

# Biostratigraphy of the nummulitids and lepidocyclinids bearing Qom Formation based on larger benthic foraminifera (Sanandaj–Sirjan fore-arc basin and Central Iran back-arc basin, Iran)

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**Abstract** Qom Formation in the Sanandaj–Sirjan fore-arc and Central Iran back-arc basins was studied in order to determine its accurate age. Larger benthic foraminifera (mainly Lepidocyclinidae, Nummulitidae, and *Neoalveolina*) are biostratigraphically the main biota of the Qom Formation in the study areas. There are some debates concerning the age dating of the Qom Formation layers based on the presence or absence of *Nummulites* and *Eulepidina*. However, the last true *Nummulites* spp. became extinct at the top of Late Rupelian and all of the in situ *Nummulites* bearing layers of the Qom Formation belong to Rupelian in age. Lepidocyclinids, which originated in the Americas during the Middle Eocene, reached Iran in the Rupelian. The first appearance of *Lepidocyclina* spp. in our study sections, before the last occurrence of *Nummulites* spp., clearly indicates that the earliest Lepidocyclinidae reached Iran in the Rupelian. The Lepidocyclinids are widespread in the Chattian marine deposits of Iran. The presence of in situ *Nummulites* (with or without *Eulepidina*) in Qom Formation successions indicates an Early Oligocene (Rupelian) age, and the presence of *Eulepidina* without *Nummulites* suggests a Late Oligocene age (Chattian; possibly into Aquitanian). Moreover, *Nummulites intermedius*–*Nummulites vascus* Assemblage zone of Wynd (1965) and *Eulepidina*–*Nephrolepidina*–*Nummulites*

Assemblage zone of Adams and Bourgeois (1967), which were proposed for Oligocene (Rupelian–Chattian), should be ascribed to Rupelian in age. On the basis of biostratigraphy data and foraminifera assemblages, the Qom Formation is Rupelian–Chattian, Rupelian, and Rupelian–Burdigalian in age in Bujan, Varkan, and Qom (Khurabad) areas, respectively.

**Keywords** Qom Formation · Central Iran · Oligo-Miocene · Benthic and planktonic foraminifera · *Nummulites* · Tethyan Seaway

## Introduction

The marine Qom Formation was deposited at the north-eastern coast of the Tethyan Seaway (Reuter et al. 2009b), in the Oligo-Miocene, during the final sea transgression (Rahimzadeh 1994; Daneshian and Ramezani Dana 2007; Khaksar and Maghfouri–Moghadam 2007), in the Sanandaj–Sirjan fore-arc, Urumieh–Dokhtar magmatic arc (Intra-arc), and Central Iran back-arc basins (Mohammadi et al. 2013; Fig. 1). It is essential and important to study different properties of the oil-bearing Qom Formation because of economic importance and communicative role between Eastern Tethys (the proto-Indian Ocean) and the Western Tethys region (the proto-Mediterranean Sea) in the Iranian Plate at the same time (Mohammadi et al. 2011, 2013).

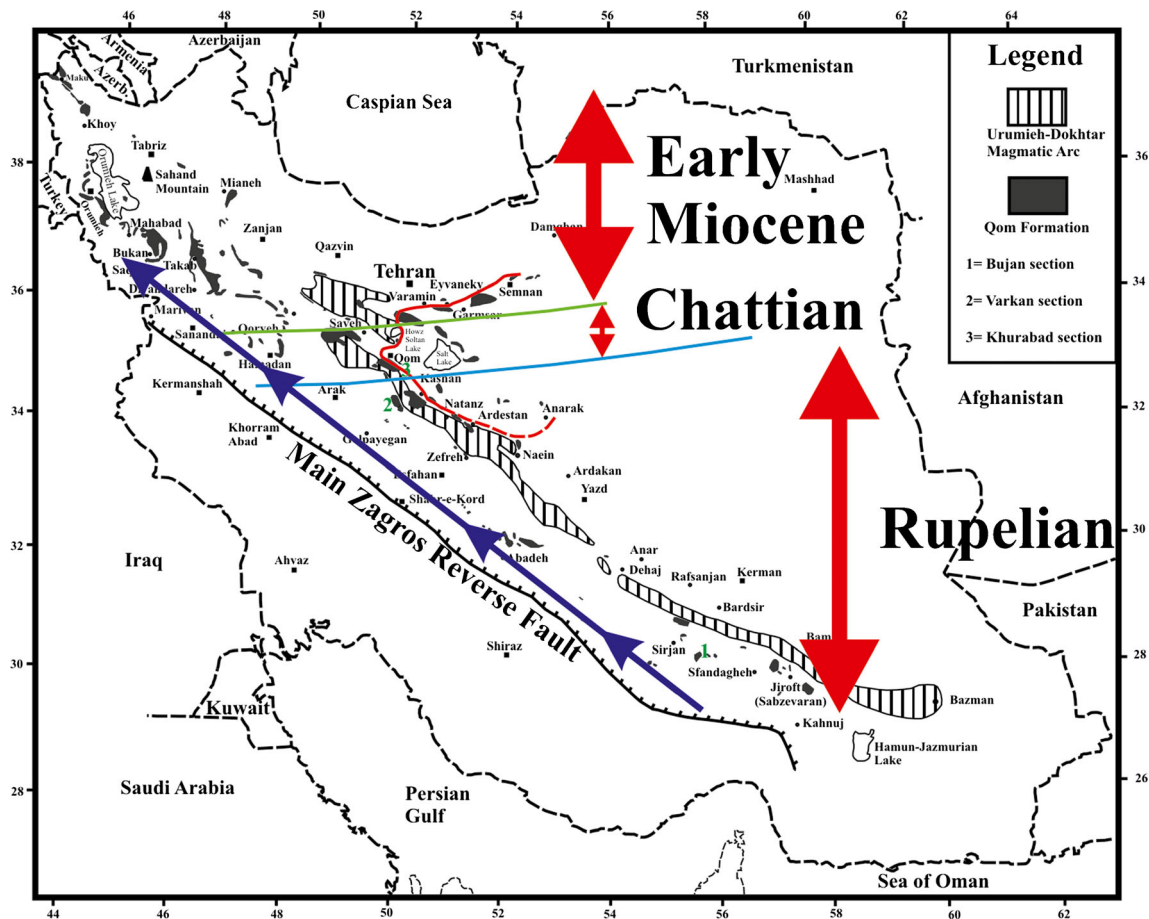
Biogenic components of the Oligo-Miocene Qom formation comprise of different biota including: larger benthic foraminifera (LBF) which are represented by nummulitids (*Nummulites*, *Operculina*, *Heterostegina*, *Spiroclypeus*), lepidocyclinids (*Eulepidina*, *Nephrolepidina*, *Lepidocyclina*), alveolinids (*Borelis*), miogypsinids (*Miogypsinoides*, *Miogypsina*), *Amphistegina*, *Archaias*, *Austrotrillina*, small benthic foraminifera (textulariids,

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**Fig. 1** A map showing (1) distribution of Tethyan Seaway Iranian Plate Oligo-Miocene deposits (Qom Formation); (2) distribution of Urumieh-Dokhtar Magmatic Arc (UDMA); (3) distribution of the Qom Formation evaporate deposits: deposition of evaporate deposits of the Qom Formation took place in concave side of the red line; and (4) time and trend of opening of the Tethyan Seaway on the Iranian plate. As indicated on the map, the Rupelian deposits of the Qom Formation deposited below 34°

20' N (blue line); the Chattian deposits continued to 35° N (green line) and above 35° N, deposition of the Qom Formation started in Miocene. The violent arrows show the direction of the transgression of the Tethyan Seaway on the Iranian plate; as indicated on the map transgression of the Tethyan Seaway on the Iranian plate started from southeast and continued northwestward gradually. The main cities and other places mentioned in the text and Table 1 are shown on this map (Mohammadi et al. 2013)

rotaliids, miliolids), planktic foraminifera, corals, coralline algae, bryozoans, bivalves, echinoderms, gastropods, and polychaete worm tubes especially *Ditrupa*. Among the biogenic components, LBF, which are the main biota of the Qom Formation in the study areas, are biostratigraphically important fossils in biozonation because of these episodes of rapid diversification and abrupt extinction (Hallock 1985; Beavington-Penney and Racey 2004).

The Foraminifera is a class of microscopic shelled protists. Foraminifera are the most abundant shelled microorganisms in benthic marine environments (Koukousioura et al. 2011). Simple forms of foraminifera appeared in the Cambrian and were common in the Early Palaeozoic. They became abundant, with the evolutionary development of relatively large and complicated test architecture, by the Late Palaeozoic, which provide a model example of evolutionary diversity throughout the Mesozoic and Cenozoic. This long and well-recorded evolutionary record makes foraminifera of outstanding value in zonal stratigraphy and palaeoenvironmental,

palaeobiological, and palaeoceanographic interpretation and analysis (BouDagher-Fadel 2008). Foraminifera that host algal endosymbionts are informally referred to as LBF (Baker et al. 2009). LBF are typically larger than 2 mm in diameter and 3 mm<sup>3</sup> in volume and have complex internal structures which, when studied in thin section, are useful for the biostratigraphy of Tethyan and other tropical limestones (Armstrong and Brasier 2005). The tests of dead, larger foraminifera are important rock-forming materials, and foram-limestones are extensively developed in the Upper Palaeozoic, the Upper Cretaceous, and in the Cenozoic. From their structural complexity, and because of the diversity of the shelf environments that they inhabited, fossil larger foraminifera provide unique information on palaeoenvironments and biostratigraphy of shelf limestones around the world (BouDagher-Fadel 2008). These protists are important as biostratigraphical indicators in marine rocks of Late Palaeozoic, Mesozoic, and Cenozoic ages because they are abundant, diverse, and easy to study (Armstrong and Brasier 2005). The larger foraminifera

assemblage zones could be identified by the presence of a few key taxa, usually with the use of a hand lens in the field. Some groups of larger foraminifera provide excellent biostratigraphic markers, sometimes the only ones which can be used to date carbonate successions (e.g., the fusulinines in the Upper Palaeozoic, orbitoidids in the Middle to Upper Cretaceous, nummulitids in the Palaeogene, and lepidocyclinids and miogypsinids in the Oligocene and Neogene (BouDagher-Fadel 2008)). Besides, foraminifera are typically a significant component of marine benthic communities, and can provide sensitive indicators of environmental conditions because of their short reproductive cycles, great abundance in marine and estuarine habitats, good test preservation (Koukousioura et al. 2011), stress tolerance, small size, and high diversity (Martínez-Colón et al. 2009).

Eocene/Oligocene boundary belongs to the most significant extinction events in the Phanerozoic (Nebelsick et al. 2005). Oligocene carbonate and mixed siliciclastic–carbonate platforms are characterized by the re-establishment of shallow water marine benthic communities following major changes at the Eocene/Oligocene boundary. The Oligocene epoch represents a time span dominated by larger foraminiferal and coralline algal facies in carbonate environments (Bassi and Nebelsick 2010). As biostratigraphic markers, various LBF are also key organisms for dating shallow water successions using the shallow benthic zones which have also been introduced for the Oligocene and Miocene (Cahuzac and Poignant 1997; Bassi and Nebelsick 2010).

