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Diversity and paleoecological significance of zooxanthellate corals of Oligocene Qom Formation, SE Iran

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ABSTRACT

Zooxanthellate corals are Iran's most abundant macrofossils in the Oligocene-early Miocene Qom Formation deposits in the NE margin of the Tethyan Seaway. Yet, basic knowledge about the diversity of these organisms and their paleoecology is still scarce. In this paper late Rupelian–Chattian coral data from three exposed sections in the northwestern Jazmurian Lake, SE Iran, as the southeasternmost outcrops of the Qom Formation, are analyzed in terms of diversity and paleoecology. The coralline red algae and larger benthic foraminiferal assemblages associated with the corals have also been used to infer the paleoenvironmental and paleoecological conditions. The following coral genera were recognized: *Leptoria*, *Caulastraea*, *Hydnophora*, *Astreopora*, *Plesiastraea*, *Thegioastraea*, *Porites*, *Goniopora*, *Platycoenia*, *Acropora*, *Tarbellastraea*, *Favites*, *Heliastraea*, *Stylocoenia*, *Ceratotrochus*. The high abundance of z-corals, larger benthic foraminifera (LBF), and coralline red algae demonstrate that the deposition took place in tropical-subtropical warm waters mainly within the euphotic to the mesophotic zones. The presence of various coral fabrics including pillarstone, domestone, and rudstone allowed to infer high to moderate hydrodynamic energy in the studied sections. As well, given the interactions among corals, filter-feeders, green and red algae, bioeroders, and the surrounding environment, it seems that oligotrophic to slightly mesotrophic conditions also had prevailed in the studied area.

Keywords: Oligo-Miocene; Corals; Paleoecology; Larger benthic foraminifera; Tethyan Seaway;

Diversidad y significado de los corales Zooxanthellate en la formación Qom, al sureste de Irán

RESUMEN

Los corales Zooxanthellate son los macrofósiles más abundantes en los depósitos del Oligoceno Temprano de la formación Qom en el margen noreste del Oceáno Tetis. Sin embargo, el conocimiento básico sobre la diversidad de estos organismos y de su paleoecología es escaso. Este trabajo utiliza información del período Rupelian–Chattian tardío en tres secciones expuestas al noroeste del lago Jazmurian, sureste de Irán, que son los afloramientos rocosos más al sudeste de la formación Qom, y que se analizó en términos de diversidad y paleoecología. Algas rojas coralinas y grandes conjuntos de foraminíferos bentónicos asociados con los corales también se usaron para inferir el paleoambiente y las condiciones paleoecológicas. Se reconocieron los siguientes géneros coralinos: *Leptoria*, *Caulastraea*, *Hydnophora*, *Astreopora*, *Plesiastraea*, *Thegioastraea*, *Porites*, *Goniopora*, *Platycoenia*, *Acropora*, *Tarbellastraea*, *Favites*, *Heliastraea*, *Stylocoenia*, *Ceratotrochus*. La alta abundancia de corales Zooxanthellate, los grandes conjuntos de foraminíferos bentónicos y las algas coralinas rojas demuestran que la deposición tuvo lugar en aguas calidadas del orden tropical-subtropical y principalmente dentro de las zonas eufóticas a mesofóticas. La presencia de varias fábricas coralinas que incluyen pilares, domos y piedras permiten inferir la energía hidrodinámica de alta a moderada en las secciones estudiadas. Además, al parecer por las interacciones entre corales, los alimentadores por filtración, las algas rojas y verdes, los bioerosionadores, y el ambiente alrededor, en el área de estudio prevalecieron condiciones oligotrópicas a ligeramente mesotrópicas.

Palabras clave: Oligo-Mioceno; corales; paleoecología; grandes foraminíferos bentónicos; mar de Tetis.

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1. Introduction

Late Oligocene (Chattian) probably dealt with the highest coral diversity for the Cenozoic, and large reefal structures occurred worldwide (Pomar and Hallock, 2007). The shift from the warm Eocene to the Oligocene "icehouse" took place during a sequence of major changes in climate, ice volume, and oceanic circulation, which affected the composition and production of the carbonate factory (Brandano, 2017). Hallock (1996), Hallock and Pomar (2008) suggested that CO_2 reduction (as Eocene-Oligocene transition aftermath) had an influential impact on the expansion of zooxanthellate corals, probably favored by the rising Mg/Ca ratios, which enhanced hyper calcification of aragonite (Stanley and Hardie, 1998). During the Oligocene-Miocene, the biogeography of reef corals progressively changed from the Tethyan Province in the Eocene to three reef-coral provinces: the Mediterranean, the Indo-Pacific, and the western Atlantic-Caribbean (Perrin and Bosellini, 2012; Pomar et al., 2014). After a temporary platform crisis during the earliest Oligocene, coral reefs spread throughout the Tethys and increased with new lineages of LBF (Hontzsch et al., 2013; Pomar et al., 2017). As well, Oligocene reefs depict the peak of Cenozoic reef growth (Pomar et al., 2014).

The lower Oligocene–lower Miocene rocks (Rupelian–Burdigalian), known as Qom Formation are deposited at the northeastern margin of the Tethyan Seaway during the final sea transgression in the Sanandaj–Sirjan, Urumieh–Dokhtar, and Central Iran basins (e.g. Mohammadi et al., 2013, 2015; Mohammadi, 2022, 2024; Fig. 1). Biogenic constituents of the Qom Formation include corals, corallinacean algae, larger benthic foraminifera, small benthic foraminifera, planktic foraminifera, bivalves, bryozoans, echinoderms, gastropods as well as polychaete worm tubes, especially *Ditrupa*. Herein, we will concentrate specially on corals.

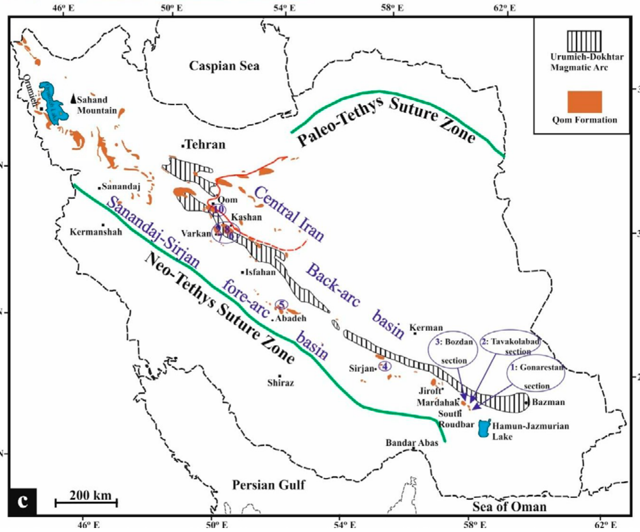

Figure 1. A map illustrating the distribution of the Urumieh-Dokhtar Magmatic Arc, the Qom Formation outcrops, suture zones of Paleotethys and Neotethys in Iran, and the situation of the studied sections (adopted from Mohammadi, 2023).

