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Research Paper

The lower parts of the Oligo–Miocene Qom Formation in the Kegharaki (SE Jiroft) and Shurab (SE Qom) areas: biostratigraphy, microfacies, and depositional environments

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Abstract
In order to determine the transgression time of the Tethyan Seaway in the Jiroft and Qom areas, and to analyzis depositional conditions at the same time, the basal parts of two exposed sections (Kegharaki and Shurab) were studied in terms of biostratigraphy, microfacies, and depositional environments. In the Kegharaki section, larger benthic foraminifera are mainly represented by nummulitids, lepidocyclinids, and *Amphistegina*. In the Shurab section foraminifera are mainly represented by miliolids, *Operculina*, *Amphistegina*, and textularids. The presence of *Nummulites fichteli/intermedius*, *Nummulites vascus*, and lepidocyclinids in the lower parts of the Kegharaki section indicates that the basal deposits could be attributed to the late Rupelian. The basal part of the Shurab section is indicative of the late Rupelian?–Chattian. Besides, the presence of tuffaceous layers in the study sections is indicative of contemporaneous volcanic activity. Ten microfacies were identified in the basal parts of the study sections. Microfacies associations of the Kegharaki section cover a range of subdepositional environments from open marine to open lagoon environments. Coral patch reefs are present, but there is no reef complex with sigmoidal geometries. Microfacies cover a range of subenvironments from restricted lagoons to open marine environments in the Shurab section. Most parts of the Kegharaki section with an association of large and flat perforate foraminifera were deposited in normal saline waters in open marine environments (in the middle ramp). The Shurab section was deposited mainly in the restricted lagoons to open marine environments. The abundance of larger benthic foraminiferal and coralline red algae and coral facies indicates a tropical-subtropical palaeoenvironment.
Keywords: Oligo–Miocene, Larger benthic foraminifera, Biozonation, Tethyan Seaway, Iran.

Introduction

Due to the connection between Eastern Tethys (the proto-Indian Ocean) and the Western Tethys (the proto-Mediterranean Sea) regions in the Iranian Plate at the same time, an advance in the knowledge of the Qom Formation biostratigraphy (and transgression time) is of major importance (Mohammadi et al. 2011, 2013, 2015, 2019; Mohammadi and Ameri 2015, 2024; Daneshian and Ramezani Dana 2018; Mohammadi 2020, 2021c, 2023a). The Qom Formation (with Rupelian– Burdigalian age range) was deposited along the northeastern coast of the Tethyan Seaway (Reuter et al. 2009a) in Middle Iran, located between the Paleotethys and Neotethys suture zones (Aghanabati 2004; Mohammadi et al. 2013, 2015; Mohammadi 2021c, Mohammadi and Ameri 2024; Mohammadi and Ghaedi 2024) (Fig. 1). Deposition of the Qom Formation took place in three NW–SE-trending basins (>1800 km length) including Central Iran back-arc basin, Urumieh–Dokhtar magmatic arc (Intra-arc basin), and Sanandaj–Sirjan fore-arc basin (Mohammadi et al. 2013, 2015; Mohammadi 2020; 2021c, 2023a, 2023b; Mohammadi and Ameri 2024; Mohammadi and Ghaedi 2024) (Fig. 1). The outcrops of the Qom Formation are extended from Khoy and Maku (NW Iran) to northwest of the Jazmurian Lake (SE Iran) (Rahimzadeh 1994; Mohammadi et al. 2011, 2013) (Fig. 1).

Due to high facies changes of the Qom Formation and its deposition in intermountain basins, defining a depositional model for this formation for the whole of Middle Iran is impossible (Mohammadi et al. 2011). According to Mohammadi et al. (2019), different depositional models such as rimmed shelf, open shelf, homoclinal ramp, carbonate ramp, mixed carbonate–siliciclastic homoclinal ramp, carbonate platform, and epicontinental platform are suggested for deposition of the Qom Formation in different areas.

Based on Mohammadi (2023a, 2023b) all reported early

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Rupelian strata (as the oldest deposits) of the Qom Formation (introduced as the "Varkan Member" in Mohammadi 2023b) are restricted to southwestern and southern Kashan. Mohammadi (2023a) proposed the following two scenarios for the transgression of the Tethyan Seaway over the Iranian plate: (1) considering the common trend of the transgression of the Tethyan Seaway over the Iranian Plate (from southeast to northwest; Mohammadi et al. 2013), the oldest deposits must be deposited in southeastern Iran, but they have not been reported to date; (2) there was a sea transgression from the Zagros Basin to southwestern and southern Kashan areas, then it transgressed both northwestward and southeastward contemporaneously. Mohammadi (2023a) noted that undoubtedly further works are required to confirm or rebut these scenarios. Furthermore, little information is available on the southeasternmost outcrops of the Qom Formation. Besides, the northmost Rupelian deposits of the Qom Formation are reported from the Khurabad section (20 km SE Qom City; Mohammadi et al. 2015; Mohammadi 2020, 2023a). Accordingly, dating the transgression time of the Tethyan Seaway in Jiroft and Qom areas and analyzing of depositional conditions at the same time is the focus of this paper. Therefore, the Shurab section (SE Qom; located between the Khurabad section and the type locality of the "Varkan Member") and the Kegharaki section (SE Jiroft, as one of the southeasternmost outcrops of the Qom Formation) were sampled in order to analyze biostratigraphy, sedimentary microfacies and depositional environments of their basal parts.

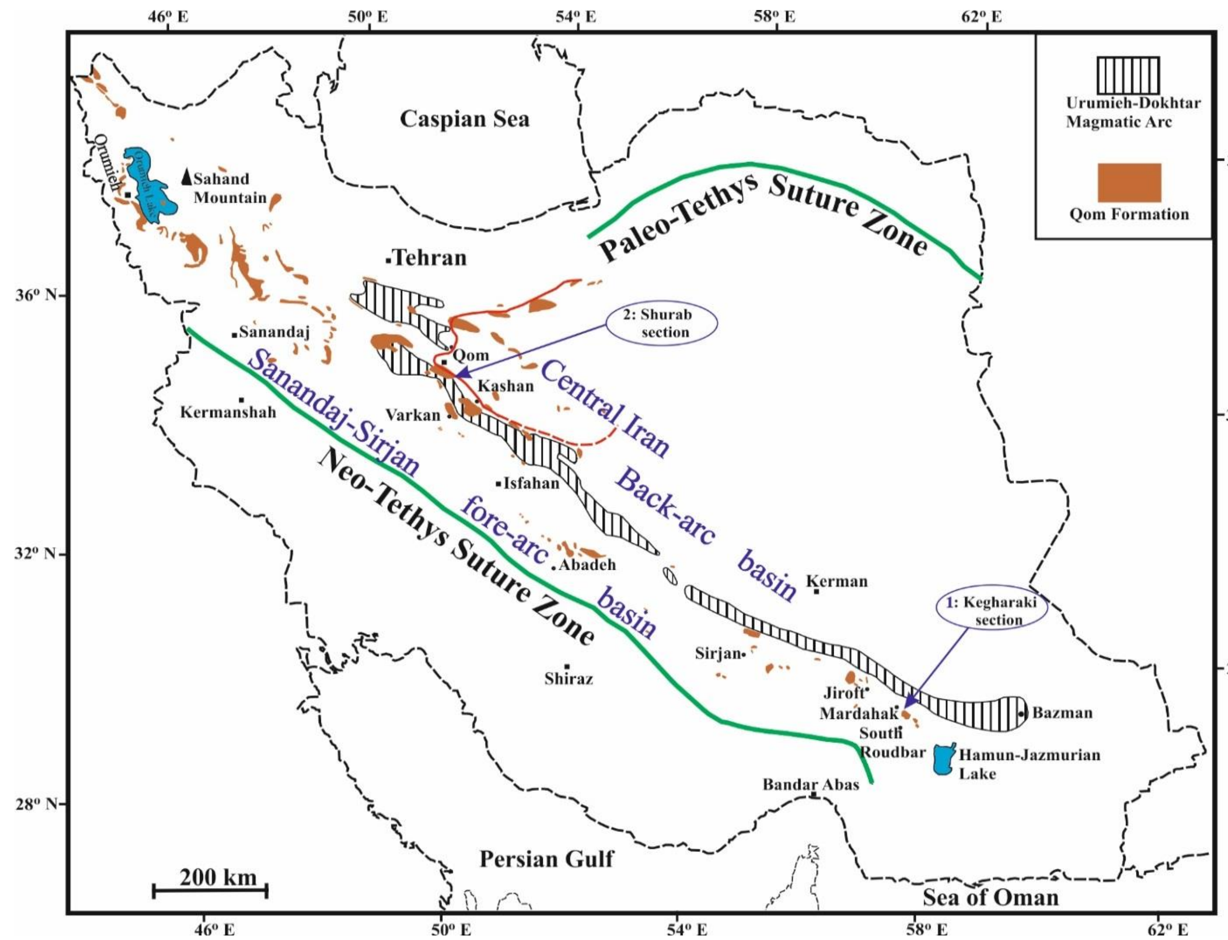

Fig 1- Map showing the distribution of the Urumieh–Dokhtar Magmatic Arc, the Qom Formation outcrops, evaporate deposits (concave side of the red line), suture zones of the Paleotethys and Neotethys in Iran, and locations of the study sections (after Mohammadi et al. 2013, Mohammadi 2021c).

