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ORIGINAL ARTICLE

Foraminiferal biostratigraphy across the Eocene–Oligocene transition, in the Zagros Basin, Southern Iran

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Abstract

The studied wells were located in the Bandar Abbas, Southeast Persian Gulf, and crosscut mainly from Eocene to Oligocene sequences spanning the Pabdeh, Jahrum, and Asmari formations respectively. The present work aims to characterize the biostratigraphy of the Eocene–Oligocene transition based on planktic and benthic foraminifera. Upper Eocene–Oligocene transition are subdivided into three lithostratigraphic units which are the Pabdeh Formation (Priabonian–Chattian), Jahrum Formation (Priabonian), and Asmari Formation (Rupelian-Chattian). Based on the stratigraphical range of the studied foraminifera, ten biozones have been established:- *Morozovella velascoensis* Zone (early Eocene) (I), *Morozovella edgari* Zone (Ypressian) (II(, *Morozovella formosa formosa* Zone (Ypressian) (III), *Hantkenina alabamensis* Highest-Occurrence Zone (Priabonian) (IV), *Turborotalia cerroazulensis cunialensis* Zone (Priabonian) (V), *Cassigerinella chiploensis–Pseudohastigerina micra*) Zone (Rupelian) (VI), *Turborotalia ampliapertura* Zone (Rupelian) (VII), *Praegloborotalia opima opima* Zone (Rupelian) (VIII), *Nummulites* spp., *Discocyclina* spp. Zone (Chattian) (IX) and *Eulepidina–Nephrolepidina-Nummulites* Zone (Chattian) (X). The recognized biozones were correlated with comparatively standards biozones for the Tethyan realm which demonstrates a good comparison between the biostratigraphic zones that recognized in this study with other biozones in different areas.

Keywords Planktic foraminifera · Benthic foraminifera · Biostratigraphy · Eocene–Oligocene transition · Zagros Basin · Iran

Introduction

Zagros Basin which extended from northeastern Syria through northern and northeastern Iraq into southwestern Iran (Moghaddam et al. 2013, Fig. 1). Planktic and benthic foraminifera are of great interest in the marine environment and are used as geological standard tools for biostratigraphic studies. (Hendy et al. 2004; Field et al. 2006; Olsson et al. 2006; Ghafor 2011, 2015; Sajadi et al., 2015; Taheri et al., 2017; Bejaoui et al 2019, Ghafor et al. 2021; Rashidi et al. 2023; Al-Taee et al. 2024a). Biostratigraphy of the Eocene–Oligocene transition in the folded Zagros mountains has been studied by Rostami et al. (2014a; b), of four surface stratigraphic sections and one subsurface stratigraphy section crossing the deposits of Jahrum and Asmari formations, they concluded that the age of the Jahrum Formation is late Paleocene to late Eocene based on the index species of *Alveolina*, *Misscellanea*, *Kathina*, *Opertorbitolites*, *Nummulites*, and the Asmari Formation of Rupelian to Burdigalian age, based on these index species *Nummulites fichteli-Nummulites vascus*, *Archaias asmaricus-Archaias hensoni- Miogypsinoides complanatus Peneroplis evolutus- Austroterillina howchini* and *Borelis melo* group-*Meandropsina iranica.* Raviz et al. (2020), show the presence of 5 planktic foraminifera and 2 large benthic foraminifers (LBF) biozones in the Sabzevaran and Sad sections, NW Jiroft (Iran), and determine Middle-Late Eocene to Rupelian and Chattian ages. Foraminiferal specimens of the Jahrum and Asmari formations have been studied by Adams and Bourgeois (1967); Rahimzadeh (1994): Sadegholvad and Faghih (2007); Hakimzadeh and Seyrafian, (2008); Sadeghi et al. (2009); Mahmoodabadi et al. (2010); Rostami et al. 2014a, b; Amiri-Bakhtiar and Norainejad 2014: Amirshahkarami

