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Biostratigraphy and depositional architecture of the Kazhdumi formation (Aptian-Albian) in the Izeh zone, Zagros mountains, SW Iran

Asiyeh Arampour[1], Massih Afghah[*1], Mahnaz Parvaneh Nejad Shirazi[2]

1. Department of Geology, Shiraz Branch, Islamic Azad University, Shiraz, Iran
2. Department of Geology, Payment Noor University, Tehran, Iran

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Abstract

In the easternmost part of the Izeh Zone of the Zagros Mountains, the Kazhdumi Formation of upper Aptian-middle Albian interval is superbly exposed in three-main exposures as argillaceous carbonate facies. The main bioclastic components of the Kazhdumi Formation are Orbitolinid and other larger benthic foraminifers, planktonic foraminifera and calcareous algae. The depositional system in the study area during the upper Aptian-middle Albian corresponds to a shaly carbonate ramp. Two depositional sequences are determined, as prograding system from west to east. Comparison of the proposed depositional sequences with those reported in the Arabian Plate and adjacent areas suggests a correlation with the global sea-level curve. The Lower Cretaceous, Aptian carbonates of Kazhdumi Formation contain nine microfacies, which were deposited on a ramp system deepened in both directions (west and east). Stratigraphic sequence led to recognize two third-order sequences. On the other hand, rudstone and boundstone lithofacies of the studied formation have higher reservoir potential and were deposited during Apt 3 and Apt 5 sequences of the Arabian Plate. The Kazhdumi Formation in the study area was deposited in an intrashelf basin that should be classified as an independent basin in the future paleogeographic maps of the southwest Iran. We interpret the Kazerun Fault, as a crustal warping of basement faults of the Arabian Plate boundary, which were responsible for the creation of the intrashelf basin in the study area.

Keywords: *Izeh Zone, Kazhdumi Formation, Aptian-middle Albian, Biostratigraphy, Facies, Sequence stratigraphy.*

1. Introduction

Geologically the Zagros Mountains are assigned to the Alpine-Himalayan orogenic belt.It is not corresponds with the geodynamic models of the Alps or Himalayan chains (Takin 1972). Some differences in the geological aspect of these chains were discussed by Stocklin (1968). The Kazhdumi Formation, is named after the Kazhdumi Castel in the Tang-e- Gurguda, 10 km north of Gachsaran (south of the Mish anticline). It was described for the first time by Kent and Warman (1951) as an unpublished report, and is source rocks in Zagros region (Bordenave and Huc 1995). The Kazhdumi Formation is well exposed in Fars, Dezful Embayment and Izeh Zone (Fig 1). It changes into carbonate rocks to the northeast of Lurestan (Motiei 1993). From Khuzestan province to the southwest, Kazhdumi Formation has an intertonguing interference with the Burgan Formation in Kuwait and Nahr-e-Umar in Iraq. Previous studies of this formation have focused mainly on lithostratigraphy, biostratigraphy and palaeontology (e.g., Wynd 1965; James and Wynd 1965; Afghah and Fanati Rashidi, 2007; Ghasemi-Nejad et al. 2009; van Buchem et al. 2010a, b; Parvaneh Nejad Shirazi 2009, 2011, 2013; Abdollahi and Vahidi Niya 2014; Maghfouri Moghaddam et al. 2016). So detailed sedimentological and microfacies is still required because of lateral facies change along Zagros lithofacies zonation. During the Aptian–Cenomanian interval time, the eastern part of the Arabian Plate (southwest Iran) was characterized by large intrashelf basins surrounded by shallow-water platforms. Currently calcium carbonate factory was controlled by many factors (e.g., organic behavior) during the Cretaceous age (Langer 2008). The sediments of Kazhdumi Formation were deposited during a relative sea-level rise, and act as a regional source of hydrocarbons mainly in the southwestern Iran (Gabb 1869). The aim of this paper is to describe, interpret the biostratigraphy, microfacies, the depositional system and sequence stratigraphy of the Khazdumi Formation using both field and microscopic observations. Because of rare sedimentological data of the southeastern part of the Izeh Zone, therefore, facies architecture, paleoenvironment, and sequence stratigraphic framework are not clear in the mentioned area. On the other hand, this zone is one of the most important hydrocarbones source of the southwest Iran.

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*Corresponding author.
E-mail address (es): massihafg2002@yahoo.com

2. Regional setting and stratigraphy

Meso-Cenozoic tectonic and sedimentary events in Iran have created several distinct structural and sedimentary units (Berberian and King 1981). The Zagros region is an active tectonic area of orogenic belt located between Arabian and Eurasian plates (Al-Husseini 2000). The Zagros fold–thrust belt is divided into several zones (Fig 1b), which differ in their structural style and sedimentary history (Falcon 1961), which are consisted of (Fig 1 a,b) Thrust, Dezful Embayment, Izeh, Lurestan, Fars, Abadan Plain, Bandar Abbas Hinterland zones and Complex structure with metamorphic rocks (Motiei 1993).

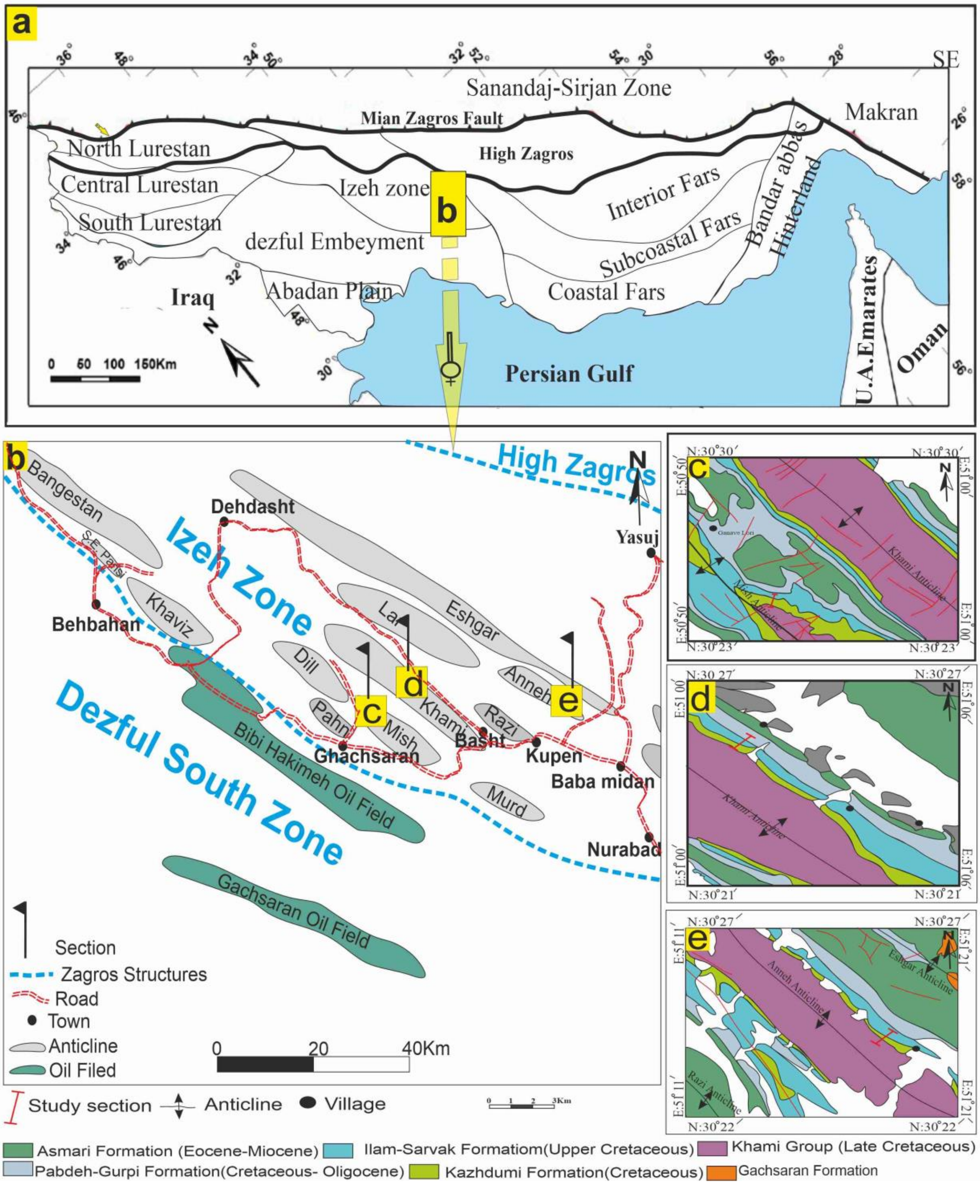

Fig 1. A. Structural subdivisions of SW Iran in Zagros orogenic domain (from Motiei 1993), B. Map showing distribution of anticlines in the studied areas and adjacent Izeh Zone, c- e. Simplified geological map of the Mish, Khami and Anneh anticlines showing the location of the study exposuers (see Fig 8). These maps are located by yellow box in the Fig 1b.

