Microfacies analysis of Eocene Ziarat Formation (eastern Alborz zone, NE Iran) and paleoenvironmental implications

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ABSTRACT

Despite belonging to an important time slice in the geological history, the Eocene shallow-marine beds of the Alborz region in Iran have received little attention from researchers. We selected two stratigraphic sections (Mojen and Kalateh) ascribed to the Ziarat Formation as suitable representatives for the current analysis, emphasising on their constituent microfacies and paleoenvironmental components. The biotic communities are characterised by larger benthic foraminifera (LBF), coralline algae, corals, and bivalves as the major carbonate facies components. The microfacies gradients and paleoenvironmental analysis suggest deposition in a shallow-marine oligotrophic ramp environment within two platform stages. Both these stages indicate an increase in water depth from the inner to the middle ramp settings with spatial distribution of the LBF and other benthic components. Our data support the previous view that the early Eocene witnessed an increase in LBF taxa with near obliteration of the coral reefs in the sedimentary platforms across the Tethys. The corals reinitiated building reefal structures in the Middle Eocene, marking an important phase in the Tethyan paleoenvironmental evolution.

1. Introduction

The eastern Alborz zone of NE Iran has been an integral part of the circum-Tethyan carbonate platforms during the Eocene. However, to date the microfacies and paleoenvironmental conditions within this central Tethyan region have not been studied in detail. An understanding of the evolution of carbonate platform successions in the Alborz region is important in determining the palaeoecological controls related to the colonisation phases on Eocene carbonate platforms as well as presenting an analogue for platforms of similar age worldwide.

Larger benthic foraminifera (LBF) are the predominant biogenic components characterising the Eocene shallow-water carbonate successions from the eastern Alborz zone. Their evolutionary trends are highly significant in evaluating palaeoecological interpretations in the Tethyan realm (Hottinger, 1997, 2001). LBF-centric studies have considerable potential to support the analysis of the evolution and development of circum-Tethyan carbonate platforms during the Eocene (e.g. Serra-Kiel et al., 1998; Martín et al., 2001; Martín-Martin et al., 2020a, 2021; Cosović et al., 2004, 2018; Özgen-Erdem et al., 2005; Barattolo et al., 2007; Scheibner & Speijer, 2008; Höntzsch et al., 2010; Afzal et al. 2011; Bassi et al., 2013; Hadi et al., 2019a, b). Since the eastern Alborz region has been largely understudied, the current study attempts to analyse the carbonate microfacies emphasising on the evolution of the biogenic assemblages and their paleoenvironmental implications.

2. Geological setting and stratigraphy

As a part of the largest mountain belt of the Alpine-Himalayan system, the Iranian plateau has been subdivided into eight sedimentary-structural provinces, each of which are characterised by multiple tectonic and sedimentary events (Stöcklin, 1968; Aghanabati, 2004; Figure 1a): (1) Alborz, (2) Central Iran, (3) Zagros, (4) Kopeh-Dagh, (5) Lut, (6) Sanandaj-Sirjan, (7) Urumieh- Dokhtar (Sahand-Bazman) magmatic arc, and (8) Makran. The Eocene sections assessed in the current study are located within the Alborz zone. The E-W trending Alborz mountain belt is recognised as one of the most tectonically active zones in the Alpine-Himalayan orogenic belt located between the Caspian Sea basin in the north and the central Iran basin in the south (Stöcklin, 1968) (Figure 1b). The Alborz range spreads westward into the Pontides Arc (in easternmost Turkey) and the Lesser Caucasus (spread over Georgia and Armenia) (Asiabanhia & Foden, 2012).

The Alborz region is a tectonically active zone formed due to the collision between the Alborz margin and the Eurasian plate after the closure of the Paleo-Tethys Ocean (Stampfli et al., 1991). The Alborz
platform is mainly composed of terrigenous and volcanic influences, in which the shallow marine deposits occurring sporadically showed spatio-temporal variations during the Early to Middle Eocene (Figure 1c). Following the northward subduction of the Tethys, the Alborz margin consisting of the western, central, and eastern sectors, was affected by the Cimmerian and Alpine orogenic phases (Alavi, 1996). The Middle Eocene witnessed significant extension and magmatism by virtue of rollback and subducting slab resulting in northward movement and closure of the Neo-Tethys between the Arabian plate and the Alborz region (Vincent et al., 2005). Correlation of the middle Palaeogene sedimentary sequences outcropping in the eastern Alborz region show conspicuous similarities with various contemporary sedimentary basins in Central Asia. The similarities in their tectonostratigraphic architecture indicate a possibly related geodynamic and paleoenvironmental history influenced apparently by the Alpine-Himalayan orogenic system (Hadi et al., 2019c). The Alborz mountains were at around paleolatitude 30°N with close palaeogeographic proximity to the Anatolia-Prebetic domain and several western Tethyan sites during the early to middle Eocene (Martin-Martín et al., 2020a, b, c, 2021) (Figure 2).

In the southern Alborz flank, three geological formations have been distinguished (Dellenbach, 1964; Stöcklin, 1972); (1) the Fajan Formation (Palaeocene-early Eocene) is mainly composed of continental, terrestrial shales, red conglomerates and sandstones; (2) the Ziarat Formation (early-middle Eocene) mainly comprising foraminiferal-sandy limestones and marls; and (3) the Karaj Formation (middle Eocene) which characterises a >3000 m-thick succession of shale, sandstone, tuffaceous sandstone and gypsum (Figure 3).

The stratigraphic successions assessed in this study belong to the Ziarat Formation. The nummulitic limestones of the Eocene Ziarat Formation are deposited

Figure 1. (A) Modified sketch map of Iran showing geologic provinces (adapted from Stöcklin, 1968; Aghanabati, 2004). (B) Tethyan mountain ranges (simplified from Okay, 1989; Özcan et al., 2016) and location of studied region in the Alborz zone from Iran. (C) Simplified geological map from eastern Alborz region (after General geological map of Iran, 1:250000 from Sharabi, 1990).
unconformably on the continental siliciclastic deposits of the Fajan Formation and are overlain by the Eocene volcano-sedimentary rocks of the Karaj Formation.

