Facies (2011) 57:101–122
DOI 10.1007/s10347-010-0231-3

ORIGINAL ARTICLE

Facies characteristic and paleoenvironmental reconstruction of the Fahliyan Formation, Lower Cretaceous, in the Kuh-e Siah area, Zagros Basin, southern Iran

Maryam Jamalian · Mohammad H. Adabi · Mir R. Moussavi · Abbas Sadeghi · Darius Baghbani · Behrooz Ariyafar

Received: 29 December 2009 / Accepted: 16 August 2010 / Published online: 3 September 2010

Abstract The Lower Cretaceous Fahliyan Formation, part of the Khami Group, unconformably overlies the Hith Formation and is conformably overlain by the Gadvan Formation in the study area in southern Iran. The Fahliyan Formation is a reservoir rock in Zagros Basin. This formation was investigated by a detailed petrographic analysis in order to clarify the depositional facies and sedimentary environment in the Kuh-e Siah Anticline in Boushehr Province. Petrographic studies led to the recognition of 25 microfacies that were deposited in four facies belts: tidal flat, lagoon, and shoal in inner ramp and shallow open-marine in mid-ramp environment. An absence of turbidite deposits, reefal facies, and gradual facies changes indicate that the Fahliyan Formation was deposited on a carbonate ramp. Calcareous algae and benthic foraminifera are abundant in the shallow marine carbonates of the Fahliyan Formation. These skeletal grains have been studied in order to increase the understanding of their distributions in time and space. A total of ten genera belonging to different groups of calcareous algae and 16 genera of benthic foraminifera are recognized from the Fahliyan Formation at Kuh-e Siah section.

M. Jamalian (✉) · M. H. Adabi · M. R. Moussavi · A. Sadeghi
Department of Geology, Faculty of Earth Sciences,
Shahid Beheshti University, Tehran, Iran
e-mail: maryam_jamalian@yahoo.com

D. Baghbani · B. Ariyafar
Department of Geology,
National Iranian Oil Company-Exploration Directorate
(NIOC-Exp), Exploration Directorate,
Sheykh Bahayi Sq., Tehran, Iran

Keywords Microfacies · Calcareous algae · Benthic foraminifer · Carbonate ramp environment · Fahliyan Formation · Zagros · Iran

Introduction

The Mesozoic carbonate systems of the Arabian Plate form one of the richest hydrocarbon provinces of the world. This is mostly due to the combination of their large scale and the presence of source rock, reservoir, and seal facies within the same depositional system (e.g., Murris 1980). The remarkable concentration of the three fundamental ingredients of a petroleum system is to a large extent due to the repeated formation of organic-rich shallow basins upon the Arabian Plate. Their formation within large carbonate platform successions assured the presence of significant source rock accumulations next to, and in immediate contact with, potential reservoir facies (Van Buchem et al. 2002).

The Kuh-e Siah anticline is located 25 km northeast of Khormoj City, Boushehr Province, in southern Iran (Fig. 1). The Fahliyan Formation was studied in detail at 51°31′ E and 28°50′ N in this paper.

The Fahliyan Formation in the Kuh-e Siah surface section overlies the evaporites of the Upper Jurassic Hith Formation with unconformable contact and underlies the Lower Cretaceous Gadvan Formation conformably (Fig. 2).

The Fahliyan Formation in the Kuh-e Siah area contains limestone and dolomite that were deposited in four facies belts in a ramp environment.

The goals of this study are: to determine the dasycladacean algae and benthic foraminifer genera, to present the main microfacies, and to interpret the depositional environment of the Fahliyan Formation.

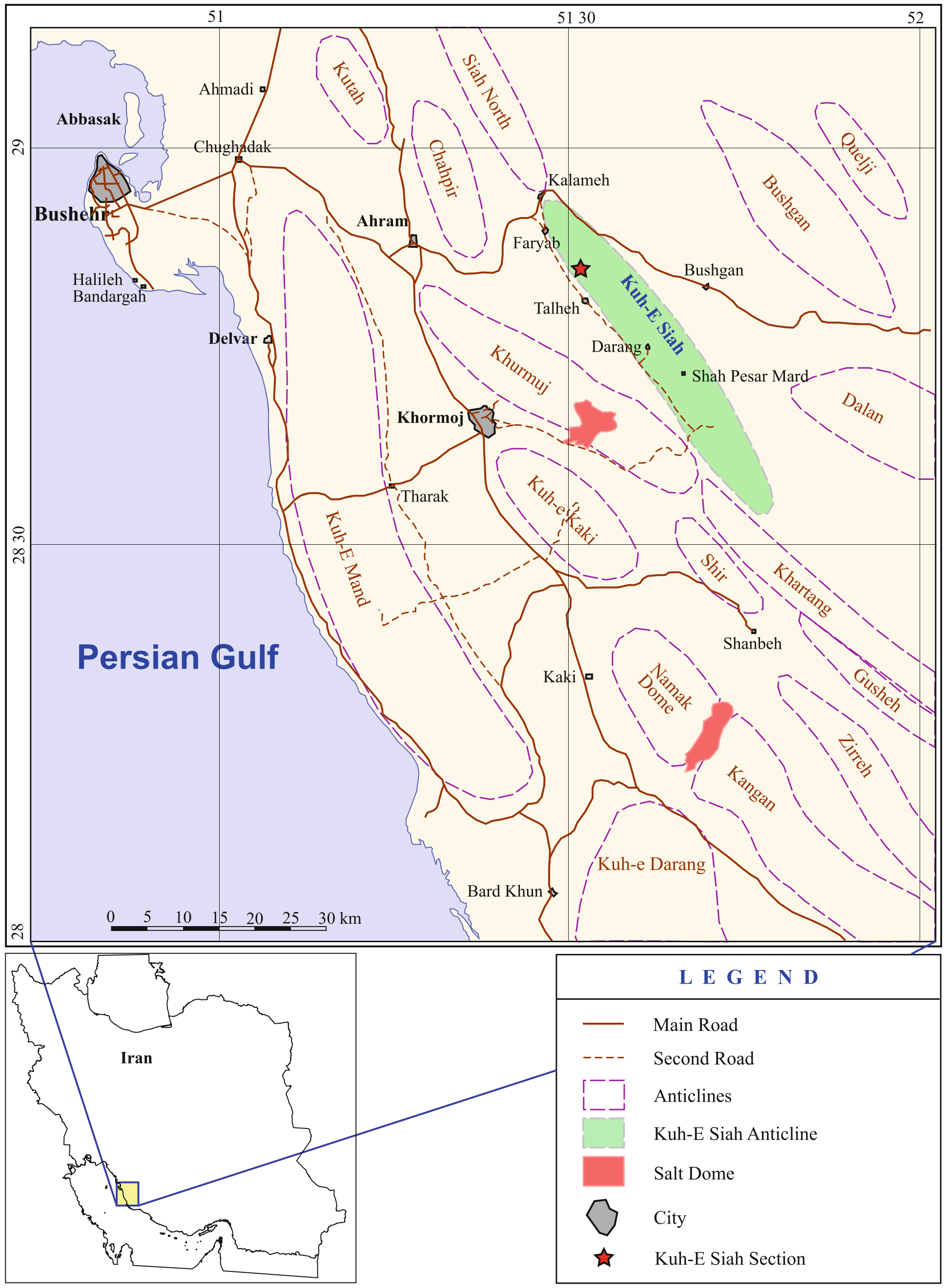


Fig. 1 Location map of the Kuh-e Siah section in SW Iran (adapted from Fakhari 1994)

Geological setting

The Kuh-e Siah anticline is located in Fars Salient in the south of the Zagros fold-thrust belt (ZFTB) (Fig. 3). The ZFTB in Iran forms the external part of the Zagros active orogenic wedge. It includes a sequence of heterogeneous latest Neoproterozoic–Phanerozoic sedimentary cover strata, about 7–12 km thick (Alavi 2007).

The Zagros fold-thrust belt is the deformed state of the Zagros sedimentary basin, a basin that extended over the northeastern (present coordinates) Afro-Arabian continental margin and was affected by the Early Cretaceous to present Zagros Orogeny. The Zagros fold-thrust belt, as the external part of the Zagros Orogen (Alavi 1980, 1994), extends southeast for nearly 2,000 km from southeastern Turkey through northern Syria and northeastern Iraq to western and southern Iran. The north western boundary of the Zagros Orogen is chosen to be the East Anatolian strike-slip fault (EAF) in southeastern Turkey and the southeastern boundary of the Orogen is the Oman Line (Falcon 1969) (Fig. 3).

The Zagros Orogen consists of three distinctive parallel tectonic zones (Fig. 3) which from the northeast to the southwest are: Urumieh–Dokhtar magmatic assemblage

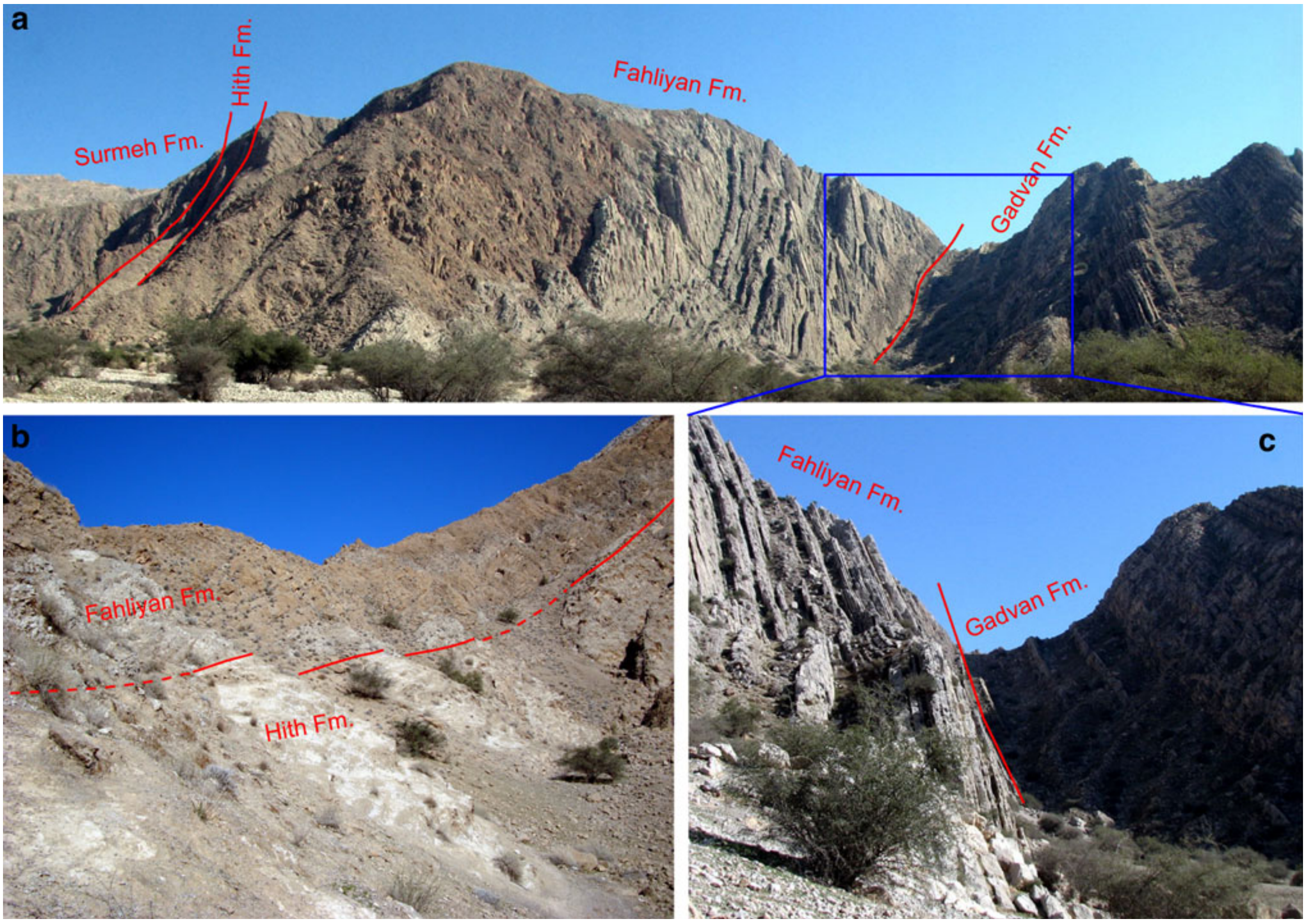


Fig. 2 Outcrop views of the Fahliyan Formation in the Kuh-e Siah section. **a** General view showing the Fahliyan Formation. **b** Lower boundary of the Fahliyan Formation with the underlying Hith Formation. **c** Upper boundary of the Fahliyan Formation with the overlying Gadvan Formation

(UDMA), Zagros imbricate zone (ZIZ), and Zagros fold-thrust belt (ZFTB). The Zagros fold-thrust belt (the Zagros "simple folded zone" of Falcon 1974), with an average width of 300 km, extends parallel and to the southwest of the ZIZ. It constitutes the external (hence less-strained) part of the orogen. In contrast to the ZIZ, in which exposed structures are predominantly thrust faults, the ZFTB is distinguished by its long (up to 150–200 km), en echelon, "whale-back" anticlines, which are spectacularly displayed on satellite images (Alavi 2007).

The salients and recesses of the Zagros fold-thrust belt from southeast to northwest are as: Fars salient, Dezful recess (formerly "Dezful embayment"), Lorestan salient in Iran, and Karkuk recess (Karkuk embayment) in Iraq (Alavi 2007).

