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Facies analysis, depositional environment and sequence stratigraphy of the Permian Ruteh Formation in north of Mahabad (NW Iran)

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Abstract

The Permian Ruteh Formation is known as one of the most significant successions in northwestern Iran. In the studied area it exposed a thick succession (201 m) of medium to thick-bedded carbonate sedimentary rocks in the west of Kuseh-Kahrizeh village in the north of Mahabad city. This formation unconformably overlain the Cambrian Mila Formation and it is unconformably underlain by the Oligo-Miocene Qom Formation The laboratory studies on the thin sections led to the identification of 15 microfacies that are arranged in three facies associations: inner ramp, mid-ramp and outer ramp. The petrographic results and facies analysis demonstrate that the depositional environment of Ruteh Formation in the studied area exhibits the characteristics of a homoclinal carbonate ramp platform of a gentle slope. This platform is mainly composed of supratidal, intertidal, lagoon, shoal, open marine, mid-ramp, and outer ramp environments. According to facies frequency analysis, the lagoon environment accounts for the highest abundance of facies (33%), whearas the outer ramp environment shows the least abundance (2%).Vertical distribution analysis of sedimentary facies led to the identification of transgressive and regressive depositional patterns. Accordingly, a total of 4 depositional sequences of third-order, 5 sequence boundaries and 4 maximum flooding surfaces were identified. The boundaries between all sequences are identified as SB1.

Keywords: *Permian, Ruteh Formation, Sequence stratigraphy, Sedimentary environment, Mahabad*

1. Introduction

The Permian succession in the northwest of Iran has been reported in vast areas in Western Alborz, Central Alborz and Sanandaj-Sirjan zones. In these areas Permian deposits are characterized by Doroud, Ruteh and Nesen formations. The Ruteh Formation is one of the most widespreaded formations situated in the northwest of Iran (Shabanian 2010). Asserto (1963) was a pioneer in introducing the Permian carbonate sediments named as the Ruteh Formation in Western Iran. In most studies, the age of the carbonate sequence of Ruteh Formation has been reported as Late Permian (Asserto 1963; Parto Azar 1992; Mokhtarpour 1997; Besse et al. 1998; Noorafkan Kondrood 2000; Lankarani and Amini. 2007; Hassani et al. 2013; Babakhuie et al. 2013; Bastami et al. 2016). In the type section (Jeirud Valley in Tehran province), Ruteh Formation is about 230 m thick (Asserto 1963). In the Western and Central Alborz, it unconformably overlain the older strata (Aghanabati 2004) and it underlain the Elika (Triassic) and Shemshak (Jourassic) formations (Shabanian et al. 2006; Mahdavi 2010; Shabanian 2010). Notwithstanding, in most areas of the northwest of Iran it has been covered by younger formations such as Oligo-Miocene Qom Formation (Noorafkan-Kondrood 2000; Bagheri and Shabanian 2014; Ebrahim-Nejad et al. 2015; Sadeghi et al. 2015) Shabanian et al (2006), Shabanian (2010) Vaziri et al. (2010),Vaziri and Mafi (2011) have studied different sections of Permian successions in the Alborz and Sanandaj-Sirjan zones. They show that in most parts of Iran, the Ruteh Formation is carbonate in terms of lithology. The Carbonate strata of the Ruteh Formation in northwestern Iran can be correlated to the Nesen Formation (in the Alborz Basin) (Glaus 1964) and Jamal Formation (in Central Iran) (Brunet et al. 2009).

Since the preliminary research by Asserto (1963), several researches have investigated the lithostratigraphy, biostratigraphy and general geology of the Permian succession in Western Alborz and Sanandaj-Sirjan zones (Shabanian 2010; Vaziri et al. 2010; Grippa and Angiolini 2012; Zand Karimi et al. 2014; Sadeghi et al. 2015; Ebrahim-Nejad et al. 2015; Arefifard 2006; Medadi et al. 2017). Even though many studies have been focused on the Ruteh Formation in Iran, this research aims at identifying the facies, depositional environment and sequence stratigraphy of the Ruteh Formation in Kuseh-Kahrizeh section (north of Mahabad).

2. Geological setting

The studied section is located in north of Mahabad (Fig 1). Iran has been divided into several structural units, each characterized by a relatively unique record of tectonic, stratigraphic, metamorphic and magmatic activities, sedimentary features and overall geological structures (Aghanabati 2004). The studied section is located in the Sanandaj-Sirjan Zone (Fig 2). This zone has also been named as Esfandagheh-Urmia or as Marivan-Esfandagheh zone.

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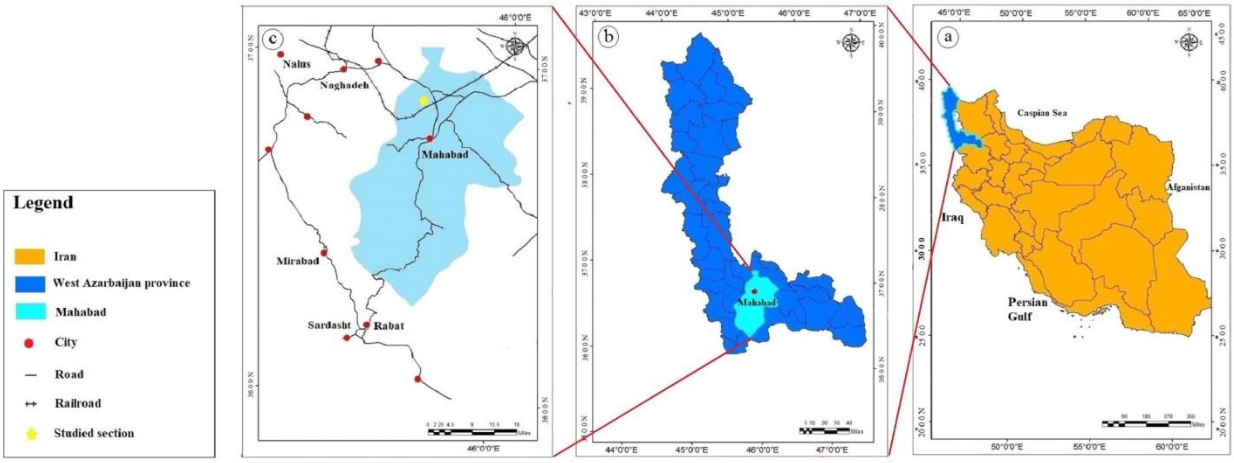

Fig 1. a) Geographical location of studied area a Geographical location of west Azarbaijan province b) Geographical location of Mahabad c) access routes to studied area

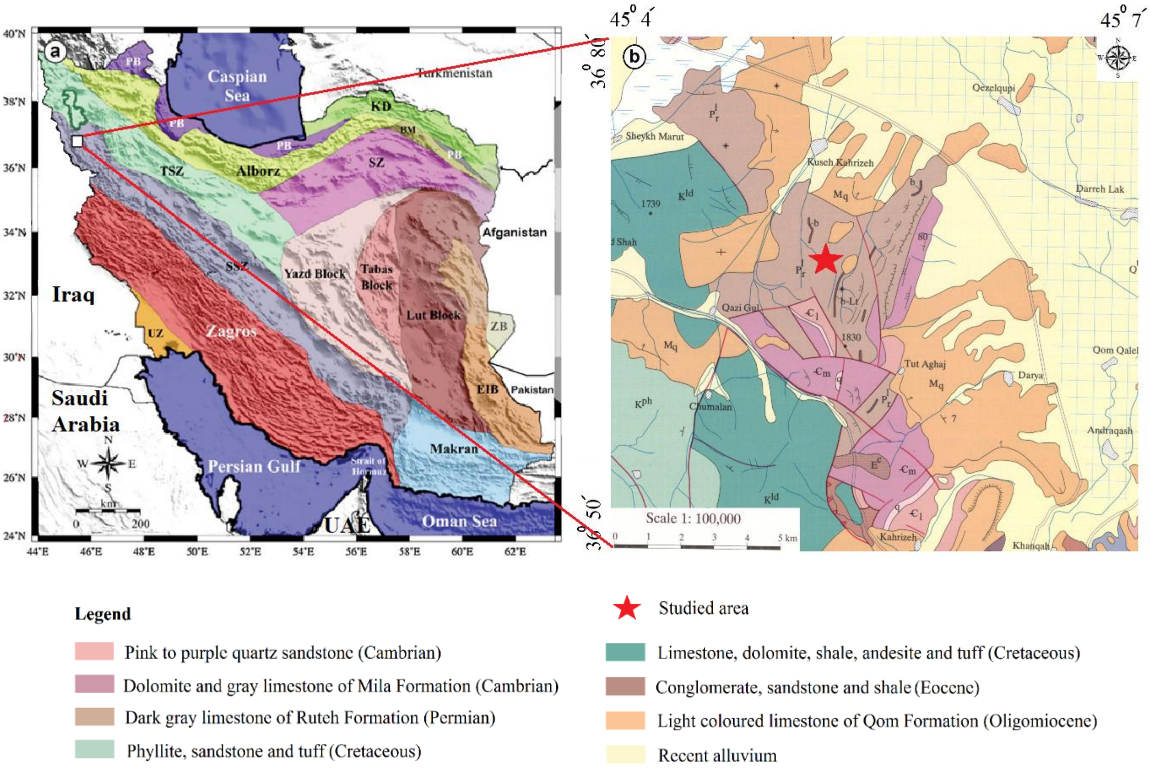

Fig 2. a) Structural map of Iran (modified after Aghanabati 2004; Hessami et al. 2006; Naimi-Ghassabian et al. 2015; Mousavi 2017). Abbreviations; UZ, unfolded zone; ZB, Zabol block; EIB, east Iran belt; SSZ, Sanandaj-Sirjan zone; TSZ, Tabriz-Saveh zone; SZ, Sabzewar zone, KD, Kopeh Dagh; BM, Binalud mountain range and PB, Paleo-Tethyan basin. b) Geological map of Mahabad section (at 1:100000 scale) (Eftekhar Nezhad 1980)

The Sanandaj-Sirjan Zone was once attached to the Zagros, Central Iran zones and to the Arabian plate. Until it severed as part of Cimmeria microcontinent in the Mid-Permian (Berberian and King 1981; Sengor 1990; Grabowski and Norton 1995; Stampfli et al. 2001; Sharland et al. 2001; Scotese 2004) (Fig 3).