3. Materials and methods

Two sections corresponding to the Ziarat Formation (Mojen and Kalateh) were analysed, from which a total of 55 rock samples were collected. A total of 218 thin-sections were prepared from these samples (Mojen: MJ and A, Kalateh: KT, N, O) for the analysis of the microfacies types. In addition, 173 free specimens were also evaluated (Hadi et al., 2019b). The thin-sections have dimensions of 6 cm × 10 cm, 2.5 cm × 7.5 cm and 2.5 cm × 2.5 cm, which were studied, and digitally photographed under transmitted-light (Olympus BX51) and binocular microscopes. Determinations of the Eocene LBF are based on taxonomic descriptions given by Hottinger (1960, 1974), Drobne (1977), Schaub (1981), Loeblich and Tappan (1988), Less (1987), and Sirel and Acar (2008) and Özcan et al. (2010, 2019). Biostratigraphic assessment of these sections have been previously carried out (Hadi et al., 2019b) with the determination of shallow benthic zones (SBZs) according to the schematic distribution ranges of larger benthic foraminifera proposed by Serra-Kiel et al. (1998), Less and Özcan (2012), and Papazzoni et al. (2017).

Major facies types (MFTs) were distinguished based on the relative abundance of the biotic components in association with the carbonate textures and fabric analysis. Sedimentary textures follow Dunham (1962) and Embry and Klovan (1972). Semi-quantitative estimates of the percentages of different facies component in the thin-sections were carried out by visual estimations and the comparison with %-distribution charts (Flügel, 2010). The diameter (D)/thickness (T) ratio was calculated from 25 Nummulites tests of isolate specimens, including N. cf. deshayesi. The biofabric types were determined based on field observations and petrographic analysis of the thin-sections (e.g. Beavington-Penney et al., 2005; Racey, 2001). The taphonomic attributes recorded in the Nummulites tests were assessed in thin-sections according to Beavington-Penney (2004a). The A/B ratios were estimated within 6 × 10 cm of samples from nummulitic limestones in the laboratory. The material is housed in the collection by M. Hadi at Ferdowsi University of Mashhad.

Figure 2. Simplified palaeogeographic reconstruction of the Mediterranean realm near the Cretaceous/Cenozoic boundary (about 70 Ma) (modified after Martin-Martin et al., 2020a, b, c, 2021).
4. Results

4.1. The analysed sections

The Eocene shallow marine successions belonging to the Ziarat Formation are analysed from two stratigraphic sections (Mojen and Kalateh) of the eastern Alborz zone, where larger foraminifera (alveolinids, nummulitids and orthophragminids) are the most abundant fossils of the carbonate platforms.

4.1.1. Mojen section

The Mojen section (~45 m thick; coordinates: 36° 29'53" latitude; 54°35'43" longitude) is located approximately 4.5 km northwest of Mojen village, about 45 km west of Shahroud. The basal unit is 7 m thick and consists of yellow to grey, medium-bedded calcareous sandstone. The middle part mainly comprises light grey to grey, medium to thickly bedded sandy limestone with abundant
and diverse, well-preserved early Eocene (middle Ilerdian to early Cuisian) *Alveolina* species (*A. decipiens*, *A. tumida*, *A. laxa*, *A. ilderensis* and *A. citrea*) and has a total thickness of 18 m, whereas the uppermost part has a thickness of 20 m and is dominated by medium-bedded limestone, including nummulitid tests as well as bivalve and echinoid assemblages. This lies unconformably over the Fajan Formation and conformably overain by the Karaj Formation (Figure 4a).

### 4.1.2. Kalateh section

The Kalateh section (~25 m thick; coordinates: 36°22'46" latitude; 59°23'54" longitude) was measured about 5 km northwest of the Kalateh village (Figure 3a). It is located 40 km north-west of Damghan and approximately 60 km south-west of the Mojen section. This outcrop is characterised by grey to brown thin to medium bedded limestones containing rich quantities of coralline red algae and *Nummulites* assemblages; however, the upper part is marly limestone with abundant *Nummulites* and orthophragminids. The Ziarat Formation is represented by a few shallow marine successions among the more frequently observed Karaj Formation deposits where the base is partly covered and underlain by marly siltstone and silty sandstone sediments of the Karaj Formation (Figure 4b).

### 4.2. Description of the major facies types (MFTs)

Ten major microfacies types (MFT1-MFT10) are distinguished (Figure 5; Tables 1–2). The MFTs of the early Eocene (Ilerdian-Cuisian) Mojen section are dominated by abundant alveolinid and nummulitid taxa (MFT1-MFT5), whereas the middle Eocene (Lutetian?-Bartonian) Kalateh section is characterised by LBF and coralgal assemblages (MFT6-MFT10).

#### 4.2.1. Early Eocene (Ilerdian-Cuisian) MFTs (Mojen section)

**MFT 1**: Terrigenous peloidal wackestone-packstone (Figure 6a)

This MFT occurs in the basal part of the Mojen section with a thickness of 6 m and characterised by a high abundance of poorly sorted, angular to sub-angular and medium to coarse quartz grains (30–35%) and peloids (up to 60%) in a wackestone to packstone matrix. Subordinate components are poorly sorted, sub-angular and fine to rarely coarse sized unidentified terrigenous grains (15–20%).

**MFT 2**: Sandy peloidal alveolinid-miliolid floatstone (Figure 6 b-c)

This MFT has a thickness of 4 m in the Mojen section. Alveolinids, smaller miliolids and peloids show nearly equal abundance (~25–30%), accompanied by the prevalence of quartz grains (10–15%) in a wackestone to packstone matrix. Additional biogenic
components include nummulits (5%) and echinoids remains. Sandy material is generally composed of poor to moderately sorted, sub-angular quartz grains.

**MFT 3**: Sandy *Alveolina* packstone-rudstone (Figure 6 d-h)
This MFT has a thickness of 15 m. It is dominated by *Alveolina* (~60%), peloids (15–20%), small miliolids (5–15%), quartz grains (10–15%) and occasionally *Nummulites* sp. (5–10%) in a packstone to grainstone matrix. All other rare biogenic components are echinoids, bivalve shell fragments and gastropods as well as intraclasts. Fine to coarse quartz grains are also present in varying amounts. The *Alveolina*-rich facies is overlain by the large oyster bank in the Mojen section (Figure 7).

