Larger foraminiferal biostratigraphy and microfacies analysis from the Ypresian (Ilerdian-Cuisian) limestones in the Sistan Suture Zone (eastern Iran)

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1. Introduction

Larger benthic foraminifera (LBF) from shallow-water carbonates of the Ilerdian-Cuisian sedimentary successions of the Birjand region, Sistan Suture Zone of eastern Iran, are significant biostratigraphic markers. Although biostratigraphic and systematic descriptions of LBF from the western parts of the Tethys are well known (Hottinger, 1960; Drobne, 1977; Hottinger and Drobne, 1980; Schaub, 1981; Less, 1987; Zakrevskaya, 2004; Papazzoni and Zoboli, 2007; Özgen-Erdem et al., 2007; Sirel and Acar, 2008; Drobne et al., 2011; Costa et al., 2013; Papazzoni et al., 2016), the eastern and central parts of the Tethys, particularly Eocene shallow-marine successions in India, Pakistan, Oman, and China, still lack extensive data regarding the shallow benthic zone (SBZ) as a correlation of the eastern and western Tethyan realms (Zhang et al., 2013; Ahmad et al., 2015; Ismail-Lattrache et al., 2015; Özcan et al., 2015, 2016). The most comprehensive studies of LBF of the Eocene shallow-water sections of Iran were conducted by Rahaghi (1978, 1980, 1983) as well as Rahaghi and Schaub (1976). Aside from the study of Hottinger (2007) (Jahrum Formation, Shiraz area, Iran), only a few studies have been deeply carried out on LBF (such as alveolinids and nummulitids) with more precise stratigraphic records (Hadi et al., 2015, 2016b; Mosaddegh et al., 2017). Investigations of LBF major groups (alveolinids, nummulitids, and orthophragminids) suggest 20 shallow water benthic foraminiferal biozones (SBZ1–20) for Paleocene-Eocene Tethys (Serra-Kiel et al., 1998) and the aforementioned zonation has been extensively utilized in more than 400 articles published so far. Research performed on Eocene LBF in Iran (western-central Tethys) would provide significant data for a fundamental understanding of the relationship between the LBF and migration pathways. In addition, LBF was properly used as an indispensable tool for reconstructing...
paleoenvironments in shallow carbonate platform sequences during Eocene time, based on the main groups of alveolinids, nummulitids, and orthophragminids. The Eocene paleoenvironmental condition was accurately interpreted in LBF studies by Cosović et al. (2004), Bassi (2005), Beavington-Penney et al. (2005), Rasser et al. (2005), Özgen-Erdem et al. (2005), Scheibner and Speijer (2008), Zamagni et al. (2008), Afzal et al. (2011), Bassi et al. (2013), Hadi et al. (2016a), and Sarkar (2017). The LBF evolution was controlled by cycles of gradual changes suggested by a global community maturation (GCM) cycle (for more details see Hottinger, 2001; Scheibner and Speijer, 2008). The highest diversification of LBF with the full recovery of K-strategy was discriminated within phase 3 of the GCM cycle in the late early Eocene–middle Eocene (Hottinger, 1997, 1998, 2001). In other words, the climax of the GCM cycle during this interval time can be indicative of the effect of environmental factors on evolutionary trends of LBF. Therefore, the variation in the LBF assemblages, especially during the Eocene, represents a synchronicity in relation with environmental conditions of varied carbonate platform settings. The main goals of this paper are as follows: 1) determination and presence of the LBF assemblages of Ilerdian–Cuisian carbonate successions in eastern Iran (Birjand area) and their comparison with the SBZ scheme suggested by Serra-Kiel et al. (1998); 2) description and interpretation of the microfacies, supported by LBF communities and paleoenvironmental reconstruction during Ilerdian–Cuisian times, although these microfacies are illustrated in a local area and, in fact, similar microfacies were described from the western Tethys basin.

2. Geological setting and stratigraphy

Iran has been divided into several tectonostratigraphic units (Figure 1a), each of which is characterized by a relatively unique record of stratigraphy, magmatic activities, metamorphism, orogenetic events, tectonics, and overall geological style (Eftekhar-Nezhad, 1980; Alavi, 1993; Aghanabati, 2004), and it is part of the largest mountain belt of the Alpine-Himalayan system (Figure 1b). In a more amplified separation, eastern Iran can be divided into two parts, the Lut Block and the Sistan Suture Zone (Figure 1c) (also called the East Iranian Ranges (Berberian, 1977; Alavi, 1991)). The Sistan Suture Zone in eastern Iran extends as a N-S trending belt over more than 700 km along the border area between the Lut block (Iran) and the Afghan block (Afghanistan), which is a result of eastward-directed subduction of a Tethyan ocean basin beneath the Afghan block (Bröcker et al., 2013).

In the present study, two shallow-marine successions of the Eocene stratigraphic sections (Robiyat and Chenesht) located in the northeast margin of the Lut block (approximately within the Sistan Suture Zone) and SE of the city of Birjand have been studied (Figure 1c). The lithostratigraphic units in the Sistan ocean zone are substantially composed of Cretaceous ophiolites and ophiolitic mélanges, followed by deposition of upper Cretaceous–Eocene flysch (Babazadeh and De Wever, 2004; Fotoohi-Rad et al., 2009). As discussed by Tirrul et al. (1983), the Sistan Suture Zone consists of flysch deposits (Maastrichtian to Eocene) considered to represent a forearc setting. Thus, the current study in the Bagheran mountains (southeastern Birjand) focuses on the successions of the Eocene shallow-water limestone that occurs within volcanic and flysch deposits in the aforesaid area. The previous studies in regard to the above-mentioned region generally concerned regional geology, tectonics, and economical geology, while the biostratigraphy of Eocene sedimentary succession based on LBF has not been studied in detail so far and is reported for the first time in this study.