According to next part and as shown in Table 1, mostly all of the previous works on the Qom Formation are limited to the middle parts of Iran. However, surprisingly little information is available concerning the different geological and paleontological properties (biostratigraphy, paleoenvironment, etc.) of the Qom Formation in the southeast of Iran. Besides, mostly all of the previous works are limited to one of the Sanandaj-Sirjan, Urumieh–Dokhtar, and Central Iran basins, and there are a few works that have compared different properties of the Qom Formation in the different basins. The aim of this study is therefore to bridge this gap by study and comparison of some stratigraphic sections in the Sanandaj-Sirjan and Central Iran basins in order to analyze their biostratigraphy, on the basis of LBF.

#### Previous works

Geological investigations of the Qom Formation started with the work of Loftus (1855) and continued by Tietze (1875), Stahl (1911), and Kuhn (1933). After oil was discovered in porous bioclastic limestones in 1934, the Qom Formation became the focus of scientific research as different properties of the Qom Formation have been studied by many authors (e.g., Loftus 1855; Tietze 1875; Stahl 1911; Kuhn 1933; Riben 1935; Furon and Marie 1939; Furon 1941; Dozy

1945, 1955; Furrer and Soder 1955; Gansser 1955; Abaie et al. 1963, 1964; Bozorgnia 1966; Rahaghi 1973, 1980). More recently, published researches on the Qom Formation were done by many authors which are listed in Table 1. Besides, Harzhauser (2000) and Mandic (2000) studied the gastropods and pectinid bivalves of the Qom Formation, respectively. However, both are unpublished PhD theses.

Mohammadi et al. (2013) have illustrated distribution of the Qom Formation on new maps showing the outcrops of the Qom Formation extended to east and southeast of the Sirjan depression in the southeast, northern, and southern of Great Kavir in the east, foothills of the Alborz Range in the north and northeast, north of Orumieh Lake (Khoy and Maku) in the northwest, and the southwest limit of the Qom Formation is coincident along with Orumieh–Mahabad–Saqqez–Hamadan–Esfahan–Abadeh–Sirjan–Jazmurian trend (Fig. 1).

Mohammadi et al. (2013) by scrutinizing (1) two stratigraphic sections of the Qom Formation in the southern and southwestern Kashan, (2) results of the study of more than 100 stratigraphic sections of the Qom Formation, (3) geological maps of Iran sheets, and (4) more than 30 geological maps of different parts of Iran, illustrated the distribution of Rupelian (Early Oligocene) and evaporate deposits as evidence for timing and trending of opening and closure of the Tethyan Seaway. Their study area encompasses more than 1,700 km (aerial distance) of the north-eastern coast of the Tethyan Seaway. They concluded that the Qom Formation is Rupelian–Burdigalian in age. Besides, Mohammadi et al. (2013) believed that evaporate deposits of the Qom Formation are deposited in a rather small area of Central Iran back-arc basin and are deposited totally in the Early Miocene (Aquitania–Burdigalian). This indicates that due to the compressive tectonic regime in the Central Iran back-arc basin, the gates to the open ocean became restricted in the Early Miocene gradually (Reuter et al. 2009b).

#### Geological setting

Iran is divisible into eight geological provinces. These provinces are: (1) Zagros, (2) Sanandaj–Sirjan, (3) Urumieh–Dokhtar (Sahand–Bazman) magmatic arc, (4) Central Iran, (5) Alborz, (6) Kopeh Dagh, (7) Lut, and (8) Makran accretionary prism, each province having experienced distinct tectonic and sedimentary histories (Heydari et al. 2003). The subduction of the Neo-Tethyan ocean floor beneath Iran (Late Cretaceous–Early Paleocene) sutured Iran to Arabia (Berberian and King 1981; Alavi 2004; Ghasemi and Talbot 2006), and the subsequent continental convergence built the Zagros Orogenic Belt. This orogenic belt consists of four NW–SE trending parallel zones: (1) Urumieh–Dokhtar Magmatic Assemblage (UDMA), (2) Sanandaj–Sirjan Zone (SSZ), (3) High Zagros, and (4) Zagros Simply Folded Belt

**Table 1** List of the more recently published researches on the Qom Formation plus their main properties

Row	Researcher(s)	Year	Number of studied sections	Sections' name	Location of studied section(s)	Local/regional	Original/comment/ review article
1	Okhravi	1998	3	Nardaghi (S of Qom), Khurabad (SE of Qom), Kamar Kuh (W of Qom)	Central Iran back-arc	Local	Original
2	Okhravi and Amini	1998	3	Nardaghi (S of Qom), Khurabad (SE of Qom), Kamar Kuh (W of Qom)	Central Iran back-arc	Local	Original
3	Schuster and Wielandt	1999	3	Abadeh, Chalheghareh (SE of Kashan), Qom	Sanandaj–Sirjan fore-arc basin and Central Iran back-arc	Regional	Original
4	Harzauser	2004	1	Abadeh	Sanandaj–Sirjan fore-arc basin	Regional	Original
5	Vaziri-Moghaddam and Torabi	2004	1	W of Ardestan	Central Iran back-arc	Local	Original
6	Seyrafian and Torabi	2005	1	N of Nain	Central Iran back-arc	Local	Original
7	Daneshian and Ramezani Dana	2007	1	N of Deh Namak (SW of Semnan)	Central Iran back-arc	Local	Original
8	Khalili et al.	2007	1	SE of Kashan	Central Iran back-arc	Local	Original
9	Khaksar and Maghfouri Moghadam	2007	1	Qom area	Central Iran back-arc	Local	Original
10	Zhu et al.	2007	2	SE and NW of Kashan	Central Iran back-arc	Local	Original but commented
11	Reuter et al.	2009b	4	Abadeh, Zefreh, (NW of Esfahan) Chalheghareh (SE of Kashan), Qom)	Sanandaj–Sirjan fore-arc basin and Central Iran back-arc	Regional	Original
12	Berning et al.	2009	1	Abadeh section	Sanandaj–Sirjan fore-arc basin	Local	Original
13	Reuter et al.	2009a	1	SE and NW of Kashan	Central Iran back-arc	Local	Comment
14	Hadavi et al.	2010	1	Kamar-Kuh area (W of Qom)	Central Iran back-arc	Local	Original
15	Behforouzi and Safari	2011	1	Chenar (NW of Kashan)	Urumieh–Dokhtar Intra-arc basin	Local	Original
16	Hasani and Vaziri	2011	1	Khavich Area (S of Sirjan)	Sanandaj–Sirjan fore-arc basin	Local	Original
17	Mohammadi et al.	2011	1	Jazeh (S of Kashan)	Urumieh–Dokhtar Intra-arc basin	Local	Original
18	Seddighi et al.	2011	1	Qom area	Central Iran back-arc	Local	Original
	Yazdi-Moghaddam	2011	1	Baranduz (S of Uromieh)	-	Local	Original
19	Mohammadi et al.	2013	More than 100		Sanandaj–Sirjan fore-arc basin, Central Iran back-arc and Central Iran back-arc	Regional ( more than 1700 km of the northeastern coast of the Tethyan Seaway)	Original and review
20	Yazdi et al.	2012	1	Dizlu area (NE Isfahan)	Sanandaj–Sirjan fore-arc basin	Local	Original

(Ghasemi and Talbot 2006; Shafiei et al. 2011). The SSZ extends for 1,500 km from Sanandaj in the NW to Sirjan (Shafiei et al. 2011). The UDMA forms a distinct linear intrusive–extrusive complex, which extends along the entire length of Zagros orogen, with a width of over 4 km (Ghasemi and Talbot 2006). Central Iran is separated from the SSZ by UDMA and a belt of steep and straight faults (Ghasemi and Talbot 2006).

The tectonic units of Central Iran originated during the subduction and final collision of the African/Arabian with the Iranian Plate (Schuster and Wielandt 1999). Northeastward subduction of the African–Arabian Plate underneath the Eurasian plates led to the formation of a volcanic arc (Urumieh–Dokhtar belt) during the Cretaceous to Eocene and compartmentalization of the region, creating the Esfahan–Sirjan (Sanandaj–Sirjan Zone) fore-arc and the Qom or Central Iran back-arc basins at the north-eastern margin of the Tethyan Seaway (Reuter et al. 2009b; Berning et al. 2009). The Eocene period of volcanism in Central Iran was followed by Late Eocene (37 Ma) movements, represented by a regional unconformity at the base of the Oligocene rocks. During this phase, the Lut zone in east-Central Iran underwent uplift (major Lut uplift), and no Oligocene–Miocene sediments were apparently deposited (Berberian and King 1981). Orogenic movements in the Late Eocene–Early Oligocene resulted in the creation of lagoonal to continental sedimentary regime characterized by detritic–evaporitic sediments of the Lower Red Formation (LRF; Khaksar and Maghfouri–Moghadam 2007). Following a short interval of intermediate to acid volcanic to subvolcanic activity and before final closure of the seaway during the latest Early Oligocene–latest Early Miocene, thick limestone and marl successions (the Qom Formation) were formed in three NW–SE-trending basins: Sanandaj–Sirjan (fore-arc basin), Central Iran (back-arc basin; Gilg et al. 2006; Berning et al. 2009), and Urumieh–Dokhtar magmatic arc (intra-arc basin (Mohammadi et al. 2013)). The Qom limestones are followed by thick continental red beds [the Upper Red Formation (URF)] with intercalated marine (to lacustrine?) evaporate deposits (gypsum and salt; Gilg et al. 2006). Rahimpour-Bonab and Kalantarzadeh (2005) believed that in the Early–Middle Miocene, development of restricted marine conditions led to a facies change from shelf carbonates of the Qom Formation to the evaporate series of the *MI* member of the overlying URF. The URF consists of sandstones, marls, and inter-layered evaporates which mostly are present in the lower parts.