Previous works

Scientific interest in the Qom Formation followed the discovery of oil in 1934. Rahaghi (1980) proposed an Oligocene–Miocene age for the Qom Formation deposits. The list of the main research on the Qom Formation (from 1858 to 2012) is presented by Mohammadi et al. (2013). By the 1990s, deciphering the details of this part of the Tethyan Seaway was recognized as essential to understanding the connection between the Eastern Tethys (the proto-Indian Ocean) and the Western Tethys regions (the proto-Mediterranean Sea). Sedimentary facies and depositional environments/models of the Qom Formation (mostly of the back-arc basin) have been studied by many researchers, listed in Mohammadi et al. (2019), and Mohammadi (2020, 2021c). Maghfori Moghadam et al. (2017), Mahyad et al. (2019), Mohammadi et al. (2019), Mohammadi (2020, 2021c), Safari et al. (2020a, b, c, d), Aftabi Arani et al. (2023), Sharifi et al. (2023), Piller et al. (2024), and Mohammadi and Ghaedi (2024) are amonge the newest most important articles on sedimentary facies and depositional environments of the Qom Formation (Table 1). Besides, evaporate deposits (Mohammadi et al. 2013), terrigenous units (Mohammadi 2021a), coral reefs

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and coral facies (Mohammadi 2021b), and pyroclastic deposits (Mohammadi 2022) of the Qom Formation are studied in terms of temporal and spatial distribution. It is worth mentioning that the Shurab section has studied in terms of sequence stratigraphy (Imandoust and Amini 2005), sedimentary environment and microfacies of c and f members (Fathi 1995), sedimentary environment of a and b members (Abasi 1995). In addition, the Khurabad section, Kuh-e Bichareh, and Kuh-e Rezaabad which are located in NW of the Shurab section were studied by Mohammadi (2020), Daneshian et al. (2008), and Keshavarzi (1997), respectively.

The main researches on the biostratigraphy of the Qom Formation are listed in Mohammadi (2023a). Mohammadi (2023a) presented a new formal biozonation (for age dating of the Qom Formation), consisting of five biozones covering Rupelian, Chattian, Aquitanian, and Burdigalian stages, and differentiated them. The new biozonation subdivides the Rupelian stage into "early Rupelian" and "late Rupelian", based on the first appearances of lepidocyclinids in the latter one.

Mohammadi (2024) re-examined the Qom Formation's biostratigraphy and age interpretations of four stratigraphic sections (Abadeh, Zefreh, Chalheghareh, and Qom) and proposed revisions. These sections were previously studied within an Austrian/German collaboration project (Schuster and Wielandt 1999; Harzhauser 2000, 2004; Mandic 2000; Harzhauser et al. 2002; Schuster 2002a, b, c; Berning et al. 2009; Reuter et al. 2009a, b), and their detailed biostratigraphy was discussed in Reuter et al. (2009a). However, some age-based interpretations were inconsistent with the biostratigraphic data. Mohammadi (2024) expressed that the main points of critique are the possible misidentification of the planktic foraminifers. Unfortunately, the age-dating and subdivisions by Reuter et al. (2009a) were based upon interpretations of those sections previously reported in several articles (Schuster and Wielandt 1999; Harzhauser 2000; Mandic 2000; Harzhauser et al. 2002; Schuster 2002a, b, c; Harzhauser 2004; Berning et al. 2009). Consequently, it is not advisable to follow the biochronostratigraphic interpretations made in the mentioned literature.

More recently other relevant research were done by Khaksar (2020), Navavajary et al. (2021), Noroozpour (2021), Rahiminejad et al (2022), Aftabi Arani et al. (2023), Lázár et al. (2023), Mohammadi (2023b), Yazdi-Moghadam et al. (2023), and Mohammadi and Ameri (2024) (Table 1).

Table 1- List of the main new research on biostratigraphy, microfacies, and depositional environments/models of the Qom Formation and their main results.

Row	Researcher(s) & Year	Study area/ section(s)	Depositional model and environment(s)	Age	Other main results
1	Maghfori Moghadam et al. (2017)	West of Ashtian	ramp; back ramp (alluvium channel, lagoon, and shoal) and the ramp (inner, middle and outer ramp)	Chattian	six different biofacies and have been recognized; and deposited in subtropical waters with oligotrophic conditions.
2	Mahyad et al. (2019)	Andabad (NW Zanjan); Nowbaran (NW Saveh)	open shelf carbonate platform; inner shelf, middle shelf, and outer shelf	Burdigalian; Aquitanian	nine biofacies, one terrigenous facies, and five taphofacies have been recognized
3	Khaksar (2020)	Dobaradar (SE Qom)	marine environment	Rupelian-Burdigalian	tropical-subtropical palaeoenvironment
4	Safari et al. (2020a)	Naragh (NW Delijan); Bijegan (NE Delijan);	open-shelf system; restricted lagoon, open lagoon and, open marine	Rupelian–Chattian	seven microfacies types have been distinguished
5	Safari et al. (2020b)	Vidoje (SW Kashan); Neizar (SE Salafchegan)	open-shelf; restricted and semi-restricted lagoons as well as open marine settings	Rupelian–Chattian	eight microfacies and five microtaphofacies have been recognized
6	Safari et al. (2020c)	Maragh (SW Kashan)	open-shelf carbonate platform; inner shelf, middle shelf, and outer shelf.	Rupelian–Aquitanian	nine microfacies and one terrigenous facies were identified
*7	Navavajary et al. (2021)	NW-W Semnan (Darjazin, Bonak, Arvaneh)	shoreline, lagoon to middle ramp	Burdigalian	
8	Noroozpour (2021)	Posht Darband (NW Hamadan)		*Rupelian–Chattian	
9	Rahiminejad et al. (2022)	Vartun (NE Esfahan)		Aquitanian	deposition took place in warm tropical to subtropical waters
10	Aftabi Arani et al (2023)	Kharzan (NW Ardestan)	open-shelf carbonate platform; lagoonal, patch-reef, and open-marine belts (inner and middle-shelf)	Chattian	seven carbonate microfacies and marl or silty marl facies were identified
11	Lázár et al. (2023)	Jaam (NE Semnan)	shallow-marine depositional environment	Burdigalian	
12	Sharifi et al. (2023)	Ghalibaf (NW Semnan)	rimmed carbonate platform; lagoon, upper slope, lower slope, platform-margin sand shoals and, margin facies.	Aquitanian–Burdigalian	five facies associations and twenty-one microfacies types were identified
13	Yazdi-Moghadam et al. (2023)	Qom area (Dobaradar, Yazdan), only Chattian deposits	warm water shallow-marine (middle ramp) environment with an oligotrophic condition	Chattian	*Postmiogypsinella intermedia* Sirel and Gedik, 2011 is reported for the first time from the upper Chattian Qom Formation
14	Mohammadi and Ameri (2024)	NW Jazmurian Lake (entire of Gonarestan and Tavakolabad; lower part of Bozdan)	mostly open marine environments; however, open and restricted lagoonal deposits were also present	Rupelian–Chattian	tropical-subtropical palaeoenvironment
15	Piller et al. (2024)	Sheikh Jaber (SW Zanjan)	frequent occurrence of planktonic foraminifers indicates an open marine environment with the greatest depth in the Qom Formation but still within the photic zone	late Burdigalian to Langhian	the mollusk fauna exhibits a pure Mediterranean character and no overlap with the Indo-Pacific fauna occurs

*: Due to the absence of Nummulites, the confirmed age is Chattian.

Material & Methods

The lower parts of two stratigraphic sections (Kegharaki in the Sanandaj–Sirjan fore-arc basin, and Shurab in the Central Iran back-arc basin) of the Qom Formation were measured and sampled bed by bed to analyze their biostratigraphy, microfacies, and depositional environments.

The Kegharaki section (28º19'24"N, 58°°7'55"E), is located about 63 km east of Jiroft City, southeast of the Kerman. It could be reached via Anbarabad–Mardahak paved road. Outcrops of the Qom Formation in the Kegharaki section, more than 300 m thick, consist mainly of medium- to thick-bedded and massive limestones, reefal limestone, tuffaceous limestones, and tuffs (Figs. 2, 7). In the Kegharaki section, the lower carbonate unit and tuffaceous limestones (from the base of the section to the top of the tuffaceous limestones, with 65 m in thickness) are at the center of our attention. These units lay on top of an older tuff unit, and the upper boundary is covered by the upper carbonate unit of the Qom Formation, which is mainly composed of thick-bedded and massive limestones, and reefal limestones (Fig. 2). It should be noted that the contact of the tuffaceous limestones and the upper carbonate unit is usually not exposed due to a cover of debris. Larger benthic foraminifera and corals are the most dominant biota in the Qom Formation in the study section. Some lepidocyclinids and nummulitids are sufficiently large to be observed easily with the naked eye on rock surfaces (Figs. 2, 3, 4).

The Shurab section (34º25'34"N, 51º9'22"E), is located in the type locality, where the Alborz, Sarajeh and, Arun oil/gas fields are present. It is located about 34 km from southeastern the Qom City. It could be reached via Qom–Kashan highway/freeway. Basal parts of the Qom Formation in the Shurab section, 45 m in thickness, consist mainly of massive and bedded limestones. A tuffaceous layer, 0.5 m in thickness, is present in the studied succession. But, due to its erosive feature, no sample was taken from this rock unit (Fig. 4). The Qom Formation in the Shurab section conformably overlies the Lower Red Formation (LRF), and its upper boundary is covered by the upper units of the Qom Formation (Figs. 3, 8). The sampled part of the succession could be considered equivalent to "a-member" of the Qom Formation (Rahimzadeh 1994; Abasi 1995; Daneshian et al. 2008). Abasi (1995) attributed the basal 62 m of the Shurab section to the "a-member". The back reef facies, which are deposited in shallow lagoons with permanent water current and circulation, are affected by volcanic activities (Abasi 1995).