The geological observations (especially paleo-magnetic data) indicate that Iran and Gondwanaland continental landmass were connected during the Late Precambrian to Permian, are consistent (Berberian and King 1981). Paleo-magnetic evidences from the Upper Devonian-Lower Carboniferous deposits of the Alborz Mountain in the north of Iran (Jeiroud Formation) (Wensink et al. 1978) and from the Upper Precambrian, Ordovician and Permian rocks of central Iran (Soffel et al. 1975; Soffel and Forster 1977), all show similar geomagnetic poles with those of Afro-Arabia.

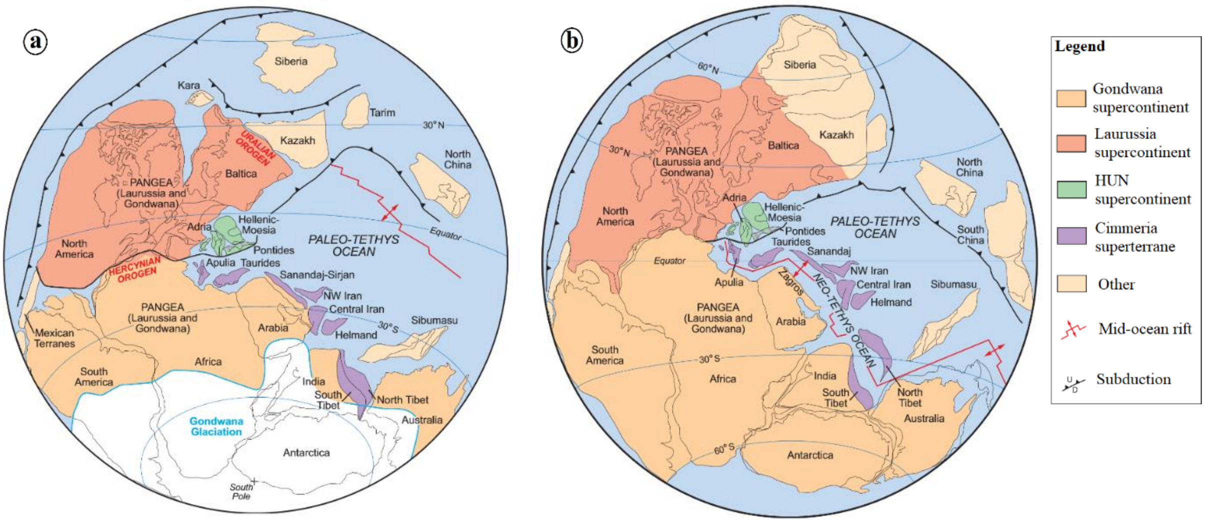

Fig 3. Plate-tectonic reconstruction of the Early Permian time (a) and Late Permian (b) (modified after Trosvik and Cocks 2004; Ruban et al. 2007).

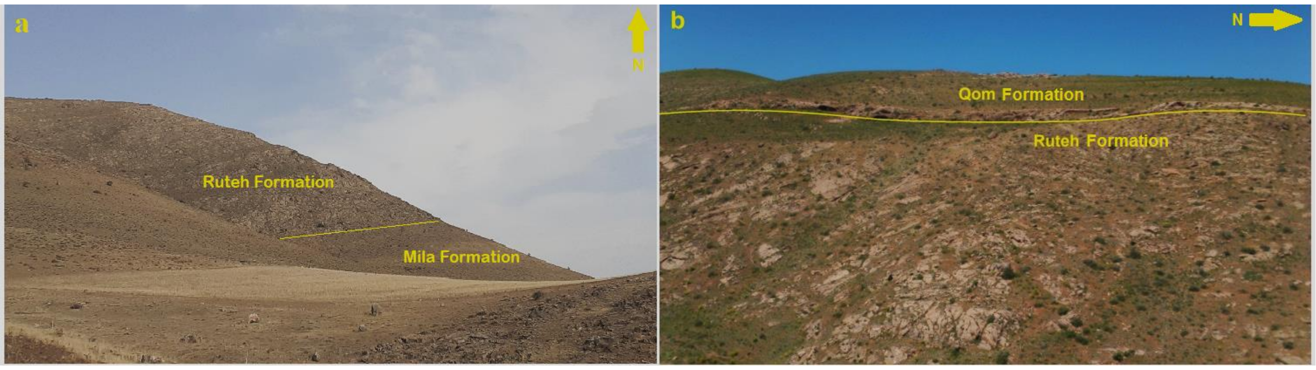

Fig 4. Field photographs of the Ruteh Formation in Kuseh-Kahrizeh section in north of Mahabad a The Ruteh Formation unconformably overlain Early Cambrian Mila Formation. b The Ruteh Formation unconformably underlain the Oligo-Miocene Qom Formation

These data indicate that during the Late Precambrian and Paleozoic, Central Iran, the Alborz in northern Iran and the Zagros in southern Iran were parts of Gondwana. In the Late Carboniferous-Early Permian, continental rifting separated these lands from the Gondwana due to the expansion of Neo-Tethys Ocean. Due to the glacier growth and Hercynian Orogeny movements at the time (Berberian and King 1981; Lasemi 2000), the Lower Permian sedimentary facies in Iran are mainly siliciclastic (the Dorud Formation in the Alborz and Sanandaj-Sirjan zones). In the Late Permian, after deposition of the Droud Formation, glaciers regression, tectonic extension and mid-oceanic ridges volume augmentation led to the sea progression and consequently carbonate platforms restoring in the southern margin of Paleo-Tethys (Lasemi 2000). The carbonate rocks of the Upper Permian Ruteh and Nesen formations in the Alborz-Azarbaijan, Sanandaj-Sirjan Zones and the Jamal Formation in Central Iran, have recorded the development of these carbonate platforms (Berberian and King 1981; Lasemi 2000). Murgabian to Midian Ruteh Formation (Jenny-Deshusses 1983; Parto Azar 1995; Gaetani et al. 2009) consists of a sequence of limestones and dolomitic limestones with a thickness of 201 m in the Western Kuseh-Kahrizeh village in the north of Mahabad. Kuseh-Kahrizeh section, is located 1640m above sea level, has a geographical coordination of 36˚ 67′23″-N and 45˚ 05 ′11″-E . The Ruteh Formation in this area unconformably overlain Early Cambrian Mila Formation and unconformably underlain the Oligo-Miocene Qom Formation (Fig 4).

3. Methodology

Studying the records of the conducted researches, the location of the sedimentary section in the field was selected in order to be sampled. The facies analysis was based on the study of sedimentary features including bedding thickness and geometry, sedimentary structures, texture and components. Some 101 rock samples were collected from non-weathered surfaces and thin sections were prepared from all of the samples to perform a petrographic analysis.

In order to identify calcite and dolomite, thin sections were stained by potassium ferricyanide and alizarin-red S solution according to Dickson's (1965) method. In order to determine the proportion of grains, the comparison charts by Bacelle and Bosellini (1965) were used. Limestone classification follows the nomenclature by Folk (1962) and Dunham (1962). The depositional setting of facies is interpreted based on the facies characteristics (type of component and its textural characteristics) and by comparisons with standard facies from well-known depositional environments (e.g, Wilson 1975; Flügel 2010). In order to determine the depositional sequences, the sedimentary stacking pattern, vertical relationships of facies and sequence boundaries, the Hunt and Tucker's (1992) method were used.

4. Results

4.1. Facies Analysis

The Ruteh Formation at the studied section is subdivided into 15 microfacies, each characterized by a depositional texture, skeletal and non- skeletal components as well as petrographic analysis. In this study based on paleoenvironmental and sedimentological analysis, a total of 7 depositional environments were differentiated including: inner ramp (supratidal, intertidal, lagoon, carbonate bar or shoal, open marine zones), middle ramp and outer ramp.

4.1.1. The inner ramp facies association

The inner ramp consists of a euphotic zone which is located between the coastal margin and the fair-weather wave base, where the sea floor is almost affected continuously by the waves. Inner ramp facies are:

4.1.1.1. Supratidal facies belt (A)

Description.

This facies consists mainly of medium-bedded cream to light gray limestone. This facies includes mudstones (FA1) without recognizable carbonate grains of fenestral porous texture and dolomudstones (FA2) (Fig 5). In some thin sections, mudcrack, bioturbation and fenestral fabrics are seen. Dolomudstone facies is composed of totally fine-grained dolomite crystals (Fig 5).

Interpretation

This facies group is identified as the shallowest facies belt of the Ruteh Formation. Porous texture in the muddy limestone facies may be an evidence of subaerial exposure, contraction and expansion, formation of gas bubbles, air escape during overflows, air bubbles trapped between irregular-shaped deposits or may be the result of drilling by worms (Shinn 1983, Korngreen and Benjamini 2010; Rankey and Berkeley 2012).

Given the lack of marine skeletal grains, micritic texture and the presence of fenestral fabric, this facies belongs to the tidal flat environment (especially to supratidal zone) (Shinn et al. 1965; Ginsburg and Hardy 1975; Adabi and Asadi Mehmandosti 2008; Adabi et al. 2010).