At the beginning of the Cretaceous period, SW Iran was located just north of the equator (less than 5°), and the large-scale basin configuration had just changed from one of a differentiated passive-margin of shallow and deep shelves and intra-shelf basins which characterized the Jurassic (Murris 1980) to that of a very low relief passive-margin ramp setting (Al-Fares et al. 1998).

The sedimentary column in the Zagros Mountains is classified into four groups of rocks accumulated in different tectonosedimentary environments through latest Neoproterozoic to Phanerozoic (Alavi 2004, 2007). The lowermost Jurassic to upper Turonian strata (third group) form a number of megasequences that accumulated on a shallow continental shelf, facing N and NE towards Neo-Tethys in a paleoequatorial setting (Alavi 2004). Facies and thickness changes in a short distance have been reported at various stratigraphic sections in the Lower Cretaceous sediments in the Zagros sedimentary basin (Setudehnia 1978; Sepehr and Cosgrove 2004). Alavi (2004) concluded that facies variation, from SW to NE of Zagros Basin through the Upper Jurassic to Lower Cretaceous, is due to reactivation of pre-existing, predominantly N–S-trending structural elements.

In Tithonian time, the climate in Middle East became arid, so that extensive evaporites were deposited in a

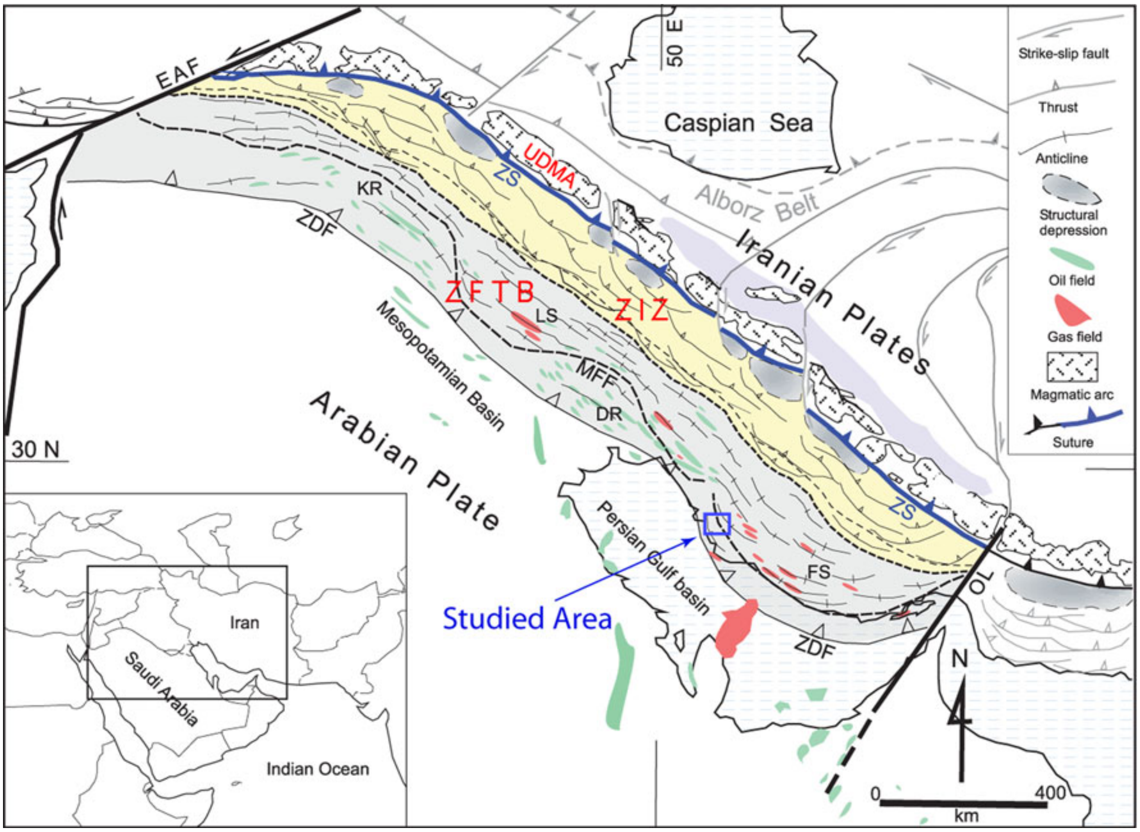


Fig. 3 Subdivisions of the Zagros orogenic belt (after Alavi 2007, with some changes). Abbreviations: *DR* Dezful recess; *EAF* East Anatolian Fault; *FS* Fars salient; *KR* Karkuk recess; *LS* Lorestan salient; *MFF* Mountain front flexure; *OL* Oman Line; *UDMA* Urumieh–Dokhtar magmatic assemblage; *ZDF* Zagros deformational front; *ZFTB* Zagros fold-thrust belt; *ZIZ* Zagros imbricate zone; *ZS* Zagros suture

sabkha environment. During the Early Cretaceous, there was a gradual return to a more humid climate and ramp-type carbonate deposition replaced the differential shelf. In the Early to Middle Valanginian, a wide carbonate platform existed. Through the Hauterivian and Barremian, the trend of abundant clastic influx continued (Murris 1980).

The type section of the Fahliyan Formation is situated on the south flank of Kuh-e Dal, near Fahliyan Village, about 10 km north of Norabad Mamasani City, in the Zagros Mountains. The Fahliyan Formation is a massive oolitic to pellety limestone with minor contemporaneous brecciation in the basal part at the type section (James and Wynd 1965). Variation in relative sea level led to the deposition of two, third-order sequences in the type section with sequence boundary types I and II in the Fahliyan Formation with Neocomian age. The facies patterns clearly indicate relative sea-level variations (Adabi et al. 2010).

Limestone sequences of the Sulaiy and Yamama Formations in Saudi Arabia/Iraq and the Minagish Formation in Kuwait, and shale/sandstone interbedded limestone sequences of the Ratawi Formation in Kuwait/Iraq are the time equivalents of the Fahliyan Formation (Fig. 4). The Yamama Formation in the Iraq consists of pelleted oolitic and pseudo-oolitic carbonates, with abundant oomoldic and vuggy porosities.

Ziegler (2001) suggested a shelf platform of the Arabian Plate that was covered by shallow-water carbonates of the Yamama Formation during the Berriasian to Valanginian (144–132 Ma). Also, Sadooni (1997) proposed sedimentation of Yamama Formation in SE Iraq on a leeward ramp on the gentle slope of the Arabian Platform. The Berriasian-Valanginian Minagish Formation in an oilfield in north Kuwait was deposited on a homoclinal carbonate ramp (Davis et al. 1997). During the Neocomian-Aptian, shallow-water carbonate sediments, containing a rich assemblage of foraminifers and calcareous algae were deposited in Zagros Mountains (Parvaneh Nejad Shirazi 2008). The Lower Cretaceous Fahliyan Formation was formed on a homoclinal gently sloped carbonate ramp in the studied area.

Materials and methods

Field studies, microscope-based investigations, and microfacies analyses were carried out on Kuh-e Siah outcrop

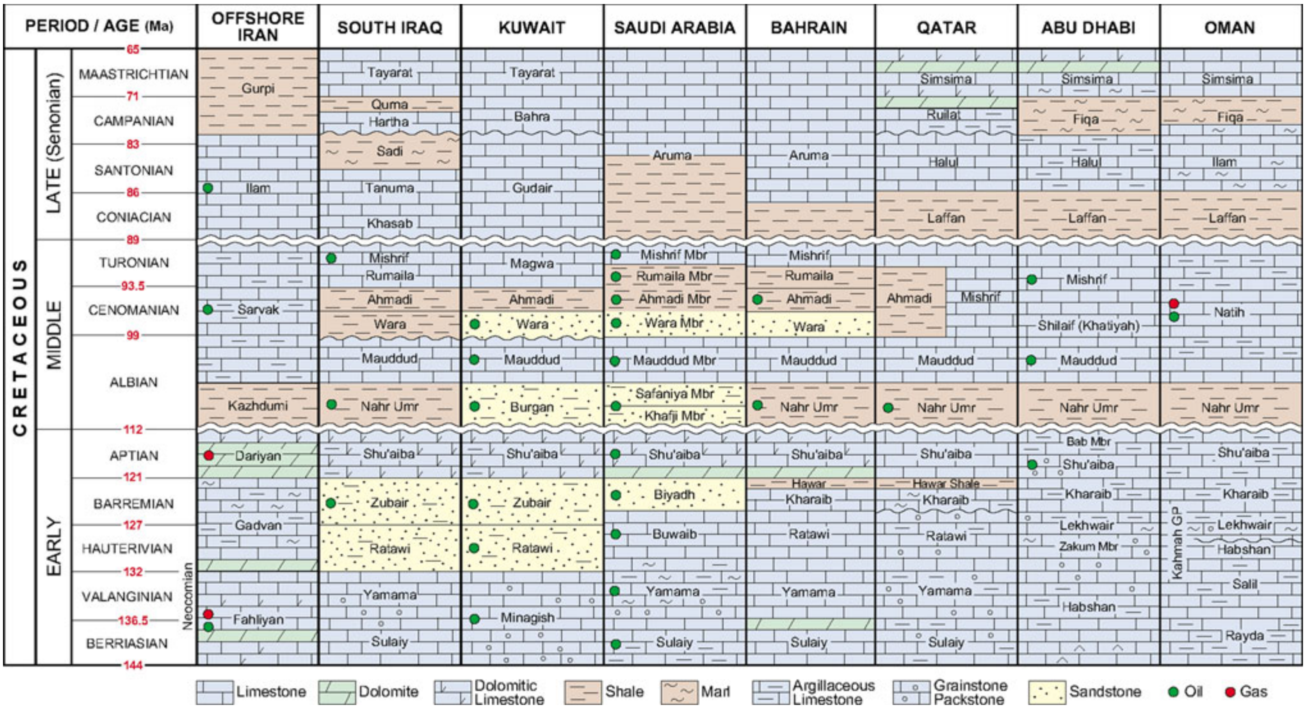


Fig. 4 Lithostratigraphic chart of the Cretaceous of the Arabian Plate (Christian 1997 with some changes)

section and 238 thin sections of the Lower Cretaceous Fahliyan Formation from outcrop were prepared.

For petrographic analysis, the grain and matrix percentages were estimated using visual percentage charts (Flügel 1982). Dunham (1962) and Folk (1962) classifications were used for carbonate facies nomenclature. The Wilson (1975) and Flügel (2004) facies belt descriptions and sedimentary models were applied.

Facies types and depositional setting were interpreted based on analyses of matrix and grains, compositional and textural fabric, fossil content, energy index classification and sedimentary data and by comparison with modern environments (e.g., Wilson 1975; Tucker and Wright 1990; Flügel 2004). Abundance of large benthic foraminifera, green algae, sponge spicules, molluscs and echinoderms, and non-skeletal grains (e.g., ooids, intraclasts, peloids, and aggregate grains) was considered. Sedimentologic textures and structures have been considered qualitatively.

Facies analysis and depositional environment

The thickness of the Fahliyan Formation in the Kuh-e Siah area is 306 m and it contains stromatolitic layers and a large variety of skeletal and non-skeletal grains, calcite cements, micrite, and late diagenetic dolomites (Figs. 5 and 6).

Skeletal grains are mostly dasycladacean algae, benthic foraminifera, gastropods, crinoids/echinoids, sponge spicules, and bivalves. Non-skeletal grains are abundant and consist mainly of ooids, intraclasts, peloids, and aggregate grains (Figs. 5 and 6).

Based on lithology, sedimentary characteristics, textures, and fossil contents of outcrop samples from the study area, there are 25 microfacies types in the Fahliyan Formation. Four main facies associations were distinguished, from distal to proximal, these are: shallow open-marine, shoal, lagoon, and tidal flat. These facies are described briefly below.

Shallow open-marine facies belt

This facies belt comprised lime mudstone, sponge spicule wackestone, sponge spicule-echinoderm wackestone, and bioclast-sponge spicule wackestone. Bioclasts are composed mainly of sponge spicules and echinoid/crinoid remains. Subordinate are thin-shelled bivalves, benthic foraminifera, and dasycladacean algal fragments that are not in situ. Due to lack of reefal facies in the Fahliyan Formation, algal fragments can be transported from lagoon to the shallow open-marine environment (Flügel 2004). The dominance of sponge spicules, the great amount of micrite, the scarcity of benthic foraminifera and dasycladacean algae accompanied by pyritization suggest a shallow, open-marine, and low-energy depositional environment.

