Turkish Journal of Earth Sciences

http://journals.tubitak.gov.tr/earth/

Research Article

Turkish J Earth Sci
(2020) 29: 853-877
© TÜBİTAK
doi:10.3906/yer-1811-12

Depositional environment and sequence stratigraphy of the Khoshyeilagh Formation in Bojnourd and Jajarm (NE Iran)

Fatemeh JAFARBEIGLOO[1], **Mahmoud Reza MAJIDIFARD**[2,*], **Bahaeddin HAMDI**[2], **Afshin ASGHARI**[3], **Mehran ARIAN**[1]

[1]Department of Earth Sciences, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Research Institute for Earth Science, Geological Survey of Iran, Tehran, Iran
[3]National Iranian Oil Company, Tehran, Iran

Received: 18.11.2018 • **Accepted/Published Online:** 10.07.2020 • **Final Version:** 04.09.2020

Abstract: In this study, depositional environment and sequence stratigraphy of the Khoshyeilagh Formation has been investigated in three stratigraphic sections including Pelmis, Robat-e Qarehbil, and Kuhe Ozon in the northeast of Iran. The thickness of the Khoshyeilagh Formation in these sections are 182, 260, and 463 m, respectively. Based on the facies analysis of the Khoshyeilagh Formation, 3 clastic facies, 11 carbonate facies, and 1 hybrid facies were identified. The vertical and lateral changes of the Khoshyeilagh Formation show a shoreface marine depositional environment that begins with alluvial sediments and continues by marine sedimentation. According to these changes, a homoclinal ramp model is proposed for the Khoshyeilagh Formation. This ramp model shows a relatively gentle slope that continues to the basin and is similar to the present-day carbonate ramps, like the southern coast of the Persian Gulf and Shark Bay in the Australian carbonate ramp. This depositional model consists of five subenvironmental units including shoreface, tidal flat, lagoon, shoal, and open marine environments. The lithofacies analyses and their interpretations represent a decrease of depth at the end of Frasnian which is followed by an intensive sea level drop like the other global examples at this time. After a period of time and during Famennian the sea level rised and the open marine facies (bioclast spicule wackestone-packstone) were deposited. With a regard to the identified biozone, Late Devonian age (Late Frasnain-Early Famennian) is obvious for the Khoshyeilagh Formation. The sequence stratigraphic analysis and depositional model evaluations led to the identification of two third-order complete sequences, which are limited by discontinuities as a result of sea level changes at the base and top of the sequence, and an incomplete sedimentary sequence at the end of the studied section. The transgressive systems tract (TST) in this sequence is mainly composed of the shoal and open marine facies, the maximum flooding surface (MFS) is identified by the bioclast wackestone facies, and the highstand systems tract (HST) mainly consists of the lagoon, tidal flat, and shoreface facies.

Key words: Sequence stratigraphy, depositional environment, Khoshyeilagh Formation, Late Devonian, NE Iran

1. Introduction

During the Silurian and Devonian periods, parts of Iran (central Iran, Alborz, and Sanandaj-Sirjan) along with the Afghan and Turkish plates were attached to the Arabian and African plates and formed the northwestern margin of the Gondwana supercontinent and the southern margin of Paleo-Tethys (Berberian and King, 1981; Al-Husseini, 1991; Ruban et al., 2007; Al-Juboury and Al- Hadidy, 2009). The current structure and geological status of Iranian platuea has been shown in Figures 1a and 1b.

The Devonian sedimentary horizons of Alborz-Azarbaijan zone show a variety of rock facies. These facies always display unique shapes, which reveal an independent basin with different sedimentary conditions. Also, the Devonian lithologic units are Juban Formation in Saudi Arabia, Kuwait (partly), and parts of Ora Formation in Iraq, Bahram Formation in central Iran, and parts of the Muli and Zakeen Formations in NW and South of Iran (Zagros), respectively (Al-Husseini, 1991; Ghavidel-Syooki, 1998; Al-Sharhan and Narin, 1997; Al-Hajri and Filatoff, 1999; Brew and Barazangi, 2001; Nairn and Alsharhan, 2003; Wendt et al., 2002; Laboun, 2010; Wehrmann et al., 2010) (Figure 2).

But in the eastern part of Alborz zone, the Padeha and Khoshyeilagh formations are the representative of the Devonian rocks (Aqanbati, 2007). The Khoshyeilagh Formation located between Padeha and Mobarak formations can be considered as a typical example of Middle-Upper Devonian deposits in the eastern Alborz. These formations together illustrate one of the thickest

* Correspondence: m_majidifard@yahoo.com

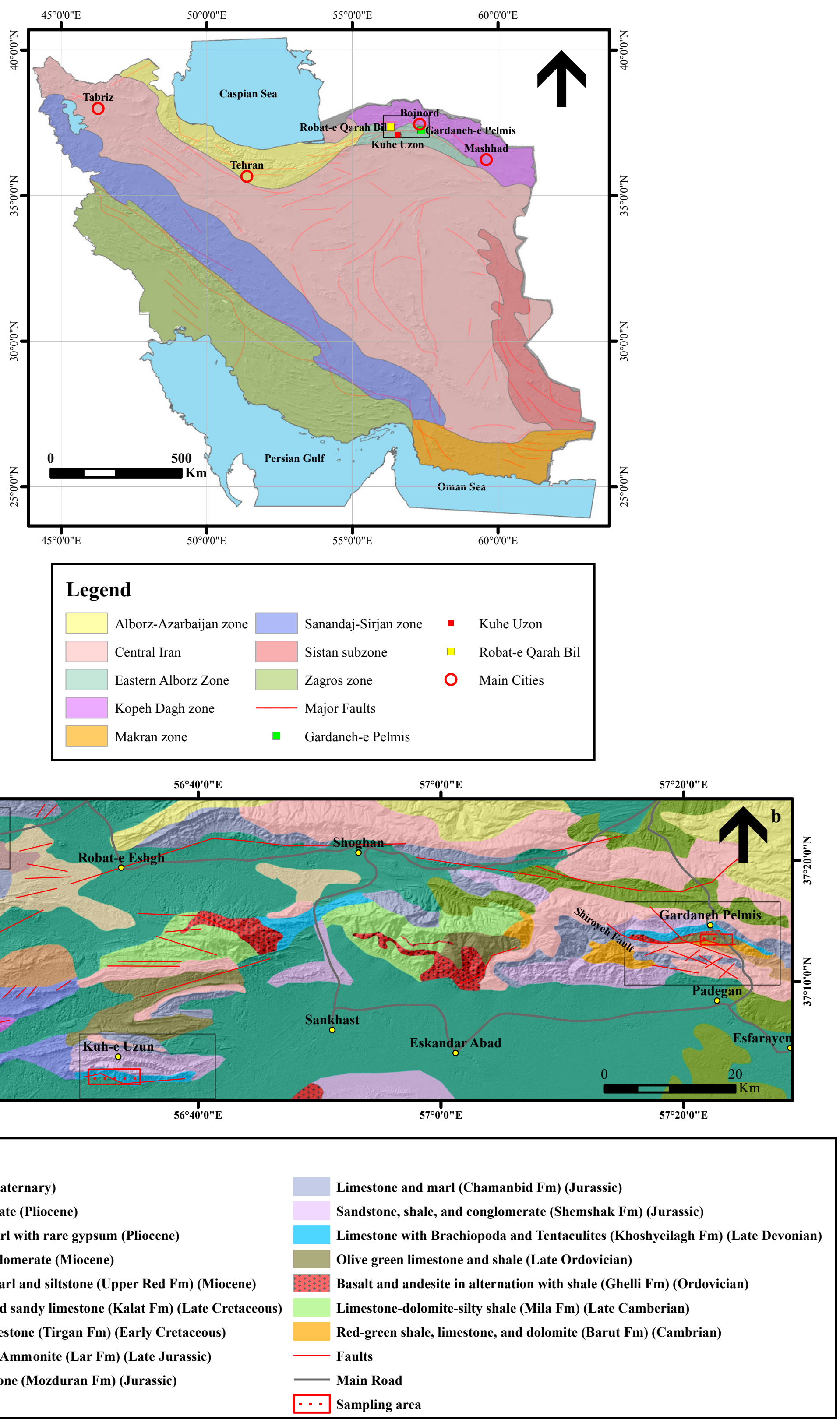


Figure 1. a) The index map of Iran showing main structural units (Stocklin, 1968); b) The geological maps of the studied areas representing different lithological units and geological features of the Robat-e Qarabil section (Salamati et al., 2001); Pelmis section (Mazaheri, 1999); Kuhe Ozon section (Soheily and Sahandi, 1999).

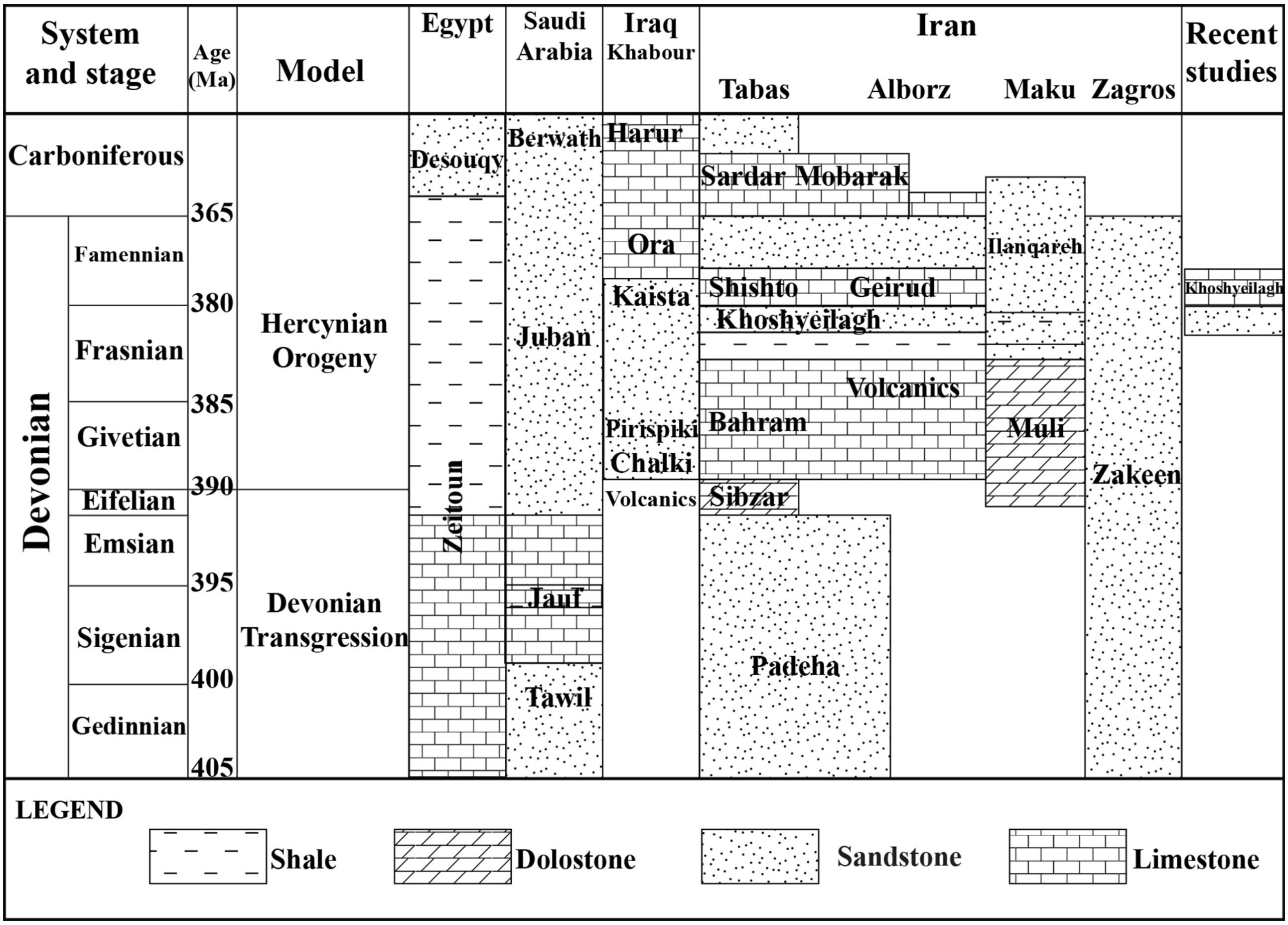


Figure 2. The stratigraphic correlation representing Devonian-Lower Carboniferous deposits in Iran, Iraq, Saudi Arabia, and Egypt (modified after Al-Husseini, 1991). Data obtained from: Al-Juboury and Al-Hadidy, 2008 (Iraq); Al-Hajri et al., 1999 (Saudi Arabia); Nairn and Alsharhan, 1997 (Oman); Özkan et al., 2019 (Turkey); and Hashmie et al., 2016 (south of Iran).

formations in this sedimentary basin. The type section of the Khoshyeilagh Formation has been studied and introduced by Bozorgnia (1973) in the Khoshyeilagh area. From the contact boundary point of view, the lower boundary between Khoshyeilagh and Padeha formations is unclear, while the upper boundary between Khoshyeilagh and Mobarak Formations displays a gradual contact (Aqanbati, 2007).

The most comprehensive studies on Devonian sequences of Iran were carried out by Wendt et al. (2002).

Limited stratigraphic studies were done in the study area in 1954 and then comprehensive investigations were carried out by Bozorgnia (1973) for this area. Bozorgnia (1973) divided this formation into 6 parts at the type section based on the paleontological evidences. There are different lithologic units from the base of the formation toward the top as follows: First part includes 45 m conglomerate, siltstone, and thin-layer limestone; second part shows 30 m gray siltstone with layered ironiferrous and fossiliferous limestone; third part is composed of 198 m limestone, dolomite, and dolomitic limestone; fourth part includes 501 m bio-terrigenous limestone, shale, and sandstone; fifth part shows 475 m bio-terrigenous limestone, shale, and clayey limestone. Finally, sixth part includes 100 m bio-terrigenous limestone, shale which has formed the upper part of the formation.

Brice et al. (1974) studied the brachiopods of the area and detected the Late Devonian age for this formation. Ghavidel-Syooki and Owens (2007) proposed the Late Devonian age for the Khoshyeilagh Formation after studying the palynomorphs of this formation in the Kuhe Ozon section. They estimated a warm tropical weather and a shallow environment at the time of deposition.

Wendt et al. (2002) determined the boundary of Frasnian-Famennian in the Khoshyeilagh Formation using the rare conodont assemblages and the other fossil species. Ahmadzadeh-Heravi (1975) studied the brachiopods and conodonts of the Khoshyeilagh Formation and recognized Early to Late Devonian age. Hamdi and Janvier (1981) also studied the Khoshyeilagh Formation. They measured the thickness of this formation 1510 m and determined Early to Late Devonian age. Weddige (1984a, 1984b) investigated the conodonts of this formation and his studies proved Late Eifelian to Givetian for the lower part of the formation. Ashouri (2006) introduced 6 new species of conodonts in the type section of the Khoshyeilagh Formation and determined the Eifelian to Tournaisian age.

The main objective of this study is to evaluate the facies and sequence stratigraphy of Late Devonian (Khoshyeilagh Formation) and to identify sedimentary environments in three different regions (Pelmis section, south of Bojnourd and 20 km northwest of Esfarayen, and Robat-e Qarabil section, 53 km southwest of Ashkhaneh and 2.8 km north of Robat-e Qarehbil village and Kuhe Ozon section, 15 km northeast of Jajarm and on the southern edge of the Kuhe Ozon (Figures 1a and 1b).

The previous works on Devonian sequences in the type section of the Khoshyeilagh Formation have been done about the biofacies and depositional environments while the sequence stratigraphy has been neglected (Wendt et al., 2002). Therefore, in this study we would like to consider the depositional environments and sequence stratigraphy of the formation to precisely determine the depositional environments of the studied sections based on the recognized facies. Furthermore, their extensive distributions should be evaluated in order to define the existing sequence stratigraphy and also to compare them with the other Devonian stratigraphic sections of the area.

2. Geological setting

Throughout the Iranian plateau, the Devonian successions have been exposed in limited places. These sequences are complete and widespread in the eastern Alborz, central Alborz, and central Iran structural zones (Wendt et al., 2002).