This microfacies is comparable to Flügel's (2010) number 19 (RMF 19) standard ramp microfacies which has been deposited in supratidal environment of a carbonate ramp. In the dolomudstone facies, the fabric and fine crystal size and lack of fossil content, suggest that these dolomites are of primary origin and formed in low temperature and superficial conditions (supratidal sub-enviroment)(Adabi 2004; GhasemShirazi et al. 2014).

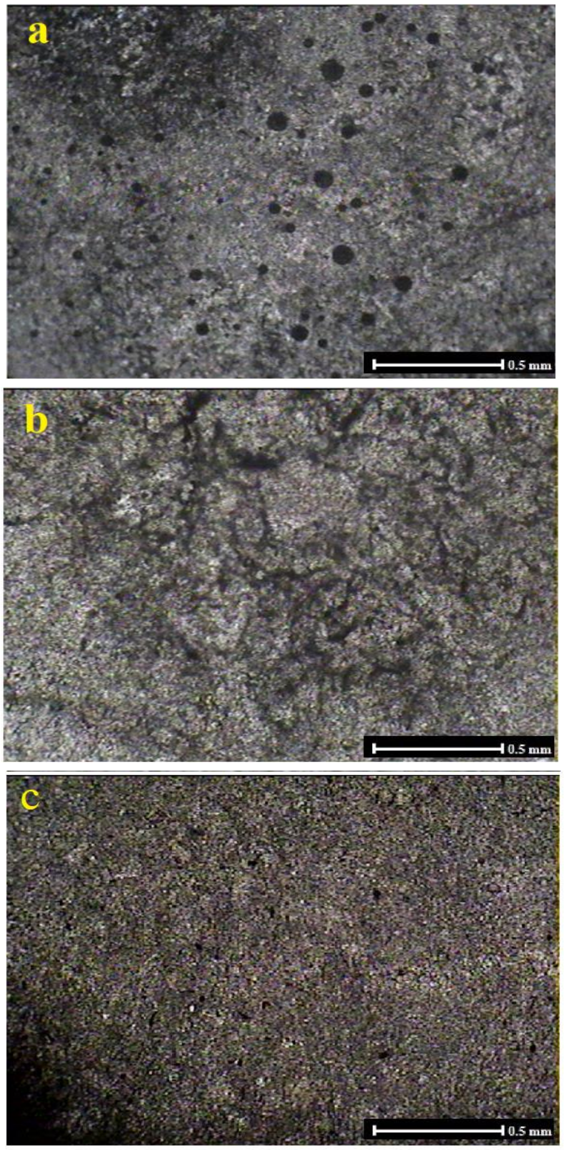

Fig 5. Microphotographs of the carbonate microfacies main types of the Ruteh Formation (supratidal facies). a) limestone with porous texture (FA1). b) Mudcrack in mud limestone c) Dolomudstone with fine-grained crystals (FA2)

This microfacies is equivalent to Flügel's (2010) number 22 (RMF 19) standard ramp microfacies and it has been deposited in the upper parts of supratidal sub-environment.

4.1.1.2. Intertidal facies belt (B)

Description.

This facies is dominated by mid to thick-bedded cream to light gray limestone. The intertidal facies is represented by intraclastic grainstone (FB3) mainly formed by abundant intraclasts (~70%) and other non-skeletal grains such as fecal pellets (~20%). Skeletal grains are also of less common constituents (~10%). Allochems constitute ~ 40% of facies components and have medium to poor sorting (Fig 6). Grains are surrounded by granular calcite cement. The diversity of skeletal grains is low and includes ostracods and echinoderms. Intraclasts are micritic and no internal structure is observed in them. They mainly have a poor roundness. Some of them have undergone recrystallization and ferrugination during diagenesis (Fig 6b). Pellets have rounded shape. Average size of intraclasts and peloids are ~2 and 0.5 mm, respectively. Geopetal texture are abundantly observed in some samples (Fig 6 a). The thickness of this facies is usually less than 10 meters, mostly observed in the upper parts of depositional sequences and gradually changes into supratidal facies upward.

Interpretation

Intraclasts usually occur due to the destruction and smashing of the coastal erosion of previous carbonate deposits. Intraclasts are commonly found in transitional environments. These environments in which intraclasts are formed are characterized by wave-dominated regimes and tides that continuously rework carbonates. Intraclastic grainstones are often interpreted as deposits formed by storm wave erosion and by reworking of various sediment types occurring in high energy environments. The poorly-sorted micritic intraclasts with different sizes and fabrics, indicate strong reworking of semi-lithified sediments. These intraclasts are indicative of the existence of subaerial environments and near shore depositional sites (Flügel 2010). Intraclasts also may be deposited in subtidal environments as intraclastic wackestone/packstone, but lack of micrite in this facies indicates that the energy of environment has been high enough to wash the intergranular matrix and transfer it from the environment to a region of lesser energy. The high energy of environment, low transfer rate of intraclasts from origin to depositional environment (poor sorting and roundness) and existence of bioclasts (representing normal salinity of water), indicate that sedimentary environment of this facies is intertidal.

4.1.1.3. Lagoon facies belt (C)

Description.

Lagoon sub-environment is represented by three facies: bioclastic algal wackestone (FC4) (Fig 7 a-b), peloidal algal packstone (FC5) (Fig 7 c-d), and bioclastic packstone/grainstone (FC6) (Fig 7 e-f).

Bioclastic algal wackestone include medium-bedded cream to gray fossiliferous limestone. This facies is mainly made up of skeletal particles embraced by fine-grained calcareous mud (micrite) background. The grains are mainly composed of algae, gastropods and diverse benthic imperforate foraminifera (porcellaneous wall benthic foraminifers) such as miliolid with complete and abundant uncrushed fossil remains (Fig7 a and b). Size of gastropods and algae are ~ 0.5 and 1 mm, respectively. Moreover, semi-sorted and semi-rounded grains, algae and gastropods are also present in some thin sections as subordinate grains of this facies.

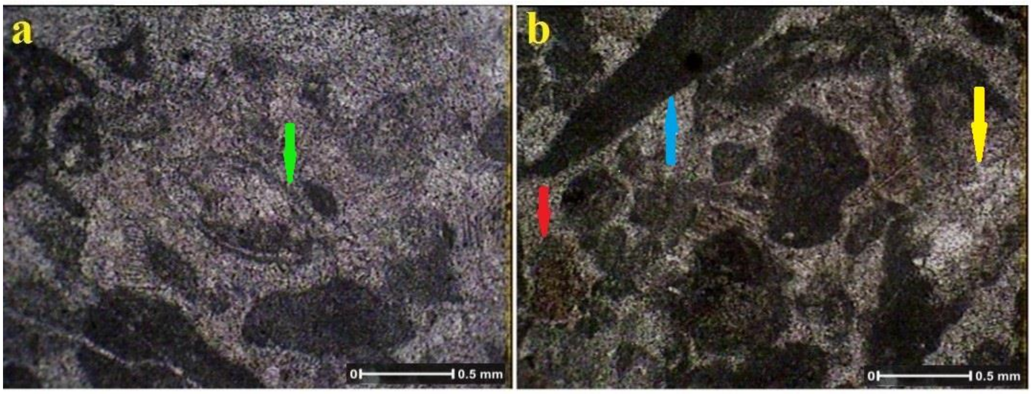

Fig 6. Microphotographs of the carbonate microfacies main types of the Ruteh Formation. (Intertidal facies). a) Geopetal texture in grainstone facies in an ostracod carapace (green arrow) b) Intraclastic grainstone (FB3) angled intraclasts (blue arrow) and rounded pellets are in a granular calcite cement, Ferrugination (red arrow) and neomorphism process (yellow arrow) take place in some allochems.

