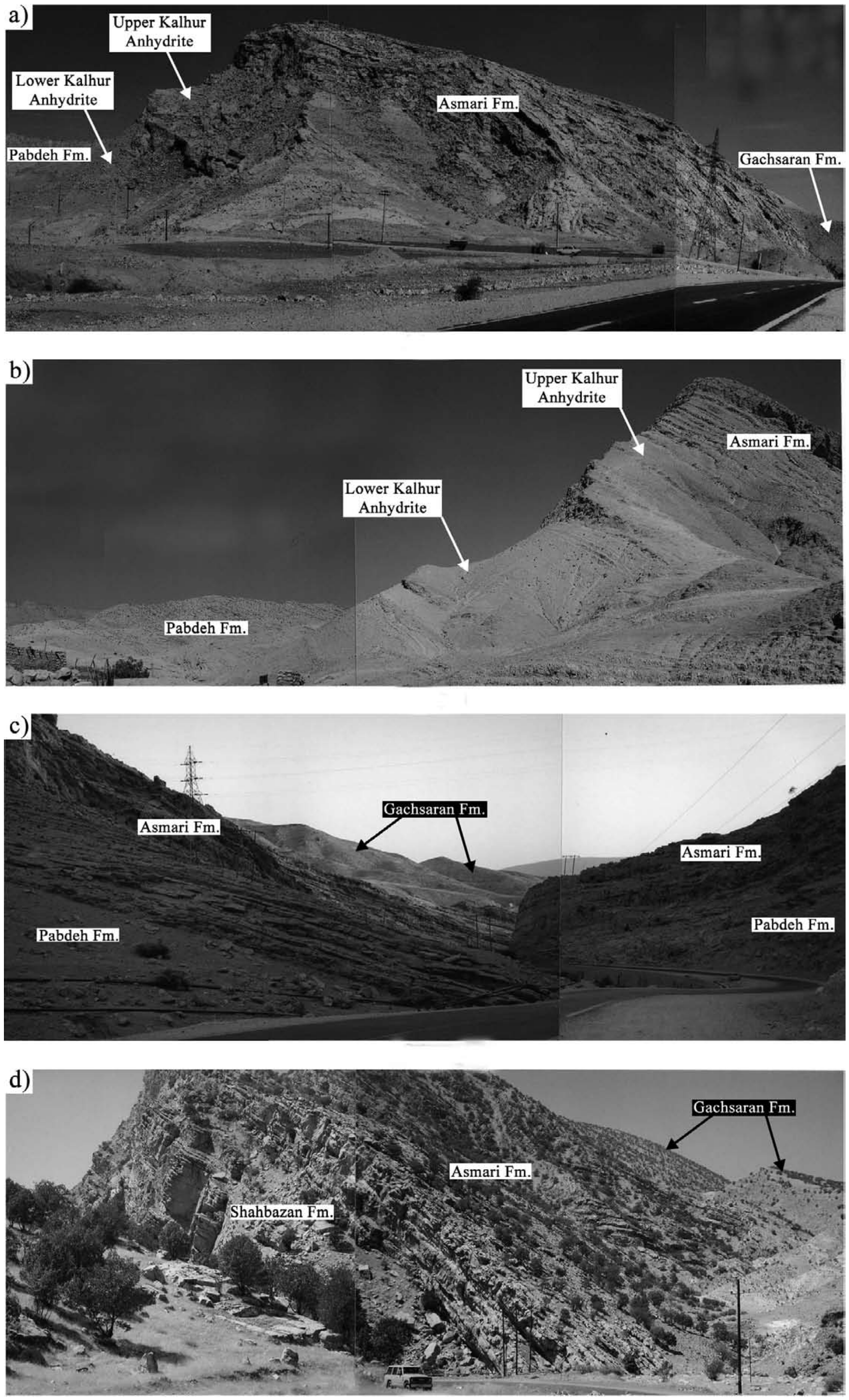

Figure 4. Outcrop photographs of three of the studied sections. Stratigraphic sections related to these outcrops are shown in Figure 13. a: Dehluran section (Pabdeh, Asmari and Gachsaran formations). b: Dehluran section (Pabdeh Formation, lower and upper Kalhur Member and Asmari Formation). c: Kabirkuh-Darreshahr section (Pabdeh, Asmari and Gachsaran formations). d: Mamulan section (Shahbazan, Asmari and Gachsaran formations).

ucts of shrinkage and expansion, gas bubbles, and air escape during flooding, or may even result from burrowing activity of worms or insects. Shinn (1983) considered similar facies representative of a tidal flat environment, where trapped air between irregularly-shaped deposits leads to the development of birdseyes.

Microfacies C. Mudstone (Figures 5.3 and 5.4)

This microfacies is composed of dense lime mudstones. Sediments also contain sparse unidentified fauna. In some samples, subordinate amounts of detrital quartz grains and gypsum are also present. This facies occurs in middle and upper parts of the Asmari Formation. Microfacies C occurs at Dehluran (Section 1), Kabirkuh-Darrehshahr (Section 2) and Mamulan (Section 3) areas. It is either next to anhydrite or intercalates with lagoonal facies.

Interpretation. Lime mudstone, with gypsum blades and small quartz grains and no evidence of subaerial exposure, was deposited in a restricted shelf lagoon. This facies indicates hypersaline conditions within a shelf lagoon.

Microfacies D. Anhydrite (Figure 5.5)

Anhydrite facies have been observed in the upper part of the Pabdeh Formation and in the lower part of the Asmari Formation. The first anhydrite deposit is surrounded by marly limestones containing pelagic fauna. There is a sharp contact with the carbonates above and below. The second anhydrite deposit is intercalated between shallow water carbonates. Microfacies D is only present at Dehluran area (Section 1) and mostly associates with mudstone facies.

Interpretation. Considering the thickness of the anhydrite deposits, their vertical stacking and lateral continuity, it is assumed that they are submarine deposits formed in an isolated saline basin. The deposition of anhydrite implicates that the depositional environment became isolated from the open ocean at that time, which allowed for the concentration and submarine precipitation of salt. An eustatic sea level drop is invoked as the most likely cause. This event took place around the Oligocene-Miocene boundary. Ehrenberg *et al*. (2007) noted that strontium dates obtained from anhydrite in the Asmari Formation were close to the expected depositional ages and suggested that the anhydrite formed as an evaporate rather than as a later diagenetic product.

Microfacies E. *Dendritina* miliolids peloids wackestone-packstone-grainstone (Figure 5.6)

Identifiable components of this facies include benthic imperforate foraminifera (*Dendritina* and miliolids) and peloids. *Borelis*, bivalves and gastropods (whole shell and broken fragments) are less common. The grains are poorly to medium sorted, are fine-to medium size and vary from sub-angular to semi-rounded. Textures are dominantly packstone, but range from wackestone to grainstone. In some samples, the predominant non-skeletal carbonate grains are intraclasts. Microfacies E is present in all sections and mostly intercalates with open lagoonal facies.