With a regard to the existing different lithological units, the areas under the study can be divided into two geological-structural zones. The Sefid-Dali fault divides this zone into western and eastern parts. In the structural classification of Iranian plateau, some parts of the study area are classified as the Kopeh-Dagh sedimentary basin (Stocklin, 1968) and the rest area has been considered as a part of Eastern Alborz structural zone (Binaloud Zone) (Nabavi, 1976) (Figure 1a). The presence of Devonian shale and carbonate facies (Khoshyeilagh Formation) in some parts of Kuhe Ozon and Pelmis sections show similarities with the eastern Alborz geological and structural features. The lack of Upper Devonian units (Upper Famennian) in the study area, presence of base sandstones in the Shemshak Formation (accompanied by Lateritic horizon) in the Pelmis section, volcanic eruptions (17m layered volcanic rocks) at the end of the Khoshyeilagh Formation in the Kuhe Ozon section and thin layer Tournaisian sedimentary rocks, all are considered as the results of epeirogenic movements in the Late Devonian and Early Carboniferous time (Afshar-Harb, 1994).

Robat-e Qarehbil section is a small part of the Kopeh-Dagh sedimentary basin (Figure 1a). This section is located in the southern margin of the Kopeh-Dagh structural zone. The Siahkuh and Sefid-Dali faults are the most important faults systems of the area (Figure 1b). According to the field observations, the thrusting Kopeh-Dagh sequences is observable upon eastern Alborz sequences (Stocklin, 1968).

Three stratigraphic sections throughout the Khoshyeilagh Formation in the Bojnurd and Jajarm area were selected for biostratigraphic studies. The Pelmis stratigraphic section with geographical coordinates of 37°14′23.1″N and 57°19′8.2″E is located 28 km from Bojnourd city, and in the vicinity of Shiroyeh village (Figure 1b). The thickness of this formation in the stratigraphic section was measured 182 m. In addition, the upper boundary of the formation with the Padeha Formation was recorded as a gradual contact while its upper boundary with the Shemshak Formation was observed as a discontinuous contact.

The Robat-e Qarehbil stratigraphic section is located 53 km southwest of Ashkhaneh and near the Robat-e Qarehbil village (Figure 1b). The coordinates of this section are 37°22′24″N and 56°19′0.82″E. The thickest part of Khoshyeilagh Formation, which is measured 260 m, is measured in this section. The upper and lower contact boundaries of the Khoshyeilagh Formation in this section are the Mobarak and Padeha Formations, which show distinct-continuous and gradual contacts, respectively.

The Kuhe Ozon stratigraphic section is located 15 km northeast of Jajarm and on the southern edge of the Kuhe Ozon area (Jajarm Bauxite mine) (Figure 1b). The geographical coordinates of this section are 37°02′11.9″N and 56°31′59.3″E. In this section, the thickness of the formation was recorded 463 m and the upper and lower boundaries of Khoshyeilagh Formation with Padeha and Mobarak Formations are continuous.

3. Method of investigation

In order to investigate the depositional environment and sequence stratigraphy of the study area, three stratigraphic sections including Pelmis, Robat-e Qarehbil, and Kuhe Ozon were selected, a detailed fieldwork was done, and required samples were taken precisely. Finally, a total of 366 (Kuh-e-Ozon 170, Pelmis 101, and Robat-e-Qarehbil 95 samples) thin sections were prepared from the selected samples.

The sampling was carried out systematically at certain intervals and in the conjunction of facies and the boundary of formations. In the layers with uniform lithology, the maximum and minimum sampling intervals were considered 3 m and 1 m, respectively.

The position of samples have been marked on the stratigraphic columns (Figures 3–5).

Several parameters related to the sections such as weathering profiles, size, color, lithology, relevant characteristics of the beds in vertical succession, lateral variations were evaluated during field observations.

The prepared thin-sections were studied by polarizing microscope. The carbonate microfacies were categorized based on the Dunham's classification (Dunham, 1962) while for the description of these facies, the classification of Flugel (2010) was used. Clastic facies were described using Folk (1980) method and the hybrid rocks were classified based on Pettijohn classification (1975). In the case of microfacies descriptions, the main and minor components were explained, followed by discussing the depositional environment of each microfacies, the dominant energy in the environment, and the adaptation of microfacies with Flugel facies belt (Flugel, 2010).

Facies definitions were done based on the microfacies characteristics, including depositional texture, grain size, grain composition, energy index classification, and fossil contents. Facies characteristics were described considering to the thin sections obtained from 366 samples. The abundance of tentaculites, *Umbella*, brachiopods ostracods, bryozoans, gastropods bivalves, echinoderms, and non-skeletal grains (ooids, intraclasts, and peloids) were also considered. Sedimentological textures and structures were considered qualitatively. For sequence stratigraphic interpretations, the concepts developed by many researchers (Emery and Myers, 1996; Catuneanu et al., 2009) were used.

In order to the identification of depositional sequences and the reconstruction of stratigraphic columns, the

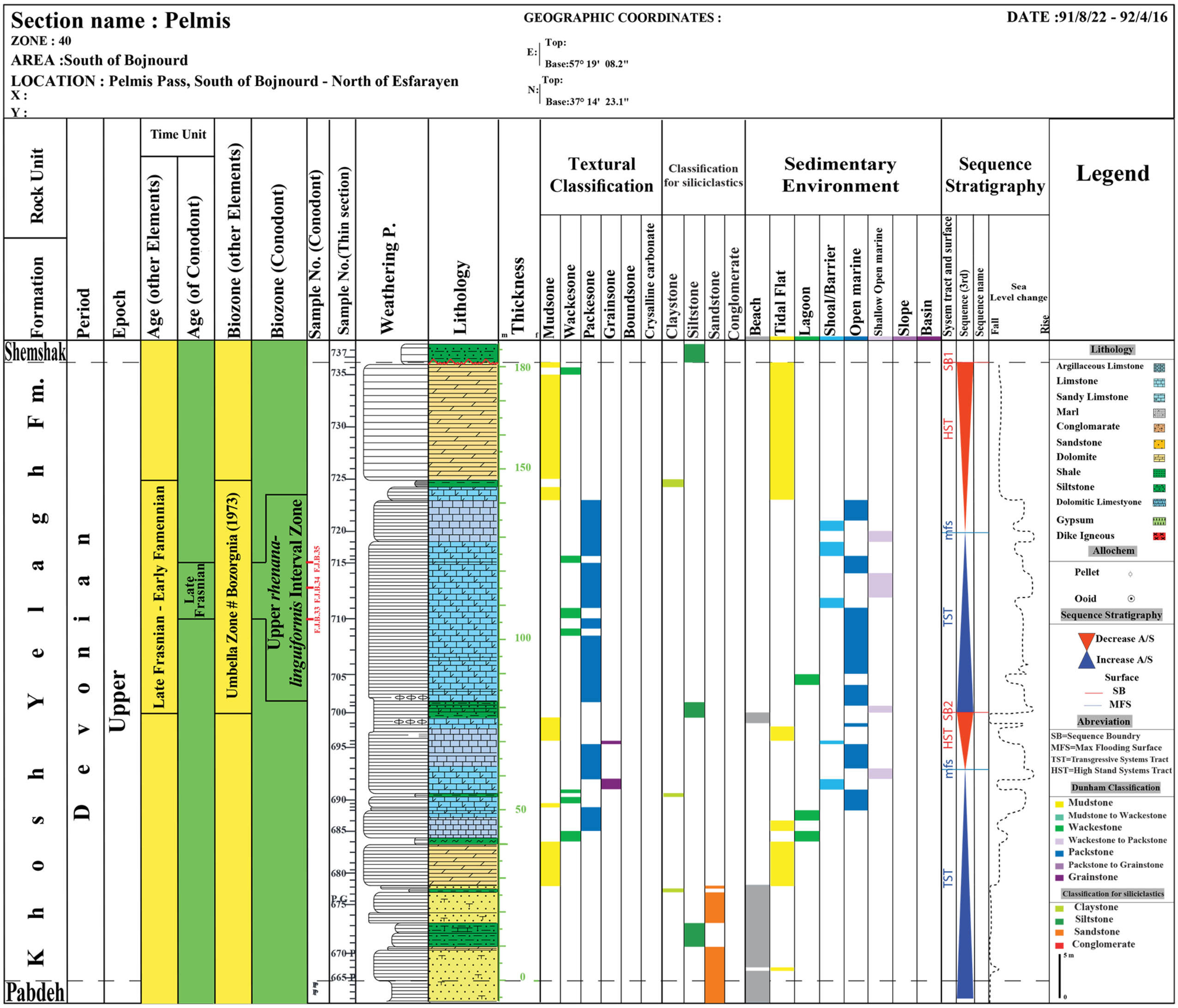


Figure 3. The stratigraphic column of the Khoshyeilagh Formation in the Pelmis stratigraphic section.

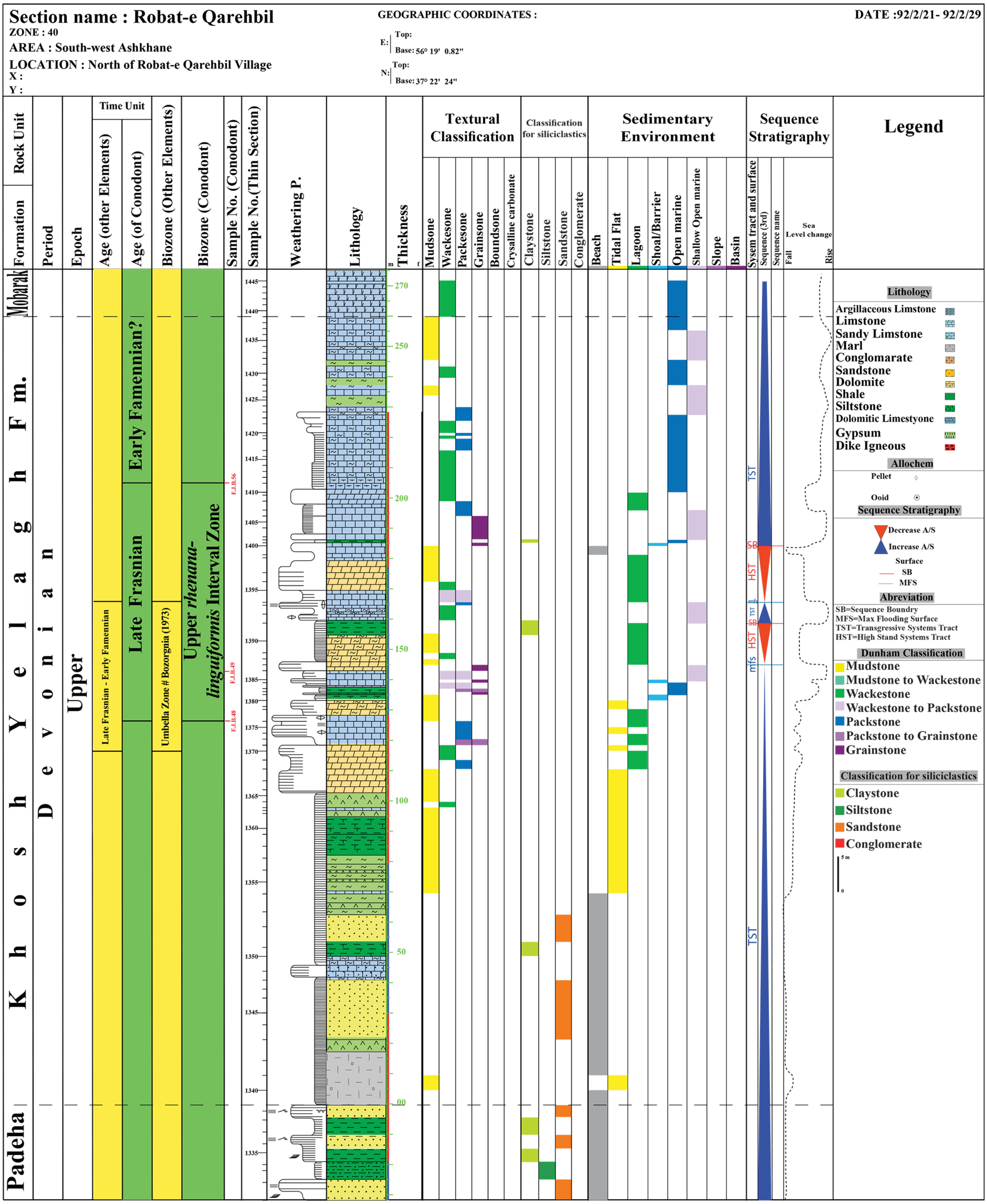


Figure 4. The stratigraphic column of the Khoshyeilagh Formation in the Robat-e Qarehbil stratigraphic section.

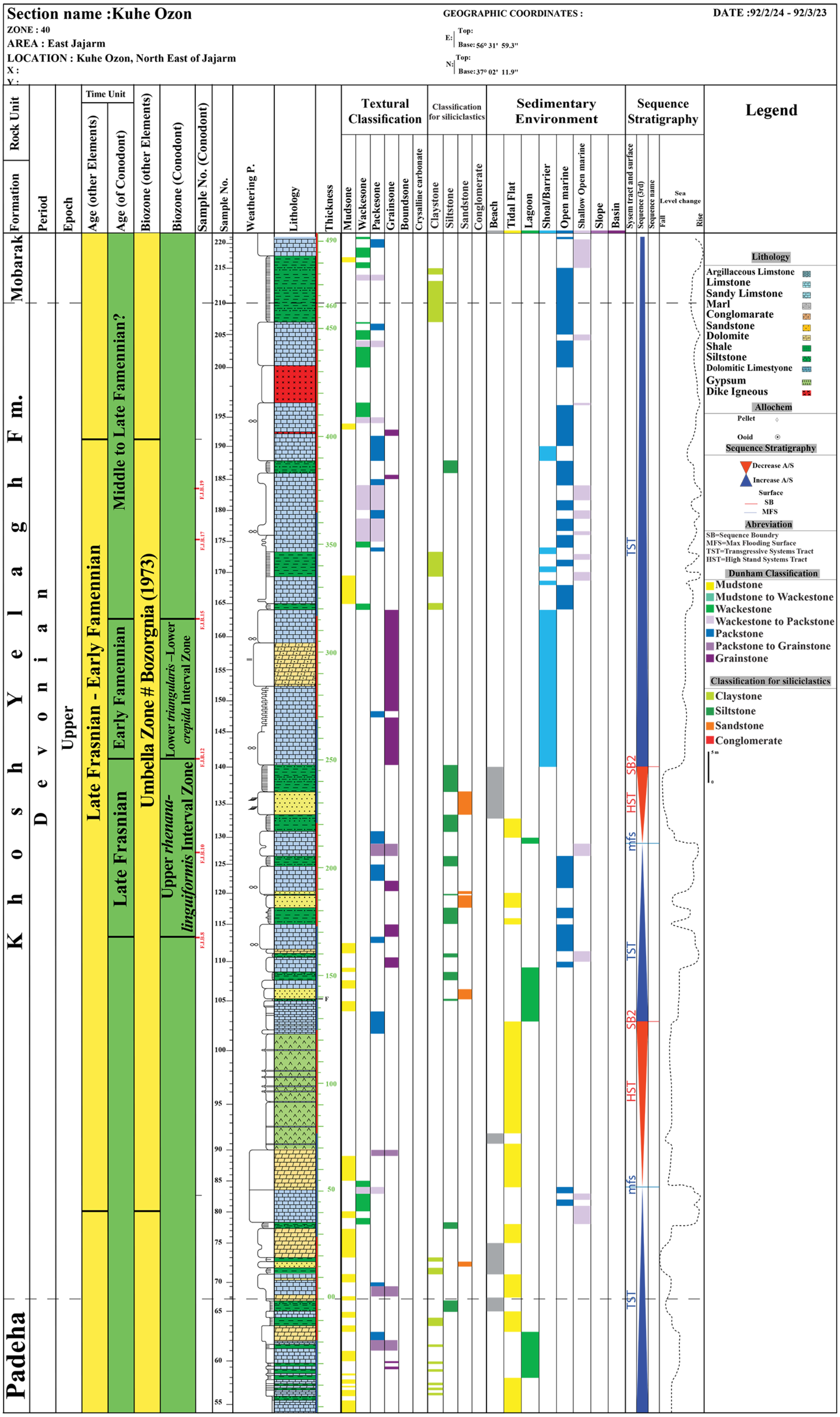


Figure 5. The stratigraphic column of the Khoshyeilagh Formation in the Kuhe Ozon stratigraphic section.

vertical change of facies, the effects of different events on deposition, the presence of unconformities, the identification of sedimentary cycles and the relations between sedimentary cycles and sea level changes have been taken into consideration.

