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Paleoecology of Lower Miocene coralline red algae-rich grainstone facies in the Qom Formation (Vartun section, central Iran)

Paleoecología de la facies grainstone rica en algas rojas coralinas del Mioceno Inferior de la Formación Qom (sección Vartun, Irán central)

Amir Hossein **Rahiminejad**[1,*], Mehdi **Yazdi**[2], Amit Kumar **Ghosh**[3]

[1] Department of Ecology, Institute of Science and High Technology and Environmental Sciences, University of Advanced Technology, Kerman, Iran.

[2] Department of Geology, Faculty of Sciences, University of Isfahan, Isfahan 81746-73441, Iran.

[3] Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow-226 007, Uttar Pradesh, India.

* Corresponding author: (A.H. Rahiminejad)
ah.rahiminejad@kgut.ac.ir

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ABSTRACT

In this paleoecological study we focused on coralline red algae-rich shoal grainstone facies in the Lower Miocene (Aquitanian) carbonates of the Qom Formation in the Vartun section in central Iran. The identified coralline red algae are mainly non-geniculate, although very rare geniculate forms of corallines were also recognized in thin section analysis. The identified algae are represented by Melobesioideae (*Lithothamnion* cf. *valens*, *Lithothamnion* cf. *rovereoti*, *Lithothamnion* cf. *peleense*, and *Lithothamnion* spp.), Mastophoroideae (*Neogoniolithon* sp., *Spongites* spp., and *Spongites* cf. *fruticulosus*), *Sporolithon* spp. (*Sporolithon* spp. and *Sporolithon* cf. *airoldii*), and geniculate coralline (*Corallina*). The algal taxa mainly display fruticose and lumpy growth forms. The dominance of the former is consistent with high water energy in the identified shoal environment. The presence of Lower Miocene algae indicates that deposition of carbonates took place in warm tropical to subtropical waters in a euphotic marine environment during the Aquitanian. Likewise, high water energy and sediment agitation resulted in taphonomic features such as fragmentation, abrasion, and disarticulation.

Keywords: red algae, rhodophyta, carbonate producers, facies, Miocene, Aquitanian.

RESUMEN

En este estudio paleoecológico se enfocó en las facies grainstone rica en algas rojas coralinas en los carbonatos del Mioceno Inferior (Aquitaniano) de la Formación Qom en la sección Vartun del centro de Irán. Las algas rojas coralinas identificadas en las facies son principalmente no geniculadas, aunque también se caracterizaron formas geniculadas mediante análisis de láminas delgadas. Las algas identificadas están representadas por Melobesioidea (Lithothamnion cf. valens, Lithothamnion cf. rovereoti, Lithothamnion cf. peleense, y Lithothamnion spp.), Mastophoroidea (Neogoniolithon sp., Spongites spp., y Spongites cf. fruticulosus), Sporolithon spp (Sporolithon spp. y Sporolithon cf. airoldii), y por coralinas geniculadas (Corallina). Los taxones de algas muestran principalmente formas grandes y grumosas de fructicoso. Donde predomina consistentemente con alta energía del agua en el ambiente arrecifal identificado. La presencia de algas del Mioceno Inferior indica que la exposición de carbonatos tuvo lugar en aguas cálidas tropicales a subtropicales en la zona eufótica marina durante el Aquitaniano. Asimismo, tanto la alta energía del agua como la agitación de los sedimentos, dieron lugar a características tafonómicas tales como fragmentación, abrasión, y desarticulación.

Palabras clave: algas rojas, rhodophyta, productoras de carbonato, facies, Mioceno, Aquitaniano.

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1. Introduction

Coralline red algae were one of the major components of calcareous benthic communities, reef builders, and carbonate producers in the Miocene shallow marine paleoenvironments (Halfar and Mutti, 2005; Braga *et al.*, 2010; Sarkar and Ghosh, 2015; Sarkar *et al.*, 2016). Several of the reported genera of coralline red algae in Miocene deposits encompass still living species and constitute a useful tool for paleoenvironmental interpretations (Braga *et al.*, 2010), since they are good indicators of water depth, temperature, light intensity, and hydrodynamic energy of carbonate paleoenvironments (Bosence, 1991; Aguirre *et al.*, 2000; Brandano *et al.*, 2005; Braga *et al.*, 2010).

Generally, the Oligocene–Miocene carbonate paleoenvironments represent the highest diversity of coralline red algae in the geologic record (Aguirre *et al.*, 2000; Braga *et al.*, 2010), with its maximum levels of diversity recorded in the Lower Miocene (Aquitanian) and represented by 245 species (Aguirre *et al.*, 2000; Braga *et al.*, 2010). Mainly, non-geniculate coralline red algae were dominant in the Miocene paleoenvironments, whereas, geniculate corallines were subordinate (*e.g.* Ghosh, 2002; Rösler *et al.*, 2015; Coletti *et al.*, 2018; Roozpeykar *et al.*, 2019a).

The carbonate facies of the Qom and Asmari formations in central Iran and the Zagros Basin are the principal deposits of Miocene coralline red algae in Iran (Zabihi Zoeram *et al.*, 2014;