Interpretation. This facies was deposited in a restricted shelf lagoon. The restricted condition is suggested by the rare to absent normal marine biota and abundant skeletal components of restricted biota (imperforate foraminifera such as miliolids and *Dendritina*). The subtidal origin is supported by the lack of subaerial exposure and stratigraphic position. This microfacies represents the shallowest upper part of the photic zone, with very light, highly translucent and soft muddy substrate (Geel, 2000; Romero *et al*., 2002; Corda and Brandano, 2003; Vaziri-Moghaddam *et al*., 2006; Bassi *et al*., 2007).

Table 1. Distribution of foraminiferal assemblages in the Asmari Formation (refer to Figure 1 for locations).

Biozones (Laursen *et al*., 2009)	**Age/Epoch**	**Sec. 1**	**Sec. 2**	**Sec. 3**	**Sec. 4**
Borelis melo curdica- Borelis melo melo Ass. Zone	Burdigalian	●	●	●	●
Miogypsina- Elphidium sp. 14 - *Peneroplis farsensis* Ass. Zone	Aquitanian	●	●		
Lepidocyclina- Operculina- Ditrupa Ass. Zone	Chattian		●		

Microfacies F. Bioclastic rotaliids miliolids bioclast wackestone-packstone (Figure 5.7)

Skeletal grains consist of diverse fauna, including benthic foraminifera (miliolids, rotaliids), echinoid, corallinacean and bivalve fragments. Texture varies from wackestone to packstone. Microfacies F was identified at Dehluran (Section 1), Kabirkuh-Darrehshahr (Section 2) and Mamulan (Section 3) areas.

Interpretation. The co-occurrence of normal marine biota such as rotaliids, corallinaceans and echinoids with lagoonal biota such as miliolids, indicates that sedimentation took place in an open shelf lagoon. A similar facies with imperforate foraminifers and perforate foraminifers was reported from the inner ramp of the Oligocene-Miocene sediments of the Zagros basin (Vaziri-Moghaddam *et al*., 2006).

Microfacies G. Bioclastic miliolids coral floatstone-rudstone (Figure 5.8)

This facies is predominantly composed of miliolids and corallite fragments or fragments of coral colonies. Additional components are echinoderm fragments, recrystallized bivalve fragments and small benthic foraminifers (*Austratrillina* and *Dendritina*). Grains are poorly sorted and are medium to coarse sand to granule in size. Microfacies G is present at Kabirkuh-Darrehshahr (Section 2) and Mamulan (Section 3) areas.

Interpretation. Co-occurrence of normal marine (perforate foraminifera and corals) and platform-interior (imperforate foraminifera) components in facies F and G suggests the absence of an effective barrier. Restricted shelf organisms are effectively separated from the normal marine environment by barriers.

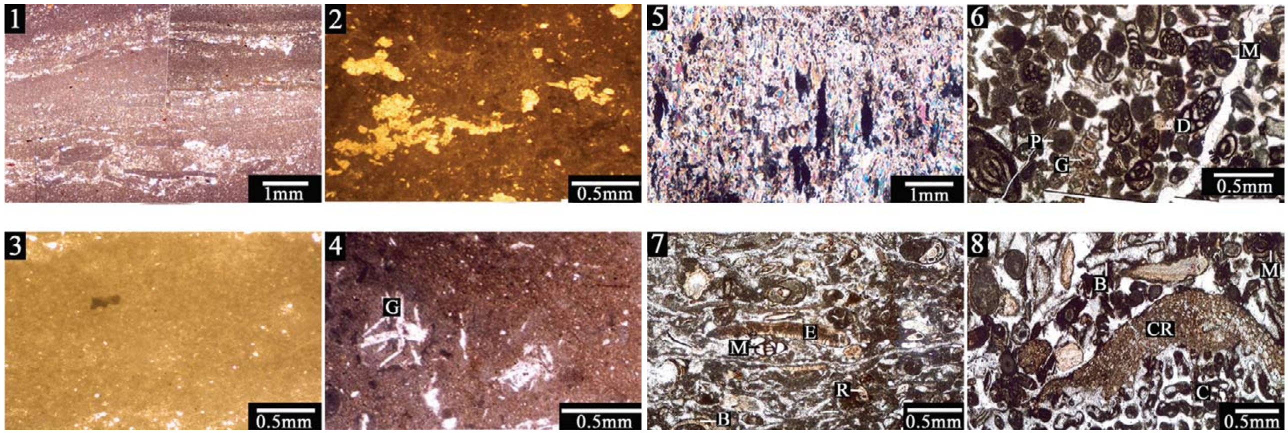

Figure 5. Microfacies types of the Asmari Formation. 1: Stromatolitic boundstone, microfacies A (Sample No. O37, Dehluran section). 2: Fenestrate mudstone, microfacies B (Sample No. M 122, Kabirkuh-Darreshahr section). 3: Mudstone, microfacies C (Sample No. M119, Kabirkuh-Darreshahr section). 4: Mudstone with gypsum, microfacies C (Sample No. O79, Dehluran section), G: gypsum. 5: Anhydrite, microfacies D (Sample No. O20, Dehluran section). 6: *Dentritina* miliolid peloid grainstone, microfacies E (Sample No. M73, Kabirkuh-Darreshahr section). M: miliolids, P: peloid, D: *Dendritina* and G: gastropod. 7: Rotaliids miliolids bioclast packstone, microfacies F (Sample No. O40, Dehluran section), R: rotaliids, M: miliolids, B: bivalve and E: echinoid. 8: Miliolids coral bioclast rudstone, microfacies G (Sample No. M82, Kabirkuh-Darreshahr section), C: coral, B: bivalve, M: miliolids, and CR: corallinacea.

Microfacies H. Bioclastic ooids packstone-grainstone (Figure 5.9)

The predominant grain types are skeletal fragments and ooids. Biotic grain types include echinid and gastropods. Ooid nuclei consist of recrystallized bivalve fragments, miliolids and rotaliids, with oval, circular or elongate outlines. Grains are fine- to coarse-sand size and sorting is moderate. Microfacies H was only identified at Kabirkuh-Darrehshahr area (Section 2) and mostly intercalates with imperforated coral rudstone to bioclastic *Miogypsina* corallinacea packstone facies.

Interpretation. The features of this facies indicate moderate to high energy shallow waters with much movement and reworking of bioclasts and the production of ooids. Sediments are interpreted to have been deposited in sand shoal (Wilson, 1975; Flügel, 2004).

Microfacies I. Bioclastic corallinacean coral floatstone-rudstone (Figures 5.10 and 11)

The main characteristic of this microfacies is abundant fragments of corallinacean and corals. Echinoid and bryozoan fragments are also present. The fragments are coarse sand to granule in size. Due to changes in the type of fauna in some samples, the name of this facies changes to bioclastic *Miogypsina* coral floatstone-rudstone. Microfacies I referred to Sepid Dasht (Section 4) and mostly intercalates with bioclastic *Miogypsina* foraminifera corallinacea wackestone-packstone.