The sea level drop has caused to the formation of two distinct surfaces which are known as sequence boundaries. The sea level drop in type 1 boundary (SB1) shows erosional evidences and the presence of bauxite horizons. The type 2 boundary (SB2) reveals relatively continiues change of facies and does not show complete sea level drop and the occurrence of erosion.

In order to the identification and determination of the percentages of constituents in thin sections, the chart proposed by Compton (1962) were used.

A total of 93 samples from limestone units (i.e., 17 samples from Pelmis section, 36 samples from Robat-e Qarehbil section, and 40 samples from Kuhe Ozon section) were taken for conodont fauna analysis. All these samples were crushed, leached by acid, and placed inside 20% Acetic acid buffer solution for four days. After dissolution, the obtained sediments were passed through 60, 150, and 200 mesh sieves and washed down. The conodont elements and the other microfossils (the fish remains, ostracods, brachiopods, and gastropods) were collected from washed samples, and identified under an optical microscope. Eventually, the required photos were taken using a scanning electron microscope (SEM; Leo 1450VP) in the laboratory of Razi Metallurgical Research Center.

4. Lithostratigraphy

In the studied stratigraphic sections, Khoshyeilagh Formation is mainly composed of limestone, sandstone, shale, and dolomite.

The thickness of Khoshyeilagh Formation was measured about 182 m, which is mainly composed of thick to very thick pale goldenrod sandstones, limestones, and dolomitic limestones and light to dark gray medium layered dolomites with marl, shale, and siltstone interlayers. The upper boundary of the Padeha Formation with Khoshyeilagh Formation is transitional, while the contact between Khoshyeilagh and Shemshak Formations is discontinuous (Figure 3). In the Robat-e Qarehbil section, it shows a thickness of 260 m and is composed of the alternations of limestone, sandstone, shale, marl, anhydrite, and dolomite. Due to the alternation of marl-anhydrite layers in this formation, the cream color is dominant and makes it look different compared to the lower formation. The lower boundary of Khoshyeilagh Formation with Padeha Formation is distinct and continuous in the studied section, but the upper boundary between Khoshyeilagh and Mobarak formations is transitional (Figure 4). The thickness of Khoshyeilagh Formation in Kuhe Ozon section was measured 436 m, which mainly contains the alternation of limestone and shale. The shale unit is composed of silt and silty sand, which is seen in gray color. At the end of this volcanic layer, limestone and silty shale units are seen with thicknesses of 20 and 10 m, respectively. The lower boundary between Khoshyeilagh and Padeha Formations and the upper boundary between Khoshyeilagh and Mobarak Formations are conformable and continuous in Kuhe Ozon section (Figure 5). Table 1 represents the lithostratigraphy of the Khoshyeilagh Formation in the studied areas.

5. Biostratigraphy

During this study, 12 conodont elements were recognized and the evaluation of these 12 samples led to the identification of 7 species belonging to 2 genera. The identified conodont species include *Icriodus alternatus alternatus, Icriodus expansus, Icriodus symmetricus, Icriodus brevis*, *Icriodus cornutus*, *Icriodus* sp., *Polygnathus xylus xylus* (Figure 6).

Conodont biozonation has been constructed based on Ziegler and Sandberg (1990), and Sweet (1988). Regarding to high distribution rate of the species and their age variations, two biozones (Upper *rhenana–linguiformis*، Lower *triangularis*–Lower *cripida*) with the age of Late Frasnian to Early Famennian were determined. In order to improve the paleontological aspects of the study and precise dating, the main macrofossils such as ostracods, brachiopods, tentaculites, *Umbella*, were studied in detail.

The paleontological investigations in the Khoshyeilagh Formation led to the identification of 6 genera and species of *Umbella*, 3 genera and species of brachiopods, two genera of tentaculites, and 3 genera of ostracods and the identified genera and species include *Umbellas* such as *Umbella bella*, *Umbella cutis*, *Umbella rotunda, Umbella ovatla, Umbella shahrudensis*, *Umbella* sp., braciopods such as *Spinatrypina camitata*, *Spinatrypina explanata*, tentaculites such as *Tentaculites* sp., *Stylionilina* sp., and ostracods such as *Knoxiella semilukiana*, *Nodella faceta*, *Cryptophyllus* sp._

Bozorgnia (1973) introduced an *Umbella* Zone of Upper Frasnian to Lower Famennian. The previous works of Ashouri (2002, 2004), Gholamalian and Kebriaei (2008)، Gholamalian (2006), Bahrami et al. (2011a and 2011b, 2013, 2014), Gholamalian et al. (2011, 2013) about the paleontological investigations of Upper Devonian sequences, were used in order to make a reasonable comparison between the studied sections and the other Devonian sequences in the other places of Iranian plateau. Supplement 1 represents all of the recognized biozones in the study areas.

6. Facies description

Considering the field and laboratory studies, Khoshyeilagh Formation is composed of clastic and carbonate facies.

Table 1. The lithostratigraphy of the Khoshyeilagh Formation in the studied areas.

Kuhe Ozon stratigraphic section	Robate Qarabil stratigraphic section	Pelmis stratigraphic section
13 m limestone with intermediate layer of dolomite- medium thick (Base Formation)	16 m marl, cream in color with thin horizons of argillaceous limestone (Base Formation)	10 m sandstone- yellow- the alternation of thick layers of sandstone and thin layer of limestone (Base Formation)
8 m alternation of shale and sandstone- white to gray	27 m alternation of cream marl and white anhydrite layers	1 m dolomite- thin layer
14 m dolomite- medium to thick layer- brown to yellow	4 m limestone- thin layer- dark- massive	7 m siltstone- cream in color- thick- thin limestone layers
3 m siltstone- dark gray- thin layer	8 m alternation of shale and marl- the shale unite is increased upward	11 m sandstone- medium to thick layer- gray to dark gray
15 m limestone- thick layer- dark gray	36 m alternation of cream marl and white anhydrite layers	12 m dolomite- medium to thick layer
19 m dolomite- medium to thick layer- dark gray	15 m alternation of marl- black to gray- white anhydrite layers along with a few limestone horizons- dark in color	2 m marl- very thin layers
54 m gypsum with a thin layer of white limestone	14 m dolomite- thick to massive- yellow to gray in color- thin horizons of dolomite high brachiopods, bivalves, and gastropods fossil content	35 m limestone and dolomitic limestone- gray to dark gray- medium to thick layer with brachiopod fossils
158 m alternation of thin to medium- dark gray limestone with thick layer white sandstone, quartz-arenaite, siltstone- dark shale	11 m limestone- dark gray- thin to medium layer- different types of bioclasts	5 m shale and siltstone- thin layer
21 m sandy dolomite- medium layer	16 m alternation of calcareous shale and marl- coarse-grained- dark- bioclast limestone	46 m dolomitic limestone and limestone- gray to cream color- medium to thick- bryzoans, corals, brachiopods, tentaculites, and bivalve fossils
28 m limestone- medium layer- fossil debris- gray with gray shale	13 m alternation of calcareous shale and marl- the shale unite is increased upward	12 m limestone- medium to thick- gray
10 m shale and limestone with fossils	12 m limestone- dark- yellow to cream marl	4 m dolomitic limestone- medium to thick
38 m limestone- medium layer- dark gray	18 m dolostone- thick to thin layer- yellow to gray- fossils such as gastropods, brachiopods, and other bioclasts	2 m shale- thin layer- gray
5.5 m sand shale and shale- dark gray	15 m limestone- dark- thin to thick- different bioclasts.	35 m dolomite- thick layers- gray
27.5 m limestone- medium layer- gray	55 m black marl, and marl limestone	-
17 m of igneous rocks	-	-
20 m limestone- medium layer- dark to gray with fossils	-	-
10 m alternation of siltstone and shale- dark in color	-	-

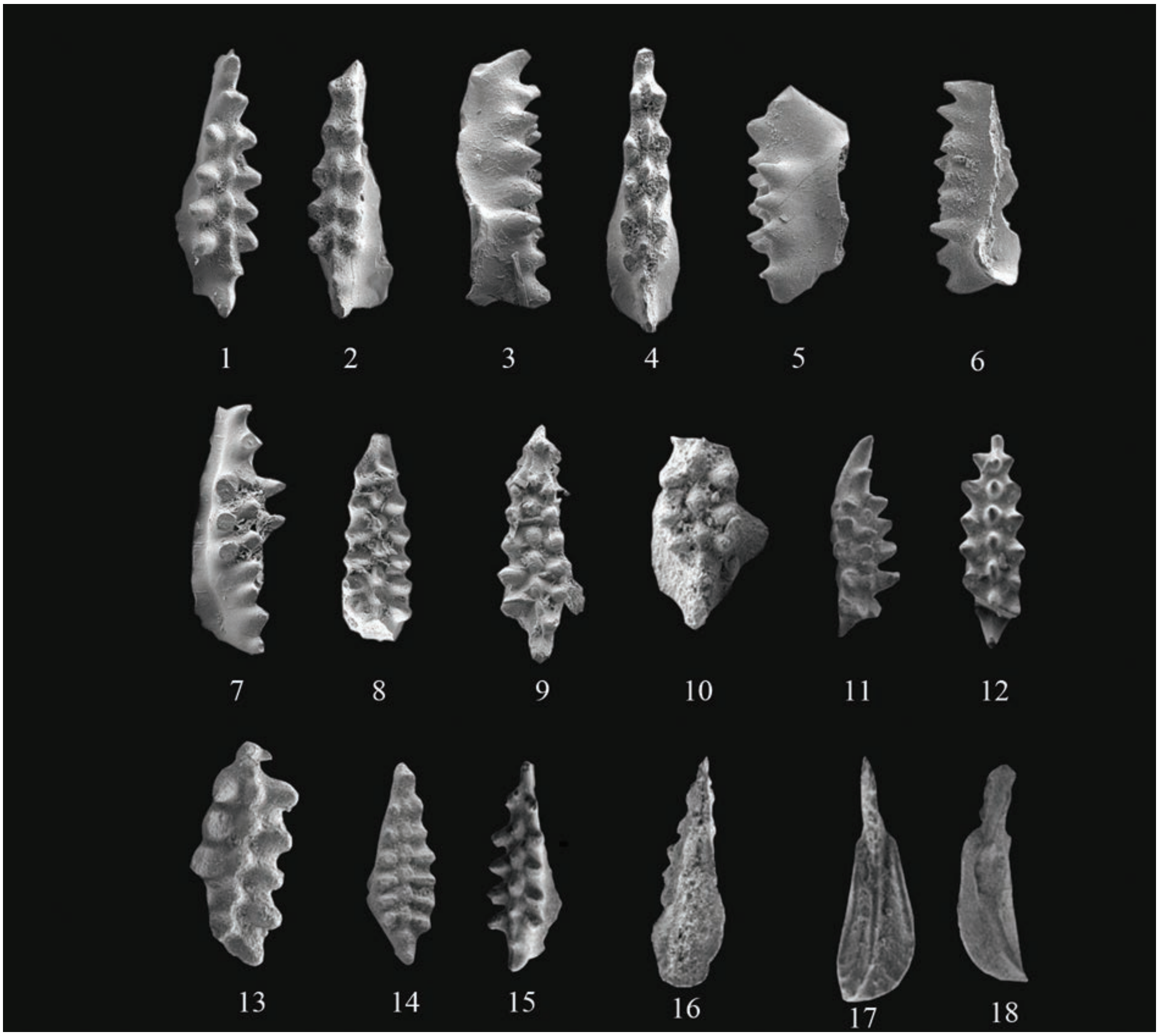


Figure 6. 1–3) *Icriodus cornutus* (Sannemann, 1955), 1) Upper view, 212x, sample F.J.B.48; 2) Upper view, 212x, sample F.J.B.48; 3) Lateral view, 212x, sample F.J.B.48. 4–5 & 8–6–9) *Icriodus alternatus alternatus* (Branson and Mehl, 1934). 4) Upper view, 246x, sample F.J.B.48; 5) Lateral view, 253x, sample F.J.B.12; 8) Upper view, 207x, sample F.J.B.48; 6) Lower view, 260x, sample F.J.B.49; 9) Upper view, 204x, sample F.J.B.49. 7) *Icriodus expansus* (Sandberg and Dressen, 1984), 7) Lateral view, 303x, sample F.J.B.8. Figures. 10 & 13–14) *Icriodus* sp. 10) Upper view, 316x, sample F.J.B.34. 13) Upper view, 284x, sample F.J.B.33; 14) Upper view, 212x, sample F.J.B.33. Figures 11–12) *Icriodus symmetricus* (Branson and Mehl, 1934) 11) Upper view, 212x, sample F.J.B.49; 12) Upper view, 257x, sample F.J.B.49. Figures 15–16) *Icriodus brevis* (Stauffer, 1940) 15) Upper view, 212x, sample F.J.B.8; 16) lower view, 207x, sample F.J.B.8. Figures 17–18) *Polygnathus xylus xylus* (Stauffer, 1940) 13) Upper view, 290x, sample F.J.B.56; 14) lower view, 296x, sample F.J.B.56.

These facies, which are observed in different parts of the stratigraphic column, include 3 clastic facies, 11 carbonate facies, and 1 hybrid facies that have been deposited in 5 subenvironments (Table 1).

To achieve this objective, skeletal grains, nonskeletal constituents, the amount of cement, matrix, and the textural properties from thin sections of the studied samples were recognized in detail and the microfacies were determined.

The depositional environments of facies show changes from shallow to deep water as described below:

6.1. Shoreface clastic microfacies

6.1.1. Sandstone facies (KHPF1)

Massive sandstone is a facies identified in some parts of Khoshyeilagh Formation. According to the Folk's classification, these sandstones are quartz arenite, quartz wack, and sublitharenite, (Folk, 1980). Quartz forms the main constituent of this unit. These sandstones have a good maturity and show cross bedding structure. Massive sandstones of this part are related to a shallow shoreface associated with the tidal flat environment (Miall and Arush, 2001) and are found in all studied stratigraphic sections (Figures 7a and 7b).

6.1.2. Siltstone facies (KHPF2)

The siltstone facies in the study area includes a set of the fine-grain matrix. The grains are mostly in silt size, and the parallel lamination is the dominant sedimentary structure of siltstone facies. The fine-grain matrix of KHPF2 unit represents sedimentation conditions under a relatively low-energy environment (Miall and Arush, 2001). This facies is present in all studied stratigraphic sections (Figures 7c).

6.1.3. Shale facies (KHPF3)

The shale facies, which is identified and named as thin layer mudstone, contains a small part of studied sediments. This facies is found alternately with lagoonal and tidal flat facies and in some parts with open marine deposits. The shale lithofacies in the study area is dark green to dark gray and consists of a thin layer of mudstone. The formation environment of this facies was most likely a low energy environment (Reineck and Singh, 1986). The grain size, bioturbation and bioclastic debris indicate that the light brown and gray shales were deposited in a low energy marine setting in an intermediate continental-marine environment (Warren, 2006). Also the bioturbated shales which are intercalated with sandstones indicate mixed mud-sand tidal flat deposition (Reineck and Singh, 1975). This lithofacies is found throughout the studied stratigraphic sections (Figures 7d–7f).