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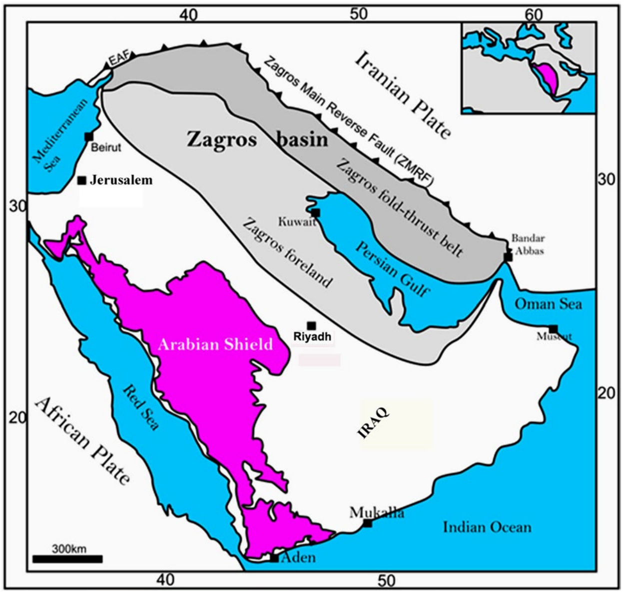


Fig. 1 Map of the Middle East showing the location of the Zagros Basin (Sajadi et al. 2015)

and Zebarjadi 2018; Raviz et al. 2020). The studied wells are located in southern Bandar Abbas Hinterland where the strait of hormuz is located (Fig. 2). The aims of this study, are to establish a high-resolution biostratigraphy study of the Eocene–Oligocene transition based on planktic and large benthic foraminifera, and the chronostratigraphic study between Eocene and Oligocene deposit of Southern Iran is not studied in detail from the viewpoint of biostratigraphy.

Geological setting

The Zagros Basin is the second largest basin in the Middle East and is defined by a 7–14-km thick succession of coverage sediments deposited over a region located along the north-northeast edge of the Arabian plate, it was continuous from the Paleozoic era to the Cenozoic era. The Paleogene deposits in the Zagros Basin can be categorized into two primary sedimentary sequences. (i.e., Jahrum cycle from Paleocene to Oligocene and Asmari cycle from Oligocene to early Miocene. The Zagros Basin is located in southwestern Iran lying at the eastern edge of the Persian Gulf (Fig. 1) and is a part of the Alpine-Himalayan Mountain chain (It is A second nearly continuous chain of mountains can be traced from Morocco in North Africa through Europe, then across Turkey and Iran through the Himalayas to Southeast Asia) that stretches across much of Southwest Asia and the Middle East (Motiei 1993). Aghanabati (2004), clarified that the Hormozgan province is located in Southern Iran and is part of the Zagros Folded belt (Fig. 2). The Zagros Fold-and-Thrust Belt of Iran is a result of the Alpine orogenic events (Ricou et al. 1977; Sadeghi et al. 2009) in the Alpine-Himalayan Mountain range. It extends in a NW–SE direction from eastern Turkey to the Strait of Hormoz in Southern Iran. The tectonic activity in this area was entirely due to the convergence of the Arabian and Eurasian continents. After the closure of the Neo-Tethys basin, during late Oligocene-early Miocene times, the Zagros Basin was gradually narrowed, and the Asmari Formation was deposited with a lithology including lithic sandstone (Ahwaz Member) and evaporites (Kalhur Member) (Vaziri-Moghaddam et al. 2010; Ahmadhadi et al. 2007). The Zagros Fold-Thrust Belt is one of the youngest mountain belts, located in the middle part of the Alpine mountain system. The NW–SE trending belt developed during the collisional stage between the Arabian Plate and Central Iran in late Cretaceous (Ricou et al. 1977). The belt has been grouped into different structural subzones including the High Zagros, the Zagros Simply folded belt, and the Dezful embayment zones (Berberian 1995) from NE to SW from eastern Turkey to the Strait of Hormoz in Southern Iran. The tectonic evolution of the Zagros Mountains was entirely due to plate tectonics and the converging of the Arabian and Eurasian continents. The principal Cenozoic sediments consist of Paleocene to Eocene shallow-water limestones and dolomites assigned respectively to the Sachun–Jahrum formations and basinal marl and marly limestone assigned to the Pabdeh Formation. The Oligocene to Miocene Asmari Formation consists of shallow-water, neritic limestones (Fig. 2, James and Wynd 1965; Motiei 1993), late Eocene unconformity, which is only observed to the northeast, did not affect the deeper basin to the southwest (Sepehr and Cosgrove 2004). In the Oligocene-early Miocene, shallow marine shelf limestones of the Asmari Formation were conformably deposited over the Pabdeh Formation to the southwest. To the northeast, the Asmari Formation was unconformably deposited over the uplifted Jahrum Formation. Most of the interior Fars stayed above sea level during the Oligocene (Berberian and King 1981). (Fig. 3). The studied area has been selected based on the exploration goals of new oil resources, to study lithostratigraphy and biostratigraphy, transect along a NE to SW of the Persian Gulf length 293.6 km. The nine selected wells from east to west have been studied transactions modified after a Geological map (National Iranian Oil Company 2004). (Fig. 4).