Interpretation. This facies is interpreted as an open marine facies that formed seaward of the platform margin and within the storm wave base. Open marine, well-oxygenated conditions are indicated by the diverse fauna. A similar microfacies was reported by Wilson (1975), Longman (1981), Flügel (1982), Riding *et al*. (1991), and Melim and Scholle (1995).

Microfacies J. Bioclastic *Miogypsina* corallinacean wackestone-packstone (Figures 5.12 and 5.13)

A diverse assemblage of poorly to moderately sorted, fragmented and whole fossils in lime mud is characteristic of this microfacies. *Miogypsina* and corallinacean fragments are the dominant bioclasts. Less common bioclasts include bryozoan and fragments of recrystallized bivalves and echinoderm. In a few samples with increasing nummulitids, the name of this microfacies changes to bioclast nummulitids corallinacean wackestone-packstone. Microfacies J was identified at Dehluran (Section 1), Kabirkuh-Darrehshahr (Section 2) and Sepid Dasht (Section 4) areas and intercalates with open marine facies.

Interpretation. The presence of high diverse stenohaline fauna such as red algae, bryozoan, echinoid and larger foraminifera (*Miogypsina* and nummulitids) indicate that the sedimentary environment was situated in the oligophotic zone in a shallow open marine environment or near a fair-water wave base on the proximal middle shelf (Pomar, 2001a, 2001b; Brandano and Corda, 2002; Corda and Brandano, 2003; Cosovic *et al*., 2004). In open marine, shallow waters, foraminifera produce robust, ovate tests with thick walls, as a protection against photo inhibition of symbiotic algae inside the test in bright sunlight, and/or as a protection against test damage in turbulent water.

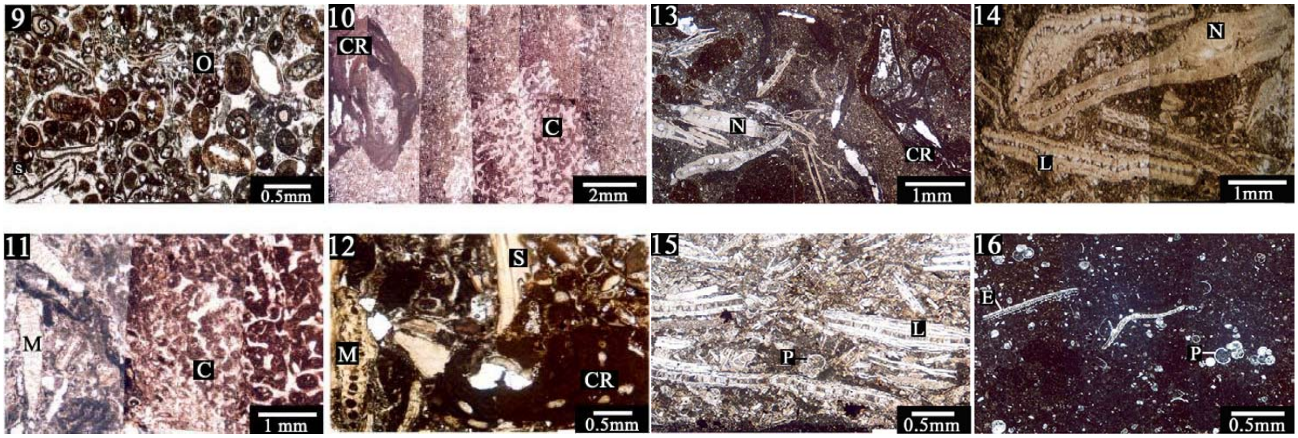

Figure 5 (continued). 9: Bioclastic ooids packstone-grainstone, microfacies H (Sample No. M78, Kabirkuh-Darreshahr section), O: ooid and S: shell fragment. 10: Corallinacean coral bioclast floatstone, microfacies I (Samples No. T26, Sepid-Dasht section), CR: corallinacea and C: coral. 11: *Miogypsina* coral bioclast floatstone-rudstone, microfacies I, (Sample No. T75, Sepid-Dasht section), M: *Miogypsina*, C: coral. 12: *Miogypsina* corallinacean bioclast packstone, microfacies J (Samples No. M61, Kabirkuh-Darreshahr section), M: *Miogypsina*, S: shell fragment, and CR: corallinacea. 13: Bioclast nummulitids corallinacean, Microfacies J, (Sample No. O10, Dehluran section), N: nummulitids and CR: corallinacea. 14: Lepidocyclinids nummulitids bioclast wackestone-packstone, microfacies K (Sample No. M48, Kabirkuh-Darreshahr section), L: lepidocyclinids, N: nummulitids 15: Planktonic foraminifera lepidocyclinids bioclast packstone, microfacies L (Sample No. M5, Kabirkuh-Darreshahr section), P: planktonic foraminifera and L: lepidocyclinids. 16: Bioclastic planktonic foraminifera wackestone, microfacies M (Sample No. O3, Dehluran section), P: planktonic foraminifera and E: echinoid.

Microfacies K. Bioclastic lepidocyclinids nummulitids wackestone-packstone (Figure 5.14)

The main components are bioclasts and large perforate foraminifera. Bioclasts include bivalve, corallinacean (including articulated and crustose fragments), echinoderm and bryozoan fragments. The foraminifera are characterized by a relatively diverse assemblage of nummulitids (*Operculina*, *Hetorestegina* and *Spiroclypeus*) and lepidocyclinids (*Eulepidina* and *Nephrolepidina*). This facies is most prominent in lower parts of the Asmari Formation. Grains are coarse sand to granule in size and are in a fine-grained carbonate matrix. Fragmentation of larger foraminifera is rare. In a few samples, *Amphistegina* are more or less equal to lepidocyclinids in abundance, therefore, the name of the microfacies changes to bioclast *Amphistegina* nummulitids wackestone-packstone. Microfacies K referred to Kabirkuh-Darrehshahr (Section 2), Mamulan (Section 3) and Sepid Dasht (Section 4) areas.

Interpretation. The presence of large flat lepidocyclinids and nummulitids indicate that sedimentation took place in relatively deep water. Flatter test and thinner walls with increasing water depth reflect the decreased light levels at greater depths (Geel, 2000; Beavington and Racey, 2004; Nebelsick *et al*., 2005; Bassi *et al*., 2007; Barattolo *et al*., 2007).

Microfacies L. Bioclastic planktonic foraminifera lepidocyclinids wackestone-packstone (Figure 5.15)

The most frequent skeletal components of this microfacies are test fragments of echinoids, bryozoan, corallinacean, larger benthic foraminifera (lepidocyclinids) and entire tests of planktonic foraminifers. Bioclasts are angular to rounded and size ranges from silt to granule. Bioclastic planktonic foraminifera nummulitids wackestone-packstone and bioclastic planktonic foraminifera *Miogypsina* wackestone-packstone are similar to the microfacies described above in overall character, but differ from each other by their larger foraminifera. Microfacies L occurs at Kabirkuh-Darrehshahr (Section 2) and Sepid Dasht (Section 4) areas and intercalates with bioclastic planktonic foraminifera wackestone facies.