A total of 46, and 36 samples were collected from Kagharaki, and Shurab sections, respectively, based on field evidence and lithofacies changes. Sampling intervals were mostly between 1 to 2 m (Figs. 7, 8). All the collected samples were lithified rock samples. Random thin sections (2.5 cm × 7.5 cm) were taken from samples. The samples cover only the lower part of the study sections. All samples were studied in detail with particular attention paid to their biotic components, especially larger benthic foraminifera, coralline red algae, and corals. The generic classification of foraminifera follows Loeblich and Tappan (1988) and BouDagher-Fadel (2018). The foraminiferal-based new biozonation of the Qom Formation (Mohammadi 2023a) is applied for age dating. However, the age of the Kagharaki section is briefly discussed in Mohammadi (2022). The carbonate rocks were classified based on the schemes of Dunham (1962) and Embry and Klovan (1971).

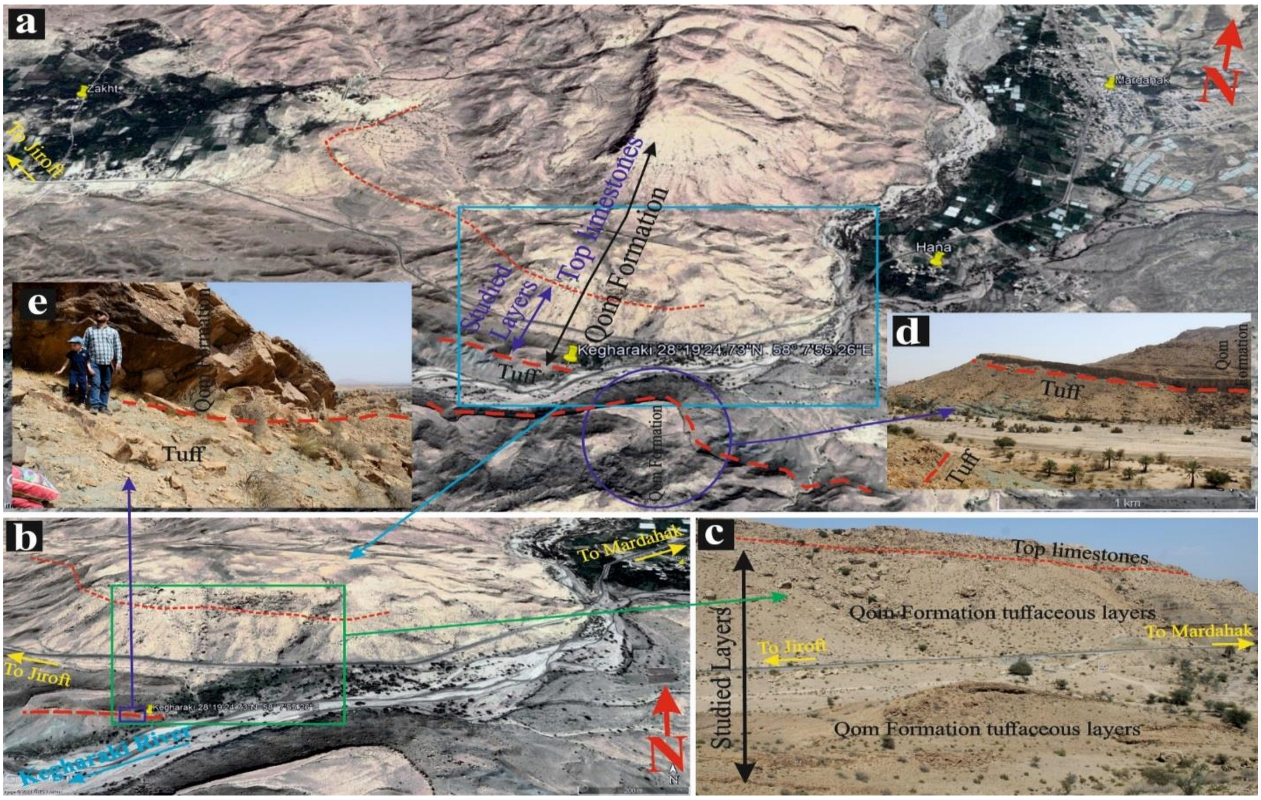

Fig 2- Satellite images and outcrop views of the Qom Formation in the Kagharaki section (SE Jiroft). a–b) Satellite images of the Kagharaki section. c) outcrop views of the studied layers (basal parts) of the Kagharaki section. d) Panoramic views of the Qom Formation on the opposite side of the sampled section. e) close-up view of the lower contact of the Qom Formation.

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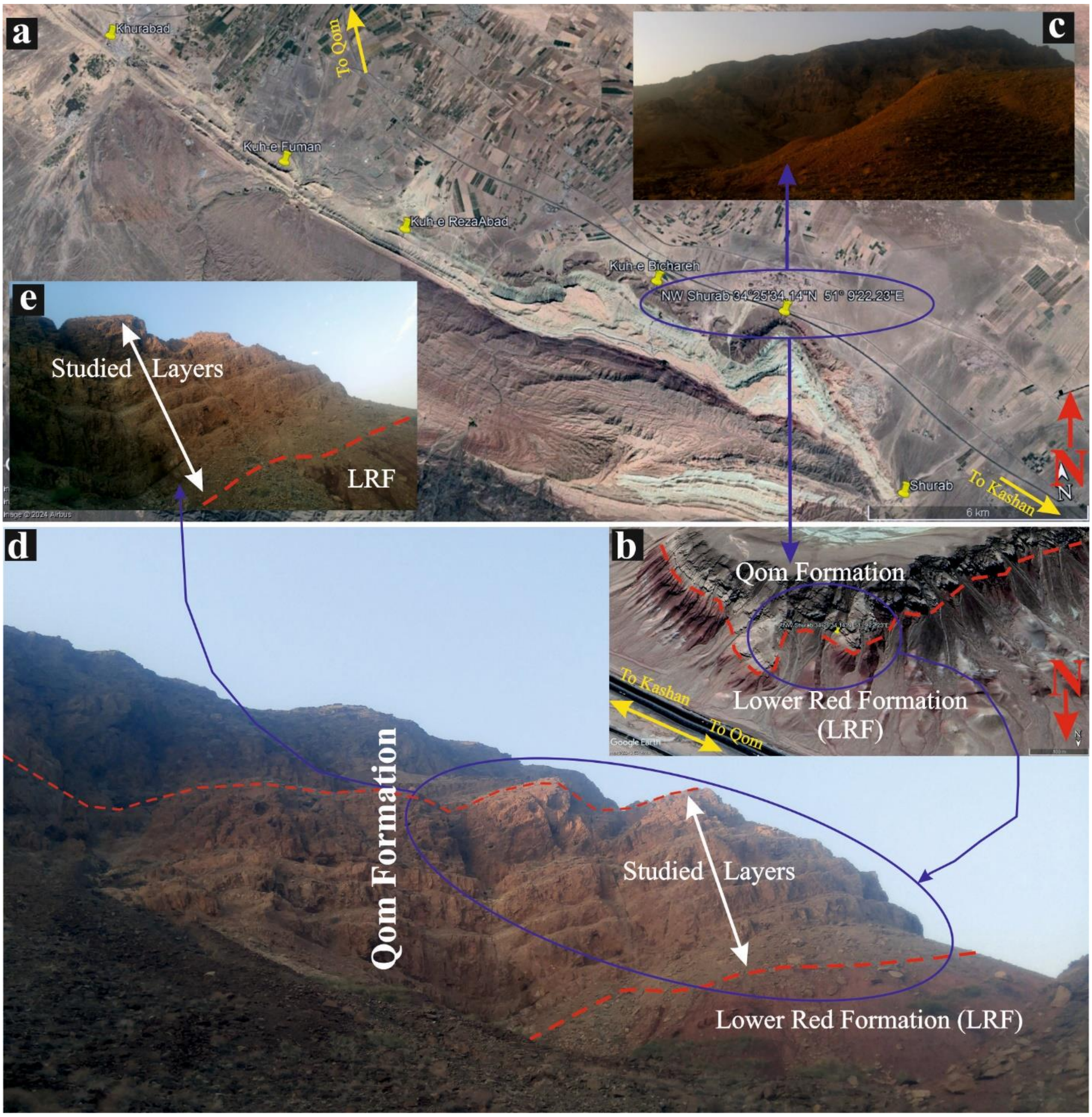

Fig 3- Satellite images and outcrop views of the Qom Formation in the Shurab section (SE Qom). a–b) Satellite images of the Kagharaki section. b: close-up view of the study section. c) Panoramic views of the Shurab section. d) field views of the lower parts of the Qom Formation in the Shurab section, showing the lower contact. e) close-up view of the studied layers (basal parts) of the Shurab section. Locations of the Khurabad section, Kuh-e-Bichareh, and Kuh-e-Rezaabad area are also shown.