An advance in the knowledge of the corals from the Qom Formation deposits is of major importance because they are located between the Western and the Eastern Tethys regions (Mohammadi et al., 2011, 2013, 2015, 2019; Mohammadi and Ameri, 2015, 2024; Daneshian and Ramezani Dana, 2018; Mohammadi, 2020, 2021, 2023, 2024) and thus, paleogeographically, they are significant. Most investigations on the Qom Formation have been conducted on the central parts of Iran and especially, on its foraminiferal content; however, surprisingly little information is available about the corals as well as about the southeasternmost outcrops of the Qom Formation (Mohammadi, 2022, 2023, 2024). Therefore, this paper aims to bridge the gap by investigating the southeasternmost outcrops of the Qom Formation on corals to 1) recognize coral components and 2) analyze the paleoecology of the identified corals.

2. Previous works

The fossil assemblages of scleractinian corals comprise one of the dominant carbonate components of the Qom Formation that are widely considered in environmental interpretations of fossil corals reefs (Brandano et al., 2010; Perrin and Bosellini, 2012; Yazdi et al., 2012). A total of 32 and 13 genera of scleractinian corals from the Formation were recorded by Schuster and Wielandt (1999) from the Isfahan–Sirjan fore-arc and the Qom back-arc basins, respectively. Reuter et al. (2009) studied scleractinian corals from Abadeh and Zefreh sections (in the fore-arc Basin) and Chalehghareh and Qom sections (in the back-arc Basin). Rahiminejad et al. (2017) presented the paleoenvironment of scleractinian corals of the Qom Formation in northeastern Isfahan (Central Iran) and identified nine colonial coral genera. Mohammadi and Ameri (2015) analyzed the biotic constituents of the Qom Formation in northern Abadeh and recorded a Rupelian-Chattian age for the studied section. These authors noted isolated, branched, and colonial growth forms of corals as well as some scattered coral colonies. The main recognized coral genera represented by Mohammadi and Ameri (2015) are *Favites*, *Hydnophora*, *Astrocoenia*, *Porites*, *Leptoria*, *Cyphastrea*, and *Favia*. Besides, Miocene coral-rich deposits of Makran have been studied by Ghaedi et al. (2016) and Ghaedi and Yazdi (2016). In addition, coral boundstone facies were recorded from some stratigraphic sections of the Qom Formation by Mohammadi et al. (2011, 2019) and Mohammadi (2020, 2021).

3. Geological setting

The geology and especially the tectonic structure of Iran are highly infuenced by the development and history of the Tethyan (Paleotethys and Neotethys Oceans) region (Alavi, 2004; Ghaedi et al., 2022). Deposition of the Qom Formation took place in the NE margin of the Tethyan Seaway in three NW–SE-trending basins (>1800 km length) including the Sanandaj–Sirjan fore-arc basin, Urumieh–Dokhtar magmatic arc (Intra-arc basin), and Central Iran back-arc basin (Mohammadi et al., 2013, 2015; Fig. 1). The outcrops of the Qom Formation are distributed from the Khoy and Maku regions (northwestern Urumieh Lake) in the northwest to northwest of the Jazmurian Lake in the southeast (Rahimzadeh, 1994; Seyrafian and Toraby, 2005; Mohammadi et al., 2011, 2013; Mohammadi, 2023, 2024; Fig. 1).

All of the studied sections (Bozdan, Tavakolabad, and Gonarestan) are located in the Sanandaj-Sirjan basin. This basin constructs a narrow band, situating between Urumieh and Sanandaj cities in the northwest, and Sirjan and Esfandagheh cities in the southeast (Ghasemi and Talbot, 2006), bounded by the UDMA to the NE and the Main Zagros Reverse Fault in the SW (Fig. 1).

4. The age range

The foraminiferal-based new biozonation of the Qom Formation (Mohammadi, 2023) is applied in this research to define age. The biostratigraphy of the studied sections is discussed in Mohammadi and Ameri (2024). So the biostratigraphy is only briefly discussed here. In all, 35 genera and 55 species of benthic foraminifera were identified.

In the Gonarestan section, based on the vertical distribution of foraminifera, two assemblages were recognized. Assemblage 1 extends from the base of the Qom Formation to 68m. The presence of *Nummulites fichteli*, *Nummulites intermedius*, and *Nummulites vascus* allows the age of the Assemblage 1 to be determined as Rupelian. Due to the co-occurrence of lepidocyclinids and *Nummulites*, this assemblage corresponds to the *Lepidocyclina-Nummulites* concurrent range zone of Mohammadi (2023). It is attributed to the late Rupelian. Assemblage 2, 17m in thickness, occurs from 68 to 85m (top of the section). The main biotic event in this assemblage is the absence of *Nummulites vascus*, *Nummulites fichteli*, and *Nummulites intermedius.* This assemblage is correlated with *Lepidocyclina* partial range zone of Mohammadi (2023) and consequently is considered to be Chattian in age.

In the Tavakolabad section, two foraminiferal assemblages were recognized. Assemblage 1 expands from the basal boundary of the Qom Formation to 44m. Due to the co-occurrence of lepidocyclinids and *Nummulites*, Assemblage 1 corresponds to the *Lepidocyclina-Nummulites* concurrent range zone of Mohammadi (2023). It is attributed to the late Rupelian. Assemblage 2, 36m in thickness, extends from 44 to 80m (top of the section). The main difference between assemblages 1 and 2 is the absence of *Nummulites vascus* and *Nummulites fichteli/intermedius* in the second one. This assemblage correlates with the *Lepidocyclina* partial range zone of Mohammadi (2023), that is the Chattian in age.

In the lower carbonate part of the Bozdan section, 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 is pertaining to the late Rupelian in age. This assemblage correlates with the *Lepidocyclina-Nummulites* concurrent range zone of Mohammadi (2023). The assemblage is attributed to the late Rupelian. It should be noted that the preliminary study of 62 samples from the upper carbonate part of the Bozdan section revealed that its age is Rupelian?- Chattian.

In summary, based on the biostratigraphic data, the recognized foraminifera assemblages, and Mohammadi and Ameri (2024), the Qom Formation is late Rupelian−Chattian in age in Bozdan, Tavakolabad, and Gonarestan stratigraphic sections.