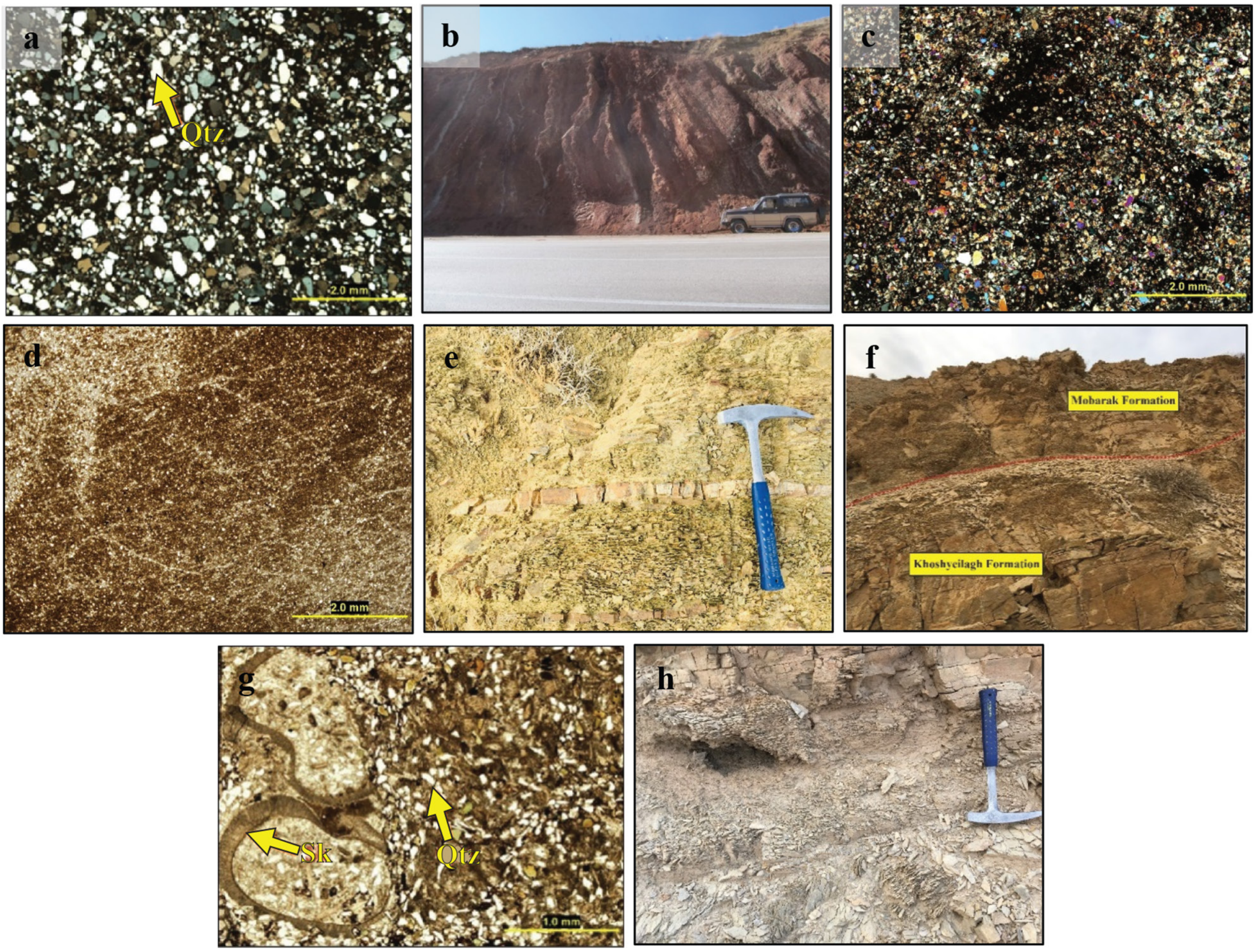


Figure 7. Microphotographs representing the identified microfacies in the Khoshyeilagh Formation; a) Sandstone facies (KHPF1) containing quartz grains (Qtz) as the main components, Pelmis section, S. No. 675 Clastic facies in the Khoshyeilagh Formation; b) Sandstones unit in Khoshyeilagh Formation, which forms the lower part of the formation in Pelmis section, S. No. 665 to 670; c) Siltstone facies (KHPF2), including fine-grained silt size mudstones, Pelmis section, S. No. 664; d) Shale facies (KHPF3), which is seen as thin layer mudstone in dark-dark gray color, Kuhe Ozon section, S. No. 133; e) shale layers containing thin layer of limestone in Robat-e Qarehbil section, S. No. 1391; f) shale unit in the upper part of Khoshyeilagh Formation, S. No. 187 g) Sandy bioclast wackestone-packstone facies (KHMF4), which contains 20%–30% quartz grains (Qtz) and 10%–30% of skeletal grains (Sk), Kuhe Ozon section, S. No. 164; and h) Anhydrite unit from Khoshyeilagh Formation (S. No. 101) in the Kuhe Ozon section, which belongs to a tidal flat and shoreface environment.

6.2. Hybrid facies

6.2.1. Sandy bioclast wackestone-packstone (KHMF4)

This facies includes 20%–30% of sand-sized quartz grains and 10%–30% of the skeletal debris. Bioclast component of this unit consists of echinoid fragments, brachiopods, corals, bivalves, and ostracods. The lime mud of the facies has been recrystallized into microspar. With regard to some characteristics of this unit such as lamination, the hybrid nature of the facies, the co-existence of siliceous and calcareous grains, and the reworked allochems, a shoreface/tidal flat depositional environment can be proposed for this facies (Da Silva and Boulvain, 2006). These features and their association with shallow facies (sandstone, shale, and lagoon facies), demonstrate the deposition in tidal flat and supratidal environments (Tucker, 2009; Bodzioch, 2003; Flugel, 2010) (Figure 7g).

6.3. Tidal flat facies

6.3.1. Layered to massive anhydrite facies (KHMF5)

The layered to massive anhydrite facies contains evaporites and represents a warm and dry climate in the sedimentation time. In many parts, anhydrite has been formed as massive or thin layers. In general, the evaporites of this facies indicate tidal flat and shoreface environments (Kerr and Thompson, 1963), and can be considered as the equivalent of RMF25 in the Flugel (2010) classification. These units are recognized in two stratigraphic sections of Robat-e Qarehbil and Kuhe Ozon sections (Figures 7h and 8a).

6.3.2. Dolomitized mudstone facies (KHMF6)

Dolomitized mudstone facies consists of dark matrix and fine grain micrite, containing very low fossil content, showing laminated and fenestrate fabrics. Bioturbation is rarely seen in this facies while quartz is its main clastic particle. According to this evidence, the facies belongs to the middle to upper parts of the tidal flat (Tucker, 1990; Flugel, 2010). High amounts of micrites demonstrate a low energy environment (Adachi et al., 2004). The dolomitized micrite and fenestral dolomudstone were deposited in upper intertidal environments and according to Flugel (2010), dolomitization in this facies indicates the deposition close to the tidal flat environment (Lasemi et al., 2008). KHMF6 is equivalent of units RMF19 and RMF22 in Flugel classification (Flugel, 2010) that belongs to the tidal flat environment. This unit is seen in all three stratigraphic sections (Figure 8b).

6.4. Lagoon facies

6.4.1. Bioclast mudstone-wackestone facies (KHMF7)

Bioclast mudstone-wackestone facies contains allochems such as ostracods, echinoids, and peloid with a frequency of about 10%. Low content of skeletal components, along with micrite and the presence of peloid, reveal the deposition in a shallow ramp environment under FWWB.

The bioturbation occurs in lagoonal environments and the mud-rich facies are deposited in a low-energy conditions (Flugel, 2010). The presence of mudstone facies associated with bioturbation represents a low-energy condition (Wilson, 1975). The relatively low diversity and low abundance of marine fauna, in the bioclast wackestone suggest that the deposition has been occurred in a quiet water and lagoonal environment (Wilson, 1975; Hine, 1977; Nichols, 2000). This unit is seen in all three stratigraphic sections (Figure 8c).

6.4.2. Peloid bioclast mudstone-wackestone facies (KHMF8)

The main components of KHMF8 unit are bioclasts such as ostracods (10%–40%), gastropods (5%–15%), and minor components including echinoids and bivalves. Peloid grains (20%) and a few intraclasts are also present in this facies. Regarding to the skeletal grains assemblage, the development of micritization, and bioturbation, this subfacies can be related to a lagoonal environment (Wilson 1975; Alsharhan 2006; Maurer et al. 2009; Flugel 2010). In peloid bioclast mudstone-wackestone, the presence of bioclasts and dominance of peloids indicate deposition in a low energy, shallow lagoonal environment with poor connection with an open marine (Tomasovych, 2004). This unit is seen in all three stratigraphic sections (Figure 8d).

6.4.3. Bioclast packstone-grainstone facies (KHMF9)

KHMF9 is composed of echinoids (20%–25%), bivalves (5%–10%), brachiopods (10%–15%), peloid (5%–10%), and ooids (5%). Microfacies in such a broad facies belt were recognized by fossil and sedimentary fabrics. KHMF 9 is interpreted to be located in the outer facies of a lagoon. The presence of sparry calcite cement in some parts of KHMF 9 indicates that this microfacies is deposited in a moderate to high energy environment influenced by tidal currents near shoal (Flugel, 2010; Koehrer et al., 2010; Wilson, 1975). This facies, which is equivalent to the RMF8 and RMF9 (Flugel, 2010), is present in all three stratigraphic sections (Figure 8e).

6.5. Shoal facies

6.5.1. Bioclast grainstone facies (KHMF10)

Bioclast grainstone facies includes bioclastic components such as brachiopods (10%–20%) and echinoids (10%–30%), which are found inside of a spar cement. The sorting of grains is poor in this facies and different grain sizes are seen. The bioclastic grainstone represents a depositional environment closed to lagoonal environment, therefore it is the host of a mixture of grains with a dual nature of dam carbonates and low-energy lagoon (Flugel, 2010; Koehrer et al., 2010). KHMF10 is equivalent to the RMF30 of Flugel classification (Flugel, 2010) and exists in all stratigraphic sections of Pelmis, Robat-e Qarehbil, and Kuhe Ozon (Figure 8f).

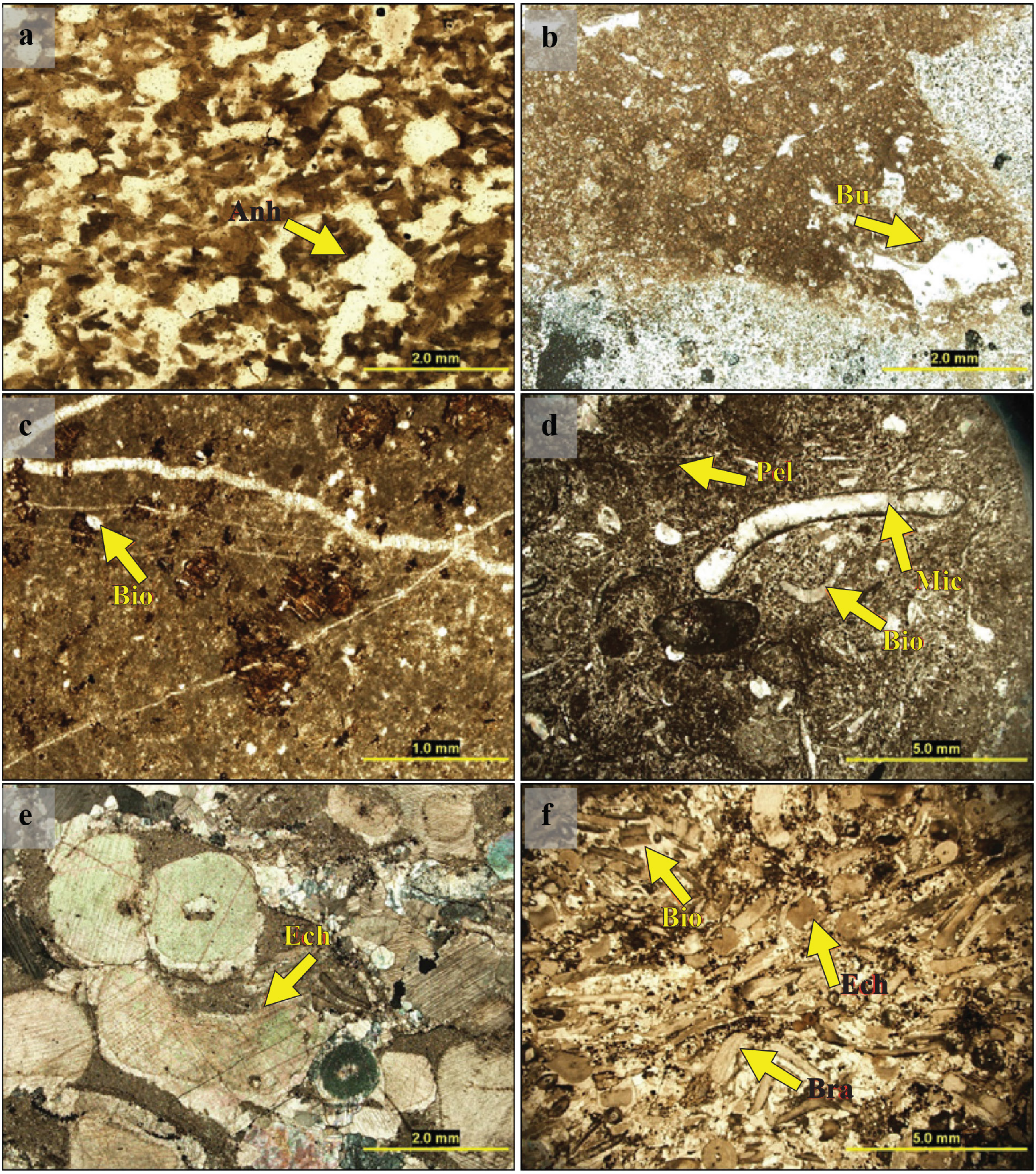


Figure 8. Microphotographs showing the identified microfacies in the Khoshyeilagh Formation; a) Layered to massive anhydrite facies (KHMF5) (Anh) (tidal flat), Kuhe Ozon section, S. No. 95; b) Dolomitized mudstone facies (KHMF6) presenting fenestrate structure and bioturbation (Bu) (tidal flat), Robat-e Qarehbil section, S. No. 1354; c) Bioclast mudstone-wackestone facies (KHMF7) along with bioturbation (Bu) (Lagoon) Kuhe Ozon section, S. No. 107; d) Peloid (Pel) bioclast (Bio) mudstone-wackestone facies (KHMF8) with fossil debris, micritization (Mic) (micritization on a bioclast shell (orange arrow), and bioturbation (Lagoon), Robat-e Qarehbil section, S. No. 1373; e) Bioclast packstone-grainstone facies (KHMF9), with echinoderms debris (Ech), Kuhe Ozon section, S. No. 128; and f) Bioclast grainstone facies (KHMF10) containing different bioclasts (Bio) such as brachiopods (Bra) and echinoderms (Ech), Kuhe Ozon section, S. No. 141.

6.5.2. Ooid bioclast grainstone facies (KHMF11)

The allochems, mainly ooids (10%), together with a high amount of bioclastic components such as brachiopods (30%) and echinoids (35%) form the most important part of this facies (Table 2). Light sparite is a major matrix of KHMF11. In some samples, the amount of umbella genera reaches 15%. According to data, the KHMF11 belongs to a carbonate shoal toward the open marine environment. To create ooids, it is required a saline and energetic environment (Tucker et al., 1993; Flugel, 2010). The features of this facies indicate moderate to high energy shallow waters with much movement and reworking of bioclasts and the formation of ooids. Present bioclasts, ooids with tangential structures in this facies indicate a high energy environment that has been subjected to constant wave agitation and produced a well sorted grainstone (Tucker and Wright, 1990; Flugel, 2010) and cements demonstrate deposit on high energy environments of a seaward shoal within the surf zone (Wilson,1975; Palma et al., 2007; Reolid et al., 2007; Adabi et al., 2010; Flugel, 2010) such energetic deposits mostly spread as barriers on carbonate platforms (Van Buchem et al., 2002). This facies has been observed in two stratigraphic sections of Robat-e Qarehbil and Kuhe Ozon (Elrick and Read, 1991) (Figure 9a).

6.6. Open marine facies

6.6.1. Mudstone facies (KHMF12)

The mudstone facies is related to a deep carbonate environment. The main characteristics of this facies are the presence of sponge spicules and fossil debris such as ostracods. Pyrite and clay minerals are observed with low contents among the constituents. This facies belongs to a deep environment of a carbonate ramp (Flugel, 2010)

Table 2. Recognized facies belts and microfacies in the Khoshyeilagh Formation with main allochems (skeletal and nonskeletal) and dominant diagenetic processes.

