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RESEARCH PAPER

Age and paleoenvironment of the Sirenia-bearing deposits in the Zagros Basin, south-southwest Iran

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Abstract
The chronological and paleoenvironmental settings of the Sirenia-bearing strata in the Zagros Basin of Iran were studied in four sections. These sections, located in the Izeh (Asmari Formation), Interior Fars (Gachsaran Formation), and Coastal Fars (Mishan Formation) zones of the Zagros Basin, were investigated for the details of their micropaleontology, biostratigraphy, and microfacies. A total of 113 thin sections were analyzed. Fossils from the Asmari Formation and the Gachsaran Formation were younger (Burdigalian), while those from the Mishan Formation were older (Aquitanian). Thirteen carbonate microfacies were identified in three facies belts; tidal flat, inner ramp, and middle ramp. The tidal flat facies association included mudstone microfacies. Inner ramp facies association consisted of bioclast with porcelaneous tests wackestone, peloid and miliolids packstone to grainstone, bioclast and miliolids wackestone to packstone, benthic foraminifera grainstone, red algae with bryozoan and miliolids wackestone to grainstone, and echinoid and miliolid packstone to grainstone facies. Middle ramp facies association was comprised of red algae and meandrous coral packstone to rudstone, coral floastone, bioclast and bryozoan wackestone to packstone, echinoid and bryozoan packstone, bryozoan and benthic foraminifera wackestone to packstone, and echinoid and bioclast wackestone facies. A shallow carbonate ramp was identified as the habitats of sea cows in the Aquitanian-Burdigalian of the Zagros Basin.

Keywords: Asmari Fm., Carbonate Ramp, Gachsaran Fm., Miocene, Mishan Fm., Sirenia.

Introduction

In the Zagros Basin, until lately, Cenozoic fossil vertebrates were limited to the fish fauna. Sea cows (Sirenia) are among the most recent fossil vertebrate discoveries in this basin. Sea cows are herbivorous marine mammals which inhabit the warm and shallow seas and coasts. They also live in some rivers. Indo-Pacific region is the main area of their distribution. They have funneled shaped, large bodies with paddle like forearms and large tails. They graze on sea grass and are depended on these resources. Their stratigraphic range is from Eocene to present. Such fossils have been found in several Miocene strata from different localities in the Zagros Basin, consisting of postcranial (skeletal) material only (Mirzaie Ataabadi et al., 2014). These fossil localities are situated in the Interior Fars and Coastal Fars zones of the Zagros Basin in the southern parts of Iran, as well as Izeh zone in the southwest.

In the Izeh zone, the fossil sea cow occurs in the Asmari Formation (Fm.). This formation has been the topic of numerous studies (see Shabafrooz et al., 2015; Naseri Karimvand et al., 2019). However, most of these studies have been focused on the central parts of this zone, while

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outcrops in the northwestern parts, where the fossil sea cow exists, are not well understood. In the Interior Fars zone, sea cow remains are discovered in the Gachsaran Fm. Most of the previous research has focused on the biostratigraphy of this formation and its general aspects (Sakhavati et al., 2020). As such, research regarding the sedimentary environment of this formation in this zone has been sparse.

The Mishan Fm. in the Zagros Basin Coastal Fars zone also contains fossil sea cow remains. Major studies on this formation are centered on the Bandar Abbas area in the southern and marginal parts of this zone (Heidari et al., 2012; Fanati Rashidi et al., 2015). In the southern parts of the Fars province, where our studied locations are situated, research on facies distribution and paleoenvironment of the Mishan Fm. is scarce.

Thus, besides revealing the chronological distribution and paleoenvironmental settings of the Sirenia-bearing deposits of the Zagros Basin, this study adds significant information to the micropaleontology and sedimentary environments of the Asmari Fm., Gachsaran Fm., and the Mishan Fm. in the less studied areas of this basin.

Geological settings

Sirenia fossils in the Zagros Basin (south-southwest Iran) are discovered from several localities in the Khuzestan, Fars, and Hormozgan provinces (Fig. 1a). Geologically, they occur in different Miocene deposits attributed to the Asmari Fm., Gachsaran Fm., and the Mishan Fm. These three formations constitute two major sedimentary cycles of the Zagros Basin.

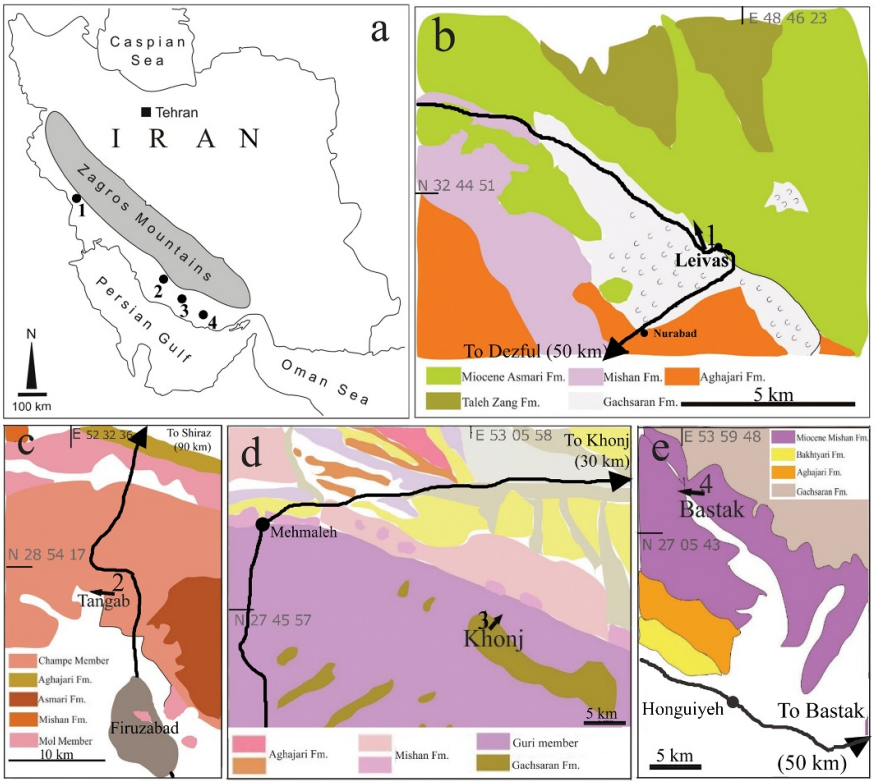

Figure 1. Geographic (a) and geological settings of the studied areas (b-e). (b) Geological map of Dezful area, north of Khuzestan (modified after Llewellyn 1973). (c) Geological map of the Firuzabad area, south of Shiraz (modified after Fakhari 1994). (d) Geological map of Mehmaleh area, south of Fars (modified after Yousefi 2005). (e) Geological map of the Bastak area, north of Hormozgan (modified after Farzipour Saeen et al., 2004). Numbers refer to the studied sections: (1) Leivas section, (2) Firuzabad section, (3) Khonj section, (4) Bastak section

The studied areas are located in the folded Zagros region, more precisely Izeh zone and Fars Arc.