5. Material and methods

5.1. Description of sections

We collected samples and prepared thin sections from three stratigraphic sections of the Qom Formation, with special emphasis on scleractinian corals. These are Gonarestan, Tavakolabad, and Bozdan stratigraphic sections in northwestern Jazmurian Lake (Fig. 1). The studied sections represent the southeasternmost outcrops of the Qom Formation. All stratigraphic sections (Fig. 2) are approachable via motorable long roads (Valeh, 1956). Outcrops of the Qom Formation in the Bozdan section are unconformably underlain by volcanic rocks (Valeh, 1956). However, in the Gonarestan and Tavakolabad sections they lie on top of older tuff units. The tuff units may be equivalent to the tuff unit separating the lower and upper carbonate units of the Bozdan section. The Qom Formation in all three stratigraphic sections is covered by Quaternary alluvium (Valeh, 1956). Besides, up to 3 m of the basal part of the Gonarestan and Tavakolabad sections were covered by debris.

The Gonarestan section (28˚ 08´ 30″ N, 58˚ 22´ 12″ E) is situated approximately 90 km northwest of the center of Jazmurian Lake (Fig. 1). It is located more than 1800 km southeast of the northwesternmost outcrops of the Qom Formation (in NW Maku). The Gonarestan section, with a thickness of 85 m, consists of medium to thick-bedded and massive limestones, and coral reef-bearing limestone. There are a lot of scleractinian coral colonies in some parts, which are diverse and mostly in their growth position, forming a connected and relatively dense framework.

The Tavakolabad section (28˚ 09´ 22″ N, 58˚ 21´ 55″ E) is situated between Gonarestan and Bozdan stratigraphic sections. It is located approximately 45 km northeast of Roudbar-Jonoub City (Fig. 1). The section (80 m thick) is mainly composed of medium to thick-bedded and massive limestones, coral reef limestone, and marls. The marly succession is deposited in one interval in the lower part and contains millimeter-sized *Nummulites*.

The Bozdan section (28˚ 13´ 35″ N, 58˚ 14´ 24″ E) is situated northwest of both Tavakolabad and Gonarestan stratigraphic sections. It is approximately located 35 km northeast of Roudbar-Jonoub City (Fig. 1). Its lower contact with volcanic rocks of Eocene is well exposed. Outcrops of the Qom Formation in the Bozdan section 440m thick), consist mainly of medium to thick-bedded and massive limestones, reefal limestones, marls, tuffaceous limestones, and tuffs. A tuff unit (90m thick) is intercalated in the lower part and separates the lower (30m thick) and upper carbonate units (320m thick). It should be noted that the contact between the tuff unit and the upper carbonate unit is not usually exposed due to the debris. Coralline red algae, LBF, corals, and echinoderms are the most prevailing biota in the studied section. Although scleractinian corals are rare in the lower part, distinct coral horizons are abundant and traceable for several hundreds of meters in the upper part. Two yellow marly units with centimeter to millimeter-sized *Nummulites* occur in the lower carbonate unit. In the Bozdan section, the lower carbonate unit is sampled systematically. However, only 62 hard samples were collected from the upper limestone unit. In fact, due to the cliff-forming topography of the upper 100 meters and the inaccessible route, systematic sampling was neglected.

Scleractinian coral colonies are abundant and diverse in all three stratigraphic sections, but they are very rare in the studied lower part of the Bozdan section. Echinoderms are present in some layers of the Gonarestan and Bozdan stratigraphic sections; surprisingly they are absent in the Tavakolabad section (which is located between two other echinoderm-bearing sections). Some lepidocyclinids and nummulitids are sufficiently large to be observed easily with the naked eye on rock surfaces.

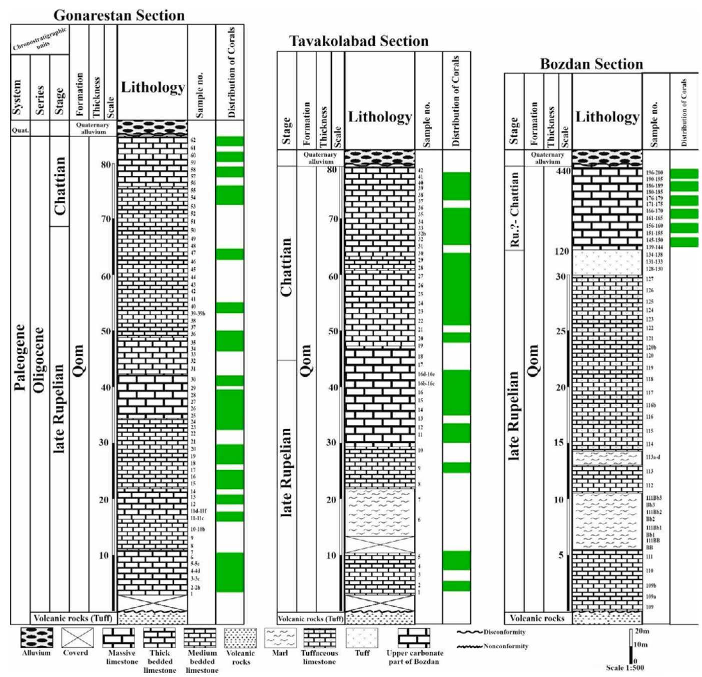

Figure 2. Stratigraphic columns of the studied sections in Gonarestan, Tavakolabad, and Bozdan.

5.2. Field and laboratory studies

To analyze the corals, 46, 76, and 89 samples were collected from Tavakolabad, Gonarestan, and Bozdan sections, respectively. Besides, more than 120 zooxanthellate coral macro specimens were collected from the coral-bearing units. Tests of *Nummulites* are the main biotic component of the Bozdan marly layers. Sampling intervals were mostly between 1 to 2m. Thin sections (2.5 × 7.5cm) were prepared from consolidated samples, while loose marly samples were washed, sieved, and screened for foraminifera. Besides, 22 larger thin sections (10 × 10cm) were prepared from the collected coral specimens. All samples were analyzed in detail with a particular interest in the corals and other biotic components, especially LBF, and coralline red algae. The authors tried to collect diverse coral specimens in the field to be investigated in detail in the laboratory, but some of them could not be collected as they were too hard to be broken and separated from the source rock. However, all necessary features (e.g. coral fabrics, forms, and shapes) were observed and photographed in the field. The biostratigraphy of the studied sections is based on Mohammadi (2023). To identify various genera and species, macromorphological characters related to corallites structures and the distributions of them in coral colonies were scrutinized. After measuring different parameters including forms, shapes, number of septa, cycles degree, coenosteum and columella types, wall structures and other traits in corals, original systematics references were used to identify each specimen. Coral growth fabrics were classified according to Insalaco (1998). The classification of the coral-bearing limestones was based on the scheme of Dunham (1962) and Embry and Klovan (1971).