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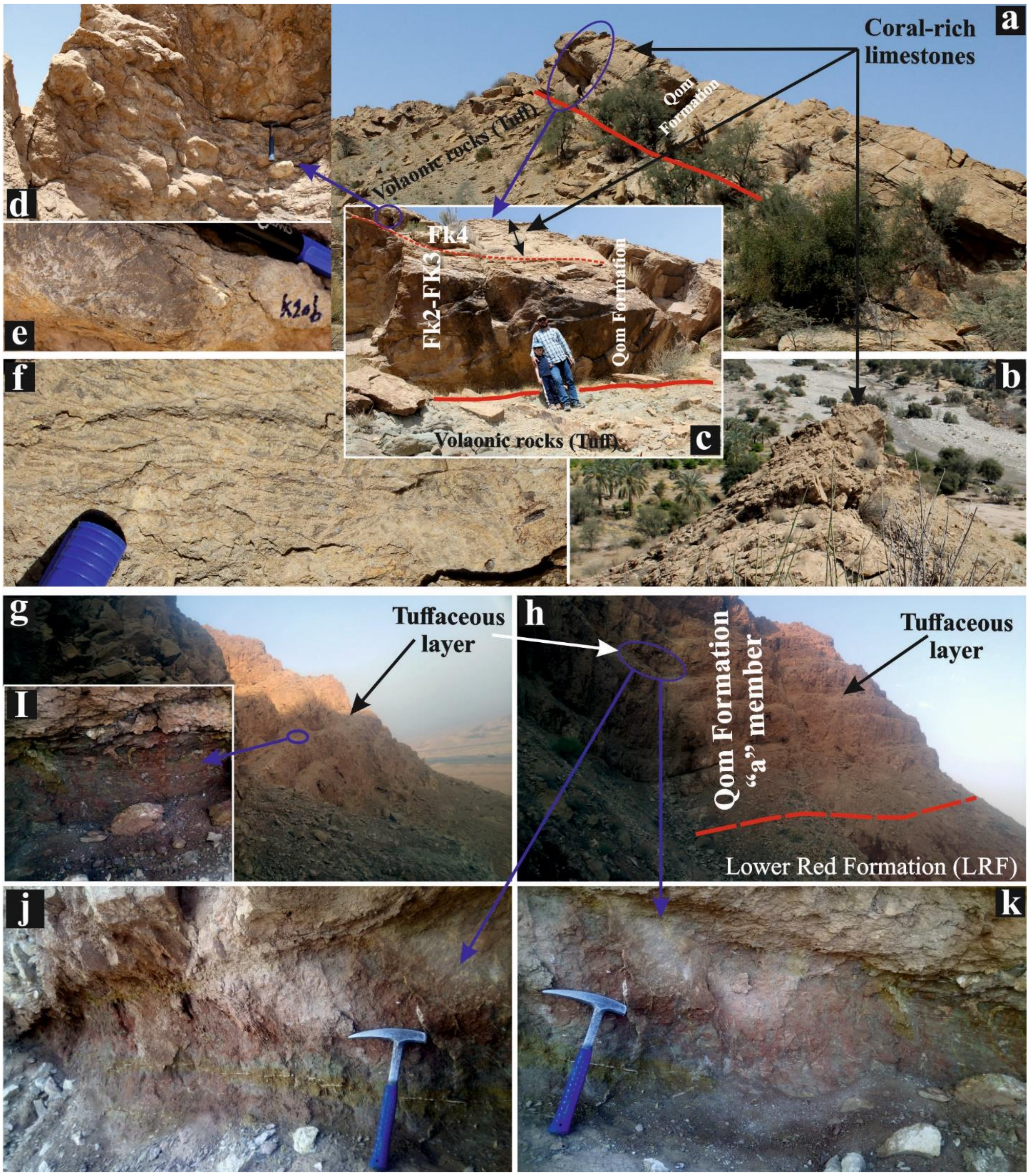

Fig 4- **Outcrop views of two different facies. a–f) coral-rich limestones in the Kegharaki section: a–b) panoramic views of the coral-rich limestones. c) close-up view of the coral-rich layer. d-f) close-up view of the corals. g–k) tuffaceous layer in the Shurab section: g–h) panoramic views of the tuffaceous layer. I–k) close-up view of the tuffaceous layer.**

Results

The results are presented with respect to biostratigraphy, microfacies analysis, and depositional environments, derived from field investigations and thin-section analysis.

Biostratigraphy

In this research, the foraminiferal-based new biozonation of the Qom Formation (Mohammadi 2023a) is applied. In all, 20 genera and 27 species of benthic foraminifera were identified. The foraminiferal biostratigraphy of the study sections is presented below.

Kegharaki section

The recognized foraminifera in the lower part of the Kegharaki section are *Eulepidina dilitata*, *Eulepidina* sp., *Nephrolepidina* sp., *Lepidocyclina* sp., *Nummulites fichteli/intermedius*, *Nummulites vascus*, *Operculina* sp., *Heterostegina* sp., *Amphistegina* sp., *Neorotalia viennoti*, *Neorotalia* sp., *Sphaerogypsina* sp., *Elphidum* sp., *Cibicides* sp., *Peneroplis thomasi*, *Borelis hauri*?, *Borelis* sp., *Dendritina* sp.?, *Pyrgo* sp., *Triloculina trigonula*, and *Textularia* sp.. In this part, the last presence of *Nummulites* spp. occurred in the last samples which are consequently indicative of Rupelian. The co-occurrence of lepidocyclinids and *Nummulites vascus* and *Nummulites fichteli/intermedius* shows that this assemblage correlates with the *Lepidocyclina-Nummulites* concurrent range zone of Mohammadi (2023a). This assemblage is attributed to the late Rupelian. It is worth mentioning that some sporadic *Nummulites* were present within the tuff layers. Considering the stratigraphic position and the presence of *Nummulites*, the volcanic ash fell in the late Rupelian.

Shurab section

The recognized foraminifera in the lower 20 m (Samples No. S1–S15) of the Shurab section is those of the restricted lagoons including: *Peneroplis* sp., *Peneroplis thomasi*, *Dendritina* sp.?, *Pyrgo* sp., *Triloculina trigonula*, *Quinqueloculina* sp., *Schlumbergerina* sp., and *Textularia* sp.,. However, from 20 to 45 m, hyaline foraminifera is also present. They are *Operculina* sp., *Heterostegina* sp., *Amphistegina* sp., *Neorotalia viennoti*, *Neorotalia* sp., *Elphidum* sp., *Peneroplis* sp., *Archaias* sp., *Dendritina* sp.?, *Pyrgo* sp., *Triloculina* sp., *Quinqueloculina* sp., *Schlumbergerina* sp., and *Textularia* sp.,. The lower 45 m of the Shurab section, could be considered the equivalent to "a-member", (Rahimzadeh 1994; Abasi 1995; Daneshian et al. 2008) which is Chattian in age based on the previous age dating criteria (Mohammadi 2023a, 2023b). *Nummulites* spp. (index of Rupelian), *Miogypsina* (index of Aquitanian), and *Borelis melo curdica* (index of the lower boundary of Burdigalian) are absent in this part. It should be noted that previous researchers, before publishing Mohammadi (2023a), dated the Qom Formation based on the Asmari Formation biozones; because there was no formal biozonation for the Qom Formation. Besides, all LBF-based biozones (except for zone 58 of Wynd) for the Oligocene of the Asmari Formation, which were proposed by Wynd (1965) and Adams and Bourgeois (1967), are based on hyaline foraminifera. However, the lower 45 m of the section was mainly deposited in lagoonal environments (see microfacies section). Its basal 20 m was deposited in restricted lagoons and thus there is no index hyaline foraminifera (*Nummulites* spp., lepidocyclinids). Therefore, the absence of *Nummulites* spp. and lepidocyclinids may be due to unfavorable paleoecological conditions. This claim could be confirmed by the results of the previous works. For example, Mohammadi et al. (2013) reported Rupelian deposits and *Nummulites vascus*, from the Qom Formation in the Khurabad section (SE Qom and 15 km NW Shurab section). Besides, Keshavarzi (1997) reported Rupelian deposits from the Qom Formation near Rezaabad village (SE Qom; Fig. 3). In addition, Seddighi et al. (2011) suggested the Chattian–Aquitanian age for deposition of C member of the Qom Formation in Kuh-e-Bichareh and Kuh-e-Rezaabad area (Fig. 3). In other words, "a" and "b" members in the Kuh-e-Bichareh and Kuh-e-Rezaabad area could not be younger than the Chattian. Therefore, they could be attributed to late the Rupelian?–Chattian? In addition, Keshavarzi (1997) reported *Nummulites* from the basal 50 m of the Kuh-e-Rezaabad section (which is attributed to the "a" member) and proposed a "Rupelian" age for its deposition. Likewise, Mohammadi et al (2015), emphasized that *Nummulites intermedius-Nummulites vascus* Assemblage zone of Wynd (1965) and the *Eulepidina-Nephrolepidina-Nummulites* Assemblage zone of Adams and Bourgeois (1967), which were proposed for Oligocene (Rupelian–Chattian), must be ascribed to the Rupelian in age. Therefore, despite it is impossible to precise dating of the lower 45 m of the Shurab section (which could be considered as "a-member") due to the absence of index taxa, more likely it could be deposited late Rupelian?–Chattian based on the ages of the neighboring stratigraphic sections and its stratigraphic position.

In summary, based on the biostratigraphic data (and the recognized foraminifera), neighboring stratigraphic sections, and stratigraphic position, the Qom Formation is the late Rupelian and the late Rupelian? –Chattian in age in the Kegharaki, and Shurab stratigraphic sections, respectively.

Microfacies analysis

Ten microfacies were identified based on field investigations, lithology, depositional textures, and dominant biogenic components in the basal parts of the Kegharaki, and Shurab sections. Microfacies associations of the Kegharaki section (designated as FK1–FK5) cover an area from open marine towards open lagoon environments. Microfacies associations of the Shurab section (designated as FS1–FS5) cover an area from restricted lagoons towards open marine environments. The palaeoenvironmental interpretation is based on the facies architecture and the distribution of both skeletal components and rock textures. Microscopic views of the recognized microfacies are presented in Figures 5 and 6. The distribution of the different microfacies recognized through the Kegharaki and Shurab sections are shown in Figures 7 and 8, respectively. The recognized microfacies are discussed below.