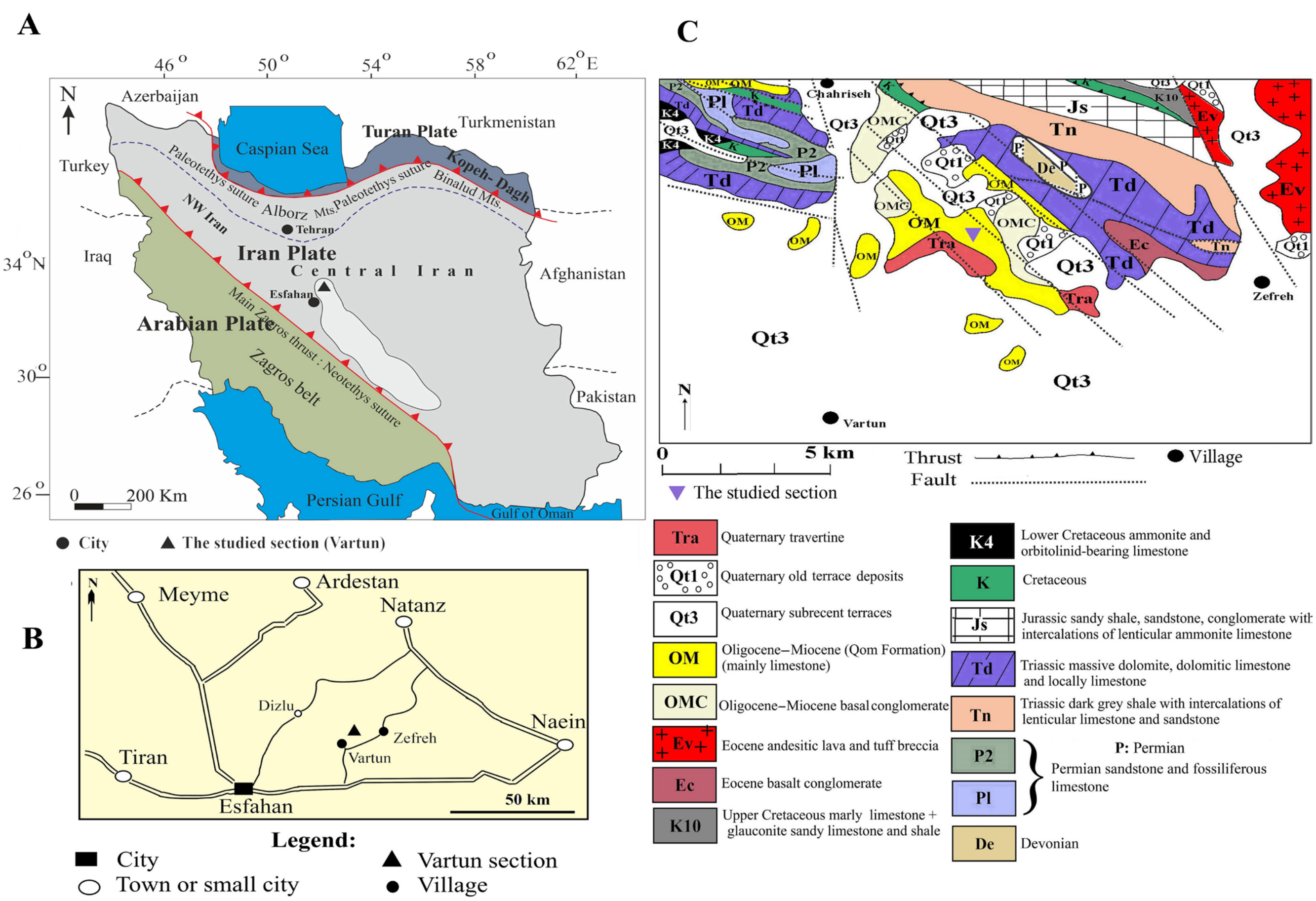

Figure 1 (A) Geological and structural map of Iran and location of the studied section (Vartun section) in the north of the Esfahan–Sirjan Basin in central Iran (modified from Rahiminejad and Hassani, 2016; Rahiminejad *et al.*, 2017, 2018; Rahiminejad and Zand-Moghadam, 2018, 2020; Moosavizadeh *et al.*, 2020). (B) Location map of the Vartun section (modified from Zágoršek *et al.*, 2017). (C) Geological map of the studied area (redrawn and modified from Zahedi, 1978 and Rahiminejad *et al.*, 2020).

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Roozpeykar *et al.*, 2019a). This paper focuses on the paleoecological aspects of Lower Miocene coralline red algae from the Qom Formation and contributes data from the algal-rich Cenozoic carbonates of Iran.

2. Geological Setting

In the present study, samples yielding fossil coralline red algae were collected from the Lower Miocene Qom Formation in the Vartun section (Figures 1 and 2). This section is located about 50 km northeast of the city of Esfahan (32° 56′13.79″ N and 52° 08′45.32″E; Figure 1) and is situated in the north of the Esfahan–Sirjan fore-arc basin in central Iran (Figure 1A). The most exposed strata in the studied area comprise Quaternary terraces in addition to Triassic (massive dolomite, dolomitic limestone, limestone, shale), Jurassic (sandy shale, sandstone, conglomerate), and Oligocene–Miocene deposits (Figure 1C). Strata of the Qom Formation were deposited on the northeastern edge of the Tethyan Seaway in the Sanandaj–Sirjan fore-arc basin, and/or Esfahan–Sirjan fore-arc basin, and the Urumieh–Dokhtar magmatic arc basin in central Iran during the last marine transgression in the Oligo–Miocene (Daneshian and Ramezani Dana, 2007; Reuter *et al.*, 2009; Zágoršek *et al.*, 2017).

Generally, the Oligocene and Miocene deposits of the Qom Formation in central Iran consist mainly of limestone, marl, gypsum, and subordinate siliciclastic sediments containing diverse fossil invertebrates represented by corals, gastropods, echinoids, bivalves (particularly pectinids), and coralline red algae (Seyrafian and Toraby, 2005; Reuter *et al.*, 2009; Yazdi *et al.*, 2012; Rahiminejad *et al.*, 2020). These unconformably overlie the continental rocks of the Lower Red Formation (Oligocene) and are unconformably overlain by the Middle to Upper Miocene continental strata of the Upper Red Formation (Stöcklin and Setudehina, 1991; Yazdi- Moghadam, 2011; Amirshahkarami and Karavan, 2015; Rahiminejad *et al.*, 2020). The depositional environments of the Qom Formation in the Esfahan–Sirjan Basin are consistent with mixed carbonate–siliciclastic homoclinal ramp (Reuter *et al.*, 2009), open shelf (SE Chahriseh (Moradi, 2012)), and inner and middle ramps Vartun section (Rahiminejad *et al.*, 2020).