6. Paleoecology of the corals

6.1. Details of the recognized coral taxa

In this research, the paleo-environmental conditions of the studied sections are explored based on biotic evidence, environmental and lithological features, fabric type, and the relationship between these items. A significant number of corals can be seen in the studied areas (Fig. 3). They are present in *in-situ* and reworked forms in the sections. In total, the corals recognized in the studied sections include *Leptoria* sp., *Porites* sp., *Hydnophora* sp., *Hydnophora pulchra*, *Hydnophora* cf. *pulchra*, *Stylocoenia taurinensis*, *Thegioastraea* sp., *Caulastraea* sp., *Caulastraea farsis*, *Heliastraea* sp., *Heliastraea* (*Athecastraea*) *stellata*, *Heliastraea* sp., *Tarbellastraea reussiana*, *Favites* sp., *Favites neglecta*, *Ceratotrochus* (*Conotrochus*) sp., *Goniopora* sp., *Astreopora meneghiniana*, *Plesiastraea* sp., *Platycoenia* sp., *Acropora* sp., *Astreopora stellaris*.

The coral fabrics (Figs. 4) are defined based on the classification of Insalaco (1998). The shape of corals here is limited to dome-shaped, branching, and columnar. The colony types are phaceloid, hydnophoroid, meanderoid, plocoid, cerio-plocoid, cerioid, and sub-cerioid, together with solitary forms. According to Insalaco (1998), the coral horizons in Tavakolabad and Bozdan sections show domestone, rudstone, and pillarstone fabrics, while the domestone fabric is the dominant one in the Gonarestan section (Fig. 4).

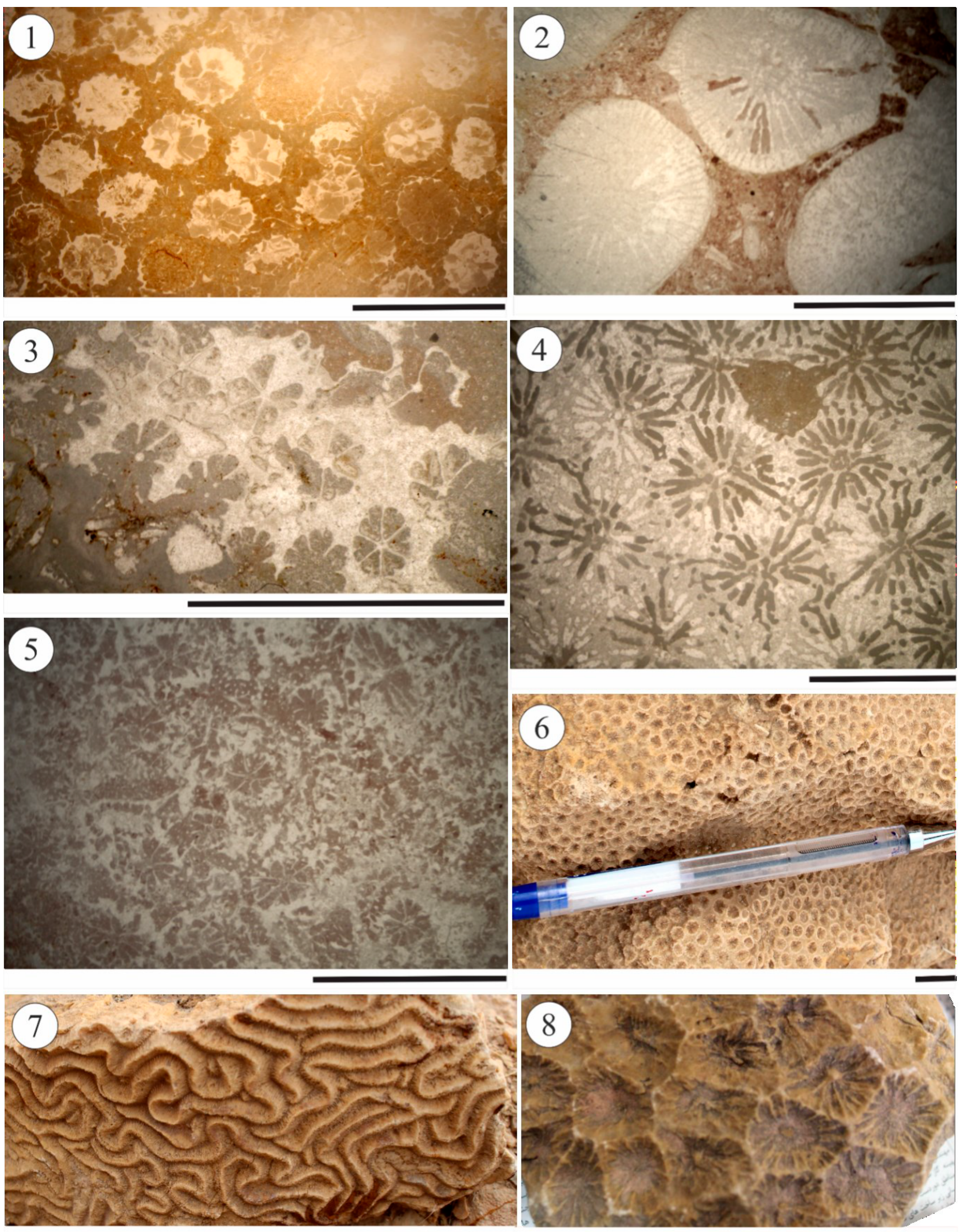

Figure 3. Some coral species present in the studied sections: 1) Astreopora *stellaris*, Bozdan section; 2) *Caulastraea farsis*, Bozdan section; 3) *Platycoenia* sp., Tavakolabad section; 4) *Plesiastraea* sp., Tavakolabad section; 5) *Astreopora meneghiniana*, Gonarestan section; 6) *Tarbellastraea reussiana*, Tavakolabad section; 7) *Leptoria* sp., Tavakolabad section; 8) *Favites neglecta*, Gonarestan section; (scale bars are 1cm)