3. Description of sections

Two stratigraphic sections with outcropping early Eocene limestone (Robiyat and Chenesht) were selected for the present study due to their foraminiferal richness. These outcrops are represented by LBF assemblages such as alveolinids, nummulitids, and orthophragminids.

Robiyat section: The Robiyat is a 12-m-thick section of limestone located approximately 3 km southeast of Robiyat village, which is about 30 km southeast of the city of Birjand. The section is situated in sheet 7855 (32°42′03″N, 59°18′44″E) (Figure 2). The limestone range markedly varies between dark gray and brown in color; moreover, distinct beds are often less than 60 cm thick.

Chenesht section: The Chenesht section is about 30 m thick, located about 1 km northwest of Chenesht village, which is 50 km southeast of the city of Birjand. It is situated in sheet 7855 (32°38′22″N, 59°23′54″E) (Figure 2). The lithological characteristics of the unit are similar to those of the Robiyat section.

4. Materials and methods

Eocene LBF was sampled from two sections in the Birjand region, Robiyat and Chenesht, from which a total of 47 rock samples and almost one sample per meter were collected. Thus, we prepared about 200 thin sections (4 thin sections per sample) obtained from these samples (Chenesht: CH, CHC, CP; Robiyat: R, RP). Likewise, we studied directly some isolated specimens of Nummulites and Assilina in their equatorial plane from limestones. The thin sections have dimensions of 2.5 × 7.5 cm and 6 × 10 cm and were also digitally photographed under transmitted-light (Olympus BX51) and binocular microscopes. Determinations of the Eocene LBF are mainly based on taxonomic descriptions given by Hottinger (1960, 1974, 2014), Drobne (1977), Hottinger and Drobne (1980), Schaub (1981), Less (1987),
Figure 1. (a) Modified sketch map of Iran showing the major tectonic units (Lensch et al., 1984) and the inner microcontinental nucleus (Yazd, Tabas, and Lut blocks) (Şengör et al., 1988). (b) Tethys mountain ranges (simplified from Okay, 1989 and Özcan et al., 2015) and location of studied region in the Sistan Suture Zone (eastern Iran). (c) Simplified geological map of the Sistan Suture Zone (modified after Tirrul et al., 1983).
Zhang (1988), Özcan et al. (2007), and Sirel and Acar (2008). The SBZs were determined according to the species ranges proposed by Serra-Kiel et al. (1998) (Figure 3).

The authors have followed Dunham (1962) and Embry and Klovan (1972) in describing determinations of major microfacies types (MFTs). Semiquantitative data on the different component distributions were estimated from thin sections using comparison charts (Flügel, 2010). On the other hand, the abundance of main allochems in the microfacies was expressed based on the texture, fossil assemblages, and grain types (biogenic or abiogenic). Relative differences were used in the diameter (D)/thickness (T) and T/D measurements of A-forms including nummulitid and orthophragmimid tests of axial sections, respectively, along with their biofabric types for paleoenvironmental interpretation. These data were analyzed based on photographs that were taken either from field observations or thin sections in randomly selected areas, and the ranges of D and T values were determined from 18 A-forms of Nummulites (N. cf. distans) and 9 A-forms of orthophragmimids in ideal axial and nearly axial sections of MFT3–MFT4 and MFT5, respectively. The ratio of A- to B-forms of Nummulites was determined from bedding surfaces (4 cm²) consistent with MFT3 and MFT4. All samples and thin sections are deposited in the collection of M. Hadi at Ferdowsi University of Mashhad (FUM), Iran.

5. Larger benthic foraminifera (LBF) assemblages

Based on our studies, several assemblages of LBF have been distinguished to age the Ilerdian-Cuisian, corresponding to SBZ8 and SBZ10–12 after Serra-Kiel et al. (1998). The LBF assemblages contain species widely reported from the entire Tethys realm, particularly in the western part. The LBF zonation presented in Figures 4 and 5 will be described as follows.

5.1. SBZ8

The base of SBZ8 is defined by the first appearance of A. decipiens (Schwager) (Figure 6a), A. ex gr. guidonis (Drobné) (Figure 6b) accompanied by A. elliptica nuttalli (Davies) (Figure 6c), A. cf. citrea (Drobné) (Figure 6d), and N. cf. atacicus (Leymerie) (Figures 6e–6i). LBF assemblages such as A. decipiens, A. ex gr. guidonis, A. cf. citrea, A. elliptica nuttalli (Davies), N. cf. atacicus, Assilina sublaminosa (Gill) (Figure 6j), A. aff. leymerie (d'Archiac and Haime) (Figure 6k), Neorotalia sp., Lockartia cf. conditi (Nuttall.) (Figure 6l) Operotorbitolites cf. douvillei (Nuttall) (Figure 6m), O. aff. gracilis (Lehmann) (Figure 6n), O. cf. ibericus (Nuttall) (Figure 6o), Orbitolites cf.
minimus (Binggao) (Figure 6p), Orbitolites sp. (Figure 6q), Coskinolina sistanensis (Schlagintweit and Hadi) (Figure 6r), Periloculina sp. (Figure 6s), Idalina sp. (Figure 6t), and Gypsina sp. can also be referred to SBZ8. The upper boundary of SBZ8 is marked with the last occurrence of A. cf. citrea; however, it is not so reliable. On the other hand, the lack of more index zonal markers with good preservation of LBF does not allow us to confidently determine the upper boundary of this interval.