The open-marine facies belt was developed at the seaward part of the platform margin. Sponge spicules-bioclast

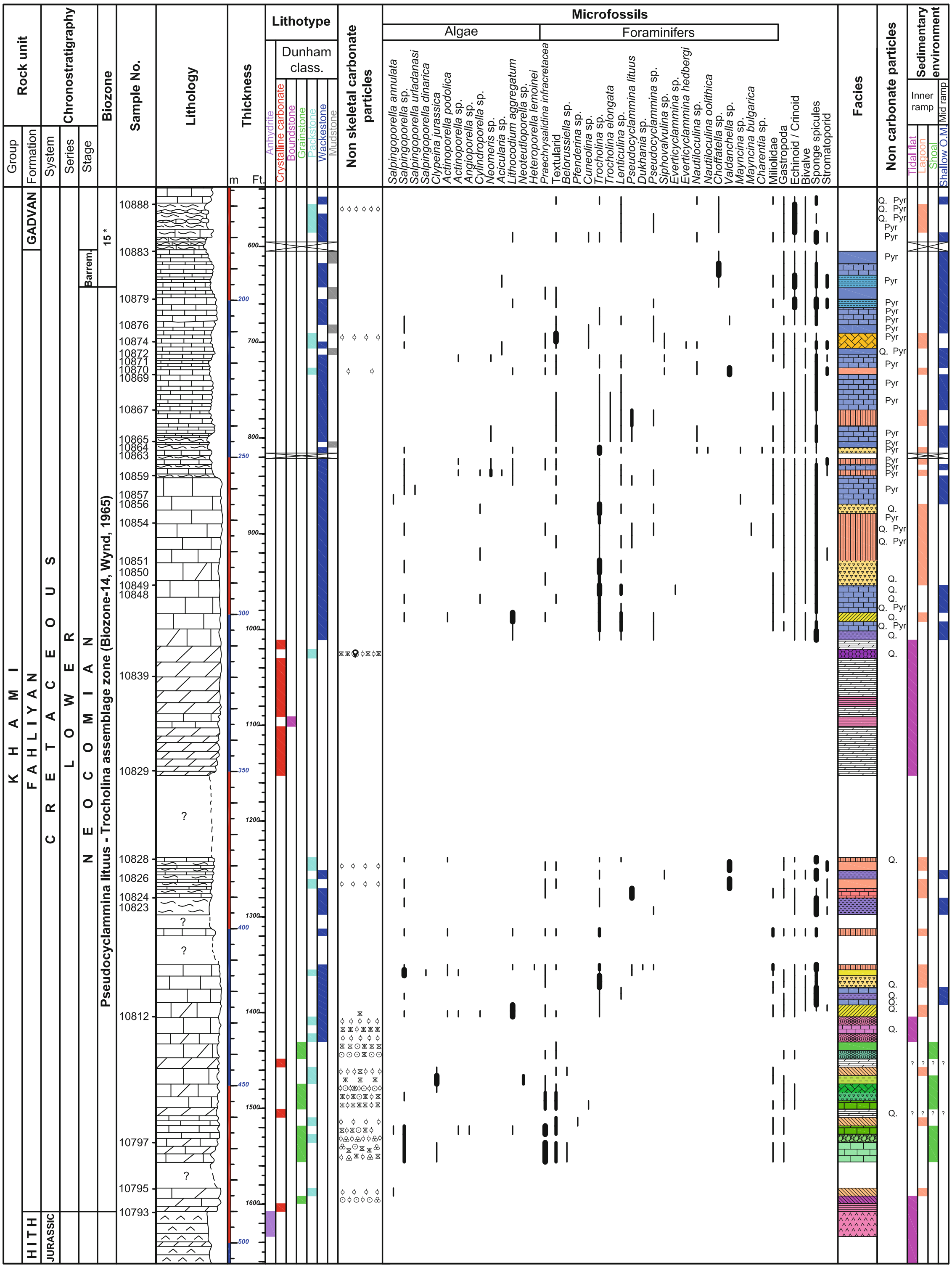


Fig. 5 Stratigraphic column of the Fahliyan Formation in the Kuh-e Siah section with microfacies, microfossils, and depositional environments

wackestones are deposited in shallower parts, whereas subordinate transported fragments of lagoonal environment (e.g., some benthic foraminifera and dasycladacean algae) are present. Mudstone to fossiliferous mudstone facies has a large amount of mud and a low content of bioclasts (e.g., sponge spicule and thin-shelled bivalve) and therefore indicates deeper parts of the basin. Due to the lack of effective porosity, this facies belt has no reservoir quality.

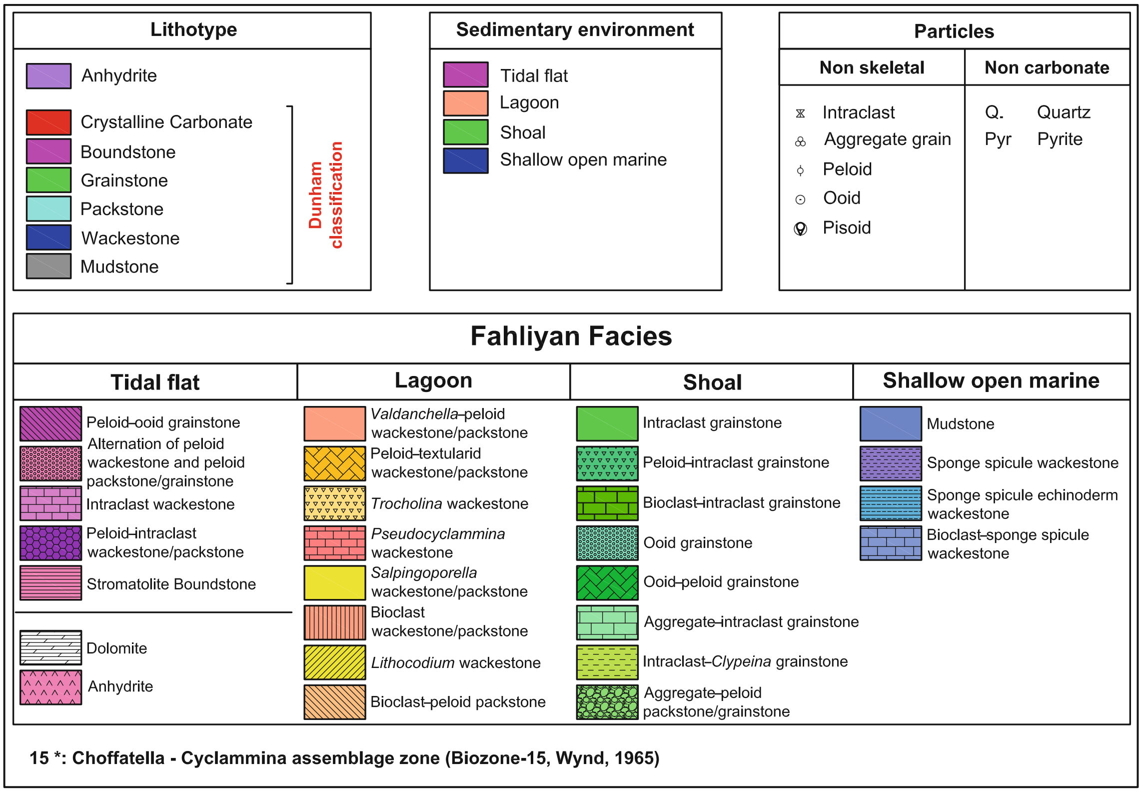


Fig. 6 Legend of Fahliyan Formation stratigraphic column in the Kuh-e Siah section

These microfacies from distal to proximal environments consist of:

Mudstone

This microfacies consist of micrite with less than 10% bioclasts (Fig. 7a). Bioclasts mainly are sponge spicules and echinoid/crinoid remains with subordinate bivalve, gastropod, small benthic foraminifer, green algae (such as *Acicularia* sp.), and shell fragments. This microfacies is equivalent to a fossiliferous micrite. Bioturbation is common. Pyritization is the major diagenetic process of this microfacies. Partial dolomitization also occurs in some intervals. Large amounts of micrite are indicative for a low-energy environment. This microfacies is comparable to SMF3 and RMF2 of Wilson (1975) and Flügel (2004), respectively.

Sponge spicule wackestone

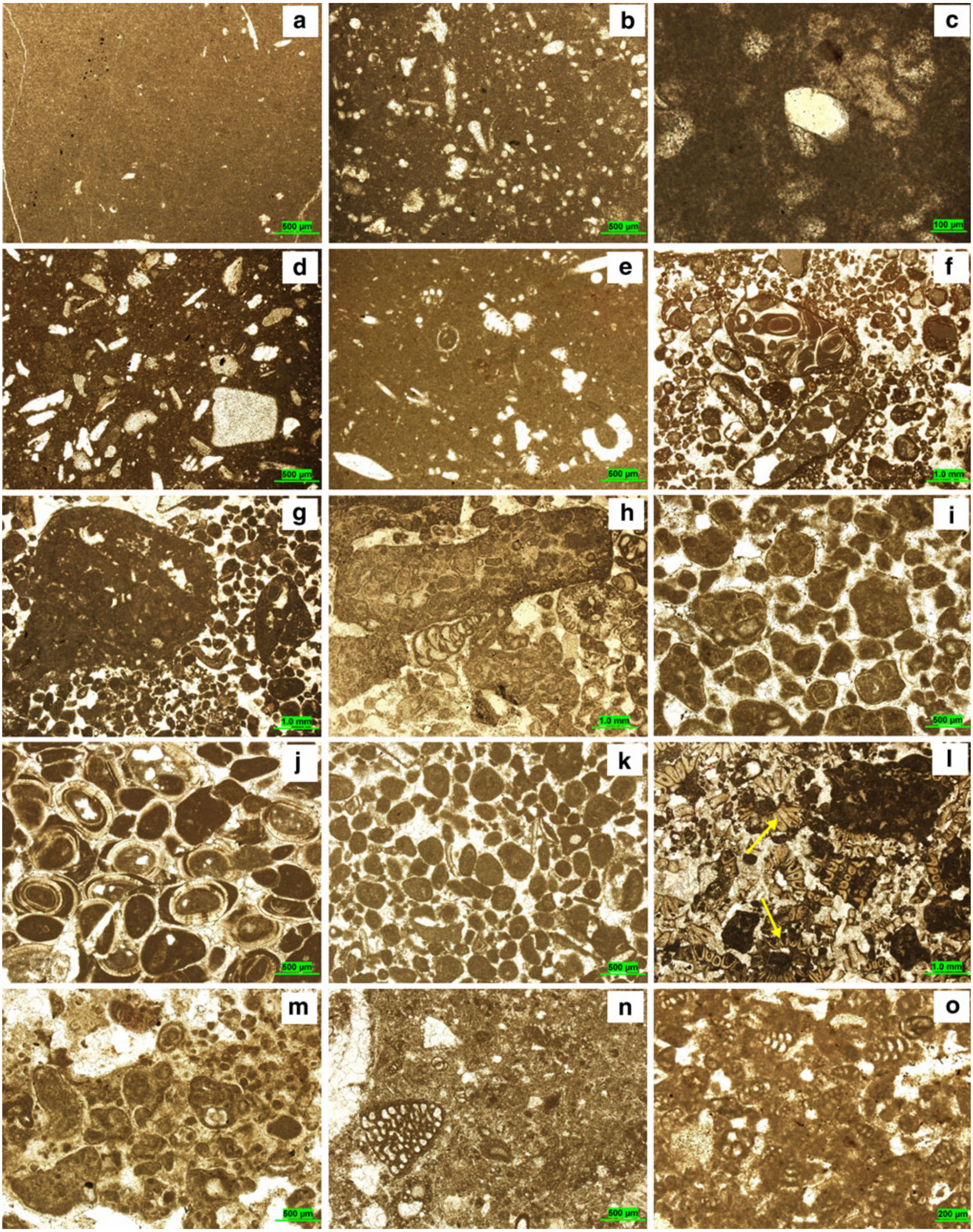
This microfacies is dominated by sponge spicules (20–40%) with less than 10% of other bioclasts (Fig. 7b). Subordinate bioclasts comprise mainly echinoid/crinoid remains, thin-shelled bivalves, gastropod, stromatoporoid, and algal fragments as well as benthic foraminifera such as *Lenticulina* sp. and *Trocholina* sp. Authigenic quartz and pyrite are the non-carbonate components present (Fig. 7c). This microfacies is comparable to SMF8 and RMF3 of Wilson (1975) and Flügel (2004), respectively, and corresponds to biomicrite according to Folk (1962).

Sponge spicule-echinoderm wackestone

The main allochems of this microfacies are echinoderm (15%) and sponge spicules (10%) (Fig. 7d). Large amounts of shell fragments are also present. Bivalves, gastropods, stromatoporoids, green algae, and benthic foraminifera are rare. Pyritization is the major diagenetic process. This microfacies is comparable to SMF12 and RMF7 of Wilson (1975) and Flügel (2004) as well as biomicrite of Folk (1962).

Bioclast-sponge spicule wackestone

This microfacies is dominated by sponge spicules (20%) as well as subordinate thin-shelled bivalves and echinoid/crinoid fragments. Dasycladacean algae, *Lithocodium aggregatum*, benthic foraminifera, gastropods, stromatoporoid, and bivalves are also present (Fig. 7e). Bioturbation is common. This microfacies is comparable to SMF8 and RMF3 of Wilson (1975) and Flügel (2004), respectively (biomicrite according to Folk 1962). Due to lack of a


a
500 µm
b
500 µm
c
100 µm
d
500 µm
e
500 µm
f
1.0 mm
g
1.0 mm
h
1.0 mm
i
500 µm
j
500 µm
k
500 µm
l
1.0 mm
m
500 µm
n
500 µm
o
200 µm

◀ **Fig. 7** Microfacies of the Kuh-e Siah section. **a** Mudstone, open-marine facies, sample RAP.10879 (plane polarized light). **b** Sponge spicule wackestone, open-marine facies, sample RAP.10815, PPL. **c** Authigenic quartz in sponge spicule wackestone, open-marine facies, sample RAP.10815, PPL. **d** Sponge spicules-echinoderm wackestone, shallow open-marine facies, sample RAP.10880, PPL. **e** Bioclast-sponge spicule wackestone, open-marine facies, sample RAP.10857, PPL. **f** Intraclast grainstone, shoal facies, sample RAP.10808, PPL. **g** Peloid-intraclast grainstone, shoal facies, sample RAP.10802, PPL. **h** Bioclast-intraclast grainstone, shoal facies, sample RAP. 10798, PPL. **i** Aggregate-intraclast grainstone, shoal facies, sample RAP.10796, PPL. **j** Ooid grainstone, shoal facies, sample RAP.10807, PPL. **k** Ooid-peloid grainstone, shoal facies, sample RAP.10803, PPL. **l** Intraclast-*Clypeina* grainstone, shoal facies, *arrows* indicate *Clypeina jurassica*, sample RAP.10804, PPL. **m** Aggregate-peloid packstone/grainstone, shoal facies, near lagoon, sample RAP.10797, PPL. **n** *Valdanchella*-peloid wackestone/packstone, lagoon facies, sample RAP.10825, PPL. **o** Peloid-textularid wackestone/packstone, lagoon facies, sample RAP.10874, PPL

rimmed margin in the Fahliyan Formation, movement of sediments was common and algal fragments could be transported from lagoon to shallow open-marine environments.