Microfacies of the Kegharaki section (from open marine to open lagoon)

FK1: Perforate foraminifera packstone (Figs. 5a–b)

This microfacies was characterized by diverse hyaline foraminifera. Larger benthic foraminifera include large lepidocyclinids (*Eulepidina*, *Nephrolepidina*, *Lepidocyclina*), and nummulitids (*Operculina*, *Nummulites*, *Heterostegina*). Other taxa includes *Amphistegina*, and *Neorotalia*. Nummulitids and lepidocyclinids show well-preserved large, flat tests. Most specimens do not show damage, but some are fragmented. Other components include scattered fragments of echinoids. Some skeletal components are sufficiently large to be observed easily on rock surfaces durin field investigations. With the faunal changes, this subfacies could be named "*Nummulites* packstone/ wackestone" (Fig. 5b).

Interpretation: Foraminifera with flatter, thinner test walls tend to occur with reduced light, with increasing water depth or turbidity (Beavington-Penney and Racey 2004; BouDagher-Fadel 2018). Abundant well-preserved large lepidocyclinids (*Eulepidina* and *Nephrolepidina*, in association with nummulitids) are indicative of normal marine salinity, lower parts of photic zone, and quiet environment without wave agitation (Hottinger 1983, 1997; Pomar 2001; Romero et al. 2002; Brandano et al. 2009). Under minimal hydrodynamic conditions, large rotalid taxa reached large sizes with very flat shapes and were prolific in meso-oligophotic conditions (Pomar et al. 2017). The genera *Heterostegina* and *Operculina* are flat, discoid larger benthic foraminifera that characterizes modern open shelf foraminiferal assemblages in the water depth interval between 40 and 120 m (Brandano et al. 2016). The abundance of large and flat tests of Lepidocyclinidae, Nummulitidae, and *Amphistegina*, together with a micritic groundmass, suggests that this microfacies is deposited in low energy, open marine conditions in the lower photic zone in the distal middle ramp.

FK2: Bioclast perforate foraminifera packstone/ wackestone (Fig. 5c)

This microfacies (MF) was characterized by the presence of perforate foraminifera and bioclasts. Larger foraminifera include *Operculina*, *Eulepidina*, *Nephrolepidina*, *Heterostegina*, and *Lepidocyclina*. Lepidocyclinids and Nummulitids are the dominant components and show well-preserved flat and large-size tests. Fragments of mollusks are the main bioclasts. In the layers pertaining to this microfacies, some skeletal components are sufficiently large to be observed easily on rock surfaces during the field investigations. In most thin sections, *Lepidocyclina* is represented by thin and strongly flattened tests. Tuff grains are abundant in some layers.

Interpretation: The large and flat tests of lepidocyclinidae and nummulitidae suggest that this microfacies was deposited in the lower photic zone in the distal middle ramp (Hottinger 1983; Romero et al. 2002; Beavington-Penney and Racy 2004). Larger symbiont-bearing foraminifera typically live in shallow tropical seas (Renema and Troelstra 2001). The presence of *Lepidocyclina* with thin and flattened tests indicates normal salinity and calm environments (Hottinger 1997; Romero et al. 2002). *Nummulites* occupied a broad range of open marine environments on both ramps and shelves and were generally absent in more restricted waters. The large benthic rotaliines host diatoms that have a great potential for using a wide spectrum of light quality, being able to reach depths down to 130 m (Beavington-Penney and Racey 2004; Mateu-Vicens et al. 2009). The large discoidal tests of lepidocyclinids have been classically located in the deeper part of the photic zone in which low energy, turbid, and low light environment is postulated; they are prolific in meso-oligophotic conditions (e.g. Hallock and Glenn 1986; Beavington-Penney and Racey 2004; BouDagher-Fadel and Price 2010; Pomar et al. 2017). Deposition of this microfacies took place in the lower parts of the photic zone, in a distal middle ramp under mesophotic to oligophotic conditions.

FK3: Coral, perforate foraminifera packstone (Fig. 5d)

This MF is characterized by larger benthic foraminifera (*Operculina*, *Nummulites*, *Eulepidina*, *Lepidocyclina*, and *Nephrolepidina*), and corals. Lepidocyclinids and nummulitids (*Nummulites*, *Operculina*) are relatively large and flat to relatively ovate and well preserved. The *Lepidocyclina* are visible in the field on the surface of rocks and their diameters reach a few centimeters. These specimens are more robust in comparison to those present in FK1 and FK2.

Interpretation: Prevailing corals and the presence of perforate larger benthic foraminifers were identified as living in the oligophotic zone of the middle ramp environment (Pomar 2001; Brandano and Corda 2002; Corda and Brandano 2003).The high diversity of plentiful hyaline, large, flat to ovate foraminifera such as lepidocyclinids and nummulitids and the presence of typical open marine skeletal fauna point to low-medium energy, normal salinity, mesophotic depths in an open marine setting, probably middle shelf/ramp (Pomar 2001; Brandano and Corda 2002). Mohammadi et al. (2019) recorded similar microfacies from the Oligocene deposits of the Qom Formation (SW Kashan), and attributed its depositional environment to the middle ramp.

FK4: Coral boundstone (Fig. 5e)

The microfacies is characterized by the abundance of scleractinian coral colonies that are mostly in their growth position. The texture is framestone or bafflestone. Sporadic *Neorotalia* are present between framework components. This MF is in alternation with open marine MFs.

Interpretation: Corals are dominant in tropical/subtropical and oligotrophic conditions. The coral reefs flourish where the movement and water mobility are significant (Hallock et al. 2003). Generally, corals are supposed as light-dependant organisms that thrive in clear nutrient-poor oligotrophic waters (Ghaedi et al. 2016), but different trophic conditions could be considered for zooxanthellate corals (Hallock and Schlager 1986; Ghaedi et al. 2016). Based on its alternation with open marine facies and field investigations, this microfacies was formed by *in-situ* fauna as organic patch reefs, in open marine environments.

FK5: Bioclastic perforate and imperforate foraminifera wackestone/packstone (Fig. 5f)

This microfacies characterized by medium to coarse-grained packstone-wackestone dominated by significant amounts of perforate and imperforate foraminifera. Tuff grains are abundant in some layers. The main components with a wide range of biogenic organisms include imperforate foraminifera (such as *Pyrgo*, *Triloculina*, *Quinqueloculina*, *Borelis*, *Dendritina*, and *Peneroplis*), ovate and robust hyaline perforate foraminifera (such as *Operculina*, *Heterostegina*, *Nummulites*, and *Lepidocyclina*), and other bioclasts such as fragments of corallinacea red algae, and mollusks. The rotaliids are very robust in comparison to those present in FK1–FK3.

Interpretation: The diverse foraminiferal assemblage, including both smaller and larger foraminifera, indicates a moderately well-illuminated inner-shelf or lagoonal depositional environment (Hallock and Glenn 1986; Geel 2000; Romero et al. 2002; Nebelsick et al. 2013; Sarkar 2017). Open-lagoon environments are characterized by the presence of a mix of bioclasts in open marine and protected environments. The occurrence of *Nummulites* and *Operculina*, along with the common presence of miliolids, supports the additional interpretation of a lower energy environment in a distal inner ramp setting (e.g., Beavington-Penney and Racey 2004; Brandano et al. 2009; Nebelsick et al. 2013). The open lagoon is characterized by MFs that include mixed open marine bioclasts and restricted environment bioclasts (Vaziri-Moghaddam et al. 2010). In summary, the deposition of this microfacies likely took place in a distal inner ramp of the open lagoon with normal circulation.

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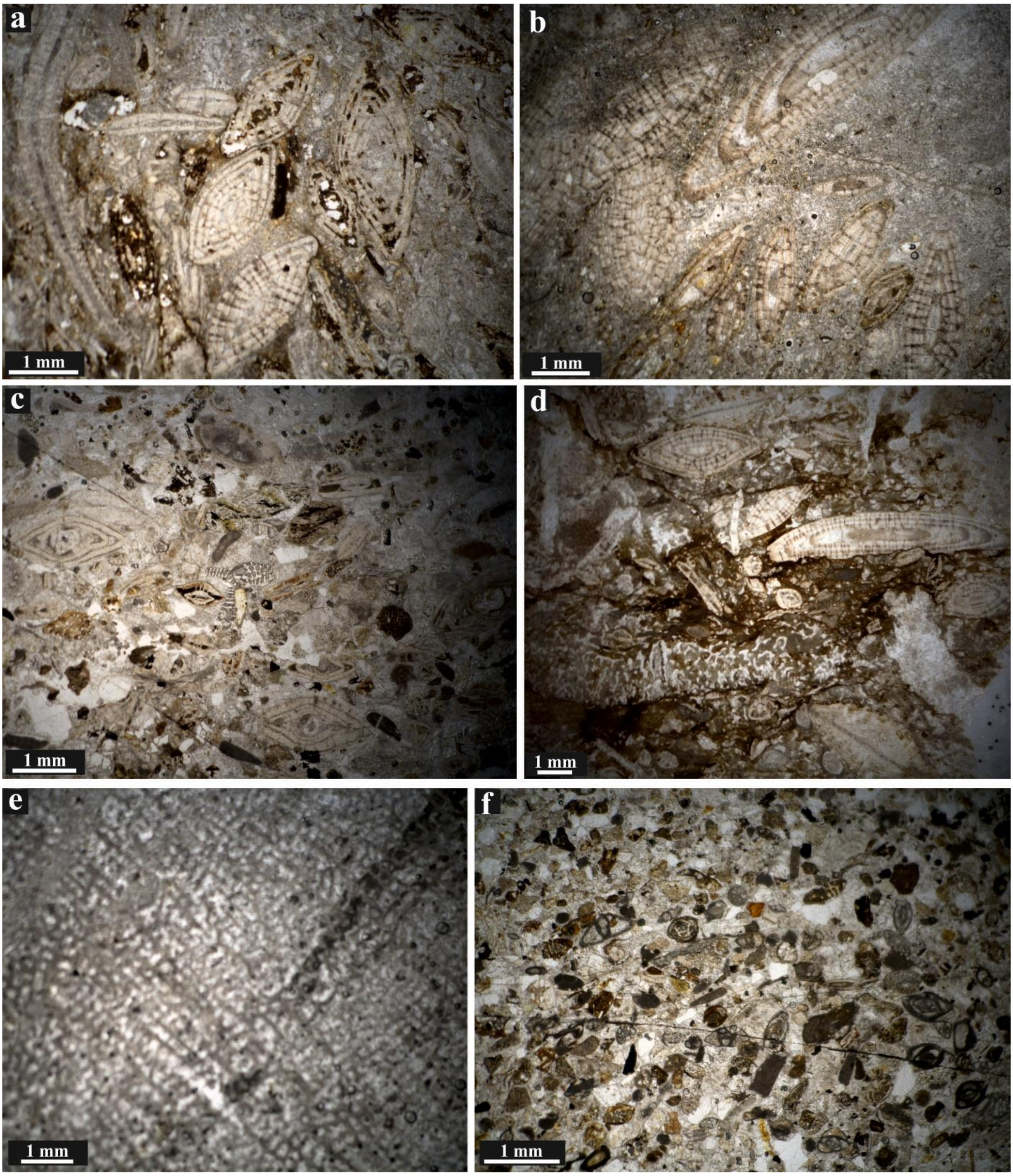