3. Materials and Methods

The investigation of fossil coralline red algae and their associated facies or sedimentary texture was based on microscopic analyses of thin-section slides from thirty rock samples of algal limestone that were examined with a Stereo binocular Microscope model Yaxun YX AK21 and photographed using a CCD digital camera model KECam. The classification of carbonate facies followed that of Dunham (1962) and Flügel (2010), which is based on the types and abundance of grains and the matrix in the deposits. Taxonomic analysis of the identified coralline red algae was based on Braga (2003), Brandano and Piller (2010), and Sarkar (2017). Coralline red algal growth forms were described according to Woelkerling *et al.* (1993), and Nebelsick and Bassi (2000).

Since the collected algal specimens in the studied section are present as bioclasts and partially preserved fossils, confirmation of taxa at the species level cannot be accurately established. However, detailed statistical analyses on well-preserved algal samples may improve paleoecological interpretation in future studies.

The age of the Qom Formation in the Vartun section (Figures 1 and 2) is based on previous studies carried out by Rahiminejad *et al.* (2020) (Figure 3).

4. Results

4.1. STRATIGRAPHY AND FACIES ANALYSIS OF THE STUDIED ALGAE-RICH LIMESTONE

We focused our paleoecological studies on a 1 m thick interval of Lower Miocene (Aquitanian)

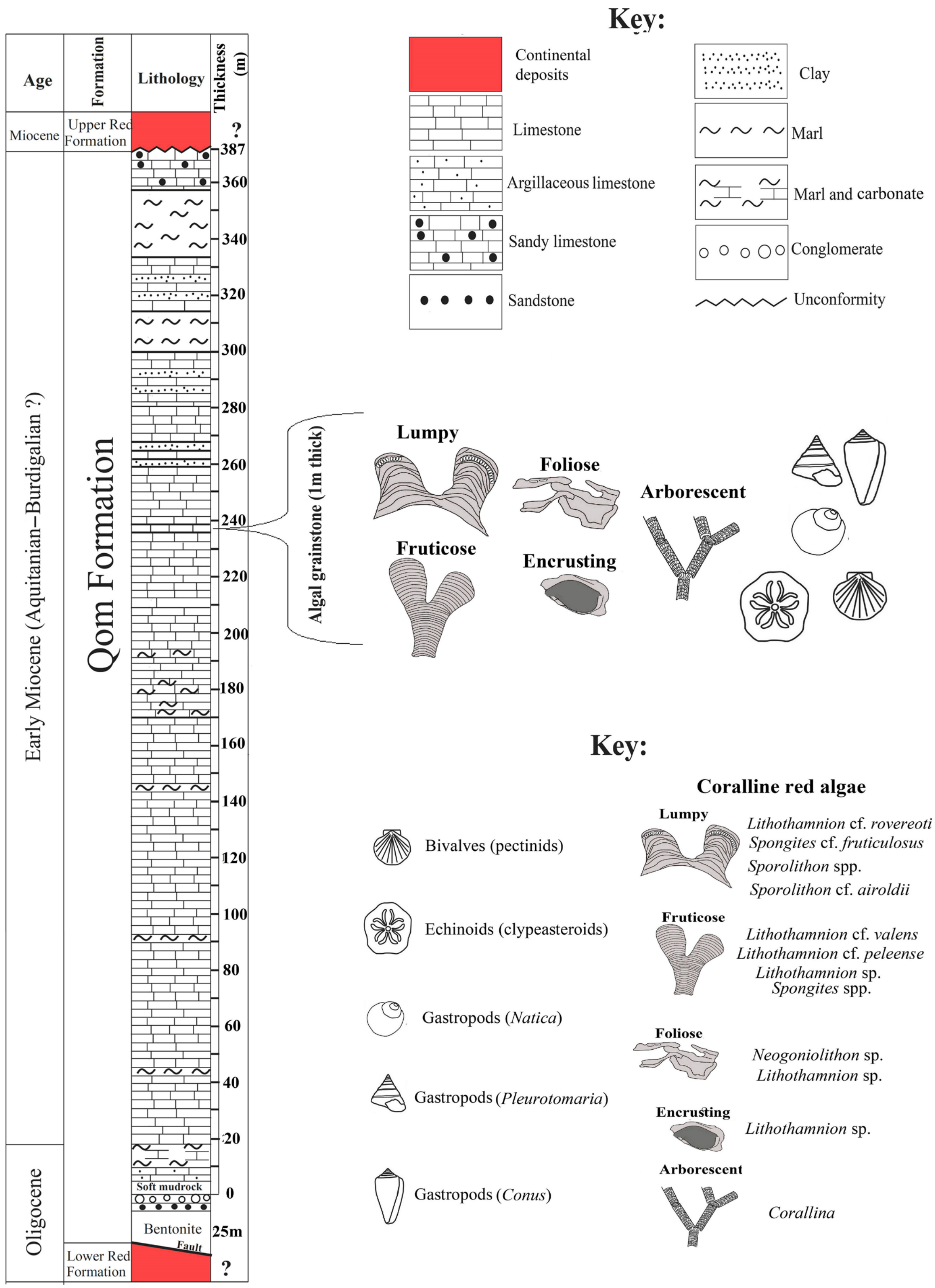

Figure 2 Measured stratigraphic column of the Qom Formation in the Vartun section. Age of the Qom Formation in the section is based on Rahiminejad *et al.*, 2020. Our studies focused on a 1 m-thick interval algal limestone comprising coralline red algae-rich grainstone. The symbols illustrating the growth forms of the identified algae are redrawn and modified from Woelkerling *et al.*, (1993), and Nebelsick and Bassi (2000). The percentage or relative abundance of different algal growth forms in the studied grainstone facies is as follows: fruticose: 70 %, lumpy: 20%, foliose, encrusting, and arborescent: 10%.