Interpretation. In general, the observed higher faunal diversity and the associated benthic foraminifers (lepidocyclinids, nummulitids and *Miogypsina*) and planktonic foraminifers, as well as bioclasts, indicate an open marine environment. Poorly washed matrix and mud-supported textures suggest environments below wave-base influenced by bottom-currents (Geel, 2000; Vaziri-Moghaddam *et al*., 2006; Amirshahkarami *et al*., 2007a).

Microfacies M. Bioclastic planktonic foraminifera wackestone (Figure 5.16)

In this microfacies, planktonic foraminifera are the dominant biotic components, but fine fragments of bryozoan and echinoid are also present. The planktonic foraminifers include non-keeled globorotalids and globigerinids. Some planktonic tests are filled with sparry cement. This facies occurs mostly in lower parts of the Asmari Formaton in most sections; however, it is recorded in the upper part of the formation at Sepid-Dasht area. Microfacies M is present at Dehluran (Section 1), Kabirkuh-Darrehshahr (Section 2) and Sepid Dasht (Section 4) areas.

Interpretation. The general lack of sedimentary structures, the fine-grained character, and the presence of undisturbed whole fossils from planktonic foraminifera suggest that this facies was deposited in calm, deep, normal-salinity water (Buxton and Pedley, 1989; Cosovic *et al*., 2004; Flügel, 2004).

SEDIMENTARY MODEL

The recognized microfacies have allowed the differentiation of several carbonate marine system environments including tidal flat, restricted lagoon, open lagoon, shoal, slope and basin. These six depositional environments of the Oligocene-Miocene in the study 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 inference of ancient water depths, because it shares many similarities with the Zagros foreland basin during the Oligocene-Miocene. 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). According to Burchette and Wright (1992), carbonate ramp environments are separated into inner ramp, middle ramp and outer ramp. Outer ramp facies are characterized by marl and marly limestone lithologies. Wackestones predominate with abundant planktonic foraminifera. The presence of mud-supported textures and the apparent absence of wave and current structures suggest a low energy environment below storm wave base (Burchette and Wright, 1992).

Larger perforate foraminifera are abundant biogenic components of the shallow water carbonate succession in the Asmari Formation. A proliferation of perforate foraminifera is indicative of normal marine conditions (Geel, 2000). The lack of abrasion of the foraminifera indicates autochthonous accumulations, thus wackestone-packstone with lepidocyclinids and nummulitids were deposited under low energy conditions, below fair weather wave base (FWWB) and above storm wave base (SWB) in the middle ramp setting. The variation in the shape of the test reflects the differences in water depth. The sediments with perforate robust and ovate specimens reflect the presence of shallower water than those containing large and flat lepidocyclinids and nummulitids. Larger foraminifera are limited geographically to temperate to tropical/subtropical environments (Hohenegger *et al*., 2000; Langer and Hottinger, 2000).

The common association of symbiotic algae with perforate foraminifera implies that light is a main factor in determining the depth distribution (Hansen and Buchardet, 1977; Hallock, 1979, 1981; Bignot, 1985; Hallock and Glenn, 1986).

Inner ramp deposits represent a wider spectrum of marginal marine deposits, indicating high-energy shoal, open lagoon and protected lagoon. In the restricted lagoon environment, the faunal diversity is low and the normal marine fauna are lacking, except for imperforate benthic foraminifera (miliolids, *Dendritina*, borelisids), which indicates quiet, sheltered conditions. A large number of porcellaneous imperforate foraminifera points to the presence of slightly hypersaline waters (Geel, 2000). Open lagoonal conditions are characterized by mixed open marine fauna (such as red algae, echinoids and perforate foraminifera) and protected environment fauna (such as miliolids). The shallow subtidal environment above the fair-weather wave base is characterized by the presence of a facies association showing signs of long-term water agitation (packing, sorting, poor taphonomic preservation and ooids). Such high-energy deposits are typically associated with carbonate shoals on carbonate platforms (Figure 6).

During the Chattian, outer ramp facies (Pabdeh Formation) was predominant at the Dehluran area (Section 1, Figure 7). Simultaneously, outer to middle ramp conditions occurred at the Kabirkuh-Darrehshahr area (Section 2). The Dehluran area was experiencing outer-middle ramp conditions during the Early Aquitanian. At the same time, sedimentation at the Kabirkuh-Drarrehshahr area took placed in the middle and inner ramp environments. These areas experienced inner ramp (mostly lagoon sub-environment) condition during the Late Aquitanian (Figure 7). Eastern parts of the study area (Mamulan and Sepid Dasht were sites of non-deposition or erosion during Chattian through Aquitanian. In Mamulan area (section 3), middle and inner ramp environments prevailed through Burdigalian, whereas middle and outer ramp conditions were predominant in Sepid Dasht area (section 4) during the Burdigalian (Figure 7).

SEQUENCE STRATIGRAPHY

The studied succession can be framed in a sequence stratigraphic context. As a guide, we used the principal sequence stratigraphic concepts developed by many workers (*e.g.*, Sarg, 1988, Posamentier *et al*., 1988; Van Wagoner *et al*., 1988, 1990, Read and Hrbury, 1993; Emery and Myers, 1996; Coe and Church, 2003; Catuneanu, 2006) to recognize TST (transgressive systems tract), mfs (maximum flooding surface), HST (highstand systems tract) and sequence boundaries.

Based on the distribution of planktonic and benthonic foraminifera, and on the detailed sedimentological and stratigraphical study, we defined four third-order sequences.

Sequence 1

The depositional sequence 1 is present in sections 1 (Dehluran, 17 m thick) and 2 (Kabirkuh-Darrehshahr, 60 m thick) of the study area (Figures 8 and 9). The sediments of sequence 1 are Chattian in age. Sequence 1 includes