Shoal facies belt

The shoal facies belt was deposited in the platform margin sub-environment. Eight microfacies are associated in this sub-environment and are composed mainly of intraclasts, ooids, peloids, bioclasts, and aggregate grains. Some ooids are diagenetically altered by micritization and cementation (first generation of fibrous and bladed cements followed by equant or blocky cements). The abundance of allochems, grain-supported texture, concentric ooids, good sorting and roundness and subordinate mud content of this facies belt indicate high-energy conditions (Tucker et al. 1993; Lucia 1999; Palma et al. 2007; Reolid et al. 2007; Adabi et al. 2010). All facies of this belt have no mud except the aggregate-peloid packstone/grainstone, an environment with lower energy conditions close to the lagoon as is indicated by the abundance of *Clypeina* sp.

Based on faunal and lithological composition, this facies belt developed within an inner ramp environment of the lower parts of Kuh-e Siah section (Figs. 5 and 6).

Propagation of carbonate shoals is one of the factors that characterize ramp environments (Elrick and Read 1991). Peloids present in this facies belt show a transition from low-energy to high-energy conditions. The presence of intraclasts and peloids with sparry cement forms a peloid-intraclast grainstone facies characteristic of channels which cut shoals (Tucker and Wright 1990). This microfacies is considered as high-energy shoal facies (Adabi et al. 2010).

The main porosities in this facies belts are interparticle, intraparticle, vuggy, and moldic that are partially filled with sparry cements. Dissolution, micritization, cementation, physical compaction, and in some intervals dolomitization are major diagenetic fabrics.

Intraclast grainstone

Intraclasts (~25%) with good roundness are the dominant component here (Fig. 7f). The size of intraclasts varies from 100 μm to 4 mm (intraclasts were observed in two size classes). Micritic peloids (5%) are also present. Dissolution and cementation (equant cement) are the main diagenetic fabrics in this facies. This microfacies is comparable to SMF14 and RMF11 of Wilson (1975) and Flügel (2004), respectively. This microfacies is an intrasparite according to Folk (1962).

Peloid-intraclast grainstone

Intraclasts (~30%) and peloids (~25%) are the dominant components (Fig. 7g). Intraclasts have good roundness with 500 μm to 4 mm in size. Bioclast (~5%) include green algae (such as *Salpingoporella* sp.), benthic foraminifera (such as *Praechrysalidina infracretacea*), gastropods, echinoderms, and *Lithocodium aggregatum*, ~5% ooids are present. This microfacies is comparable to SMF14 and RMF11 of Wilson (1975) and Flügel (2004), respectively. This microfacies is a pelintrasparite (Folk 1962).

Bioclast-intraclast grainstone

This microfacies is characterized by the abundance of coarse intraclasts (~30%) with up to 2 mm size (as flat pebble conglomerate) and bioclasts (~15%) (Fig. 7h). Bioclasts of this microfacies consisted of gastropods, brachiopods, green algae (such as *Salpingoporella* sp. and *Angioporella* sp.), benthic foraminifers (such as *Textularia* sp. and *Praechrysalidina infracretacea*), echinoderms and *Lithocodium aggregatum*. Peloids and ooids are subordinate components. This microfacies is a biointrasparite according to Folk (1962). Good roundness of intraclasts proof high-energy conditions. Intraclasts have different textures such as ooid packstone/grainstone and bioclast wackestone with signs of transportation of intraclasts from different parts of basin such as from the lagoon. The presence of allochems in sparry calcite cement with lack of micritic matrix points to high-energy conditions. This microfacies is comparable to SMF18 and RMF26 of Wilson (1975) and Flügel (2004), respectively.

Aggregate-intraclast grainstone

Intraclasts (~30%) and aggregate grains (~20%) are the dominant components (Fig. 7i). Bioclasts, ooids, and peloids are also present (~10%). This microfacies is an intrasparite according to Folk (1962). The presence of intraclasts and aggregate grains in sparry calcite cement is indicative of high-energy conditions (Adabi et al. 2010). Bioclasts are composed of gastropods, benthic foraminifers (such as *Praechrysalidina infracretacea*), and dasycladacean algae (e.g., *Salpingoporella* sp.). This microfacies is comparable to SMF17 and RMF26 of Wilson (1975) and Flügel (2004), respectively. This microfacies indicates temporarily quiet energetic periods so that aggregates can be formed.

Ooid grainstone

This microfacies is characterized by a high abundance of ooid with concentric structure (~40%) (Fig. 7j). Subordinate bioclast, intraclast and aggregate grains are also present. Bioclasts of this microfacies consist of gastropods, echinoderms and benthic foraminifers (mainly *Praechrysalidina infracretacea*). This microfacies is an oosparite according to Folk (1962). Composite and half moon ooids as well as ooids with bioclast nuclei are observed in this facies. This microfacies is comparable to SMF15 and RMF29 of Wilson (1975) and Flügel (2004), respectively.

Ooid-peloid grainstone

This microfacies is characterized by a high abundance of peloids (~30%) and micritized small ooids (~25%) (Fig. 7k). Peloids have good sorting and roundness with ~0.4 mm size. Subordinate intraclasts, aggregate grains and bioclasts are also present. Bioclasts of this microfacies are composed of gastropods, echinoderms, benthic foraminifers (mainly *Praechrysalidina infracretacea*), and dasycladacean algae. This microfacies is a peloosparite according to Folk (1962). This microfacies is comparable to SMF16 and RMF29 of Wilson (1975) and Flügel (2004), respectively.

Intraclast-Clypeina grainstone

This microfacies is characterized by the presence of abundant *Clypeina jurassica* (~50%) and intraclast (~15%) (Fig. 7l, intrabiosparite of Folk 1962). The lack of muddy matrix in this microfacies shows deposition in a high-energy environment. This microfacies is comparable to SMF18 and RMF26 of Wilson (1975) and Flügel (2004), respectively.

Aggregate-peloid packstone/grainstone

Peloids (up to 30%) and aggregate grains (10–15%) are the dominant components of this microfacies (Fig. 7m, pelsparite of Folk 1962). Subordinate bioclasts (dasycladacean algae) and ooids are also present. This microfacies is comparable to SMF16 and RMF27 of Wilson (1975) and Flügel (2004), respectively.

Lagoon facies belt

Eight microfacies are associated with the lagoon sub-environment. It is characterized by large amounts of mud and the presence of abundant benthic foraminifers and calcareous green algae associated with gastropods and bivalves (Purser 1973; Tucker and Wright 1990; Flügel 2004; Husinec and Sokač 2006; Bachmann and Hirsch 2006; Palma et al. 2007; Adabi et al. 2010). Calcareous algae are common in shallow-marine limestone of Cretaceous strata in the Zagros Mountains in SW Iran (Parvaneh Nejad Shirazi 2008; Mosadegh and Parvaneh Nejad Shirazi 2009; Adabi et al. 2010). Dasycladacean algae inhabit illuminated warm seas with normal salinity and are common in 3–5 m water depth (Wray 1977; Riding 1991). Diverse skeletal grains with abundant calcareous green algae present in the Fahliyan Formation. Some petrographic evidence such as an abundance of aragonite skeletal and non-skeletal components calls for a sub-tropical environment with original aragonite mineralogy (Adabi et al. 2010).

Some components of the shallow open-marine environment were transported by storm wave into the lagoon (e.g., sponge spicules). Calcareous sponge spicules are also present in low-energy environments with normal salinity in depths of about 10 m and are associated with green algae fragments (Wells 1965). Based on faunal and lithological composition, this facies belt is part of the inner ramp environment.

In the lagoon sub-environments bioclasts have a high diversity and are associated with peloids (Bachmann and Hirsch 2006; Adabi et al. 2010). Peloids are common in some microfacies in this facies belt. Bioclastic peloid packstones suggest higher energy conditions in a shallow subtidal setting (Flügel 2004). The wackestone and packstone textures indicate deposition in the proximal part of a subtidal lagoon (Lasemi et al. 2008).

All of the facies in this facies belt deposited in the lagoon sub-environment, but differ from each other by their skeletal grain composition. Skeletal grains are in micritic matrix and thus were deposited under low-energy conditions.

Micritization is one of the commonest destructive processes in this sub-environment. One of the main characteristics of the lagoon is that almost all aragonite shells (e.g., *Trocholina* sp.) are preserved as moulds that are filled with sparry calcite cement (Booler and Tucker 2002). Boring and cementation are the other taphonomic features that are observed. Dissolution and vuggy porosity in bioclast-peloid packstone facies is high. This microfacies is located near the tidal flat sub-environment.

Valdanchella-peloid wackestone/packstone

This microfacies consists mainly of peloids (~20%) and tests of the benthic foraminifer *Valdanchella* sp.) (~15%) (Fig. 7n). Subordinate benthic foraminifers (such as *Textularia* sp., *Praechrysalidina infracretacea, Praechrysalidina* sp., *Nautiloculina* sp., *Siphovalvulina* sp., and *Trocholina* sp.), dasycladacean algae, *Lithocodium aggregatum*, gastropods, stromatoporoids, echinoid/crinoid remains and sponge spicules are also observed (biopelmicrite according to Folk 1962). Partly washed micrite shows increasing water energy and indicates higher energy parts of lagoon. This microfacies is comparable to SMF10 and RMF13 of Wilson (1975) and Flügel (2004), respectively.

Peloid-textularid wackestone/packstone

This microfacies consists mainly of benthic foraminifera (Textularidae) (~30%) and peloids of 300-μm size (~15%) with good sorting and roundness (Fig. 7o). Subordinate benthic foraminifera (such as Miliolidae, *Cuneolina* sp., *Trocholina* sp., *Pseudocyclammina* sp., *Pseudocyclammina lituus, Praechrysalidina* sp., *Nautiloculina* sp., and *Siphovalvulina* sp.), green algae (such as *Acicularia* sp.), gastropods, stromatoporoids, echinoid/crinoid remains, bivalves, brachiopods, sponge spicules, and shell fragments are also present (pelbiomicrite according to Folk 1962). Pyrite (10%) is observed in some intervals. This microfacies is comparable to SMF18 and RMF20 of Wilson (1975) and Flügel (2004), respectively.

Trocholina wackestone

The main component of this microfacies is *Trocholina* sp. (20–40%) (Fig. 8a) and it corresponds to a biomicrite of Folk (1962). Moulds of *Trocholina* sp. are filled by sparry calcite cement and show the unstable mineralogy (aragonite) of this foraminifer (Figs. 8b and c). Subordinate skeletal grains are sponge spicules, gastropods, bivalves, echinoid/crinoid remains, dasycladacean algae (such as *Salpingoporella* sp.), *Lithocodium aggregatum*, benthic foraminifers (e.g., miliolids, *Textularia* sp., *Pseudocyclammina lituus, Praechrysalidina infracretacea, Lenticulina* sp., *Siphovalvulina* sp., and *Nezzazata* sp.) and shell fragments. Also, 2% authigenic quartz is seen in some intervals. This microfacies is comparable to SMF18 and RMF20 of Wilson (1975) and Flügel (2004), respectively.