The Zagros Basin was associated to the Gondwana supercontinent during the Paleozoic. It was a passive margin during the Mesozoic, then a convergent orogeny during the Cenozoic (Heydari 2008; Nazari Sarem et al. 2021; Yazdi and Sharifi Teshnizi 2021). Jurassic-Cretaceous carbonate rocks of the Khami group, which is the oldest lithostratigraphic units of the studied area, consist of limestones and shales forming the Faliyan, Gadvan and Dariyan formations (Fig 1c, d, e). The study area is located in the southeastern portion of the Izeh Zone of the Zagros Basin (Fig 1a). This study interests on the Kazhdumi Formation in the Mish, Khami and Anneh anticlines (Fig 2) located in the northern margin of the Early Cretaceous intrashelf basin.

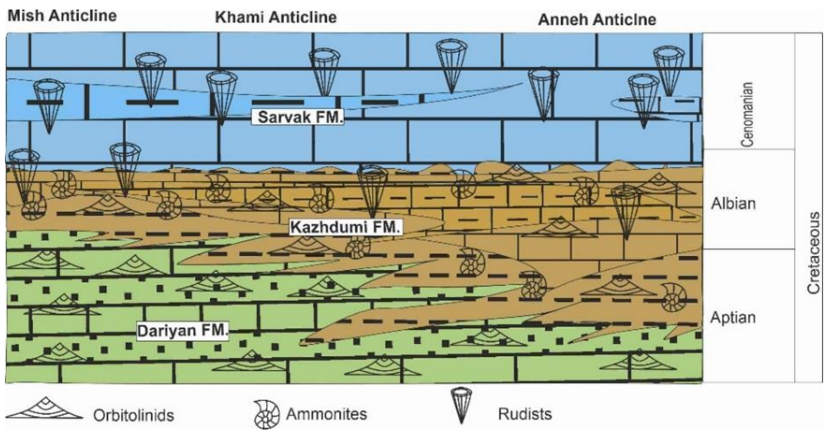

Fig 2. Schematic regional chronostratigraphic chart representing the spatial extension of the Dariyan, Khazhdumi and Sarvak formations and the lateral facies change between Dariyan and Khazhdumi formations.

Three sections at Genave-lori village (Mish anticline): the Shahzein-ali section, in the Khami anticline, and the Marskhoon section in the Anneh anticline were selected for this study. The general Cretaceous stratigraphic subdivision of the study area (Fig 2) includes four lithostratigraphic units: (1) Aptian shallow-water facies carbonates of Dariyan Formation; (2) the deeper-water marlstone of the Kazhdumi Formation; (3) shallow-water carbonates of Sarvak Formation; and (4) deep marine shaly limestone, carbonates and marlstone of the Gurpi Formation. The Kazhdumi Formation in the mentioned sections conformably overlies the Dariyan Formation with a diachronous contact and is covered by the Sarvak Formation. Various thickness of the Kazhdumi Formation were measured in the studied sections: 240m, in the Genave-lori section; 210m in the Shahzein-ali section and 195m in the Marskhoon anticline section, and consists of limestones, shaly limestones and shale containing skeletal grains from various fossil groups, including bioclastic debris and benthic or planktonic foraminifera which are very common with coral, echinoderms, gastropods, calcareous algae and bivalves. Stratigraphic succession and lateral facies variations of the three formations are given in the

3. Methods

Three Early Cretaceous sections of the Izeh Zone belonging to the Kazhdumi Formation were studied, in order to characterize lithological facies and architecture and bedding geometries of the mentioned zone. They were sampled and described reflecting coeval environments along an east-west direction (Gachsaran) (Fig 1). The field work is consisted of lithostratigraphic description (thickness, color, lithologic characteristic and bedding style) and lateral facies change categorization. Stratigraphic interpretations are proceeded on the basis of facies mapping. Detail field study were provided with microscope investigation of 473 thin sections, including: 163 thin sections from the Mish anticline (Genave-lori section), 182 from the Khami anticline (Shahzein-ali section), and 126 form the Anneh anticline (Masarkhoon section). The combined of facies and sedimentologic features have resulted in high-resolution correlations for the lower Cretaceous strata across the sections and provided a framework for interpretation of a detailed depositional environment. Stratigraphic sequences are defined as a conformable succession of genetically related strata, bounded at the top and the bottom by disconformities.

4. Lithology and foraminifer biozones

Biostratigraphic subdivision of the investigated Lower Cretaceous successions is studied, based on the occurrences of foraminifera and calcareous algae. Stratigraphic ranges of the identified microfossil assemblages indicate an Aptian to Albian age which is represented in Figs. 3 and 4. Foraminiferal biozonation for the Kazhdumi Formation were first established by James and Wynd (1965), and latter reviewed by Khalili (1976) and Bolz (1977), but only in unpublished reports. According to Wynd (1965), van Hinte (1976), Sigal (1977), Caron (1985), Hardenbol et al. (1998), Nishi et al. (2003), Premoli Silva and Verga (2004) the biozones were established.

4.1. Biozone 1 (*Ticinella primula* Interval Zone)

This zone is represented in the Anneh and Khami anticlines with 22m and 26m thickness respectively. It is marked by the first occurrence of *Ticinella primula*. Its consists of light grey thin- to medium-sized limestone beds with shale. Its foraminifera content includes: *Mesorbitolina subconcava*, *Globigerinelloides* sp., *Edomia iranica*, *Ticinella* sp., *Trocholina* sp. According to Premoli Silva and Verga (2004), Wynd (1965) who have defined the interval range of the taxon *Ticinella primula* and they suggested for lower Aptian-middle Albian age. This age of this taxa has also been obtained by van Hinte (1976), Sigal (1977), Caron (1985), Hardenbol et al. (1998), Nishi et al. (2003), Gradstein and Ogg (2004), and van Buchem et al. (2010b).

Tab 1. Biozonation of the Kazhdumi Formation in the study area.

Stage	No	Assemblage zone	Foraminiferal asemblage	Location			SBZ (wynd, 1965)	Van Hinte, 1976	Sigal,1977 (MCI Z)	Caron,1985	Hardenbol et al. (1998)	Nishi et al., 2003
				Genavelori (Mish)	Shazinali (Khami)	Mraskhoun (Anneh)						
Lower Albian	1	Ticinella primula Interval Zone	Ticinella primula+Mesorbitolina subconcava+ Globigerinelloides sp.+Edomia iranica+ Ticinella sp.+Trocholina sp.		✓	✓	Trocholina - Orbitolina assemblage zone(21)	Ticinella bejaouensis, Ticinella primula, Globigerinelloides gyroidinaeforimis	Ticinella primula(MCi25)	Ticinella primula	Ticinella primula	Ticinella primula
Upper Aptian	2	Globigerinelloides ferreolensis Partial range Zone	Globigerinelloides ferreolensis + Orbitolina sp. +Trocholina sp. + Hedbergella sp.	✓	✓		Giobigerina assemblage zone(17)	Globigerinelloides blowi	Globigerinelloides blowi(M Ci20)	Globigerinelloides spp	Globigerinelloides blowi	Globigerinelloides blowi
Upper Aptian	3	Hedbergella trocoidae Partial Rang Zone	Hedbergella trocoidae+Hedbergella occulata+ Conicorbitolina conica	✓	✓			Hedbergella trocoidae, Globigerinelloides ferreolensis	Hedbergella trocoidae(MCi 22)	Hedbergella gorbachikae	Hedbergella trocoidae	Hedbergella trocoidae
Apptian/Albian	4	Dictyoconus arabius range zone	Dictyoconus arabius+Orbitolina sp.+ Hedbergella sp.+ Rotalipora ticinensis+ Mesorbitolina aperta			✓	Pseudocyclammina lituus - Trocholina assemblage zone(14)					
Albian	5	Conicorbitolina conica range zone	Mesorbitolina subconcava+ Neomeris cretacea +Mesorbitolina texana+ Millolidea	✓	✓	✓	Conical Orbitolina assemblage zone(18)					

4.2. Biozone 2 (*Globigerinelloides ferreolensis* Partial Range Zone)

Lithologically, the mentioned zone is mainly characterized by medium- to thick-bedded dark grey to grey limestones with intercalation of thin grey shale levels. Its thickness is about 25m in Anneh anticline and 40m in Khami anticline. It is defined by the first occurrence of *Globigerinelloides ferreolensis* and contains *Orbitolina* sp., *Trocholina* sp., and *Hedbergella* sp. Wynd (1965); Gorbachik (1971); van Hinte (1976); Sigal (1977); Hardenbol et al. (1998); Nishi et al. (2003); Premoli Silva and Verga (2004); van Buchem et al. (2010b) have documented *Globigerinelloides ferreolensis* as a foraminifer species of upper Aptian assemblage.