Materials and methods

This study involves nine wells located in Southern Iran (Fig. 2c). These wells include the Pabdeh, Jahrum, and Asmari formations. A detailed lithostratigraphic column was drawn for each well (Figs. 5, 6, 7 ,8 ,9 ,10). A total of

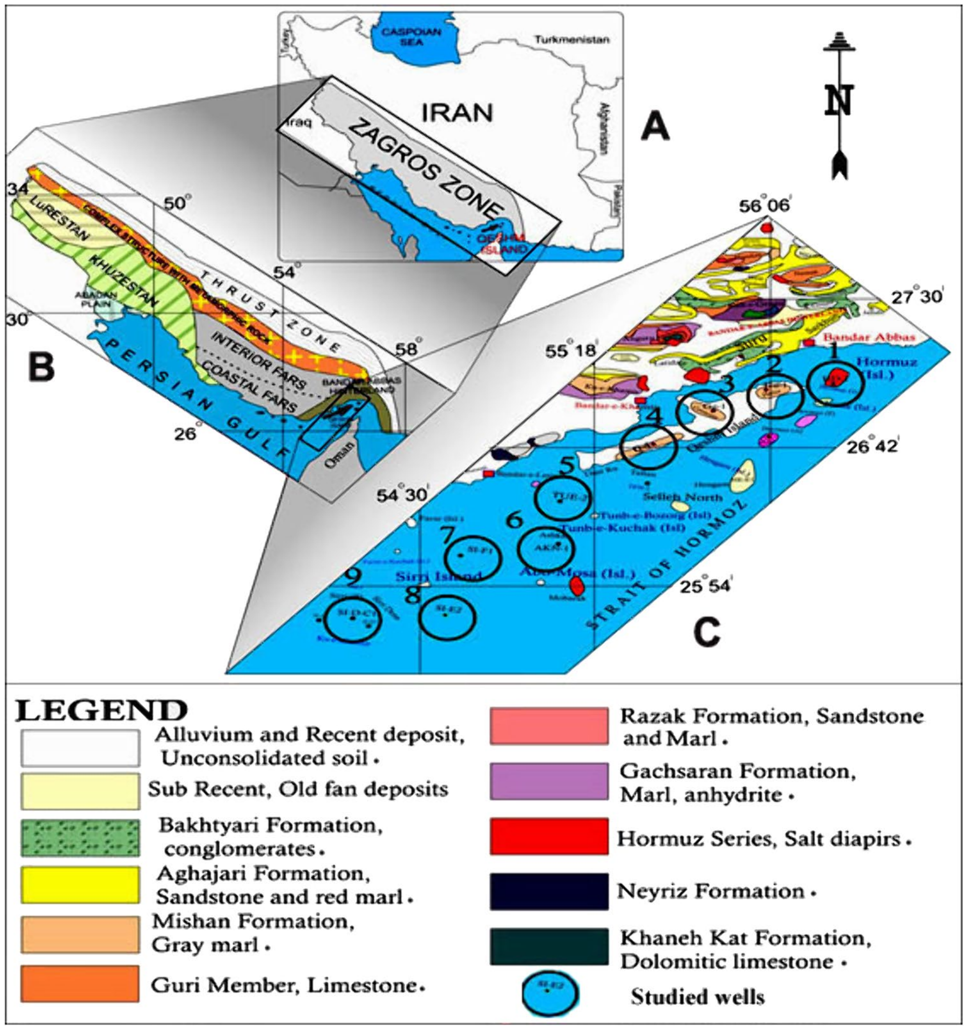


Fig. 2 (A) Location map of Iran showing the Zagros Zone; (B) Structural map of the Zagros Basin (Aghanabati 2004); (C) The studied wells modified after Geological map (National Iranian Oil Company 2004)