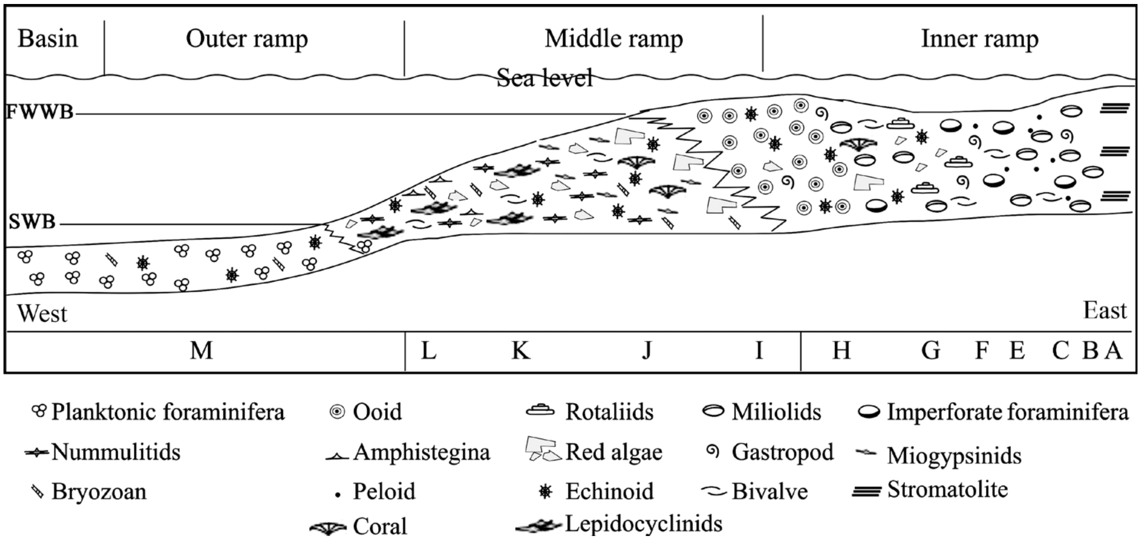

Figure 6. Depositional model for the carbonate platform of the Asmari Formation at the northwest of Zagros basin. Interpretation adopted from Hottinger (1997), Pomar (2001b) and Rasser and Nebelsick (2003). FWWB: Fair weather wave base; SWB: Storm wave base; A-M: facies defined in Figures 8-11.

the upper part of the Pabdeh Formation at Dehluran area, whereas at Kabirkuh-Darrehshahr area it encompasses the upper part of the Pabdeh Formation and the lower part of the Asmari Formation. At Dehluran area, TST and HST could not be differentiated because the relatively uniform deep sub-tidal succession is composed of planktonic foraminifera wackestone without distinct changes in microfacies. TST was clearly recognized at Kabirkuh-Darrehshahr area. Shale and marly limestone of the TST contain abundant planktonic foraminifera and document a deep-subtidal, low energy environment during the TST. The maximum flooding surface (mfs) coincides with the boundary between the Pabdeh and Asmari formations. The highstand systems tract (HST) comprises the lower part of the Asmari Formation. The early HST was characterized by constant shallow open marine environmental conditions (wackestone-packstone with perforate foraminifera). The late HST shows a trend toward more protected sediments (wackestone-packstone

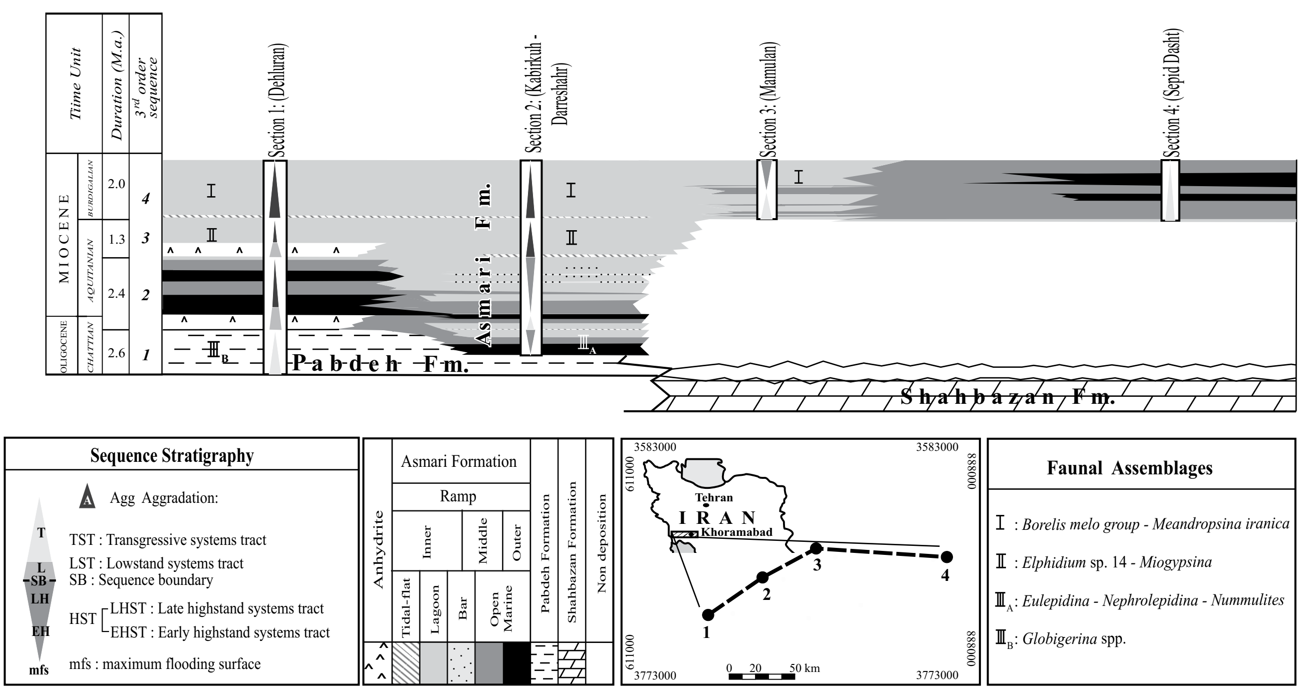

Figure 7. Chronostratigraphic scheme for the Asmari Formation across the northwestern part of the Zagros basin. Correlation of depositional environments, biozones and third-order sequences across the study area is shown (see text for explanations). Deposition of the Asmari Formation started earlier in the southwest, in a deeper environment (over the Pabdeh Formation) and continued in a relatively shallower environment. The Asmari Formation is younger to the east.