The Asmari Fm. is a thick carbonate sequence of the Late Oligocene–Early Miocene. It mainly consists of limestone, dolomitic limestone, dolomite, and argillaceous limestone. Minor evaporite and sandstone deposits also occur locally in this formation.

The evaporites of the Gachsaran Fm. overlie the carbonates of the Asmari Fm. It demonstrates the initiation of the Fars Group deposition. The Fars Group cycle (Gachsaran Fm., Mishan Fm., and the Aghajari Fm.), also known as Neogene foreland sediments (Pirouz et al., 2017), shows a general regressive depositional pattern after the closure of the Neotethys Ocean. This regression is temporary, interrupted by an Early to Middle Miocene transgression of the Mishan Fm. The sequence ends with the sand -bearing deposits of the Aghajari Fm. This Group has a great thickness and is deposited from Early Miocene to Pliocene (Motiei, 1993).

The Gachsaran Fm. includes thick beds of evaporites and colored mudstone units. The Gachsaran Fm. has lateral equivalents/members across the Zagros fold-and-thrust belt. They include the clastics (conglomerate, red mudstone and sandstone) of the Razak Fm. (toward the north, particularly in the interior Fars) and the Chel, Champeh, and Mol members (farther to the south). The Chel and Champeh members are anhydrite and carbonate, while the Mol Member consists of red and green marls. They are well-developed in the southeastern Zagros and the Persian Gulf region (Motiei, 1993).

The Mishan Fm. consists of green and grey marls with intercalations of shell beds and limestone. A significant basal cream-colored, fossiliferous, massive-to-thick-bedded limestone unit called the Guri Member exists in this formation. The thickness of the Mishan Fm. varies from 50 m to 1600 m. The Guri Member also varies in the thickness from several meters to 1200 m, both increasing toward the eastern Zagros, i.e. Fars Arc and Persian Gulf region (Motiei, 1993).

Materials and methods

Fossil remains of sea cows, including vertebrae and ribs, were discovered from the Asmari Fm. in the Leivas section (32^0 44' 50.9" N; 48^0 46' 23" E). This section is located near the Leivas village, northeast of Dezful, Khuzestan province, southwest of Iran (Fig. 1b). Other similar fossils have also been recovered from the Gachsaran Fm. in the Firuzabad section of the Fars province (28^0 54' 17.3" N; 52^0 32' 36.4" E). It is located south of the Fars province near the Tangab village (Fig. 1c). Also, such fossils are known from the Mishan Fm. in two sections, namely the Khonj and the Bastak, in the Fars and the Hormozgan provinces. The Khonj stratigraphic section (27^0 45' 57.6" N; 53^0 5' 58.7" E) is located south of the Fars province near the Mehmaleh village (Fig. 1d). The Bastak stratigraphic section (27^0 5' 43" N; 53^0 59' 48.3" E) is located north-west of the Hormozgan province and near the Honguiyeh village (Fig. 1e).

These four sections were measured and sampled for micropaleontological and microfacies studies. The outcrops were sampled in 2–4-meter intervals to conduct microfacies analysis. A total of 113 thin sections were studied (50 in the Leivas, 20 in the Firuzabad, 43 in the Khonj and the Bastak (Guri Member)). Loeblich & Tappan (1987) is used for the generic classification of foraminifera. The larger foraminiferal biozonal schemes for the Zagros Mountains by Wynd (1965), James & Wynd (1965), and Adams & Bourgeois (1967) have been applied to the studied sections. Classification of the microfacies is based on the abundance percentage of skeletal and non-skeletal elements, matrix and texture characteristics, and their final compilation with field data. To describe the texture of the sediments, the classification of Dunham (1962) with the modification by Embry & Klovan (1971) was employed. Microfacies belts and sedimentary models of Flügel (2010) were used for the interpretation of the depositional environment.

Results

Stratigraphy

The Leivas section with a thickness of 150 meters includes two rock units: limestone and sandy limestone. The Asmari Fm. here is gradually placed on the silty marl layers of the Pabdeh Fm., and is disconformably covered with the Gachsaran Fm. evaporitic layers (Fig. 2a). In this section, the sea cow fossils are found in the thick-layered limestones along with *Quinqueloculina* sp., *Spiroloculina* sp., *Austrotrillina* sp., *Textularia* sp. and *Meandropsina* sp..