4.3. Biozone 3 (*Hedbergella trocoidae* Partial Rang Zone)

This biozone of upper Aptian age, is well expand and distributed in the study area mainly in the Khami and Anneh outcrops. *Hedbergella trocoidae* Partial Rang Zone is made of dark grey shale of 45m and 60m thickness in the Mish and Khami anticlines respectively. It is characterized by the total range of *Hedbergella trocoidea* from its occurrence to its disappearance. The most important and common foraminifer species recorded in the three study sections are: *Hedbergella occulata* and *Conicorbitolina conica*. This zone is corresponds with the *Hedbergella trocoidea* Zone (Maci 22) of Sigal (1977); Hardenbol et al. (1998); Nishi et al. (2003), Premoli Silva and Verga (2004) and *Hedbergella gorbachikae* of Caron (1985), and van Buchem et al. (2010b).

4.4. Biozone 4 (*Dictyoconus arabius* Total Range Zone)

This biozone, of 45m thickness, only crops out in the Shahzein-ali section. Lithological aspect is characterized by light grey, thin to medium-bedded limestone and argillaceous limestone. It is characterized by the appearance of *Montseciella arabius*. Others common foraminifera are: *Orbitolina* sp., *Hedbergella* sp., *Rotalipora ticinensis* and *Mesorbitolina aperta*. The mentioned foraminifer assemblage corresponds to the *Dictyoconus arabius* Zone of Wynd (1965) and indicates an Aptian/Albian transition in age. Regarding the stratigraphic position and faunal assemblage of the biozone 4, the age of this biozone is referred to upper Aptian.

4.5. Biozone 5 (*Conicorbitolina conica* Total Range Zone)

This biozone is extended 45m, in Mish, 56m, in Khami and 75 m thickness, in Anneh anticlines, and consists of grey, medium-bedded limestone with intercalation of dark grey, thin to very thin-bedded shale and marlstone. Its benthic foraminiferal speciemens are well expanded particularly the orbitolinids, and others common taxa consisting of *Mesorbitolina subconcava*, *Mesorbitolina texana*, Millolidea and calcareous algae (*Neomeris cretacea*) (Fig 3), Wynd (1965) has previously recorded *Conicorbitolina conica* from Albian successions. This species is recorded as a lower Albian taxon, whereas *Neomeris cretacea* is considered as an upper Aptian calcareous algae. Nevertheless, upper Aptian foraminifers are well developed in this zone.

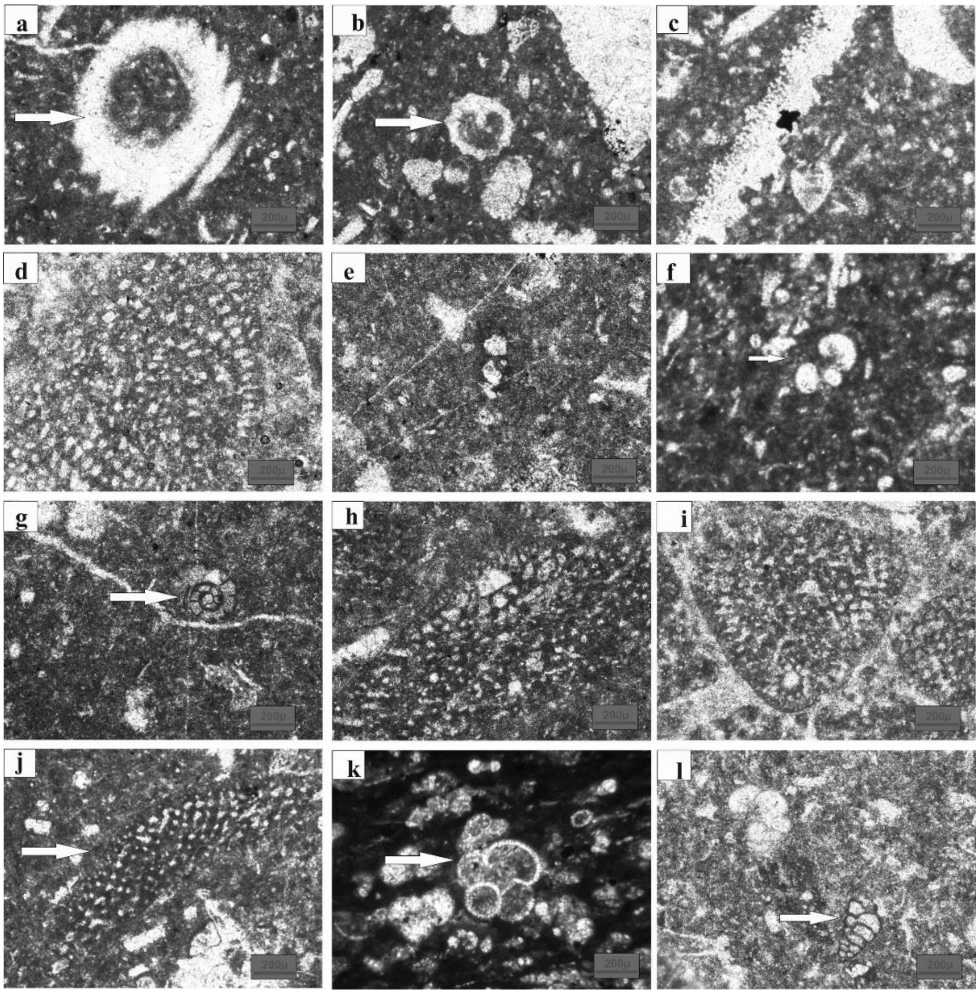

Fig 3. Photomicrograph showing Aptian-Albian microfossils from the study sections a. *Salpingoporella* sp. (upper Aptian, Shazein-ali section), b. *Permocalculus* sp, (upper Aptian, Genave-lori section), c. *Neomeris cretacea* (upper Aptian, Masarkhoon section), d. *Mesorbitolina texana* (Albian, Genave-lori section), e. *Edomia iranica* (middle Albian, Genave-lori section), f. *Hedbergella occulata* (upper Albian, Genave-lori section), g. *Hemicyclammina sigali* (upper Albian, Masarkhoon section), h. *Mesorbitolina subconcava* (Albian,), i. *Conicorbitolina conica* (Albian), j. *Orbitolina* sp. (Albian, Shazein-ali section), k. *Hedbergella* sp. (Albian, Shazein-ali section), l. *Globigerinelloides* sp. (Albian, Masarkhoon section).

Moreover, Schroeder et al. (2010) have documented *Conicorbitolina conica* as an association of the lower Albian foraminifer assemblage. Therefore, lower Albian age is acceptable for this biozone (Figs 3, 4).

4.6. Biozone 6 (*Hemicyclammina sigali* Total Range Zone)

This biozone is represented in the Khami and Mish sections, with 20m, 35m and 45m thickness respectively, and is consisted of gery medium- to thick-bedded limestone. It is characterized by the presence of *Hemicyclammina sigali* associated with *Edomia iranica*, *Conicorbitolina conica* and calcareous algae (*Neomeris cretacea*). Its faunal assemblage suggests a middle Albian age.The index taxon of this zone, *Hemicyclammina sigali*, is present in the three studied sections. This biozone corresponds to the zone number 17 of Wynd (1965). van Buchem et al. (2010a) and Parvaneh Nejad Shirazi et al. (2011) have documented *Hemicyclammina sigali* as an association of the middle Albian.

5. Facies analysis

According to microscopic investigation (e.g. textural aspect, skeletal grain type, and other microfacies features) seven microfacies (Fig 5; Tab 2) were identified. These facies associations represent various paleoenvironment (bathymetry, hydrodynamics). Depositional system were determined by stratigraphic distribution of identified microfacies with using of Srivastava and Singh (2017), van Buchem et al. (2010a, b) and Dunham (1962). These facies associations are described and interpreted below, and summarized in the Table 2.