5.2. SBZ10–SBZ11
SBZ10 is marked by the first appearance of A. cf. oblonga (d’Orbigny) (Figure 7a), A. cf. minuta (Checchia-Rispoli) (Figure 7b), A. cf. rugosa (Hottinger) (Figure 7c), A. cf. distefanoi (Checchia-Rispoli) (Figure 7d), and A. elliptica nuttalli (Davies), along with Sphaerogypsina globula (Reuss) (Figures 7e and 7f), Lockartia cf. haimei (Davies), and Haymanella sp. In addition to the low diversity of LBF, the generally poorly oriented sections of alveolinids as well as nummulitids do not provide more zonal marker species for reliably determining the SBZ10 zone. Nevertheless, the lower boundary of this interval is represented by the first occurrence of A. cf. oblonga and A. cf. minuta, while a little later the upper boundary is recognized by the first appearance of A. decastroi. However, the cooccurrence of A. distefanoi along with A. decastroi and A. cremae was attributed to SBZ11 in northern Italy (see Papazzoni et al., 2017).

SBZ11 is characterized by the presence of Alveolina elliptica nuttalli, A. cf. decastroi (Scotto Di Carlo) (Figure 7g), A. aff. cremae (Checchia-Rispoli) (Figures 7h and 7i), and nummulitid taxa such as N. cf. tauricus (De la Harpe) (Figures 7j and 7k), N. pratti (d’Archia and Haime) (Figures 7l and 7m), N. cf. distans (Deshayes) (Figure 8a), and A. placenta (Deshayes) (Figures 8b–8d) associated with other lamellar-perforate LBF like Operculina sp. (Figure 8e), Asterigerina sp. (Figure 8f), Sphaerogypsina sp. (Figure 8g), Gyroidinella magna (Le Calvez) (Figure 8h), and Neorotalia cf. alicantina (Colom) (Figure 8i). Alveolina cf. decastroi and simultaneously the appearance of three index Nummulites, including N. tauricus, N. pratti, and N. cf. distans, are recorded for the first time from the central Tethys region, approximately corresponding to the SBZ11 zone (middle Cuisian in Serra-Kiel et al., 1998). N. tauricus was reported along with some nummulitid taxa such as Nummulites campesinus, N. partschi, N. rotularius, and Assilina cf. major for the late Cuisian age from the Birjand area by Rahaghi and Schaub (1976), while Zakrevskaya (2004, 2005) showed the simultaneous presence of three species, N. tauricus, N. pratti, and N. distans, in the late Ypresian (Cuisian) corresponding to the SBZ11–SBZ12 zones from numerous sections in Russia.

5.3. SBZ12
SBZ12 is primarily dominated by alveolinid and nummulitid (Nummulites and Assilina) assemblages.
Figure 4. Stratigraphic distribution of larger foraminiferal species in the Chenesht section, eastern Iran.

Figure 5. Stratigraphic distribution of larger foraminiferal species in the Robiyat section, eastern Iran.
The alveolinid assemblage of the lower boundary of the interval is recognized by the first occurrence of *A. frumentiformis* (Schwager) (Figure 8j) as well as *A. aff. palermitana* (Hottinger) (Figure 8k). The lower boundary is subsequently defined with more reinforced index markers by the first appearance of *Nummulites polygyratus* (Deshayes) (Figure 8l), *N. cf. campesinus* (Schwager) (Figure 8m), *N. cf. praelorioli* (Herb and Schaub) (Figure 8n), *N. aff. britannicus* (Hottinger and Schaub) (Figure 8o), *N. aff. manfredi* (Schaub) (Figure 8p), and *Assilina cf. major* (Heim) (Figures 8q–8s) together with *Asterocyclina cf. Schweighauseri* (Less) (Figure 8t), *Discocyclina archiaci cf. staroseliensis* (Less) (Figure 8u), and *D. cf. archiaci bartholomei* (Schlumberger) (Figure 8v). Therefore, the local assemblage is precisely in accordance with the SBZ12 of Serra-Kiel et al. (1998); furthermore, it has not thus far been recorded from the stratigraphic levels of Iran. However, only a few index nummulitids of SBZ12,
Figure 7. LBF of the early-middle Cuisian (SBZ10–11): (a) Alveolina cf. oblonga, sample CH6; (b) A. cf. minuta, sample CH6; (c) A. cf. rugosa, sample CH6; (d) A. cf. distefani, sample CH7; (e–f) Sphaerogypsina globula (Reuss), samples CH20 and R9; (g) A. cf. decastroi, sample CH11; sample R1; (h–i) A. aff. cremae, sample CH11, Chenesht; (j–k) Nummulites tauricus (De la Harpe), samples RP 3/1 and 3/2; (l–m) Nummulites pratti (d’Archia and Haime), samples RP 2/2 and RP 2/8.
Figure 8. LBF of the middle-late Cuisian (SBZ11–12): (a) *N. cf. distans*, sample CP1/1; (b–d) *Assilina placenta* (Deshayes), samples CP1/2 and CH18; (e) *Opecollina* sp., sample R9; (f) *Asterigerina* sp., sample R9; (g) *Sphaerogypsina* sp., sample CH18; (h) *Gyroidinella magna* (Le Calvez), sample CH19; (i) *Neorotalia cf. alicantina*, sample CH17; (j) *A. frumentiformis*, sample CH12; (k) *A. aff. palermitana*, sample CH13; (l) *N. polygyratus* (Deshayes), sample CP1/5; (m) *N. cf. campesinus*, sample CP1/6; (n) *N. cf. praelorii*, sample RP3/4; (o) *N. aff. britannicus*, sample RP2/7; (p) *N. aff. manfredi*, sample RP2/6; (q–s) *Assilina* cf. *major*, samples CH23 and PR3/5; (t) *Asterocyclina cf. schweighauseri*, sample CH23; (u) *Discocyclina archiacci* cf. *staroselensis*, sample CH22; (v) *D. cf. archiacci bartholomei*, sample CH 21.
i.e. *N. compesinus*, *N. manfredi*, and *A. major*, were reported from the Late Cuisian of eastern Iran by Rahaghi and Schaub (1976). Also, the occurrence of the above two orthogragminid taxa coexisting with *Assilina* and *Nummulites* has been newly identified from SBZ12 in Iran as the central Tethys region or further east. In addition, the above-mentioned species are widely known in northern Tethys platforms in Europe and the eastern Mediterranean region (Less, 1987, 1998; Özcan et al., 2007; Zakrevskaya et al., 2011).