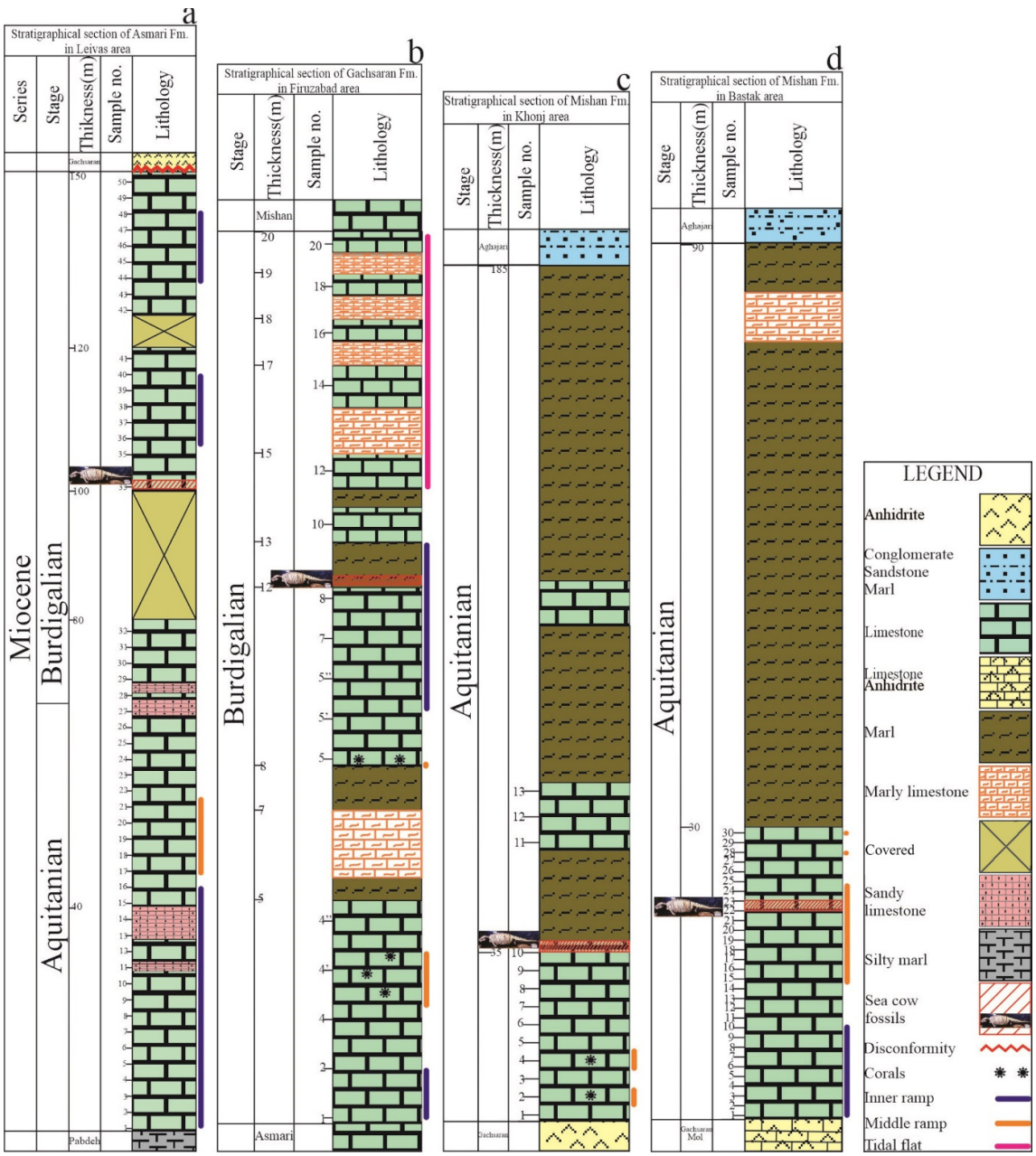

Figure 2. Lithostratigraphic columns of the Asmari Fm., Gachsaran Fm. and the Mishan Fm. in the studied sections, with indication of the Sirenia-bearing horizons and the recognized paleoenvironments. (a) Leivas section, (b) Firuzabad section, (c) Khonj section, (d) Bastak section

The Firuzabad section with a measured thickness of 20 meters includes three rock units: limestone, marl, and marly limestone (Fig. 2b). Here, the Gachsaran Fm. has a gradual boundary with the Asmari limestone layers in the lower part, and is covered with the Mishan limestone layers. In this section, sea cow fossils are found in the limestone layers along with *Quinqueloculina* sp., *Spiroloculina* sp., *Austrotrillina* sp., *Textularia* sp., red algae and bryozoans.

The Khonj section with a thickness of 185 meters consists of two rock units: limestone (Guri Member) and marl (Fig. 2c). In this section, the Mishan Fm. has a gradual boundary with the Gachsaran Fm. evaporitic layers in the lower part, and is covered with sandstones of the Aghajari Fm. Here, the sea cow fossils are found in a thick-bedded limestone rock unit along with corals, bryozoans, red algae, miliolids, echinoid, bivalve fragments, and fractured benthic foraminifera with hyaline tests.

The Bastak section with a thickness of 90 meters includes three rock units: limestone, marl and marly limestone. Here, the Mishan Fm. covers the Gachsaran Fm. evaporitic layers in the lower part, and is gradually covered with the sandstone layers of the Aghajari Fm. in the upper boundary (Fig. 2d). In this section, the sea cow fossils in the limestone layers (Guri member) occur along with benthic foraminifera with porcelaneous tests such as *Quinqueloculina* sp., *Spiroloculina* sp., *Austrotrillina* sp., as well as peloids, echinoids, gastropods, red algae, bivalves, bryozoans and benthic foraminifera with hyaline tests including Rotaliidae.

Micropaleontology and biostratigraphy

The study of fossil assemblages led to the identification of 30 genera and 43 species of foraminifera. According to the age and the stratigraphic range of the benthic foraminifera, and the defined biozonation for the Oligocene/Miocene of the Zagros Basin (Wynd, 1965; Adams & Bourgeios, 1967), four biozones in the Asmari Fm., two biozones in the Gachsaran Fm., and two biozones in the Mishan Fm. have been identified. These biozones are: *Borelis melo curdica* Assemblage Zone (Wynd, 1965: Zone (z.) 61-62), *Borelis melo* group-*Meandropsina iranica* Assemblage Zone (Adams & Bourgeios, 1967: z. 1), *Miogypsinoides*-*Archaias*-Valvulinid Assemblage Zone (Adams & Bourgeios, 1967: z. 2), and *Austrotrillina howchini*-*Peneroplis evolutus* Assemblage Zone (Wynd, 1965: z. 59).

The identified microfossils from the studied sections and details of biozonation and some index taxa are presented in the supplementary information, which is available upon request from authors.

Based on the stratigraphic range of the presented microfauna, Early Miocene (Aquitanian/Burdigalian) age is recognized for the sea cow fossil -bearing strata. The fossils from the Asmari Fm. (Leivas section) and the Gachsaran Fm. (Firuzabad section) are younger (Burdigalian), while those from the Mishan Fm. (Bastak and the Khonj sections) are older (Aquitanian).

Microfacies analysis

Investigating 113 thin sections resulted in the identification of 13 microfacies (three in the Asmari Fm., three in the Gachsaran Fm., and seven in the Mishan Fm.). These microfacies are briefly expressed according to the depth of the environment as follows (Table 1).

Tidal flat facies association

Mudstone*:* this microfacies has been identified in the upper parts (14- to 20-meter interval) of the Firuzabad section. The main groundmass of the rock is micrite, with the texture of facies

being mudstone. Carbonate and non-carbonate grains are found in very small quantities, where non-carbonate grains can be referred to as 5% of small clastic, silt sized, scattered quartz grains (Fig. 3a). According to the facies belts and sedimentary models of Flügel (2010), this microfacies is similar to RMF19.