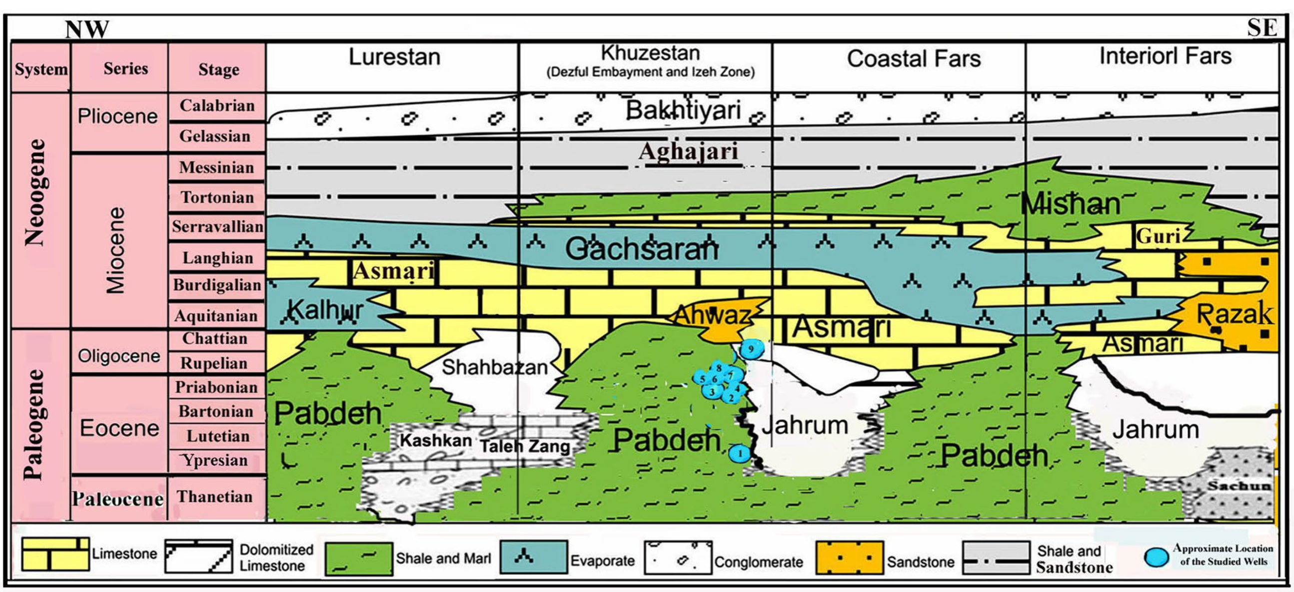


Fig. 3 Cenozoic stratigraphic correlation chart of the Iranian sector of the Zagros Basin, adopted from (James and Wynd 1965)