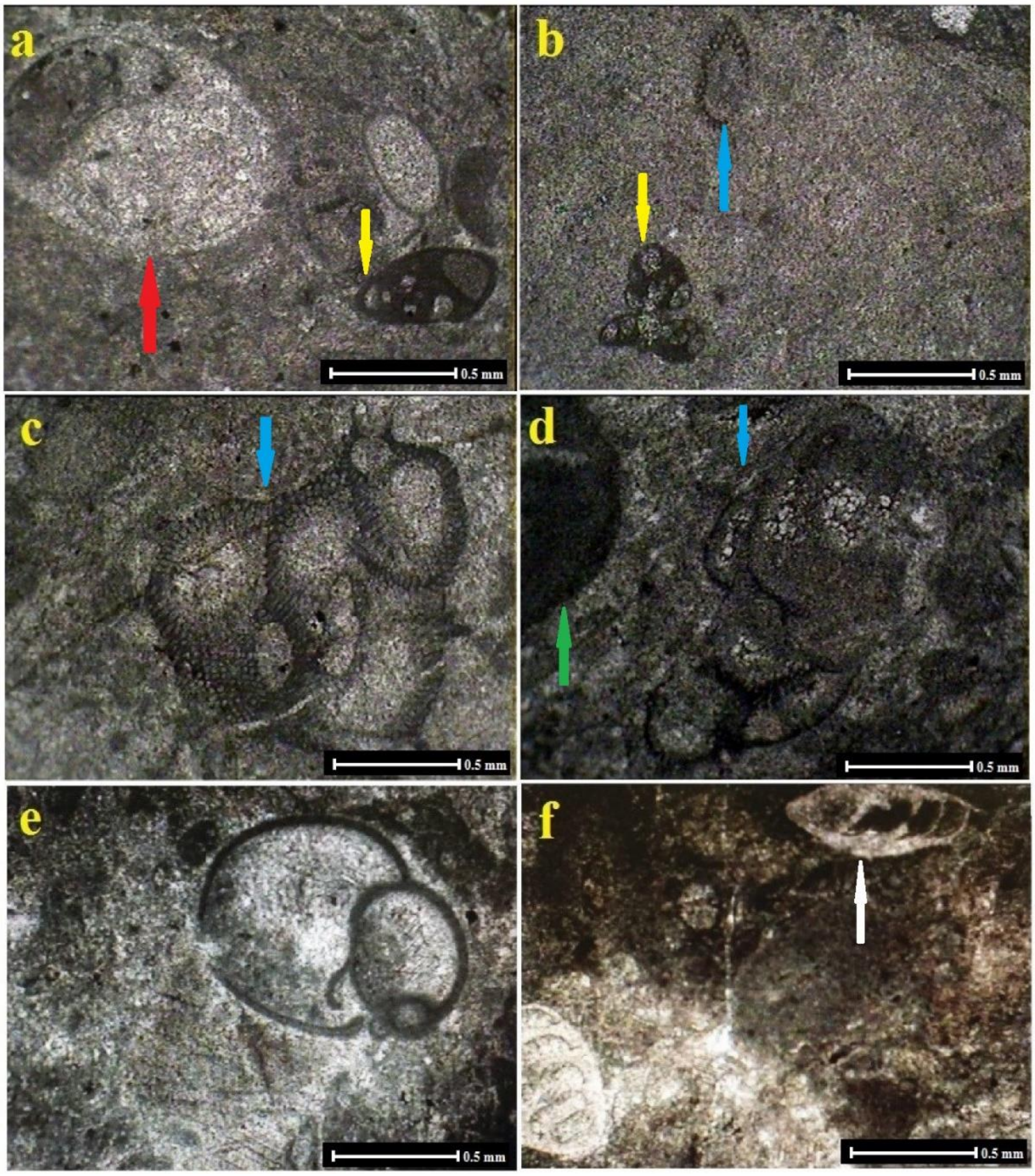

Fig 7. Microphotographs of the main carbonate microfacies types of the Ruteh Formation (lagoon facies). a and b) Bioclastic algal wackestone (FC4), gastropods (red arrow), algae (blue arrow) and benthic foraminifera with imperforate crusts (yellow arrow) in a micritic context. c and d) Peloidal algal packstone (FC5) (blue arrows: red algae) (green arrow: peloid). e) Geopetal texture in bioclastic packstone/grainstone facies f) Bioclastic packstone/grainstone (FC6) in this section foraminifera with hyaline light crusts (white arrow) surrounded by both matrix and sparite

Peloidal algal packstone occurs as thick-bedded and in some cases as cliff- forming cream to light gray limestone. This facies mostly consists of skeletal components (mainly Vermiporella algae) and peloid, encirced by a dark lime mud (micrite) (Fig 7 c and d). The other major skeletal components are composed of echinoderms (3 to 4 percent), ostracods (3 to 4 percent) and benthic foraminifera (1 to 2 percent) such as milliolids. Peloid is the only non-skeletal allochems (30 to 40 percent). The grains have undergone micritization due to the effects of microboring organisms (Fig 7 d).

Bioclastic packstone/grainstone

This facies occurs mainly as thin-bedded cream to light gray limestone. The matrix of this facies predominantaly is micrite, nevertheless there is sparry cement among it. The main skeletal grains are benthic foraminifera and gastropoda along with bivalve and crinoid fragments (spine and plates). Benthic foraminifera constitute 20 percent of skeletal grains. They have complete and uncrushed fossil remains. The average particle size of foraminifera is 0.5 mm. Non-skeletal fragments include peloid. Bioturbation is prevalent and most of grains are surrounded by a micritic envelope (Fig 7 f).

Interpretation

Given the paleontological characteristics (presence of algae, gastropods, benthic foraminifers and ostracod) of sedimentary texture (abundance of calcareous mud), this facies belt belongs to the subtidal shallow marine environment (Flügel 2010; Mahdavi 2010). Packstone to wackestone textures along with the abundance of carbonate mud (micritic texture), low diversity of carbonate allochems, the existence of lagoon fauna particularly imperforate porcellaneous-wall benthic foraminifera with oligotypic fauna, the plentitude of peloid grains and complete fossil remains, all point to a low-energy restricted lagoon environment (Shinn 1968; Wilson 1975; Geel 2000; Tucker and Wright 2001; Alshahran and kendall 2003; Bachmann and Hirsch 2006; Brandano et al. 2010; Flügel 2010; Arefifard and Isaacson 2011; Lasemi et al. 2012). Wackestone to packstone facies with bioturbated and micritized features of this facies belt, attest to slow sedimentation in the low energy shallow subtidal and calm sedimentary environment (especially lagoon) (Bathurst 1966; Longman 1980; Bottjer and Droser 1994; Patterson and Walter 1994; Bromley 1996; Ale Ali et al. 2013; Hajian Barzi et al. 2015).

The presence of green algae suggests good aeration and light penetration (Zhicheng et al. 1997). Also, the dominant components of gastropods and benthic foraminifera, such as miliolids, and the low variation of the fauna of this facies is indicative of the internal parts of the lagoon environment and the euphotic zone. Because of the regular changes in salinity, the diversity of stenohaline organisms has reduced and favorable conditions have been created for the growth of euryhaline organisms such as gastropods, ostracods, and algae (Vachard and Flores 2002). Also in stressful environments (such as environments with very high salinity), gastropods can be the main constituent of sediments (Scholle and Scholle 2006). The micrite mud is abundant in this environment, and one of the sources that form these micrites are algae (Vachard et al. 1991). The microfacies in which their primary allochems are imperforate foraminifera, are related to the central parts of the lagoon (Mamet 1991).

In the bioclastic packstone/grainstone facies, there are both perforate and imperforate foraminifera. The symbiosis of the perforate and imperforate benthic foraminifera in bioclastic packstone/grainstone, suggests that the sedimentary environment has been an open lagoon (upper parts of lagoon) with a circulation of normal seawater and waters of enough oxygen (Pomar 2001; Romero et al. 2002; Renema 2006).

4.1.1.4. Carbonate bar facies belt (Shoal) (D)

Description.

This facies is dominated by mid to thick-bedded cream to light gray fossil bearing limestone (Fig 8). There are three facies that represent shoal sub-environment: ooid grainstone (FD7) (Fig 9 a), peloid-bioclast grainstone (FD8) (Fig 9 b) and algal grainstone (Fig 9 c). Ooid grainstone (FD9*)* consists of medium-thick-bedded dark gray limestones with cross bedding stratification. This facies has small thickness in the studied section and is mainly formed by medium-sized (0.5-1 mm) and well-sorted ooids and surrounded by sparry calcite cement. Both concentric and deformed types are seen but the latter is dominant. Most of the ooids are of the superficial type and deformed as a result of diagenetic processes such as physical compaction. The nuclei of some of the ooids has been lost as a result of the micritization process and it is difficult to recognized their type. The average particle size of ooids is 0.5-1 mm. In some cases ooids are affected by the ferrugination diagenetic process.

Peloid bioclast grainstone is mainly formed by well-sorted medium to coarse-sized skeletal grains. Major proportion of grains are crushed and micritized. The matrix of this facies is covered by light-colored sparry calcite.

Fig 8. Field view of the lagoon facies, gastropod-bearing carbonate rocks

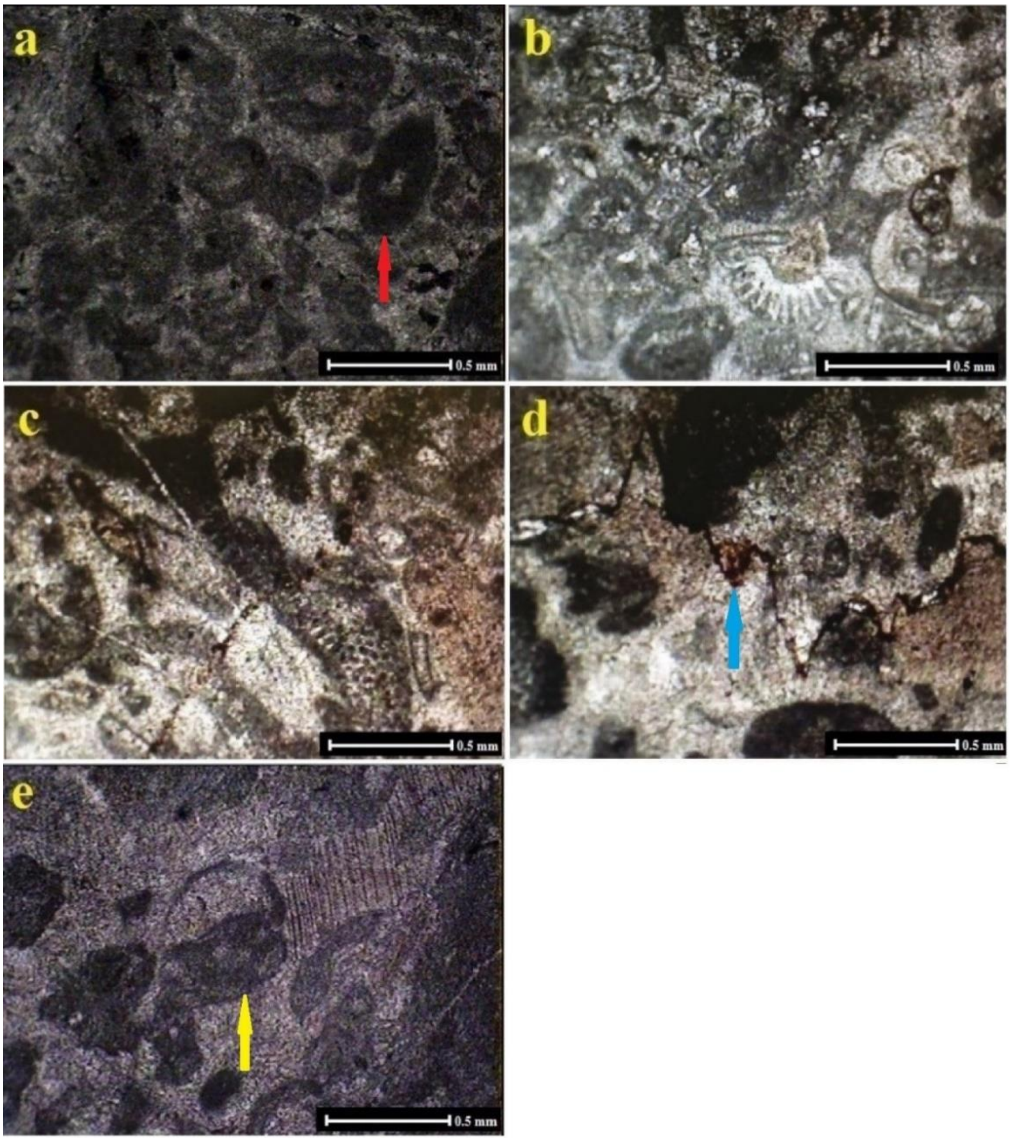

Fig 9. Microphotographs of the main types of carbonate microfacies of the Ruteh Formation (Carbonate bar facies). a) Ooid grainstone (FD7) most of the ooids have an elongated, concave shape as a result of diagenetic processes (red arrow). b) Peloid bioclast grainstone(FD8) (most of the bioclasts are crushed due to high energy of the environment) c) Algal grainstone (FD9). d) Stylolite in grainstone facies (blue arrow). e) Geopetal texture (yellow arrow).