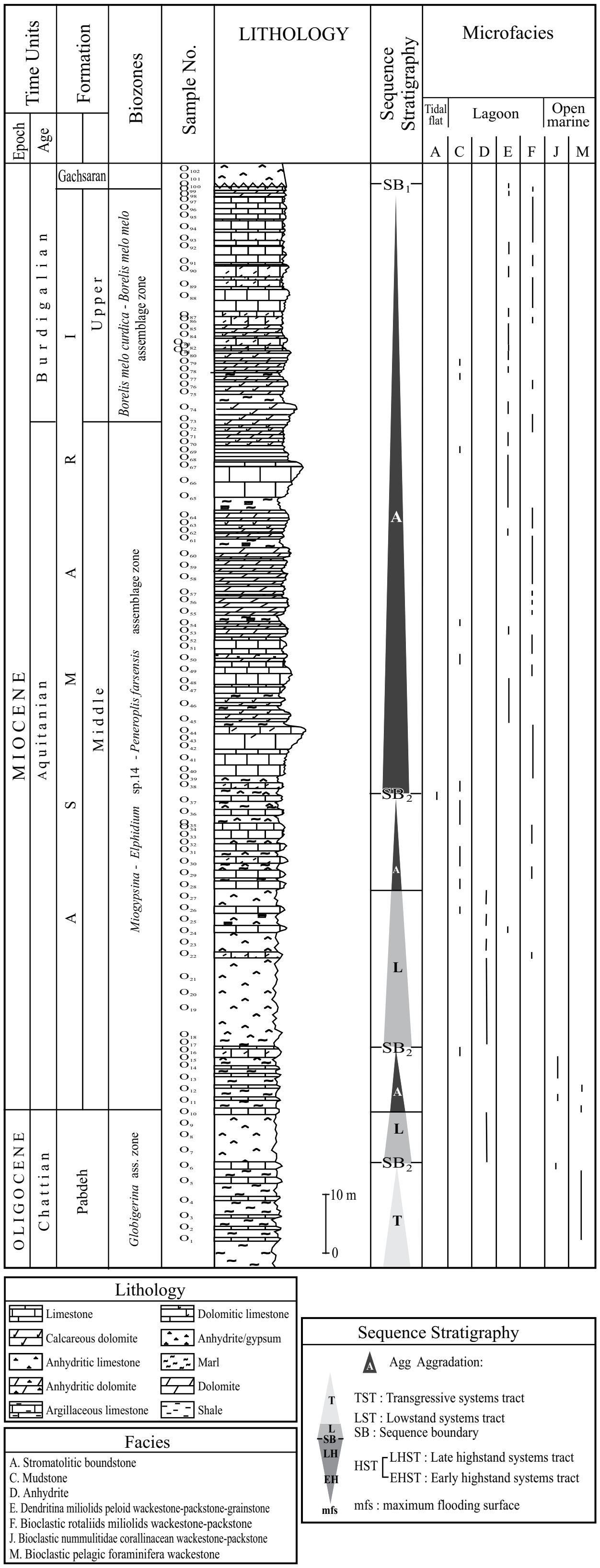

Figure 8. Microfacies and sequence stratigraphy of the Asmari Formation at Dehluran area (Section 1). TST: transgressive systems tract; LST: lowstand systems tract; Agg: aggradation; SB1 and SB2: sequence boundaries.

with imperforate foraminifera), expressing a filling of the accommodation space. The sequence boundary is characterized by abrupt facies changes from subtidal-lagoonal to tidal flat environments. Such changes reflect a significant decrease in water depth (Figures 8 and 9).

Sequence 2

The depositional sequence 2 formed during the late Chattian-early Aquitanian transgression. At Dehluran area, this sequence is 21 m thick, (Figure 8), and begins with 9 m-thick sediments of the anhydrite facies. These are interpreted as the lowstand systems tract (LST) of this sequence. The contact between the LST and the basinal deposits with pelagic fauna (Pabdeh Formation) below is sharp. At this section, the TST and HST comprise an 11 m-thick, monotonous succession of open marine deposits, demonstrating that prograding shallow-water sediments did not reach far west. At Kabirkuh-Darrehshahr area, 130/5 m thick (Figure 9), the vertical variations in the facies during the transgression are different from those described in sequence 1. An increase in third-order accommodation space is indicated by shallow lagoonal facies overlain by shallow-open marine facies. Wackestone with abundant planktonic foraminifers represent deep-water facies; this is, therefore, interpreted as the mfs. An upward-shallowing facies trend (HST) is indicated by shallow open marine gradational facies, overlain by shallow-lagoonal facies (Figures 8 and 9).

Sequence 3

This sequence is late Aquitanian in age and is present in Dehluran area (48/5 m thick) and in Kabirkuh-Darrehshahr area (14/5 m thick). At Dehluran (Figure 8), the lowstand deposits of this sequence consist of a well developed anhydrite. A temporary isolation of the sedimentary environment would be necessary in order to be able to precipitate the anhydrite. At the base, the anhydrite is homogenous, but passes up into a more heterogenous composition and interdigitates with shallow water carbonates. The sea level transgression caused the deposition of shallow subtidal facies within an aggradational staking pattern in Dehluran and Kabirkuh-Darrehshahr areas. The sequence boundary is characterized at the top by stromatolitic boundstone (Dehluran area) and mudstone with quartz (Kabirkuh-Darrehshahr area), which marks the end of a shallowing-upward trend (Figures 8 and 9).

The development of a long, narrow, evaporitic intra-basin, during the latest Oligocene-earliest Miocene (Chattian-Aquitanian) likely indicates an abrupt facies change (both laterally and vertically), which seems to be difficult to interpret simply by eustasy or any sedimentological process alone, without any tectonic control (Ahmadhadi *et al*., 2007). An abrupt facies change from marls to evaporites suggests a direct relationship between this restricted intra-basin lagoon and the deep-seated basement faults. Nevertheless, eustatic control cannot be ruled out. Ahmadhadi *et al*. (2007), suggest that the genesis of this sub-basin has been, at least, partly tectonically controlled.

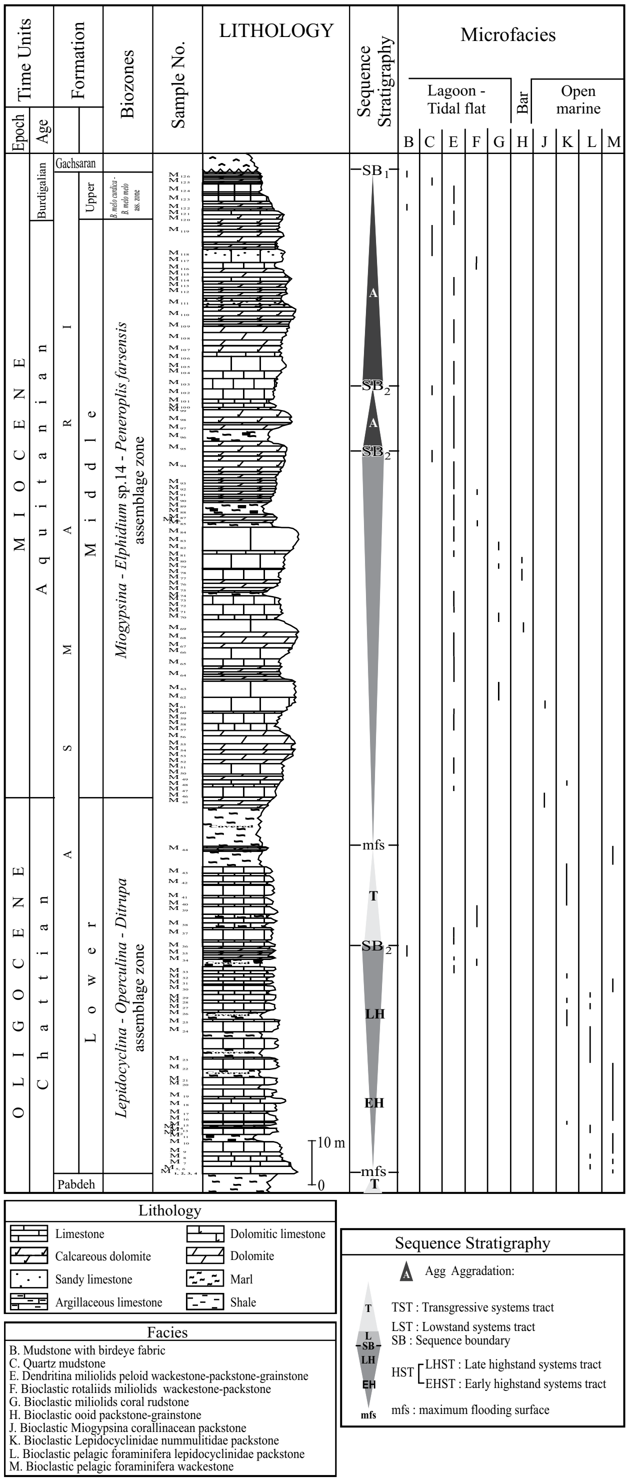

Figure 9. Microfacies and sequence stratigraphy of the Asmari Formation at Kabirkuh-Darreshahr area (Section 2). TST: transgressive systems tract; EHST; early highstand systems tract; LHST; late highstand systems tract; mfs: maximum flooding surface; Agg: aggradation; SB1 and SB2: sequence boundaries.