**MFT 4**: Bivalve-nummulitic rudstone (Figure 8 a-c)
This MFT occurs in the upper part of the Mojen section with a thickness of 9 m (Figures 5, 7) and is mainly represented by fragments of large bivalves (oysters) with an alveolar shell structure and echinoid remains (~30–40%) along with *Nummulites* spp. (15–20%) and nummulitic fragments (5%) in a packstone matrix. *Alveolina* (15%) such as A. canavarii (Checchia-Rispoli) and A. fomasinii (Checchia-Rispoli) are also present together with smaller miliolids (5%). Subordinate components are small rotaliids and

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*Figure 5.* Stratigraphic columns of the Mojen and Kalateh sections with distribution of the major microfacies types.
| Major microfacies types | Age | Main components | Subordinate components | Distinctive characters | Paleoenvironmental interpretation |
|-------------------------|-----|-----------------|------------------------|------------------------|----------------------------------|
| Terrigenous peloidal Unidentified | High | middle Ilerdian? | wackestone-packstone | middle Ilerdian? | Quartz grains and peloids |
| Sandy peloidal Alveolina-miliolid floatstone | middle Ilerdian? | Alveolinids, peloids and quartz grains | Nummulitids, small miliolids, echinoid remains and green algae and quartz grains | The dominance of A-form alveolinids with rarely abrasion evidences on outer walls along with nummulitids and also the better sorting of the quartz grains |
| Sandy Alveolina | packstone-rudstone | middle Ilerdian-early Cuisian | Alveolina, peloids, and quartz grains | Echinoids, bivalve shell fragments, intraclasts, gastropods and quartz grains |
| Both A-B-forms (A: diameters less of 7 mm; B: maximum diameter of 14 mm) | alveolinids with some exfoliation and abrasion in the outer walls and also the presence of slightly robust and ovate Nummulites nummulitid rudstone | inner-ramp/ tidal currents and waves with moderate-energy | Bivalves (oysters), echinoids, *Nummulites* and *Alveolina* | Small rotaliids, green algae, gastropods and quartz grains |
| The | predomiance of large bivalves and echinoids assemblages together with The occupancy of alveolinids-dominated niches by hyaline-lamellar foraminifera assemblages such as nummulitids | early Cuisian | *Nummulites* | Peloids, rotaliids, small benthic foraminifera, bivalves, echinoid fragments, bryozoans, calcareous worm tubes, glauconite and quartz grains |
| Nummulitid | grainstone | early Cuisian | inner-ramp, also may be proximal middle-ramp/currents and waves with high-energy | *Nummulites* | |
| A-forms of nummulitid fragments with high degrees of damaged and abrasion | middle-ramp/ storms and/or bottom currents with high-energy | | | |
Table 2. Summary of the major microfacies types in the Kalateh section.

| Major microfacies types | Age      | Main components                        | Subordinate components | Distinctive characters | Paleoenvironmental interpretation                      |
|-------------------------|----------|----------------------------------------|------------------------|------------------------|--------------------------------------------------------|
| Coral- Coralline algae packstone-grainstone | Late Lutetian? | Corals, Coralline algae | Nummulites | Milolids, Nummulites, rotalids, bivalves (mainly oysters) echinoid fragments, bryozoans and serpulid worm tubes. | The coexistence of scleractinian corals and coralline red algae with the growth of serpulid worms, rare Nummulites tests (BTI:1) |
| inner-ramp, currents and waves with moderate energy | Bartonian | Coralline algae and Nummulites | Operculina sp., orthophragminids, other benthic foraminifera, roatalids corals, bivalves, echinoid debris and serpulid worm tubes. | The assemblage of Coralline algae and robust Nummulites tests with the categories 1 and 2 of the BTI index | middle-ramp/currents and waves with moderate energy/A-forms dominated by ovate forms and high degree of abrasion middle-ramp/waves and currents (storms?) with high energy |
| Nummulites rudstone | Bartonian | Nummulites | indeterminate coralline algae, orthophragminids, bryozoans, corals and serpulid worm tubes | robust and slightly ovate (average D/T ratio 1.8) A-form Nummulites with high degree of abraded/damaged tests (BTI: 1–3) in both A-8 (ratios from 20:1 to 30:1) forms | middle-ramp/bottom currents with low-moderate energy |
| Crustose coralline algal bindstone | Bartonian | Coralline red algae | Nummulitids, orthophragminids, rotalids, encrusting foraminifera, fragments of green algae, corals, bioclasts, bivalve debris, bryozoans, echinoids, serpulid worm tubes | The presence of coralline algal assemblages with encrusting, foliose, and rarely lumpy-warty growth forms along with excrusted foraminifera, rare Nummulites tests (BTI:1–2) | Nummulites orthophragminids and corallines |
| Nummulites- coralline algae | High | relative abundance of B-form Nummulites with discoidal, flat, saddle-like and undulating-wrinkled tests with the categories 0–1 and rarely 2 of the BTI index | | middle-ramp/bottom currents with low-energy | |

4.2.2. Middle Eocene (late Lutetian Bartonian) MFTs (Korateh section)

**MFT 5:** Nummulitid grainstone (Figure 8d-f)

This MFT occurs in the uppermost part of the Mojen section with a thickness of 11 m. The nummulitid grainstone is characterised by LBF assemblages that are mostly composed of A-form nummulitids (50–60%), rare orthophragminids (5–10%) (highly abraded/fragmented in several cases) in a locally wackestone matrix where the subordinate components are peloids, small benthic foraminifera, bivalves, echinoid fragments as well as bryozoans. In addition, calcareous worm tubes, glauconite grains (green to brown) in the chamberlets of nummulitid tests and intraparticles are observed with fine to medium-sized quartz grains.