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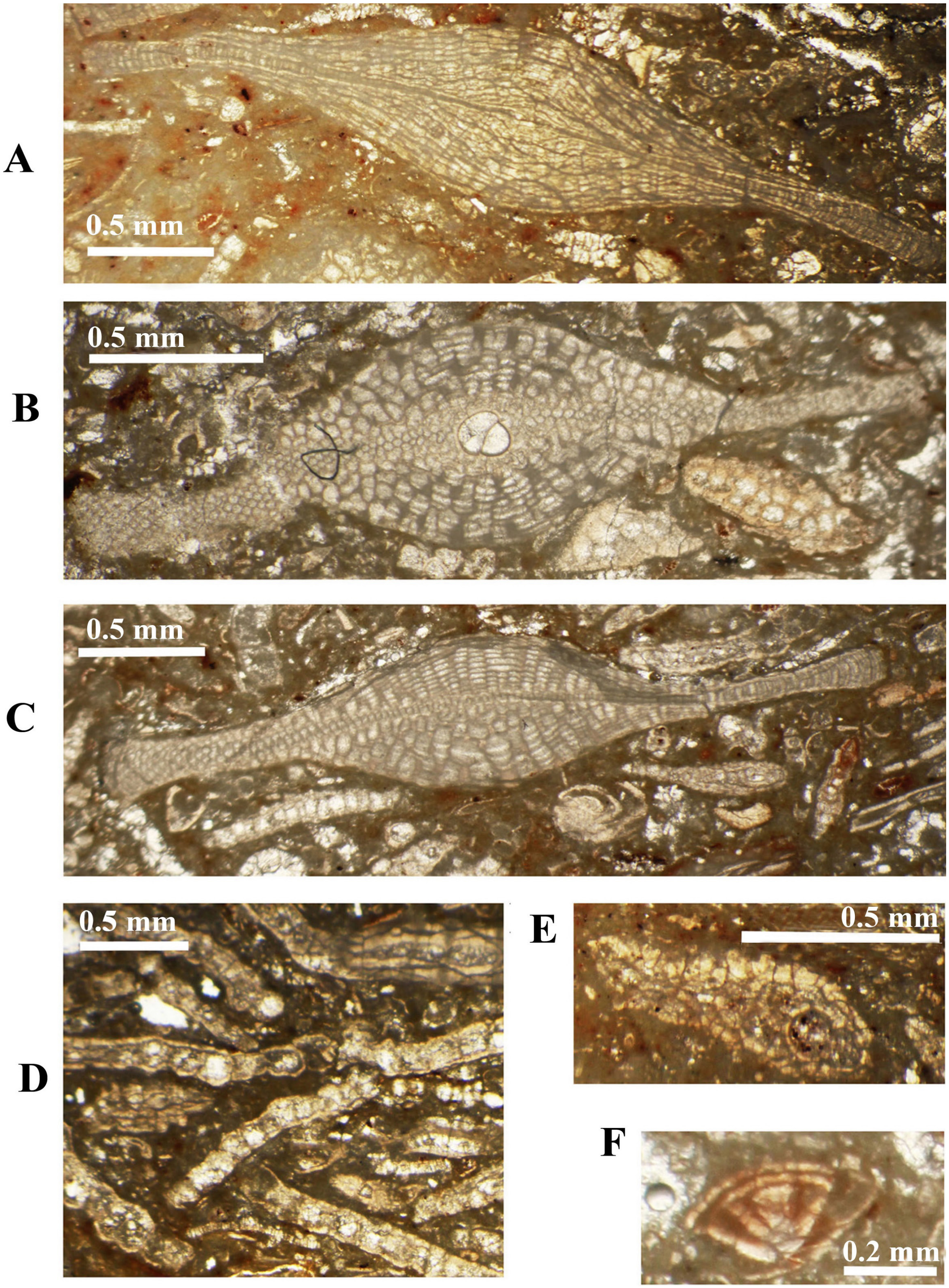

Figure 3 Some of the identified large benthic foraminifera used for age determination of the Qom Formation in the Vartun section (Rahiminejad *et al.,* 2020). (A) *Lepidocyclina* sp., (B) *Nephrolepidina* sp., (C) *Eulepidina* sp., (D) *Operculina* spp., (E) *Miogypsina* sp., (F) *Amphistegina* sp. Note that these microfossil specimens were not collected from the algal grainstone facies in this study.

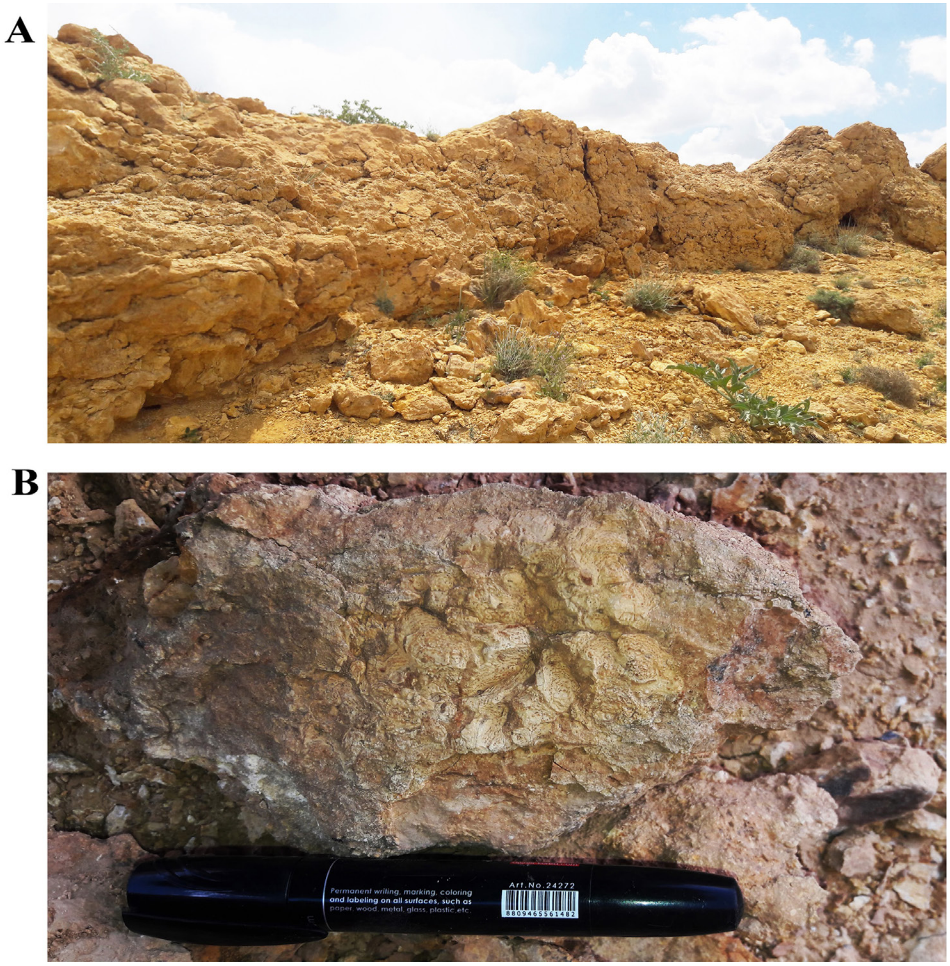

Figure 4 **(A) Outcrop view of the studied coralline red algae-rich limestone (*1 m thick*) in a grainstone facies. (B) Rock sample of the studied algae-rich limestone.**