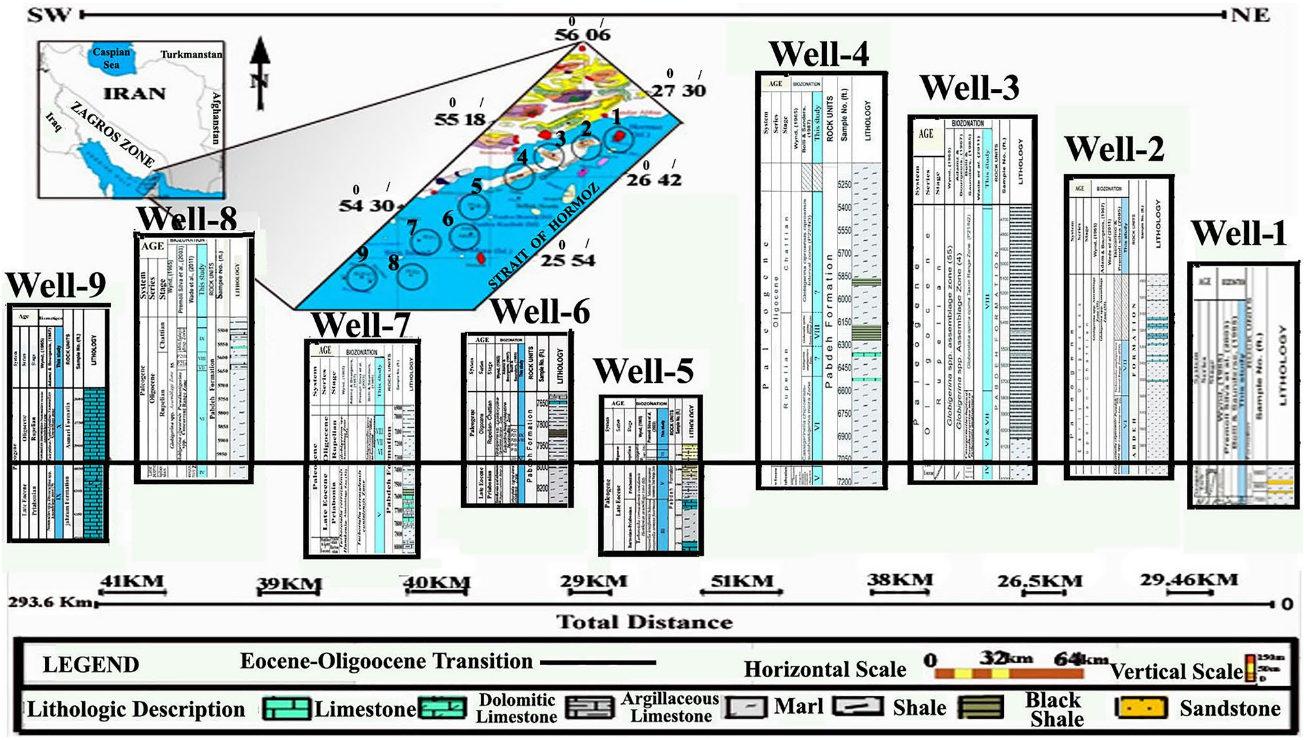


Fig. 4 Biostratigraphic correlation chart of Eocene–Oligocene time's scale of nine wells in Southeast Persian Gulf

2000 samples of cores and cuttings have been studied and thin sections have been analyzed under the microscope for biostratigraphic studies of the benthic foraminifera are based on these studies (Adams and Bourgeois (967; Gedik 2014; Ferrandez-Candell and Bover-Arnal, 2017; Moghaddam et al. 2019), the taxonomic determination of the planktic foraminifera is based on classification by (Pearson and wade 2015; Olsson et al. 2018; Leckie et al. 2018; Wade et al. 2018a; Seyrafian and Mojikhalifeh, 2005; Berggren and Pearson, 2005; Wade et al. 2011; Sirel et al. 2013; Loeblich and Tappan, 2015; Serra-Kiel et al. 2016; Roozpeykar and Moghaddam 2016; Coccioni et al. 2018; Joudaki and Baghbani 2018 and Moghaddam et al. 2019).

Results

Lithostratigraphy

The Eocene–Oligocene successions of the studied wells are extends for approximately 300 km in length and is about 5285 m -thick, and fully described and subdivided into three lithostratigraphic units (Fig. 4). (1) the Pabdeh Formation denoting of neritic-deep marine facies, and the Jahrum and Asmari formations of the shallow marine facies (Taheri 2010).

Jahrum Formation

The type section of the Jahrum Formation at Kuh-e Jahrum in Fars province includes Paleocene to Eocene sediments of dolomite and dolomitic limestone with a thickness of 467.5 m. (Setudehnia 1972; James and Wynd 1965). Jahrum Formation in the studied well is deposited at the southwestern end of the transect, composed of limestone at the lower part of the unit and the upper part of the formation consists of dolomitic limestone, the formation overlies the Asmari Formation and it appears only at well no. 9 with 450 m -thick. (Table 1) (Fig. 10).

Pabdeh Formation

The type section of the Pabdeh Formation is located at the Tang-e-Pabdeh on the southeastern end of Kuh-e-pabdeh (Southwestern Iran). 2620 feet (798.576m) of low-weathering grey shales and thin argillaceous limestones were measured. Hadavandkhani and Sadeghi (2010) and Khaloasgari et al. (2023), studied the Pabdeh Formation in Southern Iran, Zagros Basin, Pabdeh Formation in the present study, composed of *Globigerina* deep-marine hemipelagic–pelagic calcareous shale, marl, and lime-mudstone. The thickness of this formation is varied from the eight wells of the studied area (Table 1).