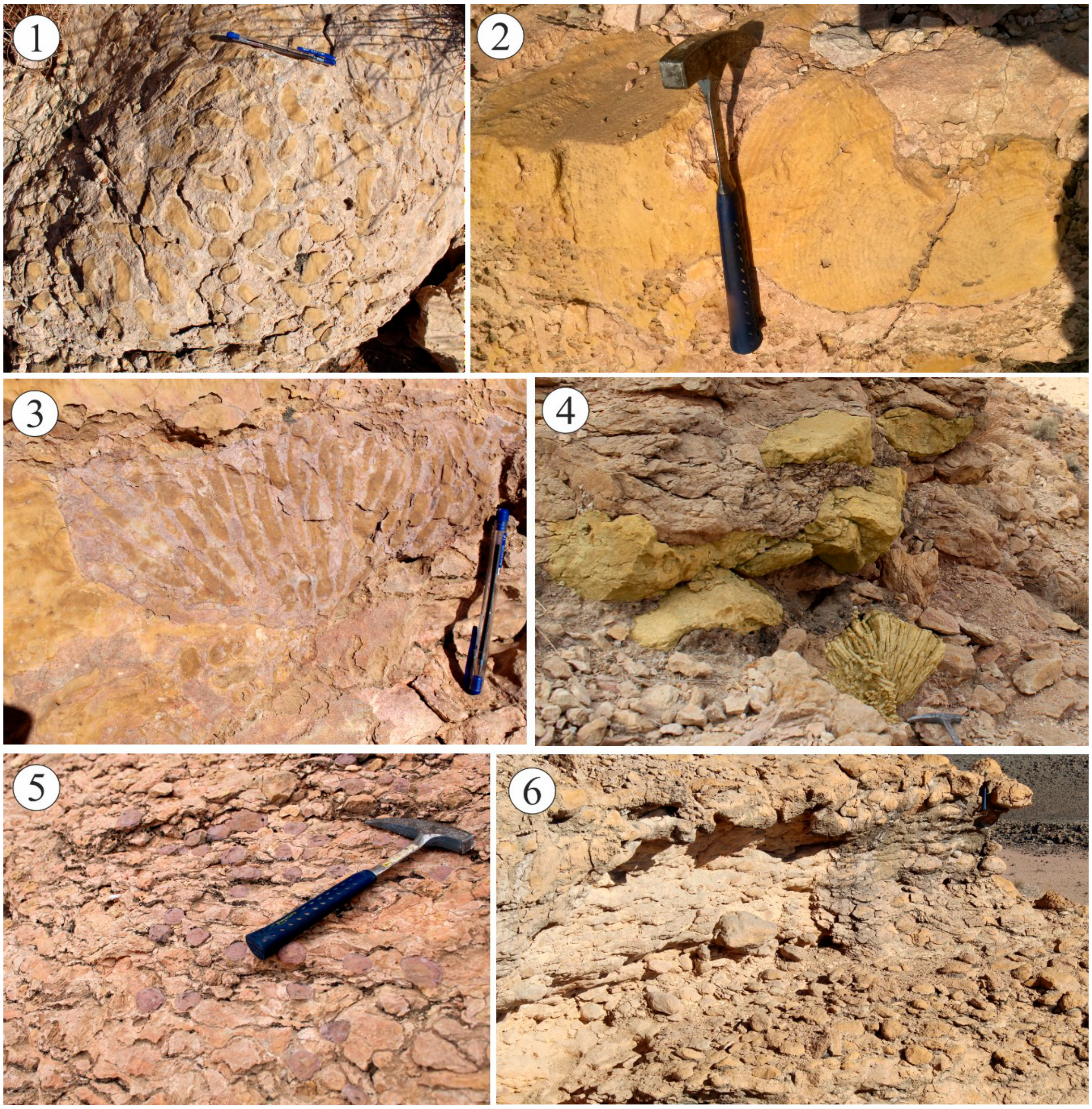

Figure 4. Coral growth fabric. 1) upper view of a dense pillarstone fabric, Bozdan section; 2) a rudstone fabric, Bozdan section; 3) the growth of *Caulastraea farsis* on the debris of rudstone fabric, Bozdan section; 4) domestone fabric, Tavaolabad section; 5) upper view of a dense pillarstone fabric, Tavaolabad section; 6) domestone fabric, Gonarestan section.

6.2. Estimation of water surface temperature

One method of estimating the temperature range is to survey the constituents. According to Adams et al. (1990), the symbiotic foraminifers are restricted to tropical-subtropical waters. Besides, Betzler et al. (1997) believe that large Oligo-Miocene benthic foraminifers such as *Lepidocyclina*, *Miogypsina*, *Archaias,* and *Borelis* are restricted to tropical regions with a mean temperature greater than 18-20°C during the coldest months of the year. *Porites* forms, which are among the scleractinian corals, belong to tropical regions; likewise, the presence of *Heterostegina*, *Operculina,* and *Amphistegina* genera together with red algae (*Lithoporella*, *Lithothamnion,* and *Lithophyllum*) are ecologically related to tropical to subtropical areas (Brandano and Corda, 2002).

Based on the above-discussed methods, the estimation of temperature based on coral richness combined with the temperature range method based on the constituents seems to be a more appropriate method.

Bozdan and Gonarestan sections: The presence of zooxanthellae corals (Table 1) along with benthic foraminifers (such as *Amphistegina*, *Lepidocyclina*, and *Operculina*), green algae, red algae, serpulid worms, gastropods, bivalves, echinoids, and some other mollusks represents the tropical to subtropical temperatures (Sadeghi et al., 2018; Mohammadi, 2021).

Tavakolabad section: The abundant presence of zooxanthellae corals (Table 1) along with benthic foraminifera (such as *Amphistegina*, *Lepidocyclina*, and *Operculina*), green algae, red algae, and mollusks is an indicative of tropical to subtropical temperatures (Sadeghi et al., 2018; Mohammadi, 2021).

6.3. Water energy

Morphological and textural characteristics of corals together with other factors are important for determining water energy. As well, hydrodynamic energy plays a role in the development of coral communities and can be inferred from the coral morphotypes (Tomás et al., 2008). The hydrodynamic energy of water can control the CO_2 content of water and thus affect the water's acidity; accordingly, the water energy can affect the rate of carbonation or dissolution in sediments (Mutti and Hallock, 2003; Pilson, 2013, Ghaedi et al., 2016; Fig. 5).

Table 1. Distribution of symbiont-bearing coral genera of the studied sections.

	Symbiont-bearing Genera	Form	Shape	The sections		
				Bozdan	**Tavakkolabad**	**Gonarestan**
1	***Hydnophora***	Hydnophoroid	Dome-shaped	✔	✔	✔
2	***Leptoria***	Meandroid	Dome-shaped	✔	✔	✔
3	***Caulastraea***	Phaceloid	Dome-shaped	✔	✔	✔
4	***Tarbellastraea***	Plocoid	Dome-shaped	✗	✔	✗
5	***Favites***	Sub-Cerioid	Dome-shaped	✗	✔	✗
6	***Thegioastraea***	Cerio-Plocoid	Dome-shaped	✔	✔	✗
7	***Heliastraea***	Plocoid	Dome-shaped	✗	✔	✗
8	***Astreopora***	Plocoid	Dome-shaped	✔	✗	✔
9	***Plesiastraea***	Plocoid	Dome-shaped	✗	✔	✗
10	***Platycoenia***	Plocoid	Dome-shaped	✗	✔	✗
11	***Acropora***	Plocoid	Branching	✔	✔	✔
12	***Porites***	Cerioid	Dome-shaped, Branching, Columnar	✔	✔	✗
13	***Goniopora***	Cerioid	Dome-shaped, Branching, Columnar	✔	✔	✔
14	***Stylocoenia***	Cerioid	Branching	✗	✔	✗
15	***Ceratotrochus***	Solitary	-	✗	✗	✔
	Unidentified genera	-	-	1	1	3
	TOTAL GENERAL			**9**	**14**	**10**