6. Description and interpretation of major microfacies types (MFTs)

Five microfacies types were identified: MFT1 (*Alveolina-Opertorbitolites* packstone (locally grainstone)), MFT2 (nummulitids-*Alveolina* rudstone), MFT3 (*Nummulites* rudstone), MFT4 (*Assilina-Nummulites* rudstone), and MFT5 (orthogragminid-nummulitid pack-rudstone) (Figures 9 and 10a–10d). Assemblages of LBF as major elements of biogenic components are present with different characteristics in all microfacies. They are represented by abundant larger porcellaneous foraminifera such as *Alveolina*, *Orbitolites*, and *Opertorbitolites* in association with agglutinated conical foraminifera (*Coskinolina*), and larger hyaline-lamelar foraminifera represented by nummulitids (*Nummulites*, *Assilina*, and *Operculina*) and orthogragminids (*Discocyclina* and *Asterocyclina*). Subordinate components of other benthic foraminifera were dominated by smaller rotaliid foraminifera (e.g., *Neorotalia* and *Lockhartia*); moreover, there were agglutinated *Textularia* and small miliolids along with larger miliolids (e.g., *Idalina*, *Periloculina*) and orbitoidal and encrusting foraminifera (*acervulinids*).

6.1. MFT1: *Alveolina-Opertorbitolites* packstone (locally grainstone)

6.1.1. Description

This microfacies (Figures 9) occurs only in the basal part of the Chenesht section with thickness of about 5 m. The microfacies is characterized by a high abundance of *Alveolina* (35%–40%) (A-form dominance; *A. decipiens*, *A. ex gr. guidonis*, *A. elliptica nuttalli*, *A. cf. citrea*) with globular to slightly elongated forms and diameters of less than 5 mm, *Opertorbitolites* (e.g., *O. douvileii*, *O. cf. ibericus*), and *Orbitolites* (e.g., *Orbitolites* sp. cf. *O. minimus*) (15%–20%) as well as conical foraminifera (*Coskinolina*) in a packstone with rare grainstone matrix (Figures 11a–11d). Small benthic miliolids such as *Quinqueloculina*, *Triiloculina*, *Biloculina*, small rotaliids (*Neorotalia* sp.), *Periloculina*, encrusting foraminifera (*Gypsina* sp.), echinoids, and green algae, as well as fragments of bivalves, are also present. Detrital quartz grains are present in varying amounts with fine to medium sizes.

6.1.2. Interpretation

This MFT with a predominance of larger porcellaneous tests such as *Alveolina* and orbitolitids is restricted to the proximal inner ramp setting, as the LBF index species are indicators of SBZ8 (middle Ilerdian) (Table). Drobne et al. (2011) noted that the alveolinids are very compatible with a broad tolerance of salinity and temperature fluctuation. Thus, they can have a widespread distribution in various parts of shallow-water carbonate platforms. As reported by Langer and Hottinger (2000), living forms such as *Borelis* sp. and *Alveolinella quoyi* proliferated to depths of less than 35 m, whereas Yordanova and Hohenegger (2002) noted that recent alveolinids occur in a wide range of habitats, from deep lagoons to fore-reef settings, down to a depth of 60 m. Nevertheless, some authors (e.g., Severin and Lips, 1989; Langer and Hottinger, 2000; Beavington-Penney et al., 2006; Zamagni et al., 2008) also stated that their distributions can be influenced by the substrate type. In this MFT the assemblages of *Alveolina* species with A-form dominated by globular to slightly elongated test morphologies, without evidence of high abrasion on outer walls of tests in a packstone with rare grainstone matrix, may suggest moderate-high-energy water conditions near the fair weather wave base (FWWB). As in this MFT, the abundance of quartz grains under the effect of high hydrodynamic energy (waves and currents) could have had a significant impact on outer walls of the alveolinids tests. However, the morphological features of alveolinid tests show a rare abraded and high adaptation in response to environmental changes in comparison with other groups (especially nummulitids). In other words, this adaptation may be similar to those noted in *Alveolinella quoyi* with this species preferring to dwell on firm and hard substrates, within tiny grooves or holes, which provide shelter from extreme hydrodynamic forces (see Hohenegger et al., 1999; Hohenegger, 2009). Likewise, the abundance of larger porcellaneous foraminifera (orbitolids and alveolinids) associated with miliolids can be known as epiphytes that lived within the vegetated substrates. They were mainly considered the common epiphytes during the Eocene (Beavington-Penney et al., 2004; Tomáš et al., 2016; Tomassetti et al., 2016). Today, living sortit foraminifera of the genus *Orbitolites* and smaller miliolids, and recent alveolinid fauna, are observed in sea-grass areas and/or sandy adjacent substrates (e.g., Brasier, 1975; Eva, 1980; Hottinger, 1997; Beavington-Penney and Racey, 2004). It seems that vegetated substrates with individual plants can be places of shelter for epiphytes against such hydrodynamic forces, so this interpretation might be a good explanation for low degrees of abrasion on outer walls of the alveolinid tests. According to all the above-mentioned interpretations, this MFT is representative of a deposition in the open waters of the inner ramp setting.
Figure 9. Stratigraphic columns of the Robiyat and Chenesht sections with distribution of the microfacies (MFTs).