The skeletal allochems are bryozoans, bivalves, brachiopod remains, Fusulinids, echinoderm and ostracods and foraminifera to a lesser proportion. Besides, micritic grains and sorted and rounded peloid grains are minor grains (5%) (Fig 9 b). This facies is seen as medium- bedded dark gray limestone in the field.

Algal grainstone includes thin- medium-bedded cream to red limestone and entails coralline red algae as a dominant constituent (30-35%). The size of algae is ~1 to 2 mm. Echinoderms and peloids also exist in lesser proportion. Also, Vermiporella algae, foraminifera and brachiopods exist in some sections of this facies (Fig 9 C). Also geopetal texture and stylolites are seen in abundance especially in bioclast grainstone facies.

Interpretation

The ooid grainstone This microfacies originate predominantly in disturbed marine environments (Flügel 2010). In general, the grain-supported nature and lack of micrite represents a high energy environment, this microfacies is comparable to Flügel’s (2010) number 29 (RMF 29) standard ramp microfacies which has been deposited in seaward shoals. A similar ooid grainstone shoal facies was reported from high energy shoal in the Ruteh Formation and its equivalent carbonate deposits in Iran (Rezavandi et al. 2016 Baharluei-Yancheshmeh et al. 2018; Zohdi 2018)

Peloid bioclast grainstone. The Fusulinid foraminifera in these facies are indicative of the flow of seawater of normal salinity (Bastami et al, 2016). The presence of peloids, the grain supported nature, lack of mud, the presence of algae in medium to large grain size, good sorting of these allochems and types of fauna all refer to a high-energy turbulent shoal environment (Wilson 1975; Tucker and Wright 1990; James and Jones 2015). This microfacies is equivalent to Flügel's (2010) number 26 (RMF 26) standard ramp microfacies and it has been deposited in the middle and high-energy parts of the shoal. A similar facies was reported from shoal environment in the Ruteh Formation and its equivalent carbonate deposits in Iran (Hasani 2010; Bagheri and Shabanian 2014; Aghajani and Ale Ali 2019)

In the algal grainstone facies, the lack of micrite indicates that the energy has been high enough to wash the micrite out and to move it away from the environment. The algae live in shallow environments above the maximum depth of light penetration (Flügel 2010; Wilson 1975). From a totally sparite context and abundant algae in this facies, it can be inferred that this facies has been deposited in a shallow and high energy environment. This microfacies is equivalent to Flügel (2010) number 27 (RMF 27) standard ramp microfacies and has been deposited in shoal and bank environment.

4.1.1.5. Open marine facies belt (E)

Description

There are three facies that define open marine environment: Large foraminifera packstone/wackestone (FE10) (Fig 10 a), bioclastic packstone(FE11) (Fig 10 b) and bioclastic wackestone (FE12) (Fig 10 c). Large foraminifera packstone/wackestone is seen, in some cases, as dark gray and as mid-bedded cream limestone. Around 80% of the allochems are large and well-preserved foraminifers that are included in a totally micrite background. The size of foraminifers is usually ~ 1 to 2 mm and in some cases it reaches up to 2 mm. All foraminifers of this facies are observed completely transparent in thin sections (Fig 10 a). Other components which can be pointed out include bivalves and ostracods that are found in very low proportions.

Bioclastic packstone is seen as mid- thick-bedded dark gray limestone. The main constituents of this facies include different types of bioclasts such as foraminifera crusts and bivalve shells (35-40%) that are in a mud matrix. Bioclastic wackestone is seen as medium-bedded cream limestone in the field. Echinoderms and bivalve shells are observed to a lesser extent (5-10%). The amount of allochems in this facies is >30%. This facies is distinguished from the bioclastic packstone by the foraminifera crusts sizes and matrix amounts. The foraminifera crusts of this facies are far smaller than those of previous facies, so that their maximum size is 0.5 mm (Fig 10 b).

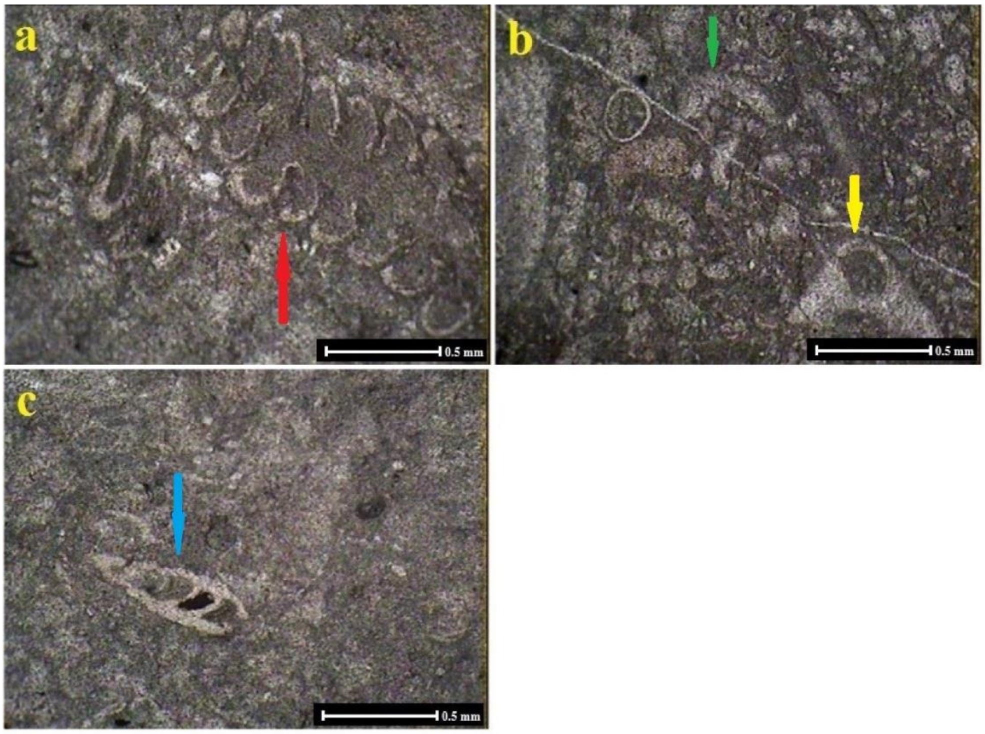

Fig 10. Microphotographs of the main carbonate microfacies types of the Ruteh Formation (open marine facies). a) Large foraminifera packstone / wackestone (FE10) (red arrow: large scale foraminifer). b) Bioclastic packstone (FE11) (green arrow: bivalve shell) (yellow arrow: crushed foraminifera). c) Bioclastic wackestone (FE12) (blue arrow: benthic foraminifera).

Fig 11. Field features of the middle ramp facies a and b) Echinoderm-bearing limestone c) Coralinaceous limestone sample d) Discontinuous coral boundstone

Interpretation

In the first facies, bioclasts have well-protected, uncrushed and well preserved. The presence of micrite in this facies also indicates that these allochems have been deposited in a relatively calm environment and on spot. The abundant matrix indicates a lack of sufficient energy to transfer calcareous mud, while a small amount of cement in a part of them, represents an open marine environment of higher energy (Folk 1962). This microfacies is equivalent to Flügel's (2010) number 13 (RMF 13) standard ramp microfacies and has been deposited in the upper parts of open marine environment.

Preservation criteria including shape, roundness, breackage, size and sorting of fossils are good indicators of transport and allochthonous deposition (Flügel 2010). With regard to the bioclastic packstone facies, increase in crushed allochems and the decrease in micrite indicate the sedimentation of this facies in open marine environment. this microfacies is comparable to Flügel's (2010) number 14 (RMF 14) standard ramp microfacies which has been deposited in seaward open marine environment.

In the bioclastic wackestone facies, slump in the allochems' concentration, increase in micrite and decrease in the size of bioclasts indicate sedimentation in an environment of lower energy (deeper) than facies 1 and 2 in deeper parts of open marine zones.

4.1.2. The middle ramp facies association (F)

Description

Echinoderm bearing wackestone (FF13) and coral boundstone (FF14) are defining the microfacies of this environment. Bioclastic wackestone occurs as thin- to medium-bedded dark gray limestone in the field. The main abundant bioclasts are echinoderm fragments that represent ~ 30-40 % of the allochems. Bivalves, brachiopods, foraminifers and, to a lesser extent (<10%), ostracods. Micritization and bioturbation processes are abundant. Bioclasts usually can be easily observed in macroscopic samples (Fig 11 a-b).