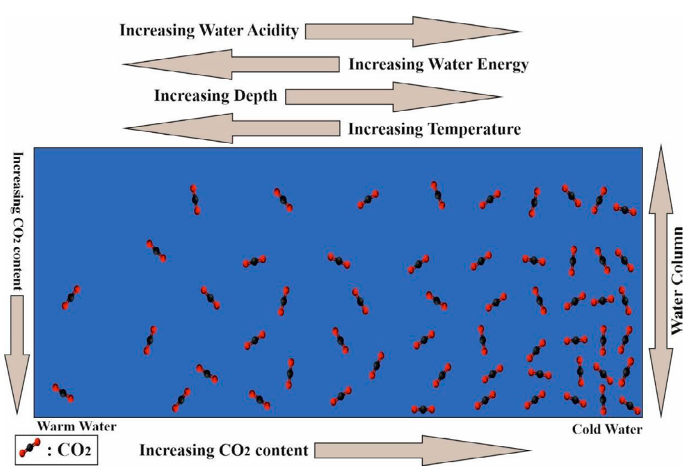

Figure 5. The effect of various factors on the CO_2 content in the marine environment related to the depth and energy (after Mutti and Hallock, 2003; Pilson, 2013, Ghaedi et al., 2016).

The domestone facies in the Capo Testa (northern Sardinia, Italy) based on sediment textures and growth morphologies indicate relatively high hydrodynamic energy (Brandano et al., 2010). On the other side, in the western Taurides (Turkey), the diversified colonies of domal, massive, globular, and hemispherical forms with a lesser extent by branching colonies, dominated by *Heliastraea*, *Tarbellastraea*, *Favia*, *Favites*, *Aquitanastarea*, *Caulastraea*, *Cladocora*, *Stylophora,* and *Porites* indicate a marine shallow environment with moderate to high water energy (Karabiyikoglu et al., 2005). Therefore, the coral assemblages with massive, hemispherical, and domal colonies usually indicate high to moderate energy (Karabiyikoglu et al., 2005; Brandano et al., 2010; Yazdi et al., 2012; Ghaedi et al., 2016). The pillarestone fabric (e.g. branching *Acropora*, *Porites*, *Goniopora,* and *Stylophora*) without serious breakage, accompanied by green algae erected stems demonstrates moderate to low energy.

Massive corals (mostly with domestone fabric and sometimes rudstone fabric) and branching corals (pillarestone fabric) are present in parts of the sections; some of them are presented separately in each section as follows (Table 2).

Table 2. The distribution of massive and branching corals in the studied sections

Section	Massive corals	Branching corals
Bozdan	*Thegioastraea* sp., *Leptoria* sp., *Hydnophora pulchra*, *Hydnophora* cf. *pulchra*, *Goniopora* sp., *Porites* sp., *Caulastraea* sp., *Astreopora stellaris*, *Favites neglecta*.	*Porites* sp., *Acropora* sp., *Goniopora* sp.
Tavakolabad	*Porites* sp., *Leptoria* sp., *Goniopora* sp., *Hydnophora* sp., *Hydnophora pulchra*, *Stylocoenia taurinensis*, *Thegioastraea* sp., *Heliastraea* sp., *Tarbellastraea reussiana*, *Caulastraea farsis*, *Hydnophora* cf. *pulchra*, *Caulastraea* sp., *Plesiastraea* sp., *Platycoenia* sp..	*Porites* sp., *Acropora* sp., *Goniopora* sp.
Gonarestan	*Leptoria* sp., *Caulastraea* sp., *Porites* sp., *Goniopora* sp., *Astreopora meneghiniana*, *Astreopora stellaris* and unidentified genera.	---

According to Karabiyikoglu et al. (2005), Brandano et al. (2010) Yazdi et al. (2012), and Ghaedi et al. (2016), corals with massive, hemispherical, and domal colonies usually indicate high to moderate energy. On the other hand, based on the field observations, the presence of rudstone coral fabric, which indicates the breakage of corals margins, can be the result of the high energy of the waves; as well, unbroken branching corals together with erected stems of green algae represent moderate to low water energy (Flugel, 2004). Therefore, according to the morphology of corals and considering the fabrics, high to moderate water energy can be expected in the studied sections.

6.4. Light

Due to the direct relationship between the photosynthesis of symbionts with light, LBF, symbiont-bearing corals, red algae and green algae are light-dependent organisms. Zooxanthellate corals as part of constituents of the Bozdan, Tavakolabad, and Gonarestan sections are very sensitive to light conditions (e.g. Trench, 1981; Cairns, 1999). The light penetration depends on the water depth; it decreases with increasing depth. In fact, it is influenced by the factors, controlling the water clarity (including clastic material, nutrients, and dissolved organic material) (Morsilli et al., 2012). According to Hallock and Schlager (1986), platy corals are under 4–20 % of surface light intensities, and in high light levels, head corals live in more than 20 % of surface light intensities and branching corals are present in more than 60 % of surface light intensities (Fig. 6, Tables 1, 2).

Bozdan section: In the Bozdan section, massive-domal corals including *Porites* sp., *Leptoria* sp., *Hydnophora* sp., *Hydnophora pulchra*, *Thegioastraea* sp., and some branching corals such as *Porites* sp., *Goniopora* sp., and *Acropora* sp. are also present. According to Hallock and Schlager (1986), Pomar (2001), and Morsilli et al. (2012), euphotic to slightly mesophotic conditions have been dominated in the Bozdan section (Fig. 6). The presence of green algae, accompanied by the branching corals confirms the well-lit euphotic environment in some intervals.

Tavakolabad section: In the Tavakolabad section, massive-domal corals such as *Leptoria* sp., *Porites* sp., *Hydnophora* sp., *Hydnophora pulchra*, *Thegioastraea* sp., *Heliastraea* sp., *Tarbellastraea reussiana* and some branching corals including *Porites* sp. and *Acropora* sp. are also present. According to Hallock and Schlager (1986), Pomar (2001), and Morsilli et al. (2012), euphotic to slightly mesophotic conditions have been dominated in the Tavakolabad section based on the distribution of branching corals (together with green algae) and massive-domal corals (Fig. 6).

Gonarestan section: In the Gonarestan section, massive-domal corals such as *Leptoria* sp., *Caulastraea* sp., *Porites* sp., and *Goniopora* sp. as well as some green and red algae are also present. According to Hallock and Schlager (1986), Pomar (2001), and Morsilli et al. (2012), euphotic to slightly mesophotic conditions have been dominated in the Gonarestan section based on the distribution of massive-domal corals (Fig. 6).

6.5. Nutrients

In the Bozdan, Tavakolabad, and Gonarestan sections, various factors such as zooxanthellate corals, foraminifera, red algae, bryozoans, mollusks, etc. can be used to determine the trophic conditions. The increase in the number of heterotrophic groups (such as mollusks, serpulids, bryozoans), and red algae in coral assemblages along with the increase in bioerosion (Fig. 7), is an indicative of the change in the trophic conditions from oligotrophic to mesotrophic in the studied sections.