Table 1. Summary of the microfacies characteristics of the Asmari Fm., Gachsaran Fm. and the Mishan Fm. in the studied areas

Microfacies Name	Stratigraphic Location	Main Lithology	Main Allochems	Minor Allochems	Sedimentary Environment
Mudstone	14 to 20 m interval of the Firuzabad section	medium-bedded limestone and marly limestone	----------	quartz grain	tidal flat
Bioclast with porcelaneous crust Wackestone	3 to 4 m interval of the Bastak section	limestone	porcelaneous crust	echinoid fragments	inner ramp
Peloid and miliolids packstone to grainstone	1 to 2 and 8 to 9 m interval of the Bastak section	limestone	miliolids and peloid	red algae and echinoid bivalve fragments	inner ramp
Bioclast and miliolids wackestone to packstone	5 to 7 and 9 to 10 m interval of the Bastak section	limestone	miliolids	bryozoans and red algae	inner ramp
Benthic foraminifera grainstone	19 to 27, 31 to 37 and 41 to 44 m interval of the Leivas section	limestone	benthic foraminifera	----------	inner ramp
Red algae, bryozoan and miliolids wackestone to grainstone	1 to 2, 5 to 7 and 9 to 13 m interval of the Firuzabad section	limestone	miliolids bryozoan and red algae	bivalve fragments	inner ramp
Echinoid and miliolids packstone to grainstone	1 to 18, 28 to 30 and 38 to 40 m interval of the Leivas section	limestone	miliolids and echinoid	quartz grain	inner ramp
Red algae and meandrous coral packstone to rudstone	3 to 4 and 6 to 9 m interval of the Khonj section	limestone	meandrous coral and large red algae	----------	middle ramp
Coral floastone	3 to 4 and 8 m interval of the Firuzabad section	limestone	Coral	----------	middle ramp
Bioclast and bryozoan wackestone to Packstone	10 to 13 m interval of the Khonj section	limestone	bryozoan	red algae and echinoid bivalve fragments	middle ramp
Echinoid and bryozoan packstone	14, 18, 21, 19 to 25 and 28 m interval of the Bastak section	limestone	bryozoan	echinoid	middle ramp
Bryozoan and benthic foraminifera wackestone to packstone	13, 15 to 17 and 30 m interval of the Bastak section	limestone	benthic foraminifera and bryozoan	red algae and echinoid bivalve fragments	middle ramp
Echinoid and bioclast wackestone	45 to 50 m interval of the Leivas section	limestone		Planktonic foraminifera	middle ramp

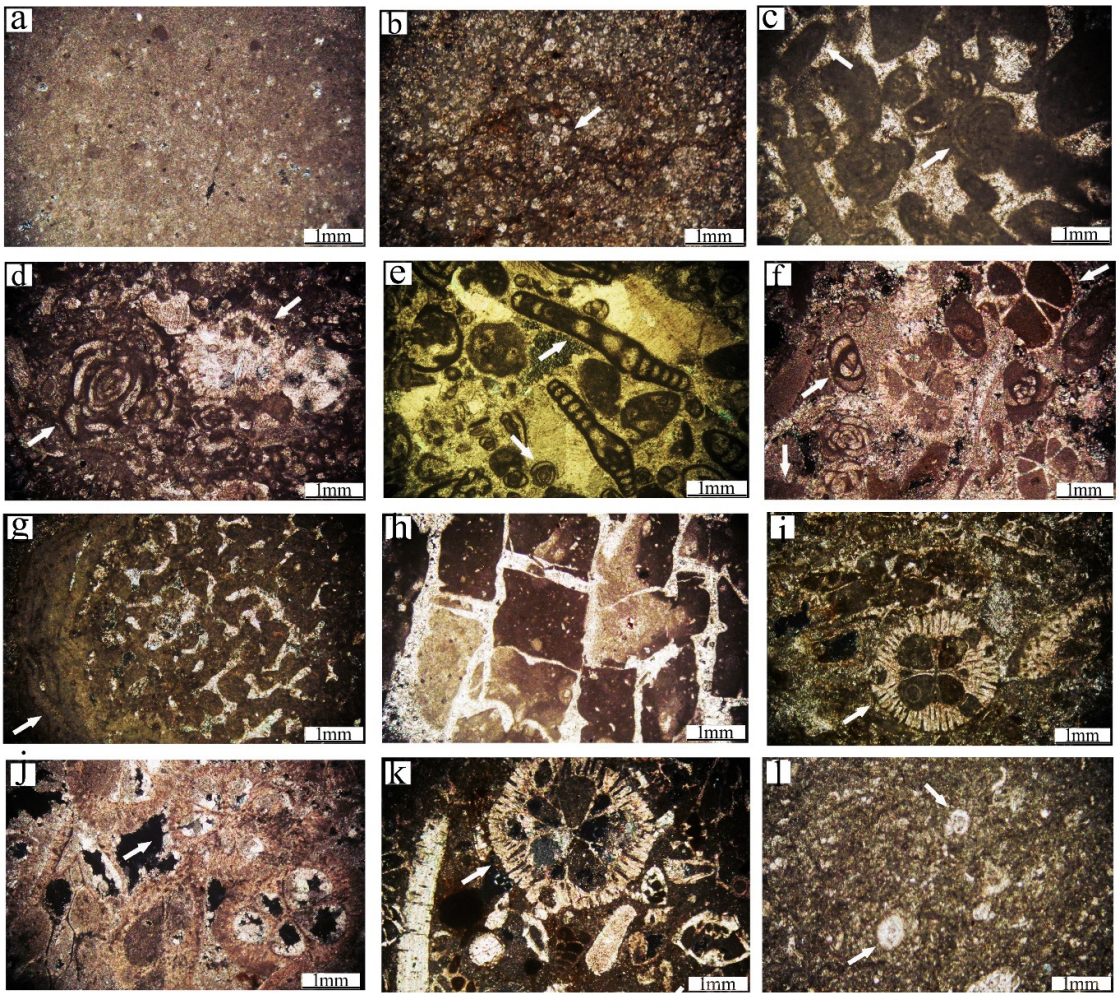

Figure 3. Microfacies of the Asmari Fm., Gachsaran Fm. and the Mishan Fm. deposits in the Leivas, Firuzabad, Bastak and the Khonj sections. (a) Mudstone (Firuzabad section). (b) Bioclast with porcelaneous tests wackestone (Bastak section). (c) Peloid and miliolids packstone to grainstone (Bastak section). (d) Bioclast and miliolids wackestone to packstone (Bastak section). (e) Benthic foraminifera grainstone (Leivas section). (f) Red algae, bryozoan and miliolids wackestone to grainstone (Firuzabad sections). (g) Red algae and meandrous coral packstone to rudstone (Khonj section). (h) Coral floastone (Firuzabad section). (i) Bioclast and bryozoan wackestone to packstone (Khonj section). (j) Echinoid and bryozoan packstone (Bastak section). (k) Bryozoan and benthic foraminifera wackestone to packstone (Bastak section). (l) Echinoid and bioclast wackestone (Leivas section). Main skeletal components mentioned in the captions are also marked with arrows in the figures. All figures are PPL, scales are 1mm