Coral boundstone: this microfacies is characterized by colonial corals. Macroscopically it is a distinct autochthonous limestone containing autochthonous colonial corals (Fig 11. c-d). Figure 12 shows the microphotographs of the middle ramp facies.

Interpretation

The Echinoderm bearing wackestone is equivalent to Flügel's (2010) number 7 standard ramp microfacies and has been deposited in the shallow parts of the middle ramp. Bastami et al. (2016) has reported a similar facies to the Ruteh Formation in Sangsar and Makaroud sections. Nouri et al. (2019) interpreted that this facies is deposited in proximal mid-ramps. The occurrence of autochthonous organisms such as colonial corals suggests a reef environment (Wilson 1975; Flügel 2010). In coral boundstone, facies is composed totally of corals that are in a fully sparite context.

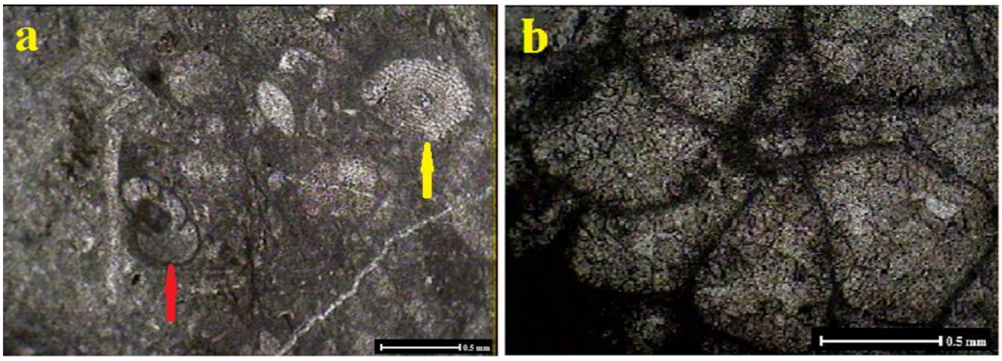

Fig 12. Microphotographs of the main carbonate microfacies types of the Ruteh Formation (Middle ramp facies). a) Echinoderm bearing wackestone (FF13) (yellow arrow: echinoderm) (red arrow: benthic foraminifer) b) Boundstone (FF14)

In the field, coral boundstones are not a continuous facies but individual (patch reef). This microfacies is equivalent to Flügel (2010) number 12 (RMF 12) standard ramp microfacies and it has been deposited as patch reefs in a middle ramp environment. Figure 11 shows the microscopic features of middle ramp microfacies.

4.1.3. The outer ramp facies association (G)

Lime mudstone (FG15) This facies contains thin-bedded dark gray limestones in the field and includes lime mudstone without fossils in thin sections. In the rock there are several parallel planes of pressure solution and micro-stylolites. In the deep zones of the carbonate platforms where calcareous muds is deposited, the resulted pressure from the water column bar causes the compression and chemical dissolution of calcium carbonate (Fig 13). Absence of wave and flow structure, high amount of lime mud, mud-dominant texture, lack of shallow water neritic (benthic) fauna suggest low energy, calm and deep conditions, below fair-weather wave base for this facies association (Wilson 1975; Buxton and Pedley 1989; Reading 1996; Flügel 2010; Ale Ali 2013). Similar microfacies was reported from the outer ramp to basinal low-energy deep sub-tidal environment by Bastami *et al.* (2016).

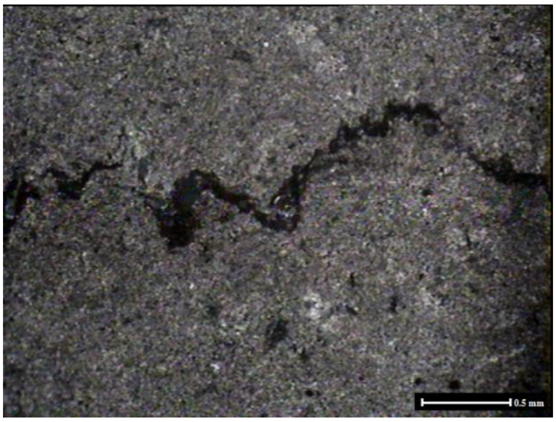

Fig 13. Microphotograph of the main carbonate microfacies type of the Ruteh Formation (outer ramp facies). Lime mudstone with parallel pressure solution planes (FG15)

4.2. Depositional model of the Ruteh Formation

In the Late Permian, a large region of the warm-water carbonate sedimentation corresponded to the Cimmerian and Cathaysian micro-continents, large areas of which were occupied by shelf seas. Carbonate sedimentary basins were located along the entire southern and northern peripheries of the Cimmerian microcontinents stretching from Western Iran to Sibumasu (Given and Wilkinson 1987; Ross and Ross 1987). The territory of the Western and Central Iran was occupied by a large carbonate sedimentary basin, where intertidal and littoral zones of carbonate accumulation surrounded the relatively deep-water central areas. Thus, carbonate sedimentation of the Late Permian prevailed in the seas surrounding the system of Cathaysian and Cimmerian microcontinents. Iran microcontinent, particularly widespreaded in the climatic belts, was a warm-water sedimentation setting. All of those sedimentary basins were located ~ 0˚-30˚ S where the largest amounts of carbonates were produced.

According to microfacies type, facies interpretation and vertical facies changes, carbonate depositional environment of the Ruteh Formation is characterized as a homoclinal ramp of low angle (Fig 14), which is confirmed by gradual shallowing trend of facies. Due to the gentle slope of the carbonate ramps, shallow-water facies gradually change into deeper facies. Also in the Ruteh Formation, vertical distribution of facies (as shown in Fig 14) shows that tidal flat facies gradually change into lagoon, bar, open marine, middle and outer ramp facies respectively, whereas in rimmed carbonate platforms, because of slope breakings, the facies groups boundaries are usually sharp. In the studied section, bioturbated wackestone to packstone facies, abundant benthic foraminifera and peloid, strong bioturbation and micritization are interpreted as to have deposited in the restricted inner ramp. Middle ramp deposits are interpreted, mainly, based on grain-supported texture (allochemical texture), echinoderm-bearing facies and rounded and large grains.

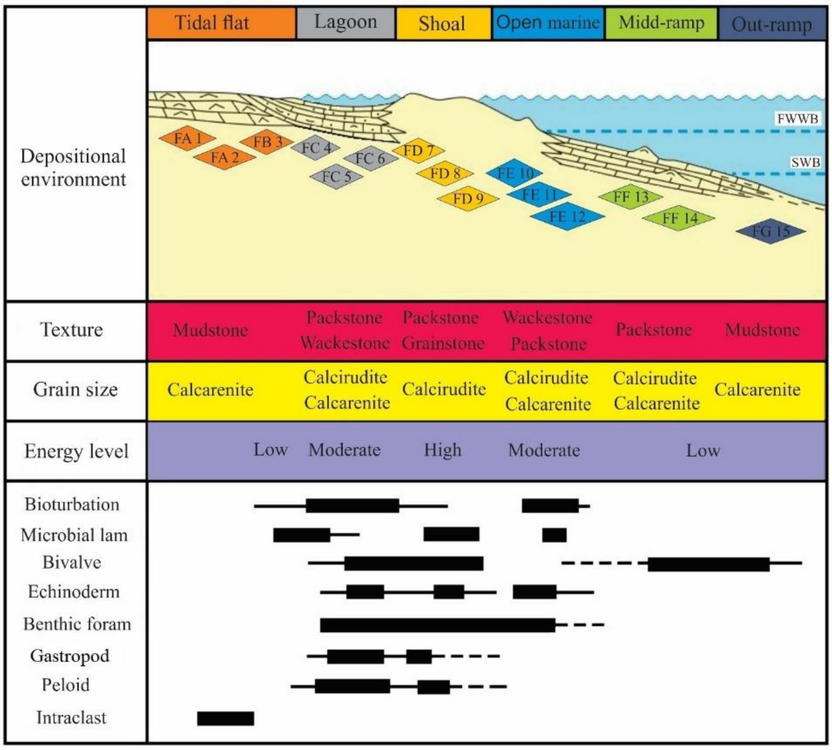

Fig 14. Schematic diagram showing a ramp platform depositional setting reconstructed for the Ruteh carbonate succession in the study area. 15 microfacies identified in this environment are juxtaposed along the inner ramp to outer ramp as shown. Distribution of facies, carbonate particles and sedimentary characteristics are shown on the model

The outer ramp and basin settings are characterized by mud-dominated sediments. With regard to the identified microfacies, the absence of oncoids, pisoids and aggregate grains (which are specific to carbonate platforms and are rarely found in carbonate ramps) (Flügel 2010), also, lack of re-deposited carbonates of gravity flow processes (calciturbidite, talus and slumping deposits) (Tucker and Wright 1990; Burchette and Wright 1992; Pomar 2001; Flügel 2010) in sediments of the Ruteh Formation indicates that sedimentation of these deposits occurs in a gentle slope environment with approximately uniform gradient in the basin floor. Due to the low expansion of the corals in carbonate ramps compared to that of the rimmed platforms, lack of widespread barrier reefs in the Ruteh Formation is another reason for this fact that the sedimentary environment of this formation is a homoclinal ramp carbonate platform (Bastami et al. 2016). On the other hand, by reviewing distributed facies in sub-environments and their constituents, it can be deducted that Ruteh Formation depositional environment is a bioclastic carbonate ramp similar to that introduced by Kolodka et al. (2012) for Dalan Formation in Zagros basin (Fars Province).