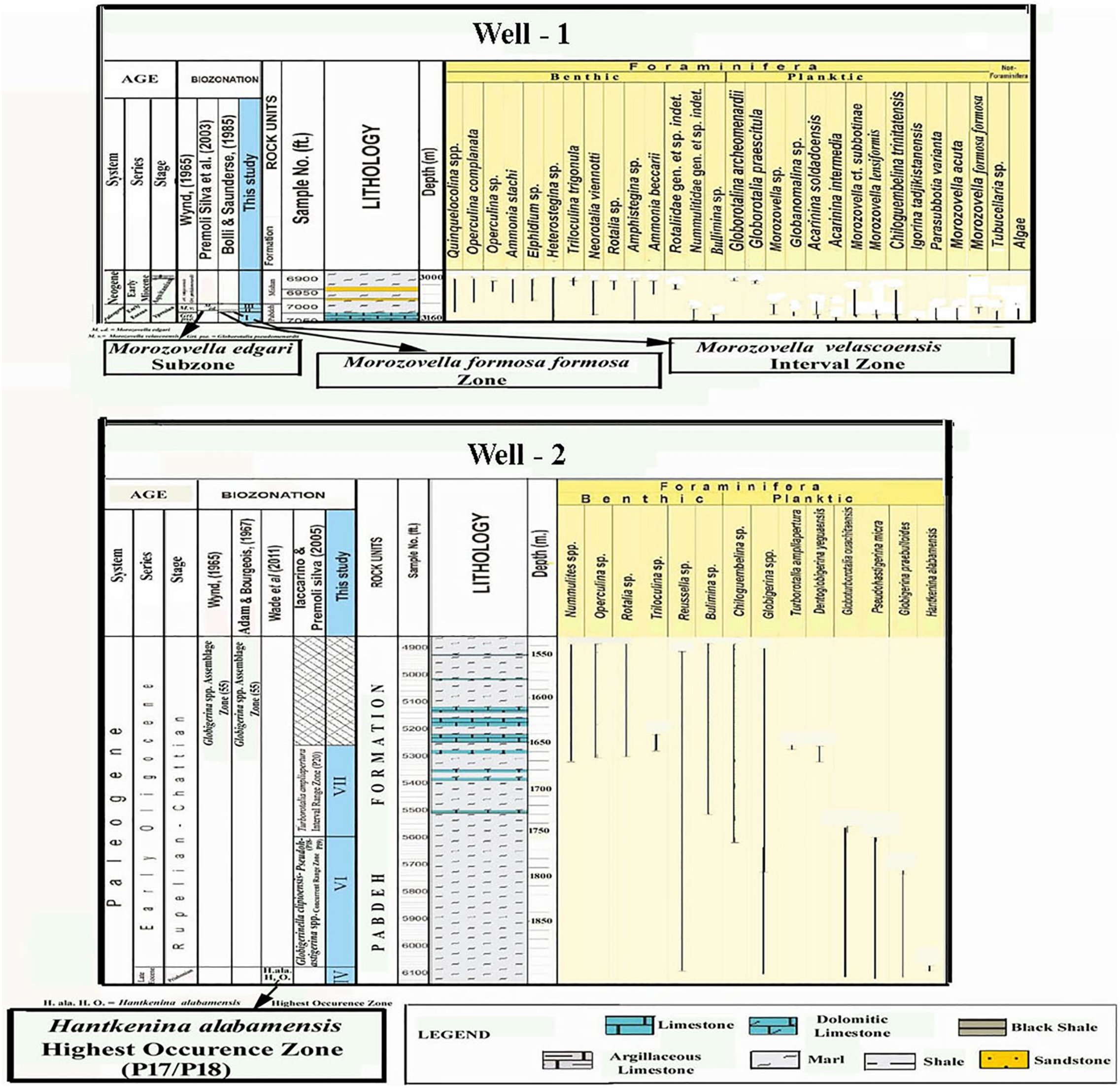


Fig. 5 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene/Oligocene times of the Pabdeh, Jahrum, and Asmari formations in wells 1 and 2

Asmari Formation

The type section of the Asmari Formation was measured first in the Tang-e-Gele Torsh, Khuzestan province, southwest Iran (Richardson 1924). It consists of 314 m of limestones, dolomitic limestones, and argillaceous limestones at the type locality (Thomas 1950). In the present study, the Asmari Formation was obvious only in well no. 9 with a thickness of 450 m. (Table 1), and composed of limestone, underlain by the Jahrum Formation. Rajab and Ghafor, studied the Asmari Formation in the view of biostratigraphy, microfacies, and depositional environment, in western Iran (In Press.

Biostratigraphy

In this study, the biozonation of nine wells was founded on the apportionment of the planktic and benthic foraminifera and other microfossils (non-foraminifera) such as bryozoa, algae, *Onychocella, Tubucellaria* sp., echinoid fragments, gastropods, and coral fragments (Plates 1, 2). Upper Eocene through lower Oligocene deposits, contains 60 species from 23 genera of planktic foraminifera, and 10 species among other microfossils such as coral and algae. Ten biozones have been recognized in this study (Figs. 5, 6, 7, 8, 9, 10).