- **Microfacies types (MFT)**
  - **MFT1**: *Alveolina-Opertorbitolites* packstone (locally grainstone)
  - **MFT2**: *Nummulites-Alveolina* packstone-rudstone
  - **MFT3**: *Nummulites* rudstone
  - **MFT4**: *Assilina-Nummulites* rudstone
  - **MFT5**: Orthophragminid-Nummulitid packstone-rudstone
Figure 10. Field photographs of the Eocene successions (Chenesht and Robiyat sections) of eastern Iran. (a) Field aspect of the Chenesht section (b) Distribution of MFTs along the Chenesht section. (c–d) Robiyat section, where limestone sediments dominate the Eocene part of the section and highlights show the limestone beds rich in LBF.
Figure 11. Description of the Ilerdian-Cuisian microfacies types (MFTs) including dominant components, subordinate components, texture. (a-d) *Alveolina-Opertorbitolites* packstone (locally grainstone), proximal inner ramp, middle Ilerdian. (e-f) Nummulitid-*Alveolina* rudstone, proximal inner ramp, late Ilerdian-early Cuisian.
Figure 11 (Continued). (g–j) *Nummulites* rudstone, middle-distal inner ramp, middle-late Cuisian. (k–l) *Assilina-Nummulites* rudstone, distal inner ramp to proximal middle ramp, late Cuisian.

**MFT3**: *Nummulites* rudstone  
**Dominant Components**: *Nummulites* (Num), *Assilina* (As)  
**Subordinate Components**: *Alveolina*, *Asterigerina*, *Sphaerogypsina*, bivalves, bryozoans, echinoids, calcareous worm tubes (W)  
**Texture**: Rudstone with packstone/grainstone matrix  
**Sample number & sample position**: CH14 (g&j), CH15 (h) (Chenesht section)- R3 (i) (Robiyat section)

**MFT 4**: *Assilina-Nummulites* rudstone  
**Dominant Components**: *Assilina* (As), *Nummulites* (Num)  
**Subordinate Components**: Orthophragminids (Or), *Alveolina*, *Operculina*, *Sphaerogypsina*, rotaliids, echinoids, bivalves, calcareous worm tubes  
**Texture**: Rudstones with packstone and locally grainstone matrix  
**Sample number & sample position**: CH18 (k), CH19 (l) (Chenesht section)
with dominance of alveolinid tests that can be somewhat indicative of a moderate-high-energy environment. Additionally, the accompanying occurrences of other LBF such as orbitolitids (Opertorbitolites, Orbitolites), miliolids, and conical foraminifera together with Alveolina are situated in the shallowest deposits of the proximal inner ramp setting within the euphotic zone. Furthermore, it is roughly comparable to the Alveolina-Orbitolites microfacies of carbonate successions from France (Minerve section) described by Rasser et al. (2005) and Scheibner et al. (2007) as the shallowest (inner lagoonal) part of a carbonate ramp. In addition, the presence of fine- to medium-grained quartz as well as occasional occurrences of grainstone matrix may represent a higher water energy event, probably influenced by tidal currents or waves.

**MFT5: Orthophragminid-nummulitid packstone-rudstone**

**Dominant Components:** Orthophragminids, Nummulites, Assilina, coralline red algae (Cr)

**Subordinate Components:** Operculina, Sphaerogypsina (S), Alveolina, encrusting forams, smaller benthic foraminifera (textulariids, rotaliids and miliolids), bivalves

**Texture:** Packstones and rudstones with wackestone/packstone matrix

**Sample number & sample position:** CH21 (m-n), CH23 (o&q), (Chenesht section) - R9 (p) & (Robiyat section)

**Figure 11** (Continued). (m–q) Orthophragminid-nummulitid packstone-rudstone, proximal middle ramp, late Cuisian.
Table. Summary of the microfacies types for the Chenesht and Robiyat sections.

<table>
<thead>
<tr>
<th>Number</th>
<th>MFT</th>
<th>Age</th>
<th>Main components</th>
<th>Occurrence</th>
<th>Microenvironments / Current types / Test morphology of index LBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Alveolina-Opertorbitolites</em> packstone (locally grainstone)</td>
<td>Middle Ilerdian</td>
<td><em>Alveolina, Orbitolites, Opertorbitolites</em>, conical forams, small and large miliolids</td>
<td>Chenesht</td>
<td>Proximal inner ramp / Waves and currents with moderate energy / Globular to elongate forms, without any evidence of abrasion on outer walls</td>
</tr>
<tr>
<td>2</td>
<td>Nummulitid-<em>Alveolina</em> rudstone</td>
<td>Late Ilerdian-early Cuisian</td>
<td><em>Alveolina, Nummulites, Assilina</em></td>
<td>Chenesht, Robiyat</td>
<td>Proximal inner ramp with slightly deeper depth range than MFT1 / Wave and currents with moderate energy / Robust forms with intact (in situ?) tests</td>
</tr>
<tr>
<td>3</td>
<td><em>Nummulites</em> floatstone</td>
<td>Middle-late Cuisian</td>
<td><em>Nummulites, Assilina</em></td>
<td>Chenesht, Robiyat</td>
<td>Distal inner ramp / Waves with high energy / Small and robust forms with thick walls</td>
</tr>
<tr>
<td>4</td>
<td><em>Assilina-Nummulites</em> rudstone</td>
<td>Late Cuisian</td>
<td><em>Assilina, Nummulites</em></td>
<td>Chenesht, Robiyat</td>
<td>Distal inner ramp to proximal middle ramp / Currents and waves with high energy / Robust and ovate forms</td>
</tr>
<tr>
<td>5</td>
<td>Orthophragminid-nummulitid pack-rudstone</td>
<td>Late Cuisian</td>
<td>Orthophragminids, <em>Nummulites, Assilina</em>, coralline red algae</td>
<td>Chenesht, Robiyat</td>
<td>Proximal middle ramp / Currents (storms?) / Inflated lenticular and sometimes flattened forms with well-developed crystalline cones</td>
</tr>
</tbody>
</table>
**6.2. MFT2: nummulitids-Alveolina rudstone**

**6.2.1. Description**

This MFT (Figure 9) is 11.5 m thick and is present in the Chenesht section. The microfacies with predominance of small nummulitids (30%-35%) (Nummulites) and Assilina, i.e. N. cf. atacicus, A. sublaminosa, N. tauricus, N. pratti, and N. cf. distans, is associated with Alveolina (20%) (e.g., A. cf. minuta, A. elliptica nuttalli, A. cf. decastroi) (Figures 11e and 11f). Subordinate components are encrusting foraminifera (acervulinids), orthophragminids, conical foraminifera miliolids, orbitolitids, small tests of rotalidids (undetermined), green algae, echinoids, and quartz grains occurring in wackestone to packstone and occasionally in grainstone matrix (Figures 11e and 11f).