massive and lithified coralline red algae-rich limestone in the Qom Formation (Figures 2 and 4). The stratigraphic details of the Qom Formation in the studied section are shown in Figure 2. In the field, the limestone interval (Figures 2 and 4) is laterally exposed up to ca 70 m, is discontinuous, and untraceable in a wide area. Cylindrical *Skolithos* burrows are common and fossils of bivalves (pectinids), gastropods *(Conus, Natica, and Pleurotomaria)*, and echinoids *(Clypeasteroids)* are abundant in the interval (Figure 2). Likewise, the limestone interval is composed of coralline algae-rich grainstone facies dominated by skeletal grains embedded in a sparitic matrix or sparry cement (Figures 5A and 5B). The latter (65%) include coarse-grained bioclasts and partially preserved specimens of abundant coralline red algae. Coarse-grained bioclasts of corals, echinoids, gastropods, and bivalves (22%) as well as scarce (13%) larger benthic foraminifera (*Nephrolepidina* sp., *Amphistegina* sp., and miliolids) comprise the subordinate skeletal grains.

4.2. THE IDENTIFIED CORALLINE RED ALGAE AND THEIR GROWTH FORMS

The micropaleontological studies revealed the presence of five genera of coralline red algae in the studied grainstone facies (Table 1 and Figures 5 to 8). Non-geniculate forms of the identified algae predominate (Table 1), whereas algae representative of geniculate forms (genus *Corallina*) are scarce. Several of the non-geniculate algae are highly fragmented and abraded, while geniculate forms are disarticulated and fragmented. The

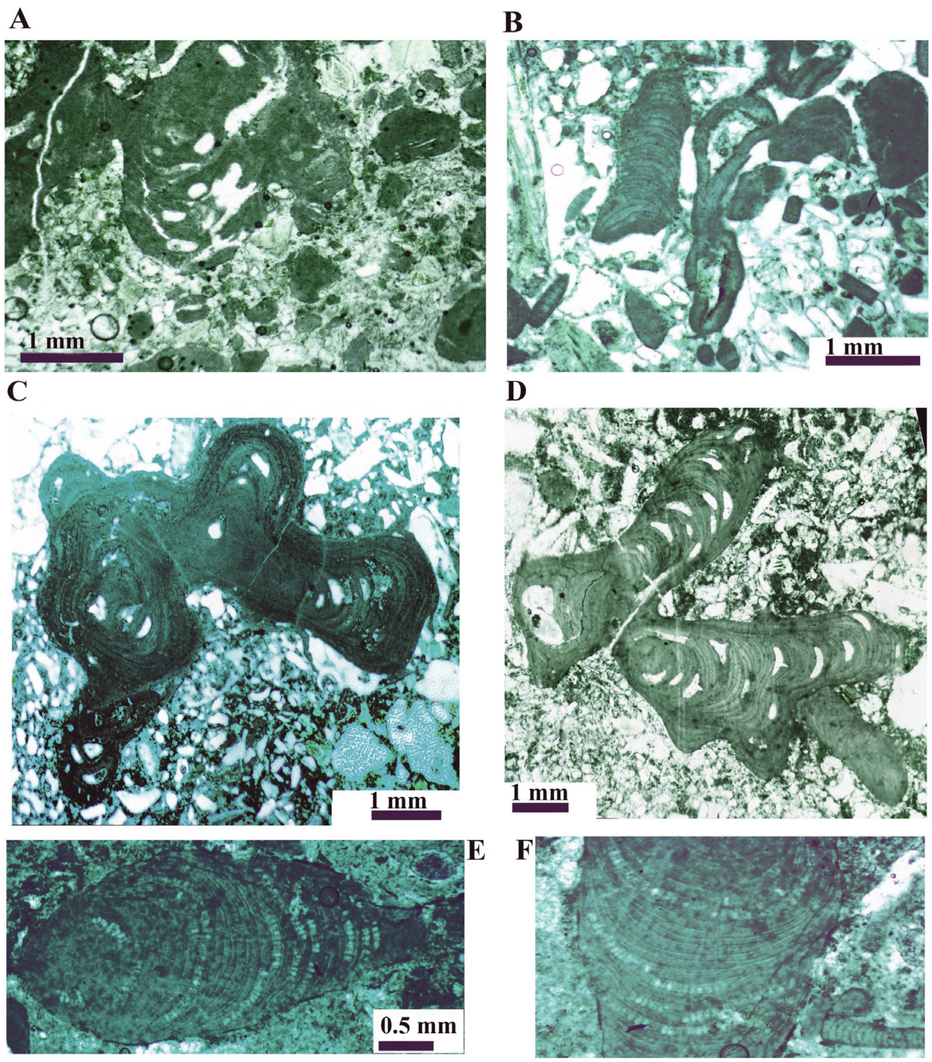

Figure 5 **(A, B) Algal grainstone facies. (C–F) Identified coralline red algae in grainstone facies; (C) Fruticose thallus of *Spongites* sp.; (D) Lumpy thallus of** *Spongites* **cf.** *fruticulosus*; **(E, F) Lumpy thalli of** *Sporolithon* **cf. *airoldii*.**

percentage or relative abundance of the algae is indicated in Table 1. The non-geniculate algae include melobesioids, mastophoroids, and sporolithaceans (Table 1). Melobesioids comprise the taxa *Lithothamnion* cf. *valens*, *Lithothamnion* cf. *rovereoti*, *Lithothamnion* cf. *peleense*, and *Lithothamnion* spp. Mastophoroids are represented by the taxa *Neogoniolithon* sp., *Spongites* cf. *fruticulosus*, and *Spongites* spp. Sporolithaceans include the taxa *Sporolithon* spp., and *Sporolithon* cf. *airoldii*.