Fig 5- Photomicrographs showing selected microfacies of the Qom Formation in the Kagharaki section (SE Jiroft). a–b) Perforate foraminifera packstone; c) Bioclast perforate foraminifera packstone/wackestone; d) Coral, perforate foraminifera packstone; e) Coral boundstone; f) Bioclastic perforate and imperforate foraminifera wackestone/packstone.

Microfacies of the Shurab section (from restricted lagoon to open marine)

FS1: Bioclastic miliolida packstone/grainstone (Fig. 6a–b)

This microfacies is dominated by small miliolids (*Triloculina trigonula*, *Quinqueloculina*, *Pyrgo*), as well as *Peneroplis*, and *Dendritina*. Coral fragments, the debris of mollusks, bryozoans, gastropods, and coralline algae are present. *Textularia* could be locally present.

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Interpretation: Abundant small miliolids, with no hyaline taxa, indicate shallow waters with some degree of hypersalinity (Geel 2000; Hallock et al. 2006; Zamagni et al. 2008; Rahmani et al. 2009). Recent miliolids are euryhaline forms that can thrive on soft substrates in shallow, subtidal, or restricted lagoonal environments with low turbulence (Zamagni et al. 2008; Sarkar 2017). The abundant presence of typical fauna of restricted environments (*Pyrgo*, *Triloculina*, *Borelis*, *Dendritina*, *Peneroplis*, *Archaias*) and the absence of typical fauna of open marine indicate restricted environments. In summary, this microfacies likely was deposited in warm, shallow water, in a restricted lagoon with relatively high salinity (proximal inner ramp).

FS2: Imperforate foraminifera, bioclast, corallinacea, echinid packstone/grainstone (Fig 6c)

The most conspicuous components are corallinacea, echinid, and imperforate foraminifers such as *Pyrgo*, *Quinqueloculina*, *Triloculina*, *Peneroplis*, and *Archaias*. Fragments of mollusks and bryozoans are subordinate biogenic components.

Interpretation: Miliolids are common throughout the open and restricted platforms, whereas they are rare in open shelf settings (Abdulsamad and Barbieri 1999). The diverse and abundant miliolids represent restricted environments, which are common in back reef lagoons and sheltered areas on the reef banks (Ghose 1977). The occurrence of miliolids, along with corallinacea, echinid, and bryozoans, indicates that this microfacies is deposited in a distal inner ramp setting (Brandano and Corda 2002; Mateu-Vicens et al. 2009).

FS3: Perforate and imperforate foraminifera corallinacea, echinid, bryozoan packstone (Fig 6d)

The main components with a wide range of biogenic organisms include imperforate foraminifera (such as *Pyrgo*, *Triloculina*, *Quinqueloculina*, *Dendritina*, *Peneroplis*, and *Archaias*), ovate and robust hyaline perforate foraminifera (such as *Amphistegina*, *Neorotalia*, *Operculina*, *Heterostegina*, and *Elphidium*), and other bioclasts such as fragments of corallinacea red algae, echinid, and bryozoans.

Interpretation: Foraminifera with hyaline walls prefer normal marine salinity to live, while foraminifera with porcelaneous walls live in shallow waters with limited circulation and high salinity (Geel 2000; Renema 2006). The coexistence of perforate benthic foraminifera (*Amphistegina*, *Neorotalia*, *Operculina*, *Heterostegina*) and imperforate foraminifera (*Pyrgo*, *Triloculina*, *Quinqueloculina*, *Peneroplis*) indicates that deposition took place in the euphotic and shallow water of a semi-restricted (open) lagoon (Geel 2000; Romero et al. 2002; Vaziri-Moghaddam et al. 2006). According to Corda and Brandano (2003), the occurrence of red algae debris together with this association characterizes an inner-shelf depositional setting. In summary, deposition of this microfacies took place in a distal inner ramp of an open lagoon with normal water circulation.

FS4: Bioclastic corallinacea, bryozoan packstone/grainstone (Fig 6e)

The constitute organisms of this microfacies include a wide range of components, including foraminifera, coralline algae, and/or bryozoans. Foraminifera are dominated by the perforate ones (*Operculina*, *Heterostegina*, *Amphistegina*, and *Neorotalia*). Rare miliolids (*Triloculina*, *Pyrgo*) are also observed. Perforate foraminifera is relatively elongated/large and well preserved. As well, *Elphidium* and *Textularia* could be seen. Bryozoans are mainly *in situ* and unbroken, and occasionally fragmented. Subordinate components include fragments of echinids and mollusks.

Interpretation: The abundance of corallinacea and larger benthic foraminifera (*Heterostegina*, *Operculina*, and *Amphistegina*) represents the middle shelf and oligotrophic settings (Brandano and Corda 2002; Corda and Brandano 2003; Mateu-Vicens et al. 2009; Sarkar et al. 2016). The abundant presence of hyaline foraminifera together with the absence of porcelaneous ones is indicative of normal marine salinity. The co-occurrence of relatively elongated large perforate foraminifera and *in situ* bryozoans is indicative of deposition in relatively deeper parts of the oligophotic zone. The high diversity of plentiful hyaline, large, flat-to-ovate foraminifera such as lepidocyclinids and nummulitids and the presence of typical open marine skeletal fauna, including echinoids and coralline algae point to low-medium energy, normal salinity, mesophotic depths in an open marine setting, probably middle shelf/ramp (Pomar 2001; Brandano and Corda 2002). Therefore, this microfacies was deposited in open marine in relatively deeper parts of the photic zone (oligophotic to rarely mesophotic) in low to moderate energy waters of the middle ramp. Mohammadi et al. (2019) recorded similar microfacies from the Oligocene deposits of the Qom Formation (SW Kashan), and attributed its depositional environment to the middle ramp.

FS5: Perforate foraminifera bryozoan, echinid packstone (Fig. 6f)

This microfacies characterized by the presence of perforate foraminifera and bioclasts. Larger foraminifera include *Operculina*, *Heterostegina*, *Amphistegina*, and *Neorotalia*. Fragments of bryozoans and echinoids are the main bioclasts.

Interpretation: Foraminifera that live in shallow water produce ‘robust’, ovate tests with thick walls to prevent photoinhibition of symbiotic algae within the test in bright sunlight, and/or to prevent test damage in turbulent water. Flatter, thinner test walls tend to occur with reduced light, with increasing water depth or turbidity (Beavington-Penney and Racey 2004; BouDagher-Fadel 2018). *Operculina* can occur in medium light conditions in a somewhat deeper part of the photic zone (Bassi et al. 2007; Sarkar et al. 2016). Heterotrophic organisms, such as bryozoans, are independent of light and water depth; therefore they are capable of living in sub euphotic waters (Pomar 2001; Brandano and Corda 2002). The co-occurrence of *in situ* bryozoans and mainly flat, symbiont-bearing larger foraminifera indicate that this microfacies occurred in environments that were either slightly cooler or where their food supply (plankton) was more abundant so that reduced or intermittent light reaching the benthos favored heterotrophic bryozoans over zooxanthellate corals (Hallock et al. 2006). In summary, deposition of this microfacies took place in the lower parts of the photic zone, in a distal middle ramp with low-energy waters.