Facies code	Facies name	Skeletal components	Nonskeletal components	Dominant diagenetic phenomena	Subenvironment
KHPF 1	Sandstone	-	Quartz	-	Shoreface
KHPF 2	Siltstone	-	Silt	-	Shoreface
KHPF 3	Shale	-	-	-	Shoreface
KHMF 4	Sandy Bioclest Wackestone-Pakstone	Echinoids	Quartz	-	Shoreface/Tidal flat
KHMF 5	Layered to massive anhydrite	-	-	-	Tidal flat
KHMF 6	Dolomitized mudstone	-	Quartz	Fenestrate structure	Tidal flat
KHMF 7	Bioclast mudstone-wackestone	Ostracods and echinoids	Peloid	Bioturbation	Lagoon
KHMF 8	Peloid bioclast wackestone-packstone	Ostracods and gastropods	Peloid	Bioturbation, micritization	Lagoon
KHMF 9	Bioclast packstone-grainstone	Echinoids, bivalves, and brachiopods	Peloid	-	Lagoon
KHMF 10	Bioclast grainstone	Echinoids and brachiopods	-	-	Carbonate shoal
KHMF 11	Ooid bioclast grainstone	Echinoids and brachiopods	Ooid	-	Carbonate shoal
KHMF 12	Mudstone	Sponge spicule and ostracods	Pyrite and clay minerals	-	Open marine
KHMF 13	Peloid bioclast wackestone-packstone	Echinoids, tentaculites and brachiopods	Peloid	Bioturbation	Open marine
KHMF 14	Bioclast wackestone	Echinoids and brachiopods	-	-	Open marine
KHMF 15	Bioclast spicule wackestone-packstone	Sponge spicules	-	-	Open marine

and is an equivalent of RMF2 unit of Flugel classification (Flugel, 2010). The KHMF12 unit has been observed in Robat-e Qarehbil and Kuhe Ozon stratigraphic sections (Figure 9b).

6.6.2. Peloid bioclast wackestone-packstone facies (KHMF13)

Peloid (10%–15%) and fossils such as echinoids, styliolina, tentaculites, and brachiopods (10%–20%) are the main components of this microfacies. Some bioclasts such as trilobites, bryozoans, and gastropods (5%–10%) are found in this unit. The minor components of this facies are calcisphere fossils (less than 5%) (Table 2). The main and minor components are distributed inside a micrite context. The high rate of bioturbation is seen in this unit. The depositional environment of this facies belongs to a low energy open marine environment (Flugel 2010). The fabric and size of skeletal grains and their similarity to bioclasts of barrier facies indicate an open marine setting close to barion below seaward barrier. The presence of micrite and the lack of detrital grains demonstrate the deposition under wave base and low energy environment. Variety and size of bioclasts indicate deposition in shallow open marine setting (Spalletti et al., 2001). KHMF13 is an equivalent of RMF4 in Flugel classification (Flugel, 2010). All of the studied stratigraphic sections contain KHMF13 facies (Figure 9c).

6.6.3. Bioclast wackestone facies (KHMF14)

Echinoids and brachiopods are the main allochems of bioclast wackestone and arthropods, gastropods, bryozoans, and peloid are the minor allochems of this unit. Echinoids and brachiopods form 10%–15% and peloid as a nonskeletal allochem form 5% of this facies (Table 2). The environment of this facies has been predicted as a low-energy open marine setting (Flugel, 2010; Koehrer et al., 2010). The lime-mud dominated lithology, presence of bioclasts, and stratigraphic position indicate that deposition has been taken place in a low energy shallow water environment below storm wave base (Corda and Brandano, 2003). This facies is the equivalent of RMF7 in Flugel classification (Flugel, 2010) and is detected in all three studied sections (Figure 9d).

6.6.4. Bioclast spicule and wackestone-packstone facies (KHMF15)

The main components of this facies are 15%–20% sponge spicules and 5%–10% bioclasts. The minor components include echinoids and bivalve fossils. Sponge spicules often appear in longitudinal transverse sections.

This facies, which has been most likely deposited in the deepest part of an open marine environment (Tucker and Wright, 1990), can be considered as an equivalent to RMF3 part of Flugel classification (Flugel, 2010). KHMF15 is detectable in Robat-e Qarehbil and Kuhe Ozon stratigraphic sections (Figure 9e).

7. Depositional environments

Many information can be obtained from facies models which represent evidences of ancient and modern facies (Walker, 2006). In the Khoshyeilagh Formation (Middle-Upper Devonian), a relative rise of sea level flooded the preexisting carbonate platforms and surrounding siliciclastic shelves (Wendt et al., 2002). After a long period of near shore and intertidal conditions during the early and early middle Devonian (Padeha Formation), the onset of open marine conditions appears diachronous (Wendt et al., 2002). According to the Devonian paleogeography of Iran (Wendt et al., 2002, 2005; Ruban et al., 2007; Domeier and Torsvik, 2014), the sediments of the Khoshyeilagh Formation were deposited in a divergent passive margin setting at the southeast margin of Paleotethys Ocean (Domeier and Torsvik, 2014).The study of vertical and lateral changes in different facies of Khoshyeilagh Formation represents a shoreface-marine depositional environment and a homoclinal ramp model. The proposed ramp has a relatively gentle slope, which extends inside the basin. This ramp was similar to the present-day carbonate ramps such as the southern coast of the Persian Gulf (Purser, 1973; Gischler and Lomando, 2007) and the Shark Bay in Australia (Flugel, 2010). The carbonate ramps are often expanded in the zones without reefs fauna (Burchette and Wright, 1992). The low development mid ramp facies and the absence of outer ramp facies show a low depth for this carbonate ramps (Flugel, 2010). This depositional model consists of 5 subenvironments including shoreface, tidal flat, lagoon, shoal, and open marine (Figure 10). In tidal flat, there is an alternation of high energy and quiet conditions. The lamination and fenestrate structures, evaporitic minerals, and microcrystalline dolomites are the most important characteristics of this environment. In a lagoon environment, a quiet condition had been dominant. Moreover, a high content of pellet grains and bioclasts such as gastropod, ostracod, and bioturbation are detectable in this unit. The presence of ooids, large allochems such as echinoids, bryozoans, and brachiopods are the main characteristics of shoal environment. Another important feature of this environment is the formation of calcite cement.

The presence of calcite cement represents a high energy environment and the removing of carbonate mud from the environment. These cements are always in the form of blocky and drusy sparite. The drusy cement is usually formed in the meteoric and burial environments and the blocky cement shows a burial environment (Carannanate et al., 2000).

Several fossil groups such as brachiopods, bryozoans, echinoderms, tentaculites, styliolina, and sponge spicules are common in open marine environment, and lime mud is also present in this environment.

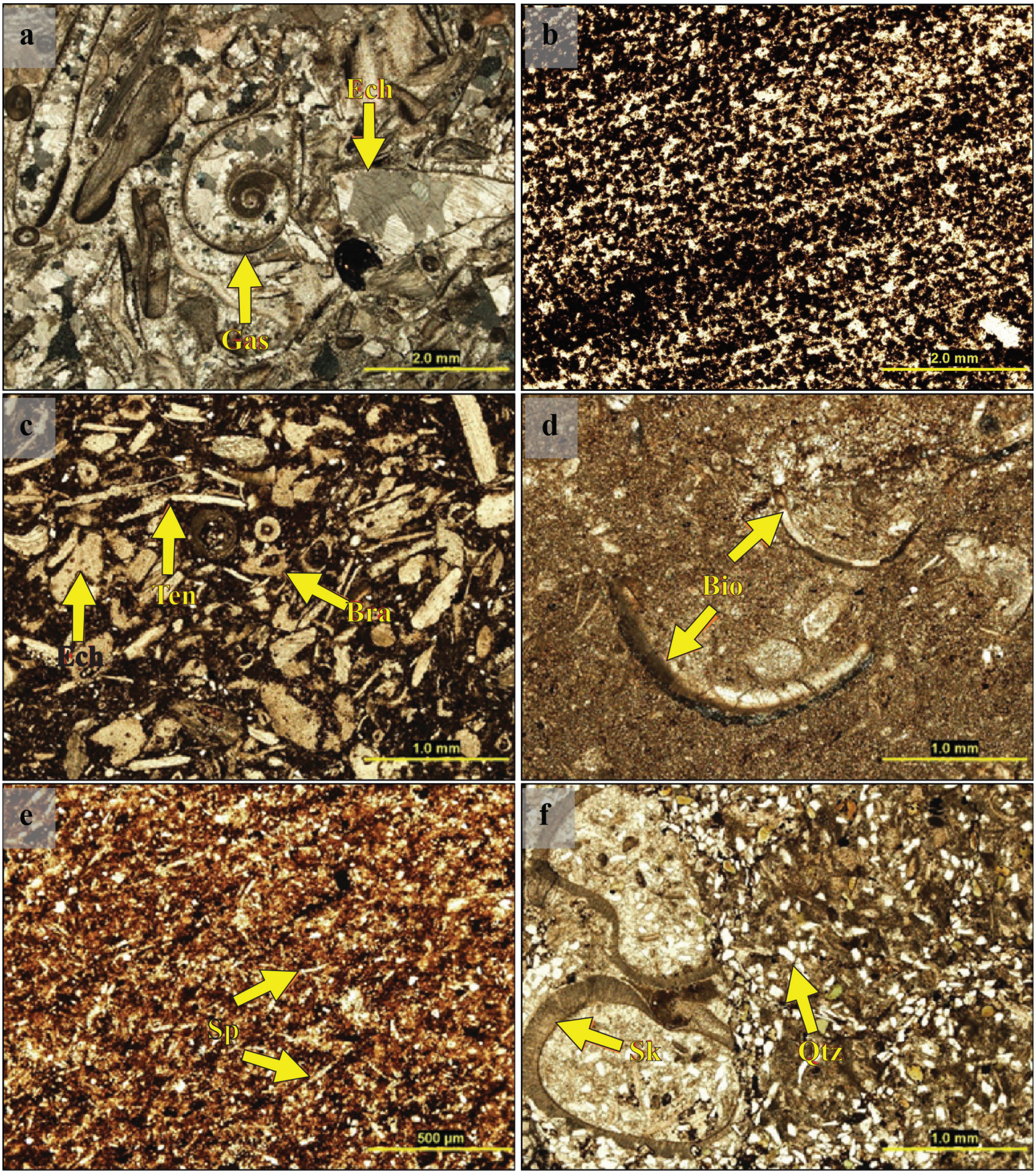


Figure 9. Microphotographs representing the identified microfacies in the Khoshyeilagh Formation; a) Ooid bioclast grainstone facies (KHMF11) (shoal) and the fossil content [gastropods (Gas), and echinoids (Ech)], Kuhe Ozon section, S. No. 150; b) Mudstone facies (KHMF12) relating to an open marine facies, Kuhe Ozon section, S. No. 216; c) Peloid bioclast wackestone facies (KHMF13) presenting an open marine environment and different bioclast debris such as echinoids (Ech), tentaculites (Ten), and brachiopods (Bra), Kuhe Ozon section, S. No. 174; d) Bioclast wackestone facies (KHMF14) associated with fossil debris (Bio) belonging to an open marine environment, Kuhe Ozon section, S. No. 208; e) Bioclast spicule (Sp) wackestone-packstone facies (KHMF15) related to an open marine setting, Kuhe Ozon section, S. No. 213; and f) Sandy bioclast wackestone-packstone facies (KHMF4), which contains 20-30% quartz grains (Qtz) and 10%–30% of skeletal grains (Sk), Kuhe Ozon section, S. No. 164.

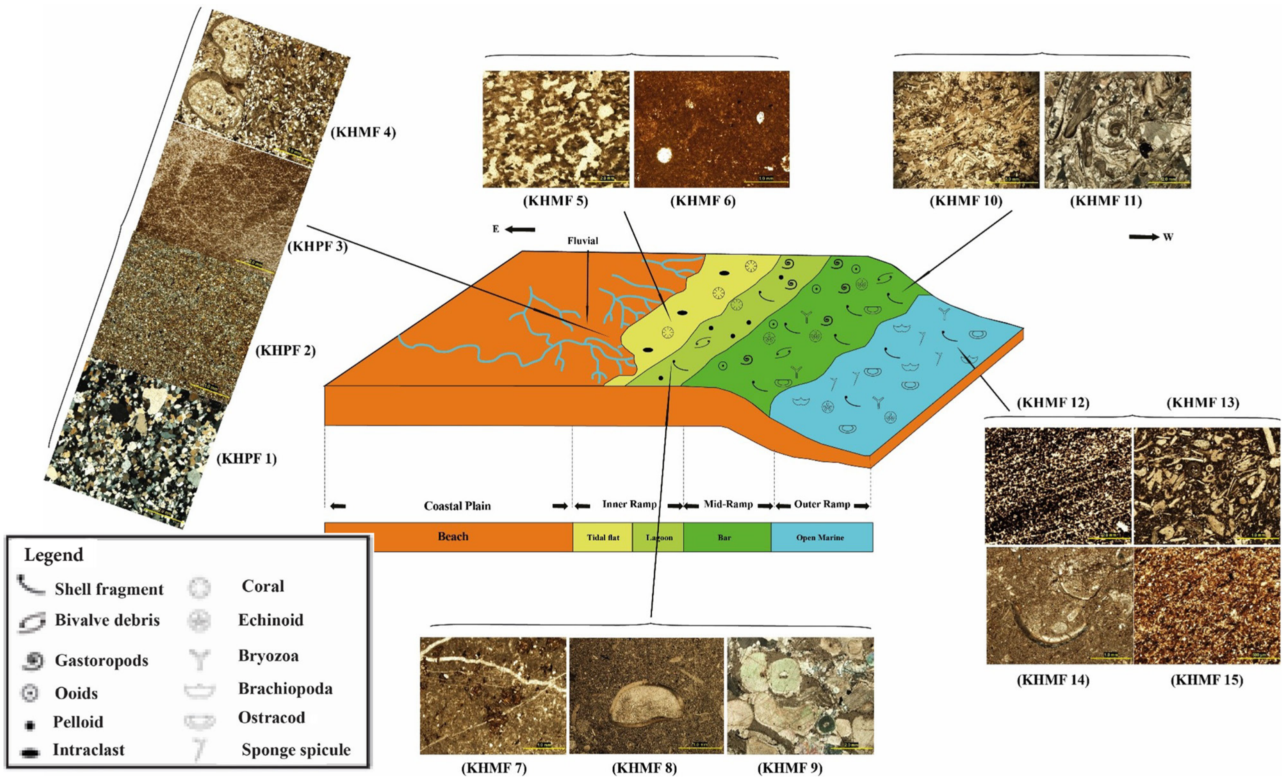


Figure 10. The depositional model proposed for the Khoshyeilagh Formation in the Kuhe Ozon section.

8. Sequence stratigraphy

The sedimentary facies characteristics of the Khoshyeilagh Formation show a distinctive number of sequence boundaries, systems tracts and depositional sequences. In the description of sections, deepening trends are considered to be a transgressive systems tract (TST), shallowing trends are interpreted as a highstand systems tract (HST), the change from deepening towards shallowing is interpreted as maximum flooding surface (mfs). During the early and early middle Devonian near shore and intertidal conditions afterward the onset of open marine conditions appears diachronously (transgressive) (Wendt et al., 2002), therefore more carbonate sediments were supplied to the sedimentary basin (southern margin of the Paleo-thetys Ocean or northern parts of the Gondwana land). Based on the Martin-Chivlet method (2003) and with respect to sea level curves, sedimentation, tectonic evidence, and the vertical changes of facies (Catuneanu 2002), three third-order depositional sequences were recognized in Khoshyeilagh Formation. The first and second depositional sequences (sequence-1 and sequence-2) consist of TST, MFS, and HST. These sequences, which are confined by discontinuities caused by a sea level drop, are observable in the upper and lower boundaries. The third depositional sequence (sequence-3) is simply composed of TST. All of the sequences identified in Khoshyeilagh Formation refer to a third-order sequence. Figures 11a–11f and 12a–12c represent the sequence boundaries and systems tract in Pelmis, Kuhe Ozon, and Robat-e Qarehbil stratigraphic sections.

Supplement 2 represents the correlation of the studied sections and comparison to the global sea level diagrams.