### Study area and methods

Three stratigraphic sections of the Qom Formation were measured and sampled bed by bed in order to analyze their biostratigraphic conditions. They included (1) the Bojan

section with these coordinates: 29° 26' 04" N, 55° 59' 27" E, about 40 km eastern Sirjan City, (2) Varkan section with these coordinates: 33° 41' 29" N, 51° 04' 54" E, about 75 km southwestern Kashan City, and (3) Khurabad (Khourabad in Mohammadi et al. 2013) section with these coordinates: 34° 30' 53" N, 50° 56' 58" E, about 20 km southeastern Qom City (Fig. 1). Based on Schuster and Wielandt (1999), Reuter et al. (2009b), Berning et al. (2009), Mohammadi et al. (2013) geological maps of Sirjan (Soheili 1995), Kashan (Zahedi and Amidi 1991), and Qom (Hajian and Emammi 1991) and Geological Maps of Iran Sheets (no. 1, 2, and 5; NIOC 1969, 1978, 1977), Bojan and Varkan sections are located in the Sanandaj–Sirjan fore-arc basin and Qom section is located in Central Iran back-arc basin (Fig. 1). Outcrops of the Qom Formation in Bujan area with 156-m thickness mainly consist of medium to thick bedded and massive limestone, shale, and marl (Fig. 4). They lay unconformably on top of the polygenetic conglomerate with indeterminate age (Fig. 4), and their upper boundary is covered by quaternary alluvium. The Qom Formation Outcrops in the Varkan area, with 190-m thickness, consist mainly of medium to thick bedded and massive limestone, marly limestone, marl, and conglomerate (Fig. 6). They lay unconformably on top of the LRF, and their upper boundary is covered with polymictic Pliocene conglomerate (Fig. 6). Outcrops of the Qom Formation in Qom area (Khurabad), with 260-m thickness, consist mainly of medium to thick bedded and massive limestone, marly limestone, nodular, limestone, shale and marl, sandstone, conglomerate, and evaporate deposits (Fig. 9). They lay on top of the Eocene volcanic rocks, and their upper boundary is covered with URF (Fig. 9). Field and microscopic studies were carried out for biostratigraphical analysis of the studied sections. Up to 330 samples were collected based on field evidences and lithofacies changes. Thin sections were obtained from harder samples, while softer samples were disaggregated and their microfauna were processed, and finally thin sections and released specimens were analyzed. All samples were studied in detail, and particular attention has been paid to the larger benthic foraminiferal associations, since they are excellent bio-indicators for age dating and paleoenvironmental interpretation. Obtained foraminifera were identified based on different studies by Stainforth et al. (1975), Rahaghi (1980), Loeblich and Tappan (1988), Boudagher-Fadel and Lord (2000), Boudagher-Fadel and Lokier (2005), Iaccarino and Premoli Silva (2005), Sharaf et al. (2005), BouDagher-Fadel (2008), Kuss and Boukhary (2008), Özcan et al. (2009), and BouDagher-Fadel and Price (2010). The fossil contents of the study section are so well preserved, abundant, and diverse that these conditions improved this investigation's process. The last occurrence of the *Nummulites*, the time range of Lepidocyclinids (genera/subgenus), the first appearance, and last occurrence of Lepidocyclinids in Iran are studied and analyzed based on several previous researches and are shown

	Wynd (1965)		Adams & Bourgeois (1967)		Laursen et al. (2009) & Van Buchem et al. (2010)		Author (s)		
	Borelis melo curdica (zone 61)		Borelis melo – Meandropsina iranica		Borelis melo curdica – B. melo melo		Stage	Epoch	Age Ma
Aquitanian	Austrotrilina howchini – Peneroplis evolutus (zone 59) (includes: M. anahensis, B. pygmaea, P. Delicata)		Miogypsinoidea – Archaia – Valvulinid	Elphidium sp. 14 – Miogypsina	Miogypsina – Elphidium sp. 14 – Peneroplis farsenensis		Aquitanian	Miocene	15.97
				Archaia asmaricus – Archaia hensoni					Indeterminate Zone
Oligocene undivided	Archaia operculiniformis (zone 58)	Nummulites intermedius – N. vascus (zone 57)	Eulepidina – Nephrolepidina – Nummulites	Archaia asmaricus – A. hensoni – Miogypsinoidea complanatus		Chattian	Oligocene	23.03	
	Lepidocyclina – Operculina – Ditrupa (zone 56)	Globigerina spp. (Zone 55)						28.4	
			Globigerina	Nummulites vascus – Nummulites fichteli		Rupelian		33.9	
				Lepidocyclina – Operculina – Ditrupa Globigerina spp. – Turborotalia cerroazulensis – Hantkenina					

**Fig. 2** Biozonations of the Asmari Formation, after Wynd (1965), Adams and Bourgeois (1967), Laursen et al. (2009), and Van Buchem et al. (2010). Absolute ages are based on Gradstein et al. (2005)

in different Tables in this paper. Besides, age of the study sections is determined according to several authors including: Wynd (1965), Adams and Bourgeois (1967), Rahaghi (1980), Adams (1984), Loeblich and Tappan (1988), Racey (1995), Cahuzac and Poignant (1997), Beavington-Penney and Racey (2004), Harzhauser (2004), Ehrenberg et al. (2007), BouDagher-Fadel (2008), Laursen et al. (2009), BouDagher-Fadel and Price (2010), Van Buchem et al. (2010), and Mohammadi et al. (2013).

## Discussion

There is no formal biozonation for the Qom Formation. However, conspicuous similarity is observed between the Qom Formation foraminifera and those of the Asmari Formation (Zagros region, SW Iran) by many authors correlating the Qom Formation with the Asmari Formation (Bozorgnia 1965; Daneshian and Dana 2007; Mohammadi et al. 2011). LBF, which are the main biota of the Qom Formation in the study sections, are biostratigraphically important fossils in biozonation.

Biostratigraphy criteria of the Asmari Formation was established by Wynd (1965) and reviewed by (Adams and Bourgeois 1967); however, both are unpublished reports. Adams and Bourgeois (1967) designed four assemblage zones for the Asmari Formation (Fig. 2). They could not recognize the stages of the Oligocene as individual.

Biostratigraphically, *Nummulites* and *Lepidocyclinids* are more important for age dating of Rupelian, Chattian (and Aquitanian) deposits of the Qom, and Asmari formations. Racey (1994) believed that the presence of *Nummulites* indicates an Early Oligocene age, and the presence of *Eulepidina* without *Nummulites* suggests a late Oligocene age. But *Eulepidina* has been reported with *Nummulites* in Late Oligocene and without *Nummulites* in Early Miocene by some researchers (e.g., Bozorgnia 1966; Adams and Bourgeois 1967). Besides, using Sr isotope dating, Ehrenberg et al. (2007) and Laursen et al. (2009) believed that the last occurrence of *Nummulites* in the Asmari Formation was recorded before the end of Rupelian time. As cited above, there are some debates concerning the age dating of the Qom Formation layers based on the presence or absence of *Nummulites* and *Eulepidina*. Therefore, their ranges are discussed in the following sections (Tables 2, 3, and 4).

### *Nummulites* range

The Nummulitidae are common throughout the Cenozoic, and most of them are extant. They are in fact the largest extant calcareous foraminifera (BouDagher-Fadel 2008). Living nummulitids are widely distributed in modern tropical and subtropical shallow-water seas and achieve their highest diversity in the subtropical and tropical West Pacific (BouDagher-Fadel 2008). Several nummulitids genera, especially *Assilina* and *Nummulites*, are particularly useful for

**Table 2** The last occurrence of the *Nummulites* based on different authors

Genus/species	Researcher(s)	year	the last occurrence	Area/region
<i>Nummulites intermedius</i>	Rahaghi	1980	Rupelian	SW Kashan
<i>Nummulites</i>	Adams	1984	Near the end of Rupelian	
<i>Nummulites</i>	Loeblich and Tappan	1988	Holocene	Tropical and subtropical cosmopolitan
<i>Nummulites</i>	Racey	1995	Near the end of Rupelian	N Oman
<i>Nummulites</i>	Cahuzac and Poignant	1997	Chattian	
<i>Nummulites</i>	Beavington-Penney and Racey	2004	Early Oligocene	
<i>Nummulites sublaevigatus</i>	Harzhauser	2004	Early Oligocene	N Abadeh (Qom Formation)
<i>Nummulites</i>	Ehrenberg et al.	2007	Before the end of Rupelian	SW Iran (Asmari Formation)
<i>Nummulites</i>	BouDagher-Fadel	2008	Late Rupelian	
<i>Nummulites</i>	Laursen et al.	2009	Before the end of rupelian	SW Iran (Asmari Formation)
<i>Nummulites</i>	Van Buchem et al.	2010	Before the end of rupelian	SW Iran (Asmari Formation)

zoning Tethyan shelf sequences (Haynes et al. 2010). *Nummulites* are good markers for Early Tertiary (Eocene, Oligocene) sedimentary sequences in the Tethyan realm. The species of this genus have evolved very rapidly and are classified into evolutionary groups which have common characteristic morphologic features that undergo changes during evolution (Boukhary and Scheibner 2009). In the Eocene, *Nummulites* and *Assilina* witnessed a major radiation and

increase in test size, which persisted up to the major extinction of the last large species at the Middle–Late Eocene boundary. Few small species of *Nummulites*, but no *Assilina*, survive into the Late Eocene, and *Nummulites* finally became extinct in the end of Early Oligocene (BouDagher-Fadel 2008).

As shown in Table 2, all of the recent works (published since 2000) plus most of the older ones attribute the last occurrence of *Nummulites* to the Late Rupelian. For example,

**Table 3** The ranges of Lepidocyclinids (genera/subgenus) based on different authors

Genus	Researcher(s)	year	the age range	Area/region
<i>Nephrolepidina</i> Douville, 1911	Loeblich and Tappan	1988	Middle Eocene to Early Miocene (Burdigalian)	N and S America, Europe, N Africa, Indo-Pacific
<i>Nephrolepidina</i> Douville, 1911	BouDagher-Fadel	2008	Middle Eocene (Lutetian, in America), Late Oligocene (Early Chattian, P21b in the Mediterranean, Late Chattian, P22 in the Indo-Pacific province) to Early Miocene (in America), Middle Miocene (in Tethys) (Serravallian)	America, Mediterranean, Indo-Pacific, Tethys,
<i>Nephrolepidina</i> Douville, 1911	BouDagher-Fadel and Price	2010	Middle Eocene (Lutetian, P10) to Early Miocene (Burdigalian, N7 in America), Late Oligocene in Mediterranean (Early Chattian, P21b) and Indo-Pacific (Late Chattian, P22) to late Miocene (Early Pliocene?) in the Tethyan province.	America, Mediterranean, Indo-Pacific, Tethys
<i>Eulepidina</i> Douville, 1911	Loeblich and Tappan	1988	Rupelian to Aqitanaian	N and S America, Europe, Africa, Asia, Australia
<i>Eulepidina</i> Douville, 1911	BouDagher-Fadel	2008	Oligocene (Rupelian, P18 in America, P19 in Tethys) to Miocene (Middle Burdigalian)	America, Tethys
<i>Eulepidina</i> Douville, 1911	BouDagher-Fadel and Price	2010	Early Oligocene (Rupelian, P18 in America, P19 in Tethys) to Early Miocene (Middle Burdigalian, N12)	America, Tethys
<i>Lepidocyclina</i> Gümbel, 1870	Loeblich and Tappan	1988	Middle Eocene to Early Miocene (Aqitanaian)	N and S America
<i>Lepidocyclina</i> ( <i>Lepidocyclina</i> ) Gümbel, 1870	BouDagher-Fadel	2008	Middle Eocene (Lutetian in America) to Early Miocene (in America), Oligocene (in Tethys)	America, Tethys
<i>Lepidocyclina</i> ( <i>Lepidocyclina</i> ) Gümbel, 1870	BouDagher-Fadel and Price	2010	Middle Eocene (Lutetian, P10) to Early Miocene (Burdigalian, N7) in America, Oligocene in Tethys (P18–P22)	America, Tethys
<i>Lepidocyclina</i> sp. <i>sensu lato</i> Gümbel, 1870	BouDagher-Fadel	2008	Middle Eocene (in America), ?Early Oligocene/Late Oligocene (in Tethys) to Early Miocene (in America) and Middle Miocene (Serravallian, in Tethys)	America, Tethys
<i>Lepidocyclina</i> sp. Gümbel, 1870	BouDagher-Fadel and Price	2010	Middle Eocene (P10) to Early Miocene (N7) in America; Early/Late Oligocene to Late Miocene (Early Pliocene?) in Tethys	America, Tethys

