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Foraminiferal paleoecology and paleoenvironmental reconstructions of the lower Miocene deposits of the Qom Formation in Northeastern Isfahan, Central Iran

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Abstract

The early Miocene Qom Formation is exposed in the Bagh section, northeast Isfahan, Central Iran, where it unconformably overlies Oligocene deposits and is unconformably overlain by the Upper Red Formation. The formation is mainly represented by carbonate deposits (marl, marly limestone facies) and subordinate siliciclastic facies. The planktonic foraminiferal biostratigraphical analysis led to recognition of two main planktonic foraminiferal zones: 1. the *Globigerinoides primordius* Zone in the lowermost part of the section indicating early Miocene (Aquitanian) and 2. the *Globigerinoides trilobus* Zone in the upper most part of the Qom Formation of Burdigalian age (early Miocene). Composition and abundance of benthic and planktonic foraminifers were examined for paleo-environment reconstruction and paleoecology. The Q-mode cluster analysis performed on the benthic foraminifers led us subdivide the section into three distinct benthic foraminiferal clusters: I. the *Cibicidoides ungerianus* cluster in the lower part of succession, indicating predominantly inner neritic environments; II. the *Lenticulina orbicularis* cluster in the middle part of section, indicative of middle-outer neritic environments, and III. the *Elphidium-Amphistegina* cluster recorded in the upper part of the formation and characterizing a typical outer neritic environment. The planktonic foraminifers are interspersed in the upper part of the section with relatively low diversity, indicating open marine shelf segments, whereas the lower part of the section is characterized by an abundance of benthic foraminifers. As a point to consider for paleoecology and paleoenvironment, abundant although with low diversity benthic foraminifera with small tests, and calculated data based on these clusters are indicative of high nutrient and high oxygen environment with normal marine salinity during the early Miocene at the Bagh section.

Keywords: Aquitanian, Burdigalian, benthic foraminifera, paleoenvironmental condition.

Resumen

La Formación Qom del Mioceno temprano está expuesta en la sección Bagh, al noreste de Isfahan, Irán Central, en donde sobreyace discordantemente a los depósitos del Oligoceno, y a su vez, está cubierta discordantemente por la Formación Upper Red. La formación está compuesta principalmente por depósitos de carbonatos (margas, facies de calizas margosas) y facies subordinadas de siliciclásticos. Los análisis bioestratigráficos de foraminíferos planctónicos permitieron reconocer dos zonas principales: 1. Zona de Globigerinoides primordiusen en la parte inferior de la sección, indicando una edad del Aquitaniano (Mioceno temprano) y 2. Zona de Globigerinoides trilobus en la parte superior de la Formación Qom, representando una edad del Burdigaliano (Mioceno temprano).

La composición y abundancia de foraminíferos bentónicos y planctónicos fue examinada para la reconstrucción del paleoambiente y paleoecología. Los análisis de grupo (cluster) en modo Q, realizados para los foraminíferos bentónicos, permitieron subdividir la sección en tres grupos distintos de foraminíferos bentónicos: I. Cibicidoides ungerianus, en la parte inferior de la sucesión, indica predominio de ambientes neríticos internos. II. El grupo de Lenticulina orbicularis, en la parte media de la sección, es indicativa de ambientes neríticos mediosexternos y, III. El grupo de Elphidium-Amphistegina se registró en la parte superior de la formación y caracteriza un ambiente nerítico externo típico. Los foraminíferos planctónicos están dispersos en la parte superior de la sección, con una diversidad relativamente baja, indicando segmentos de plataforma marina abierta, mientras que los segmentos más someros que intervienen en la parte inferior de la sección están caracterizados por abundancia de foraminíferos bentónicos. Con base en estos grupos y como contribución a la paleoecología y paleoambiente, la alta abundancia con baja diversidad y talla pequeña de las testas de foraminíferos bentónicos, son características indicativas de un ambiente oligotrófico con alto contenido de nutrientes y alta oxigenación, con salinidad normal durante el Mioceno temprano en la sección Bagh.

Palabras clave: Aquitaniano, Burdigaliano, foraminíferos, bentónicos, condición paleoambiental.

1. Introduction

The Qom Formation was deposited in the interval from early Oligocene until the end of the early Miocene in northern and central Iran (Stöcklin and Setudehina, 1991; Abaie *et al*., 1964; Reuter *et al*., 2009; Yazdi *et al*., 2012) (Figure 1). The Qom Formation crops out along the Zagros fold belt (Figure 1), and is mainly composed of marine marls, limestone, gypsum and siliciclastics strata (Reuter *et al*., 2009). This basin has been examined since 1934 because of economic interests (Furon and Marie, 1939; Abaie *et al*., 1964). Most of those studies were carried out based on the distribution of larger assemblages of benthic foraminifers and sedimentary sequences (Furon and Marie, 1939; Furon, 1941; Furrer and Soder, 1955; Gansser, 1955; Dozy, 1944, 1945, 1955; Abaie *et al*., 1964; Bozorgnia, 1966; Kashfi, 1988; Aghanabati, 2003; Daneshian and Ramezani Dana, 2007; Zhu *et al*., 2007; Behforouzi and Safari, 2011). In general, the Lower Red Formation underlies the Qom Formation; on the other hand, this unit is conformably overlain by the Upper Red Formation (Stöcklin and Setudehina, 1991). The Qom Formation was divided by Furrer and Soder (1955) into six members: a. basal limestone, b. sandy marl, c. alternating marl and limestone, d. evaporate, e. green marl, and f. limestone. Abaie *et al*. (1964) based their study on the sedimentary cycles; they separated members C1 and C3 and increased the number of members to ten. Nogole-Sadat (1985) introduced at least three sedimentary cycles for the Qom Formation. Reuter *et al*. (2009) recognized two basins for the Qom Formation: the Qom backarc basin and Isfahan-Sirjan forearc basin (Figure 1). Subsequently, Oligocene-Miocene sedimentation in the Qom basin took place along a ramp carbonate platform including: intertidal, shelf lagoon, platform margin and open marine environments (Aghanabati, 2003; Seyrafian and Toraby, 2005; Daneshian and Ramezani Dana, 2007; Zhu *et al*., 2007; Behforouzi and Safari, 2011).

Small benthic foraminiferal assemblages from the Qom Formation have been poorly studied (Rahagi, 1980; Daneshian and Aftabi, 2010). Hence, in this study we define important foraminiferal assemblages and reconstruct the paleoenvironmental setting of the Qom Formation in the Bagh outcrop.

2. Geological setting and lithostratigraphy

During the early-middle Miocene, periodic connections prevailed between the Mediterranean Sea, Paratethys province, Indo-Pacific region and the Atlantic Ocean (Rögl, 1998; Popov *et al*., 2004; Pippèrr, 2011). Intermittent seaway connections and regional closings were mainly driven by regional and global geotectonics and sea-level fluctuations (Rögl, 1998).

The Qom basin, in the Iranian plate, on the southeastern margin of the Paratethys, is an important basin for the interpretation of paleogeography and the construction of the Paratethys, the Mediterranean Sea to the Indo-Pacific region from the late Oligocene to early Miocene (Stöcklin and Setudehina, 1991; Rögl, 1998; Seyrafian and Toraby, 2005; Reuter *et al*., 2009, Khaksar and Maghfouri Moghaddam, 2007; Daneshian and Ramezani Dana, 2007; Mohammadi *et al*., 2011; Behforouzi and Safari, 2011; Yazdi *et al*., 2012).

The Bagh section is located at 32˚57´61˝ N and 52˚01´95˝ E, 55 km northeast of Isfahan (Isfahan-Sirjan forearc basin) (Figure 1). The investigated section is located along the NW-SE trend of the Qom-Zefreh fault. This fault formed during the closure of the Neotethys and the collision of the Arabian plate with the Iranian plate during Late Cretaceous time (Reuter *et al*., 2009).

Active tectonics led to the formation of complicated horst and graben structures and influenced thickness change in the Qom Formation, producing lateral variation of facies (Poroohan *et al*., 2009; Jalali and Feizi, 2010).