In the studied grainstone facies, the identified coralline red algae mainly display fruticose (70 %) and lumpy (20%) growth forms (Table 1). Algae with foliose, encrusting, and arborescent growth forms are also present (Table 1), although subordinately (10%).

5. Discussion and interpretation

5.1. PALEOECOLOGY OF THE IDENTIFIED CORALLINE RED ALGAE

The dominance of a sparitic matrix or sparry cement in the identified algal grainstone facies and the abundance of bioclasts and skeletal grains

Table 1. The identified coralline red algae and their growth forms in the algal grainstone facies. The algae are dominated by non-geniculate forms. Geniculate forms (*Corallina* sp.) of the algae are scarce. The percentage or relative abundance of different growth forms of the algae in the studied grainstone facies is as follows: fruticose: 70 %, lumpy: 20% foliose, encrusting, and arborescent: 10%.

	Algae: percentage (relative abundance)	Genera / species	Growth form
Non-geniculate	Melobesioids: 60%	*Lithothamnion* cf. *valens* *Lithothamnion* cf. *rovereoti* *Lithothamnion* cf. *peleense* *Lithothamnion* spp.	Fruticose Lumpy Fruticose 1–Encrusting, 2–Foliose, 3–Fruticose
	Mastophoroid: 25%	*Neogoniolithon* sp. *Spongites* spp. *Spongites* cf. *fruticulosus*	Foliose Fruticose Lumpy
	Sporolithaceans: 10%	*Sporolithon* spp. *Sporolithon* cf. *airoldii*	Lumpy Lumpy
Geniculate	*Corallina* : 5%	*Corallina*	Arborescent

point to a shoal environment (in an inner ramp) in a high-energy water zone above the fair-weather wave base during the Aquitanian (Flügel, 2010; Sadeghi *et al*., 2011; Vescogni *et al*., 2014; Roozpeykar *et al*., 2019b).

The presence of *Skolithos* burrows in the algal grainstone-bearing limestone indicates high hydrodynamic (water) energy (Vinn and Wilson, 2013; Sedorko *et al*., 2018). Further details on the depositional environment of the Lower Miocene deposits of the Qom Formation in the Vartun section have been provided by Rahiminejad *et al*. (2020), whose results confirm our environmental interpretation.

The co-occurrence of melobesioids (*Lithothamnion*), mastophoroids (*Neogoniolithon*, *Spongites*), and *Sporolithon* may be representative of the basinward part of the shoal environment, although a number of these algae could have been reworked and transported in the shoal environment.

Usually, the occurrence of coralline red algae in a grainstone facies is related to nutrient influx due to encroachment of siliciclastics (Erlich *et al*., 1990, 1993; Roozpeykar *et al*., 2019a). For instance, Ghosh and Sarkar (2013) have reported a grainstone facies comprising an algal association of *Corallina*, *Lithothamnion*, and *Spongites* from Pliocene reef and back-reef shelf environments as well as a melobesioid coralline algal assemblage of *Phymatolithon*, *Mesophyllum*, and *Lithothamnion* from a coralline algal boundstone in a Pliocene fore-reef environment. Roozpeykar *et al*. (2019a, 2019b) have studied a coralline red algae-rich grainstone in a Miocene shoal environment in the Zagros Basin and have reported non-geniculate (dominant *Spongites* and reworked melobesioids) and geniculate algae (*Corallina*).

Generally, coralline red algae were one of the major and most abundant'biotic components of photozoan and heterozoan communities of Oligocene–Miocene cool waters (non-tropic) and tropical carbonates (Bassi and Nebelsick, 2010; Braga *et al*., 2010). Mastophoroids (specifically *Spongites*) are common in shallow tropical carbonates (Adey *et al*., 1982; Braga and Aguirre, 2001, 2004), but are also present in subtropical and temperate environments. Some genera (*e.g. Lithothamnion* and *Mesophyllum*) of the subfamily Melobesioideae

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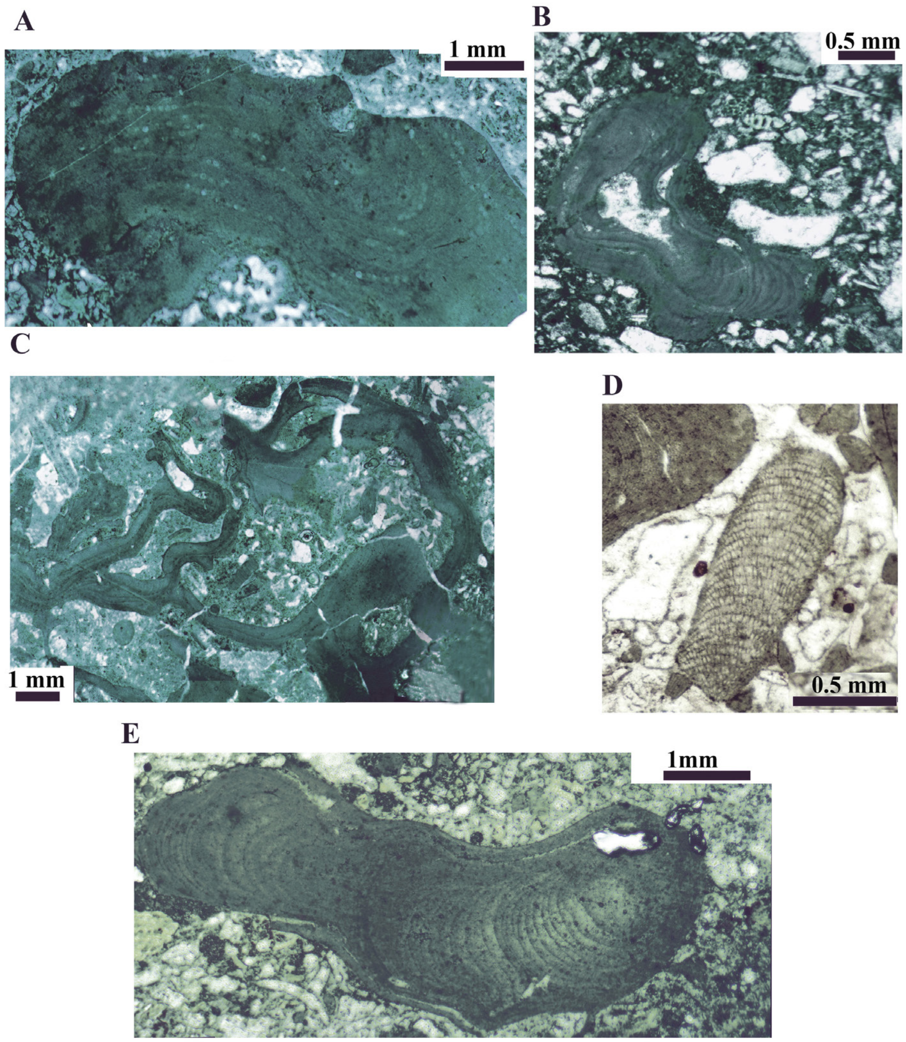