**Table 4** Time of the first appearance (FA) of Lepidocyclinids in Iran

Row	Area/region	Researcher(s)	year	The FA of Lepidocyclinids	Description
1	Jovsheghan-e-ghali (SW Kashan)	Rahaghi	1980	Rupelian	<i>Nephrolepidina</i> sp. and <i>Eulepidina</i> aff. <i>Dilatata</i> are co-occurred with <i>Nummulites intermedius</i>
2	Lali (N Ahwaz)	Vaziri-Moghaddam et al.	2006	Rupelian	Assemblage 1: is corresponds to the <i>Eulepidina-Nephrolepidina-Nummulites</i> assemblage zone of Adams and Bourgeois (1967)
3	Tang-e-Gurgdan (NW Gachsaran)	Amirshahkarami et al.	2007a, b	Rupelian	Assemblage 1: is correlated with <i>Eulepidina-Nephrolepidina-Nummulites</i> assemblage zone of Adams and Bourgeois (1967)
4	SW Iran (Asmari Formation)	Laursen et al.	2009	Rupelian	For more information see Fig. 1 and main text of Laursen et al. 2009
5	Tang-e Abolhayat (W Shiraz)	Sadeghi et al.	2009	Rupelian	The first appearance of <i>Eulepidina dilitata</i> , <i>Eulepidina elephantina</i> , <i>Nephrolepidina tournoueri</i> , <i>Lepidocyclina</i> sp., occurred before the last occurrence of <i>N. vascus-incrassatus</i> group
6	Lali (N Ahwaz)	Sadeghi et al.	2009	Rupelian	The first appearance of <i>Eulepidina dilitata</i> , <i>Eulepidina elephantina</i> , <i>Nephrolepidina tournoueri</i> , <i>Lepidocyclina</i> sp., occurred before the last occurrence of <i>N. vascus</i>
7	Rag-e-Safid oil field (SE Ahwaz)	Amirshahkarami et al.	2010	Rupelian	Assemblage I: corresponds to the <i>N. vascus-N. fichteli</i> assemblage zone of Laursen et al. (2009) and <i>Eulepidina-Nephrolepidina-Nummulites</i> biozone of Adams and Bourgeois (1967)
8	Firozabad section (SSW Shiraz)	Kalanat et al.	2010	Rupelian	The first appearance of <i>Eulepidina dilatata</i> , <i>Eulepidina elephantina</i> , <i>Lepidocyclina</i> sp., <i>Nephrolepidina tournoueri</i> , occurred before the last occurrence of <i>N. fichteli-intermedius</i> group and <i>N. vascus-incrassatus</i> group; based on Vaziri-Moghaddam et al. (2011) Assemblage zone I of this section is correlated with <i>N. vascus-N. fichteli</i> assemblage zone of Laursen et al., (2009)
9	SW Iran (Asmari Formation)	Van Buchem et al.	2010	Rupelian	For more information see Fig. 15 and main text of Van Buchem et al. 2010
10	Naura anticline (SE Shiraz and Firozabad)	Sooltanian et al.	2011	Rupelian	The first appearance of <i>Lepidocyclina</i> sp., <i>Eulepidina</i> sp., <i>Eulepidina dilatata</i> , <i>Eulepidina elephantina</i> , <i>Nephrolepidina</i> sp., <i>Nephrolepidina</i> cf. <i>marginata</i> , occurred before the last occurrence of <i>N. vascus</i> and <i>N. fichteli</i>

Beavington-Penney and Racey (2004) believed that from among the principal nummulitid genera, only *Operculina*, *Palaeonummulites*, *Heterostegina*, and *Cycloclypeus* have extant descendants; *Nummulites* became extinct in the Early Oligocene, *Assilina* in the late Middle Eocene, *Ranikothalia* in the late Palaeocene, and *Spiroclypeus* in the Early Miocene. It is worth mentioning that, some researchers (e.g., Hohenegger 2000) refer to one living species of *Nummulites* (*Nummulites venosus*) from the Pacific, although this has closer affinities with *Operculinella*, and following the more recent revised classification of Haynes et al. (2010) should be reassigned to *Palaeonummulites*. Besides, BouDagher-Fadel (personal communication 2011) believed that all megalospheric large *Nummulites* with large proloculus disappeared in the Late Rupelian. And that the small *Nummulites* (or *Nummulites*-like foraminifera) which are mainly called *Paleonummulites/Operculinoides*, etc., are still living today (BouDagher-Fadel, personal communication 2011; Mohammadi et al. 2013).

BouDagher-Fadel (2008) in her great book “*Evolution and Geological Significance of Larger Benthic Foraminifera*” noted that the range of *Nummulites* is from Middle

Palaeocene to Early Oligocene. She believed that the extinction of *Nummulites* can be correlated with the Rupelian stage and planktonic zones P18-P21a. The last true *Nummulites* spp. became extinct at the top of the Td “Letter Stage” (Late Rupelian) with *Nummulites fichteli* from the upper Early Oligocene of Italy (BouDagher-Fadel 2008).

#### Lepidocyclinids ranges

Lepidocyclinids are important elements of Tertiary larger foraminiferal assemblages in Iran and in many other parts of the world. They originated in the Americas during the Middle Eocene and migrated eastward through the Tethyan/Mediterranean corridor and reached Iran in the Rupelian (BouDagher-Fadel 2008; BouDagher-Fadel and Price 2010). In Iran they have been recorded from sedimentary sequences of Early Oligocene (Rupelian) to Early Miocene times of the Qom and Asmari formations.

The LBF family Lepidocyclinidae has been described extensively in the literature, with occurrences ranging from the Middle Eocene in the Americas to the Late Miocene (or possibly Early Pliocene) in the Indo-Pacific



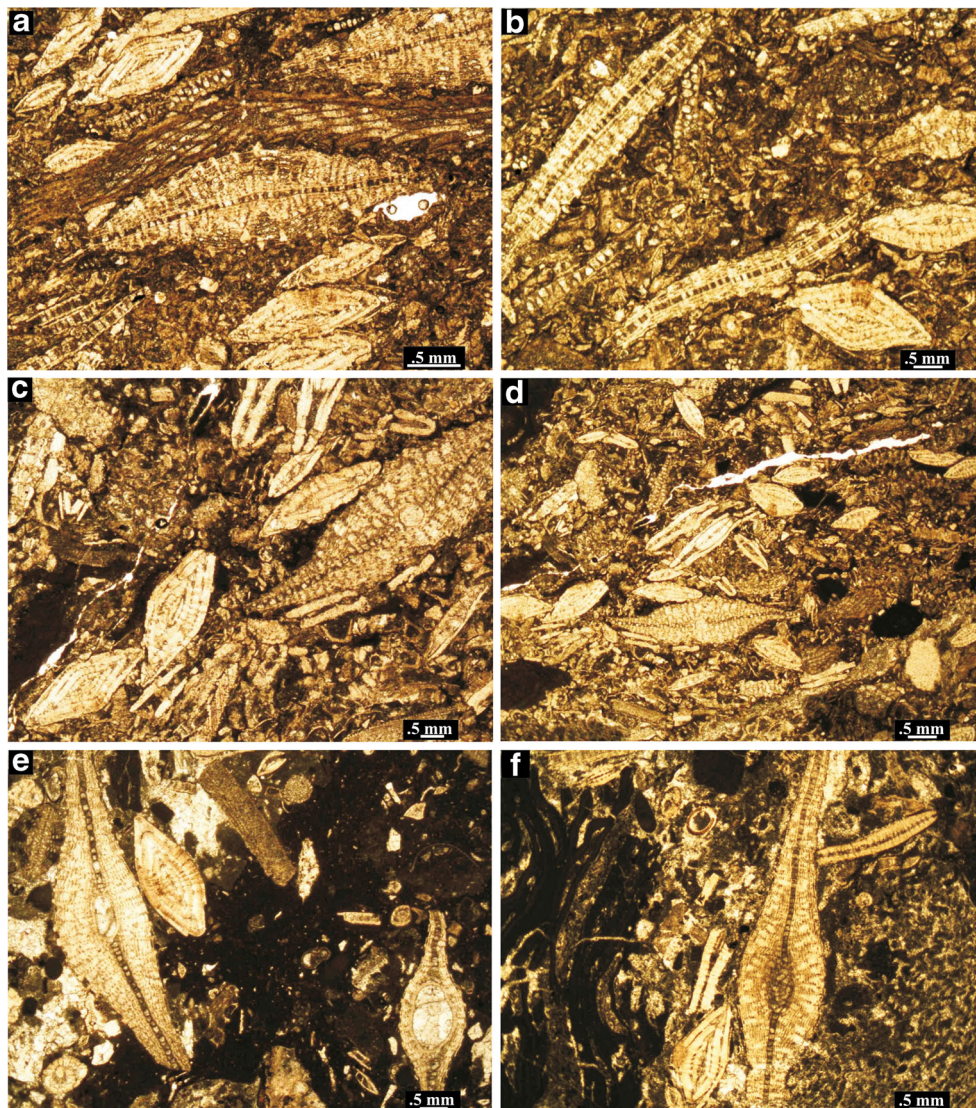
Tethyan sub-province (BouDagher-Fadel and Price 2010; Table 3). *Lepidocyclus* (*Lepidocyclus*) of Tethys was almost certainly the direct descendant of *Lepidocyclus* (*L.*) of the Eocene and Oligocene to Early Miocene of Central America (BouDagher-Fadel 2008). By the study of new samples from 37 wells drilled off South America, and systematic comparisons of the Lepidocyclusidae from the South America and the Tethyan sub-provinces of the Mediterranean–West Africa and the Indo-Pacific, BouDagher-Fadel and Price (2010) traced the timing and route of the paleogeographic migration of the lepidocyclusids from the Americas, through the Tethyan/Mediterranean corridor, and into the Indo-Pacific region. These authors believed that Lepidocyclusids originated in the Americas during the Middle Eocene, Lutetian; but related forms are reported from West Africa from the Middle Eocene–Early Oligocene pointing to an eastward migration. They only reached the Mediterranean during the Early

Oligocene, filling ecological niches that had previously been occupied in the Eocene by *Nummulites*. This migration continued within the Tethys until the lepidocyclusids finally colonized the Indo-Pacific in the late Early Oligocene (BouDagher-Fadel and Price 2010).