Lithologically, the Qom Formation is mainly composed of a thick interbedding of grayish yellow to yellowish white, highly fossiliferous marl and greenish grey, yellowish, friable, fossiliferous argillaceous to sandy

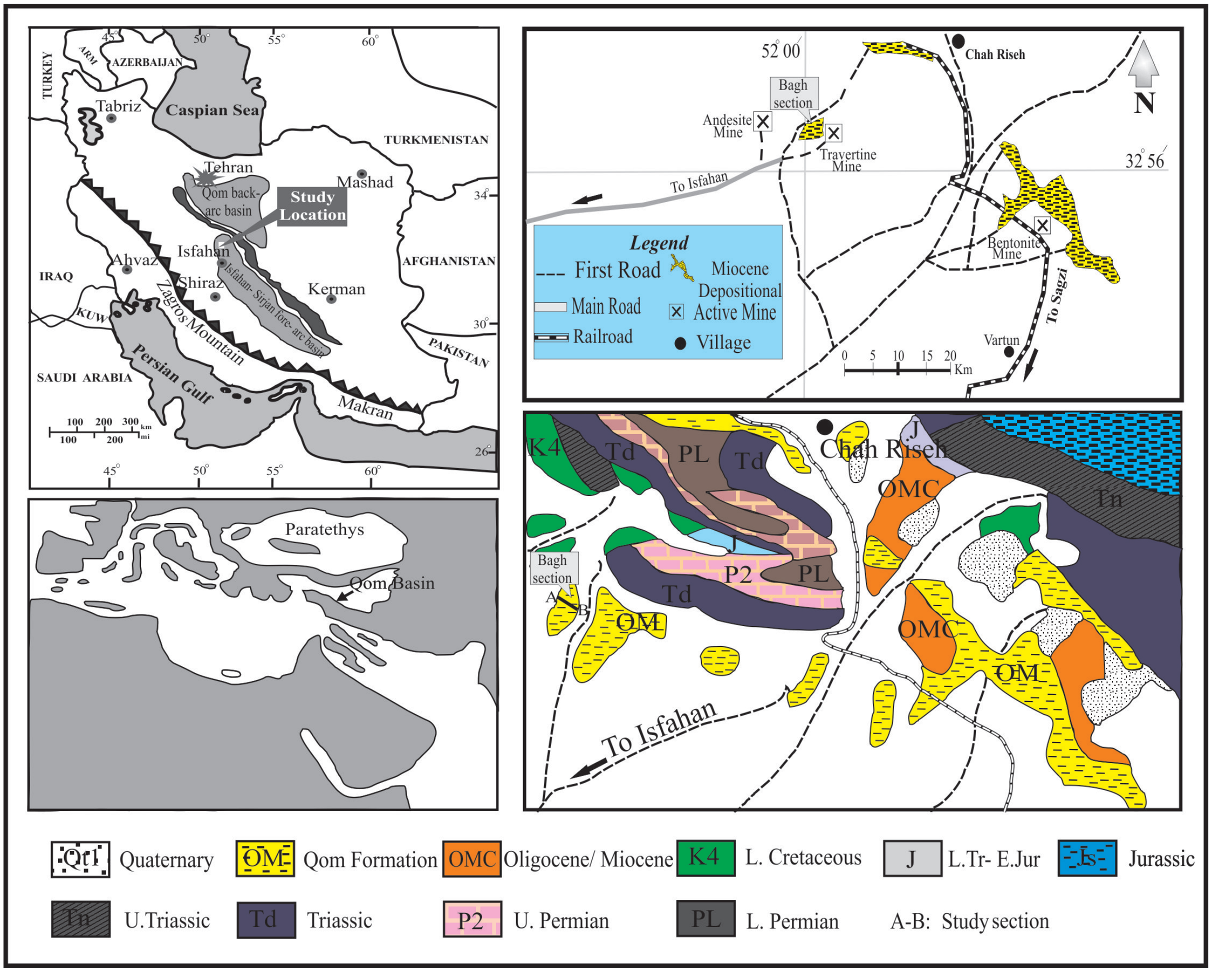

Figure 1. Location map of the study area in the Bagh section, northeast of Isfahan. a) Geological position of outcrop, the position of the Isfahan-Sirjan basin and the Qom basin in light gray and the volcanic arc in dark gray (modified from Schuster and Wieland, 1999; Reuter *et al*., 2009). b) Simplified road map of the area northeast of Isfahan, in the direction of Naein. c) Geographical overview of Paratethys Sea and position of Qom basin in the late Oligocene – early Miocene (modified from Reuter *et al*., 2007). d) Geographical map of the Bagh section (modified from Geological Survey of Iran by Zahedi and Amidi, 1978).

marly limestone. At the base, predominant greenish gray, fissile, fossiliferous calcareous shale is locally interbedded with thin beds of argillaceous limestone (Figure 2). The sequence is rich in macrofossils: *Clypeaster confuses* (Pomel, 1887), *Clypeaster intermedius* (Desmoulins, 1837), *Eucidaris zeamays* (Sismonda, 1842), *Spondylus crassicosta* (Lamarck, 1882), *Echinolampulus ampulus* (Fuchs, 1882), *Turritella subarchimedies* (Sacco, 1897) and *Scutella* sp. It is noteworthy to mention that the lowermost part of the Qom Formation yields large benthic foraminifers as *Amphistegina lesson* (d'Orbigny, 1843), *Operculina complanata* (Defrance, 1822), *Operculina* cf. *bartschi* (Cushman, 1921), *Lepidocyclina tournoueri* (Lemoine and Douville, 1904) *Lepidocyclina* sp., as well as coralline, red algae like *Lithophyllum* sp. and *Lithothamnium* sp. This type of macrofaunal and larger foraminiferal assemblages suggest that a shallow warm marine environment (inner neritic zone) prevailed during the early deposition of this unit. The thickness of the Qom deposits reaches 85 m in the Bagh outcrop (Figure 2). The base of the Bagh outcrop is covered by the Lower Red Formation. The upper part of the Bagh section is composed of silty clay (channel deposition) overlying the Qom Formation with a sharp unconformity.

3. Materials and methods

The present study is based on the examination and investigation of about 30 samples collected from the Bagh section, northeastern Isfahan, Iran (Figure 1). For soft samples, about 100 grams of each were gently crushed and soaked in a solution of 10 – 20 % hydrogen peroxide to accelerate the process of disintegration. The samples were washed several times through a set of sieves ranging between 63 to 162 µm, by using gently flowing water. The hard samples were first crushed and heated in metal bowl and then soaked in a solution of 10 – 30 % hydrogen peroxide for at least two days, and then soaked in water. After that,