Sequence 4

The sequence 4 is present in all sections (Dehluran, 117/5; Kabirkuh-Darrehshahr, 55; Mamulan, 69/5; and Sepid Dasht, 82/5 m thick).

The lower boundary of Sequence 4 in Dehluran and Kabirkuh-Darrehshahr areas is characterized by a type 2 sequence boundary (Figures 8 and 9), whereas in Mamulan, (section 3) and Sepid Dasht, (section 4) areas it is defined by a type 1 sequence boundary (Figures 10 and 11). A long period of lagoonal conditions reflecting a balanced situation between accommodation and sedimentation characterizes the sequence 4 in Dehluran and Kabirkuh-Darrehshahr

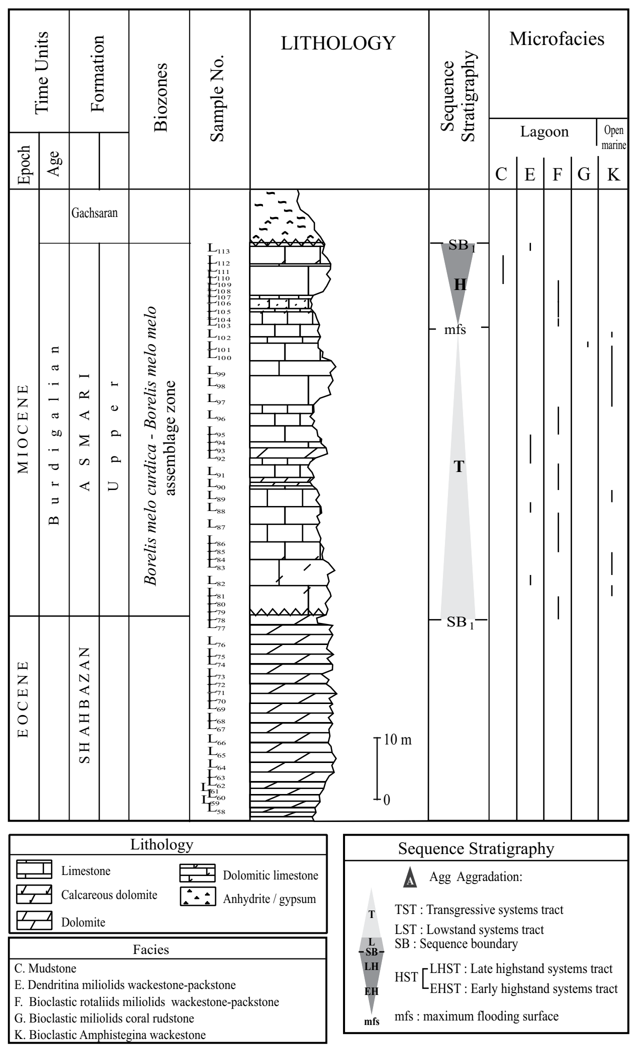

Figure 10. Microfacies and sequence stratigraphy of the Asmari Formation at Mamulan area (Section 3). TST: transgressive systems tract; HST; highstand systems tract; mfs: maximum flooding surface; SB1 and SB2: sequence boundaries.

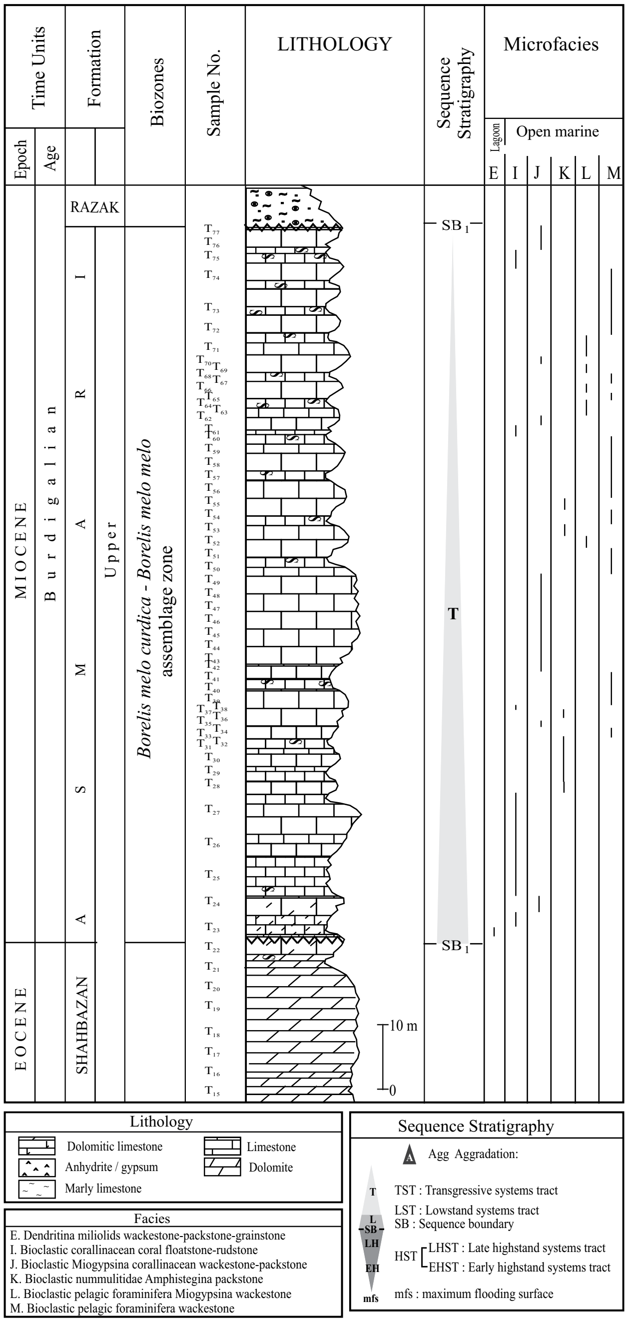

Figure 11. Microfacies and sequence stratigraphy scheme of the Asmari Formation at Sepid-Dasht area (Section 4). TST: transgressive systems tract; SB1 and SB2: sequence boundaries.

areas. Following the very shallow subtidal deposition of the uppermost part of the sequence 4 at Mamulan area, a clearly marine deepening occurred and led to the deposition of shallow lagoonal facies, forming a TST. The overlying wackestone-packstone with diverse fauna reflects a mfs, and the beginning of deposition of a HST. The overlying mfs, rich in imperforate foraminifera, have been deposited in a calm and shallow-lagoonal environment; this part is interpreted as a HST. Above type 1 sequence boundary at Sepid Dasht area, there are limestones of open marine facies with a rich planktonic foraminifera, perforate larger benthic foraminifera, corallinacean and coral fragments. These sediments were characterized by constant open marine environmental conditions, representing constant accommodation at Sepid Dasht area.