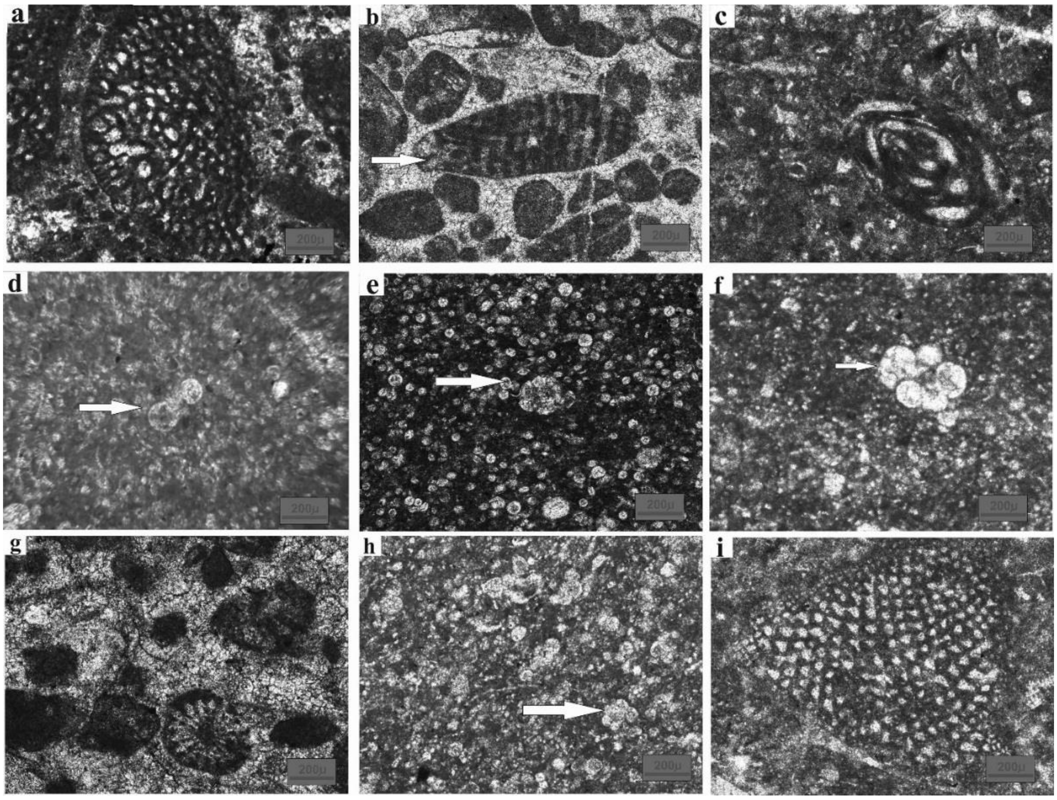

Fig 4. Photomicrograph showing Aptian-Albian microfossils from the study sections. a. *Mesorbitolina aperta* (Albian, Shazein-ali section), b. *Montseciella arabica* (Aptian-Albian, Genave-lori section), c. Miliolid (Albian, Genave-lori section), d. *Hedbergella plani*spira (Albian, Genave-lori section), e. *Globigerinelloides ferreolensis* (Albian, Masarkhoon section), f. *Ticinella* sp. (Albian, Masarkhoon section), g. *Clypeina occidentalis* (Albian, Shazein-ali section), h. *Hedbergella* cf. *mitra* (Albian, Shazein-ali section), i. *Dictyoconus arabius* (Aptian-Albian, Genave-lori section).

Tab 2. Main microfacies of the Kazhdumi Formation in the study area with description and depositional environments.

Microfacies name	Components	MFS (No)	Geomety	Sorting	Location	-	-	Age	-	Depositional environment
					Genavelori (Mish)	Shazinali (Khami)	Mraskhoun (Anneh)	Aptian	Albian	
Foraminifera and gastropod wackestone microfacies	Gastropod,algea,bivalves,debris fossil, *dictyoconus*,mollusc	MFS1	Nodular bedded	Poor	✓		✓	✓	✓	Restricted shallow lagoon
Orbitolitnids wackestone –packstone microfacies	*Mesorbitolina,coniorbitolina moulladei ,edomia iranica,millolide, echnoid,*	MFS2	Nodular bedded and shale form	Poor	✓	✓	✓	✓	✓	Proximal inner ramp
Foraminifera algal packstone and, Foraminifera packstone microfacies	Algea, *hedbergella* sp., *pseudochrysalidina, Conicorbitolina, Mesorbitolina (Orbitolina) subconcava*	MFS3	Nodular bedded and shale form	Poor to moderate	✓		✓		✓	Inner ramp/Open lagoon
Low diversity benthic foraminifera and, rudist wackestone microfacies	*Hemicyclammina sigali ,Montseciella arabicus , Ticinella primula, Dictyoconus arabius*	MFS4	Nodular bedded and shale form	Good to moderate	✓	✓		✓		Outer ramp
High diversity benthic foraminifera wackestone–packstone microfacies	*Salpingoporellinae, Permocalculus sp., Neomeris cretacea, Textularia* sp.	MFS5	Nodular bedded and shale form	Poor to moderate	✓	✓	✓	✓	✓	Outer ramp
Globigerinids wackestone–packstone microfacies	*Globigerinids,Hedbergella* sp., *Vavulamina* sp., *Small rotalia, very abundant small benthonic foraminifera*	MFS6	Nodular bedded and shale form	Poor		✓			✓	Middle and outer ramp
Foraminifera peloid bioclastic wackestone–packstone microfacies	Peloid, *miliolid,Hedbergella* sp.,*orbitolina* sp.,*fossil* debris ,coral fragments, rare bryozoans	MFS7	Nodular bedded and shale form	Poor	✓	✓	✓	✓		Lagoon with abundant miliolids
Bioclast mudstone-wackestone microfacies	Echnoid,ostrocod, *ophiomorpha, Textularia* sp.	MFS8	Nodular bedded and shale form	Moderate	✓			✓		Proximal mid ramp/Open lagoon

5.1. Foraminifera and gastropods wackestone microfacies (MF1)

This microfacies is described by an association of benthic foraminifera and gastropods as major skeletal grains. The main characteristic of this facies is comprised of well diversified foraminifera which are encompassed in mud-supported textures. Bioclastics constituents of this microfacies are represented by foraminifera mainly *Montseciella arabicus*, gastropods, calcareous algae, bivalves, bioclastic debris, echinoid debris and mollusks. This microfacies is described by wackestone textural aspect, but in some samples it occurs as mudstone. This microfacies is abundant in the lower part (Aptian) of the Mish and Anneh sections. The mentioned facies was assigned to a shallow water mid ramp paleoenvironment, suggested by the abundance of foraminifera. Similar data were previously recorded as Cretaceous/Paleogene boundary in the Central Anatolia (Turkey) by Esmeray-Senlet et al. (2015). Seaward, these microfacies pass into gray pelagic marlstone of quite deeper water (Figs 5a, b).

5.2. Orbitolitnids wackestone –packstone microfacies (MF2)

This microfacies association of Albian age basically consists of grey marlstone with interbedded medium-sized, light grey limestone beds. Orbitolinids bioclastic wackestone to packstone is characterized by an inhomogenic biozone of orbitolinids (e.g., *Conicorbitolina conica, Mesorbitolina parva, Mesorbitolina subconcava, Mesorbitolina texana.* Peloids, green algae (such as *Salpingoporella* sp.), milolids are present with minor frequency (< 5%) as subsequent skeletal grain. The matrix consists of lime mud and sparite and indicates inner ramp environments above fair- weather wave base. The faunal assemblage confirms semi- restricted lagoonal conditions with a moderate water circulation. The occurrence of peloids indicates a mixture with others facies. Thus, this microfacies either occurs as *in situ* deposits at the inner ramp or as allochthonous remains in deeper realms of the ramp (Figs 5c, d).

5.3. Foraminifera algal packstone and foraminifera packstone microfacies (MF3)

This microfacies forms the basal part of the Mish and Anneh sections of lower Albian age. It is characterized by high abundance of algae, *Hedbergella* sp., *Pseudochrysalidina conica, Conicorbitolina conica, Mesorbitolina (Orbitolina) subconcava* and conical foraminifera (*Daviesiconus* sp.) in a packstone facies with low wackestone matrix (Fig 5e). Additionally, small benthic, like miliolids such as *Triloculina* sp., rotaliids (*Neorotalia* sp.), echinoids, green algae, as well as fragments of bivalves are also present. This microfacies with the predominance of larger porcellaneous tests, such as orbitolitids which is restricted to the proximal inner ramp setting, as the limestone index species, indicating upper Aptian-Albian age. Also, the simultaneous occurrence of orbitolitids, miliolids and conical foraminifera are situated in shallower deposits of the proximal inner-ramp setting (probably less than 30-35-m depth) with effect of low-moderate energy environment. The distribution of conical foraminifera in this microfacies is reliable evidence for interpreting low-moderate energy conditions. Thus, this microfacies is representative of a sedimentation in open waters of the inner ramp setting and the shallowest portion inner lagoonal of a carbonate ramp (Figs 5e, f).

5.4. Low diversity benthic foraminifera and rudist wackestone microfacies (MF4)

The predominant skeletal grains in MF4 are foraminifera (e.g., *Hemicyclammina sigali, Montseciella arabicus, Ticinella primula, Dictyoconus arabius*). This microfacies was only observed in the Mish and Khami anticline and is dominated by lime mudstone with lacks of a shallow-water organic constituents. There is no evidences of shallow water high energy environment featuers (e.g . crushed bioclastic components). The well expand benthic foraminifera, the occurrence of small pelagic foraminifera and the fine- grained matrix, suggest a lower part of an open marine environment equivalent to a deep subtidal environment indicated by high frequency of well-preserved planktic foraminifera. The mentioned low- energy paleoenvironment was recorded by Geel (2000) as normal wave base zone. This microfacies characterizes the middle part of the two studied sections, with 2.5-m thickness in the Genave-lori and 4.5-m in the Shazinali sections and is composed of a diverse communities of rudists (65-70%), gastropods, bivalves, algae and bioclastic debris (15%) that generally are strongly abraded on side of outer walls in a packstone matrix content (Figs 5g, h). This microfacies is restricted to the Albian succession and is characteristics of the middle-distal inner ramp setting.