As in the Ruteh Formation, lagoon sub-environment mainly includes wackestone and packstone facies that contain dark crust benthic foraminifers, algae and heterozoans such as bryozoan and echinoderms. Additionally, in shoal sub-environment, existence of varied algae, echinoderms and bryozoans are seen in these facies. In shallow areas of open marine sub-environment the facies consist of packstone and wackestone containing algae, ostracod, echinoderm and large foraminifers while heterozoans such as echinoderms are dominant with increasing depth and micritic texture.

In a bioclastic ramp, in order to separate seaward from back-bar facies, bioclastic indicators are used (Koehrer et al. 2010; Forke et al. 2013; Walze et al. 2013; Yazdi and Sharifi Teshnizi 2021). The abundance of algae in the absence of stenohaline metazoans and high salinity tolerance foraminifers represent a back-bar environment. In return the seaward facies are determined by a wider variety of metazoans. Records of homoclinal carbonate ramp of the Ruteh Formation in the north and northwest of Iran have been documented by other authors (Mokhtarpoor 1997; Lankarani and Amini 2007; Babaee et al. 2013; Babakhuie et al. 2013; Hassani et al. 2013; Zohdi 2018; Jehangir Khan et al. 2021). In general, similar to many other parts of the Middle East, the Late Paleozoic sedimentation in Iran has occurred in a shallow marine environment (Berberian and King 1981). Carbonate ramps usually develop in shallow substrates of gentle slopes like in foreland basins and continental passive margins (Burchette and wright 1992). With the evolution of the Paleotethys Ocean floor in Middle

Devonian, the northern margin of the Cimmerian continent became a passive margin and this situation continued towards the Upper Triassic. Therefore, at the time of Ruteh Formation sedimentation, the conditions were suitable for development of ramp type platforms.

Frequency analysis of facies illustrates that the lagoon environment has the most frequent abundance of facies (33%), while the outer ramp environment has the least abundance (2%) (Fig 15 a). This shows that lagoon conditions were mainly predominated in Late Permian age in the study area. The most frequency of facies is bioclastic packstone/grainstone (FB) of 16% frequency, whereas the ooid grainstone (Fc) shows the least abundance of ~ 1% frequency (Fig 15 b). Figure 14 shows the proposed sedimentary environment for the Ruteh formation in the northern section of Mahabad.

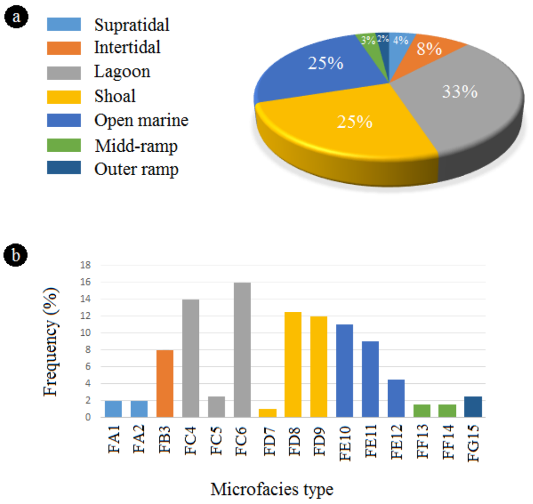

Fig 15. Frequency diagrams showing frequency of facies belts and types of the Ruteh Formation. a) Pie diagram showing facies belts frequency. b) Column diagram illustrating facies type frequency

4.3. Sequence stratigraphy

The depositional facies characteristics of the Ruteh Formation, indicate a distinct number of depositional sequences, system tracts and sequence boundaries. According to the vertical distribution of the facies association, the carbonate successions of the Ruteh Formation can be grouped into four 3rd-order depositional sequences (Fig 16). These depositional sequences were deposited during the Permian and are composed of a depositional transgressive system tract (TST) of deepening trend and highstand system tract (HST) of shallowing trend (Fig 16). In this study, according to detailed petrographic studies, distribution of facies (the vertical arrangement of facies) and stacked to form facies groups, depositional sequences were interpreted. The concepts that were advanced by many researches were applied for sequence stratigraphy interpretations (e.g. Posamentier et al. 1988; Vail et al. 1991; Van Wagoner et al. 1990; Hunt and Tucker 1992; Tucker and Wright 1992; Emery and Myers 1996; Catuneanu 2006; Catuneanu et al. 2011).

The sequence stratigraphy of Ruteh Formation (and its equivalent) has been documented in the previous studies (Arefifard and Isaacson 2011; Rezavand et al. 2016; Ale Ali 2017; Mazaheri and Ghaseminejad 2017; Baharlouei et al. 2018; Nikbakht et al. 2019).

4.3.1. Depositional sequence 1

The depositional sequence 1 formed the lower part of the Ruteh Formation in the studied area. This sequence with a thickness of ~ 64 meters directly overlays dolomite and limestones of the uppermost part of the Mila Formation. This sequence is located between two sequence boundaries with a porous mudstone facies which are the defining facies of these supratidal zones.

The thickness of transgressive sediments of this sequence is ~26 m, beginning with the intraclast and pelloid wackestone facies. Due to the progression of seawater in a deepening process, the bioclastic packstone, bioclastic grainstone and intraclastic grainstone are the defining facies of shoal zone. Then the bioclastic wackestone and mudstone facies are deposited over these facies. Due to the representation of the deepest environments in this sequence, the level of expansion of mudstone facies is considered as the maximum flooding surface. At the top of this level, there is a group of regressive sediments which, by the marine regression in a depth reduction process, cause sedimentation in the shoal (intraclastic and bioclastic grainstones), lagoon and in the facies of the bar and intertidal zones. The thickness of the regressive facies is 38 m. The upper boundary of this sequence leads to a porous mudstone facies, which is identified as the Sequence boundary. This microfacies represents the maximum regression of sea water (sequence boundary) in the first highstand system tract of shallowing trend.

4.3.2. Depositional sequence 2

The lower boundary of depositional sequence 2 is determined by a porous mudstone facies and its upper boundary will be delineated by a dolomudstone facies. The lower facies of this sequence are predominantly composed of shoal and open marine facies association which indicates a retrogradational stacking pattern of an upwardly-deepening trend. Its thickness is ~ 36 m. The facies of the transgressive sediments is 20 m thick and from the bottom to the top includes dolomudstone facies, foraminifera and crinoid grainstone, gastropod wackestone and algae packstone.

Above these facies the stylolite mudstone facies were formed in deep sea, the surface is considered as the maximum flooding surface. On this surface, sediments of the regressive facies have been deposited with a thickness of 16 m. The sediments exhibit a shallowing process, that from bottom to top, includes open marine, bar, reef, and lagoon facies. These facies are equivalent to regressive series. Dolomudstone facies are located on them as the sequence boundary.

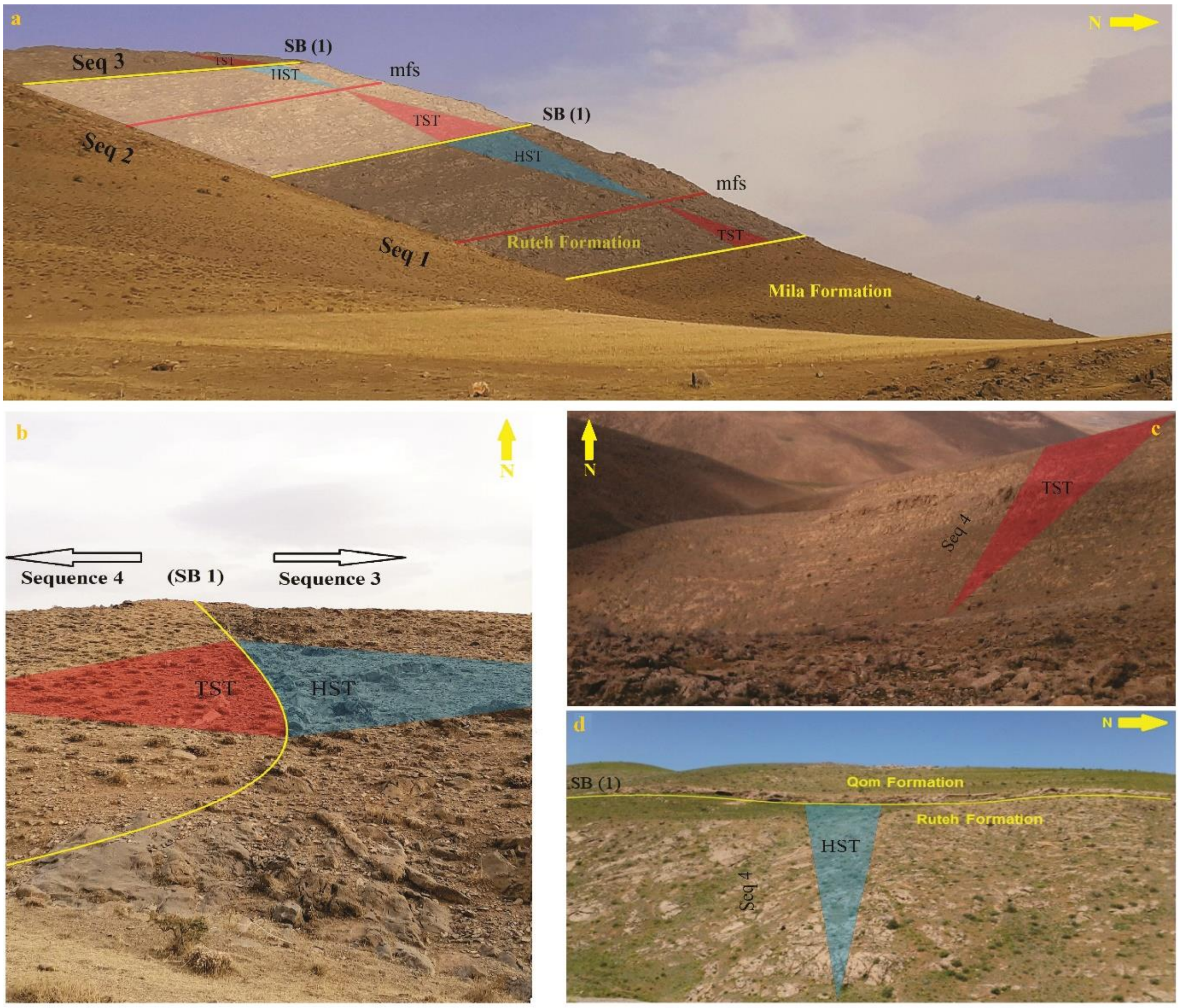

Fig 16. Depositional sequences, system tracts and sequence boundaries of the Ruteh Formation in Kuseh-Kahrizeh section

4.3.3. Depositional sequence 3

The lower and upper boundaries of this sequence are determined by the dolomudstone of supratidal environment. The thickness of this sequence is ~ 60 m. The transgressive facies of this sequence, with a thickness of 24 m, begin with the peloidal-grainstone facies of the shoal zones. The former facies are followed by the coral boundstone facies, which are the defining facies of the shallow environments.