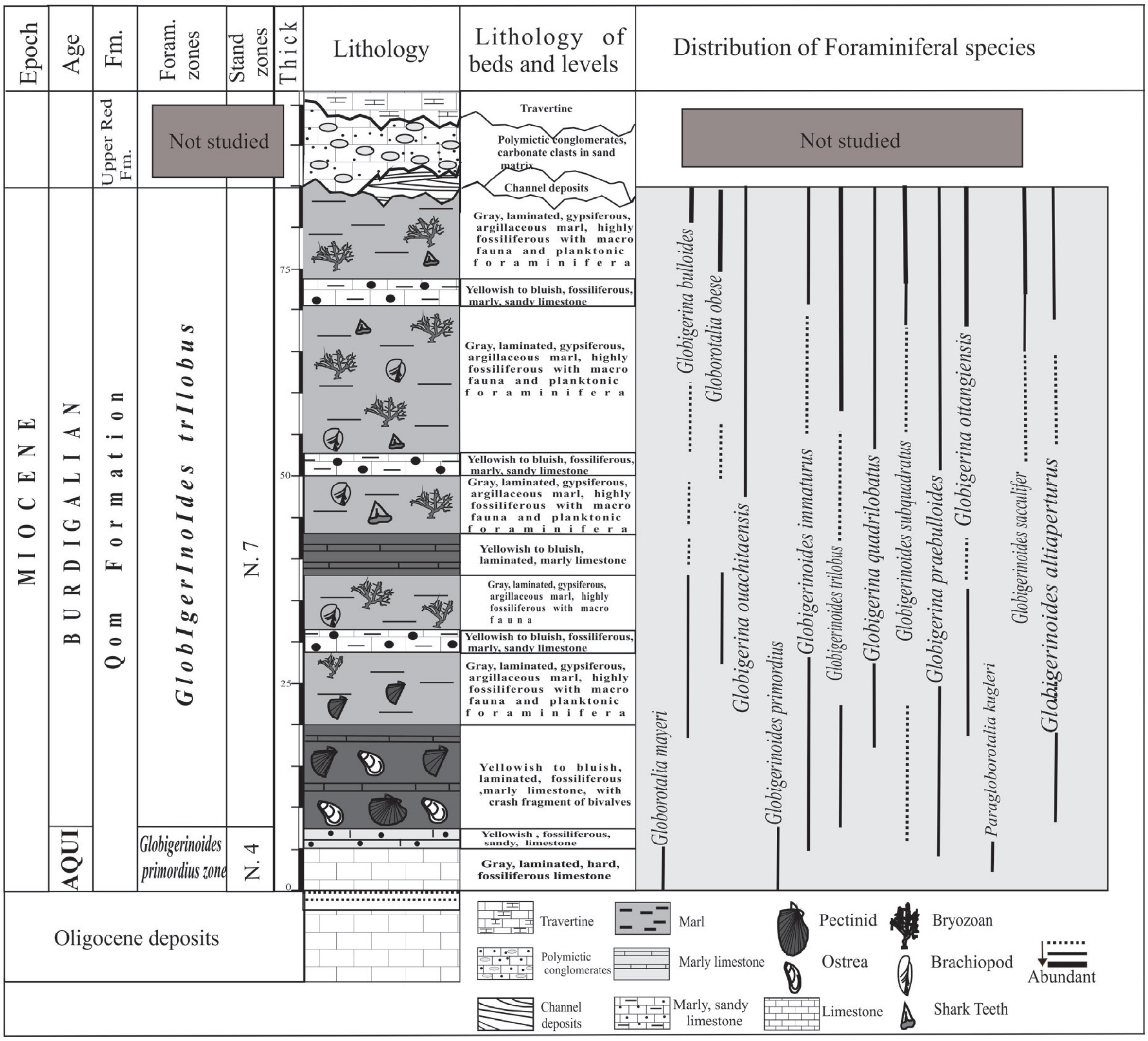

Figure 2. Schematic lithological succession of lower Miocene (Qom Formation) in Bagh area.

the washed residues were dried in an oven at 60 ˚C and sieved to retain the planktonic and benthic foraminifers. The picked samples were studied and documented by using SEM method. The identification and classification of foraminifers were performed according to Bolli *et al*. (1987) and Postuma (1971) schemes.

The benthic foraminifers are reliable indicators of paleoecological condition changes (Gebhardt, 1999; Drinia *et al*., 2007; Holcová and Zágoršek, 2008; Hohenegger *et al*., 2009; Zágoršek *et al*., 2009; Gupa *et al*., 2013).

The following data were calculated for paleoenvironment interpretation by using the computer software PAST (Holcová and Zágoršek, 2008; Pippèrr, 2011):

1) Oxygen contents were estimated using *BFOI* = benthic foraminiferal oxygen index (Kaiho, 1994, 1999; Drinia *et al*., 2003, 2009, 2010; Mandic *et al*., 2002; Pippèrr, 2011).

$$BFOI = O / (O + D) * 100$$

Where O is the number of oxic indicators and D is the number of dysoxic indicators. Oxic, suboxic and dysoxic faunas were identified (Table 1) based on the schemes by Kaiho (1994), Baas *et al*. (1998), Stefanelli (2004), Van der Zwaan *et al*. (1990), and Holcová and Zágoršek (2008). Kaiho (1994) introduced high oxic (3.0 – 6.0 mL/L) or *BFOI* ranges values 100 – 50, low oxic (1.5 – 3.0 mL/L) with *BFOI* ranges values 50 – 30, suboxic (0.3 – 1.5 mL/L) or *BFOI* < 30, dysoxic (0.1 – 0.3 mL/L), and anoxic (0 – 0.1 mL/L).

2) The percentage of euryhaline species can be indicated from salinity (Murray and Alve, 1999a; Pippèrr, 2011).

3) Paleodepth was estimated using P/B ratios, where P is the total number of planktonic foraminifers and B is the total number of benthic foraminifers (Sen-Gupta and Machain-Castillo, 1993; Drinia *et al*., 2007; Holcová and Zágoršek, 2008). The relative abundance of the P/B ratios is associated with distance from shore (Van der Zwaan *et al*., 1990; Wilson, 2003; Murray and Alve, 1999; Murray, 2006; Mandic and Harzhauser, 2003); the inner shelf environment (inner neritic) was defined with ratios of < 20 %, middle

shelf (middle neritic) with ratios of 20 – 50 % and 50 – 70 % for the outer shelf (outer neritic) environment (Murray, 1991, 2006; Murray and Alve, 1999; Pippèrr, 2011).

4) Abundance of benthic foraminifers was estimated using the relationship between diversity index (Fisher's α) and the total number of individuals (Hammer *et al*., 2001; Rai and Maurya, 2009).The fauna diversity is compared with fauna abundance. On the other hand, higher percentage indicates high diversity and it is contrasted with abundance (Pippèrr, 2011).

$$S = \alpha \ln (1 + N / \alpha)$$

Where S is the number of taxa, N is the total number of individual taxa and α is the Fisher diversity index.

5) Relative abundance (%) of cool and warm water species were used for estimation of paleotemperature (Bicchi *et al*., 2003; Holcová and Zágoršek, 2008; Hohenegger *et al*., 2009)

6) The Q-mode cluster analysis was used to statistically classify small benthic foraminifera (Hammer *et al*., 2001).

The systematic determination of the benthic foraminiferal species was based on the criteria of Loeblich and Tappan (1987a, b) and Tyszka (2001). The compilation of ecological preferences, including the depth-range for benthic foraminifers, is based on Murray and Alve (1999), Van Der Zwaan *et al*., (1990), Sgarrella and Moncharmont Zei (1993), Kaiho (1994, 1999), Zágoršek *et al*., (2009), Holcová and Zágoršek (2008), Pippèrr and Reichenbacher (2010), and Pippèrr (2011).

The specimens studied here are housed in the repository of Isfahan University, Faculty of Science under the code IUIB1-37 (Isfahan, University, Iran and Benthic Foraminifer).

4. Planktonic Foraminiferal Biostratigraphy

The detailed analysis of the planktonic and benthic foraminiferal assemblage obtained from the stratigraphic section in the Bagh area resulted in the recognition of two planktonic foraminiferal zones. The identified biostratigraphic zones are locally correlated with their equivalent biozones in Iran and with the equivalent warm and tropical water areas with special emphasis on the Mediterranean region. The stratigraphic distributions of the identified taxa is represented in Figure 2; scanning electron micrographic were also prepared for the important species and included in two plates (Figures 6, 7).

It is noteworthy to mention that the boundary zones in the study sections are defined on the basis of datum events or first and last appearance of the zonal taxa which is more applicable in the Mediterranean region (Iaccarino and Salvatorini, 1982; Iaccarino *et al*., 2005; Berggren and Pearson, 2005). In this study the late Oligocene-early Miocene boundary is defined on the basis of the first occurrence of *Globigerinoides primordius* and *Paragloborotalia kugleri* together. Following is a brief description of the identified biozones from base to top based on the zonation represented by Iaccarino and Salvatorini (1982):

4.1. *Globigerinoides primordius* Zone.

Category: Interval zone.

Age: Aquitanian (early Miocene).

Author: Blow (1969) emended here to fit the studied material.

Definition: Interval from first occurrence of the zonal marker *Globigerinoides primordius* to the first occurrence of *Globigerinoides trilobus*.