Due to the abundant presence of bioerosion resulting from the activity of filter-feeding organisms such as serpulid worm tubes (e.g. *Trypanites* isp.), bivalves (e.g. *Gastrochaenolites* isp.) bioerosion is evident in these three sections. Encruster organisms such as red algae can also be seen in the studied sections. Likewise, LBF is abundantly found in the studied intervals. Owing to the significant presence of massive corals (domestone fabric) in the Bozdan, Tavakolabad, and Gonarestan sections (which is a sign of high calcification rate) as well as branching corals in the Bozdan and Tavakolabad sections, and the presence of larger symbiont-bearing foraminifera, the dominant conditions of the sections are oligotrophic, but the presence of bioerosion, such as borings created by serpulid tube worms, bivalves and also the presence of some encruster organisms such as red algae, the nutrient conditions are considered as oligotrophic to slightly mesotrophic (Fig. 7).

In Table 3 the predominant environmental conditions of corals in the Bozdan, Tavakolabad, and Gonarestan sections are summarized.

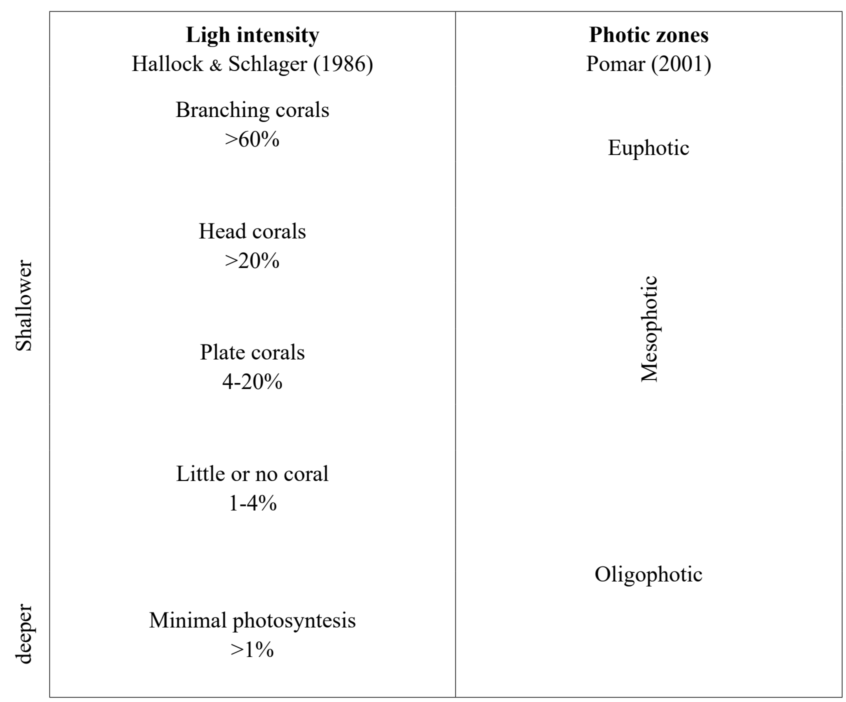

Figure 6. The position of different morphotypes of corals according to the light penetration (based on Hallock and Schlager, 1986; Pomar, 2001; Morsilli et al., 2012).