8.1. Depositional sequence-1

Sequence-1 includes carbonate and clastic facies. The lower boundary of this sequence is probably located in Padeha Formation and its upper boundary is characterized by SB2 (type II sequence boundary). The thickness of sequence-1 in Pelmis, Rabat-e Gharehbil, and Kuhe Ozon are 78, 193, and 189 m, respectively (Figure 11a). This sequence begins with TST, which consists of shale, sandstone, marl, limestone, and dolomite (which starts with clastic facies) and continues with dolomitized mudstone and bioclast wackestone-packstone belonging to a tidal flat to lagoon environments, and ends with peloid bioclast wackestone-packstone and the bioclast spicule wackestone-packstone. MFS facies is identified by bioclast wackestone-packstone, related to an open marine.The boundary between HST and TST indicates the maximum flooding surfaces (MFS), which is characterized by bioclast wackestone-packstone, and illustrates an open marine environment. HST is located above this level and represents a gradual increase in deposition space, which is characterized by bioclast mudstone-wackestone facies, related to tidal flat and lagoon environment. This facies ends with lagoon shales and evaporites such as layered to massive anhydrite (Figures 11b and 11c).

The upper boundary of this facies show type II boundary and does not show sea level drop evidences. The sea level changes has only caused to the diversity of facies.

8.2. Depositional sequence-2

The upper and lower boundaries of depositional sequence-2 are characterized by SB2 (type II sequence boundary) in Kuhe Ozon sections and Robat-e Qarehbil. Sea level drop has not been recorded in this part, and the change of facies is only related to the sea level changes.

The lower and upper boundaries of the sequence are respectively limited by SB2 and SB1 (erosional discontinuity between Upper Devonian-Upper Triassic units) in the Pelmis section.

At the end of this sequence in Pelmis layers are observable containing bauxite and laterite which belong to type II sequence boundary.

In the Pelmis, Rabat-e Gharehbil, and Kuhe Ozon stratigraphic sections, the thickness of this sequence is 104, 26, and 123 m, respectively (Figures 11d–11f). TST, which consists of shale, limestone, and dolomitic limestone, continues with bioclast packstone-grainstone facies and ends with peloid bioclast wackestone-packstone, which is associated with an open marine environment. MFS is determined by mudstone and bioclast wackestone facies and shows an open marine environment. HST, which is characterized by mudstone bioclast wackestone-packstone, represents a tidal flat and lagoon setting. This sequence ends with sandstone and siltstones of the tidal flat environment.

8.3. Depositional sequence-3

Sequence-3 only consists of TST. (Figures 12a–12c). The lower boundary of this sequence is limited by SB2 (TypeII sequence boundary) in the Robat-e Qarehbil and Kuhe Ozon sections and its upper boundary is limited by SB1 (type I sequence boundary) in Pelmis section. The presence of iron-bearing shale unit and the mineralization of hematite are the most important features of this sequence.

This sequence is not detected in Pelmis section due to the occurrence of a discontinuity at the end of Khoshyeilagh Formation.

The identification of shallow sedimentary facies such as tidal stromatolitic mudstones with dolomitic composition in the upper parts of the Khoshyeilagh Formation in Pelmis section shows a distinct decrease in the depth of the depositional environment in Frasnian-Famennian boundary. In the Pelmis section, the regressive movements and sea level drop caused to the lack of deposition of sediments until Jurassic. The first sediments of this part refer to the Shemshak Formation and the presence of red color laterites at the end of the Khoshyeilagh Formation in the Pelmis section, reveal the shallowing of the basin (Figure 12).

The thickness of this sequence is 93 m and 256 m in Robat-e Qarehbil and Kuhe Ozon sections, respectively. The depositional sequence-3 consists of the alternation of marl limestone, limestone, dolomite, and shale. The sequence begins with bioclast grainstone and continues by mudstone, peloid bioclast wackestone-packstone, and bioclast spicule wackestone-packstone .

The correlation of sequences recognized in Pelmis, Kuhe Ozon, and Robat-e Qarehbil stratigraphic sections are presented in Supplement 2. Based on these correlations, the sequence-1 and sequence-2 are detected in all studied stratigraphic sections, but sequence-3 is just detected in Robat-e Qarehbil and Kuhe Ozon sections. The maximum thickness of sequence-1 is measured in Robat-e Qarehbil and Kuhe Ozon sections while the minimum thickness is recorded in Pelmis section. The maximum thicknesses of the sequence-2 and sequence-3 are measured in Kuhe Ozon section. Sequence-2 shows the minimum thickness in Robat-e Qarehbil and Kuhe Ozon stratigraphic sections.

The recognition of shallow sedimentary facies such as tidal to lagoonal stromatolite mudstones with dominant dolomite and coastal siltstones in the contact zone of Frasnian-Famennian (Figure 13; Supplement 2) reveals a relation between sea level drop in the study area and the global sea level drop of Late Frasnian. As seen in Supplement 2, a sharp sea level drop has been occurred at the detected Frasnian-Famennian boundary.

In the Kuhe Ozon section (Zone II), the evidences of sea level drop and the lack of Famennian conodonts such as *Icriodus cornutus* have been reported, whereas these evidences have not been reported in the Pelmis section. On the other side the identification of *Icriodus-polygnathid* in the studied areas represents a decrease in the depth of sedimentary basin in Famennian-Frasnian boundary. The lack of conodont species such as *Palmatolepis* and also the lack of *polygnathid* facies due to sea level drop in Famennian sequences of the study area correspond with the global charts (Supplement 2). However, the sedimentary basin was shallow in Early Fammenian but during Late Famennian the basin became deeper and fossil population and bioclast spicule wackestone-packstone were formed.

Regarding the identified mudstone and dolomitic facies, the fossil population has been decreased in this area whereas, the fossil contents have considerable increase before and after this point. In the stratigraphic section and after the recognition of conodont biozones, the presence of this boundary has been proved (Supplement 2).

9. Discussion

Upper Devonian marine deposits have been identified and studied in some parts of Iranian plateau such as Alborz-

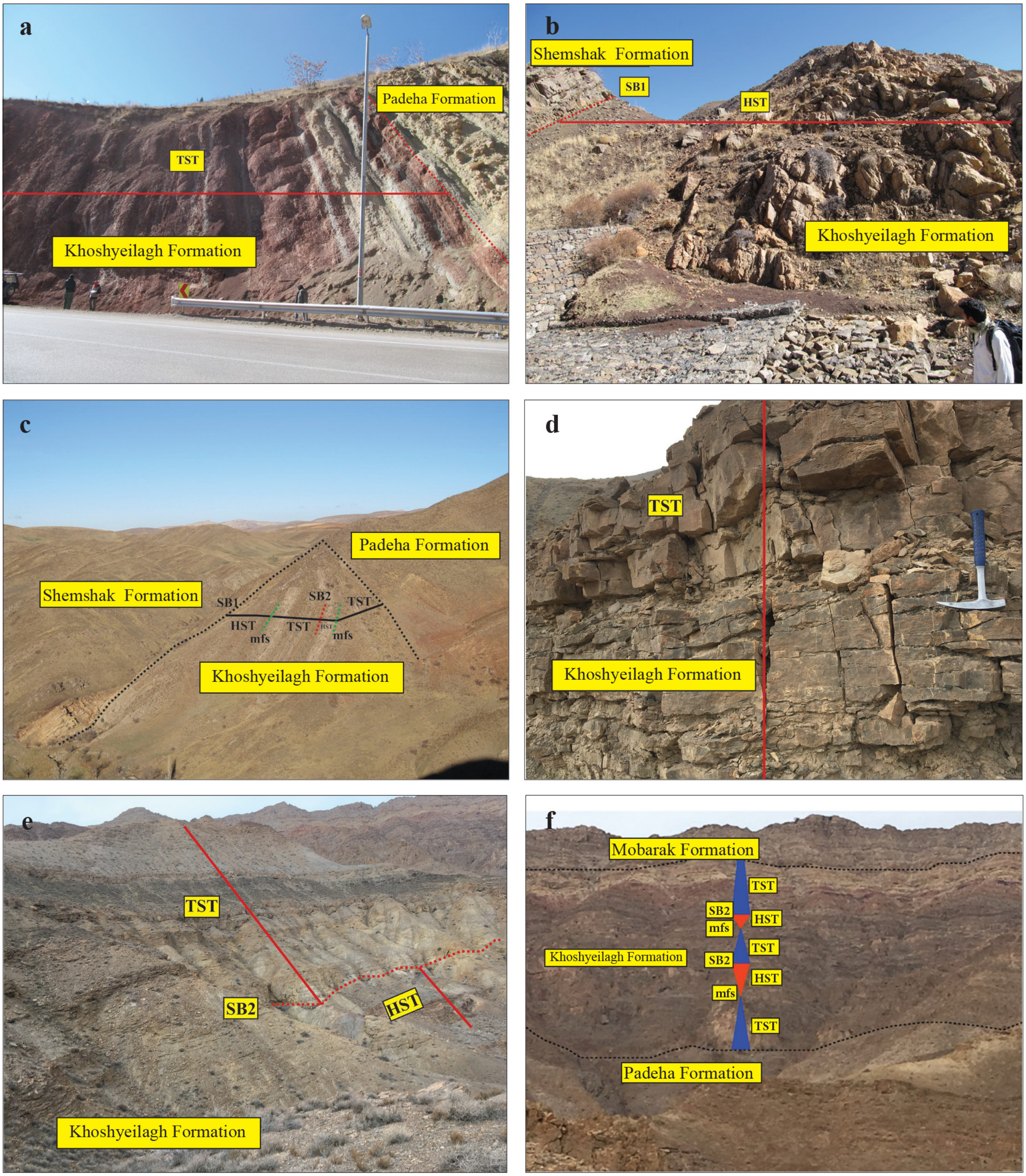


Figure 11. The sequence boundaries and systems tracts in Pelmis section (a–c) and Kuhe Ozon section (d–f); a) Depositional sequence-1, (TST consists of sandstone facies belonging to a shallow shoreface); b) Depositional sequence-2 [HST is composed of carbonate deposits (dolomite) belonging to a lagoon]; c) An overview of the identified sequences of Khoshyeilagh Formation in Pelmis section; sequence boundaries and systems tracts in the Kuhe Ozon section; d) Depositional sequence-2 (TST representing the calcareous deposits related to an open marine environment); e) Depositional sequence-2 and incomplete sequence-3 (HST consists of siltstone and sandstone in a shoreface setting and ends on the boundary of sequence type II); and f) An overview of the identified sequences in the Khoshyeilagh Formation in Kuhe Ozon section.

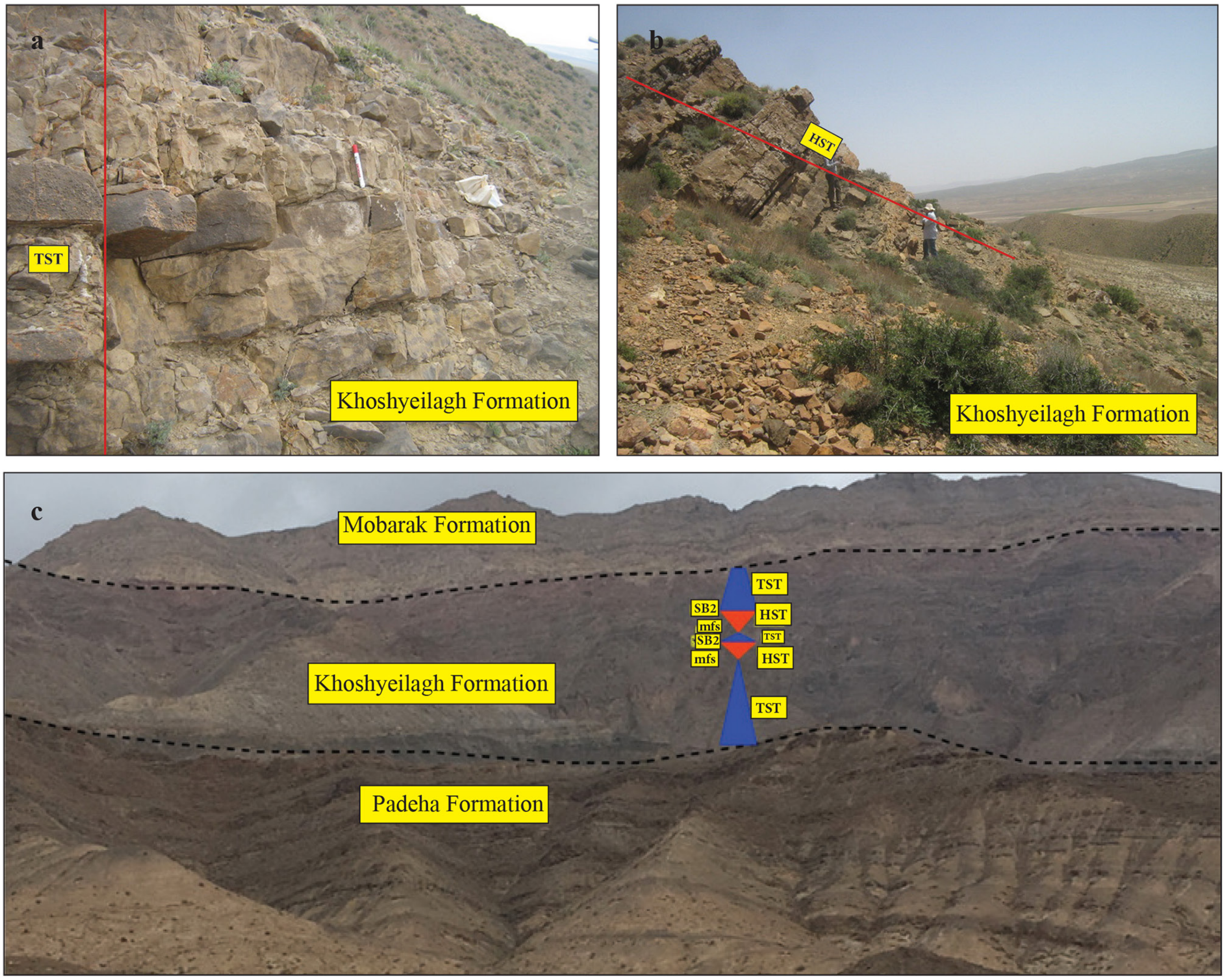


Figure 12. Sequence boundaries and systems tracts in Robat-e Qarehbil section; a) Depositional sequence-3 (TST is composed of calcareous deposits related to an open marine environment in the upper parts of Khoshyeilagh Formation); b) Depositional sequence-3 (HST is composed of dolomitic deposits related to a lagoon environment in the middle part of Khoshyeilagh Formation); and c) An overview of the identified sequences in Khoshyeilagh Formation in the Robat-e Qarehbil section.

Azerbaijan zone, Central Iran, Kopeh-Dagh, Sanandaj-Sirjan zone, and Zagros belt (Kahgom and Faraghan areas). The Khoshyeilagh Formation in the eastern part of Alborz range and Kopeh-Dagh zone contain Upper Devonian deposits. The Middle Devonian transgression in these areas has most likely occurred in SW-NE direction. Moreover, during the Late Devonian, an extensive regression occurred in the northern parts. The main parts of the northern area were exposed above the sea level in the Late Devonian, unlike Khoshyeilagh Formation (Afshar Harb, 1994).

In the central Alborz, there is no sign of Lower-Middle Devonian deposits and there are also some ambiguities regarding the presence of Early-Middle Devonian facies in the eastern Alborz and Kopeh-Dagh zone. Furthermore, the lack of similarities between western Alborz and the other Devonian formations caused Alavi and Bolourchi (1973) informally introduce Moli and Ilan-Qareh formations as the equivalents of Devonian deposits in western Alborz (Aghanbati, 2007).