This MFT occurs in the basal portion of the Kalateh section with a thickness of 6 m dominated by abundant scleractinian corals (60–70%) associated with melobesioid coralline algae, up to 1.5 mm in mean diameter featuring sub-spherical to sub-ellipsoidal and encrusting growth-forms (20–25%) within a packstone matrix. The larger foraminifera are characterised by dominant A-form Nummulites tests (Nummulites cf. deshayesi) with the Beavington Taphonomic Index (BTI) in category 1, and their tests are occasionally excrusted by the coralline crusts. Other subordinate biogenic components are miliolids, roatalids, bivalves (mainly oysters) and echinoid fragments as well as bryozoans. Also, the calcareous tubes, composed by serpulid worms on the coralline red algae are clearly observed.

**MFT 7:** Coralline algae-Nummulites rudstone (Figure 9d-e)

This MFT occurs in the lower part of the Kalateh section with a thickness of 4 m (Figure 10). The MFT7 is characterised by corallines and Nummulites demonstrating near equal abundance (30–40%) in...
Figure 6. Major microfacies types of the Ilerdian-Cuisian limestones from the Mojen section. (A) Terrigenous peloidal wackestone-packstone, inner-ramp, sample MJ1-3. (B) Sandy peloidal alveolinid (Alv)-miliolid floatstone, inner-ramp, sample MJ4-6. (C-H) Sandy Alveolina packstone-rudstone, defined by abundant Alveolina (Alv), note Nummulites (Num), miliolids (Mi), and intraclasts (Int), proximal inner-ramp, sample MJ7-20.
a packstone matrix. The laminar to columnar corallines (e.g. *Lithothamnion* and several indeterminate melobesioid thalli) range 1 to 2 mm in mean diameter. The *Nummulites* tests (e.g. *N. lyelli* (D’Archiac & Haime) N. cf. *deshayesi*) are well-preserved and rarely show abrasion limited only to the outer walls; therefore, they are assigned to categories 1 and 2 in the BTI. The tests of A-form-dominated *Nummulites* population are robust and slightly ovate form (average D/T ratio 1.8). Other larger benthic foraminifera such as *Operculina* sp. and orthophragminids (*O. zitelli* (Checchia-Rispoli) and *A. stella stella* (Gümbe)) are common along with some other rare benthic foraminifera (e.g. *Caudriella* sp.), rotaliids accompanying corals, bivalves, echinoid debris and serpulid worm tubes.

**MFT 8: Nummulites** rudstone (Figure 9F-G)

This MFT occurs in the middle part of the Kalateh section with a thickness of 6 m (Figure 10). The MFT8 is distinguished by the abundance of *Nummulites* tests (80–90%) with both A-and-B forms indicating a ratio 20/1 to 30/1 such as *N. lyelli* and *N. cf. deshayesi*. Also, the biofabrics of *Nummulites* tests include ‘chaotic stacking’ and locally ‘sub-linear accumulation’ of both forms with highly abraded outer walls of the nummulitic tests (Figure 9g). Other common bioclasts include fragments of undetermined coralline algae with diverse types of growth patterns such as encrusting, lumpy and warty forms that are scattered among the *Nummulites* tests, and especially show overgrowths with thin encrusting and foliose coralline forms around B-form *Nummulites* communities. Additionally, LBF such as orthophragminids (e.g. *Discocyclina* sp.), and subordinate proportions of bryozoans, corals and worm tubes also occur.

**MFT 9: Crustose coralline algal bindstone** (Figures 9h, 11a)

This MFT occurs in the upper part of Kalateh section with a thickness of 5 m. The main biogenic component is dominated by melobesioid coralline algae (*Lithothamnion*) and indeterminate mastophoroids displaying encrusting, foliose, and rarely lumpy/warty growth forms (60–70%) with considerable algal debris. The debris includes warty and branched corallines dispersed in a packstone matrix. The worm
tubes are locally developed on the coralline crusts along with the encrusting foraminifera (Figure 11a). Larger foraminifera assemblages are composed of nummulitids (e.g. *N. lyelli* and *Operculina* sp.) and orthophragminids. Subordinate components are encrusting foraminifera (*Carpenteria* sp. and *Gyroidinella magna*), rotalids, and fragments of red algae (e.g. *Distichoplax biserialis*), corals, bioclasts, bivalve debris, bryozoans and echinoids.

**MFT 10**: *Nummulites*-coralline algae-orthophragminid rudstone (Figure 11b-c)

This MFT occurs in the uppermost part of the Kalateh section with a thickness of 4 m dominated by larger benthic foraminifera such as *Nummulites* (60–70%) and orthophragminids (up to 10%) and coralline algae (15–20%) in a packstone matrix. The corallines show warty and rarely fruticose forms that are seldom scattered over the B-forms of *Nummulites* tests. Furthermore, the low diversity of orthophragminids (*Orbitoclypeus zitteli*, *Asterocyclina stella stella*) have been identified by thin and flattened A-form tests. The subordinate components are small benthic foraminifera, small rotalids, echinoids debris, bryozoans and bioclasts.

5. Discussion

5.1. Paleoenvironmental interpretations of the MFTs

In MFT 1, the dominance of peloids and terrigenous material (mostly quartz) suggests a depositional environment close to the area of origin of these sediments.
Figure 9. Major microfacies types of the Bartonian limestones from the Kalateh section. (A-C) Coral-Coralline algae packstone-rudstone, showing corals (Co), Corallines (Cor), Nummulites (Num), rotaliids (R), miliolids (Mi), Bryozoans (Bry), worm tubes (Wt), inner-ramp, sample KT1-5. (D-E) Coralline algae-Nummulites rudstone, note Nummulites (Num), Corallines (Cor), orthophragminids (Or), Caudriella sp. (Ca), middle-ramp, sample KT6-10. (F-G) Nummulites rudstone, note Corallines (Cor), middle-ramp, KT11-14. (H) Crustose coralline algal bindstone, middle-ramp, KT15-18.
(Hadi et al., 2016; Scheibner et al., 2007). In fact, the presence of abundant poorly sorted angular to subangular and medium to coarse-grained quartz (Figure 6a) indicates short distance transport from the source of the origin within a low-energy environment. Micrite and peloids represent degraded small porcelaneous foraminifera tests such as miliolids. In this respect, most peloids in the shallower-water settings are characterised as micritic bioclasts of green algae and smaller benthic foraminifera.