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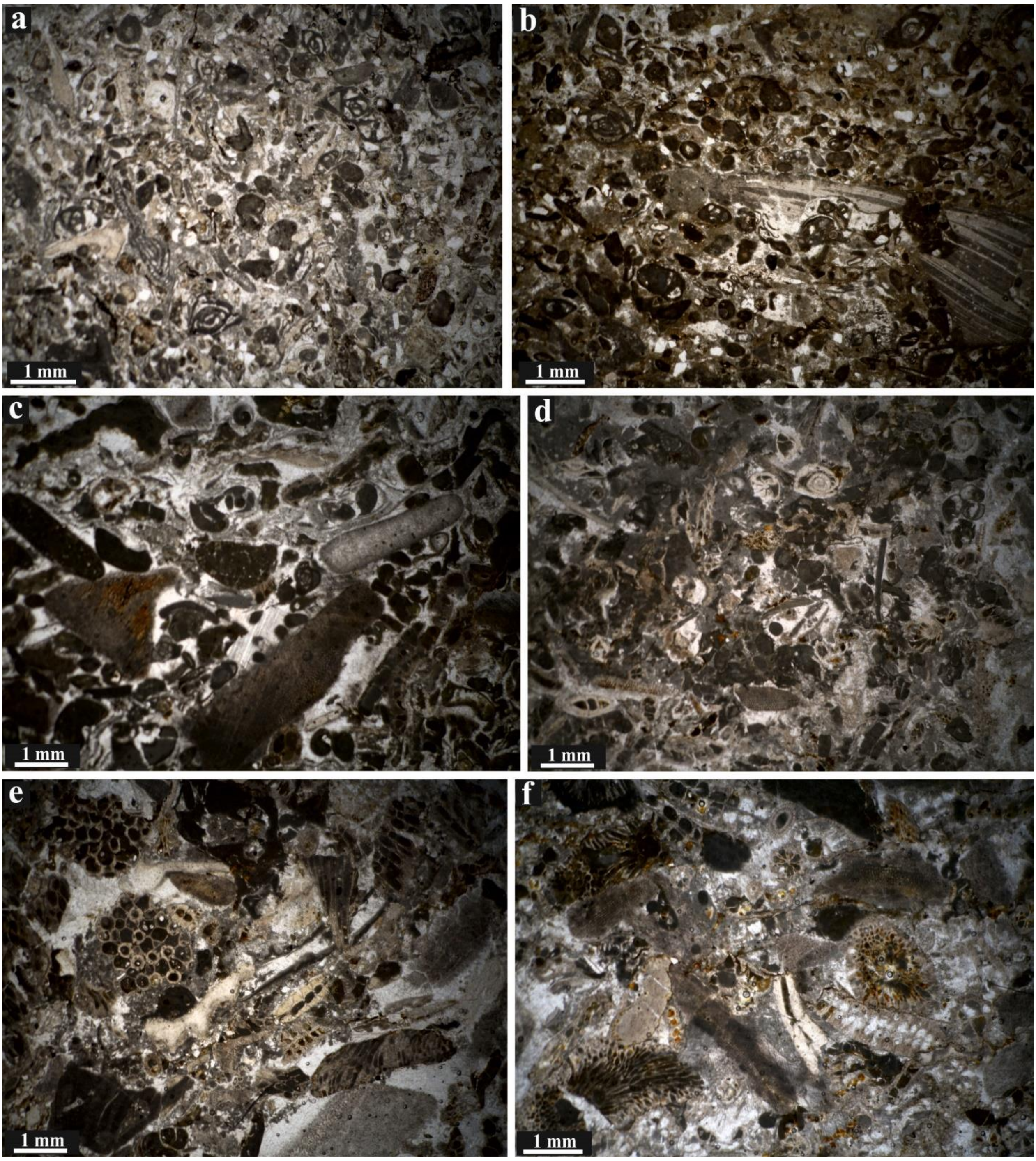

Fig 6- Photomicrographs showing selected microfacies of the Qom Formation in the Shurab section (SE Qom). a–b) Bioclastic miliolida packstone/ grainstone; c) Imperforate foraminifera, bioclast, corallinacea, echinid packstone/grainstone; d) Perforate and imperforate foraminifera corallinacea, echinid, bryozoan packstone; e) Bioclastic corallinacea, bryozoan packstone/grainstone; f) Perforate foraminifera bryozoan, echinid packstone.

Discussion

Paleoenvironmental interpretation

The recognized microfacies in the study areas together with association and distribution of perforate and imperforate foraminifera are the key factors for interpretation of palaeoenvironmental conditions. In each study section, five different microfacies have been recognized. Based on the recognized microfacies two major depositional environments were identified which include lagoon and open marine (Figs. 7–8). Generally, the Oligo–Miocene foraminiferal limestones in many places are interpreted to have accumulated as a non-rimmed shelf or ramp (Ahr 1973; Read 1982; Sadeghi et al. 2018).

In the study sections, no evidence for a biogenic reef (coral reef complex) was recognized, therefore, a rimmed shelf setting cannot be supported. The nature and distribution of facies belts within the basal parts of the study sections suggest that the depositional conditions may be characteristics of a carbonate ramp (Burchette and Wright 1992). Undoubtedly, the study of the upper parts of the study section is required to determine the precise types of carbonate platforms. The Kegharaki section is dominated by open marine facies. The Shurab section is dominated by lagoonal facies.

In the Kegharaki section, the lower parts are mainly deposited in the middle ramp. The middle ramp comprises FK1 to FK4 and is characterized by the association of larger benthic foraminifera with the hyaline wall, coralline red algae, corals, bryozoan, as well as echinoids. The inner ramp environment in the Kegharaki section is characterized by FK5. The occurrence of small to medium-sized ovate nummulitids with imperforated foraminiferal tests (miliolids) suggests an inner shelf environment (Geel 2000; Brandano and Corda 2002).

In the Shurab section, the inner ramp includes FS1–FS3. The occurrence of a large number of imperforate foraminiferal tests may point to the depositional environment being slightly hypersaline (Geel 2000; Vaziri-Moghaddam et al. 2006; Brandano et al. 2009; Sadeghi et al. 2009, 2018). The abundance of miliolids in FS1 shows that this microfacies is deposited in an environment with limited water circulation (restricted lagoon). The middle ramp comprises FS4 and FS5 and is characterized by the association of larger benthic foraminifera with the hyaline wall.

Based on the recognized microfacies and their depositional positions, the lower 45 m of the Shurab section shows a common deepening upward trend. However, the Kegharaki section is mainly deposited in a middle ramp with low sea level oscillations.

Comparison with adjacent Qom Formation stratigraphic sections

The lower parts of the Qom Formation in Shurab or in some stratigraphic sections close to the Shurab area were studied by many researchers (Furrer and Soder 1955; Abasi 1995; Keshavarzi 1997; Najafi et al. 2004; Imandoust and Amini 2005; Daneshian et al. 2008; Mohammadi 2020). Furrer and Soder (1955) studied one stratigraphic section of the Qom Formation, located 5 km east of Shurab village, and proposed an Oligo–Miocene age for its deposition. Abasi (1995) studied the sedimentary environment of the “a” and “b” members of the Qom Formation in the Shurab area. He recognized eight microfacies from the “a” member, belonging to the basin margin, fore, and back reef. The basin margin facies are indicative of sub-tidal environments. The basin margin facies represent settings under permanent water waves. The reef part is composed of coral and algal bufflestone. The back reef facies are deposited in shallow lagoons with permanent water current and circulation. The back reef facies are affected by volcanic activities. It could be concluded that the presence of permanent water currents and circulation during deposition of the back reef facies is indicative of an open lagoon and open shelf. Keshavarzi (1997) studied the Qom Formation deposits in the Kuh-e-Rezaabad section. The basal 50 m is attributed to the “a” member and is dated as “Rupelian”. *Nummulites* are recorded from the “a” member. Besides, Najafi et al. (2004) proposed a Chattian–Burdigalian for deposition of the Qom Formation in the Kuh-e-Rezaabad section. However, the age proposed by Keshavarzi (1997) is more acceptable due to the presence of *Nummulites*. A similar condition is reported from the Khurabad section (SE Qom) by Mohammadi et al. (2015) and Mohammadi (2023a; see below). Imandoust and Amini (2005), studied the sequence stratigraphy of the Qum Formation in the Shurab section and proposed a carbonate-rimmed shelf for its deposition. Daneshian et al. (2008) studied the Qom Formation in the Kuh-e-Bichareh section and recognized four facies belts including tidal flat, back reef (lagoon), barrier and, open marine facies. The thickness of the “a” member is 37.9 m in the Kuh-e-Bichareh section. Mohammadi (2020) studied the Qom Formation in the Khurabad and attributed its deposition to the Rupelian–Burdigalian. This author identified 14 different facies and suggested a homoclinal ramp for the deposition of the Qom Formation in the Khurabad section. Accordingly, open marine (middle ramp), lagoon (inner ramp), and peritidal flat/beach as major depositional environments were identified.

Concerning the coral facies in the Kegharaki section, it should be noted that Mohammadi (2021b) by studying Oligo–Miocene coral and coral reefs of the Qom Formation in seven stratigraphic sections and the analysis of previous research presented meaningful data. Despite the scattered presence of corals in a large number of sections of the Qom Formation, the coral bondstone facies (which is mainly composed of scleractinian coral colonies) are not present in most of the sections of the Qom Formation. This author revealed that although the “f” member is known as the reef member in Persian literature, even in some sections located in the type area, no evidence of continuous reefs is observed in the field evidence, and even isolated corals are rarely observed. In addition, none of the valid studies conducted on the microfacies and palaeoenvironment of the Qom Formation in the Qom area have suggested a rimmed shelf environment (which is characterized by the existence of real, barrier, and continuous reefs) for the deposition of the formation (e.g., Okhravi and Amini 1998; Mohammadi 2020). Corals of the Qom Formation are usually reported in the form of patch reefs and relatively less in the form of real reefs and rimmed reefs (Mohammadi 2021b). It's worth mentioning that Bakhshi et al. (2015) and Sharifi et al. (2023) are the only studies that were published in scientific journals and proposed a rimmed carbonate platform for deposition of the Qom Formation.