#### Iranian lepidocyclusids ranges

BouDagher-Fadel (2008) and BouDagher-Fadel and Price (2010) figured *Lepidocyclus* (*Nephrolepidina*) *marginata* (Michelotti)=*L.*(*Nephrolepidina*) *tournoueri* Lemoine, and Douvillé from Rupelian (Early Oligocene) deposits of Iran (Rahaghi NHM collection). Besides, there is clear evidence confirming that the first appearance of *Lepidocyclus* spp. in Iran occurred in the Rupelian (before the last occurrence of *Nummulites* spp.; see below).

**Fig. 3** Co-occurrence of Lepidocyclusids and *Nummulites* spp. in the study sections clearly indicates that the Lepidocyclusids reached Iran in the Rupelian (Early Oligocene). **a–d** Khurabad section, **e–f** Varkan section



The first appearance of *Lepidocyclina* spp. before the last occurrence of *Nummulites* spp. and co-occurrence of Lepidocyclinids and *Nummulites* spp. in the study sections (Bujan, Varkan, Khouarabad) clearly indicate that the earliest Lepidocyclinidae reached Tethys (Iran) in the Rupelian (Fig. 3). This feature is corroborated by the senior author's investigations from some other sections of the Qom Formation (e.g., Jazeh and Abadeh).

Schuster and Wielandt (1999) recorded the last occurrence of *Nummulites* at the end of the East Indian Letter Stage Td (in the Qom Formation deposits of Abadeh section). However, they recorded the first appearance of *Lepidocyclina* (*Eulepidina*) *formosoides*, *Lepidocyclina* (*Eulepidina*) *favosa*, and *Lepidocyclina* (*Nephrolepidina*) *morgani* at the beginning of the East Indian Letter Stage Td. In other words, Schuster and Wielandt (1999) recorded the first appearance of *Lepidocyclina* before the last occurrence of *Nummulites*.

Similarly, in Oligo-Miocene Asmari Formation (SW Iran) the first appearance of *Lepidocyclina* spp. occurred before the last occurrence of *Nummulites* spp. in several stratigraphic sections (Table 4) including: (1) Lali section (N Ahwaz, Vaziri-Moghaddam et al. 2006), (2) Tang-e-Gurgdan (NW Gachsaran, Amirshahkarami et al. 2007a), (3) Tang-e Abolhayat (W Shiraz, Sadeghi et al. 2009), (4) Lali section (N Ahwaz, Sadeghi et al. 2009), (5) Firozabad section (SSW Shiraz, Kalanat et al. (2010), Vaziri-Moghaddam et al. 2011), (6) Rag-e-Safid oil field (SE Ahwaz, Amirshahkarami et al. 2010), and (7) Naura anticline (SE Shiraz, Sooltanian et al. 2011).

The first appearance of Lepidocyclinids before the last occurrence of *Nummulites* spp. in several stratigraphic sections of the Qom (Bujan, Jazeh, Khouarabad, Varkan, Abadeh) and Asmari (Lali, Naura anticline, Tang-e Abolhayat, Tang-e-Gurgdan, Firozabad, Rag-e-Safid oil field) formations (Table 4) clearly indicates that the earliest Lepidocyclinidae reached Tethys (Iran) in the Rupelian (Early Oligocene).

Concerning the last occurrence of *Lepidocyclina* spp. in Iranian deposits (Table 5), it should be mentioned that Reuter et al. (2009b) recorded *Lepidocyclina* spp. from Aquitanian deposits of Qom, Zefreh, and Chalheghareh sections, and Burdigalian deposits of Zefreh section. Likewise, the last occurrence of *Lepidocyclina* spp. in Asmari Formation was recorded from Aquitanian deposits of Dehluran and Kabirkuh-Darrehshahr (by Vaziri-Moghaddam et al. 2010), and the Chattian deposits of several other stratigraphic sections (Khaviz Anticline, Rahmani et al. 2009; Lali section, Sadeghi et al. 2009; Tang-e Abolhayat, Sadeghi et al. 2009; Firozabad section, Vaziri-Moghaddam et al. 2011; Naura anticline, Sooltanian et al. 2011). It is worth mentioning that, Amirshahkarami et al. (2007a, b), recorded Lepidocyclinids from Aquitanian deposits of Tang-e-Gurgdan and Chaman-Bolbol sections, respectively (Asmari Formation), but considering new biozonation of the Asmari Formation, suggested by Laursen et al. (2009), their recorded Lepidocyclinids may be ascribed to Chattian in age.

As mentioned above, there are some debates concerning the age dating of the Qom Formation layers based on the presence/absence of *Nummulites* and *Eulepidina*. Racey (1994) believed that the presence of *Nummulites* indicates

**Table 5** Time of the last occurrence (LO) of Lepidocyclinids in Iran

Row	Area/region	Researcher(s)	Year	The LO of Lepidocyclinids	Description
1	Mashhad (NW Kashan)	Rahaghi	1980	Aquitania	Rahaghi (1980) recorded <i>Eulepidina dilatata</i> (A+B) (without <i>Nummulites</i> ) from Aquitanian of Mashhad section.
2	Qom and Chalheghareh	Reuter et al.	2009b	Aquitania	For more information see Figs. 6, 7, 8, and 9 and main text of Reuter et al. 2009b
3	Zefreh	Reuter et al.	2009b	Burdigalian	For more information see Figs. 6, 7, 8 and 9 and main text of Reuter et al. 2009b
4	SW Iran (Asmari Formation)	Laursen et al.	2009	Aquitania	For more information see Fig. 1 and main text of Laursen et al. 2009
5	Khaviz Anticline	Rahmani et al.	2009	Chattian	Lepidocyclinids are widespread in the Chattian deposits
6	Lali	Sadeghi et al.	2009	Chattian	Lepidocyclinids are widespread in the Chattian deposits
7	Tang-e Abolhayat	Sadeghi et al.	2009	Chattian	Lepidocyclinids are widespread in the Chattian deposits
8	SW Iran (Asmari Formation)	Van Buchem et al.	2010	Rupelian	For more information see Fig. 15 and main text of Van Buchem et al. 2010
9	Dehluran and Kabirkuh-Darrehshahr	Vaziri-Moghaddam et al.	2010	Aquitania	Assemblage 2 corresponds to the <i>Miogyopsina-Elphidium</i> sp. 14- <i>Peneroplis farsensis</i> assemblage zone of Laursen et al. (2009) and is considered to be Aquitanian in age.
10	Firozabad	Vaziri-Moghaddam et al.	2011	Chattian	Lepidocyclinids are widespread in the Chattian deposits
11	Naura anticline	Sooltanian et al.	2011	Chattian	Lepidocyclinids are widespread in the Chattian deposits

an Early Oligocene age, and the presence of *Eulepidina* without *Nummulites* suggests a Late Oligocene age. On the contrary, *Eulepidina* have been reported with *Nummulites* in Late Oligocene and without *Nummulites* in Early Miocene by many researchers (e.g., Bozorgnia 1966; Adams and Bourgeois 1967).

It must be mentioned that, Rahaghi (1980) believed that the Rupelian beds of the Qom Formation are characterized by the presence of *Nummulites intermedius*. He attributed the Qom Formation in Jovsheghan-e-ghali area (SW of Kashan) to Rupelian based on the presence of *N. intermedius*. It is worth mentioning that *N. intermedius* of the Jovsheghan-e-ghali area is co-occurred with *Nephrolepidina* sp. and *Eulepidina* aff. *dilatata*. Likewise, Harzhauser (2004) attributed the *Nummulites* bearing layers of the Qom Formation to Early Oligocene based on the occurrence of *Nummulites sublaevigatus*.

Concerning *E. dilatata*, it should be mentioned that Rahaghi (1980) recorded *E. dilatata* (without *Nummulites*) from Aquitanian deposits of Mashhad section (NW Kashan). Likewise, he believed that *Borelis melo curdica* is an index of Burdigalian age.

Besides, it is worth mentioning that Jones and Racey (1994) attributed the Early Oligocene age for Ashawq Formation (S Oman) based on occurrence of *N. fichteli*.

#### Biostratigraphy of study sections

In fact, *Nummulites* is an important Early Oligocene genus whose last occurrence marks the upper boundary of the Rupelian (Rahaghi 1980). Its last occurrence has been used (see Table 2) to mark the upper boundary of the Rupelian. Based on the extinction of the last true *Nummulites* spp. (Table 2) at the Late Rupelian, we believe that the presence of in situ *Nummulites* (with or without *Eulepidina*) in Qom Formation successions indicates Early Oligocene (Rupelian) age, and the presence of *Eulepidina* without *Nummulites* suggests a Late Oligocene age (Chattian; possibly into Aquitanian). Our claim is closely similar to Racey's (1994) belief, but we strongly disagree with Bozorgnia (1966) and Adams and Bourgeois' (1967) ideas regarding the last occurrence of *Nummulites*.

Concerning the Chattian, Aquitanian, and Burdigalian index LBFs, we would like to say that *Borelis melo curdica*/*Borelis melo melo* is an important Early Miocene species whose first occurrence marks the lower boundary of biozone-1 of Adams and Bourgeois (1967) (Heidari et al. 2012; Fig. 2). The first occurrence of *B. melo curdica* is used by many researchers to mark the lower boundary of the Burdigalian (Wynd 1965; Adams and Bourgeois 1967; Rahaghi 1980; Seyrafian et al. 1996; Laursen et al. 2009; Van Buchem et al. 2010; Heidari et al. 2012). In this case, there is full agreement between all researchers who worked on

the Iranian Oligo-Miocene Biozonation (Wynd 1965; Adams and Bourgeois 1967; Laursen et al. 2009; Van Buchem et al. 2010). Besides, according to Adams et al. (1983), *B. melo curdica* indicates an age no older than Burdigalian, although Cahuzac and Poignant (1997) suggested that it may be no older than Langhian (Ehrenberg et al. 2007). However, the first occurrence of *B. melo curdica* is used by Cahuzac and Poignant (1997) to mark the lower boundary of the Burdigalian deposits of the European basin (see SB25 of Cahuzac and Poignant: *Borelis melo* group-*Miogypsina*).