In general, the Devonian period represents a sea level drop pattern (Vail et al., 1977; Heydari, 2008). Although the Late Devonian in the study area shows the reestablishment of ramp conditions and shallow sea level, most parts of the Arabian plate raised and emerged from seawater. During this time, Devonian formations was formed in the east of Zagros, which is named Zakeen Formation. The terrigenous Zakeen Formation is the representative of Devonian deposits of Zagros zone (Ghavidel-Syooki, 1998). This formation is the equivalent of the Khoshyeilagh

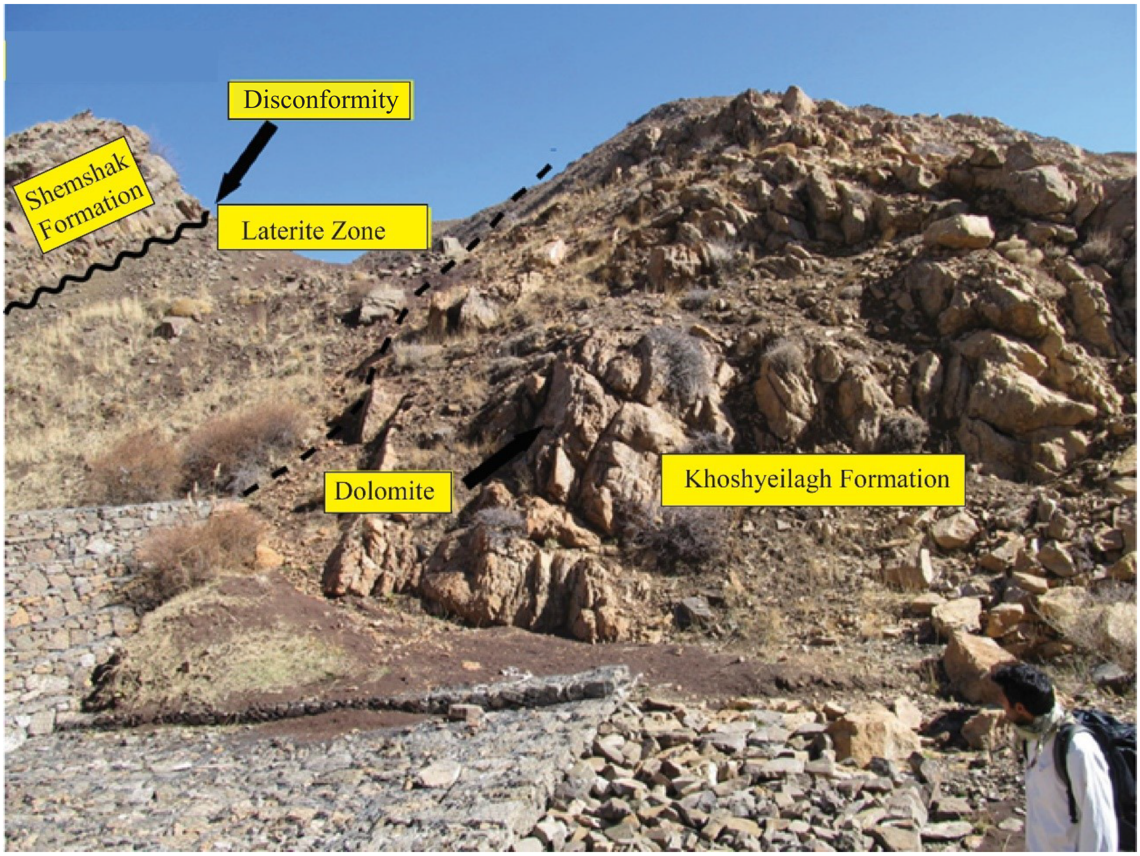


Figure 13. The dolomitic layer in the upper part of the Khoshyeilagh Formation and contact with Shemshak Formation along with the identified unconformity and lateritic horizon.

Formation in Zagros zone (Al-Husseini, 1991) and does not show strong similarities with the Khoshyeilagh Formation in lithology and fossil contents.

A sea level transgression was started in Late Devonian after a hiatus in Late Silurian (Vail et al., 1977), and the sea level reached the maximum level. This condition caused the formation of a complete depositional sequence in the Arabian plate. This complete depositional sequence is observable in Turkey (Özkan et al., 2019), Iraq (Al-Juboury and Al-Hadidy, 2008), Saudi Arabia (Al-Hajri et al., 1999), Oman (Nairn and Alsharhan, 1997), and the south of Iran (Hashmie et al., 2016) (Figure 2). The Upper Devonian Tawil Formation and the Middle Devonian Juaf Formation are the remnants of this sequence (Al-Husseini, 1991; Al-Hajri et al., 1999).

Jubah Formation was deposited in Syria, Iraq, and the central parts of the Arabian plate during Early-Middle Devonian (Al-Husseini, 1991). At the same time, the shallow water conditions were dominant in Turkey, Oman, and Zagros (Konert et al., 2001). It is worth to note that before Emsian there was no sign of sedimentation in Turkey, Syria, and Iraq (Al-Husseini, 1991; Konert et al., 2001), and there is a lack of sedimentation related to uplift structures (Al-Husseini, 1991).

The absence of Lower-Middle Devonian deposits in some parts of Zagros can also be related to the uplift structures caused by the epeirogenic activities of Hercynian orogeny (Faqira and Rademakers, 2009).

10. Conclusions

Three stratigraphic sections including Pelmis, Robat-e Qarehbil, and Kuhe Ozon in the northeast of Iran were evaluated in this study. The field and laboratory observations revealed 15 facies including 3 clastic facies, 11 carbonate facies, and 1 hybrid facies throughout the Khoshyeilagh Formation. These facies have been deposited in five subenvironments including shoreface, tidal flat, lagoon, shoal, and open marine.

According to the obtained data, the homoclinal ramp model is proposed for the formation of Khoshyeilagh Formation in the northeast of Iran. The carbonate-clastic sequences in Khoshyeilagh Formation consist of three third-order depositional sequences and show a deepening in the depositional environment.

The recognized biozones and facies in the study area show that the Upper-Devonian sea was the host of various fossil groups in different depositional depths, so that the ostracods, brachiopods, tentaculites, *Umbella*, and conodonts such as *Icriodus* and *Polygnathus* which are the representatives of a shallow environment, are recognized in the studied succesions. With a regard to the recorded fossils and the comparison of the sedimentary basins of Zagros, central Iran, Bahrami et al. (2014) and Turkey (Çapkınoğlu and Gedik, 2000) and Armenia (Ginter et al., 2011) illustrates that the Iranian plateau was located in the northern part of the Gondwana supercontinent.

The transgressive systems tracts (TST) for these sequences is mainly composed of the shoal and open marine facies and the maximum flooding surface (MFS) is characterized by bioclast wackestone facies. The highstand systems tracts (HST) is composed of the alternation of the lagoon, tidal flat and shoreface facies. Furthermore, several sequence boundaries have been recognized in Khoshyeilagh Formation, including SB1 (type I sequence boundary) and SB2 (type II sequence boundary). The sea level changes and variations in depositional conditions were recognized precisely and some considerable results were obtained:

The comparison of recognized sequences in the studied sections shows some similarities and differences. A high conformity is seen in the lower and middle parts and the least conformity is observable in the upper parts of the sequences. There is good accordance related to recorded biozones in the upper parts of the sequences. The recorded differences may occur due to some factors such as difference in the sediment supply, the topography, the rate of subsidence, and the tectonic setting of the area.

There is reasonable accordance between Devonian sea levels and global patterns in the prepared stratigraphic columns, where minimum sea levels in Frasnian-Famennian boundaries are recognized, like the other parts of the world.

The paleontological studies on conodonts species and the other faunas of the Khoshyeilagh Formation in the northeast of Iran led to the identification of 7 conodont species and subspecies and 19 species and macro- and microfossil genera. According to the fossil population distribution throughout the studied sections, two conodont biozones and one fossil biozone were detected which are Upper *rhenana-linguiformis*, Lower *triangularis*-Lower *crepida*, and *Umbella* Zone, respectively.

Acknowledgment
This study has been supported by the Islamic Azad University Science and Research Branch (Tehran, Iran) and the National Iranian Oil Company (Tehran, Iran). The authors would like to express their deepest appreciations to the staffs of these organizations.

References

Adabi MH, Salehi MA, Ghabeishavi A (2010). Depositional environment, sequence stratigraphy and geochemistry of lower Cretaceous carbonates (Fahliyan Formation), south-west Iran. Journal of Asian Earth Sciences 39 (3): 148-160.

Adachi N, Ezaki Y, Liu J (2004). The origins of peloids immediately after the endpermian extinction, Guizhou Province, South China. Sedimentary Geology 164 (1): 161-178.

Afshar-Harb A (1994). Kopet Dagh geology. 1st ed. Tehran, Iran: Geological Survey and Mineral Explorations of Iran (in Persian).

Ahmadzadeh-Heravi M (1975). Brachiopods and Conodonts of the sediments of South of Bojnord and the stratigraphic results of them. Journal of Faculty of Engineering (University of Tehran) 45: 20-35.

Alavi M, Bolourchi MH (1973). Explanatory text of the Maku Quadrangle Map (1:250,000). Tehran, Iran: Geological Survey of Iran..

Al-Hajri SA, Filatoff J, Wender LE, Norton AK (1999). Stratigraphy and operational palynology of the Devonian System in Saudi Arabia. GeoArabia 4 (1): 53-68.

Al-Husseini M (1991). Tectonic and depositional model of the Arabian and adjoining plates during the Silurian-Devonian. American Association of Petroleum Geologists Bulletin 75: 108-120.

Al-Juboury A, Al-Hadidy A (2008). Facies and depositional environments of the Devonian–Carboniferous succession of Iraq. Geological Journal 43 (2-3): 383-396.

Al-Juboury A, AL-Hadidy AH (2009). Petrology and depositional evolution of the paleozoic rocks of Iraq. Marine and Petroleum Geology 26 (2): 208-231.

Al-Sharhan AS, Nairn AEM (1997). Sedimentary Basins and Petroleum Geology of the Middle East. 1st ed. Amsterdam, Netherlands: Elsevier.

Alsharhan AS (2006). Sedimentological character and hydrocarbon parameters of the middle Permian to Early Triassic Khuff Formation, United Arab Emirates. GeoArabia 11: 121-158.

Aqanbati A (2007). Geology of Iran. 1st ed. Tehran, Iran: Geological Survey and Mineral Explorations of Iran.

Ashouri AR (2002). Palmatolepis (conodonta; Late Devonian) from the Tabas region, east Iran. Iranian International Journal of Science 3: 187-220.

Ashouri AR (2004). Late Devonian and Middle-Late Devonian conodonts from eastern and northern Iran. Revista Española de Micropaleontología 3: 355-365.

Ashouri AR (2006). Middle Devonian-Early Carboniferous conodont faunas from the Khoshyeilagh Formation, Alborz Mountains, north Iran. Journal of Sciences 17: 53-65.

Bahrami A, Corradini C, Yazdi M (2011a). Conodont biostratigraphy across the Devonian-Carboniferous boundary in the Shotori Range, Tabas area, central east Iran Microplate. Bollettino Della Societa Paleontologica Italiana 50 (1): 35-53.

Bahrami A, Gholamalian H, Corradini C, Yazdi M (2011b). Upper Devonian conodont biostratigraphy of Shams Abad section, Kerman, Iran. Rivista Italiana di Paleontologia e Stratigrafia 117 (2): 199-209.

Bahrami A, Corradini C, Over DJ, Yazdi M (2013). Conodont biostratigraphy of the upper Frasnian- lower Famennian transitional deposits in the Shotori Range, Tabas area, Central-East Iran Microplate. Bulletin of Geosciences 88: 369-388.

Bahrami A, Zamani F, Corradini C, Yazdi M, Ameri H (2014). Late Devonian (Frasnian) conodonts from the Bahram Formationin the Sar-e-Ashk Section, Kerman Province, Central-East Iran Microplate. Bollettino Della Societa Paleontologica Italiana 53 (3): 179-188.

Brew G, Barazangi M (2001). Tectonic and geologic evolution of Syria. GeoArabia 6 (4): 573-616.

Berberian M, King GCP (1981). Toward a palaeogeography and tectonic evolution of Iran. Canadian Journal of Earth Sciences 18: 210-265.

Bodzioch A (2003). Calcite pseudomorphs after evaporates from the Muschelkalk (Middle Triassic) of thy Holy Cross Mountains (Poland). Geologos 7: 169-180.

Bozorgnia F (1973). Paleozoic foraminiferal biostratigraphy of central and east Alborz Mountains, Iran. 1st ed. Tehran, Iran: National Iranian Oil Company Publication (in Persian).

Branson EB, Mehl MG (1934). Conodonts from the Grassy Creek Shale of Missourri. The University of Missouri Studies 8: 171-259.

Brice D, Lafuste J, Lapparent AF, De Pillet J, Yassini I (1974). Etude de deux gisements paleozoiques (Silurien et Devonien) de Elbourz oriental (Iran). Annales de la Société géologique du Nord Lille 93: 177-218.

Burchette TP, Wright VP (1992). Carbonate ramp depositional systems. Sedimentary Geology 79: 3-57.

Çapkınoğlu S, Gedik I (2000). Late Devonian conodont fauna of the Gumusali Formation, the eastern Taurides, Turkey. Turkish Journal of Earth Sciences 9: 69-89.

Carannanate G, Ruberti D, Sirna M (2000). Upper Cretaceous low-energy ramp limestones from the Sorrento Peninsula (southern Apennines, Italy): micro and macrofossil associations and their significance in the depositional sequences. Sedimentary Geology 132 (1): 89-123.

Catuneanu O (2002). Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. Journal of African Earth Sciences 35 (1): 1-43.

Catuneanu O, Abreu V, Bhattacharya JP, Blum MD, Dalrymple RW et al. (2009). Towards the standardization of sequence stratigraphy. Earth Science Reviews 92 (1): 1-33.

Compton RR (1962). Manual of Field Geology. 1st ed. New York, NY, USA: John Wiley and Sons.

Corda L, Brandano M (2003). Aphotic zone carbonate production on a Miocene ramp, Central Apennines, Italy. Sedimentary Geology 161: 55-70.

Da Silva AC, Boulvain F (2006). Upper Devonian carbonate platform correlations and sea level variations recorded in magnetic susceptibility. Palaeogeography, Palaeoclimatology, Palaeoecology 240: 373-388.

Domeier M, Torsvik TH (2014). Plate tectonics in the late Paleozoic. Geoscience Frontiers 5 (3): 303-350.

Dunham RJ (1962). Classification of carbonate rocks according to depositional texture. American Association of Petroleum Geologists Bulletin 1: 108-211.

Elrick M, Read J (1991). Cyclic ramp to basin carbonate deposites, Lower Mississipian, Wyoming and Montana. Journal of Sedimentary Petrology 61: 1194-1224.

Emery D, Myers K (1996). Sequence Stratigraphy. 1st ed. Oxford, UK: Blackwell.

Faqira MM, Rademakers AM (2009). New insights into the Hercynian orogeny, and theirimplications for the Paleozoic Hydrocarbon System in the Arabian plate. GeoArabia 14: 199-228.

Flugel E (2010). Microfacies of Carbonate Rocks, Analysis, Interpretation and Application. 1st ed. Berlin, Germany: Springer.

Folk RL (1980). Petrology of sedimentary rocks. Austin, TX, USA: Hemphill Publishing Company, pp. 51-560.

Ghavidel-Syooki M (1998). Investigation on the Upper Paleozoic strata in Tang-e Zakeen, and introducing Zakeen Formation, Kuhh-e-Faraghan, Zagros basin, South Iran. Scientific Quarterly Journal Geosciences 29: 54-73 (in Persian).

Ghavidel-Syooki M, Owens B (2007). Palynostratigraphy and palaeogeography of the Padeha, Khoshyeilagh, and Mobarak formations in the eastern Alborz Range (Kopet-Dagh region), northeastern Iran. Revue de micropaléontologie 50 (1): 129-144.

Gischler E, Lomando AJ (2007). Offshore sedimentary facies of a modern carbonate ramp, Kuwait, northwestern Arabian-Persian Gulf. Facies 53 (2): 317-317.

Gholamalian H (2006). Biostratigraphy of Late Devonian sequence in Hutk section (North of Kerman) based on conodonts. Geosciences Scientific Quarterly Journal 15: 94-101 (in Persian with English abstract).

Gholamalian H, Kebriaei MR (2008). Late Devonian conodonts from the Hojedk section, Kerman Province, Southeastern Iran. Rivista Italiana di Paleontologia e Stratigrafia 114 (2): 171-181.

Gholamalian H, Hosseini-Nezhad SM, Khosravi Z, Turkzadeh-Mahani I (2011). Late Devonian conodonts from Baghin section, west of Kerman. Geosciences Scientific Quarterly Journal 21 (81): 165-172 (in Persian with English abstract).

Gholamalian H, Hairapetian V, Barfehei N, Mangelian S, Faridi P (2013). Givetian-Frasnian boundary conodonts from Kerman Province, Central Iran. Rivista Italiana di Paleontologia e Stratigrafia 119 (2): 133-146.

Ginter M, Hairopetian V, Grigorian A (2011). Chondrichthyan microfossils from the Famennian and Tournaisian of Armenia. Acta Geologica Polonica 61 (2): 153-173.