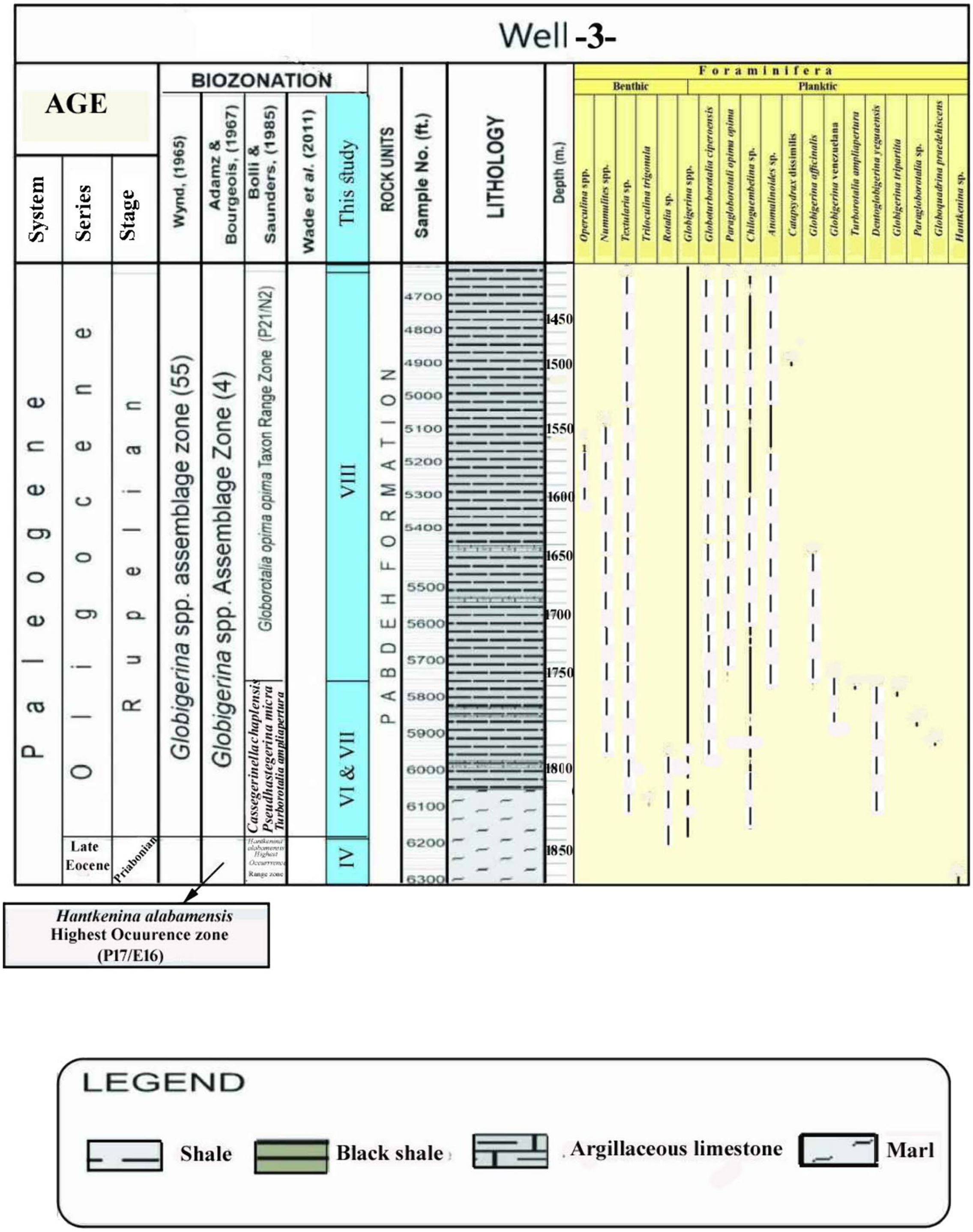


Fig. 6 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene–Oligocene times of the Pabdeh, Jahrum, and Asmari formations in well 3

Morozovella velascoensis Zone (I)