5.5. High diversity benthic foraminifera wackestone-packstone microfacies (MF5)

This microfacies is identified by occurrence of mm-sized skeletal grains of mollusk and echinoid. Moreover, the calcareous algae is recognizable in this microfacies remarkably (e.g., Salpingoporellinae, *Permocalculus* sp., *Neomeris cretacea, Textularia* sp.) According to Scholle et al. (1983), this microfacies is addressed to the beginning of open marine environment which light penetration zone is occurred with particles transported from adjacent shallow-water areas. (Fig 6i).

5.6. Globigerinids wackestone-packstone microfacies (MF6)

Globigerinid are the main skeletal components of this microfacies. They are distinguished as spherical or ovoid skeletal grains.

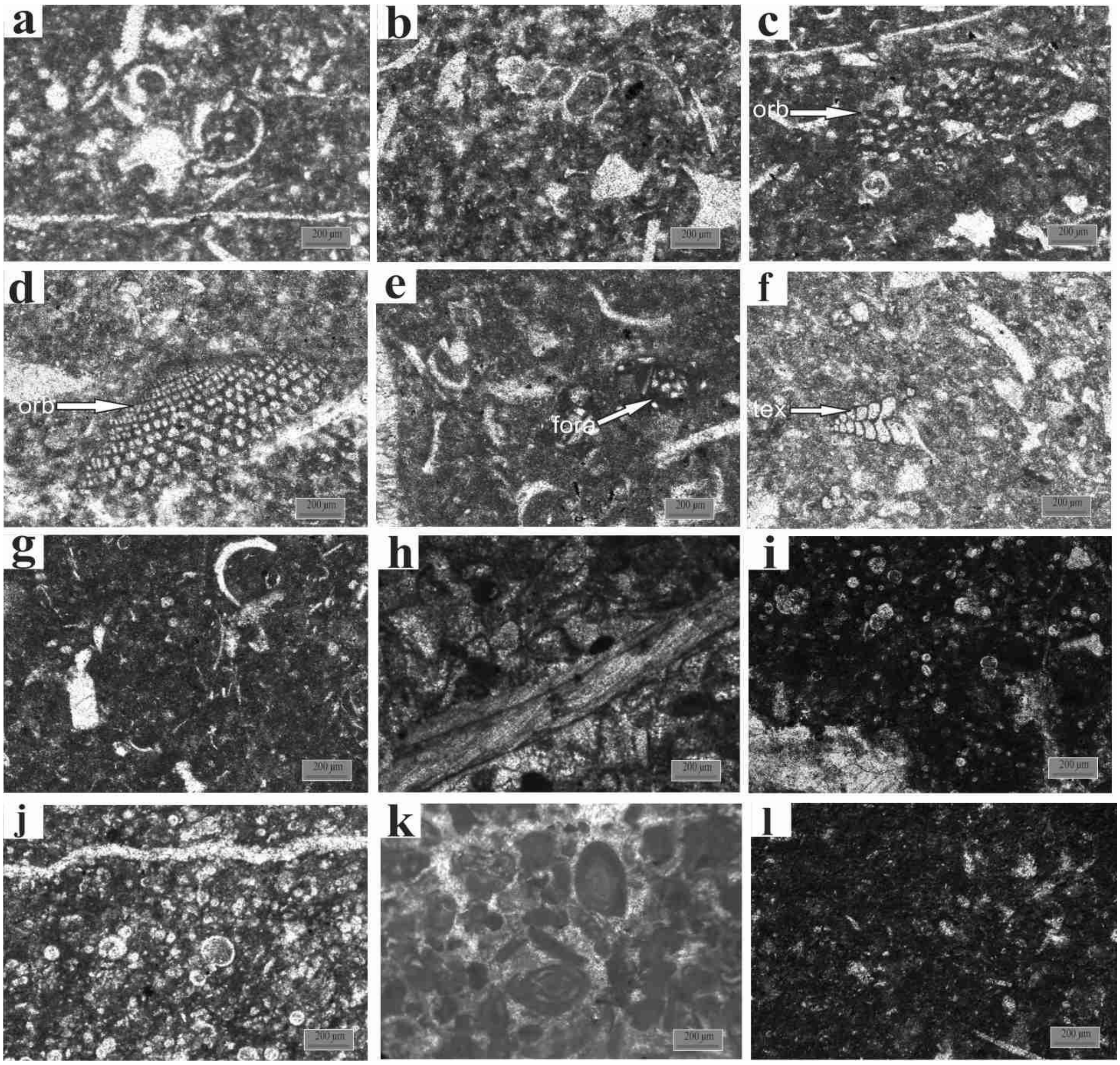

Fig 5. Photomicrograph showing Aptian-Albian microfossils and microfacies from the study sections a, b. Foraminifera and gastropod wackestone microfacies. c, d. *Orbitolina* packstone–wackestone microfacies (*Orbitolina* is shown by arrow) e, f. foraminifera algal packstone, foraminifera packstone microfacies. g, h. Low diversity benthic foraminifera, rudist wackestone microfacies. i. High diversity benthic foraminifera wackestone–packstone microfacies. j. Globigerinids wackestone–packstone microfacies. k. Foraminifera peloid bioclastic wackestone– packstone microfacies. l. Bioclastic mudstone to wackestone microfacies. (Orb: *Orbitolina*: For: foraminifera: Tex: *Textularia*).

These pelagic foraminifera include: *Globigerina*, *Hedbergella* sp., *Vavulamina* sp., small rotaliids, very abundant small benthonic foraminifera are co-occurred with fragments of echinoderms and ostracods in packstone and occasionally wackestone microfacies. MF5 microfacies was only observed in the Khami section. The presence of *Globigerina* sp. with very rare platform derived material such as small echinoid debris and rotaliids suggested a low-energy paleoenvironment below the fair- weather wave base in a distal setting (Morshedian et al. 2012).

5.7. Foraminifera peloid bioclastic wackestone-packstone microfacies (MF7)

Bioclasts are majorly characterized this microfacies include small textularids, ostracods, bivalves and echinoid fragments. Foraminifera and others grains are present with common peloids, miliolids, *Hedbergella* sp., *Orbitolina* sp., fossil debris, coral fragments, rare bryozoans (Fig 5k). The presence of common marine macro- and micro-faunal assemblages, with great frequency of planktonic foraminifers and the muddy textures, indicate as open marine environment. The presence of Hebergelids is index of shallow openmarine setting which is correspond with MF2. MF7 facies is represented in the three sections of the study area.

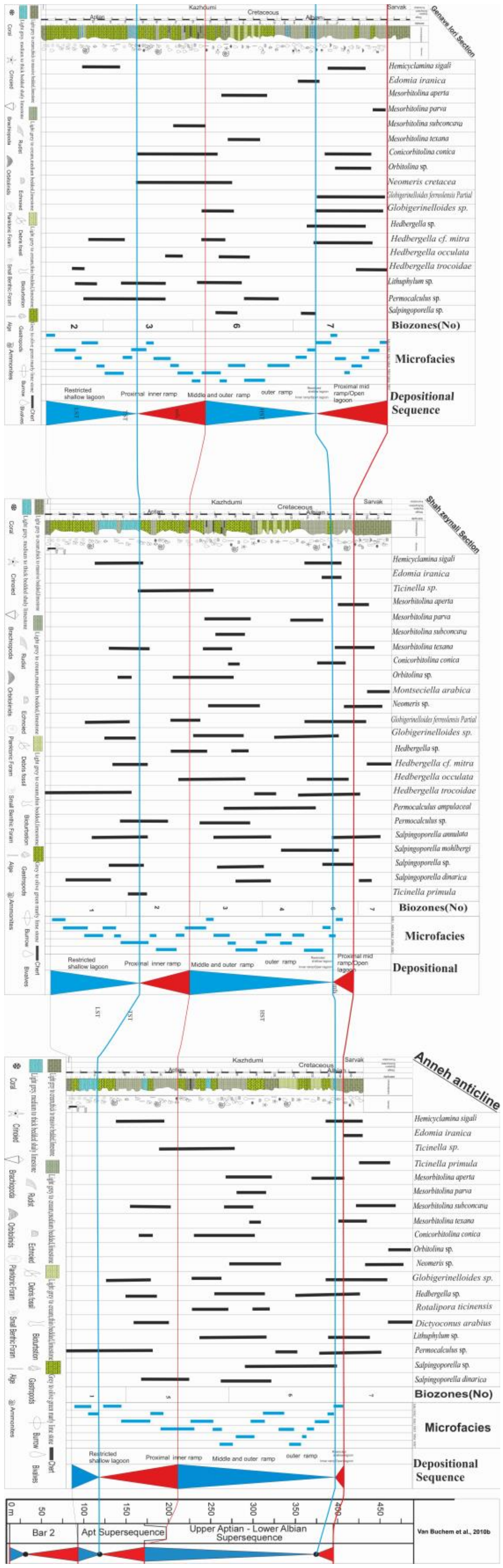

Fig 6. Lithology, biostratigraphy, microfacies, biozonation chart of the study area and sequence stratigraphy correlation chart of the study area sections according to the studies by van Buchem et al. (2010b). (See supplementary file)

5.8. Bioclast mudstone-wackestone microfacies (MF8)

This microfacies is composed of dense lime mudstones containing sparse non-diagnostic faunas. In some samples, subordinate amount of detrital debris fossil, are present. This microfacies occurs in the upper part of the Kazhdumi Formation at the Anneh and Mish outcrops (Fig 5l). Lime mudstone with small bioclastic debris of this microfacies with no evidence of subaerial exposure evokes this microfacies was deposited in a restricted shelf lagoon, and indicates hypersaline conditions, in an area of a shelf lagoon diversity of foraminifersa, and point to a high-stressed habitat in a very shallow restricted shelf lagoon. The appearance of sparse particles of bivalves, echinoids and ostracods within a micritic groundmass is typical of restricted inner lagoon environments (Rasser et al. 2005; Mahdavi et al. 2015).