Inner ramp facies association

Bioclast with porcelaneous tests wackestone*:* this microfacies has been identified in the lower parts (3- to 4-meter interval) of the Bastak section. Around 50% of the main allochem in this microfacies consists of porcelaneous tests bioclasts that have become dolomitic, and are located in a dense groundmass of micrites plus dolomites. About 5% of the matrix also contains fragments of echinoid (Fig. 3b). This microfacies is comparable with RMF22 of Flügel (2010). Peloid and miliolids packstone to grainstone*:* this microfacies has been identified in 1- to 2- and 8- to 9-meter intervals of the Bastak section. About 50% of the main allochem in this microfacies consists of benthic foraminifera with porcelaneous tests such as *Quinqueloculina,*

Spiroloculina, Austrotrillina, and peloid. On the other hand, nearly 10% of allochems contain benthic foraminifera with hyaline tests, echinoids, gastropods, red algae, and bivalves. The fossil components are compactly stacked on a clear groundmass of calcite cement (Fig. 3c). According to Flügel (2010), this microfacies is similar to RMF20. Bioclast and miliolids wackestone to packstone*:* this microfacies has been only identified in 5- to 7- and 9- to 10-meter intervals of the Bastak section. Specifically, 30% of the main allochem in this microfacies consists of benthic foraminifera with porcelaneous tests and miliolids, along with 5% of bryozoans, red algae as well as 5% of quartz grains, which are scattered in the micritic groundmass. Less than 10% of the groundmass is affected by rhombic-shaped dolomite grains, which destruct the primary texture of the rocks (Fig. 3d). Consistent with the facies belts and sedimentary models of Flügel (2010), this microfacies resembles the RMF20. Benthic foraminifera grainstone*:* this microfacies has been identified in 19- to 27-, 31- to 37- and 41- to 44-meter intervals of the Leivas section. The main allochem in this microfacies consist of benthic foraminifera with porcelaneous tests, including *Quinqueloculina* sp., *Spiroloculina* sp., *Austrotrillina* sp., *Textularia* sp. and *Meandropsina* sp. They are cemented with blocky calcite (Fig. 3e). This microfacies resembles RMF20 of Flügel (2010). Red algae, bryozoan and miliolids wackestone to grainstone*:* this microfacies has been identified in 1-, 2-, 5- to 7- and 9- to 13-meter intervals of the Firuzabad section. Between 35% and 45% of the main allochem in this microfacies consists of benthic foraminifera with porcelaneous tests, including *Quinqueloculina* sp., *Spiroloculina* sp., *Austrotrillina* sp. and *Textularia* sp., along with bryozoan and red algae. Bivalve debris (around 5%) is also present. The cavities of some fossils such as ostracods are filled with drusy cement. The walls of some bryozoans are also silicified. The groundmass of this microfacies is mainly micrite with some calcite cement (Fig. 3f). Based on Flügel (2010), this microfacies is similar to RMF20.

Echinoid and miliolid packstone to grainstone*:* this microfacies has been identified in 1- to 18-, 28- to 30- and 38- to 40-meter intervals of the Leivas section. More than 40% of the main allochems in this microfacies consist of benthic foraminifera with porcelaneous tests, including *Quinqueloculina* sp., *Spiroloculina* sp., and *Austrotrillina* sp., along with some echinoid debris within the micritic groundmass and also calcite cements. There are also 5% quartz grains. Some cavities have later been filled with blocky calcite cements. This microfacies resemble RMF20 of Flügel (2010).

Middle ramp facies association

Red algae and meandrous coral packstone to rudstone*:* this microfacies has been identified in 3- to 4- and 6- to 9-meter intervals of the Khonj section. Between 40 and 50% of the main allochems in this microfacies are composed of meandrous corals with large fragments of red algae, located in dense groundmass. Local calcite cement is also visible in the groundmass (Fig. 3g). The mentioned microfacies correspond to RMF12 of Flügel (2010).

Coral floastone: this microfacies has been only identified in 3- to 4- and 8-meter intervals of the Firuzabad section. The main allochem in this facies includes corals, of which meandrous corals are the most prominent. Some calcite cement, filling the groundmass between the coral walls, is also present (Fig. 3h). In agreement with the facies belts and sedimentary models of Flügel (2010), this microfacies is similar to RMF12.

Bioclast and bryozoan wackestone to packstone*:* this microfacies has been identified in the 10- to 13-meter interval of the Khonj section. About 45% of the main allochems in this microfacies consists of bryozoan fragments, along with other fossil components such as red algae, miliolids, echinoids, bivalve fragments, and even fractured benthic foraminifera components with hyaline tests. Local calcite cements are also present (Fig. 3i). This microfacies is comparable to RMF8 of Flügel (2010).

Echinoid and bryozoan packstone*:* this microfacies has been identified in 14-, 18-, 21-, 19- to 25- and 28-meter intervals of the Bastak section. Specifically, 50 % of the main allochems in this microfacies consists of bryozoans, along with echinoid debris. In some parts of the bryozoans, needle-shaped cements surround them while in some others drusy calcite cements have partially filled the cavities (Fig. 3j). According to Flügel (2010), this microfacies is similar to RMF7.

Bryozoan and benthic foraminifera wackestone to packstone*:* this microfacies has been identified in 13-, 15- to17- and 30-meter intervals of the Bastak section. Around 35% of the main allochems in this microfacies compose of benthic foraminifera with hyaline tests, including Rotaliidae. Other bioclasts include bryozoans, red algae, echinoids, bivalves, and worm tubes (Fig. 3k). This microfacies resembles RMF8 of Flügel (2010).