**6.2.2. Interpretation**

This MFT is restricted to the proximal inner ramp setting from SBZ2 to SBZ11 (middle Ilerdian-middle Cuisian) with slightly deeper depth range than the former microfacies (MFT1) (Table). On the other hand, it is somewhat similar to previous microfacies on the basis of both texture and biotic components, but the appearance of Assilina, Nummulites, and orthophragminids (Discocyclina) is indicative of an increase in water depth. This MFT constitutes a transitional microfacies between the shallower Alveolina-Orbitolites microfacies and the deeper Nummulites rudstone microfacies. Similarly, it was described by Beavington-Penney et al. (2006) from the Eocene in Oman with assemblages dominated by Alveolina, Nummulites, and Assilina found in an inner ramp setting. Additionally, the locally abundant quartz grains in this MFT are less than in the adjacent microfacies (MFT1), which could be related to a decrease in hydrodynamic energy (such as tidal currents and waves) with water depth.

**6.3. MFT3: Nummulites rudstone**

**6.3.1. Description**

The middle parts of the two studied sections, with a thickness of 4.5 m in Chenesht and 3.5 m in Robiyat, are characterized by this microfacies (Figure 9). MFT3 is composed of a diverse community of nummulitids (65%-70%), largely Nummulites (e.g., N. pratti, N. cf. distans), that it is generally dominated by A-forms (the A- to B-form ratio varies between 20:1 and 30:1), associated with Assilina (e.g., A. cf. major); Nummulites tests have dominant lenticular, robust shapes (average A-form D/T ratio 1.85) strongly abraded on the sides of outer walls in a packstone/locally grainstone matrix with scarce quartz grain content (Figures 11g-11j). Other benthic foraminifera are represented by rotalidids (e.g., Lokhartia cf. hunti) and common Alveolina, Asterigerina, and Sphaerogypsina. Additionally, calcareous worm tubes, echinoids, scarce bryozaos, and bivalve fragments are present. Also observed are biofabrics such as “edgewise contact imbrication” of nummulitid tests.

**6.3.2. Interpretation**

This MFT is more represented by a high-energy water condition than the previous microfacies (MFT2). Also, many authors (e.g., Racey, 2001; Beavington-Penney and Racey, 2004; Beavington-Penney et al., 2006) have stated that small and lenticular A-forms of Nummulites tests occur more in shallower inner shelf/ramp/platform settings. However, the presence of rare B-form among an A-form-dominated assemblage (the A- to B-form ratio varies between 20:1 and 30:1) may be the influence of water depth, where the environmental condition was tolerable for reproduction. The appearance of B-forms within natural populations of nummulitid A-forms accumulations can be the result of increasing water depth in comparison with the preceding microfacies (MFT2). Studies of living and ancient LBF showed that B-forms are rare or even absent in the shallower water, while they become present in great abundance in deeper waters (<100 m) (e.g., Hottinger, 1977; Leutenegger, 1977; Beavington-Penney et al., 2005). In addition, the distribution of LBF with the first occurrence of the genus “Operculina” along with dominance of small and robust Nummulites tests can be indicative of an increasing water depth in this microfacies.

**6.4. MFT4: Assilina-Nummulites rudstone**

**6.4.1. Description**

This MFT (Figure 9) occurs in the upper part of the studied sections and possesses a thickness of about 5.5 m and 3 m in Chenesht and Robiyat, respectively. The microfacies is distinguished by high diversity and abundance of both A- and B-forms of Nummulites (e.g., N. cf. distans, N. cf. praerioioli, N. polygyratus) and Assilina (e.g., A. cf. major) specimens (up to 75%). Other bioclasts are LBF such as Alveolina, Discocyclina, Operculina, Sphaerogypsina, and rotalidids (e.g., Neorotalia alicantina, Lokhartia cf. conditi) associated with fragments of echinoids, bivalves (mainly oysters), and rare quartz grains with calcareous worm tubes that are dispersed in a packstone and locally grainstone matrix (Figures 11k and 11l). Bioclasts are highly abraded; moreover, A-form tests of Nummulites are dominated by robust, ovate shapes (average D/T ratio 1.88). Also, in this
MFT, the biofabrics of nummulitid tests are indicated by the presence of chaotic stacking and linear accumulation.

6.4.2. Interpretation
This MFT, dominated by nummulitid assemblages, indicates distal inner ramp to proximal middle ramp settings of SBZ12 (late Cuisian) (Table). It substantially formed in proximal middle ramp settings, indicated by the abundance of broken tests of LBF, including fragments of the robust and ovate tests of Nummulites (average A-form D/T ratio 1.88) as well as Assilina within a packstone and locally grainstone matrix. The nummulitid assemblages are dominated by broken A-forms together with intact B-forms (the A- to B-form ratio varies between 15:1 and 20:1), combined with wave- and current-produced biofabrics such as chaotic stacking and linear accumulation, suggesting deposition in a high-energy area influenced by currents and waves, possibly close to the FWWB. The cooccurrence of rare larger porcellaneous foraminifera, i.e. Alveolina and Orbitolites, can be the result of downslope transport and deposition in a distal inner ramp to proximal middle ramp area. On the other hand, the orthophragminids (mainly Discocyclina) with common genera such as Assilina, Nummulites, and Operculina are strong evidence of an increase in water depth.