Planktonic association: This zone is characterized by low frequency and low diversity of planktonic foraminiferal taxa. The most common assemblage includes: *Globigerinoides primordius* (Blow and Banner, 1962), *Globigerinoides immaturus* (Le Roy, 1939), *Paragloborotalia kugleri* (Bolli, 1957), *Globigerinoides subquadratus* (Brönnimann, 1954), *Globorotalia mayeri* (Cushman and Ellisor, 1939), and *Globigerina praebulloides* (Blow, 1959).

Remarks: In the examined material, the *Globigerinoides primordius* Zone represents the oldest Miocene planktonic foraminiferal zone recorded. Some authors believed that the Oligocene-Miocene boundary should be established at the first evolutionary occurrence of the genus *Globigerinoides*, especially the appearance of *Globigerinoides primodius* (Blow, 1979; Bolli *et al*., 1987). Others considered that *Gs. primordius* makes its first occurrence as early as the *Paragloborotalia kugleri* zone of late Oligocene age (Stainforth *et al*., 1975; Berggren *et al*., 1995). Bolli *et al*. (1987) recognized that determination of the Oligocene-Miocene biozone is dependent on the local environmental conditions and therefore stratigraphically less reliable. This controversy motivated these workers to redefine the lower boundary of the lowest Miocene zone. Iaccarino (1985) overcame this problem and considered the first occurrence of the *Globoquadrina dehiscens dehiscens* to delineate the lowest Miocene biozone. But in the present study, it is suggested that the lowest Miocene biozone could be referred to as the *Gs. primordius* zone, since *Globoquadrina dehiscens dehiscens* is not recorded. This zone could be correlated with the standard planktonic foraminiferal zone N4 of Blow (1969). In the present study, the last extinction of the nominated zonal marker is stratigraphically reliable to delineate the late Oligocene-early Miocene boundary. Whereas the next zonal marker, *Globigerinoides trilobus*, is not recorded in this zone and makes its first occurrence with the last extinction of *Gs. primordius*. This zone could be correlated to M1 of Berggren *et al*. (1995).

Occurrences: This zone is generally recorded in the Qom Formation. It is recorded in the lower part of the Bagh section from 0 – 5 m. This zone is considered as Aquitanian in age (early Miocene) on the basis of the total range of the zonal taxa.

4.2. *Globigerinoides trilobus* Zone

Category: Interval zone.
Age: Burdigalian (early Miocene).
Author: Bizon and Bizon (1972).
Definition: This zone occupies the interval from last occurrence of *Globigerinoides primordius* to the last occurrence of *Globigerinoides trilobus* (Postuma, 1971).

Planktonic association: This zone is characterized by the high frequencies and moderate diversity of planktonic foraminiferal species *e.g*. *Globigerinoides trilobus* (Reuss, 1850), *Gs. immaturus* (Le Roy, 1939), *Gs. sacculifer* (Brady, 1877), *Gs. Subquadratus* (Brönnimann, 1954), *Gs. altiaperturus* (Bolli, 1957), *Globigerina praebulloides* (Blow, 1959), *Globigerina bulloides* (d'Orbigny, 1826), *Globigerina ouachitaensis* (Howe and Wallace, 1932), *Globigerina ottangiensis* (Rögl, 1969), and *Globorotalia obese* (Bolli, 1957).

Remarks: This zone is characterized by moderate diversity of planktonic foraminifers. Such occurrence suggests development under open, deep marine environments (middle to outer neritic zone). This zone is strongly matched with the standard planktonic foraminiferal zone N7 of Blow (1969). The absence of the *Catapsydrax dissimilis*/*Globigerinoides altiaperturus* Zone of early Burdigalian age may be attributed to ecological changes during the deposition of the Qom Formation. This zone could be correlated with M4 of Berggren and Pearson (2005).

Occurrence: This zone is generally recorded in the Qom Formation, in the upper part of the section, from 5 – 85 m. This zone is considered as Burdigalian (early Miocene) age on the basis of the total range of the *Globigerinoides trilobus* zonal taxon.

5. Ecology of Planktonic Foraminifers

Abundance, diversity and composition of foraminifers are strongly controlled by temperature. According to Spezzaferri (1995), Bicchi *et al*. (2003) and Holcová and Zágoršek (2008), the *Globigerinoides primordius*, *Gs. sacculifer*, *Gs. quadrilobatus* and *Gs. trilobus* are commonly indicative of warm waters, whereas *Globigerinoides immaturus*, *Globigerina praebulloides*, and *Globigerina ottangiensis* are considered to be cool-water indicators (Table 1). Indeed, Spezzaferri (1995) considered *Globigerina ottangiensis* and *Globigerina praebulloides* as indicators of high productivity (Rögl and Spezzaferri, 2003).

Table 1. Paleotemperature marker column (Spezzaferri *et al*., 2002; Holcová and Zágoršek, 2008).

Paleotemperature markers	Spezzaferri *et al*., 2002	Zagrosek *et al*., 2009
Globorotalia mayeri	warm	warm – temperate
Globigerina bulloides	cold	cold
Globorotalia obese	warm	—
Globigerina ouachitaensis	warm	—
Globigerinoides primordius	warm	—
Globigerinoides immaturus	cold	cold
Globigerinoides trilobus	warm	warm
Globigerina quadrilobatus	warm	warm
Globigerinoides subquadratus	warm	—
Globigerina praebulloides	cold	cold
Globigerina ottangiensis	cold	cold

6. Ecology and classification of benthic foraminifers by cluster techniques

The microfossil assemblages of the Qom Formation have been described by many authors based on large benthic foraminifer distribution (Schuster and Wielandt, 1999; Abaie *et al*., 1964; Seyrafian and Toraby, 2005; Reuter *et al*., 2009; Daneshian and Ramezani Dana, 2007; Mohammadi *et al*., 2011; Behforouzi and Safari, 2011). The Qom Formation can be correlated with the lower part of Asmari Formation (Zagros fault belt) (Figure 1) and was assigned a Rupelian to Burdigalian age. In the Bagh outcrop, benthic foraminifer assemblages are generally abundant and small in size. A summary of the paleoenvironment preference of the dominant benthic foraminifers from the Bagh Section is shown in Table 2. The ecology of benthic foraminifers was studied by Spezzaferri *et al*. (2002) and Bicchi *et al*. (2003).

The *Lenticulina* sp. is dominant and a large-sized genus (> 250 μm). The benthic foraminifer assemblages increase in diversity upwards (Figures 3 and 4). In order for the best analysis of paleoenvironment, we used cluster modeling. Q-Mode clustering corresponding to Ward's minimum variance method and the percentage contribution of benthic foraminifers distinguished three major clusters (Figures 3, 4 and 5).

I) The *Cibicidoides ungerianus* cluster is recorded in samples A1 – A13. This cluster is characterized by the abundance of *Cibicidoides ungerianus* (39 %) and relatively common occurrence of *Bolivina digitalis* (16 %) and *Cibicidoides* sp. (18 %). The hyaline taxa are abundant whereas agglutinated taxa are represented by *Textularia agglutinans* (11 %) and *Quinqueloculina triangularis* (4 %) that are dominated by small-sized test. Less abundant species (0 – 3 %) are represented by *Lenticulina orbicularis*, *Lenticulina inornata*, *Uvigerina* sp. Fisher's α diversity is small (α = 3.2) and indicates high frequency. Planktonic foraminifer abundance becomes relatively rare toward the upper position of this cluster and diversity is low (3 – 6 %). P/B ratios are about 3.38 – 17 (Figures 5 and 7). *BFOI* is high, from 64.61 – 89.4, and indicates a highly oxygenic environment (Murray and Alve, 1999; Murray, 2006; Wilson, 2003; Pezelj *et al*., 2007, 2012). The depth estimate for this cluster matches closely the depths given by Holcová and Zágoršek (2008) and is approximately 35 – 70 m.