Echinoid and bioclast wackestone*:* this microfacies has been identified in 45- to 50-meter interval of the Leivas section. More than 30% of the main allochems in this microfacies consists of bioclast fragments along with echinoids. The minor allochem consists of 10% of planktonic foraminifera with hyaline tests, including *Globorotalia* sp., *Globigerina* sp., and *Globogerinoides* sp., which are scattered in micrites (Fig. 3l). This microfacies resembles RMF7 of Flügel (2010).

Microfacies of the Sirenia-bearing beds

The horizons containing sea cow fossils in the studied sections indicate four microfacies that are shown in Figure 4. In the Leivas (Asmari Fm.) and the Firuzabad (Gachsaran Fm.) sections, fossil remains of the sea cows have been found in deposits containing benthic foraminifera with porcelaneous tests, including miliolids and other fossil components related to inner ramp environment. In the Khonj and the Bastak sections (Mishan Fm.), these fossils occur in the proximal part of the middle ramp. The microfacies of the studied sections suggest that sea cows inhabited warm and shallow marine environments.

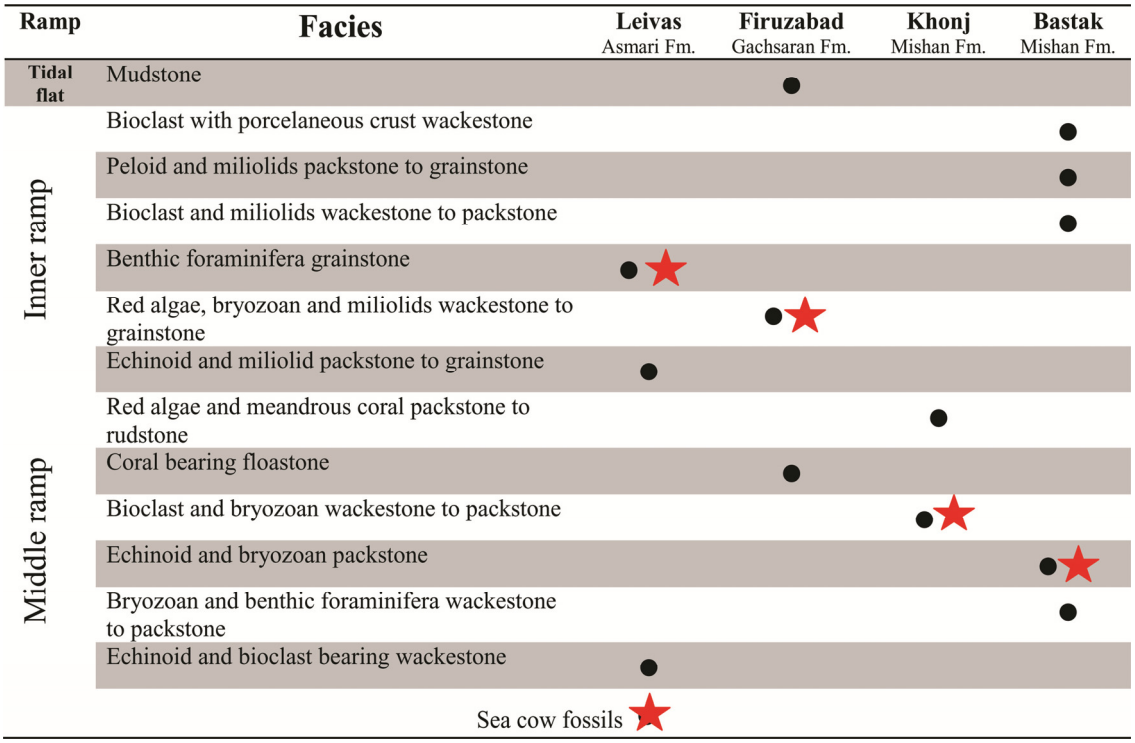

Figure 4. Distribution of microfacies and sedimentary environments in the four studied sections and the characteristics of the Sirenia-bearing horizons in these sections (red stars)

Presence of warm tropical seas during the Early Miocene has been already documented in several sections of the Asmari Fm. (Kakemem et al., 2016; Hatefi et al., 2018), the Guri Member of the Mishan Fm. (Rahmani et al., 2010; Heidari et al., 2014), and the Gachsaran Fm. (Soleimani & Bahadori, 2015).

Sedimentary model

Based on the identified facies and their alteration to each other, their gradual and slight disparity, and lack of reef structures, the sedimentary environment of the Asmari Fm., Gachsaran Fm. and Mishan Fm. in the studied sections is a carbonate ramp. The absence of turbidites facies that indicate a high slope of the sedimentary environment during sedimentation also supports this interpretation. This carbonate ramp model consists of three main environments; tidal flat, inner ramp, and middle ramp.

Asmari Formation

In the Leivas section, the presence of angular quartz grains in the vicinity of carbonate microfacies with porcelaneous benthic foraminifera indicates that this facies has been deposited in the shallow parts of the basin. The abundance of benthic foraminifera with porcelaneous tests such as Quinqueloculina sp., Spiroloculina sp., Austrotrillina sp., Peneroplis sp., Archaias sp. and Meandropsina sp., as well as various types of calcite cement indicate the proximal to the distal part of the inner ramp setting. In some places, the energy levels of the sedimentary environment are oscillating and the reduction in energy causes mud to form in the sediments. On the other hand, an increase in the energy washes away the mud where the cement and echinoid residues increase. Also, the presence of marine bioclasts indicates the connection of this part of the inner ramp to the middle ramp. The presence of benthic foraminifera with hyaline tests and the abundance of other fossil components such as bryozoans reveal the proximal part of the middle ramp. The rare occurrence of planktonic foraminifera indicates a decline in the environmental energy and an increase in mud, which refers to the distal parts of the middle ramp. Thus, this microfacies belongs to the proximal to the distal parts of the middle ramp (Fig. 5a).

Gachsaran Formation

In the Firuzabad section, the presence of pointed quartz grains, in the zone of benthic foraminifera facies with porcelaneous tests, indicates that this facies has been deposited in a very shallow part of the sedimentary basin. Also, lack of faunal diversity in the Gachsaran Fm. indicates the absence of suitable conditions for living organisms and attributes this formation to the very shallow parts of the basin. The abundance of benthic foraminifera with porcelaneous tests indicates the proximal parts of the inner ramp (Fig. 5a). The study of the sedimentary environment of the Gachsaran Fm. (Champe Member), southeast of Firuzabad, also indicates sedimentation in tidal flat and lagoon environments (Holakouee et al., 2011).