6.5. MFT5: orthophragminid-nummulitid packstone-rudstone

6.5.1. Description
This MFT (Figure 9) occurs in the uppermost samples of the Chenesht and Robiyat sections with a thickness of about 3.5 m and 5.5 m, respectively. This so-called microfacies is characterized by the occurrence of orthophragminid assemblages (30%–35%), which are represented by Discocyclina (e.g., D. archiace cf. bartholomei, Discocyclina archiace cf. staroseliensis), Asterocyclus (e.g., A. cf. schweighauseri), and some species of Nummulites (20%–35%), i.e. N. pratti, N. cf. distans, and N. polygyratus, and subordinates like Alveolina, Operculina, Assilina (e.g., A. cf. major), Sphaerogypsina, Textularia, rotalids, and miliolids within a wackestone/packstone matrix (Figures 11m–11q). Other bioclastic components are fragments of echinoids, bivalves related to the presence of coralline red algae (e.g., Sporolithon sp.), and encrusting foraminifera (acervulinids) (Figure 11q). In the assemblages of the current study, the tests of orthophragminids and nummulitids are sometimes fragmented and abraded; moreover, the LBF is locally encrusted by thin coralline crusts. Crystalline cone structures are also well developed on the test surfaces with robust-inflated lenticular and sometimes flattened forms (T/D ratio between 0.3 and 0.6) of orthophragminids.

6.5.2. Interpretation
In this MFT, the distribution of LBF is limited to below the FWWB and above the storm wave based in the proximal middle ramp setting, as it has been developed in the SBZ12 biozone (Table). This MFT has similarities with the Assilina-Nummulites rudstone microfacies (MFT4) within the deposits of approximately the same area in deeper waters. However, they differ in the deepening trend for the following reasons: (1) the prevalence of LBF tests with less fragmentation/abrasion, (2) the appearance of tropical deep-water encrusting nongeniculate coralline red algae of the genus Sporolithon and rhodolith fragments along with encrusting foraminifera (acervulinids), and (3) the occurrence of inflated, lenticular, and sometimes flattened Discocyclina tests with well-developed crystalline cones. All of this evidence can be explained by an increase in water depth and corresponding decrease in the magnitude of hydrodynamic energy within the lower mesophotic zone. Some other evidence, such as the presence of porcellaneous larger foraminifera with the community of robust, often abraded nummulitid tests, admits the occasional reworking of storms and/or bottom currents. According to morphology characteristics, orthophragminids can be regarded as homeomorphic Baculogypsinoides (Cosović et al., 2004). Today, most their species are limited to deep waters and down to the lower limit of the photic zone (Reiss and Hottinger, 1984; Hohenegger et al., 2000; Hohenegger and Yordanova, 2001; Yordanova and Hohenegger, 2002). Changes in their test morphologies are consistent with many environmental factors (e.g., light intensity, water energy, and substrate), which can lead to their distribution in different environmental settings. During the Eocene, the spreading of orthophragminids (mainly Discocyclina and Asterocyclus) has been described in shallow environments within the photic zone (e.g., Ghose, 1977; Anketell and Mriheel, 2000) to deeper environments (e.g., Fermont, 1982; Buxton and Pedley, 1989; Gilham and Bristow, 1998; Cosović et al., 2004; Bassi, 2005; Baratotto et al., 2007; Zamagni et al., 2008; Sarkar, 2017). The coralline algal assemblage is dominated by the genus Sporolithon and unidentified coralline algal crusts and rhodolith-forming species. The genus Sporolithon inhabits recent tropical deep-water to temperate shallow-water environments (Adey and Macintyre, 1973; Adey et al., 1982; Braga and Bassi, 2007; Basso et al., 2009). Although the latitude and depth distributions of Sporolithon are wide, there are some indications of rather deep-water settings than shallow ones (Adey and Macintyre, 1973; Adey, 1979). First, there is the absence of shallow to mid-depth lithophylloids and mastophoroids (according to Aguirre et al., 2000). Second, the coexistence of sporolithacean and LBF assemblages suggests bathymetric levels in depths of less than 40–45 m (Sarkar, 2017), while the presence of LBF and rhodoliths and the abundance of acervulinid macroids indicated moderate water depths (Eocene from Liguria, Italy; Varrone and d’Atri, 2007; Sarkar, 2017).
7. Discussion and depositional model
The distribution of LBF assemblages provides a valuable tool for the paleoenvironmental reconstruction of the Eocene sedimentary successions of eastern Iran (Birjand area) within the Sistan Suture Zone. The transition between facies and a gradual deepening trend with the spreading of LBF and other significant components (e.g., calcareous red algae) on a low-gradient slope without evidence of reef-building organisms is largely comparable with carbonate ramp environments including inner and middle ramp settings with a biostratigraphical age of SBZ8 and SBZ10–12 biozones. In general, this interpretation was reinforced by the great lateral extent of the facies zones in both studied sections and the relative uniformity of the sediments in vertical successions. Additionally, there is the evidence of the MFTs, according to a proximal-to-distal facies distribution, which refers to deposition on a nonrimmed carbonate platform under the control of sea-level fluctuations. Paleoenvironmental models of LBF distribution into a shallow carbonate platform are mainly related to environmental factors (light intensity, water depth, hydrodynamic force, etc.). Some authors suggested that the combined effect of depth and substrate are noticeable parameters of LBF distribution (Hottinger, 1983; Zamagni et al., 2008). Therefore, depth-dependence of LBF distribution could be used for the interpretation of the microfacies during the Eocene since they were characterized by the highest diversity in shallow-marine settings of the Tethys (Luterbacher, 1984; Hottinger, 1997). Accordingly, the depth distribution of LBF in the Eocene carbonate platforms showed rich deposits of larger porcellaneous foraminifera (i.e. Alveolina, Orbitolites), which occur in the shallowest parts (i.e. inner platform/ramp/shelf) and then were replaced by hyaline-lamellar foraminifera assemblages such as nummulitids (i.e. Nummulites, Assilina, and Operculina) and orthophragminids with increasing water depth in a seaward direction (Luterbacher, 1998; Höntzsch et al., 2010; Ćosović et al., 2017). In the present study, the middle Ilerdian-middle Cuisian (SBZ8 and SBZ10–SBZ11) are represented by two different microfacies types comprising Alveolina-Operorbitolites packstone (locally grainstone) (MFT1) (Figures 11a–11d and 12a) and nummulitids-Alveolina rudstone (MFT2) (Figures 11e, 11f, and 12b). In this respect, both microfacies types were identified in the proximal inner ramp setting under the influence of wave action above the FWWB. In fact, the distribution and changes in the LBF assemblages in the transition of MFT1 to MFT2 are represented by a decrease in the abundance of the larger porcellaneous foraminifera instead of the predominance of nummulitids, which can be a demonstration of an increase in water depth. Within MFT2, the high abundances of larger porcellaneous and conical foraminifera along with robust A-forms of Nummulites are interpreted as deposits that are still in a proximal inner ramp setting with the effect of hydrodynamic energy in near-shore environments. MFT3 (Nummulites rudstone) is represented by nummulitid assemblages under the influence of high-energy conditions (waves and currents) within the middle-distal inner ramp settings during the middle to late Cuisian (SBZ11–SBZ12), so that the paleoenvironmental evidence of this microfacies (MFT3) (Figures 11g–11j and 12c) shows an increase in nummulitid abundance dominated by broken A-form Nummulites and Assilina with a decrease in abundance of alveolinid tests, which corresponds to increasing water depth. For the middle ramp environments, two microfacies including Assilina-Nummulites rudstone (MFT4) (Figures 11k, 11l, and 12d–12f) and orthophragminid-nummulitid pack-rudstone (MFT5) (Figures 11m–11q, 12g, and 12h) were defined in the late Cuisian (SBZ12) dominated by high abundance and diversity of LBF, i.e. nummulitids and orthophragminids; herein, they occupied deeper environments. MFT4 is mainly constituted by nummulite accumulations around the FWWB, which could reflect a high-energy environment along with other evidence of biofabric types such as chaotic stacking and linear accumulation. The development of this microfacies in the inner ramp area can be explained by the presence of subordinate Alveolina species, even if this occurrence may be the result of transportation of shallower water sediments directly seaward caused by downslope currents. MFT5 was deposited in the proximal middle ramp settings, below the FWWB and above the storm wave base, where orthophragminids thrived in deeper parts during SBZ12. In the above-mentioned area, morphological characteristics of orthophragminid tests (i.e. well-developed crystalline cones and inflated lenticular, sometimes flattened tests) along with the appearance of encrusting coralline red algae represent an increasing trend of water depths with reduced light intensity. In this microfacies, the effects of hydrodynamic energy are not only depicted as a result of storms and/or bottom currents, but it is documented by the presence of porcellaneous larger foraminifera with the community of robust, often abraded nummulitid tests that they could be transported from shallower waters directly seaward. As a result of the microfacies interpretations, by paying close attention to the paleoecology of LBF given above from the Ilerdian-Cuisian sedimentary successions, deposits in a shallow ramp environment are suggested with deepening upward from the middle Ilerdian to the late Cuisian (Figure 13). On the other hand, the deepening trend corresponds well with the global transgression during the early Eocene (Haq et al., 1987; Zachos et al., 1994; Miller et al., 2005).
Figure 12. Field photographs of the Eocene successions (Chenesht and Robiyat sections) of eastern Iran. (a) Close-up view of Alveolina (Alv) tests in the Alveolina-Opertorbitolites packstone (locally grainstone) lithofacies, Chenesht. (b) Close-up view of Nummulites-Alveolina packstone-rudstone lithofacies with a predominance of Nummulites (Num) and Alveolina tests, Chenesht. (c) Close-up view of Nummulites rudstone in the block of limestone, Chenesht. (d–f) Close-up view of both A- and B-forms of Nummulites and Assilina tests in Assilina-Nummulites rudstone lithofacies, Chenesht and Robiyat. (g–h) Orthophragminid-nummulitid packstone-rudstone, with robust-inflated lenticular orthophragminids (Or) along with Nummulites (Num) and Assilina tests, Chenesht and Robiyat.
8. Conclusion