Figure 6 **Identified coralline red algae in the grainstone facies. (A) Fragment of *Sporolithon* sp. showing a lumpy growth form. (B) Fragment of a fruticose thallus of a melobesioid. (C) Foliose thalli of *Neogoniolithon* sp. (D) Fragment (disarticulated) of *Corallina* sp. with an arborescent growth form. (E) Fragment of a fruticose thallus of *Lithothamnion* cf. *valens*.**

occur in both temperate and warm conditions (Braga and Aguirre, 2001; Halfar and Mutti, 2005; Bassi *et al*., 2009; Braga *et al*., 2010; Brandano and Piller, 2010; Rösler *et al*., 2015; Roozpeykar *et al*., 2019a, 2019b). Also, sporolithaceans (*Sporolithon*) are common in tropical deposits (Brandano *et al*., 2005). Coralline red algae can survive in different trophic conditions ranging from oligotrophic to mesotrophic environments in different latitudes (Braga *et al*., 2010). The main paleoecological factors controlling their growth and development in benthic marine environments include depth, hydrodynamic energy, chemical composition, light intensity, and temperature of marine waters (Sarkar, 2017). The different growth forms of coralline red algae are useful tools in paleoecological interpretation of marine carbonate facies (Bosence and Pedley, 1982; Braga and Martín, 1988; Braga and Aguirre, 2001; Rasser and Piller, 2004; Brandano *et al*., 2005; Brandano and Ronca, 2014) and include warty, lumpy, fruticose, foliose, encrusting, layered (non-geniculate), and arborescent (geniculate) (Woelkerling *et al*., 1993; Nebelsick and Bassi, 2000).

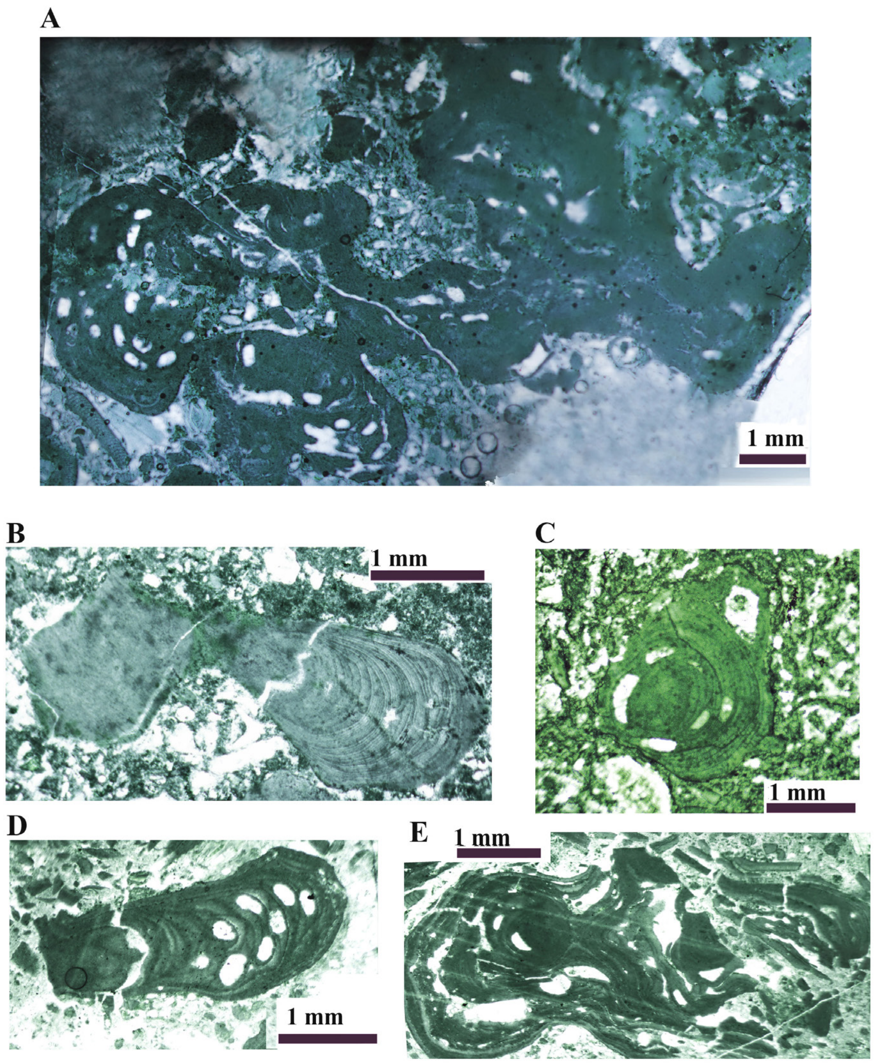

Figure 7 Identified coralline red algae in the grainstone facies. (A) Lumpy growth form of *Lithothamnion* cf. *rovereoti.* (B) Fragment of a fruticose thallus of *Lithothamnion* sp.; partially abraded. (C) Fragment of fruticose thalli of *Lithothamnion* cf. *peleense*. (D) Fruticose thallus of *Lithothamnion* sp. (E) Foliose thalli of *Lithothamnion* sp.