II) The *Lenticulina orbicularis* cluster is dominated by only six samples, from A14 – A19. *Lenticulina orbicularis* is the most abundant taxa (32 %), in association with *Cibicidoides lobatulus* (16 %), *Cibicidoides* sp. (18 %), *Lenticulina inornata* (10 %), and *Cibicidoides ungerianus* (5 %) whereas other minor taxa (1 – 2 %) are *Uvigerina costata*, *Textularia agglutinans*, *Quinqueloculina triangularis*, *Lenticulina maynae* and *Heterolepa dutemplei* (Figures 6 and 7).

The Shannon-Weaver index of diversity of assemblage

Table 2. Paleoecological preference of the dominant benthic foraminifera in the Bagh succession modified after Rögl and Spezzaferri (2003)

Species	Environment	Preferred depth range (m)	Preferred substratum	Living strategy	Dysoxic / Oxic markers
Cibicidoides ungerianus	Inner shelf	Abundant 30 – 50 m	Hard substrates	Epiphytic	Oxic
Cibicidoides sp.	Shelf to bathyal	From 50 m down	Hard substrates	Epiphytic	Oxic
Cibicidoides lobatulus	Inner shelf	30 – 50 m	Hard substrates - muddy sand	Epiphytic	Oxic
Uvigerina sp.	Shelf to bathyal	100 m to > 4500 m, rarely shallower than 100 m	Mud	Shallow endopelic, rarely epiphytic	Suboxic and high organic matter
Heterolepa dutemplei	Shelf- upper bathyal	25 – 500m	Mud		Oxic
Bolivina dilatata	Inner shelf to bathyal	Abundant from 50 – 200m	Mud	Shallow endopelic	Low oxygen
Lenticulina orbicularis	Middle- outer shelf	Abundant from 50 – 100 m	Mud		Suboxic
Lenticulina inornata	Middle- outer shelf	Down to 50 m more abundant 50 – 300 m	Mud		Suboxic
Lenticulina sp.	Outer shelf and bathyal	From 20 m down	Mud		Suboxic
Lenticulina maynae	Middle- outer shelf	Down – 50 m more abundant 50 – 300 m	Mud	Epiphytic	Suboxic
Elphidium sp.	Inner shelf	0 – 50 m	Mud and sand	Epiphytic	Oxic
Elphidium fichtelianum	Inner shelf	0 – 110 m	Mud and sand	Epiphytic	Oxic
Amphistegina planorbis	Inner shelf	0 – 110 m	Mud	Epiphytic	

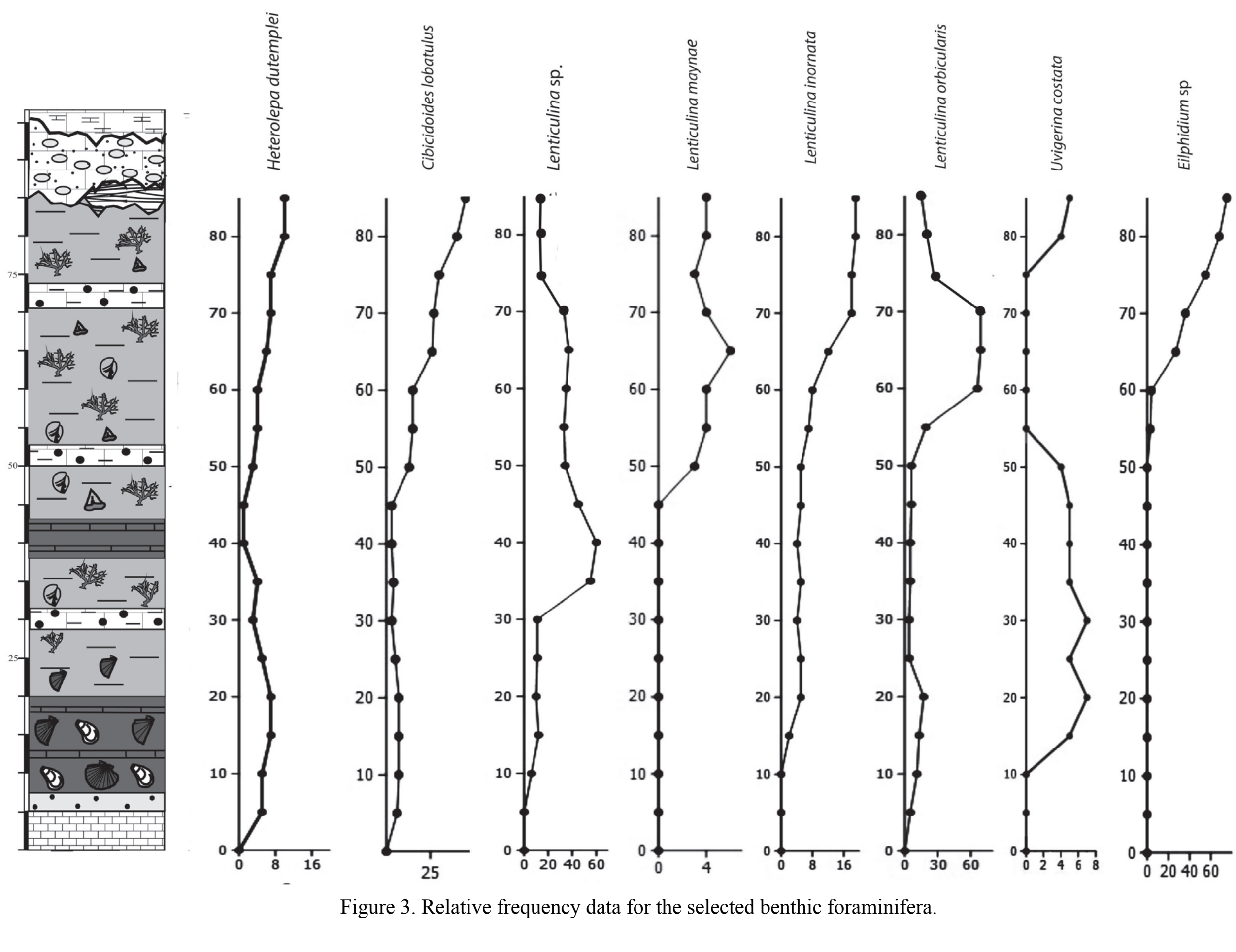

Figure 3. Relative frequency data for the selected benthic foraminifera.