The present study provides more meticulous biostratigraphy and microfacies data in comparison with preceding studies that had been initially conducted concerning the Ilerdian-Cuisian sedimentary successions in eastern Iran (Sistan ocean zone). As stated in the current paper, 4 biozones from SBZ8 and SBZ10–12 (middle Ilerdian-late Cuisian) are identified in accordance with the coeval fauna of the Tethys province. The distribution of MFTs and the paleoecological LBF interpretation have indicated a deepening trend from the shallowest area of the proximal inner ramp, above the FWWB and the upper photic zone, with a preponderance of larger porcellaneous assemblages of foraminifera (including Alveolina and orbitolitids), to the distal inner ramp and middle ramp into deeper surrounding water settings, which is defined by an increase in abundance and diversity of larger nummulitids along with orthophragminids during the early Eocene (SBZ8 and SBZ10–12).

Acknowledgments

This study represents part of the PhD thesis of the first author and was supported by the Geology Department of Ferdowsi University of Mashhad. The first author is deeply indebted to György Less (Miskolc) for his comments on Nummulites and orthophragminids. The contribution of Juraj Hrabovský was supported by research grant VEGA 2/0122/18 of the Slovak Academy of Sciences. We are most grateful to Amin Moudi for field work assistance. Finally, reviewer Antonino Briguglio (Genoa) and two anonymous reviewers were extremely helpful in improving the manuscript. We would especially like to thank the associate editor, Nazire Özgen Erdem, for editorial comments that helped to further improve the manuscript.
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