Pseudocyclammina wackestone

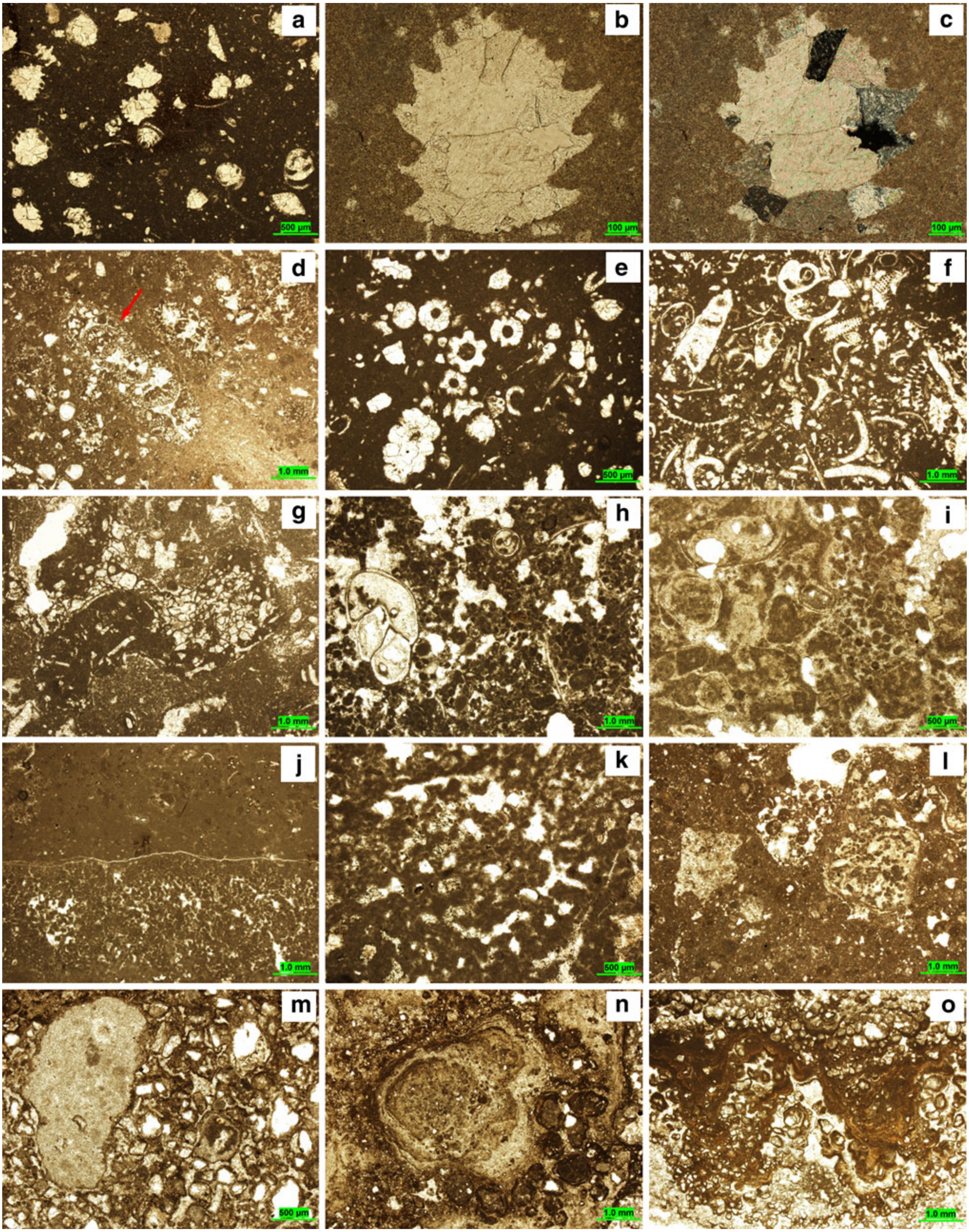
The main component of this microfacies is *Pseudocyclammina lituus* (20–30%) (Fig. 8d). Subordinate skeletal grains are sponge spicules, gastropods, bivalves, stromatoporoids, echinoid/crinoid debris, dasycladacean algae, benthic foraminifers (e.g., miliolids, *Textularia* sp., *Trocholina* sp., *Praechrysalidina* sp., and *Lenticulina* sp.) and shell fragments. This microfacies corresponds to a biomicrite according to Folk (1962) and comparable to SMF18 and RMF13 of Wilson (1975) and Flügel (2004), respectively.

Salpingoporella wackestone/packstone

The main feature of this facies is the dominance of green algae (*Salpingoporella* sp.) (~40%) (Fig. 8e); it corresponds to a biomicrite according to Folk (1962). Other minor biogenic components include sponge spicules, gastropods, *Lithocodium aggregatum*, echinoid/crinoid debris and benthic foraminifera (e.g., *Trocholina* sp., miliolids, *Praechrysalidina infracretacea*, and *Pseudocyclammina lituus*). The presence of dasycladacean green algae suggests a very shallow marine setting (Wray 1977). These bioclasts are characteristic for a lagoon sub-environment (Wray 1977; Riding 1991, 2000; Adabi et al. 2010). This microfacies is comparable to SMF18 and RMF17 of Wilson (1975) and Flügel (2004), respectively.

Bioclast wackestone/packstone

The predominant skeletal grains are dasycladacean algae (mainly *Salpingoporella* sp. and minor *Actinoporella podolica, Actinoporella* sp. and *Acicularia* sp.) associated with benthic foraminifers (e.g., Miliolidae, *Trocholina* sp., *Pseudocyclammina lituus, Nautiloculina* sp., *Praechrysalidina infracretacea*, *Lenticulina* sp. and *Textularia* sp.) (~20–30%) (Fig. 8f). Other bioclast components are sponge spicules, stromatoporoids, *Lithocodium aggregatum*, gastropods, bivalves, echinoid/crinoid remains, and shell fragments. Non-carbonate grains such as authigenic quartz (2–5%) and pyrite (2–10%) are observed. This microfacies is a biomicrite according to Folk (1962) and comparable to SMF18 and RMF20 of Wilson (1975) and Flügel (2004), respectively.


a
500 µm
b
100 µm
c
100 µm
d
1.0 mm
e
500 µm
f
1.0 mm
g
1.0 mm
h
1.0 mm
i
500 µm
j
1.0 mm
k
500 µm
l
1.0 mm
m
500 µm
n
1.0 mm
o
1.0 mm

◀ **Fig. 8** Microfacies of the Kuh-e Siah section. **a** *Trocholina* wackestone, lagoon facies, sample RAP.10855, PPL. **b** Mold of *Trocholina* sp. has been filled with sparry calcite cement, lagoon facies, sample RAP.10852, PPL. **c** Mold of *Trocholina* sp. has been filled with sparry cement, lagoon facies, sample RAP.10852 (cross polarized light). **d** *Pseudocyclammina* wackestone, lagoon facies, *arrow* shows *Pseudocyclammina lituus*, sample RAP.10824, PPL. **e** *Salpingoporella* wackestone/packstone, lagoon facies, sample RAP.10819, PPL. **f** Bioclast wackestone/packstone, lagoon facies, sample RAP.10828, PPL. **g** *Lithocodium* wackestone, lagoon facies, sample RAP.10812, PPL. **h** Bioclast-peloid packstone, lagoon facies, sample RAP.10799, PPL. **i** Peloid-ooid grainstone, tidal flat facies, sample RAP.10794, PPL. **j** Alternation of peloid wackestone and peloid packstone/grainstone, tidal flat facies, sample RAP.10809, PPL. **k** Fenestral porosity, tidal flat facies, sample RAP.10809, PPL. **l** Intraclast wackestone, tidal flat facies, sample RAP.10810, PPL. **m** Peloid-intraclast wackestone/packstone, tidal flat facies, sample RAP.10841, PPL. **n** Pisoid in peloid-intraclast wackestone/packstone, tidal flat facies, sample RAP.10841, PPL. **o** Stromatolite boundstone, tidal flat facies, sample RAP.10834, PPL

Lithocodium wackestone

The predominant skeletal grain is *Lithocodium aggregatum* (~30%) (Fig. 8g). Subordinate biogenic components include gastropods, dasycladacean algae, stromatoporoids, echinoid/crinoid debris, benthic foraminifers, sponge spicules, and bivalves. In some intervals, ~10% intraclast is observed. Authigenic quartz is present in some intervals. This microfacies (biomicrite sensu Folk 1962) is comparable to SMF18 and RMF17 of Wilson (1975) and Flügel (2004), respectively.

Bioclast-peloid packstone

This microfacies consists mainly of peloids (~40%) and bioclasts (mainly gastropods and small benthic foraminifera) (~10%). Peloids are well sorted and rounded (Fig. 8h). Dasycladacean algae (*Salpingoporella* sp.) are the other minor biogenic components. Ooids (~2%) and intraclasts (~5%) are also present in some intervals. This microfacies, a biopelmicrite sensu Folk (1962), is comparable to SMF16 and RMF20 of Wilson (1975) and Flügel (2004), respectively.

Tidal flat facies belt

Five microfacies are recognized in this sub-environment. Strong dissolution processes and abundant vuggy porosity, lamination, presence of silt, and sand-sized quartz and fenestral fabric suggest deposition in supratidal to intertidal environment. Low diversity faunal assemblages imply stressed paleoecological conditions such as elevated salinities. These criteria and association with shallow-marine facies suggest a peritidal sub-environment (Adabi 2009; Bodzioch 2003). Stromatolite boundstone is also observed and interpreted to have been deposited in intertidal to supratidal environment (Palma et al. 2007).

Peloid-ooid grainstone

This microfacies is characterized by a high abundance of ooids (~ 30%) and peloids (~20%) (Fig. 8i). Subordinate aggregate grains are also present. Different kinds of ooids such as superficial ooids, composite ooids, micritic ooids and spastoliths have been observed in this microfacies. These ooids are affected by dissolution and therefore moldic porosity (oomold) is created. This facies is located in the lower part of Kuh-e Siah section (Figs. 5 and 6). Association of this facies with dolomitized facies of tidal flat sub-environment, lack of bioclasts, widespread dissolution and abundant vuggy porosity indicate a tidal flat sub-environment (Flügel 2004). This microfacies (oosparite sensu Folk 1962) is comparable to SMF15 and RMF29 of Wilson (1975) and Flügel (2004), respectively.

Alternation of peloid wackestone and peloid packstone/grainstone

This microfacies consists mainly of peloids (~20% in peloid wackestone and ~40% in peloid packstone/grainstone) (Fig. 8j) and corresponds to a pelmicrite to pelsparite according to Folk (1962). This alternation caused the lamination. Presence of lamination, the low amount of bioclasts and occurrence of fenestral porosity show a tidal flat environment (Fig. 8k). Partly dolomitization is the main diagenetic feature in this facies. This microfacies is comparable to SMF16 and RMF22 of Wilson (1975) and Flügel (2004), respectively.

Intraclast wackestone

The main components of this microfacies are intraclasts (~20%) (Fig. 8l), and it consequently has been named intramicrite according to Folk (1962). Lack of bioclasts, fenestral porosity and association with tidal flat facies indicates a tidal flat environment. Quartz grains (~2%) with 50–80 µm (probably transported by wind) are also observed. This microfacies is comparable to SMF24 and RMF24 of Wilson (1975) and Flügel (2004), respectively.

Peloid-intraclast wackestone/packstone

This microfacies consists of intraclasts (~25%) and peloids (~20%) (Fig. 8m). Pisoids are also present in this facies (~10%) (Fig. 8n). Silt-sized (40–50 µm) quartz (transported by wind) is observed in this facies (~20%). This facies underwent extensive dissolution. Fenestral, vuggy, and moldic porosities are the main porosities in this facies. This microfacies corresponds to a pelintramicrite according to Folk (1962) and was deposited in upper intertidal to supratidal sub-environment. This microfacies is comparable to SMF24 and RMF24 of Wilson (1975) and Flügel (2004), respectively.

Stromatolite boundstone

This microfacies consists of stromatolite laminae (Fig. 8o) and was affected by extensive dissolution and dolomitization in some intervals. Mineralization with iron oxide is seen in some parts. Silt and sand-sized (50–100 μm) quartz grains (transported by wind) (2–20%) are also observed. Stromatolite lamination, large amounts of fenestral, and vuggy porosities show an intertidal to supratidal sub-environment. This microfacies, a biolithite according to Folk (1962), is comparable to SMF20 and RMF22 of Wilson (1975) and Flügel (2004), respectively.

Paleoenvironmental model

The Lower Cretaceous Fahliyan Formation (Neocomian) of the Zagros Mountains was deposited on a gently dipping carbonate ramp (Hosseini and Conrad 2008; Mosadegh and Parvaneh Nejad Shirazi 2009). In this study, this formation is also interpreted to have been deposited on a carbonate ramp with a very gentle slope (Fig. 9). The lack of any marginal reef development, absence of major break of slope from shoreline into deeper water, no evidence of resedimentation (e.g., calciturbidites), and the presence of high-energy grainstone facies are consistent with the Fahliyan Formation having been deposited on a carbonate ramp (Wright 1986; Tucker et al. 1993).

According to Burchette and Wright (1992), carbonate ramp environments are separated into (1) the inner ramp between upper shoreface and FWWB, which is constantly affected by wave agitation (2) the middle ramp, between FWWB and storm-wave base with sediment reworking by storms (water depths between a few tens of meters and 100–200 m), and (3) the outer ramp below normal storm-wave base down to the basin plain. In the studied section, the inner ramp depositional environment includes tidal flat, lagoon and shoal sub-environments, and mid-ramp includes the shallow open-marine sub-environment. In the shoal sub-environment, grainstones are common. In the lagoon, the microfacies are mud-rich and dominated by benthic foraminifers and green algae. Sponge spicules are very common in the microfacies of the mid-ramp, associated with green algae and small benthic foraminifers in shallower parts (Fig. 9).

Paleoecological analyses

The most important skeletal components of the studied carbonate samples are calcareous green algae and benthic foraminifera. These bioclasts are strongly controlled by local ecological conditions (Husinec and Sokač 2006). In the absence of open-marine organisms (e.g., planktonic foraminifera, etc.), which are commonly used in high-resolution biostratigraphy, these organisms play a key role in chronological dating (Husinec and Sokač 2006; Hosseini and Conrad 2008). We studied the Early Cretaceous benthic foraminifera and calcareous algae in order to better understand the distribution of these microorganisms and determination the age of formation. The Fahliyan Formation in Kuh-e Siah area corresponds with biozone 14, the Neocomian *Pseudocyclammina lituus*-*Trocholina* assemblage zone, and reaches biozone 15, the *Choffatella*-*Cyclammina* assemblage zone of Barremian-Aptian age (Wynd 1965). We suggest a Neocomian–Early Barremian age for the age of the Fahliyan Formation here (Figs. 5 and 6).

A total of ten genera belonging to different groups of calcareous algae and 16 genera of benthic foraminifera have been recognized from the sedimentary units of the Kuh-e Siah section (Figs. 10, 11 and 12).

In the Cretaceous of Iran, calcareous algae are one of the less studied groups compared to the other fossil groups such as foraminifers, molluscs, and others (Parvaneh Nejad Shirazi 2008).

Gollestaneh (1965) studied the Upper Jurassic–Lower Cretaceous calcareous algae in SW Iran for the first time and reported several taxa from this area. Since then, his paper was used as a reference for algal identification in Iran. In this paper, some taxa from the Kuh-e Siah section in the Zagros Mountains were recognized.