Mishan Formation

In the Khonj and the Bastak sections, it seems that the dolomitization process has been more selective, since the groundmass has been dolomitized, but the fossil grains have remained intact. The recognized microfacies and the presence of fossil components with porcelaneous tests such as miliolids, together with algae and peloid grains, indicate an inner ramp setting. The presence of calcite cements also indicates high-energy environments. The presence of benthic

foraminifera with hyaline tests, echinoids, gastropods, red algae, and bivalves shows that the inner ramp was not enclosed, and was connected with the middle ramp. The presence of corals as well as the abundance of other fossil components such as bryozoans, echinoids, and benthic foraminifera with hyaline tests including rotaliidae, proves the proximal parts of the middle ramp setting (Fig. 5b).

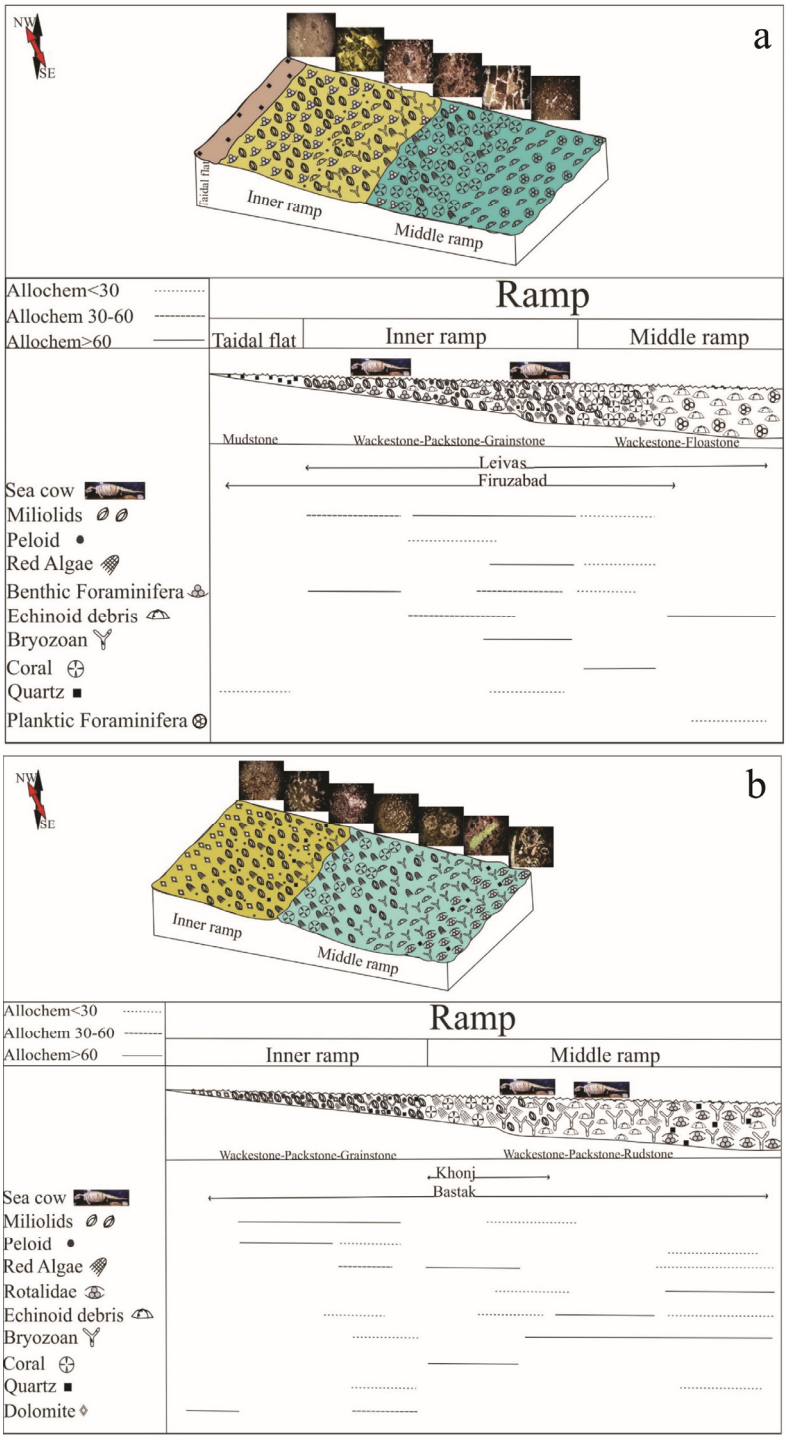

Figure 5. Sedimentary model of the Early Miocene deposits (a) the Asmari Fm. and the Gachsaran Fm. in the Leivas and the Firuzabad sections, and (b) the Mishan Fm. in the Khonj and the Bastak sections, with indication of the sea-cow habitats

Discussion

Stratigraphy and age

The Asmari Fm. appears to be Oligocene to Early Miocene in many sections (Seyrafian et al., 2011; Shabafrooz et al., 2015; Kakemem et al., 2016; Naseri Karimvand et al., 2019; Kamalifar et al., 2020). On the other hand, in parts of the Dezful embayment and Izeh zone (Vaziri Moghaddam et al., 2010 and this study), as well as Interior Fars zone (Hatefi et al., 2018), it is more restricted in age (Oligocene or Early Miocene). This is due to lateral changes in the vast sedimentary basin of Zagros (Vaziri Moghaddam et al., 2010; Taheri et al., 2017).

As Sakhavati et al. (2020) demonstrate, the age of the Gachsaran Formation is the Early Miocene (Aquitanian-Burdigalian). Our biostratigraphic results in the studied section of the Gachsaran Fm. comply well with this. The Guri Member of the Mishan Fm. is considered Early to Middle Miocene in age (Heidari et al., 2014; Fanati Rashidi et al., 2015; Mohammadkhani et al., 2022). The Middle Miocene age is usually present in areas (e.g. northern Bandar Abbas) where the Guri Member is significantly thick (Fanati Rashidi et al., 2015). In the studied areas here, due to the small thickness of the Guri Member, only the earliest Miocene (Aquitanian) has been recorded. This is evident in some other sections where the early intervals of this member are Aquitanian (Daneshian et al., 2016).