In summary, based on the above discussion and by comparing with other stratigraphic sections, the lower part of the Shurab section could be considered equivalent to “a-member” and could be deposited in the late Rupelian?–Chattian. In addition, the coral-rich limestones (FK4: Coral boundstone) in the lower part of the Kegharaki section were formed by *in-situ* fauna as organic patch reefs, in open marine environments, but there is no reef complex with sigmoidal geometries.

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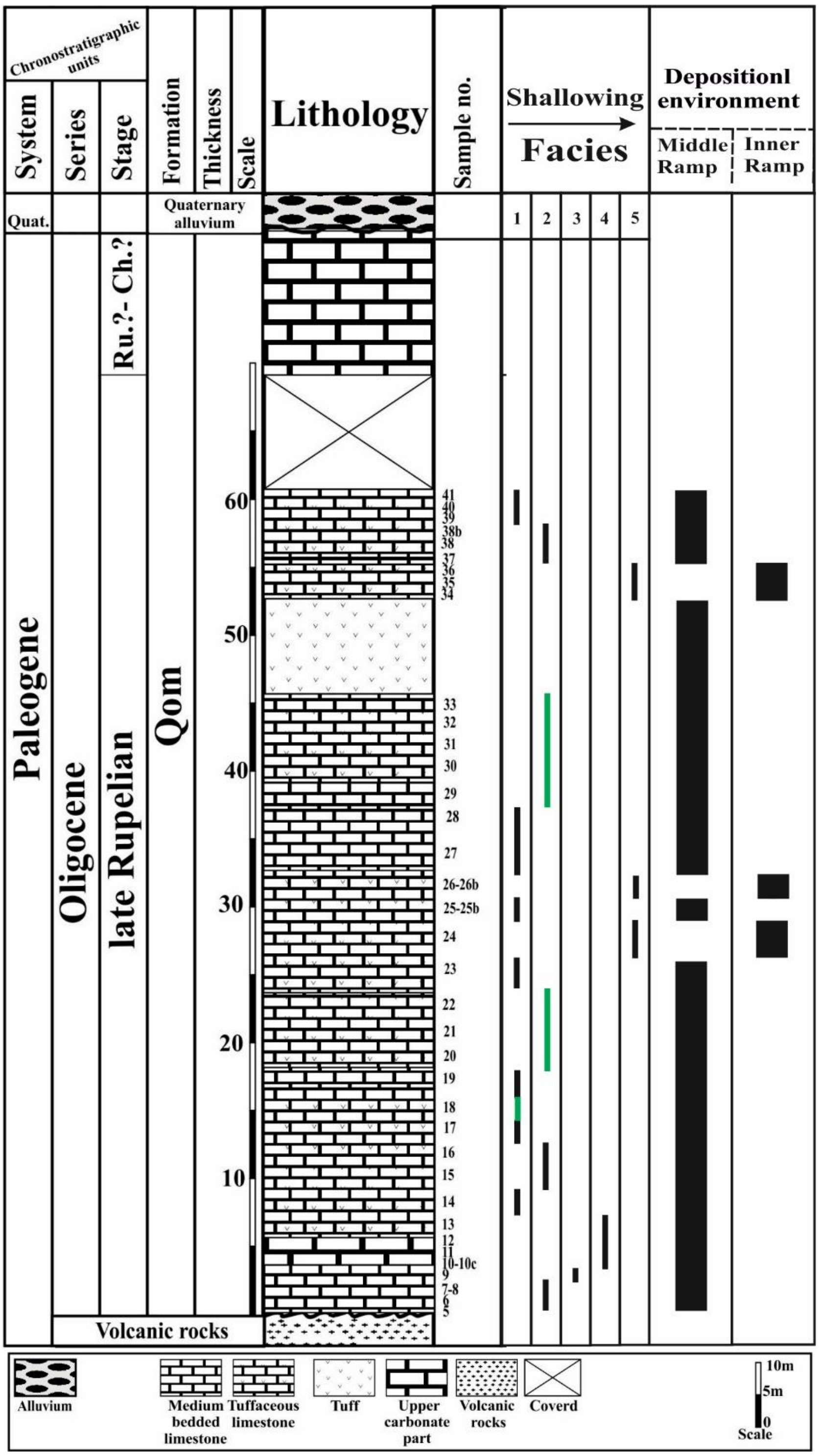

Fig 7- Vertical facies distribution and depositional environments of the Qom Formation in the Kagharaki section (SE Jiroft). Green color (in FK1 and FK2) refers to thin sections with abundant tuff grains.

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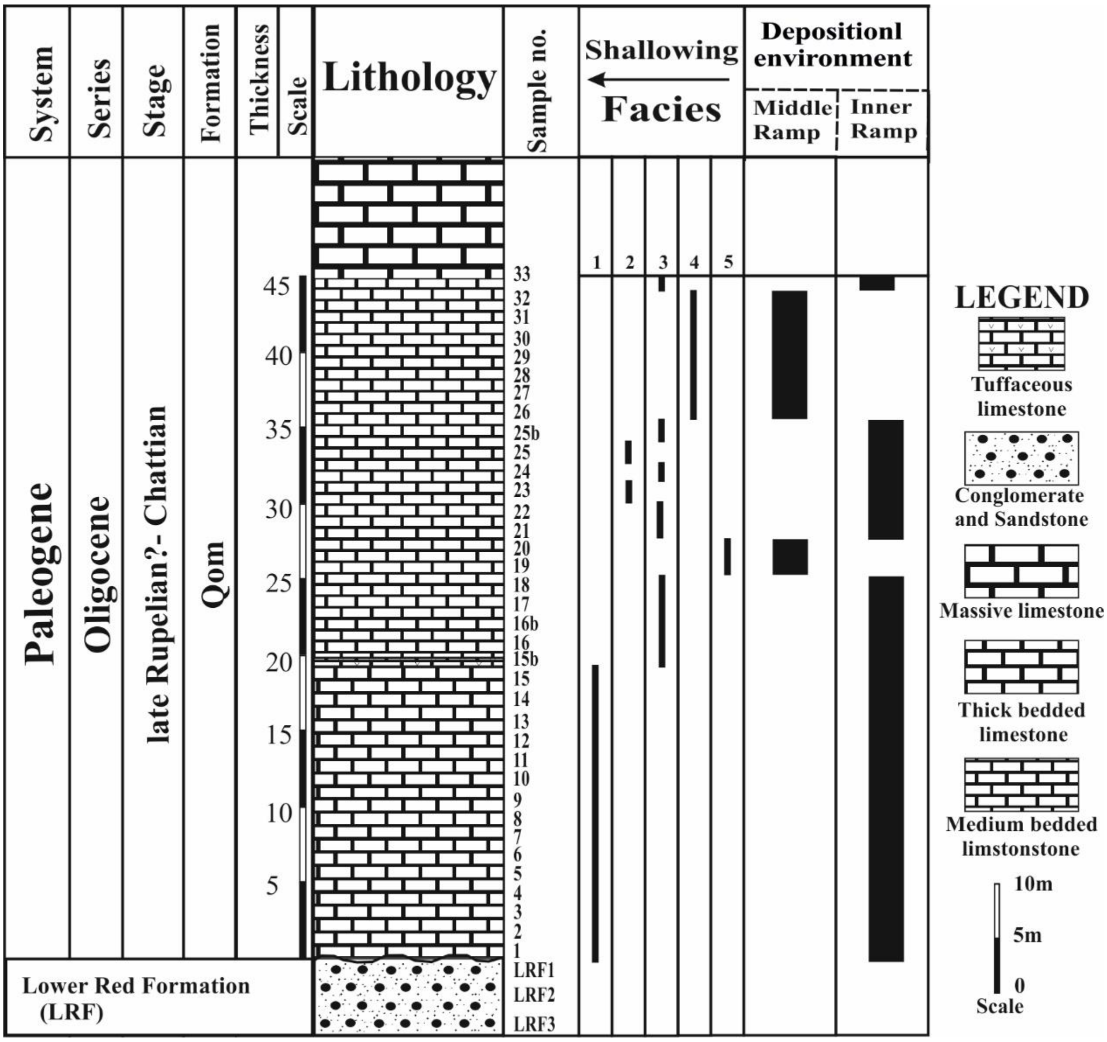

Fig 8- Vertical microfacies distribution and depositional environments of the Qom Formation in the Shurab section (SE Qom).

Conclusion

Basal parts of the Qom Formation in the Kegharaki section (SE Jiroft) in the Sanandaj–Sirjan fore-arc basin, and the Shurab section (SE Qom) in the Central Iran back-arc basin were studied to analyze their biostratigraphy, microfacies and depositional environments.

The Qom Formation is the late Rupelian and late Rupelian? –Chattian in age in the Kegharaki, and Shurab stratigraphic sections, respectively. The Kegharaki section is dominated by open marine facies. However, the Shurab section is dominated by lagoonal facies. The abundance of perforate foraminifera and the absence of biofacies indicating restricted lagoonal or intertidal environments suggest that the Kegharaki section was deposited mainly in open marine environments (in the middle ramp) with normal salinity. The open marine is distinguished by associations of hyaline larger benthic foraminifera such as Nummulitidae (*Nummulites*, *Operculina*, and *Heterostegina*), *Lepidocyclina*, *Amphistegina* and *Neorotalia* coralline red algae, echinoids, as well as bryozoans. The co-occurrence of imperforate and perforate foraminifera in some layers shows that deposition occurred in an open lagoon. In the restricted lagoons (in the Shurab section), normal marine fauna were absent, while imperforate benthic foraminifera were dominant. The abundance of LBF and coralline red algae, together with the corals, emphasizes a tropical–subtropical palaeoenvironment. Syndepositional contemporaneous volcanic activities (with the late Rupelian age) in the Kegharaki section affected the abundance and diversity of the biota.

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