Dasycladacean algae are the most abundant fauna in this area (Fig. 10). They are associated with subtidal, sometimes restricted (lagoonal) environments (Bucur and Săsăran 2005).

Calcareous algae in the Fahliyan Formation in the Kuh-e Siah are illustrated in Fig. 10. The following taxa were distinguished:

Salpingoporella sp., *Salpingoporella annulata, Salpingoporella dinarica, Salpingoporella urladanasi*, *Clypeina jurassica*, *Angioporella* sp., *Cylindroporella* sp., *Neomeris* sp., *Actinoporella* sp., *Actinoporella podolica, Acicularia* sp., *Neoteutloporella* sp., *Heteroporella lemoinei*, *Bacinella irregularis (Lithocodium aggregatum)*, an enigmatic microencruster interpreted as cyanobacteria (e.g., Camoin and Maurin 1988; Schmid 1996).

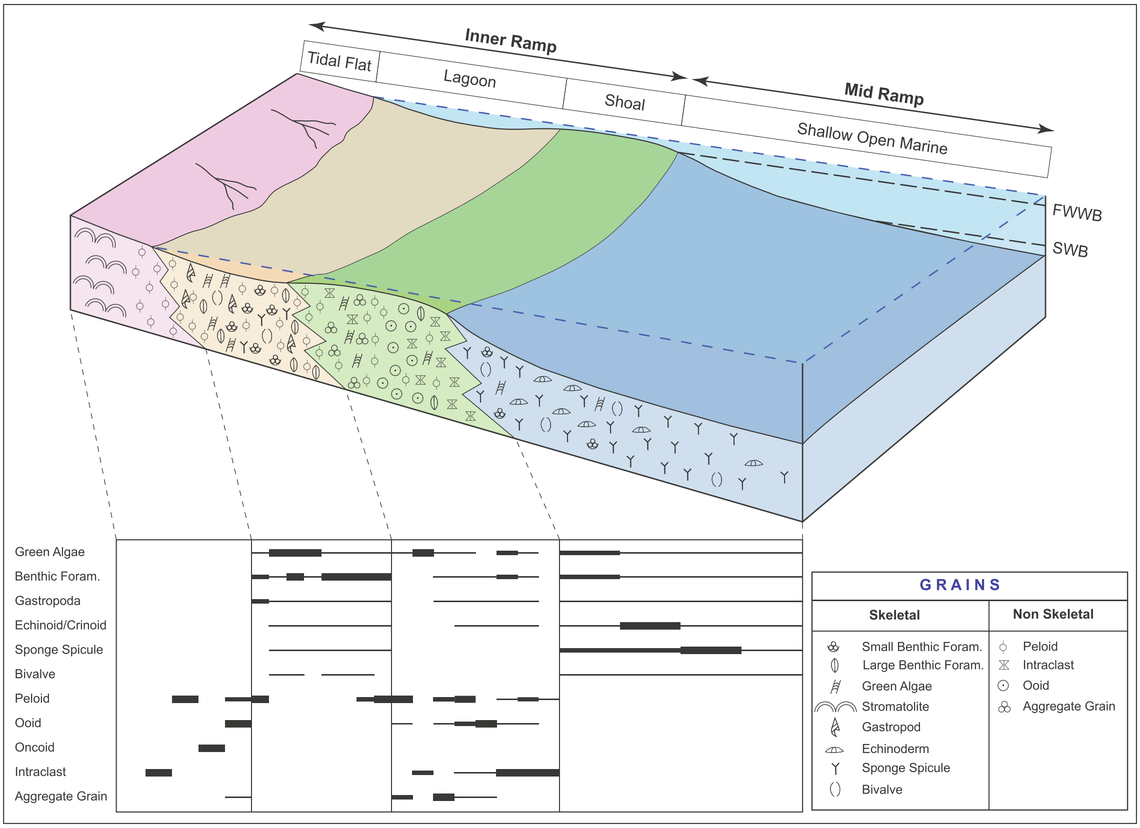


Fig. 9 Schematic diagram of a ramp platform carbonate environment of the Fahliyan Formation. *FWWB* fair weather wave base; *SWB* storm wave base

The lower boundary of the Fahliyan Formation is dolomitized but the lower intervals are associated with the appearance of *Salpingoporella annulata, Salpingoporella* sp., *Clypeina jurassica*, *Salpingoporella dinarica*, *Neoteutloporella* sp., and *Heteroporella lemoinei* (Figs. 5 and 6). These bioclasts were only observed in the lower part of the section and indicate Neocomian age. *Salpingoporella annulata* was observed in Neocomian times elsewhere (Husinec and Sokač 2006).

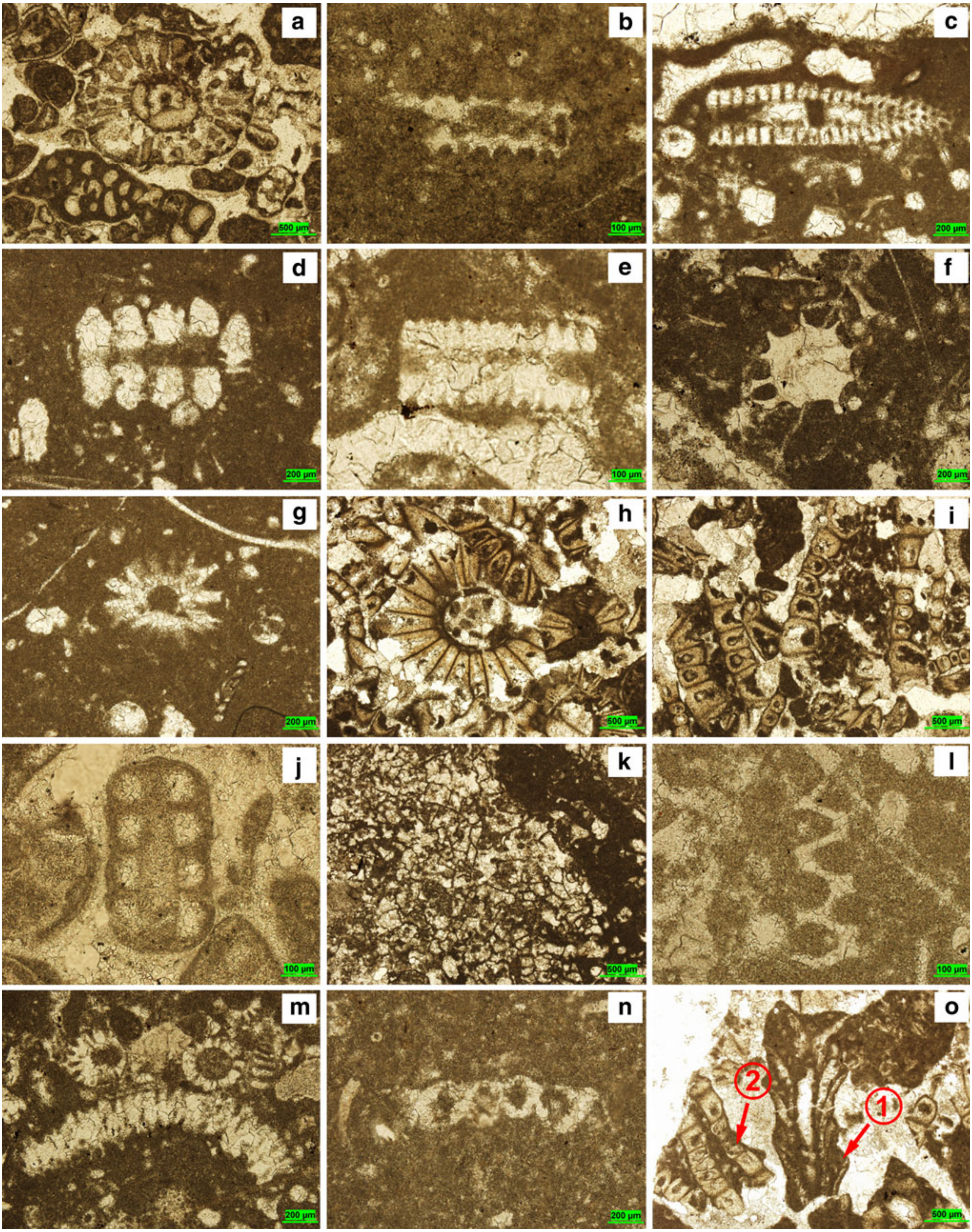
Calcareous algae have traditionally been considered as very suitable ecological and paleoenvironmental indications (Wray 1977; Roux 1985; Bosence 1991; Berger and Kaever 1992; De Castro 1997). As the case with other fossils, ecological considerations based on dasycladacean algae are founded on the principle of uniformitarianism. Jaffrezo (1980) emphasized that the ecological information regarding present-day dasycladacean algae is scarce and, apparently, often contradictory, but some essential data on the ecology of modern dasycladacean algae are provided (Valet 1979; Berger and Kaever 1992). The ecology of living dasycladacean algae is defined by the relationship with their substrate, temperature, light, and salinity.

According to Valet (1979), it is not the substrate that influences the distribution of living dasycladacean algae, but water temperature determined by the climate. Recent dasycladacean algae are tropical–subtropical forms and, even if some degree of variation occurs, they develop best in warm waters. According to Berger and Kaever (1992), the temperature tolerance of recent dasycladacean algae is low with most genera occurring between 20°C isocrymes (15°C according to Jaffrezo 1980). One of the effects of low temperatures on these algae is the inhibition of calcification (Bucur and Săsăran 2005). Calcification of some dasycladacean algae was observed in the studied area, which indicates high temperature.

According to Valet (1979), most living dasycladacean algae can hardly tolerate strong light. As far as bathymetry is concerned, most present-day dasycladacean algae are known from 0 to 10 m depth interval and they prefer normal marine conditions.

Benthic foraminifers that were observed in the Fahliyan Formation in the Kuh-e Siah are illustrated in Figs. 11 and 12. The following taxa were recognized:

Quinqueloculina sp., *Trocholina* sp., *Trocholina elongate, Pseudocyclammina lituus*, *Pseudocyclammina* sp.,


a
500 µm
b
100 µm
c
200 µm
d
200 µm
e
100 µm
f
200 µm
g
200 µm
h
500 µm
i
500 µm
j
100 µm
k
500 µm
l
100 µm
m
200 µm
n
200 µm
o
2
1
500 µm

◀ **Fig. 10** Calcareous algae of the Kuh-e Siah section. **a** *Salpingoporella* sp., sample RAP.10798, PPL. **b** *Salpingoporella urladanasi*, sample RAP.10857, PPL. **c** *Salpingoporella dinarica*, sample RAP.10819, PPL. **d** *Salpingoporella annulata*, sample RAP.10819, PPL. **e** *Salpingoporella* sp., sample RAP.10859, PPL. **f** *Acicularia* sp., sample RAP.10859, PPL. **g** *Heteroporella lemoinei*, sample RAP. 10820, PPL. **h** *Clypeina jurassica,* sample RAP.10804, PPL. **i** *Clypeina jurassica,* sample RAP.10804, PPL. **j** *Angioporella* sp., sample RAP.10798, PPL. **k** *Bacinella irregularis (Lithocodium aggregatum)*, sample RAP. 10812, PPL. **l** *Cylindroporella* sp., sample RAP.10859, PPL. **m** *Neomeris* sp., sample RAP.10859, PPL. **n** *Actinoporella podolica,* sample RAP. 10812, PPL. **o** *Neoteutloporell* sp. (*1*) and *Clypeina jurassica* (*2*), sample RAP.10804, PPL

Siphovalvulina sp., *Belorussiella* sp., *Praechrysalidina infracretacea*, *Mayncina* sp., *Mayncina bulgarica*, *Pfenderina* sp., *Lenticulina* sp., *Dukhania* sp., *Everticyclammina* sp., *Evertycyclammina hedbergi*, *Charentia* sp., *Nautiloculina oolithica*, *Nautiloculina* sp., *Cuneolina* sp., *Valdanchella* sp., *Choffatella* sp.

Pfenderina sp. and *Dukhania* sp. were only observed in the lower part of the section and indicate Neocomian age, but *Choffatella* sp. was only observed in the upper part of the section and indicates Early Barremian age (Figs. 5 and 6).

Paleoecological and -bathymetric investigations indicate that the studied samples were deposited in a tropical shallow-marine (inner to mid-ramp) platform environment with salinity ranging from normal marine to hypersaline (in tidal flat sub-environment). The character of inner-platform, shallow coastal waters, restricts the occurrence of fully marine organisms and carbonate producers are restricted to sea grasses, molluscs, benthic foraminifera, and calcareous green algae (Bosence and Wilson 2003). Such environments correspond to tidal flat microfacies of Kuh-e Siah area and those of Early Cretaceous in the area investigated, which were extensively colonized by almost exclusively benthic associations (predominantly gastropods and some foraminifera and calcareous algae in the lagoon sub-environment).