MFT 2 is characterised by abundant *Alveolina* associated with peloids and quartz grains showing a close stratigraphic association with the MFT 1 in the inner-ramp setting during the middle Ilerdian (SBZ8), where the LBF are poorly preserved. In this MFT, the assemblages of *Alveolina* with dominant A-forms and abraded outer test walls (Figure 6b) clearly suggest increased hydrodynamic energy, owing to possible tidal currents or waves. Besides, the co-existence of nummulitids is indicative of an increase in water depth compared to MFT 1. The dominance of alveolids together with small, lens-shaped nummulitids is indicative of a seaward orientation (Beavington-Penney, 2004b) as well as the better sorted quartz grains possibly indicating long-distance transportation.

The MFT 3 occurs from the middle Ilerdian (SBZ8) to early Cuisian (SBZ10), and is attributed to an inner-ramp setting that was mainly represented by the *Alveolina*-dominated assemblage (e.g. *A. decipiens* (Schwager), *A. tumida* (Hottinger) and *A. ilerdensis* (Hottinger), *A. trempina* (Hottinger), *A. fornasini* (Checchia-Rispoli), *A. canavarii* (Checchia-Rispoli)). The *Alveolina* species illustrate characteristics of exfoliation and abrasion in the outer walls (Figure 6d,e,f-g), and the presence of nummulitids (e.g. *Nummulites* spp.) with slightly robust and ovate tests (Figure 6f) are all indicators of depositional environments close to the fairweather wave base (FWWB) which may be the current-dominated environment in the inner part of a ramp (Hadi et al., 2016, 2019a). Additionally, amounts of quartz grains in this MFT are lesser in quantity and finer in comparison to the adjacent microfacies (MFT 2), which can be caused by an increase in water depth and greater distance of transportation under the effect of hydrodynamic energy (tidal currents and waves).

MFT 4 (early Cuisian, SBZ 10) dominated by bivalves, indicates a distribution in the inner-ramp to probably the middle-ramp settings with the occupancy of alveolinid-dominated niches by hyaline-lamellar foraminifera.

Figure 10. (A) Panoramic view of the Ziarat Formation in the Kalateh section. (B) Close up view of Coralline algae-Nummulites rudstone lithofacies that over lain by Nummulites beds (C) nummulitic limestones with medium-thick bedded, and (D) Close-up view of nummulite accumulations with predominately of A-forms of Nummulites rudstone lithofacies.
assemblages such as nummulitids that could be indicative of an increase in the depth ranges influenced by a light gradient (Hottinger, 1983). Although the presence of porcellaneous foraminifera (e.g. smaller milolids and alveolinids) usually indicates an inner ramp area, they could possibly have been transported into parts of the deeper middle-ramp setting. Alternatively, an increase in the nutrient levels might have triggered an increase in bivalves and echinoids, diminishing the LBF.

The MFT 5 is mainly constituted by nummulitid fragments between the FWB and storm wave base (SWB) which can reflect a high-energy environment in the middle-ramp setting where this environmental condition can be interpreted as storm and/or current bottoms (Zamagni et al., 2008); moreover, it probably developed in the early Cuisian (SBZ10?) so that this age is assessed by the last co-occurrence of A. canavarii (Checchia-Rispoli) and A. fornasini (Checchia-Rispoli). In this MFT the absence of porcellaneous foraminifera tests and the appearance of orthophragminids with a rich nummulitid assemblage (Figure 8E-F) shows a substantial increase in the water depth. Also, the high number of damaged/abraded tests within a grainstone matrix suggests some bottom current reworking. In fact, the simultaneous occurrence of nummulitids and orthophragminids, which were highly abraded and fragmented within a grainstone and locally wackestone matrix adjacent to the shoal-microfacies (bivalve-nummulitid rudstone), shows sporadic reworking by storms and/or bottom currents at a depth range between 40 and 80 m (Hottinger, 1983, 1997). Besides, the presence of glauconitic fillings in nummulitids and intraparticles may be the result of near-bottom return currents during storm conditions, although the deposition of glauconite is normally interpreted into deeper parts of the platform indicating low-energy and low-sedimentation rate settings (see Bassi et al., 2013; Ćosović et al., 2004; Scheibner et al., 2007).

In MFT 6, the presence of scleractinian corals and corallines (Figure 9A-B) indicates a wide distribution in the inner-ramp, possibly during the Late Lutetian (SBZ16?), in which index marker LBF species are absent. In sharp contrast to the early Eocene, the middle Eocene sediments indicate signature of patch reefs with dominant corals that indicate reinitiation of reef-building. In addition, the coexistence of the melobesioid coralline algae with scleractinian corals demonstrates deposition within the photic zone close to the FWB, influenced by moderate energy (i.e. currents and waves). The suitable condition for their growth is affected by relative stability of the substrate with a hydrodynamically favourable regime, enabling the thin coralline crusts to grow over the Nummulites tests. Besides, this interpretation is also reinforced by

Figure 11. Major microfacies types of the Lutetian?-Bartonian limestones from the Kalateh section (A) Crustose coralline algal bindstone, middle-ramp, sample KT15-18. (B-E) Nummulites-coralline algae-orthophragminids rudstone, middle-ramp, sample KT19-21.
the growth of serpulid worms on the corallines. Although the presences of corallines, milolids and A-form Nummulites (BTI: 1) are indicative of current effects with moderate energy in shallow waters, this may also be interpreted as deposition within a back-bank/shoal environment.

The replacement of scleractinian corals (MFT 6) by the LBF particularly Nummulites in MFT 7 could be the consequence of an increasing water depth within the proximal middle-ramp deposits in the SBZ17 and SBZ18b. Such assemblages of robust Nummulites tests and corallines (Figure 9d-e) can be interpreted to have deposited in a moderate energy environment with increased depth water, and also the occurrence of orthophragmminids and Operculina sp. commonly pointing to a tendency towards deeper settings (e.g. Beavington-Penney, 2004b; Zanagni et al., 2008). The categories 1 and 2 of the BTI were estimated on outer walls of the Nummulites tests, which indicate transportation by hydrodynamic forces close to the FWWB. Besides, coralline red algae are also known from the mesophotic zone commonly below FWWB with low light intensity which is insufficient for coral growth (see Morsilli et al., 2012); moreover, in such settings the high hydrodynamic energy often leads to reworked bioclasts and produce skeletal packstones (Spanicek et al., 2017).