Open marine facies that include the foraminifera and gastropod wackestone/packstone and mudstone are located over them, respectively. The mudstone facies are considered as the maximum level of flooding. At the top of the maximum level of flooding, there are a number of regressive facies that include the mudstone and gastropod and foraminifera wackestone facies, which are the defining facies of lagoon environment. The thickness of this set of sediments is 36 m. The upper boundary of this sequence is determined by the dolomudstone facies, which is known as the first-order sequence boundary.

4.3.4. Depositional sequence 4

This sequence is about 20 m thick, and it is located between two sequence boundaries. This sequence begins with open marine facies, which consists of the bioclastic wackestone and packstone; most of its allochems are composed of echinoid. The pure mudstone facies is recognized as maximum flooding surface due to the fact it is the deepest facies of this sequence. The facies of bioclastic wackestone with foraminifera and peloid are located above that shape a set of regressional facies in this sequence. The end of this sequence conforms to porous mudstone facies that is known as the boundary sequence. Figure 17 shows stratigraphic column, the system tracts, sequences, and relative changes in the sea level in the basin of the Ruteh Formation in the northern section of Mahabad. In most studies that have been carried out on the Upper Permian carbonate deposits of Iran and the adjacent areas, homoclinal carbonate ramps are inferred as their depositional setting (Table. 1)

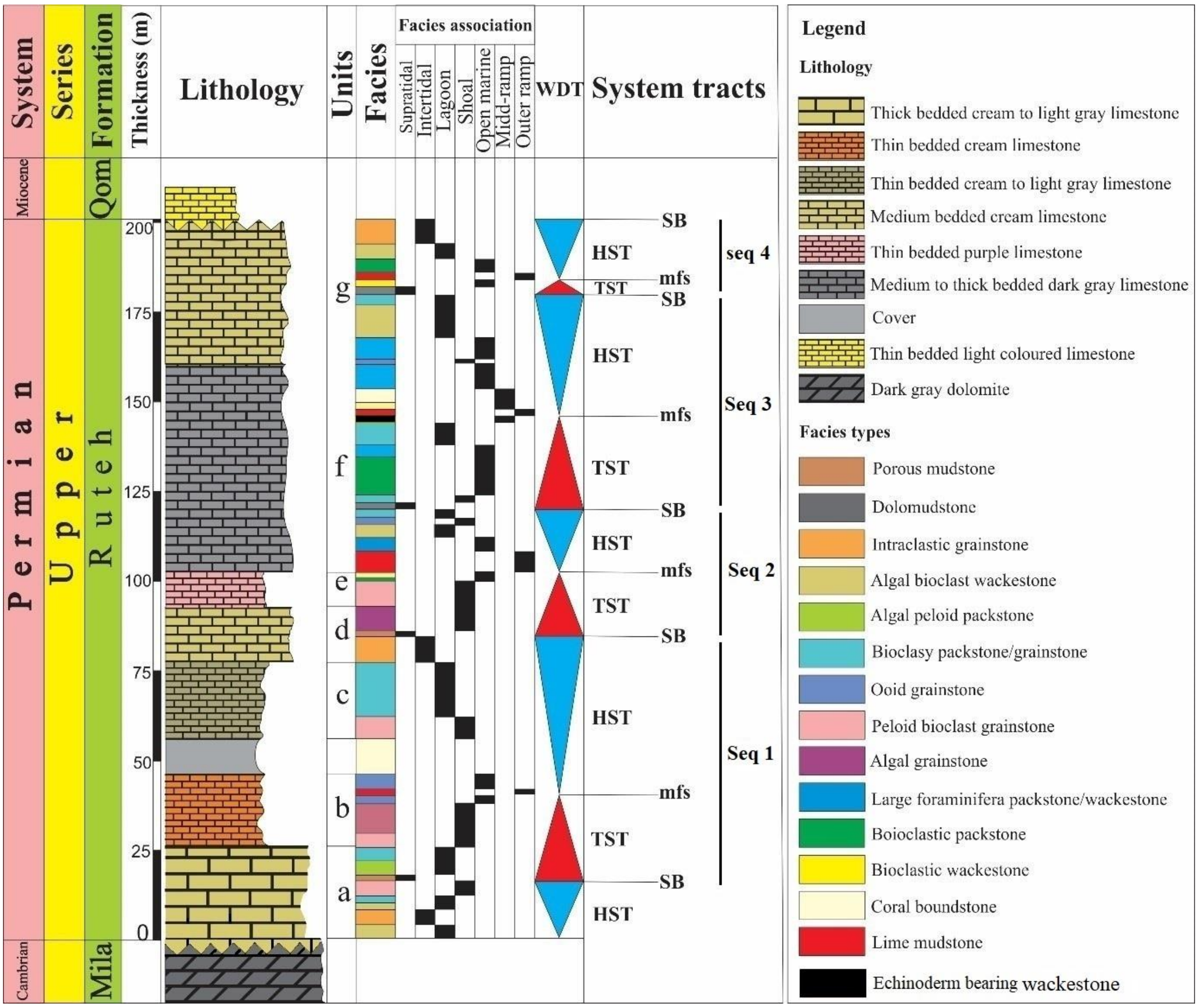

Fig 17. Sedimentological log of the Ruteh Formation in the Kuseh-Kahrizeh section in north of Mahabad. Lithological characteristics, facies associations and third-order sequences are shown

Table 1. Previous studies focused on the stratigraphy and sedimentary environments of the Ruteh and its coeval formations in Iran and adjacent areas

Formation	Researches	Studied zone	Studied section	Sedimentary environment	Sequence stratigraphy
Ruteh Formation	Mokhtarpoor (1997)	Eastern, central and western Alborz	Jolfa, Abiek, Bibishahrbanoo, Amol, Meighan, Ghaznavi	Homoclinal ramp	6 sequences
Ruteh Formation	Lankarani (2007)	Western and central Alborz	Gadvak, Labnesar	Carbonate-Terrigenious shelf	3 sequences
Ruteh Formation	Hasani et al (2010)	Eastern Alborz	Khoshyeilagh	Homoclinal ramp	5 sequences
Ruteh and Nesen Formations	Bagheri and Shabanian (2014)	Alborz-Azarbaijan	Bonab	Homoclinal ramp	5 sequences
Ruteh Formation	Mahari et al (2007)	Alborz-Azarbaijan	South of Jolfa	Homoclinal ramp	5 sequences
Ruteh Formation	Babakhuie et al (2013)	Central Alborz	Sibestan	Homoclinal ramp	2 sequences
Lower Dalan Formation	Lotfpoor (2005)	Zagros	Surmeh mountain, Dena mountain, Faraghan mountain, South pars and Salman fields	Homoclinal ramp	3 sequences

Table 1. Continued

Formation	Researches	Studied zone	Studied section	Sedimentary environment	Sequence stratigraphy
Upper Dalan Formation	Baharlooyi bancheshmeh et al (2018)	Zagros	Lavan gas field	Homoclinal ramp	2 sequences
Jamal Formation	Arefifard (2006)	West of Central Iran	Jamal, Bagh vanak and Shesh Angosht	Homoclinal ramp	3 sequences in Jamal section, 2 sequences in Bagh vanak section and 1 sequence in sesh angosht section
Jamal Formation	Sabagh bajestani et al (2009)	Central Iran	Southwest of Khorasan-e-razavi	Homoclinal ramp	3 sequences
Saiq Formation	Koehrer et al (2010)	Arabia platform (northern Oman)	Saiq plateau	Homoclinal ramp	2 sequences
Saiq Formation	Forke et al (2013)	Arabia platform (northern Oman)	Wadi Sahtan, Wadi Bani AWF, Wadi Bani HajirWadi MistalWadi Hedek, Saiq plateau	Homoclinal ramp	2 sequences

5. Conclusions

The Ruteh Formation in the Kuseh-Kahrizeh area (northwestern Iran) is unconformably underlain by Early Cambrian’s Mila Formation and is unconformably overlain by the Oligo-Miocene Qom Formation**.** This formation is a shallow water carbonate sequence. Based on the sedimentary features, 15 representative microfacies were organized into three facies associations from distal to proximal part of platform including inner ramp, middle ramp and outer ramp. Facies analysis indicates that the Ruteh Formation was deposited on a shallow carbonate ramp (homoclinal ramp) with a gentle slope. Facies frequency analysis indicates that the lagoon environment has the highest abundance (33%) while the outer ramp environment shows the least abundance of facies (2%). In adition, on the basis of the vertical distribution of facies and sequence stratigraphic analysis, four third-order depositional sequences, 5 sequence boundaries and 4 maximum flooding surfaces are recognized. These depositional sequences are composed of depositional transgressive system tract (TST) of deepening trend and highstand system tract (HST) of shallowing trend. The sequence boundaries of all of them identified as SB (1).

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