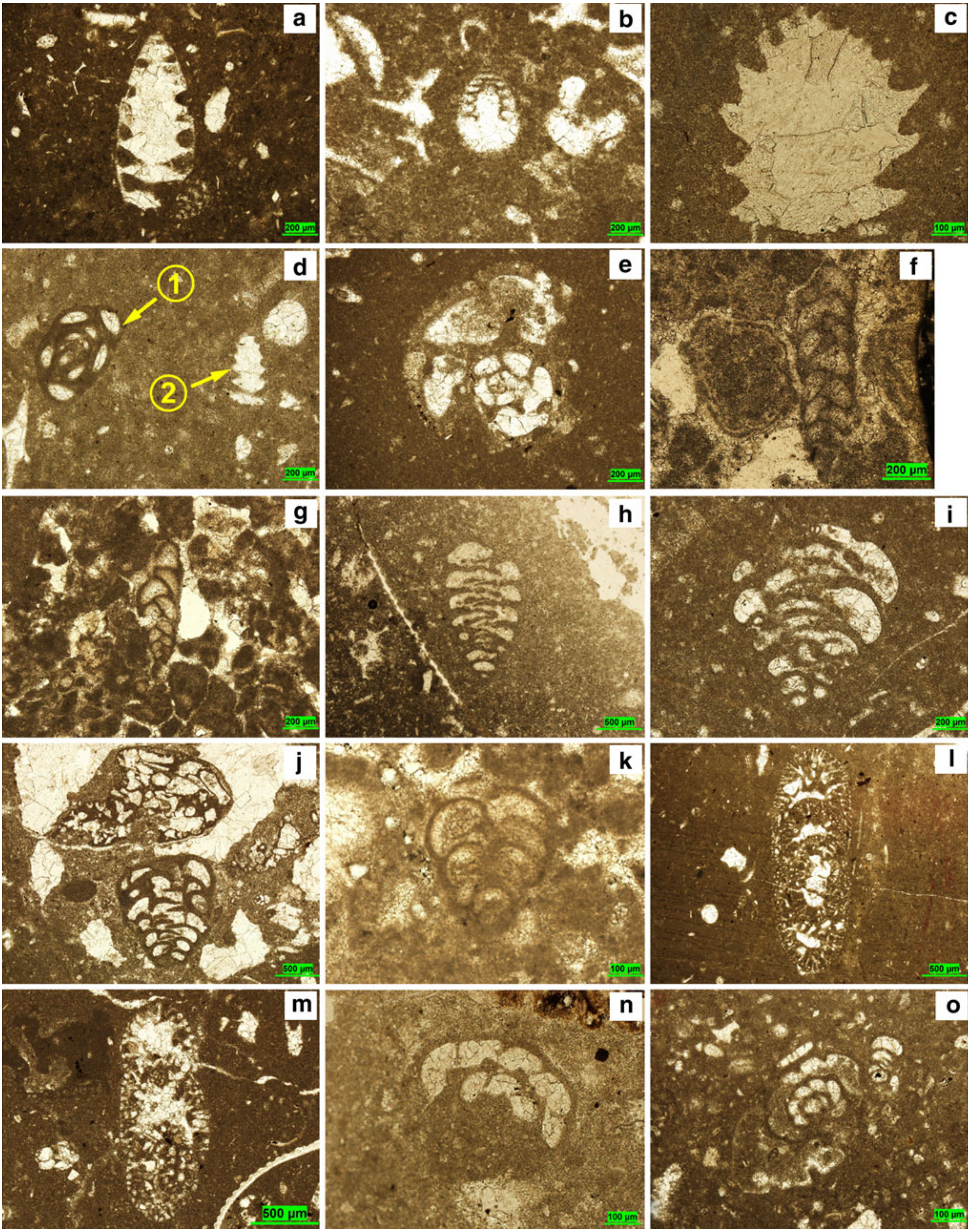
In Fahliyan Formation of the Kuh-Siah area, subtidal deposits occur in the external platform area (e.g., bioclast intraclast grainstone with various bioclast types) and the internal platform area. The subtidal limestones from the internal platform are characterized by bioturbated peloidal-bioclastic muds. Diversity of marine fauna and flora (for example in bioclast intraclast grainstone microfacies) indicates open shallow-water environments. Under restrictive conditions (for example in bioclast peloid packstone), biota were less diverse, showing dominance of gastropods and few small foraminifer species (Fig. 8h).

Among calcareous algae, *Salpingoporella annulata* and *Actinoporella podolica* are indicative mainly for the internal platform domain, either open, or sometimes restrictive (lagoonal) (Bucur and Săsăran 2005). These bioclasts in the Fahliyan Formation were mainly observed in lagoon and shoal facies belts (Figs. 5 and 6). *Salpingoporella annulata* in some cases is characteristic for restricted environments where it forms monospecific assemblages (Bucur and Săsăran 2005), but most of the authors consider *Salpingoporella annulata* to be an index fossil for normal marine environments (Conrad 1977; Jaffrezo and Renard 1979; Jaffrezo 1980). In the studied section, *Salpingoporella annulata* was observed in different facies belts such as lagoon, shoal, and shallow open-marine sub-environments and shows both normal marine and restricted environments.

Salpingoporella dinarica species deserve special interest in comparison to the other species (Carras et al. 2006). This species is very tolerant, as shown by the fact that it flourished in low energy, restricted marine environments (for a review of the genus *Salpingoporella*, see Carras et al. 2006). In the studied section, *Salpingoporella dinarica* was observed in lagoon sub-environment.

Among benthic foraminifera in the Kuh-e Siah section, *Trocholina* sp., *Trocholina elongate, Pseudocyclammina lituus*, *Pseudocyclammina* sp., *Siphovalvulina* sp., *Lenticulina* sp., *Nautiloculina oolithica, Nautiloculina* sp. and *Choffatella* sp. were observed in lagoon and shallow open-marine facies belts, which indicates both normal marine and restricted environments (Figs. 5 and 6). *Pfenderina* sp., *Dukhania* sp., *Belorussiella* sp., *Cuneolina* sp., *Everticyclammina* sp., and *Evertycyclammina hedbergi* have low distribution in the studied area. *Pfenderina* sp. and *Dukhania* sp. were only observed in lagoonal environments, which indicates they prefer restricted environments (Figs. 5 and 6). *Belorussiella* sp. and *Cuneolina* sp. were observed in lagoon and shoal sub-environments. *Praechrysalidina infracretacea* has high distribution vertically and laterally in the Kuh-e Siah section and was distinguished in lagoon, shoal, and shallow open-marine facies belts, which shows that they lived in both normal marine and restricted environments. *Everticyclammina* sp. and *Evertycyclammina hedbergi* were only recognized in shallow open-marine sub-environment indicating normal marine conditions (Figs. 5 and 6).

The Fahliyan Formation overlies the anhydrite containing Hith Formation in the Kuh-e Siah section. Due to high evaporation and large amounts of anhydrite deposits, the Hith Formation is characterized by relatively low diversity and distribution of fauna and flora in this area. In the Kuh-e Siah outcrop, different parts can be distinguished in the carbonate platform of the Fahliyan Formation, ranging from very shallow water, intertidal setting with algal mats, to high-energy shoal facies and shallow open-marine wackestones representing a mid-ramp setting. The shallowest microfacies


a
200 µm
b
200 µm
c
100 µm
d
1
2
200 µm
e
200 µm
f
200 µm
g
200 µm
h
500 µm
i
200 µm
j
500 µm
k
100 µm
l
500 µm
m
500 µm
n
100 µm
o
100 µm

◀ **Fig. 11** Benthic foraminifers of the Kuh-e Siah section. **a** *Trocholina elongata*, sample RAP.10865, PPL. **b** *Trocholina* sp., sample RAP.10812, PPL. **c** *Trocholina* sp., sample RAP.10852, PPL. **d** *Quinqueloculina* sp. (1) and *Trocholina* sp. (2), sample RAP. 10847, PPL. **e** *Everticyclammina* sp., sample RAP.10848, PPL. **f** *Belorussiella* sp., sample RAP.10796, PPL. **g** *Belorussiella* sp., sample RAP.10805, PPL. **h** *Praechrysalidina infracretacea*, sample RAP.10812, PPL. **i** *Praechrysalidina infracretacea*, sample RAP. 10860, PPL. **j** *Dukhania* sp., sample RAP.10820, PPL. **k** *Pfenderina* sp., sample RAP.10799, PPL. **l** *Pseudocyclammina lituus*, sample RAP.10865, PPL. **m** *Pseudocyclammina* sp., sample RAP.10866, PPL. **n** *Charentia* sp., sample RAP.10863, PPL. **o** *Charentia* sp., sample RAP.10873, PPL

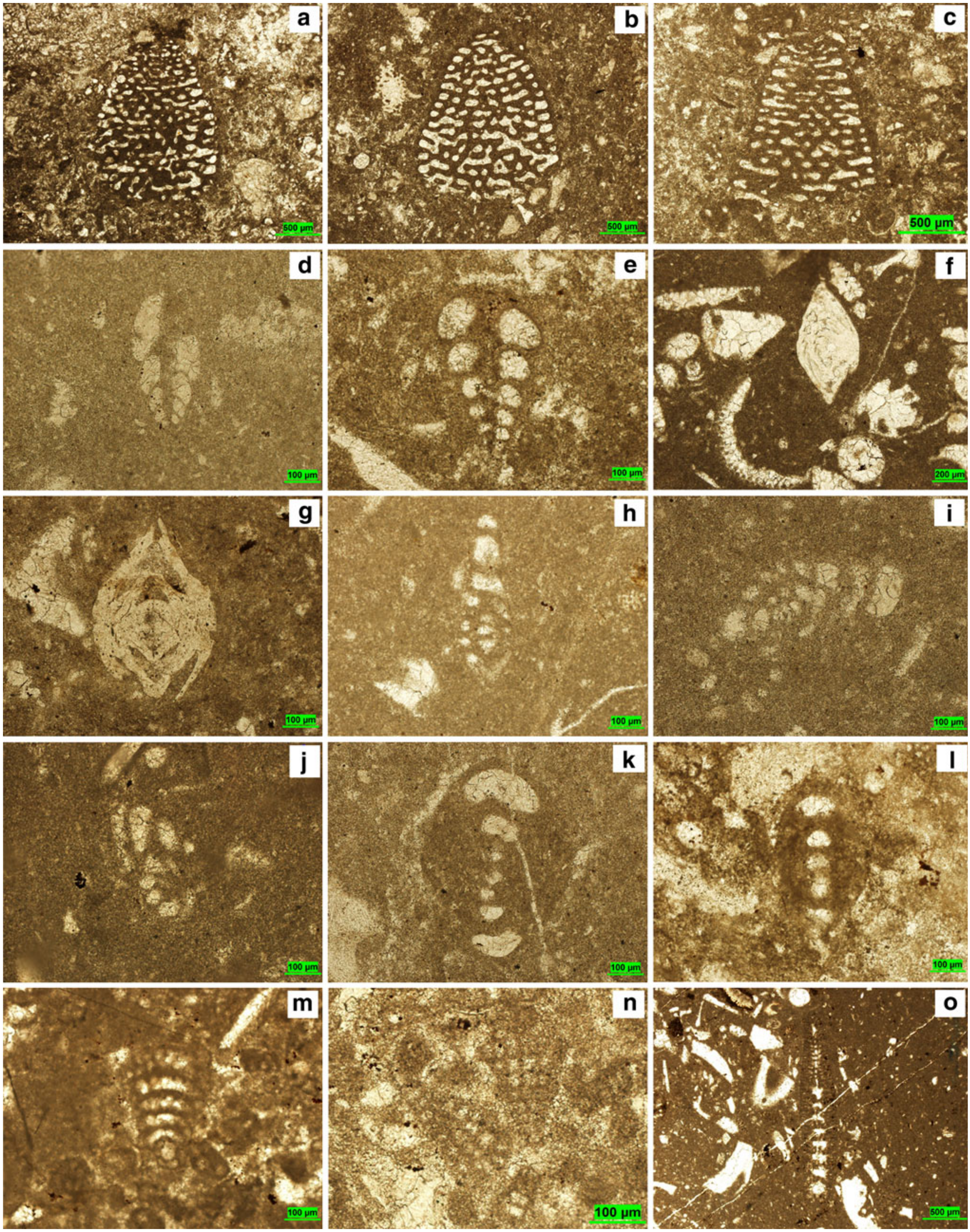
have been observed in the lower parts of the formation, including stromatolites and fenestral fabrics indicative of an intertidal environment. In the upper parts of this formation, the microfacies indicating an open-marine environment with fauna consisting of green algae (dascycladaceans) with additional *Lithocodium* and a variety of benthic foraminifera (Figs. 5 and 6).

The basal boundary of Fahliyan Formation defined as type I sequence boundary, due to subaerial exposure indicated by brecciated dolomites (Adabi et al. 2010). General sea-level rise with flooding of the previously exposed areas allowed the establishment of a regional carbonate platform during the Neocomian. This was followed by progradation of the Fahliyan carbonate platform and finally deposition of the deeper marine Gadvan Formation. The upper boundary of the Fahliyan Formation is traced by retrogradation of deeper marine limestone and marls of the Gadvan Formation (Adabi et al. 2010).

The upper parts of the Fahliyan and Gadvan Formations were a period of important clay supply in the Kuh-e Siah section. This part is distinguished by deposition of deeper microfacies (Figs. 5 and 6). Mud-dominated skeletal limestone is the dominant facies of the carbonate beds in the upper parts of the Fahliyan and Gadvan Formations. The Gadvan Formation is characterized by less diverse faunal assemblage in the mid-ramp setting, dominated by bivalves, echinoderms, and sponge spicules (Figs. 5 and 6). All of this information indicates that the Fahliyan Formation is part of a transgressive megacycle.