As yet, the biostratigraphy of the Qom Formation relies mainly on biozonations of Wynd (1965) and Adams and Bourgeois (1967). For the first time, Mohammadi et al. (2013) dated the lower deposits of the Qom Formation based on BouDagher-Fadel (2008). Mohammadi et al. (2013) believed that future works on the Qom Formation must be based on this approach, and all of the in situ *Nummulites* bearing layers of the Qom Formation should be ascribed to Rupelian in age. Therefore, in this study methods of BouDagher-Fadel (2008) and Mohammadi et al. (2013) were used for dating the in situ *Nummulites* bearing layers of the Qom Formation. Here, we use *B. melo curdica* as index of Burdigalian age. Based on BouDagher-Fadel (2008) the age range of genus *Miogypsina* is from Latest Early Oligocene (Rupelian, P21, in America), Late Oligocene (Chattian, P22, in Mediterranean), Early Miocene (Aquitanian, N4, in the Far East) to Early Miocene (Burdigalian, in America) and Middle Miocene (Middle Serravallian, in the Indo-Pacific province). However, *Miogypsina* has been regarded as indicative of Early Miocene age (Adams et al. 1983) of Iran, but based on Ehrenberg et al. (2007), Laursen et al. (2009), and Van Buchem et al. (2010) its first appearance in Iran is in latest Chattian.

In Bujan section, on the basis of the distribution of foraminifera, two foraminiferal assemblages were identified. They are described in ascending order, following the stratigraphic development.

**Assemblage 1** This assemblage extends from the base of the Qom Formation to height of 95 m. *Nummulites* spp. recorded from only a single layer of the Bujan section. Sample nos. B-59, B-59a, B-59b, and B-59c were collected from the mentioned layer. However, *Nummulites* spp. are so abundant that sometime rocks are totally formed by them (Fig. 5). Their sizes reach up to several millimeters as they are easily visible by the naked eye in the field (Fig. 5). Their abundance in thin section is so high that only remained spaces between grains are filled with carbonate mud so that their thin sections are characterized by packstone texture of grain-supported type

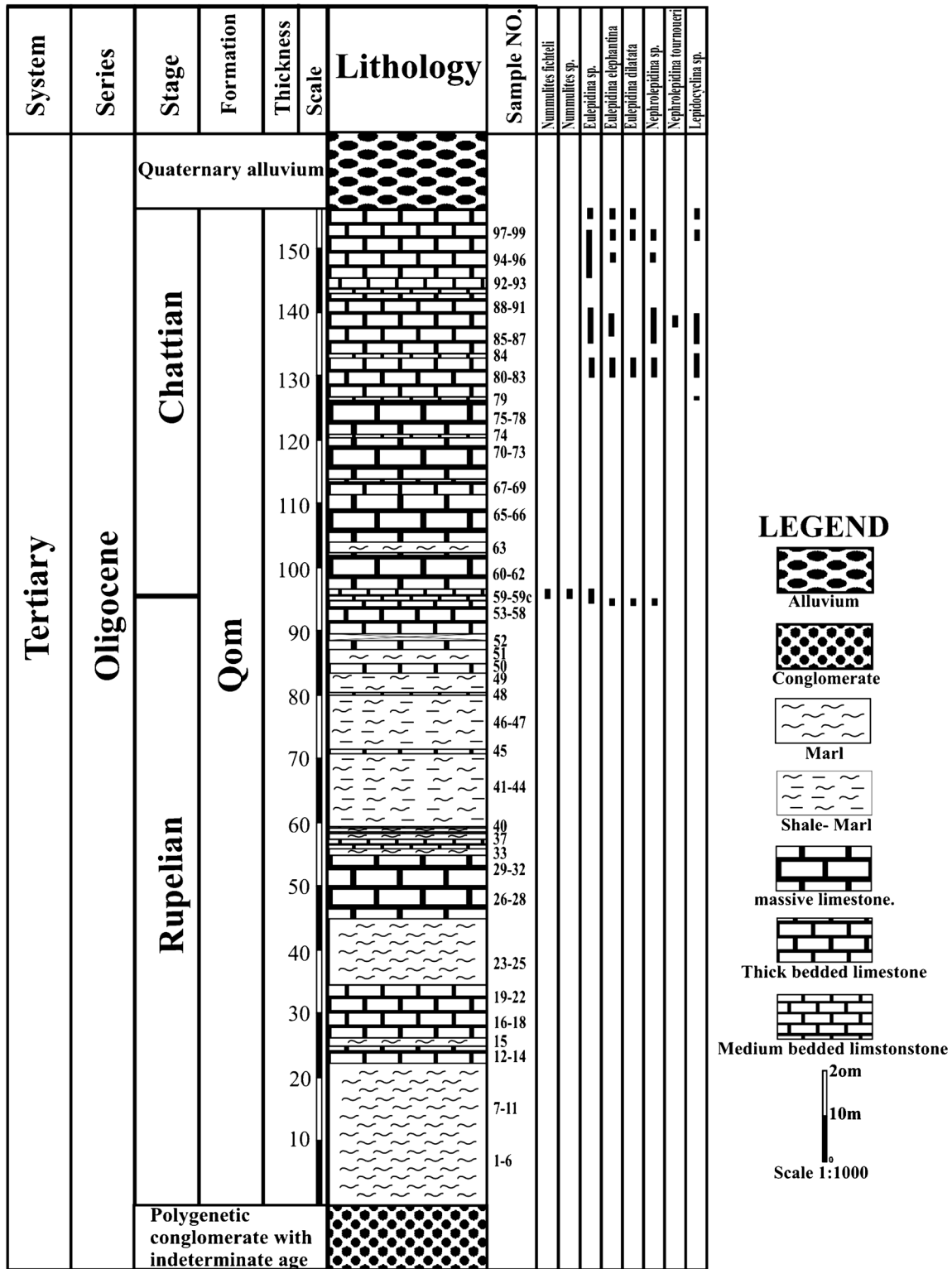


Fig. 4 Biostratigraphy of the Qom Formation at the Bujan section (S Sirjan) based on key LBF

(Fig. 5). It is worth mentioning that the mentioned *Nummulites* spp. bearing layer was recorded by Hosseinipour (2004) too. In Bujan section, the last occurrences of *Nummulites* spp. are in sample nos. B-59b

and B-59c (thickness of 95 m from the base). Therefore, the first 95-m thickness of study section is confidently deposited in Rupelian and attributed to Rupelian because of the presence of *Nummulites* spp.

(*N. fichteli-intermedius*, *Nummulites* sp; Figs. 4 and 5). However, we couldn't say that these *Nummulites* spp. indicate the end of Rupelian because they were recorded from a single layer. Therefore, maybe deposition of the Rupelian deposits continued into the related layers of the assemblage 2.

The following faunal assemblages have been recognized in this interval: *N. fichteli-intermedius*, *Nummulites* sp., *Eulepidina* sp., *Eulepidina dilatata*, *Eulepidina elephantina*, *Nephrolepidina* sp., *Neorotalia viennoti*, *Borelis pygmaea*, *Archaias kirkukensis*, *Dendritina rangi*, *Austrotrillina howchini*, *Austrotrillina* sp., *Quinqueloculina* sp., *Triloculina trigonula*, *Triloculina tricarinata*, textularids, corallinacean algae (*Lithotaminium*, *Lithophyllum*), bryozoa, and echinoids. The presence of *Nummulites* spp. (*N. fichteli*, *Nummulites vascus*, *Nummulites* sp.) leads to the age of the lower part of the formation to be determined as Rupelian (Figs. 7 and 8).

**Assemblage 2** This assemblage occurs from height 95 m to top of the section. Based on the absence of *B. melo curdica* (index of the lower boundary of the Burdigalian) and *Miogypsina* (index of

Aquitanian and latest Chattian in Iran) deposition of the upper part of the Bujan section, in latest Chattian?, Aquitanian and Burdigalian ages is impossible. However, based on its position above Assemblage 1 (Rupelian in age) and interpretations of Assemblage 1, it could be attributed to the Rupelian-Chattian. This assemblage is correlated with *Lepidocyclina-Operculina-Ditrupe* assemblage zone of Wynd (1965) and Laursen et al. (2009) (Fig. 2) which is attributed to Rupelian and Chattian. The following faunal assemblages have been recognized in this interval: *Eulepidina* sp., *Eulepidina dilatata*, *E. elephantina*, *Lepidocyclina* sp., *Nephrolepidina* sp., *N. tournoueri*, *Neorotalia* sp., *N. viennoti*, *B. pygmaea*, *Sphaerogypsina* sp., *Borelis haueri*, *Archaias* sp., *Operculina complanata*, *Heterostegina* sp., *Amphistegina* sp., *D. rangi*, *A. howchini*, *Austrotrillina asmariensis*, *Quinqueloculina* sp., *T. trigonula*, *T. tricarinata*, textularids, corallinacean algae (*Lithotaminium*, *Lithophyllum*), bryozoa, and echinoids.