6. Depositional models

The Kazhdumi Formation in the studied sections is subdivided into eight distinct microfacies, each one is characterized by a depositional and petrographic textures, skeletal and nonskeletal components. However, recognition of identified microfacies confirms five depositional envirnments in five stratigraphic intevals (Fig 7). Actually, the carbonate sources were changing during in time of Kazhdumi Formation deposition in both Mish, Khami and Anneh sections during Albian age. These facies models may be regarded as a predictive tool for the upper Aptian (Fig 7a), Aptian-Albian (Fig 7b), and the lower Albian (Fig 7c). In the platform-to-basin transition, from Mish anticline (Genave-lori section) to Khami anticline (Shahzein-ali section), the facies architecture and distribution of bioclasts and field description allow the distinction of four large-scale stratigraphic units (MF1 toMF8) within the Kazhdumi Formation. Van Buchem et al. (2010a, b) documented similar biozone and microfacies, of Aptian and Albian in age, in the Arabian Plate (Mish anticline). The upper part of the Kazhdumi Formation has a widespread distribution and conformably overlain by the Sarvak Formation.

6.1. Upper Aptian *Hedbergella* sp. and *Globigerinelloides* sp. -dominated in outer ramp

From west (Mish anticline) to east (Anneh anticline), the first and second biozones (upper part of the SBZ 21 biozone) are determined as a shallow- water with *Hedbergella* sp. and *Globigerinelloides* sp. – high carbonate content outer ramp which is assigned to the upper Aptian (Fig 7a), overlying the Dariyan formation. They correspond to an outer ramp and include an extensive MF4, 5, 6 carbonate factories (Fig 6) with a gentle slope from the outer ramp to the middle ramp. Stratigraphic section of Anneh, the both benthic and planktic foraminifer (e.g. *Hedbergella trocoidae*, *Hedbergella occulata*, *Conicorbitolina conica*, miliolids, Textularia), s are well distributed in the inner-ramp facies which indicate deposition within the medium energy (Al-Husseini 2000). The mid-ramp is composed of coarse-grained packstone and wackestone with mm- to cm-sized algae and milolids associated with others MF4,3. Basin ward (Khami and Mish anticlines) with shale form wackestone and packstone with high content of both planktonic and small benthic foraminifera of the outer ramp. The depositional model for the upper Aptian (biozones 3 and 4) corresponds to a distally-steepened carbonate ramp dominated by *Hedbergella* sp. and *Globigerinelloides* sp. (Fig 7b) that prograded from west to east. The inner part of this carbonate ramp, calcareous algae well dominated as middle ramp, is located in the mid- and outer-ramp in the Anneh anticline. The inner-ramp, sediments are including MF4 and MF3, is identified by occurrence of well diversified benthic foraminiferal assemblages. Large *Hedbergella* sp., in the lower slope settingis known as autochthonous carbonate factory. The skeletal composition of the lithology is progressively replaced by yielded miliolid packstone/wackestone. The mentioned facies confirms a progressive decrease of accommodation space and a accompanying down dip migration of the carbonate producers. With the lowering of sea-level, the large and flat *Hedbergella* sp. developed simitanousley with *Globigerinelloides* sp., where planktonic foraminifera habitat. In mentioned both portions, the outer-ramp is recognized by well dominated fine-grained sediments which is well expand for kilometers over basinal liomestone of the Dariyan Formation.

6.2. Aptian-Albian *Dictyoconus arabius* and algae-dominated in outer and middle ramp

From Khami to Anneh anticlines, the Aptian-Albian boundary interval is located into the Kazhdumi carbonate system and consists of alternative limestones with medium buff, limestone-dominated (mainly porcellaneous) carbonate ramp (Fig 7d). Nevertheless, this unit is a part of the inner ramp of the Anneh section. The distal parts of the ramp (middle part) are not appear and they only occur in the central parts of the intra-shelf basin. In the resulting restricted and stressed environment, Biozone 4 (Tab 1) and peloids became important. The inner-ramp facies consist of MF2 and MF6 (Tab 2). In most parts of the study area, the beginning of the interval has been identified by the deposition of shallow-water sediments, interpreting as entire platform was, at least temporarily, flooded during the Aptian-Albian boundary. In the part, the most common deposits in the whole area are thin-bedded shallow-water limestone with a mixture of perforated and imperforated foraminifera, coralline algae and small miliolids, strongly refere the presence of seagrass meadows (Ghasemi-Nejad et al. 2009; GhasemShirazi et al. 2014; Bazoobandi et al. 2016; Poorbehzadi et al.

2019). Toward the top, wackestone to packstone beds are rich in small miliolids, and *Dictyoconus arabicus*.

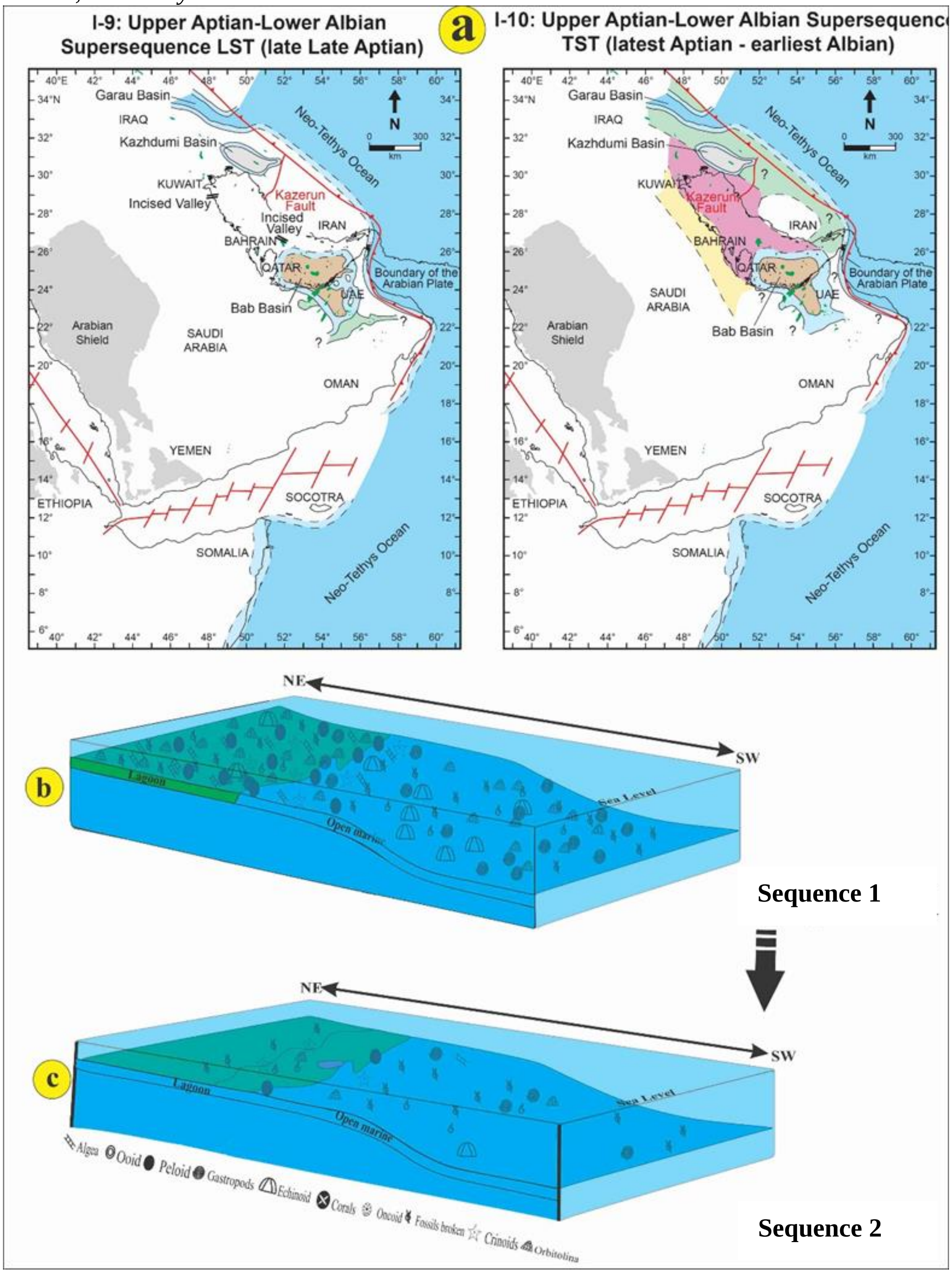

Fig 7. a. Paleo-tectonic, paleogeographic and synsedimentary tectonic maps of the Arabian Plates during the Aptian-Albian (modified from van Buchem et al. 2010b). Schematic depositional models of the Kazhdumi Formation during: b. The lower and middle Aptian, c. The upper Aptian-lower Albian. These local depositional models show a systematic progradation from NE to SW.