The occurrence of sea cows in several Early Miocene formations of the Zagros Basin demonstrates their lateral alteration to each other, along a broad northwest-southeast basin. Thus, while the Guri Member of the Mishan Fm. was deposited in the interior and coastal Fars regions of southeast Zagros, the Asmari Fm. and the Gachsaran Fm. depositional basins were active further toward the northwest in Khuzestan and parts of Fars areas (Motiei, 1993; Heidari et al., 2012; Taheri et al., 2017). This indicates that the sea cow remains in the Zagros Basin can be discovered in different lithostratigraphic units, as long as the favorable living environment of these animals existed. Chronological assessment of the Sirenia-bearing deposits of the Zagros Basin shows that from the southeast (Mishan Fm.) toward the northwest (Asmari Fm. and the Gachsaran Fm.), the age of the deposits changes from Aquitanian to Burdigalian. Although this might indicate a time transgressive pattern for the distribution of the sea cows in this basin, it is more likely an artifact of depositional environments. Apparently, the favorable environments for the thriving of the sea cows (shallow warm seas) were present in the southeast of the Zagros during Aquitanian (Guri Member of the Mishan Fm.). This member would later disappear, as the paleoenvironment of the Mishan Fm. becomes much deeper, where grey and green marls replace the limestone of the Guri Member. Therefore, the environments available for sea cows shifted to the northwestern parts of the basin, where it was restricted to the Asmari Fm. and the Gachsaran Fm. (Motiei, 1993; Bahroudi & Koyi, 2004; Vaziri Moghaddam et al., 2010; Sakhavati et al., 2020).

The Early Miocene distribution of sea cows in the Zagros Basin is very similar to the pattern so far documented from central Iran. In this region, the Sirenia-bearing horizons in the Qom Fm. from Isfahan and Hamedan also indicate an Aquitanian to Burdigalian age (Morovati et al., 2021). The Early Miocene fossils of Sirenia are relatively widespread in the Tethyan realm. They are particularly reported from the Early Miocene of India (Bajpai et al., 2010) and Europe (Domning & Pervesler, 2013).

Paleoenvironment

The carbonate ramp system recognized in the studied sections is a typical paleoenvironment of the Early Miocene Zagros formations (Rahmani et al., 2010; Heidari et al., 2014; Fanati Rashidi et al., 2015; Soleimani & Bahadori 2015; Shabafrooz et al., 2015; Kakemem et al., 2016).

Although the inner/middle ramp conditions predominate in the studied areas, the paleoenvironment of the studied sections shows slight regional differences. While the middle ramp conditions exist in the both Mishan Fm. sections, shallower inner ramp conditions were present in the Bastak section. A carbonate ramp system similar to the present study is the interpreted paleoenvironment for many studied sections of the Guri Member (Rahmani et al., 2010; Heidari et al., 2012, 2014; Fanati Rashidi et al., 2015; Mohammadkhani et al., 2022).

In the northern Dezful area (Izeh zone), where the sea cow fossil is discovered in the Burdigalian aged Asmari Fm., previous research also indicates similar paleoenvironmental conditions (Shabafrooz et al., 2015). A low angle carbonate ramp has also been recorded for the Asmari Fm. in Dehdasht area in Early Miocene (Naseri Karmimvand et al., 2019) and in the Rig anticline (Kakemem et al., 2016). Zabihi Zoeram et al. (2013) also reconstructed a homoclinal ramp, predominantly characterized by its inner and middle parts, in the Dezful Embayment. However, Khalili et al. (2021) reported that the Burdigalian platform of the Asmari Fm. in the east of the Dezful Embayment highlights a shallow water lagoon to tidal zone. Hatefi et al. (2018) and Kamalifar et al. (2020) reported similar paleoenvironmental conditions in the Asmari Fm. in the Interior and Coastal Fars zones.

In this study, tidal zone is observed only in the Burdigalian aged Gachsaran Fm. This is due to the beginning of a regressive phase (Bahroudi & Koyi, 2004; Soleimani & Bahadori, 2015; Sakhavati et al., 2020). A tidal flat and lagoon in a homoclinal ramp have been reported for a similar section near Shiraz (Mirzaee Mahmoodabadi, 2020). In addition, Holakouee et al. (2011) studied the Champeh and the Mol members of the Gachsaran Fm. in the Firuzabad and documented tidal flat as well as lagoon environments.

The paleoenvironment of the Sirenia-bearing strata studied here demonstrates that the conditions in the Aquitanian (Guri Member of the Mishan Fm.) were different from the Burdigalian (Asmari Fm. and the Gachsaran Fm.). Middle ramp conditions existed during the Aquitanian, but in the Burdigalian, the inner ramp dominates (Fig. 5). Slightly similar conditions were present in the Qom Fm. in Central Iran. Although most of the sea cows from the Qom Fm. were present in inner ramp sediments, one record was present in the more energetic middle ramp environment (Morovati et al., 2021).

A shallow warm sea supports the life of sea cows (Berta et al., 2006), which is more likely to be present in an inner ramp environment. Thus, the presence of sea cows in the middle ramp settings of the Guri Member can be explained by the transportation of these fossils after the animal's death. This is evident in the fragmentary nature of such fossils. On the other hand, the presence of a submerged ridge or bank in the form of a shoal can provide a suitable environment for these animals in a middle ramp. Such conditions have been reported in some sections of the Mishan Fm. (Heidari et al., 2012, 2014). Nevertheless, the preservation of fossils in inner ramp settings indicates their *in situ* nature and less transportation (Astibia et al., 2005; Boessenecker, 2013; Morovati et al., 2021).

Conclusions

Investigation of sedimentary facies in four localities which contain Sirenia fossils in the Zagros Basin of south-southwest Iran led to the identification of seven facies for the Mishan Fm., three for the Asmari Fm., and three for the Gachsaran Fm. The ancient sedimentary environment of these deposits was a carbonate ramp which included three main environments: tidal flat, inner ramp, and middle ramp. The age of the (sea cow) fossil-bearing strata was determined as Aquitanian for the Mishan Fm. and Burdigalian for the Asmari Fm. and the Gachsaran Fm. These temporal differences indicate that sea cows were present in several lithostratigraphic units in the Early Miocene of the Zagros Basin, provided that their living environmental settings (the warm and shallow ramp environment) were present. These (inner) ramp environments were

rich in benthic foraminifera with porcelaneous tests. This research calls for additional inquiries in other areas of the Zagros with similar stratigraphical and paleoenvironmental conditions for discovering more sea cow fossils.

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