As evidenced in this study, the dominance of coralline red algae with fruticose growth forms (Table 1) in the shoal carbonate environment is consistent with high water energy (Bosence, 1991; Basso, 1998; Nebelsick *et al*., 2000). Agitation in the shoal environment, resulted different taphonomic features such as high fragmentation, disarticulation, and abrasion of several algae (Nebelsick *et al*., 2000; Nebelsick and Bassi, 2000; Roozpeykar *et al*., 2019a, 2019b). The identified algae (Table 1 and Figures 5–8) and the presence of larger benthic foraminifera point to a well-illuminated euphotic marine zone (Vescogni *et al*., 2014; Roozpeykar *et al*., 2019a, 2019b). The overall recognition of algae indicates that the Lower Miocene grainstone was deposited in warm tropical to subtropical waters (Bosence, 1983a, 1983b; Braga and Aguirre, 2001; Brandano *et al*., 2005; Roozpeykar *et al*., 2019a). Moreover, tropical conditions can be inferred owing to the presence of skeletal grains of corals and larger benthic foraminifera such as miliolids, *Amphistegina*, and *Nephrolepidina* in the studied grainstone facies (Pomar *et al*., 2004; Brandano *et al*., 2009; Roozpeykar *et al*., 2019a, 2019b).

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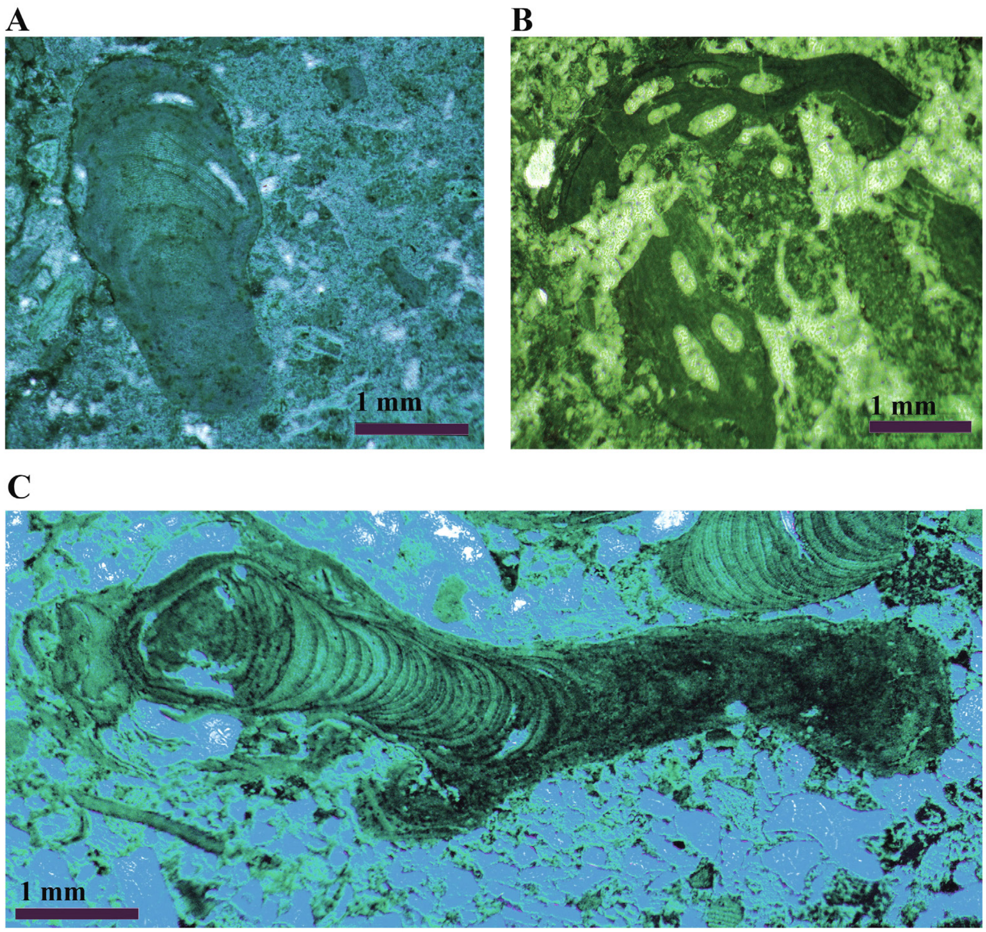

Figure 8 Identified coralline red algae in the grainstone facies. (A) Fragment of a fruticose thallus of *Lithothamnion* sp. (B) Fragment of *Lithothamnion* sp. (encrusting growth form). (C) Melobesioid algae with a fruticose growth form.

6. Conclusions

The Lower Miocene (Aquitanian) algal-rich grainstone facies of the Qom Formation of Esfahan–Sirjan basin in central Iran is characterized by non-geniculate coralline red algae represented by melobesioids, mastophoroids, and sporolithaceans. The distribution of coralline red algae in the grainstone facies is probably linked to nutrient influx and the dominance of the fruticose growth form is indicative of high-energy conditions in a shoal environment. Due to the dominance of algae in well-illuminated waters, it may be concluded that the studied facies was deposited in the euphotic marine zone, and the Lower Miocene algal forms were inhabited in warm tropical to subtropical waters during the Aquitanian, having high-energy conditions, (*i.e.* increased hydrodynamic activity coupled with sediment agitation) that led to enhanced fragmentation, abrasion, and disarticulation of many algal forms recorded herein.

Contributions of authors

Amir Hossein Rahiminejad: *conceptualization, analysis, and data acquisition, methodology, writing of the original manuscript, graphic design, fieldwork, interpretation, financing (applicant)*. Mehdi Yazdi: *conceptualization, fieldwork*. Amit Kumar Ghosh: *correction and edition of the manuscript, contributed with paleontological interpretation and confirmation of fossil taxa.*

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Conflicts of interest

The authors have no conflicts of interest to declare.

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