6.3. Lower Albian *Hemicyclammina sigali Orbitolina* sp. and *Ticinella primula*- dominated in middle and inner ramp

From west to east in Izeh Zone, the lower Albian carbonate system (Biozone 6) of the Kazdumi Formation is an algal facies containing, *Hemicyclammina sigali*, *Orbitolina* sp. and *Ticinella primula* -dominated system with buildups, down lapping on to the lower Albian and outset middle Albian substratum to the east (Fig 8). During the lower Albian, carbonate shale form production on the northern margin of the Kazhdumi intra-shelf basin, in the Anneh and Mish anticlines, marked by occurrence of a transition facies of the carbonate ramp into the overlying middle Albian clean carbonate platform of the Sarvak Formation.

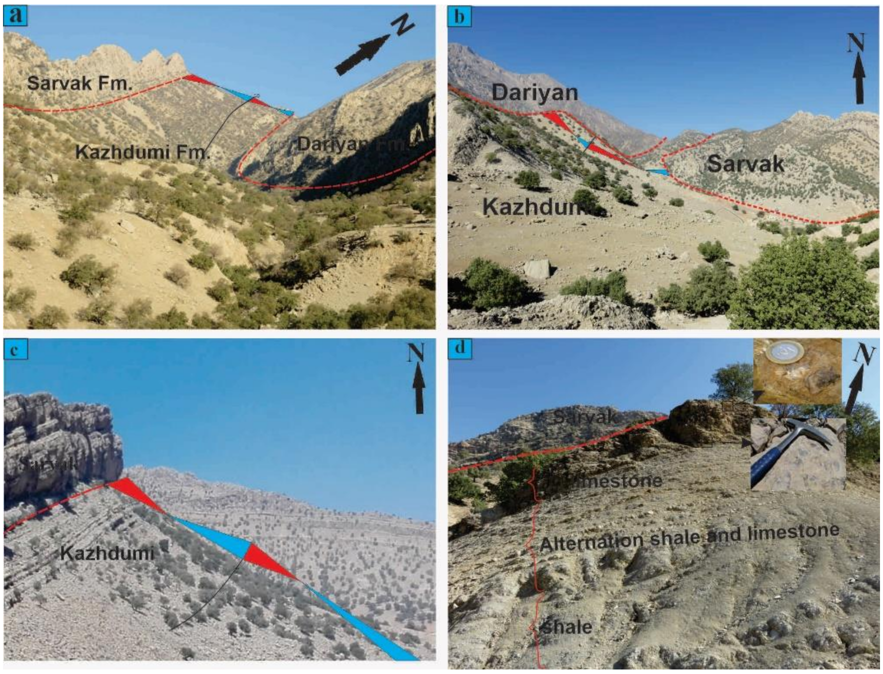

Fig 8. Field aspects of key outcrops of the Kazhdumi Formation. a. Outcrop photographs of the Mish anticline (Genave-lori section); sequence boundaries are indicated. b. General view of the Khami anticline (Shahzein-ali section). c. General view of the Anneh anticline. d. Clinoforms in the upper part of the Kazhdumi Formation in the Khami anticline.

The inner part of this carbonate ramp is recognazale in the Mish anticline, whereas, the evidence of middle-ramp setting is determined in the Anneh anticline. The inner-ramp deposits, similar to the buff and olive-green, medium to thick limestone units, consist of MF1 and MF2. The depositional environment is characterized by a appearance of benthic foraminiferal assemblages, which are commonly developed in the shallow water, particularly in the Anneh anticline. The mid-ramp, with large and isolated *Orbitolina* and rudist and organic buildups (Figs.7, 8), occur seaward of the seagrass meadow deposits. Within the buildups, *Orbitolina* and rudist colonies are mostly ocuur, whilst some large type are appeared as patched colonies. Most colonies are in contact but restricted in a packstone microfacies, and no framework cavities exist. Well abundance of a fine-grained, muddy matrix is index of the wave action zone. The facies filling the space between the buildups is characterized by a mixed normal marine biota, indicating a protected environment. Initially (Phase 1) the rudist organic builds up developed in a mid-ramp setting. Later, by falling sea-level, the seagrass belt (inner ramp) retrograded basinward. In this platform is the upper portion is marked by foraminiferal packstone with debris of porcellaneous foraminifera, mollusks and green algae. The mentioned packstone indicates the final shallowing and primary progradation of the platform, deposition rates were low frequency of porcellaneous foraminifera and green algae were the main carbonate factories in the shallow part. Basinward, the rudist buildup belts were retrograded into low-angle dipping, poorly-bedded and mud-dominated packstone to wackestone. Locally there are interbedded with rudist organic builds up pactches (Mish anticline) and scattered rudist colonies (conicided with the latest falling of sea-level as deduced above), as well as green marlstone with planktonic foraminifera.

7. Sequence stratigraphy

According to combining of the facies types, the stacking patterns of the strata, and the surfaces bounding packages of genetically related strata, along with the environmental dependence of the skeletal components, results in two major depositional sequences of the Kazhdumi Formation. Figures 6 and 8 show the relationship between the two sequences and those of other study areas. The identified depositional systems are well exposed in the study area. Sequence stratigraphy of the Barremian-Albian strata in the Arabian Plate has been studied in outcrops (Pittet et al. 2002; van Buchem et al. 2010a, b) and subsurface (Sharland et al. 2004; Yose et al. 2010; Maurer et al. 2013; Pierson et al. 2010). The Khazdumi Formation (equivalent to the Shu'aiba Formation and Bab Member) was deposited during the Aptian-Albian supersequence transgressive–regressive cycles and was bounded by unconformities (Yose et al. 2010). Van Buchem et al. (2010a) also proposed a new sequence stratigraphic framework that correlates through the Arabian Plate, Zagros and Persian Gulf regions of this plate. According to this framework, the Arabian Plate Aptian-Albian supersequence was divided into two third-order sequences, named Arabian Plate Aptian-Albian sequences. Identification of these sequences in the studied area is according to the correlation of log data and lithofacies characteristics with Arabian Plate sequences.