The Nummulites assemblage in the MFT 8 is dominated by A-forms (Figure 9f-g) in the middle-ramp during SBZ17 and SBZ18b. Several studies on the modern larger foraminifera proposed the dominance of A-forms in the shallowest and deepest parts of a definite depth range (e.g. Beavington-Penney, 2004a; Beavington-Penney et al., 2005; Hottinger, 1982). Taphonomic study such as the BTI and taph shape analysis on the A-form Nummulites shows that they were under influence of a moderate-high energy environment and might have been transported with the effects of winnowing and in situ reworking processes. Besides, at places where the Nummulites tests are directly in contact with each other, the categories 2 and somewhat 3 of the BTI are observable (Figure 9f-g).

In addition, Nummulites biofabrics, include ‘chaotic stacking’ and locally ‘sub-linear accumulation’ among A-forms dominated in this MFT, therefore suggesting a parautocbonous deposit ‘bank’ close to the FWWB by waves and currents (storms?) in deeper water (Beavington-Penney et al., 2006; Mateu-Vicens et al., 2012). On the other hand, two hypotheses were proposed with respect to the thickening of A-form tests which were independent of phylogenetic parameters, and reflected a defence mechanism against bright sunlight (UV-light) and/or hydrodynamic energy in shallow-marine setting (e.g. Hallock & Glenn, 1986; Larsen, 1976). Thus, the A-form Nummulites possess an advanced capability in the long-distance transportation seawards in comparison to the B-forms from current-to wave-dominated processes, whilst the banks are limited by the presence of physical barriers (MFT 9: crustose coralline algal bindstone) which can display a significant role in preventing the transportation of the Nummulites tests in a seaward direction. Seddighi et al. (2015) has recently described that the B-forms of Nummulites tests have adapted to slightly higher water motion, thereby they have mentioned the genesis of nummulite banks as being autochthonous deposits (Arni, 1965). This MFT clearly indicates the formation of Nummulites accumulations (banks) under short-transported or winnowing tests (especially A-forms) in a moderate-high energy condition, where wave and current actions were considerable. Meanwhile, the growth of thin encrusting and foliose coralline thalli around B-form Nummulites can represent a periodically low energy environmental condition.

The MFT 9 is represented by coralline algal assemblages (Figures 9h, 11a) along with encrusting foraminifera (Figure 11a) in the middle-ramp setting, which is assignable to the SBZ17 and SBZ18b. Barattolo et al. (2007) similarly interpreted the dominance of coralline algae such as Lithothamnion, Neogoniolithon and Sporolithon as indicators of high-substrate stability under a low-moderate energy regime. Sarkar (2015) also reported a crustose coralline algal bindstone dominated by melobesioid coralline algae that was interpreted to have deposited in a shallow marine middle shelf environment. Therefore, the development of coralline red algal assemblages (Lithothamnion, mastophoroids) with encrusting, foliose, and rarely lumpy/warty growth forms are indicative of relatively quiet waters which are still under the influence of light penetration (<80 m) (Ghosh & Sarkar, 2013; Hottinger, 1983, 1997; Sarkar, 2016). In addition, some available evidence such as broken larger foraminifera tests (BTI: 1–2) can be signs of moderate bottom currents; moreover, Nebelsick et al. (2013) noted that low abrasion rates in association with rare coralline algal debris show low-energy levels of relatively deep waters (i.e. mesophotic zone).

The MFT 10 is characterised by larger foraminifera (mainly Nummulites and orthophragminids) and corallines corresponding to SBZ17 and SBZ18b. The B-form Nummulites tests are commonly undulated and saddle-like forms, so they are obviously observable in the outer whorls (Figure 11c). Sengupta (2001) noted that the morphological characters of Nummulites tests with undulated forms may be affected by the structure of the substrate determining their fossilisation. However, the flat to saddle-like forms with well-rounded network of crystalline cones on the orthophragminid tests point to low light conditions and progressive increase of water depth (e.g. Hadi et al., 2016). It is more visible in the B-forms with flattened tests such as N. lyelli (i.e. N. lyelli, typically a member of the N. gizehensis group
characterised by lenticular or flattened tests) along with an A-form-dominated community of flat and delicate orthophragminid tests (e.g. *A. stella stella*, and *O. zitteli*; Figure 11b) can be indicative of deeper waters (see Čosović et al., 2004; Hadi et al., 2019a; Machaniec et al., 2011) where light intensity is reduced. Several studies from ancient to modern sediments pertinent to the LBF show the predominance of flattened tests in relatively deep settings over the smaller and lenticular forms, which are common in shallower areas (e.g. Beavington-Penney, 2004a; Reiss & Hottinger, 1984; Trevisani & Papazzoni, 1996). Besides, the occurrence of very flat orthophragminid tests with low shaped lateral chambers can indicate the deeper parts of the photic zone (see Čosović et al., 2004). In this MFT, the nummulitid tests are generally whole and intact (in situ) in categories 0–1 and rarely 2 of the BTI along with the coralline crusts on the A and B-forms of *Nummulites* tests and other evidences refer to deep, oligotrophic water during low energy periods around and substantially below the SWB.

### 5.2. Depositional environment and platform stages

The Early Eocene was an anomalously warm period, and the middle Eocene was a transition from last greenhouse to icehouse climate (Bhattacharya & Dickens, 2020; Dallanave et al., 2015; Westerhold et al., 2020). The studied Mojen and Kalateh sedimentary successions in the eastern Alborz zone represent a shallow ramp environment developed in two platform stages showing increasing water depth during multiple phases of the Eocene (Figure 12). The biotic communities (e.g. larger foraminifera, corals, and coralline algae) suggest deposition in an oligotrophic nutrient regime. The gradients in the biotic assemblages during both early (middle Ilerdian-early Cuisian) and middle (late Lutetian?-Bartonian) Eocene also reflects an increase in water depth ranging from the inner to the middle ramp (Figure 12). The depositional environments of the early Eocene (Mojen) and middle Eocene (Kalateh) successions correspond closely to very significant global hyperthermals – early Eocene climatic optimum (EECO) and middle Eocene climatic optimum (MECO), respectively. The relationship of these climatic turnover events with changes in global sea level curves (Haq et al., 1987; Miller, 2005) have not been envisaged in detail from the Tethyan platforms barring a few case studies (e.g. Drobin et al., 2011; Höntzsch et al., 2013). Localised changes in water depth are well established by the current study but precise potential linkage to the global fluctuations could only be ascertained by virtue of higher resolution stratigraphic analyses, where biotic diversity trends and/or microfacies gradients are assessed in detail from multiple sites across the region. Phenomena like tectonic and volcanic activities well related to the Eocene successions of the Alborz region also need to be emphasised upon.