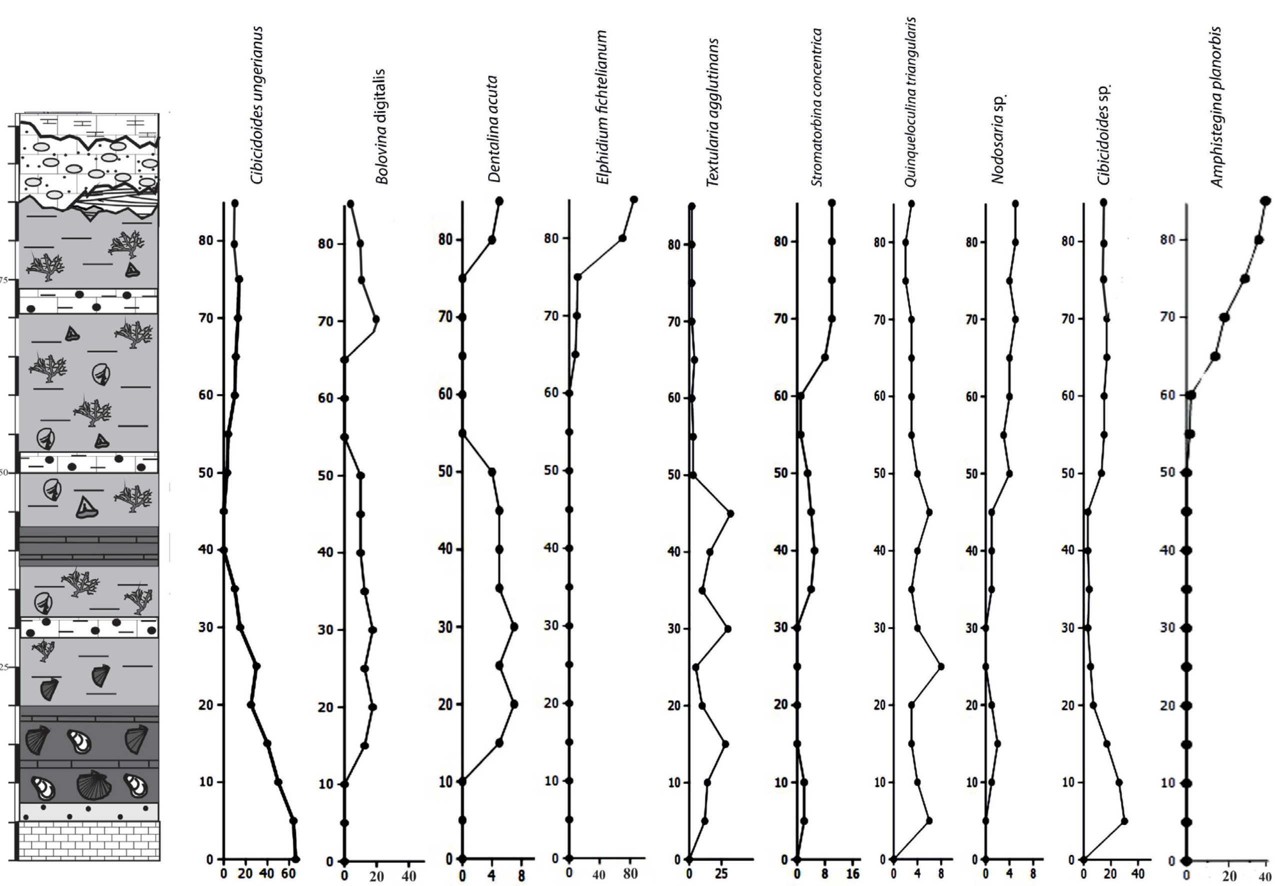

Figure 4. Relative frequency data for the selected benthic foraminifera.

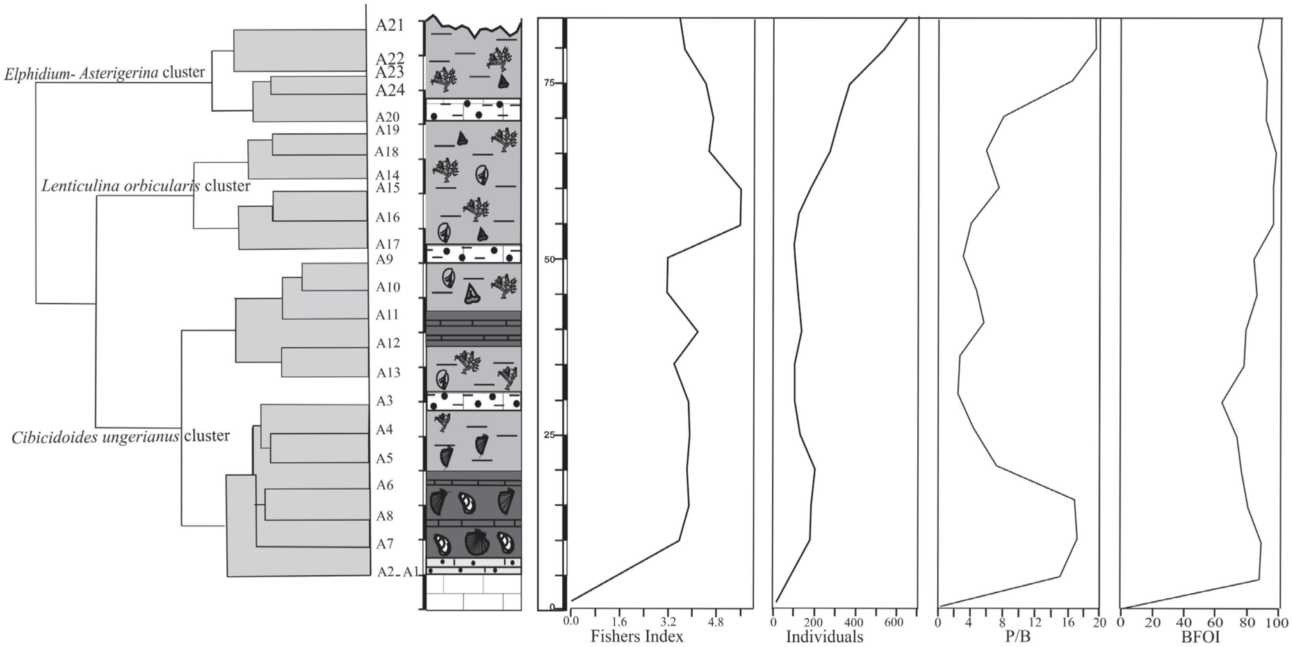

Figure 5. Classification of benthic foraminifer samples produced by Q-mode cluster analysis and distribution patterns of the Fisher's α diversity. Number of individuals, P/B ratios and Oxygen Index (*BFOI*).