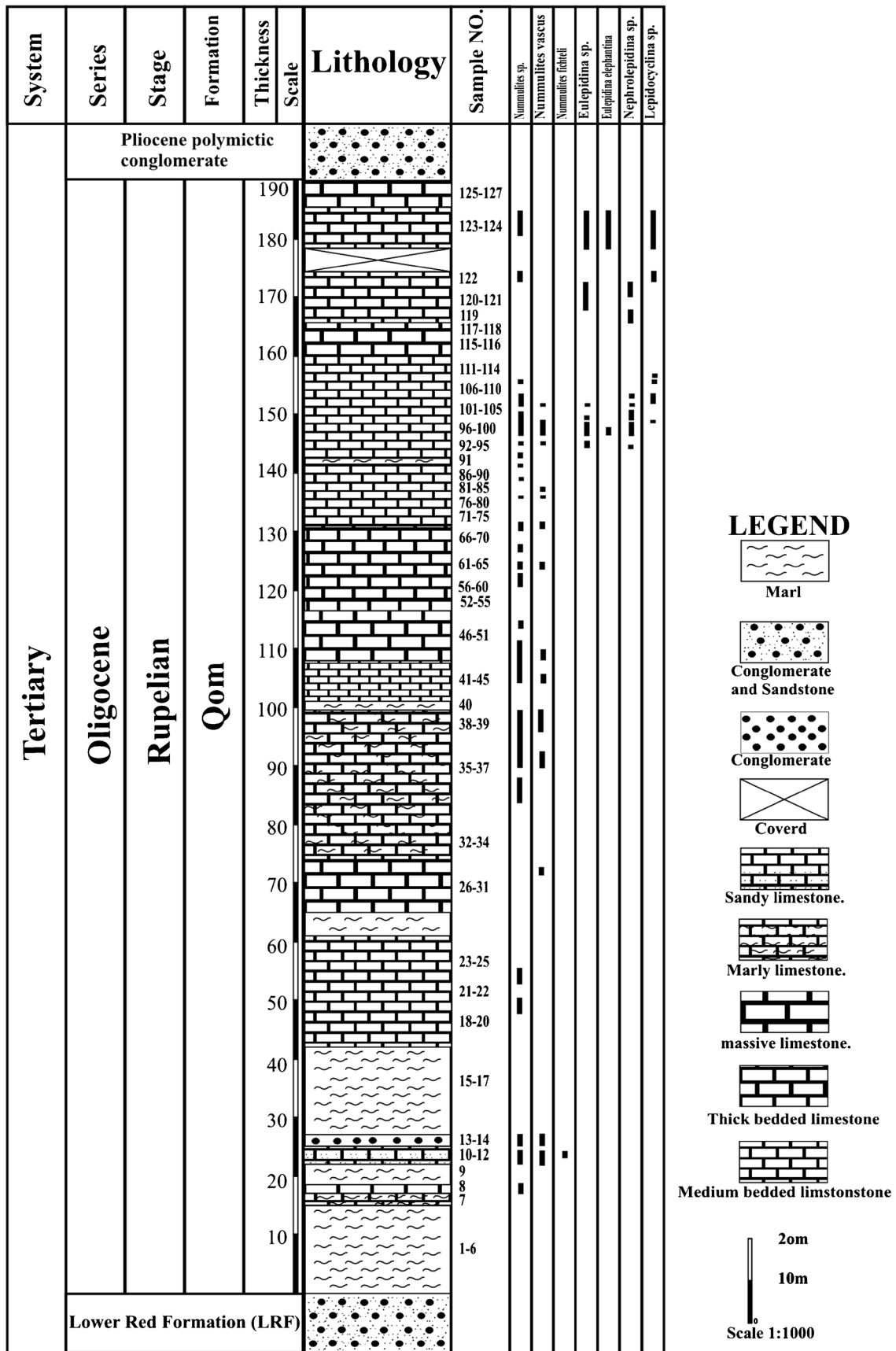
In Varkan section, the last occurrence of *Nummulites* spp. in Varkan material is in the last samples which are therefore considered to mark the end of Rupelian. Thus, according to the presence of *N. vascus* and *Nummulites* sp., throughout Varkan section, the whole deposits of the section are attributed to the Rupelian. The following faunal assemblages have been recognized in this interval: *N. vascus*, *Nummulites* sp., *N. fichteli*, *Eulepidina* sp., *Eulepidina elephantina*, *Lepidocyclina* sp., *Nephrolepidina* sp., *N. viennoti*, *Neorotalia* sp., *Nephrolepidina* sp., *O. complanata*, *Heterostegina* sp., *Amphistegina* sp., *B. pygmaea*, *Eulepidina* sp., *Sphaerogypsina globulus*, *Sphaerogypsina* sp., *B. haueri*, *Archaias* sp., *Peneroplis tomasi*, *D. rangi*, *A. howchini*, *Austrotrillina* sp., *Haplophragmium* sp., *Cibicides* sp., *Elphidium* sp., *Quinqueloculina* sp., *T. trigonula*, *T. tricarinata*, textularids, *Ditrupe* sp., corallinacean algae (*Lithotaminium*, *Lithophyllum*, *Subterraniophyllum thomasi*), bryozoa (*Tubucellaria*), and echinoids (Figs. 6, 7, and 8).

In Khurabad (Qom) section, on the basis of the distribution of foraminifera, four foraminiferal assemblages were identified. They are described in ascending order, following the stratigraphic development.

**Assemblage 1** This assemblage extends from the base of the Qom Formation to height of 60.5 m. The last occurrence of *Nummulites* spp. in Khurabad material is in sample no. K20 which is therefore considered to mark the end of Rupelian.



**Fig. 5** A figure showing abundance of *N. fichteli/N. intermedius* in hand sample and thin section of the Bujan section

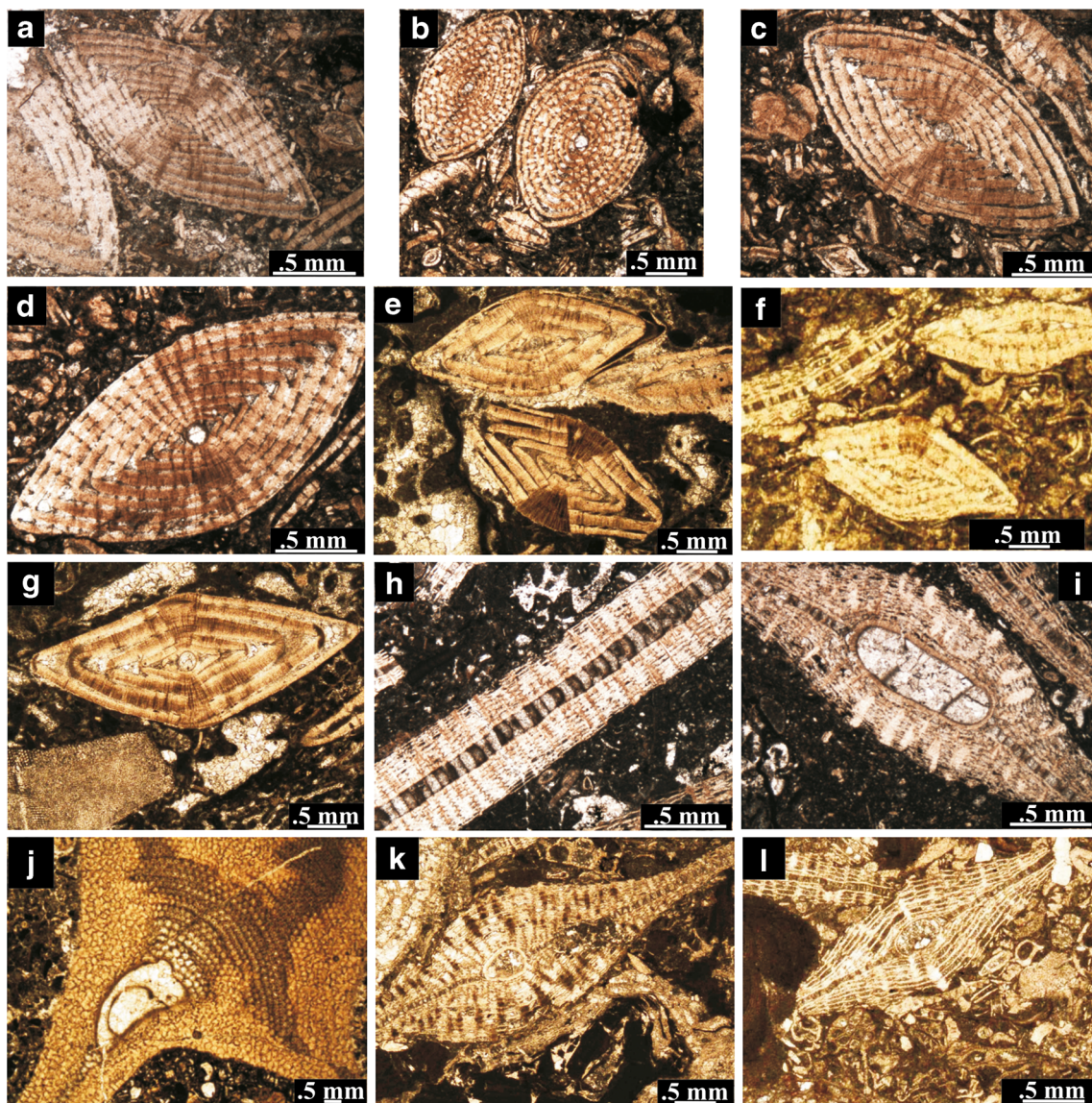


**Fig. 6** Biostratigraphy of the Qom Formation at the Varkan section (SW Kashan) based on key LBF

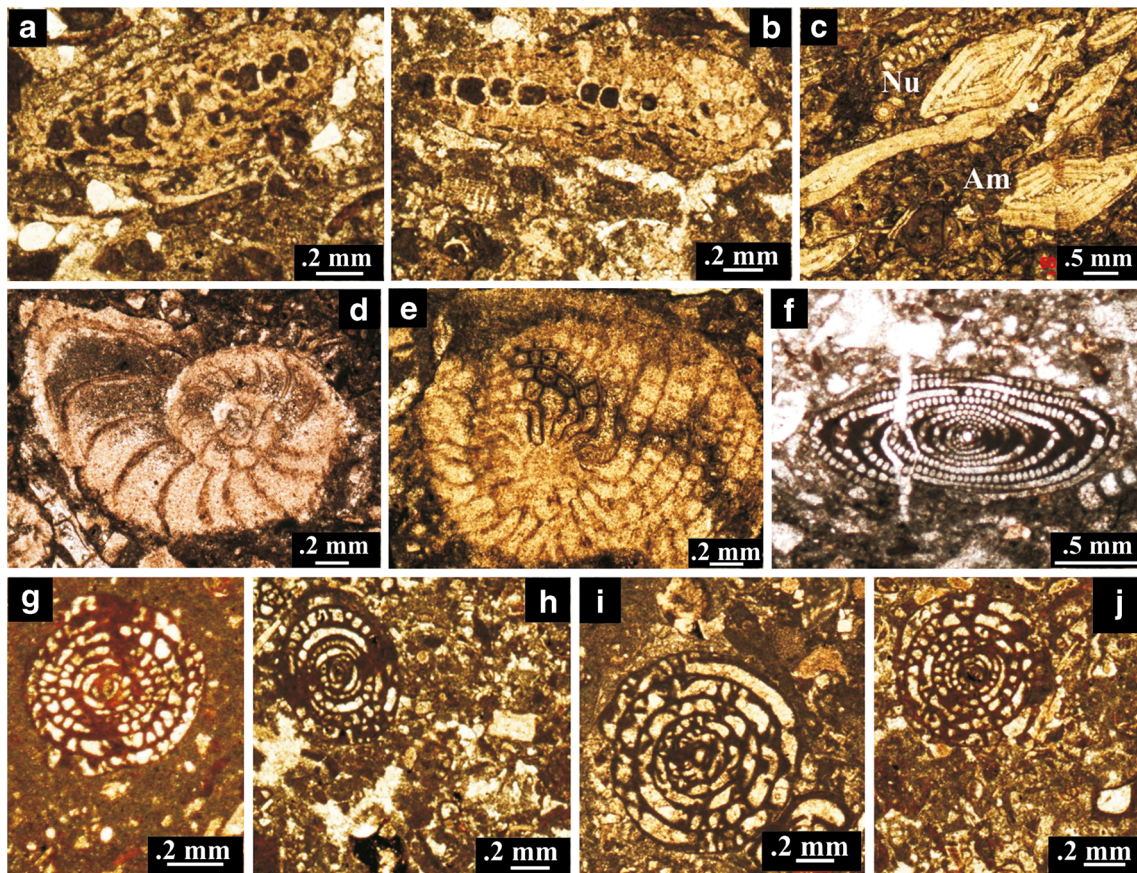
Thus, based on the presence of *N. vascus* and *Nummulites* sp. the lower 60.5 m of the Qom section is attributed to the Rupelian. The following faunal assemblages have been recognized in this interval: *N. vascus*, *Nummulites* sp., *Eulepidina* sp., *Lepidocyclina* sp., *Nephrolepidina* sp., *Nephrolepidina tournoueri*, *Neorotalia* sp., *Operculina* sp., *Amphistegina* sp. textularids, *Ditrupa* sp., corallinacean algae (*Lithotaminium*, *Lithophyllum*), bryozoa, and echinoids (Figs. 7 and 8).