#### 5.2.1. Biotic platform stage I (Mojen Section)

The Ilerdian stage generally started with high diversity and abundance of both A- and B-form *Alveolina* (MFT 2 and MFT 3) In fact, the MFT 2 and MFT 3 are characterised by high diversity of the ovoidal to slightly elongate fusiform *Alveolina* tests close to FWWB within the inner-ramp setting, under oligotrophic conditions. They show an increase of relative surface area clearly linked with water depth (e.g. M.D. Brasier, 1984); therefore, they are in accordance with an inhabitation of low energy, clear water in highly oligotrophic settings (M. Brasier, 1995).

In the MFT 1, the assemblages are dominated by unidentified alveolinids and peloids together with the presence of quartz grains in the shallow water setting. Several authors (e.g. Flügel, 2010; Tucker & Wright, 1990; Wilson, 1975) opined that peloids are common in modern shallow sub-tidal to inter-tidal settings with effects of moderate to restricted circulation. The high amount of terrigenous material can be considered as an effective factor, so that the presence of quartz grains reflects increased hydrodynamic energy. In general, the terrigenous input and high diversity of A-forms *Alveolina* might be indicative of a more and less mesotrophic (or mildly oligotrophic) condition so that Tomás et al. (2016) noted that terrigenous input may increase the nutrient contents in the environment. Also, similar to these MFT 2 and MFT 3 with the predominance of *Alveolina* assemblages were observed during the SBZ7 to SBZ9 in different parts (i.e. such as western Alborz and Sistan ocean zones, see Hadi et al., 2019d) of Iran.

The MFT 4 (bivalve-nummulitid rudstone) formed under a high-energy inner-ramp, probably also the proximal parts of the middle-ramp settings. There seems to be a relative correlation between this MFT with the bivalve floatstone (Shoal Facies) in the Eocene carbonate successions which crop out from the western Alborz zone as described by Hadi et al. (2016). In fact, this MFT may be the result of high-energy conditions (e.g. waves and currents) with the formation of relatively small shoals with low relief submerged near FWWB. The last MFT (nummulitid grainstone) of the Ilerdian stage is deposited in relatively deeper, but still upper photic zone, and a high-energy environment in the middle-ramp area between the FWWB and the SWB. The paleoenvironmental gradient from the bivalve-nummulitid rudstone (MFT 4) to the nummulitid grainstone microfacies (MFT 5) shows the disappearance of alveolinids and appearance of the orthophragminids accompanied by the presence of glauconite grains, which indicate increasing depth while the dominant packstones-grainstones in these microfacies type could indicate a high-energy condition by occasional storm currents. Although the early
Eocene microfacies of the Mojen section shows some features which are like similar facies reported from Spain and France (e.g. Rasser et al., 2005; Scheibner et al., 2007) and also the Adriatic Carbonate Platform (AdCP) (e.g. Zamagni et al., 2008) with the predominance of larger benthic foraminifera, the corals and red algae are completely absent. The Palaeogene sequence begins with the basal conglomerate (Fajan Formation) during the Palaeocene-Early Eocene (SBZ1-SBZ6) where it was overlain by the Alveolina horizons of the Ziarat Formation. e.g. Hadi et al., 2015, throughout the southern flank of the western Alborz mountains. Along with the Eocene limestones, this conglomerate has filled a set of topographic depressions formed by a phase of substantial folding and uplift in the Late Cretaceous (Huber, 1977; Stöcklin, 1972).

5.2.2. Biotic platform stage II (Kalateh Section)

In the Kalateh section, the larger benthic foraminifera and coralline algal assemblages of the Lutetian-
Bartonian shallow-water carbonates were identified within five microfacies in the inner and middle-ramp environments. The MFT 6 is dominated by phototrophic taxa (corals and coralline algae) in the photic zone and relatively stabilised substrates, which is the result of moderate-energy condition pertaining to the inner-and proximal middle-ramp settings. In fact, the predominance of coral accumulations occurs in the deepest part of the photic zone (oligophotic zone) where the light intensity is still sufficient for development. Morsilli et al. (2012), Consorti and Köröglü (2019) and several other workers noted that corals thrived together with red algae in the mesophotic zone. Within the MFT 7, the high abundance of corallines and Nummulites is interpreted to have deposited in the middle ramp under high to moderate hydrodynamic energy. This MFT shows an increase in water depth in relation to the MFT 6; therefore, these changes are expressed by (1) The replacement of scleractinian corals by Nummulites tests along with an increase in coraline assemblages, (2) the occurrence of orthophragminids and Operculina sp., though it is still within the mesophotic zone. Similar microfacies have also been reported in several studies (e.g. Barattolo et al., 2007; Bassi, 2005; Bassi et al., 2013) which substantially pointed to the inner-middle platform settings of the Eocene carbonate successions.

Although the MFT 8 is represented by Nummulites accumulations under the influence of moderate-high-energy environments (waves and currents) within middle-ramp setting, the interpretation of these accumulations is poorly understood, and their genesis is still doubtful and enigmatic. In this MFT, the formatting of these accumulations is influenced by the process of winnowing and in situ reworking where the wave and current action plays an important role accompanied by: (1) the moderate to high degrees of abrasion/damaged (BTI:1–3) (2) observation of ‘chaotic stacking’ and locally ‘sub-linear accumulation’ and (3) the dominance of A-form Nummulites (ratio of A- to B-forms varies from 20:1 to 30:1) that is clearly in accordance with nummulite banks sensu discussed by Sarkar (2018). Briguglio et al. (2017) have recently pointed out the hydrodynamic energy as a major factor in the genesis of nummulite banks. They also mentioned that other factors such as reproduction strategies, sedimentation rate, and shell growth rates must be considered to develop a comprehensive model to explain the production of such accumulations. Nevertheless, this peculiar hydrodynamic behaviour of Nummulites is still strongly debatable.