Ehrenberg *et al*. (2007) recognized some surfaces in well sections from the Bibi Hakimeh, Marun, and Ahwaz oilfields and interpreted them as sequence boundaries (Ch 20 SB, Ch 30 SB, Aq 10 SB, intra-Aq10 SB, Aq20/Bu10 SB, Bu 20 SB). Because these sequence boundaries were not recognized in the study area, the sequence stratigraphy of Ehrenberg *et al*. (2007) can not be confidently applied to these sections.

On the basis of facies changes (Figures 8 and 9), in both sections (1 and 2), sequence boundaries recognized in the upper part of the Chattian and the middle part of the Aquitanian, may be associated with the Aq 10 and Aq20/Bu10 sequence boundaries recognized by Ehrenberg *et al*. (2007).

The depositional sequences 1, 2 and 3 were observed in Dehluran and Kabirkuh-Darrehshahr areas (sections 1 and 2), and are synchronous with a period of either erosion or non-deposition represented by unconformities in Mamulan and Sepid Dasht areas (sections 3 and 4) (Figures 7-12).

CONCLUSIONS

The Oligocene–Miocene Asmari Formation of the Zagros basin is a thick sequence of shallow water carbonate. The outcrops of the Asmari Formation in northwest of the Zagros (Dehluran, Kabirkuh- Darreshahr, Sepid Dasht and Mamulan areas) allow the recognition of different depositional environments, on the basis of sedimentological analysis, distribution of foraminifera and microfacies studies. These depositional environments correspond to inner, middle and outer ramp. In the inner ramp, the most abundant lithofacies are medium-grained wackestone–packstone with imperforated foraminifera. The middle ramp is represented by packstone–grainstone to floatstone with a diverse assemblage of larger foraminifera with perforate wall, red algae, bryozoa, and echinoids. The outer ramp is dominated by argillaceous wackestone characterized by planktonic foraminifera and large and flat nummulitidae and lepidocyclinidae. Four third-order sequences are identified on the basis of deepening and shallowing microfacies patterns and on the distribution of Oligocene-Miocene foraminifers.

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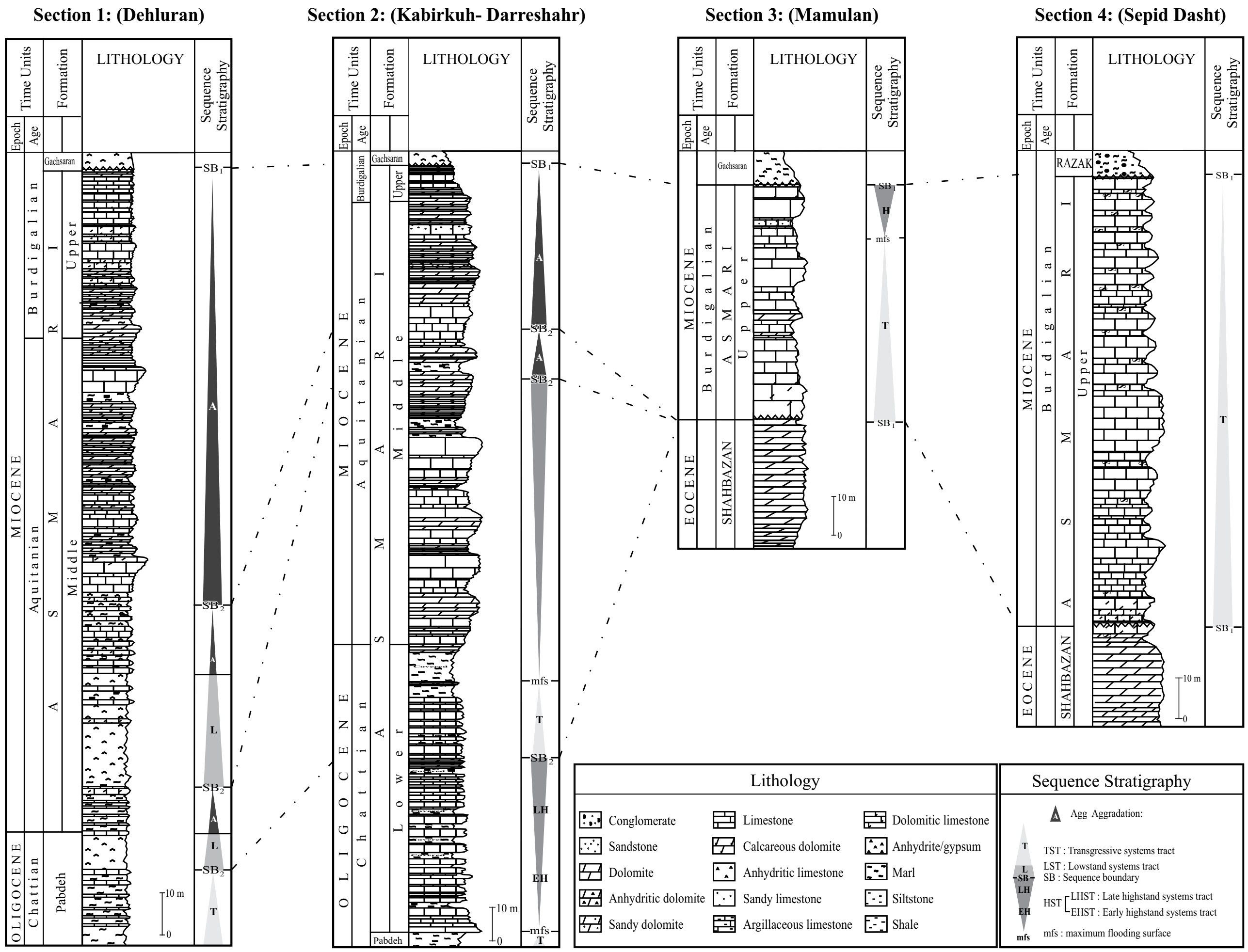

Figure 12. Sequence stratigraphy scheme for the Asmari Formation across northwest of the Zagros basin. Four third-order sequences in the Dehluran and Kabirkuh-Darrehshahr (Sections 1 and 2) and one third-order sequence in the Mamulan and Sepid Dasht (Sections 3 and 4) areas are shown.

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