Table 2 shows some characteristics of these sequences in the Arabian Plate in the study area, and Fig 6 shows the correlation of these sequences with each other and with the Arabian Plate in study area. Time ranges of each third-order sequence are according to GTS time scale of Ogg et al. (2016). Van Buchem et al. (2010b) proposed a new sequence stratigraphic framework for the Kazhdumi formations in SW Iran, but there is no detailed in the Iranian part of the Persian Gulf and no correlations performed with adjacent Arabian parts according to log data. The objectives of this study are to interpret depositional sequences by collecting and studying petrographical samples and correlation of sequences between the Iranian part and the Arabian Plate in the Izeh Zone (Fig 1) that can give a better clue in paleogeography during the Albian-Aptian time. First sequence (Apt 3) is present in the Mish (Genave-lori section) with a maximum thickness of 150 m (Fig 6) and includes the grey, medium-bedded limestones with intercalation of very thin shales levels. As in the case in the sequence A, the Apt3 sequence is presumed to be correlated (Fig 8) with the shallow-water Dariyan facies underlying the Kazhdumi Formation in the all outcrops and it can be equated to the sequence Apt 3 of van Buchem et al. (2010a, b) in the Arabian Plate. The first limestone facies with whole *Globigerinelloides ferreolensis*, *Orbitolina* sp., *Trocholina* sp., *Hedbergella* sp. were deposited during a major regression and mark the beginning of the HST sediment. The latter comprise *Globigerinelloides* sp. facies with several deepening-upward cycles ranging from 0.5 to 4 m-thick. The cycles reflect an aggradational stacking geometry that accumulated during a relative sea-level rise. The maximum flooding surface (MFS) is defined by an interval of marlstone and marly limestone, rich in planktonic foraminifera and *Hedbergella* sp. The succeeding HST of the sequence Apt3 is distinguished by the development of a prograding carbonate platform dominated by shallowing-upward cycles of *Hedbergella* sp. and *Globigerinelloides* sp. and middle and outer-ramp facies. The highstand carbonate shelf extended at least from the all outcrops (in the SW), where it changes laterally into distal mid-ramp facies (MF2, 5, 6) that pinch out into basinal limestone (MF4) of the Dariyan Formation. From field and photographic observations and a conspicuous surface on the platform top is proposed as the approximate position for the sequence boundary in the all sections. The upper boundary of this sequence is a significant biostratigraphic boundary dated as latest Aptian. This surface can be traced downslope into a correlative conformity within the Dariyan Formation. During this stage, the MF1 was replaced by colonized rudists and probably formed build-up and flank complexes. According to Al-Husseini et al. (2010) and Al-Husseini and Matthews (2010), Apt 2 and Apt 3 represent the differentiation of the southeastern Arabian Plate into the Shu'aiba Platform and intrashelf Bab Basin. In studied area, this sequence has a type 2 lower and upper boundaries. The thickness of this sequence ranges from 11 to 86 m. This sequence thickened toward the Mish anticline (86 m) and also hinned toward the west in the Khami and Anneh anticlines. Higher thickness of carbonates series in the Mish anticline represents good carbonate productivity during platform shallowing and deposition of outer and mid-ramp build-ups toward the location of these Khami anticline (Fig 7). The second sequence (Apt 5) is the lowstand system tract (LST) of the upper Aptian–lower Albian supersequence and were deposited during the late Aptian time in mixed argillaceous-carbonate platform. Therefore, the lower boundary of the Apt 5 in the three study sections is type 2, and the upper boundary with LST Apt 5 sequence is type 1. Biozonation of all sections confirms an early late Aptian to early lower Albian age for Apt 4. Note, in the Mish and Khami anticlines, the time range of Apt 4 could not be identified because of the absence of index fossils (Fig 6). In Anneh (Fig 6), the thickness of this sequence is about 17 m and contains *Mesorbitolina parva* with discoidal *Orbitolina* wackestone-packstone, bioclastic facies. This sequence is depicted in all sections and index fossils of *Mesorbitolina texana*. In Khami anticline, the thickness of this sequence reaches 30 m and contains pelagic foraminifer's wackestone. This sequence consists of conical and discoidal *Orbitolina* wackestone-packstone facies so the maximum flooding surface is placed at the discoidal *Orbitolina* wackestone-packstone facies. As this sequence deposited after exposure of the platform in the Arabian Plate. This Aptian-Albian sequence, includes grey to buff, medium- to thick-bedded limestones with intercalation of shales and marlstone and is present in the Mish (40 m), Khami (70 m) and Anneh anticlines (not completely preserved; 55 m) (Fig 6). The sequence boundary at its base is positioned close to the upper Aptian-lower Albian boundary. This sequence equates to sequences Apt5 and Apt6 and Alb1 and Alb2 of van Buchem et al. (2010a). The lower Albian sequences in most parts of the Zagros Basin are characterized by major eustatic sea-level falls, which caused their isolation from Neotethys. This led the deposition of shallow subtidal facies within an aggradational stacking pattern across the entire study area. The maximum flooding surface (mfs) is placed within the wackestone–packstone facies with a diverse fauna including small foraminifera, and debris fossils, since this unit is one of the deepest facies of the Aptian and also because it is followed by shallowing-upward, restricted lagoonal facies, which would represent the HST which is rich in imperforate foraminifera, and was deposited in a protected shallow-inner ramp setting. Within the uppermost part of the HST in the Anneh anticline, there are easily identified alternations of thin bedded limestones and red marly limestones, with a terrigenous influence, corresponding to the latest sea-level fall. Within the uppermost part of the HST at the Mish and Khami outcrops, there is a network of trace fossils unlimited (Dwelling and Grazing traces), extending down to more than 30 m.

8. Comparison of depositional sequences

During the onset of NeoTethys subduction at the Aptian, the Kazhdumi Formation has been deposited in an intrashelf basin in the northeastern passive margin of the Arabian Plate (van Buchem et al. 2010b) followed by deposition of Burgan sandstone equivalent sediments of latest Aptian to the early Albian age. This formation is equivalent to both Shuaiba Formation and Bab Member (Aptian carbonate sediments) of the Arabian Plate and the intrashelf basin in UAE containing high levels of organic matter (van Buchem et al. 2010b) (Fig 6). Kazerun fault had considerable effects on the facies changes and shallowing or deepening of the Cretaceous sedimentary basins in the studied region (e.g., Sepehr and Cosgrove 2005). The sequence subdivision proposed here and those reported by van Buchem et al. (2010a, b) broadly coincide with these global variations in climate and sea-level (Figs. 6, 8). Although in detail, there are some differences, these could reflect local–regional tectonic effects. Sea-level fluctuations in the studied stratigraphic intervals were anticipated using regional geometrical reconstructions (a transect from west to east), the sedimentological facies interpretations and the high resolution time-lines. Following a major rise in sea-level from the upper Aptian to the middle Albian, progressive filling of the intrashelf basin, led to progradation of the Kazhdumi ramp over the Dariyan Formation such that the Kazhdumi-Dariyan contact is transitional (van Buchem et al. 2010a,b). This boundary show a pattern of decreasing age toward the basin center from east and west (Fig 8), including upper Aptian-middle Albian in the Mish, Khami and Anneh anticlines, respectively. The Dariyan Formation is interpreted as a sediment-starved, shallow-water facies, deposited basinward of the advancing Kazhdumi platform. The stepwise, diachronous, termination of Kazhdumi platform into the basinal limestone of the Dariyan Formation, from west to east, can be expected in a prograding platform system. The appearance of the upper Aptian-dominated outer ramp (including sequences Apt3 and Apt5) in the Anneh anticline at this time may be related to a major eustatic sea-level rise at the end of the upper Aptian (van Buchem et al. 2010b), although there appears to be some uncertainty over the amplitude of this sea-level change. The overall architecture of the ramp system, with aggradation and progradation, denotes progressive filling of the basin and a decrease in accommodation space. The development of the lower Albian *Mesorbitolina subconcava*, *Neomeris cretacea*, *Mesorbitolina texana*, Millolidea -dominated ramp (including sequence Apt5) in the three outcrops at that time may be related to a subsequent sea-level rise to around the Aptian-Albian boundary as is clearly illustrated by the thick-bedded limestones in the Anneh and Khami sections, that downlap onto the underlying shallow-water Dariyan Formation. The Aptian-Albian boundary is characterized in the study area by a decrease of foraminifera, such as *Globigerinelloides ferreolensis*, *Hedbergella* sp. in the Mish and Khami anticlines, while an exposure surface developed onto the surrounding platforms (van Buchem et al. 2010a, b; GhasemShirazi et al. 2014). The scale of sea-level rise also varied, with a major rise occurring during the earliest Albian, with the formation of a middle ramp (including sequence Apt5), as is clearly illustrated by the series of algae and *Orbitolina* sp. in the Anneh section. At times of subsequent a-level rise, the basin was reconnected to the open ocean and thus the carbonate factory was re-established, above the Aptian-Albian limestones, with the development of a low-angle ramp dominated in the study area of this investigation. Sea-level rise along with regional tilting that started in the earliest Albian (van Buchem et al. 2010a,b) led to a shift of the depocenter to the west parts of the basin.

9. Conclusions

The shelf of the Kazhdumi Formation in the southeastern margin of the Izeh Zone has been investigated in three excellent selected outcrops with a variety of carbonate facies and exceptionally well-exposed depositional. The stratal patterns and facies architecture of the Kazhdumi Formation can be divided into following litofacies; dark grey shale, alternative shale and limestone and grey to buff, thin- to thick-bedded limestones with intercalation of grey shale. On the basis of lithology, texture, biogenic components and sedimentary features observed in the outcrops and from microfacies analysis, seven major microfacies associations (MF1to MF7) were identified. The recognition of these microfacies associations and their position within the carbonate and shale succession, along with an analysis of the skeletal components, permitted that each of these microfacies can be attributed to a particular depositional setting. From east to west, the Kazhdumi system is composed of: a shallow-water dominated carbonate ramp during the Aptian-Albian, containing: *Ticinella primula*, *Mesorbitolina subconcava*, *Edomia iranica*, *Ticinella* sp., *Trocholina* sp., *Neomeris cretacea*, *Mesorbitolina texana*, Millolidea overlying the Sarvak Formation substratum; a dominated carbonate ramp during the Aptian-Albian that prograded from west to east. Two depositional sequences are distinguished in a time interval spanning the upper Aptian-lower Albian. The age given for the third-order sequences is lower Albian-middle Albian. Generally, these depositional sequences represent large-scale progradation from west to east. This progradation is particularly marked in the upper Aptian and the middle Albian sequences causing major facies changes. This progradation is Anneh outcrop developed in the lower Albian to middle Albian, where a platform-top configuration prevailed in the studied area and there is a good correlation between the sequence subdivisions proposed in this work and those reported by van Buchem et al. (2010a) for the Arabian Plate. Broadly, the Kazhdumi sequences are correlated with global variations in terms of tectonics, climate and eustatic sea-level fluctuations.

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