Conclusions

1. In the Fars area (Kuh-e Siah) of Zagros Basin, the Fahliyan Formation is generally represented by shallow-water limestone. It overlies the evaporitic sediments of the Hith Formation unconformably and is overlain conformably by dark shale and argillaceous limestone of the Gadvan Formation.
2. In the Fahliyan Formation, four facies belts were recognized from the distal to the proximal part of the platform. These are: open-marine, lagoon, shoal, and tidal flat.
3. In this area, the Fahliyan Formation consists of 25 microfacies in open-marine, lagoon, shoal and tidal flat facies belts. The open-marine facies belt is characterized by predominantly muddy microfacies (mudstone/wackestone). Sponge spicules and echinoid/crinoid remains are the main bioclasts of this facies belt. The shoal facies belt is distinguished by grain-supported texture and composed mainly of intraclasts, ooids, peloids, bioclasts and aggregate grains with good sorting and roundness. The lagoonal sub-environment is characterized by predominantly muddy microfacies (wackestone/packstone) and is particularly rich in benthic foraminifers and calcareous algae. The tidal flat sub-environment is distinguished by strong dissolution processes and abundant vuggy porosity, lamination, presence of silt and sand-sized quartz grains, fenestral fabric, and low-diversity faunal assemblages.
4. The present study indicates that the Fahliyan Formation was deposited on a homoclinal carbonate ramp with a gentle slope.
5. A total of ten genera belonging to different groups of calcareous algae and 16 genera of benthic foraminifera have been recognized from sedimentary units of the Kuh-e Siah section.
6. Based on micropaleontological data, the age of Neocomian–Early Barremian has been determined for the Fahliyan Formation.
7. The abundance of dasycladacean algae and benthic foraminifers in Lower Cretaceous deposits indicate a shallow-water depositional environment (inner to mid-ramp) within the zone of effective light penetration.
8. Based on paleoecological analyses, dasycladacean algae and benthic foraminifers of studied area shows both normal marine and restricted environments.
9. During the Neocomian, a shallow-water platform formed in the Kuh-e Siah area. This platform was flooded and the Fahliyan platform started to grow. The seaward margin of this platform was dominated mainly by grainstone microfacies, and lagoon sub-environment is muddy and algal and benthic foraminifers dominated. Mud-dominated skeletal limestone is the dominant microfacies of the carbonate beds in the upper parts of the Fahliyan and Gadvan Formations, which indicates deeper marine conditions. The Fahliyan and Gadvan time interval was a period of important clay supply in the Kuh-e Siah section.


a
500 µm
b
500 µm
c
500 µm
d
100 µm
e
100 µm
f
200 µm
g
100 µm
h
100 µm
i
100 µm
j
100 µm
k
100 µm
l
100 µm
m
100 µm
n
100 µm
o
500 µm

◀ **Fig. 12** Benthic foraminifers of the Kuh-e Siah section. **a** *Valdanchella* sp., sample RAP.10825, PPL. **b** *Valdanchella* sp., sample RAP.10869, PPL. **c** *Valdanchella* sp., sample RAP.10869, PPL. **d** *Siphovalvulina* sp., sample RAP.10863, PPL. **e** *Siphovalvulina* sp., sample RAP.10871, PPL. **f** *Lenticulina* sp., sample RAP.10816, PPL. **g** *Lenticulina* sp., sample RAP.10867, PPL. **h** *Mayncina* sp., sample RAP.10863, PPL. **i** *Mayncina* sp., sample RAP.10856, PPL. **j** *Mayncina bulgarica*, sample RAP.10853, PPL. **k** *Nautiloculina oolithica,* sample RAP.10863, PPL. **l** *Nautiloculina oolithica,* sample RAP.10869, PPL. **m** *Cuneolina* sp., sample RAP.10874, PPL. **n** *Cuneolina* sp., sample RAP.10875, PPL. **o** *Choffatella* sp., sample RAP.10885, PPL

Acknowledgments This paper is part of a PhD thesis by M.J. at Shahid Beheshti University. This study was supported by the University of Shahid Beheshti and the National Iranian Oil Company-Exploration directorate (NIOC-Exp). We are thankful to Dr. Ali Ghabeishavi, Mr. Mohsen Goodarzi, and Mr. Mohieddin Jafari for their fieldwork assistance in the Zagros Mountains and their informative discussions as well as Mr. Amir Mohammad Jamali and Dr. Ali Kavoosi for their valuable suggestions.

References

Adabi MH (2009) Multistage dolomitization of Upper Jurassic Mozduran Formation, Kopet-Dagh Basin, N.E. Iran. Carb Evap 24:16–32

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

Alavi M (1980) Tectonostratigraphic evolution of the Zagrosides of Iran. Geology 8:144–149 (Correction in: Geology 8:353)

Alavi M (1994) Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. Tectonophysics 229:211–238

Alavi M (2004) Regional stratigraphy of the Zagros fold—thrust belt of Iran and its proforeland evolution. Am J Sci 304:1–20

Alavi M (2007) Structures of the Zagros fold-thrust belt in Iran. Am J Sci 307:1064–1095

Al-Fares AA, Bouman M, Jeans P (1998) A new look at the Middle to Lower Cretaceous stratigraphy, offshore Kuwait. GeoArabia 3:543–560

Bachmann M, Hirsch F (2006) Lower Cretaceous carbonate platform of the eastern Levant (Galilee and the Golan Heights): stratigraphy and second-order sea-level change. Cretaceous Res 27:487–512

Berger S, Kaever J (1992) Dasycladales, an illustrated monograph of a fascinating algal order. Thieme, Stuttgart

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

Booler J, Tucker ME (2002) Distribution and geometry of facies and early diagenesis: the key to accommodation space variation and sequence stratigraphy: Upper Cretaceous Congost carbonate platform, Spanish Pyrenees. Sediment Geol 146:225–247

Bosence DWJ (1991) Coralline algae: mineralization, taxonomy, and paleoecology. In: Riding R (ed) Calcareous algae and stromatolites. Springer, Berlin Heidelberg New York, pp 98–113

Bosence DWJ, Wilson RCL (2003) Carbonate depositional systems. In: Coe AL (ed) The sedimentary record of sea-level change. The Open University and Cambridge University Press, Cambridge, pp 209–233

Bucur II, Săsăran E (2005) Relationship between algae and environment: an Early Cretaceous case study, Trascau Mountains, Romania. Facies 51:274–286

Burchette TP, Wright VP (1992) Carbonate ramp depositional systems. Sediment Geol 79:3–57

Camoin GF, Maurin AF (1988) Rôles des micro-organismes (bactéries, cyanobactéries) dans la genése des "Mud Mounds". Exemples du Turonien des Jebels Biréno et Mrhila (Tunisie). Académie des Sciences, Paris 307:401–407

Carras N, Conrad MA, Radoičić R (2006) *Salpingoporella*, a common genus of Mesozoic Dasycladales (calcareous green algae). Revue de Paléobiol 25:457–517

Christian L (1997) Cretaceous subsurface geology of the Middle East region. GeoArabia 2:239–256

Conrad MA (1977) The Lower Cretaceous calcareous algae in the area surrounding Geneva (Switzerland): biostratigraphy and depositional environment. In: Flügel E (ed) Fossil algae. Springer, Berlin Heidelberg New York, pp 295–300

Davis RB, Bishop CD, Hollis CE, Gaur RS, Haider AA (1997) Architecture of the Minagish oolite reservoir in the Umm Gudair Field, Kuwait, Jurassic/Cretaceous carbonate platform—basin systems: Middle East models conference abstract. GeoArabia 2:476–496

De Castro P (1997) Introduzione allo studio in sezione sottile delle dasicladali fossili. Quad Acad Pontaniana 22:1–261

Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. AAPG Mem 1:108–121

Elrick M, Read JF (1991) Cyclic ramp-to basin carbonate deposits, Lower Mississippian, Wyoming and Montana: a combined field and computer modelling study. J Sediment Petrol 61: 1194–1224

Fakhari M (1994) Khormoj geological quadrangle map, scale 1:250,000, National Iranian Oil Company, no. F-12

Falcon NL (1969) Problems of the relationship between surface structure and deep displacements illustrated by the Zagros Range. In: Kent PE, Satterthwaite GE, Spencer AM (eds) Time and place in orogeny. J Geol Soc Lond Spec Publ 3:9–22

Falcon NL (1974) Southern Iran: Zagros Mountains. In: Spencer A (ed) Mesozoic—Cenozoic Orogenic belts: data for orogenic studies. J Geol Soc Lond Spec Publ 4:199–211

Flügel E (1982) Microfacies analysis of limestones. Springer, Berlin Heidelberg New York

Flügel E (2004) Microfacies of carbonate rocks: analysis, interpretation and application. Springer, Berlin Heidelberg New York

Folk RL (1962) Spectral subdivision of limestone types. In: Ham WE (ed) Classification of carbonate rocks—a symposium. Tulsa, OK, AAPG Mem 1:62–84

Gollestaneh A (1965) A micropaleontological study of the Upper Jurassic and Lower Cretaceous of southern Iran. Unpublished PhD thesis. University College, London

Hosseini SA, Conrad MA (2008) Calcareous algae, foraminifera and sequence stratigraphy of the Fahliyan Formation at Kuh-e-Surmeh (Zagros Basin, SW of Iran). Geologica Croatica 61:215–237

Husinec A, Sokač B (2006) Early Cretaceous benthic associations (foraminifera and calcareous algae) of a shallow tropical-water platform environment (Mljet Island, southern Croatia). Cretaceous Res 27:418–441

Jaffrezo M (1980) Les formations carbonatées des Corbiéres (France) du Dogger à l'Aptien. Micropaléontologie stratigraphique, biozonation, paléoécologie; extension des resultants à la Mésogée. PhD thesis. Etat é Sci Nat, University P et M Curie

Jaffrezo M, Renard M (1979) Eléments en traces de calcaires à dasycladales et charophytes. Bull Centr Rech Elf-Aquitaine Expl-Product Mém 3:639–649

James GA, Wynd JG (1965) Stratigraphic nomenclature of Iranian oil consortium agreement area. AAPG Bull 49:2182–2245

Lasemi Y, Ghomashi M, Amin-Rasouli H, Kheradmand A (2008) The Lower Triassic Sorkh Shale Formation of the Tabas Block, east central Iran: succession of a failed-rift basin at the Paleotethys margin. Carb Evap 23:21–38

Lucia FJ (1999) Carbonate reservoir characteristics. Springer, Berlin Heidelberg New York

Mosadegh H, Parvaneh Nejad Shirazi M (2009) Algal biozonation of Fahliyan Formation (Neocomian) in the Zagros Basin, Iran. European Geoscience Union, Geophysical Research Abstracts, EGU2009-8507, 11:1

Murris RJ (1980) Middle East: stratigraphic evolution and oil habitat. AAPG Bull 64:597–618

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

Parvaneh Nejad Shirazi M (2008) Calcareous algae from the Cretaceous of Zagros Mountains (SW Iran). World Appl Sci J 4:803–807

Purser BH (1973) The Persian Gulf: Holocene carbonates sedimentation and diagenesis in a shallow epicontinental sea. Springer, Berlin Heidelberg New York, 471 pp

Reolid M, Gaillard C, Lathuilière B (2007) Microfacies, microtaphonomic traits and foraminiferal assemblages from Upper Jurassic oolitic—coral limestones: stratigraphic fluctuations in a shallowing-upward sequence (French Jura, Middle Oxfordian). Facies 53:553–574

Riding R (1991) Calcareous algae and stromatolites. Springer, Berlin Heidelberg New York

Riding R (2000) Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. Sedimentology 47:179–214

Roux A (1985) Introduction à l'étude des algues fossiles paléozoiques (de la bactérie à la tectonique des plaques). Bull Centr Rech Elf-Aquitaine Expl-Product 8:465–699

Sadooni FN (1997) Stratigraphy and petroleum prospects of Upper Jurassic carbonates in Iraq. Petrol Geosci 3:233–243

Schmid DU (1996) Marine Mikrobolithe und Mikroinkrustierer aus dem Oberjura. Profil 9:101–251

Sepehr M, Cosgrove JW (2004) Structural framework of the Zagros fold—thrust belt, Iran. Mar Petrol Geol 21:829–843

Setudehnia A (1978) The Mesozoic sequence in southwest Iran and adjacent areas. J Petrol Geol 1:3–42

Tucker ME, Wright VP (1990) Carbonate sedimentology. Blackwell, Oxford, 482 pp

Tucker ME, Calvet F, Hunt D (1993) Sequence stratigraphy of carbonate ramps: systems tracts, models and application to the Muschelkalk carbonate platform of eastern Spain. In: Posamentier HW, Summerhayes CP, Haq BU, Allen GP (eds) Sequence Stratigraphy and facies associations. Special Publication International Associations Sediment 18:397–415

Valet G (1979) Approche paléoécologique du monde des Dasycladales à partir d'écologie des formes actuelles. Bull Centr Rech Elf-Aquitaine Expl-Product 3:859–866

Van Buchem FSP, Razin P, Homewood PW, Oterdoom WH, Philip J (2002) Stratigraphic organization of carbonate ramps and organic-rich intrashelf basins: Natih Formation (Middle Cretaceous) of northern Oman. AAPG Bull 86:21–53

Wells AJ (1965) Lithofacies and geological history of Khami Group sediment in south eastern Iran. Iranian oil operating companies, report no. 1082 (unpublished)

Wilson JL (1975) Carbonate facies in geological history. Springer, Berlin Heidelberg New York

Wray JL (1977) Calcareous algae. Elsevier, Amsterdam, p 185

Wright VP (1986) Facies sequences on a carbonate ramp: the carboniferous limestone of South Wales. Sedimentology 33:221–241

Wynd JG (1965) Biofacies of Iranian oil consortium agreement area. IOOC report no. 1082 (unpublished)

Ziegler MA (2001) Late Permian to Holocene paleofacies evolution of the Arabian Plate and its hydrocarbon occurrences. GeoArabia 6:445–504