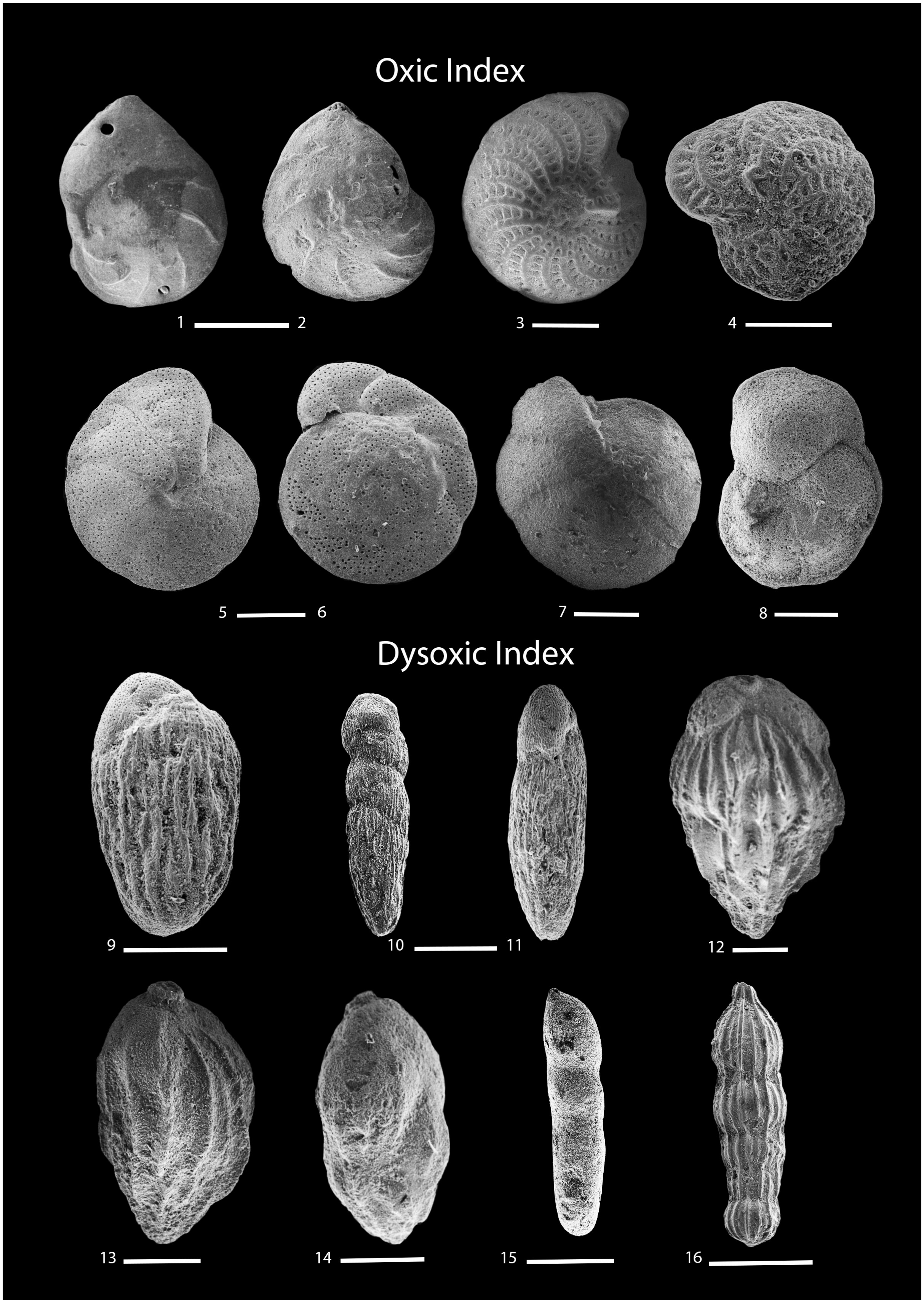

Figure 6. Benthic foraminifera IUIB1-16 (oxic- dysoxic indicator): (1) *Lenticulina maynae*; (2) *Lenticulina inornata*; (3) *Elphidium fichtelianum*; (4) *Elphidium* sp.; (5 – 6) *Heterolepa dutemplei*; umbilical view (5) and spiral view (6); (7) *Cibicidoides ungerianus*; (8) *Cibicidoides lobatulus*; (9) *Bolivina* sp.; (10-11) *Bolivina digitalis*; (12-14); *Uvigerina costata*; (15) *Laevidentalina communis*; (16) *Amphicoryna* sp. Scale bars = 200 µm.

is relatively moderate (Figure 5). The mean percentage of planktonic foraminifers is very low (7 %) and P/B ratios reaches mean values of 3.84 – 8 (Figure 5). Diversity of benthic foraminifers as well as planktonic foraminifers is low. All species belong to hyaline group, and agglutinated foraminifers of very small size decrease in number (2 %). *BFOI* ranges between 85.3 and 98 (Figures 5 and 6). Besides, sponge spicules, fragile bryozoan remains, and spine and fish teeth become abundant. The estimated paleodepth for this cluster based on foraminifer living depth is about 50 – 100 m (Murray, 1991; Holcová and Zágoršek, 2008; Pippèrr and Reichenbacher, 2010).

III) The *Elphidium-Amphistegina* cluster is recorded in the upper part of section (70 – 85 m). This cluster differs from other clusters and contains five samples, A21 – A24 (Figure 5). The assemblage is dominated by *Elphidium fichtelianum* / *Elphidium* sp. (25 %) and *Amphistegina planorbis* (13 %), and is accompanied by small *Lenticulina inornata* (9 %). Fisher's α diversity reaches values 4 – 5.1 (Figure 5). The percentage of planktonic foraminifers reaches up to 21 % with P/B ratios of 4 – 19.4 and the *BFOI* values are around 87 – 91 (Figure 5). Bryozoan and brachiopods are abundant with more diversity throughout this interval.

7. Paleosalinity

The interpretation of paleosalinity in the Bagh outcrop was measured based on biota assemblages. Frequency of bryozoans, brachiopods, echinoids and bivalves indicates normal marine salinity. In general, widespread uryhaline taxa (*e.g*. *Cibicidoides*, *Lenticulina* and *Elphidium*), along the profile indicate that normal sea-water salinity dominated. Low diversity, high abundance and small test- sized of foraminifers suggest a stable environment.

8. Paleoenvironment

Benthic foraminifer distribution and diversity is mainly dependent on oxygen concentration in pore water and organic flux (Gebhardt, 1999; Drinia *et al*., 2003) although the effect of temperature, water depth and salinity cannot be disregarded (Kaiho, 1994; Baas *et al*., 1998; Gebhardt, 1999; Pippèrr and Reichenbacher, 2010; Gupa *et al*., 2013). High oxygen content and organic flux cause eutrophic conditions. In such an environment, benthic foraminifers present low diversity and high abundance, which lead to oxygen consumption in bottom waters. A high percentage of benthic foraminifers indicates high productivity in a shallow basin or a lower sedimentation rate (Tyszka, 2001). The environmental interpretation follows the criteria established by Spezzaferri (1995) and Spezzaferri *et al*. (2002).

The distribution of benthic foraminifers in the Bagh succession is depicted in Figures 3 and 4. In the Bagh outcrop, *Lenticulina* and *Cibicidoides* are more abundant and indicate tolerance to high-oxygen (*BFOI* = 60 – 100) conditions (Kaiho, 1994; Van der Zwaan *et al*., 1990; Baas *et al*., 1998; Wilson, 2003; Stefanelli, 2004; Drinia *et al*., 2007, 2010; Holcová and Zágoršek, 2008; Pippèrr and Reichenbacher, 2010; Gupa *et al*., 2013). *Cibicidoides ungerianus* assemblages are found in the lower part of the Bagh section. *Textularia agglutinans* and *Quinqueloculina triangularis* are present in the lower part whereas in the middle and upper parts of the Bagh section gradually become more scarce. In the modern oceans, *Cibicidoides* species live in an inner neritic environment, approximately between 50 and 70 m in depth (Wilson, 2003; Holcová and Zágoršek, 2008; Pippèrr and Reichenbacher, 2010; Pippèrr, 2011), and in relatively high-energy environments of normal salinity in tropical to warm-temperate seas (Holcová and Zágoršek, 2008).

The paleodepth was estimated by percentage of planktonic foraminifers (P/B). According to Van der Zwaan *et al*. (1990), P/B ratios of < 20 % suggest inner shelf (inner neritic) environments (Pippèrr and Reichenbacher, 2010; Pippèrr, 2011).The high frequency stands for productivity and this was the result of an immense flood flux. This hypothesis is supported by high percentage of *Cibicidoides ungerianus* and *Cibicidoides* sp. in combination with high abundance of Bryozan bivalve fragments (*Spondylus coccineus*, *Pecten burdigalensis*, *Ostrea lamellose*, *Ostrea edulis* and *Ostrea gryphoides*) and echinoid spines (*Clypeaster intermedius*, *Arbacina* sp., *Eucidaris zaemays*, *Stylocidaris*? *Polyacantha* and *Prionocidaris* sp.). This assemblage supports deposition in shallow, inner neritic environments (Drinia *et al*., 2007, 2010; Holcová and Zágoršek, 2008; Pippèrr, 2011).

The middle part of the Bagh section is dominated by *Lenticulina* species. High frequency of *Lenticulina* taxa refer to a stable and suboxic environment (*BFOI* > 60) (Figure 6). The percentage of planktonic foraminifers is low (P/B < 10 %), therefore, it can be compared to sheltered coastal environments (Gibson, 1989; Drinia *et al*., 2007).

Frequency of *Lenticulina,* with low percentage of *Cibicidoides* genus, suggests possible slight oxygen depletion at the sea floor. *Lenticulina orbicularis* has been identified from middle-outer neritic to above the CCD (Pezelj *et al*., 2007, 2012). *Lenticulina orbicular*, in association with *Cibicidoides* sp., *Lenticulina inornata*, *Cibicidoides lobatulus* and *Cibicidoides ungerianus* reflect deposition in middle neritic waters with depths around 50 – 100 m. High abundance and low diversity are typical of eutrophic conditions. Finally, in the upper part of the Bagh succession, *Elphidium fichtelianum* / *Elphidium* sp. and *Amphistegina planorbis* are dominant genera and indicate deposition in an inner-middle neritic environment, while the percentage of planktonic foraminifers more than 10 %. This indicates the presence of an outer neritic environment. There is no evidence of benthic foraminifers typical of deep-water habitats while the abundance of