Hamdi B, Janvier P (1981). Some conodonts and fish remainsfrom Lower Devonian, northeast of Shahrud, Iran. Geological Suevey of Iran 49: 195-213.

Hashmie A, Rostamnejad A, Nikbakht F, Ghorbanie M, Rezaie P et al. (2016). Depositional environments and sequence stratigraphy of the Bahram Formation (middle–late Devonian) in north of Kerman, south-central Iran. Geoscience Frontiers 7 (5): 821-834.

Heydari E (2008). Tectonic versus eustatic control on supersequences of the Zagros Mountains of Iran. Tectonophysics 451: 56-70.

Hine AC (1977). Lily Bank, Bahamas: history of an active oolite sand shoal. Journal of Sedimentary Petrology 47: 1544-1581.

Kerr SD, Thompson A (1963). Origin of nodular and bedded anhydrite in Permian shelf sediments, Texas and New Mexico. American Association of Petroleum Geologists Bulletin 47: 1726-1732.

Koehrer B, Heymann C, Prousa F, Aigner T (2010). Multiple-scale facies and reservoir quality variations within a dolomite body Outcrop analog study from the Middle Triassic, SW German Basin. Marine and Petroleum Geology 27: 386-411.

Konert G, Afifi AM, Al-Hajri SA, Droste HJ (2001). Paleozoic Stratigraphy and Hydrocarbon Habitat of the Arabian Plate. GeoArabia 6 (3): 407-442.

Laboun AA (2010). Paleozoic tectono-stratigraphic framework of the Arabian Peninsula. Journal of King Saud University-Science 22: 41-50.

Lasemi Y, Ghomashi M, Amin-Rasouli H, Kheradmand A (2008). The lower Triassic Sorkh shale formation of the Tabas block, east central Iran: succession of a failed-rift basin at the paleotethys margin. Carbonate Evaporite 23 (1): 21-38.

Martin-Chivelet J (2003). Quantitaive analysis of accommodation patern in carbonate platform an example from the mid-Cretaceous of South East Spain. Palaeogeography, Palaeoclimatology, Palaeoecology 200: 83-105.

Maurer F, Martini R, Rettori R, Hillgärtner H, Cirilli S (2009). The geology of Khuff outcrop analogues in the Musandam Peninsula, United Arab Emirates and Oman. GeoArabia 14 (3): 125-158.

Mazaheri J (1999). Geological map of Bojnourd (1:100,000). Geological Survey of Iran, Sheet 7463, Tehran, Iran.

Miall AD, Arush M (2001). Cryptic sequence boundaries in braided fluvial successions. Sedimentology 48 (5): 971-985.

Nabavi MH (1976). An introduction to the geology of Iran. 1st ed. Tehran, Iran: Geological Survey of Iran (in Persian).

Nairn AEM, Alsharhan AS (2003). Sedimentary Basins and Petroleum Geology of the Middle East. 1st ed. Amsterdam, Netherlands: Elsevier.

Nichols G (2000). Sedimentology and Stratigraphy. 1st ed. Oxford, UK: Blackwell Science.

Özkan R, Nazik A, Munnecke A, Demiray DG, Schindler E et al. (2019). Givetian/Frasnian (Middle/Upper Devonian) transition in the eastern Taurides, Turkey. Turkish Journal of Earth Sciences 28 (2): 207-231.

Palma RM, Lopez-Gomez J, Piethe RD (2007). Oxfordian ramp system (La Manga Formation) in the Bardas Blancas area (Mendoza Province) Neuquen Basin, Argentina: facies and depositional sequences. Sedimentary Geology 195 (3): 113-134.

Pettijohn FJ (1975). Sedimentary rocks. 1st ed. New York, NY, USA: Harper and Row.

Purser BH (1973). The Persian Gulf. Holocene carbonate sedimentation and diagenesis in a shallow epicontinental sea. 1st ed. New York, NY, USA: Springer Verlag.

Reineck HE, Singh IB (1975). Depositional Sedimentary Environments. 1st ed. New York, NY, USA: Springer Verlag.

Reineck HE, Singh IB (1986). Depositional sedimentary environments, with reference to terrigenous clastics. 2nd ed. Berlin, Germany: Heidelberg.

Reolid M, Gaillard C, Lathuiliere B (2007). Microfacies, microtaphonomic traits and foraminiferal assemblages from upper jurassic oolitic-coral limestones: stratigraphic fluctuation in a shallowing-upward sequence (French jura, Middle Oxfordian). Facies 53: 553-574.

Ruban DA, Al-Husseini M, Iwasaki Y (2007). Review of Middle East paleozoic plate tectonics. GeoArabia 12: 35-56.

Salamati R, Shafiei A, Karimi H (2001). Geological map of Robat-e Qarabil (1:100,000). Geological Survey of Iran, Sheet 7263, Tehran, Iran.

Sandberg CA, Dreesen R (1984). Late Devonian icriodontid biofacies models and alternate shallow-water conodont zonation. Geological Society of America Special 196: 143-178.

Sannemann D (1955). Oberdevonische Conodonten (to II alpha). Senckenbergiana Lethaea 36: 123-156.

Soheily M, Sahandi MR (1999). Geological map of Sankhast (1:100,000). Geological Suevey of Iran, Sheet 7363, Tehran, Iran.

Spalletti LA, Poiré DG, Schwartz E, Veiga GD (2001). Sedimentologic and sequence stratigraphic model of a Neocomian marine carbonate-siliciclastic ramp: Neuquén Basin, Argentina. Journal of South American Earth Sciences 14: 609-624.

Stauffer RC (1940). Conodonts from the Devonian and associated clays of Minnesota. Journal of Paleontology 14: 417-435.

Stocklin J (1968). Structural history and tectonics of Iran: A review. American Association of Petroleum Geologist Bulletin 52 (7): 1229-1258.

Sweet WC (1988). The Conodonta: morphology, taxonomy paleoecology, and evolutionary history of a long-extinct animal phylum. Oxford Monographs on Geology and Geophysics 10: 212-250.

Tomasovych A (2004). Microfacies and depositional environment of an upper triassic intra-platform carbonate basin: the fatric unit of West Carpathians (Slovakia). Facies 50: 77-105.

Tucker ME, Wright VP (1990). Carbonate Sedimentology. 1st ed. Oxford, UK: Blackwell Science Ltd.

Tucker ME (2009). Sedimentary petrology: an introduction to the origin of sedimentary rocks. Hoboken, NJ, USA: John Wiley & Sons.

Vail PR, Mitchem RM, Thompson S (1977). Seismic stratigraphy and global change of sea-level. In: Payton CE (editor). Seismic stratigraphy-applications to hydrocarbon exploration. American Association of Petroleum Geologists Bulletin 83-97.

Van Buchem FSP, Razin P, Homewood PW, Oterdoom WH, Philip J (2002). Straigraphic organization of carbonate ramps and organic rich intrashelf basins: Natih formation (middle Cretaceous) of northern Oman. American Association of Petroleum Geologists Bulletin 86: 21-53.

Walker RG (2006). Facies models revisited: introduction. In: Posamentier HW, and Walker RG (editors). Facies Models Revisited SEPM Special Publication 84: 1-17.

Warren JK (2006). Evaporites: Sediments, Resources and Hydrocarbons. 1st ed. Berlin, Germany: Springer Verlag and Heidelberg.

Weddige K (1984a). Externally controlled late Paleozoic events of the Iran Plate. Neues Jahrbuch Fur Geologie Und Palaontologie-Monatshefte 168: 278-286.

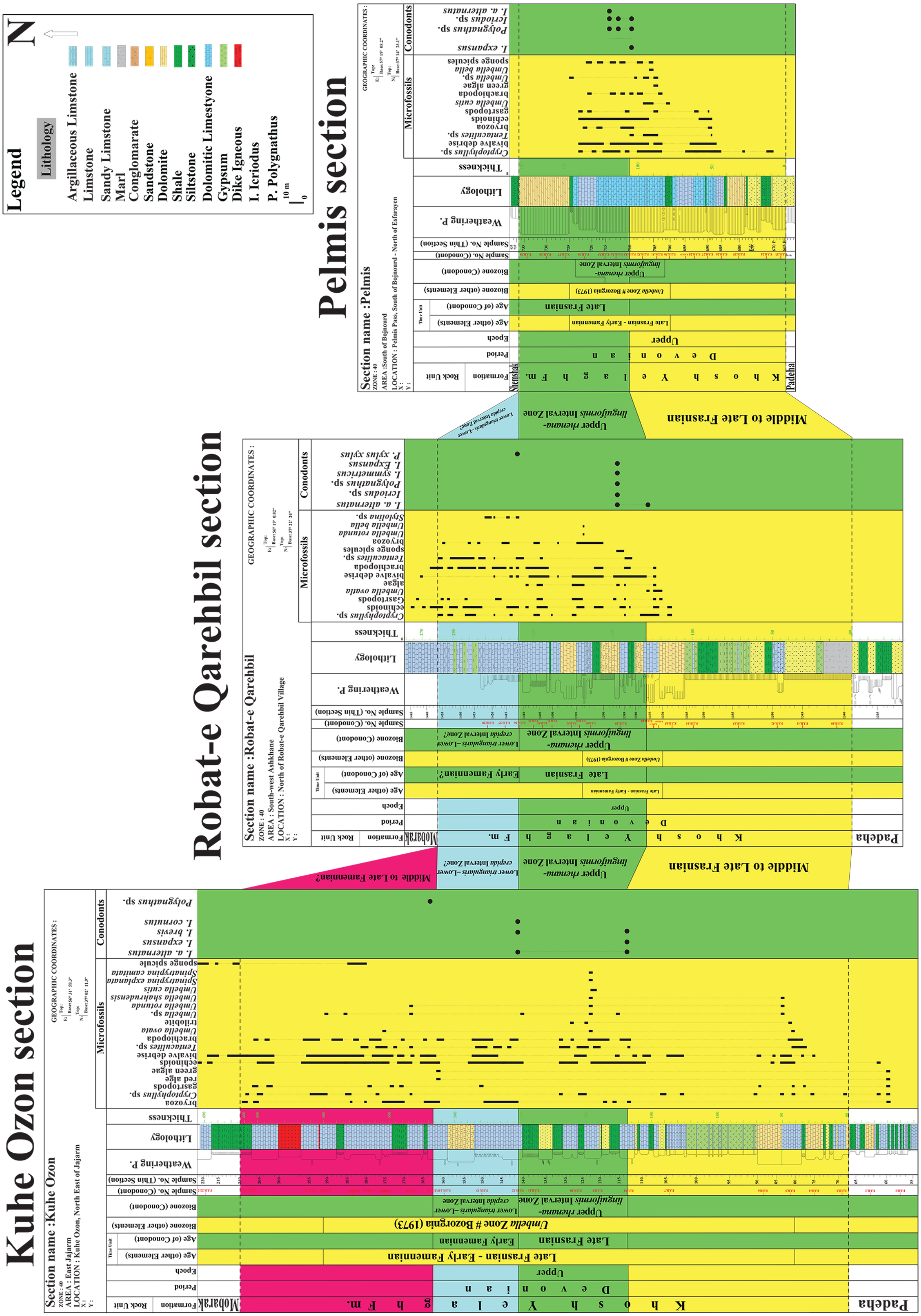
Weddige K (1984b). Zur Stratigraphie und Paläogeographie des Devons und Karbons von NE Iran. Senckenbergiana Lethaea 65:179-223.

Wehrmann A, Yılmaz I, Yalçın MN, Wilde V, Schindler E et al. (2010). Devonian shallow-water sequences from the North Gondwana coastal margin (Central and Eastern Taurides, Turkey): Sedimentology, facies, and global events. Gondwana Research 17: 546-560.

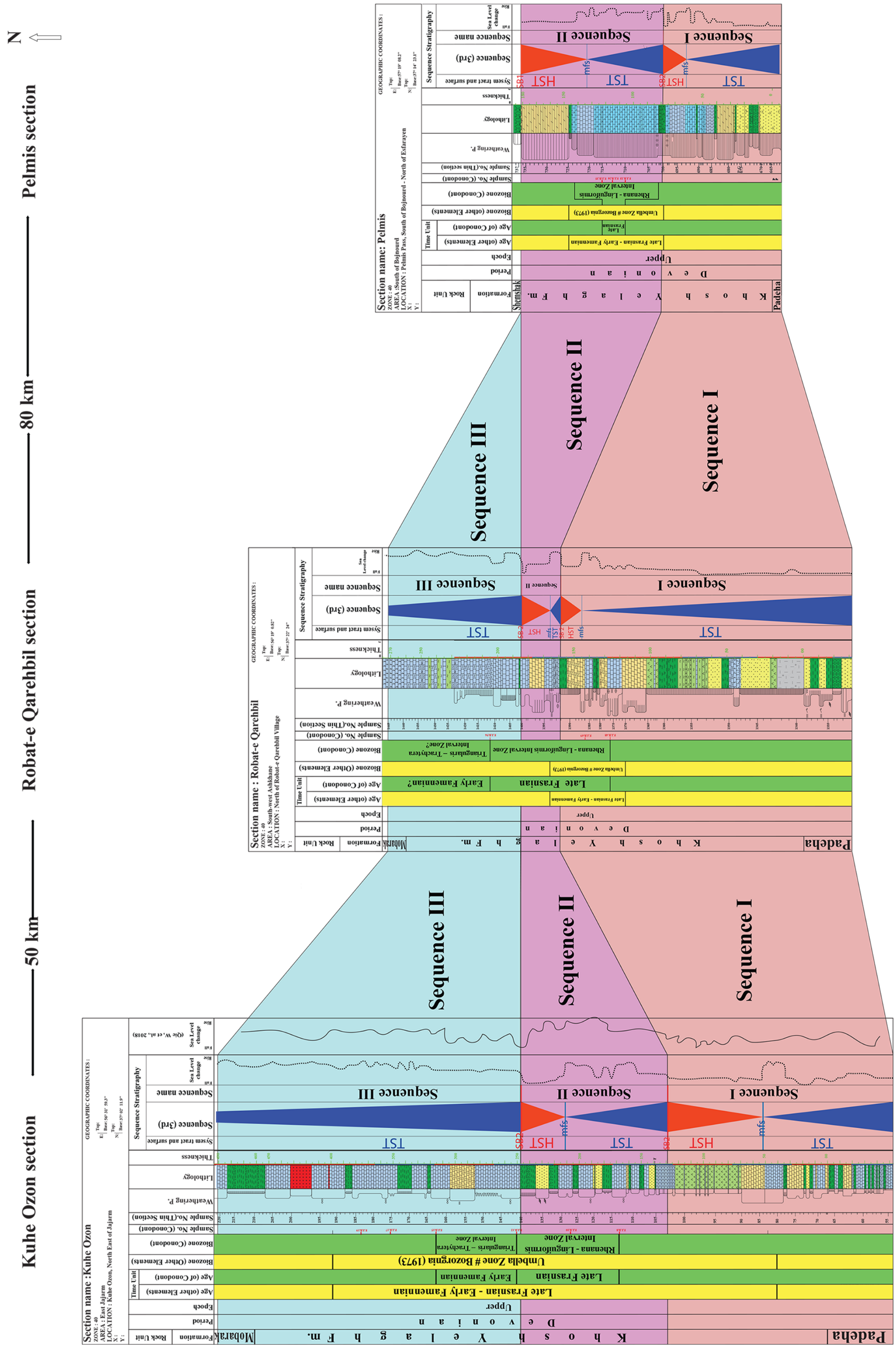
Wendt J, Kaufmann B, Belka Z, Farsan N, Karimi-Bavandpur A (2002). Devonian/Lower Carboniferous stratigraphy, facies patterns and palaeogeography of Iran, Part II. Northern and central Iran. Acta geologica Polonica 55: 31-97.

Wilson JL (1975). Carbonate Facies in Geologic History. 1st ed. New York, NY, USA: Springer Verlag.

Ziegler W, Sandberg CA (1990). Late Devonian standard conodot zonation. In: Ziegler W (editor). First International Senckenberg Conference and 5th European conodont Symposium Contribution (ECOS V). Courier Forschungs-Institute Senckenberg 121: 1-115.



Supplement 1. The correlation of the biozones recognized in the studied stratigraphic sections.



Supplement 2. The correlation of the depositional sequences recognized in the studied stratigraphic sections.