**Assemblage 2** This assemblage appears from height 60.5 to 93.5 m. The absence of *B. melo curdica* (index of the lower boundary of the

Burdigalian) and *Miogypsina* (index of Aquitanian and latest Chattian in Iran), its position above Assemblage 1 (Rupelian in age) and below the first evaporate succession of the section (evaporate deposits of the Qom Formation are deposited totally in the Early Miocene (Aquitanian–Burdigalian), Mohammadi et al. 2013), and presence of Lepidocyclinids without *Nummulites* caused the deposition of this part to be defined as Chattian. The following faunal assemblages have been recognized in this interval: *Eulepidina* sp., *Lepidocyclina* sp., *Nephrolepidina* sp., *N. tournoueri*, *Neorotalia* sp., *O. complanata*,



**Fig. 7** Selected key LBF of the Qom Formation in study sections. **a–d** *N. fichteli*; Bujan section, **e–g** *N. vascus*; **e, g** Varkan section; **f** Khurabad section; **h–j** *Eulepidina* sp., Bujan section; **k, l** *Lepidocyclina* (*Nephrolepidina*) sp., Khurabad section



**Fig. 8** Selected key LBF of the Qom Formation in study sections. **a–b** *Miogypsina* sp., Khurabad section; **c** (Nu) *N. vascus* (Am) *Amphistegina*, Khurabad section; **d** *Operculina* sp., Bujan section; **e** *Heterostegina* sp.,

Bujan section; **f** *Borelis pygmaea*, Bujan section; **g–j** *Borelis melo curdica*, Khurabad section

*Amphistegina* sp., *Eulepidina* sp., *Austrotrillina* sp., *Elphidium* sp., *Quinqueloculina* sp., *Pyrgo* sp., miliolids, textularids, corallinacean algae (*Lithotaminium*, *Lithophyllum*), bryozoa, and echinoids (Figs. 7 and 8).

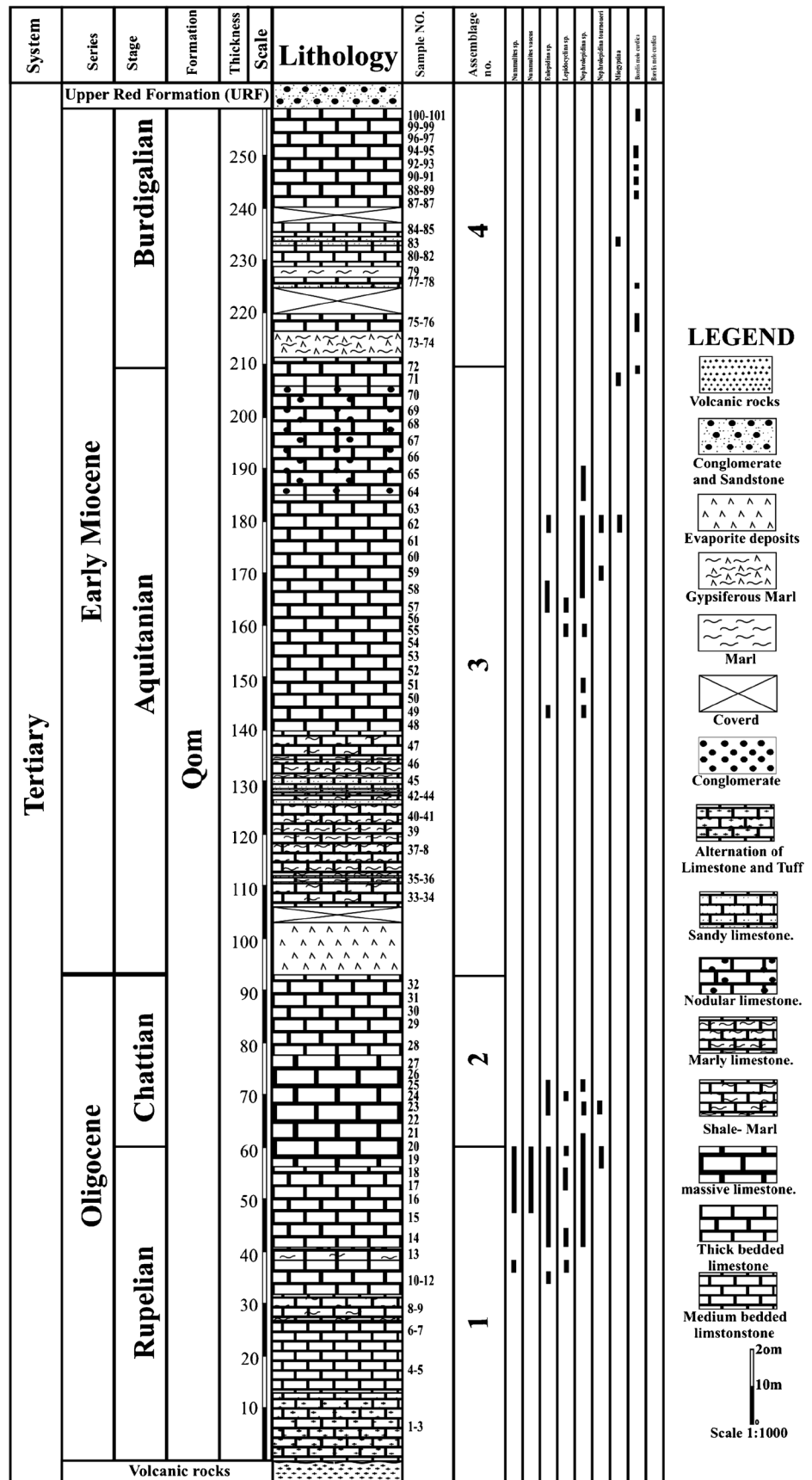
**Assemblage 3** This assemblage appears from height 93.5 to 209.5 m. The absence of *B. melo curdica* and *Nummulites* spp., the presence of *Miogypsina* and evaporate succession, its position between Assemblage 2 (Chattian in age) and Assemblage 4 (Burdigalian in age), and presence of Lepidocyclinids without *Nummulites* caused the deposition of the part including assemblage 3 to be attributed to Aquitanian. The following faunal assemblages have been recognized in this interval: *Eulepidina* sp., *Lepidocyclina* sp., *Nephrolepidina* sp., *N. tournoueri*, *N. viennoti*, *Miogypsina* sp., *Neorotalia* sp., *O. complanata*, *Heterostegina* sp., *Amphistegina* sp., *B. pygmaea*, *Eulepidina*

sp., *Sphaerogypsina* sp., *D. rangi*, *Austrotrillina* sp., *Cibicides* sp., *Elphidium* sp., *Pyrgo* sp., miliolids, textularids, corallinacean algae (*Lithotaminium*, *Lithophyllum*), bryozoa (*Tubucellaria*), and echinoids (Figs. 7 and 8).

**Assemblage 4** This assemblage occurs from height 209.5 m to the top of the section (Fig. 9). The first occurrence of *B. melo curdica* in our material is in sample no. K-72 which is therefore considered to mark the beginning of Burdigalian. Based on the presence of *B. melo curdica*, the last 50 m of the Qom section (From 209.5 to 260) is attributed to the Burdigalian. This assemblage is Burdigalian in age and is correlated with *B. melo curdica* zone of Wynd (1965), *B. melo-Meandropsina iranica* assemblage zone of Adams and Bourgeois (1967) and *B. melo curdica-B. melo melo* assemblage zone of Laursen et al. (2009) and Van Buchem et al. (2010) which are attributed to Burdigalian.



**Fig. 9** Biostratigraphy of the Qom Formation at the Khurabad section (SE Qom) based on key LBF



**LEGEND**

- Volcanic rocks
- Conglomerate and Sandstone
- Evaporite deposits
- Gypsiferous Marl
- Marl
- Coverd
- Conglomerate
- Alternation of Limestone and Tuff
- Sandy limestone.
- Nodular limestone.
- Marly limestone.
- Shale- Marl
- massive limestone.
- Thick bedded limestone
- Medium bedded limstonstone

20m  
10m  
0  
Scale 1:1000

The following faunal assemblages have been recognized in this interval: *B. melo curdica*, *Miogypsina* sp., *B. pygmaea*, *Borelis* sp., *Archaias* sp., *Peneroplis* sp., *D. rangi*, *A. howchini*, *Austrotrillina* sp., *Haplophragmium* sp., *Elphidium* sp., *Quinqueloculina* sp., *T. trigonula*, *T. tricarinata*, *Pyrgo* sp., textularids, *Ditrupea* sp., corallinean algae (*Lithotaminium*, *Lithophyllum*), bryozoa (*Tubucellaria*), and echinoids (Figs. 7 and 8).

In summary, on the basis of biostratigraphy data and foraminifera assemblages, the Qom Formation is Rupelian, Rupelian–Chattian, and Rupelian–Burdigalian in age in Varkan, Bujan, and Qom (Khurabad) areas, respectively. The obtained results are compatible with the common trend of the transgression of the Tethyan Seaway on the Iranian Plate.

## Conclusions

Three stratigraphic sections of the Qom Formation in Sanandaj–Sirjan fore-arc and Central Iran back-arc basins were studied in order to determine their accurate age. LBF (mainly *Nummulites*, lepidocyclinids, miogypsinids, and *Borelis*) biostratigraphically are the main biota of the Qom Formation in the study areas and therefore used for age dating of the study sections. This study led to the following conclusions:

1. The last true *Nummulites* spp. became extinct at the top of Late Rupelian and all of the in situ *Nummulites* bearing layers of the Qom Formation belong to Rupelian in age.
2. The presence of in situ *Nummulites* (with or without *Eulepidina*) in Qom Formation successions indicates an Early Oligocene (Rupelian) age.
3. Lepidocyclinids which originated in the Americas during the Middle Eocene and migrated eastward through the Tethyan/Mediterranean corridor reached Iran in the Rupelian.
4. The first appearance of *Lepidocyclina* spp., in our study sections and in several others stratigraphic sections of the Qom and Asmari formations, before the last occurrence of *Nummulites* spp., clearly indicates that the earliest Lepidocyclinidae reached Iran in the Rupelian (Early Oligocene).
5. The Lepidocyclinids are widespread in the Chattian marine deposits of Iran.
6. The presence of *Eulepidina* without *Nummulites* suggests a Late Oligocene age (Chattian; possibly into Aquitanian).
7. *N. intermedius*–*N. vascus* Assemblage zone of Wynd (1965) and *Eulepidina*–*Nephrolepidina*–*Nummulites* Assemblage zone of Adams and Bourgeois (1967), which are proposed for Oligocene (Rupelian–Chattian), should be ascribed to Rupelian in age.
8. On the basis of biostratigraphic data and foraminifera assemblages, the Qom Formation is Rupelian, Rupelian–Chattian, and Rupelian–Burdigalian in age in Varkan, Bujan, and Qom (Khurabad) areas, respectively.
9. The obtained results are compatible with the common trend of the transgression of the Tethyan Seaway on the Iranian Plate.

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