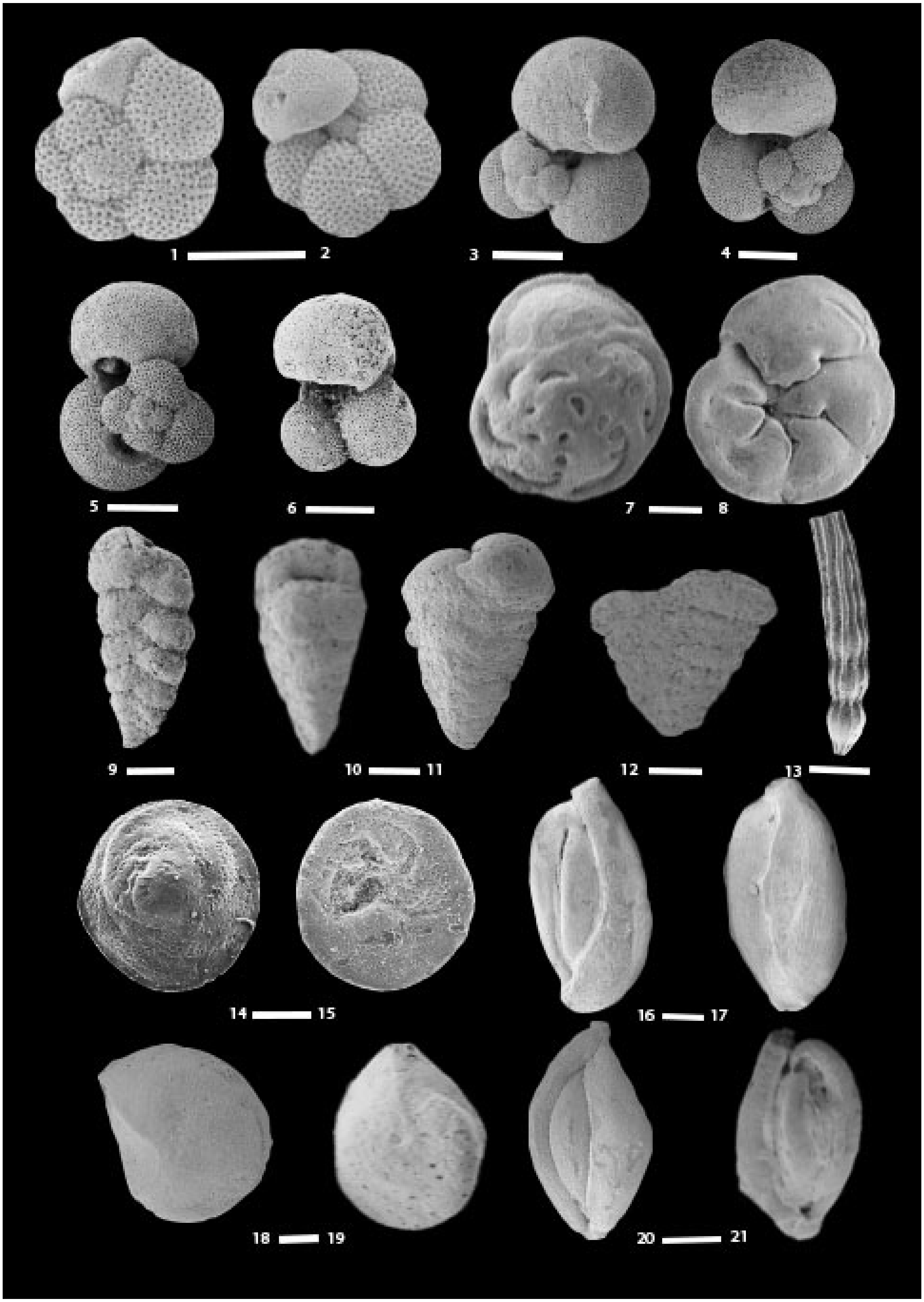

Figure 7. Benthic foraminifera IUIB17-37: (1 – 2) *Globigerina ottangiensis*; (3) *Globigerinoides premordius*; (4 – 6) *Globigerinoides trilobus*; (7 – 8) *Stomatorbina concentrica*; (9 – 11) *Textularia agglutinans*; Lateral view (9,11) and aperture view (10); (12) *Textularia mayori*; (13) *Dentalina acuta*; (14 – 15) *Sterigerinata planorbis*; (16 – 17) *Triloculina* sp.; (18 – 19) *Lenticulina inornata*; (20 – 21) *Quinqueloculina triangularis*. Scale bars = 200 µm.

Globigerinoides trilobus suggests an outer neritic to upper bathyal paleodepth (Murray and Alve, 1999; Wilson, 2003). Most of the *Elphidium* genus shows strong diversity and dissolution with small-size test. It can be concluded that the difference in the paleodepth, determined by the percentage of planktonic foraminifers and habitat preference of benthic foraminifers, suggest the post-mortem transport of euryhaline species to outer neritic environments. Larger tests and complete development of planktonic foraminifers indicate the more stable ecological conditions in this environment. Abundance of *Globigerinoides trilobus,* along this profile indicates warm-temperate to temperate climate (Van der Zwaan *et al*., 1990; Stefanelli, 2003), while the *Globigerina* group is abundant in upwelling areas, where cool waters bring nutrients to the surface and cause high productivity (Rögl and Spezzaferri, 2003). The highest abundance of *Globigerinoides* species is observed in the upper part of the Bagh succession. This fact can represent interspersion of local upwelling conditions or nutrients brought by fluvial currents. A similar condition has been reported from the western and central part of Paratethys (Rögl and Spezzaferri, 2003; Pezelj *et al*., 2012). Andreyva-Grigorovich *et al*. (1997) argued that, in the inner-middle neritic zone, the highly eutrophic environment may have been influenced by intensified upwelling of deeper waters and suggested that depths of 60 meters or more are needed to accommodate ocean upwelling dynamics when the winds blow parallel to the coast (Stassen *et al*., 2009). Paleodepth estimations of about 50 – 100 m and the presence of cool-water planktonic foraminifers support the scenario of local upwelling conditions in the succession.

9. Conclusions

The lower Miocene carbonate deposits of the Qom Formation are well exposed in the Bagh section, Northeast Isfahan (Central Iran). Lithostratigraphically, the formation unconformably overlies the Oligocene Lower Red Formation and underlies the middle Miocene Upper Red Formation. A systematic study and the taxonomic investigations of the foraminifers, as well as the stratigraphic vertical distribution of the planktonic foraminifers, resulted in the determination of the following planktonic foraminiferal zones, from base to top of the study succession:

1. The *Globigerinoides primordius* Zone spanning the lowermost part of the section and assigned to the Aquitanian (early Miocene);
2. The *Globigerinoides trilobus* Zone covering the uppermost part of the Qom Formation and assigned a Burdigalian age (early Miocene). The absence of *Catapsydrax dissimilis* Zone of early Burdigalian age may be attributed to ecological changes during the deposition of the Qom Formation.

Composition and abundance of calcareous benthic and planktonic foraminifers were examined for reconstruction of several environmental parameters such as oxygen content, bathymetry (paleodepth), temperature and salinity. The Q-mode cluster analyses performed on the benthic foraminifers led to the subdivision of the section into three distinct benthic foraminiferal clusters:

I. The *Cibicidoides ungerinanus* cluster is dominated and characterized by the predominance of eutrophic, warm water, marine salinity, highly oxygenated bottom waters, and species typical of high dissolved oxygen values (High Oxic Index).

II. The *Lenticulina orbicularis* cluster is represented in the middle part of section by only six samples characterized by deep-infaunal dysoxic and suboxic species indicative of middle neritic environments and strongly related to dissolved oxygen values and increased water depth.The benthic association with this cluster indicates warm water with normal marine salinity conditions.

III. The *Elphidium-Amphistegina* cluster is recorded in the upper part of the Bagh section and is characterized by a typical outer neritic environment.

The study sediments also showed an abundance of *Cibicidoides ungerianus*, *Textularia agglutinans*, *Quinqueloculina triangularis*, *Lenticulina orbicularis*, *Lenticulina inornata*, *Uvigerina costata*, *Lenticulina maynae*, *Heterolepa dutemplei*, *Bolivina digitalis*, *Cibicidoides* sp., *Elphidium fichtelianum*, *Elphidium* sp., and *Amphstegina planorbis*, which reflect an inner-middle neritic environment while the abundance of planktonic foraminifers in the upper succession refers to an outer neritic environment. Within outer neritic environment transportation of shallow benthic foraminifers to deeper water can clearly be observed. Abundance of epifaunal biota as well as lower species diversity and higher population of this community demonstrate a highly oxic environment, warm with normal salinity.

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