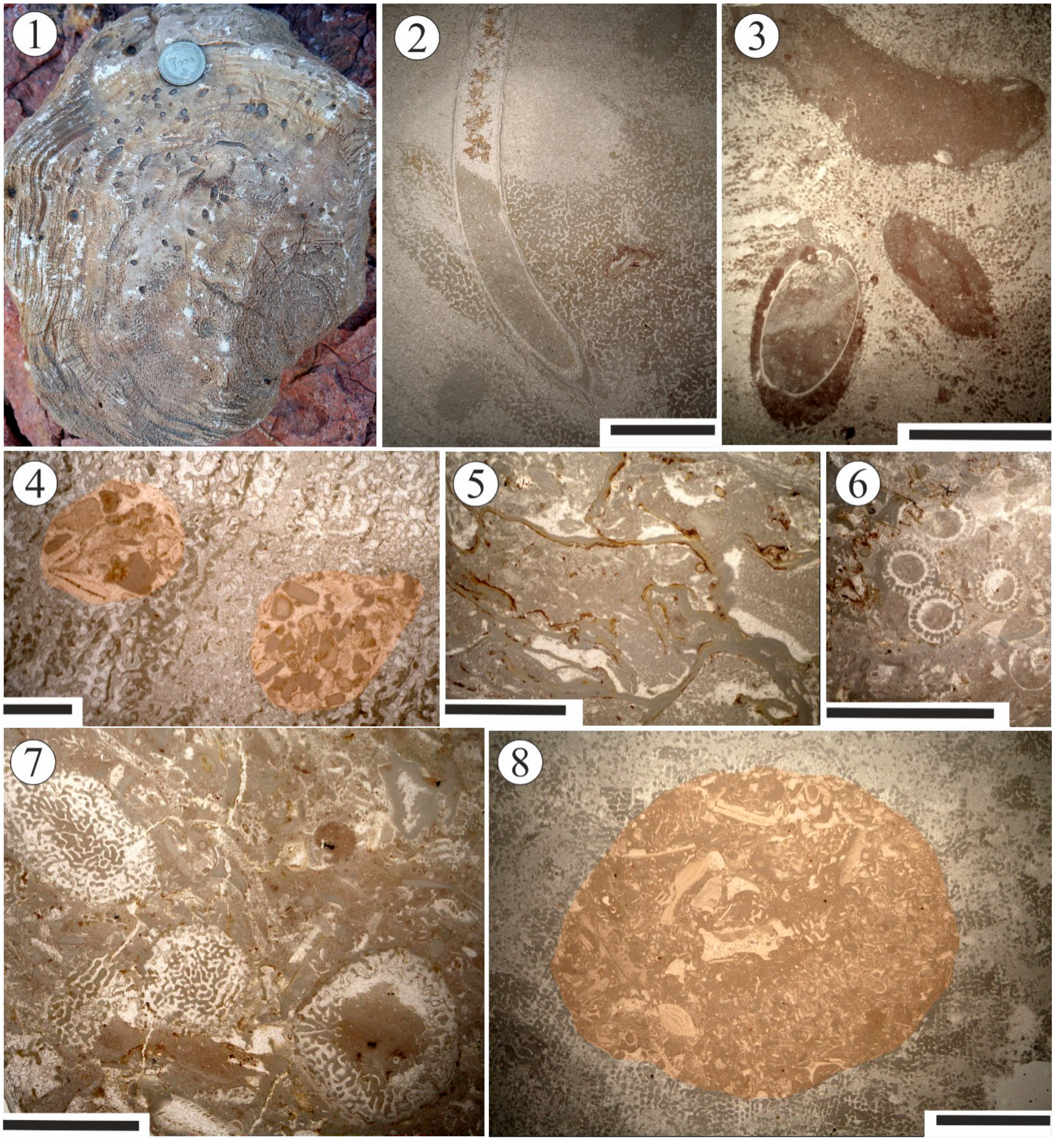

Figure 7. Some features related to biotic activities on the corals in northwestern Jazmurian Lake, SE Iran. 1) the bioerosion traces on a scleractinian coral colony in the Bozdan section; 2) a serpulid worm tube boring with distinctive lining in a *Porites* sp. in the Gonarestan section; 3) some boring traces, created by bivalves (*Gastrochaenolites* isp.) in *Goniopora* sp. in the Gonarestan section; 4) boring sections filled with red algae and other skeletal elements in a *Porites* sp. in the Tavakolabad section; 5) Coralinacean red algae, acting as encrusters in the Gonarestan section; 6) the presence of green algae together with red ones in the Tavakolabad section; 7) the presence of *Acropora* sp. covered and surrounded by red and green algae in the Tavakolabad section; 8) a large boring section, containing skeletal fragments and inflated foraminifera in *Porites* sp. in the Tavakolabad section. (scale bars are 0.5 cm)

Table 3. Predominant biological features in the Bozdan, Tavakolabad, and Gonarestan sections

Sections	Lithology	Fabrics	Calcification	Temperature	Nutrients	Light	Energy
Gonarestan	Limestone	Domestone	High	Tropical to Subtropical	Oligotrophic - Slightly Mesotrophic	Euphotic - Slightly Mesophotic	High to moderate
Tavakkol Abad	Limestone	Domestone, Rudstone, Pillarstone	High	Tropical to Subtropical	Oligotrophic - Slightly Mesotrophic	Euphotic - Slightly Mesophotic	High to moderate
Bozdan	Limestone	Domestone, Rudstone, Pillarstone	High	Tropical to Subtropical	Oligotrophic - Slightly Mesotrophic	Euphotic - Slightly Mesophotic	High to moderate

7. Discussion

Corals are prevalent in tropical-subtropical and oligotrophic conditions. As well, according to Hallock (2001) and Hallock et al. (2003), coral reefs flourish in the most nutrient-depleted oceanic waters where mixotrophic nutrition (i.e., the recycling of nutrients between the host and algal symbionts) is most advantageous.

According to Hallock and Schlager (1986), massive and domal corals prefer intermediate levels of light intensity, while branching corals tend to receive higher light levels. Since hydrodynamic energy plays an important role in the coral morphotypes' formation (Tomás et al., 2008), the presence of domestone growth fabric (e.g. *Favia* and *Favites*) can demonstrate a marine ecosystem with moderate to high energy (Karabiyikoglu et al., 2005) and unbroken branching corals seem to be influenced by moderate water energy.

Both corals and LBF are mainly heterotrophic organisms; the former as suspension feeders relying upon suspended material in surrounding waters, while the latter feeds on detritus in the sediment. Metabolically, both benefit from algal symbiosis, especially in sunlit oligotrophic warm environments (Pomar et al., 2017). Yentsch et al. (2002) evaluated that zooxanthellate corals need at least 1% of surface light for growth.

In the studied sections, the richness of zooxanthellate corals genera was applied to estimate the minimum surface temperature, but other constituents including benthic foraminifera, green and red algae as well as heterotrophic organisms were also considered to get a more precise estimation in this regard. Although there are various components in the studied sections, they all can be categorized under the tropical to subtropical temperature range.

In terms of water energy, it should be noted that morphological traits of corals can be remarkable factors, as domestone fabric, which is regularly indicative of a high calcification rate, represents high hydrodynamic energy. As well, rudstone fabric (especially in Bozdan and Tavakolabad sections), representing large coral fragments, indicates high water energy. Furthermore, in the Bozdan section, there is a specimen of *Caulastraea farsis*, growing on the rudstone coral debris without any broken parts (Fig. 4); it seems, therefore, that there has been a fluctuation in the hydrodynamic energy, and the fragments are not deposited too far from their original position. The pillarstone fabric in Bozdan and Tavakolabad sections are related to *Porites*, *Goniopora*, and *Acropora* genera, indicating their *in-situ* positions; as they are unbroken and occasionally accompanied by green and red algae (Fig. 7), they should have lived in moderate to low energy condition.

As zooxanthellate corals, LBF, red algae, and green algae are light-dependent organisms, they can be an appropriate indication of light conditions. As there are considerable head corals (in all three sections) and branching corals (in Bozdan and Tavakolabad section), based on Hallock and Schlager (1986) Pomar (2001), Morsilli et al. (2012) euphotic to slightly mesophotic conditions have been considered for all sections, but according to the presented chart (Fig. 6), due to the presence of branching corals, there was more intense light in Bozdan and Tavakolabad sections. Filter-feeders, encrusters, red algae, and bioeroders are increased through increasing nutrient supply; among them, *Trypanites* isp., *Gastrochaenolites* isp. as boring traces and corallinacean red algae as encrusters are the most significant components. As mentioned above, the head and branching corals represent oligotrophic conditions, while bioerosion demonstrates the tendency to the mesotrophic condition (Mutti and Hallock 2003). Accordingly, oligotrophic to slightly mesotrophic conditions are deemed for all studied sections.

8. Conclusion

The Qom Formation Corals in Sanandaj–Sirjan fore-arc basin (Bozdan, Tavakolabad, and Gonarestan stratigraphic sections) were studied in terms of paleoecology. The following results were obtained:

1. Benthic foraminifera, corals, and red algae are the most significant biotic constituents of the studied sections.
2. The species recognized from the studied sections are *Leptoria* sp., *Porites* sp., *Hydnophora* sp., *Hydnophora pulchra*, *Hydnophora* cf. *pulchra*, *Stylocoenia taurinensis*, *Thegioastraea* sp., *Caulastraea* sp., *Caulastraea farsis*, *Heliastraea* sp., *Heliastraea* (*Athecastraea*) *stellata*, *Heliastraea* sp., *Tarbellastraea reussiana*, *Favites* sp., *Favites neglecta*, *Ceratotrochus* (*Conotrochus*) sp., *Goniopora* sp., *Astreopora meneghiniana*, *Plesiastraea* sp., *Platycoenia* sp., *Acropora* sp., *Astreopora stellaris*.
3. Based on the diversity of zooxanthellate corals genera together with other components, the studied sections have been deposited under the tropical to subtropical temperature range.
4. According to the morphology of corals and considering the fabrics, high to moderate water energy can be expected in the studied sections.
5. Euphotic to slightly mesophotic conditions have been dominated in the studied sections.
6. Based on coral morphotypes as well as the presence of bioerosion, nutrient conditions are considered oligotrophic to slightly mesotrophic.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

The authors declare that data archiving is not mandated but data will be made available on reasonable request.

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