The MFT 9 is dominated by coralline algal assemblages in the middle-ramp position almost between the FWWB and the SWB where the hydrodynamic energy was moderately low within the mesophotic zone, while the presence of coralline algal debris might be indicative of bottom current pulses in relatively deep-water settings. Bassi (2005) noted that the predominance of thin delicate crusts along with substrate stability is essential for the dwelling of coralline algae in a low-energy setting. Barattolo et al. (2007) explained a similar community in the middle-ramp of Klokova mountain (southern continental Greece) during the Bartonian-Priabonian. Coralline algae are abundant in Cenozoic shallow-marine environments (Nebelsick et al., 2005; Sarkar, 2018; Sarkar & Ghosh, 2013). This study indicates they are one of the most important constituents of Bartonian limestones in the eastern Alborz zone.

The MFT 10 was deposited in the middle-ramp where the LBF are mainly represented by Nummulites and orthophragminids along with corallines during low energy periods around and below the SWB. Even though the Nummulites accumulations can develop within deeper waters, they appear mostly with flat forms with increasing water depth and decreasing water-energy and light intensity (Beavington-Penney, 2004b; Hallock & Pomar, 2008). On the one hand, these accumulations are largely formed by autochthonous tests adjacent to the main nummulitic ‘banks’ structure (core-bank) based on the evidence mentioned above. On the other hand, this MFT is the constituent of the components in the fore-bank position. In general, these banks are made of monospecific to oligospecific communities with low relief throughout the middle-ramp area (MFT 8 and MFT 10) between the FWWB and SWB, albeit slightly below the SWB. The test shape of Nummulites is a function of environmental parameters (i.e. light intensity, and hydrodynamic energy) and taxonomic features with ranges of spherical-robust to flat forms, which are distinct in the different parts within the banks (see Mateu-Vicens et al., 2012; and references therein; Table 1 and Figure 1).

5.3. Comparison with other Tethyan domains
The Tethyan carbonate platforms could be divided into two major categories: (1) middle latitudes above 30°N and, (2) low latitudes below 20°N (Martin-Martin et al., 2020a; Scheibner & Speijer, 2008). According to the palaeogeographic model (Hadi et al., 2016), the Alborz region was located in the northern rim and middle latitude sharing close proximity to the western Tethyan sectors like the Pyrenees and the Adriatic platform (see e.g. Drobre et al., 2011; Höntzsch et al., 2013; Martin-Martin et al., 2020a, 2021; Scheibner et al., 2007). Therefore, the Alborz region during early Eocene (SBZ7-SBZ10 Biozones) is very similar to the early Eocene deposits of most western Tethyan sites with dominance of the larger benthic foraminifera, especially Alveolina that is in accordance with the diversification of different species within phase 4 of the global community maturation cycle (GCM; Hottinger, 1997, 2001; Serra-Kiel et al., 1998) in the
Mojen section. This phase is particularly illustrated with very high species diversity of *Alveolina* species such as *A. decipiens* (Schwager, A. *tumida* (Hottinger), *A. ilerdensis* (Hottinger), A. *sp. cf. A. ilerdensis*, *A. laxa* (Hottinger), A. *citrea* (Droane), A. *tremrina* (Hottinger), A. *fornasini* (Checchia-Rispoli), A. *canavarii* (Checchia-Rispoli), A. cf. *canavarii* and A. aff. *caryzagensis* which is for instance, comparable with records from the Adriatic carbonate platform (see Zamagni et al., 2008; Droane et al., 2011; Španić et al., 2017; Čosović et al., 2018), the Turkish platform (e.g. Özcan et al., 2019) and the Prebetic platform (Höntzsch et al., 2013). Tomás et al. (2016) also showed similar faunal assemblages with predominance of larger porcellaneous foraminifera such as *Alveolina, Orbitolites*, and *Opertorbitolites* in the low latitudes during the early Eocene (Ypresian; SBZ7-SBZ10) of Oman indicating possible analogous conditions in the sedimentation time span around different latitudes across the central Tethys. The platform stage corresponding to SBZ167-SBZ18b is composed of biota like *Nummulites* and orthophragminids along with coralline algae and corals. Although there is a rich assemblage of the hyaline larger foraminifera, but the species diversity is low that is in accordance with the phase 5 of the GCM cycle characterised by a decrease in species diversity in the late middle Eocene (see Hottinger, 2001). The presence of corals indicating the occurrence of smaller patch reefs among larger benthic foraminifera-dominated platforms shows affinity to the biogenic assemblages of the northern Tethyan realm during the Bartonian (SBZ17-SBZ18) (see Höntzsch et al., 2013) that highlights the reintroduction of coral reefs in the environment after near collapse during the early Eocene owing to the Palaeocene-Eocene hyperthermal (Scheibner & Speijer, 2008).

6. Conclusions

The studied sections comprise abundant larger benthic foraminifera with coralline red algae, corals, and bivalves as the other major biotic components. Ten microfacies types are identified in the current study on basis of the dominant biotic components. The facies distribution and community evolution patterns suggest two evolutionary stages in (1) early Eocene (Mojen section); and (2) middle Eocene (Kalateh section). The early Eocene platform stage corresponds to five microfacies generally dominated by abundant *Alveolina* and nummulitid assemblages, while the middle Eocene witnessed reef-building processes with corals and coralline algae dominating the microfacies that were gradually replaced by the larger foraminifera and varying proportions of crustose coralline algae. Both the platform stages are marked by transition from the inner to middle-ramp settings with an increase in water depth. As extensive datasets pertaining to the carbonate platform evolution during the middle Eocene from several Tethyan sectors remain poor, further research inputs are required to put forward a comprehensive paleoenvironmental record assignable to the overall Tethys.

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