This zone is initially defined by Bolli, (1957). Biostratigraphic interval of this zone is characterized by the co-occurrent range of the nominate taxa of *Acarinina soldadoensis* and *Morozovella acuta.* The two index species of *Acarinina soldadoensis* and *Morozovella acuta* indicate the biozone P5 (*Morozovella velascoensis* Interval Zone). This zone occurs only in well 1 and appears at a depth of 3160 m in the lower part of the Asmari

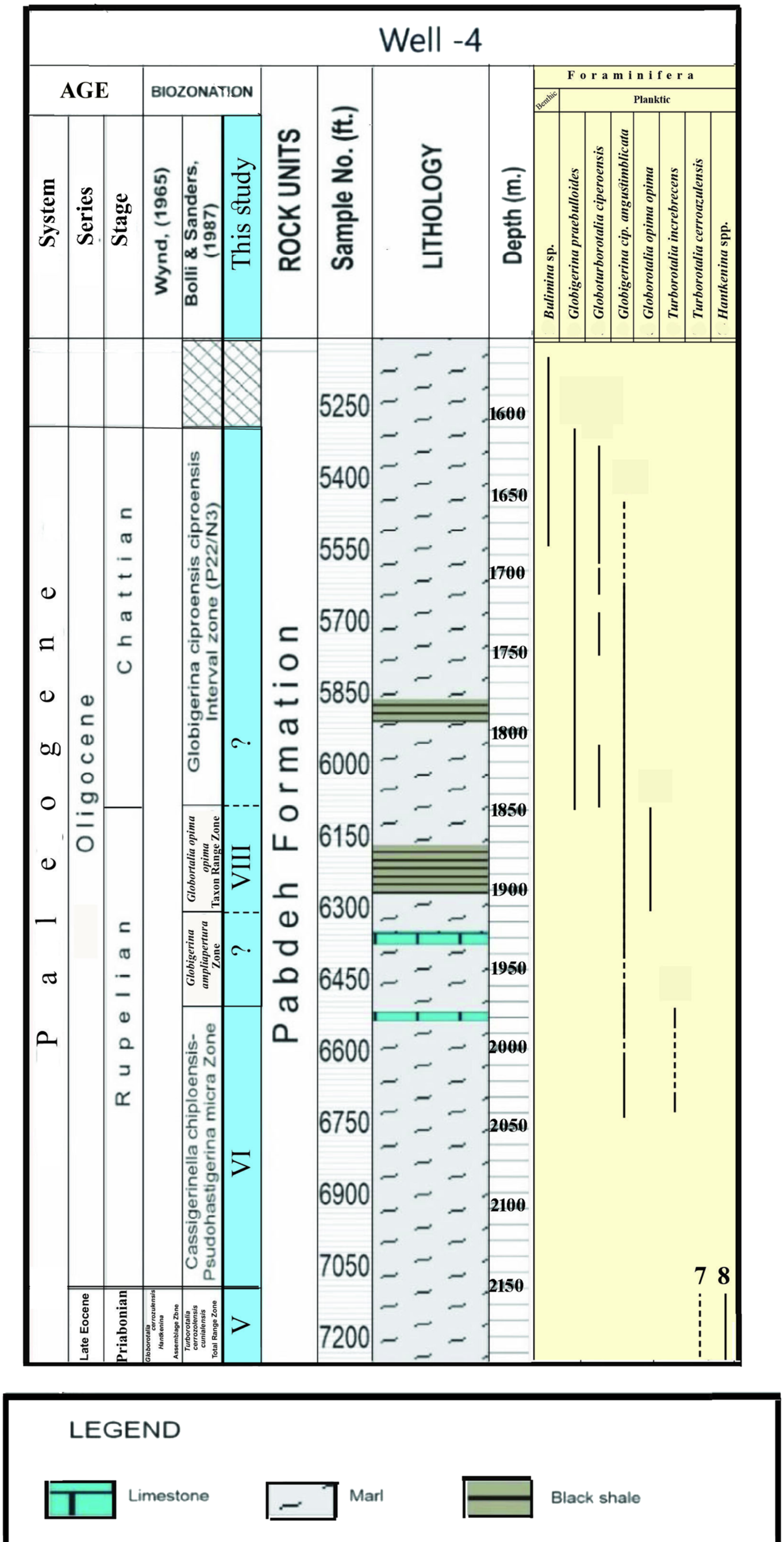


Fig. 7 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene–Oligocene times of the Pabdeh, Jahrum, and Asmari formations in well 4

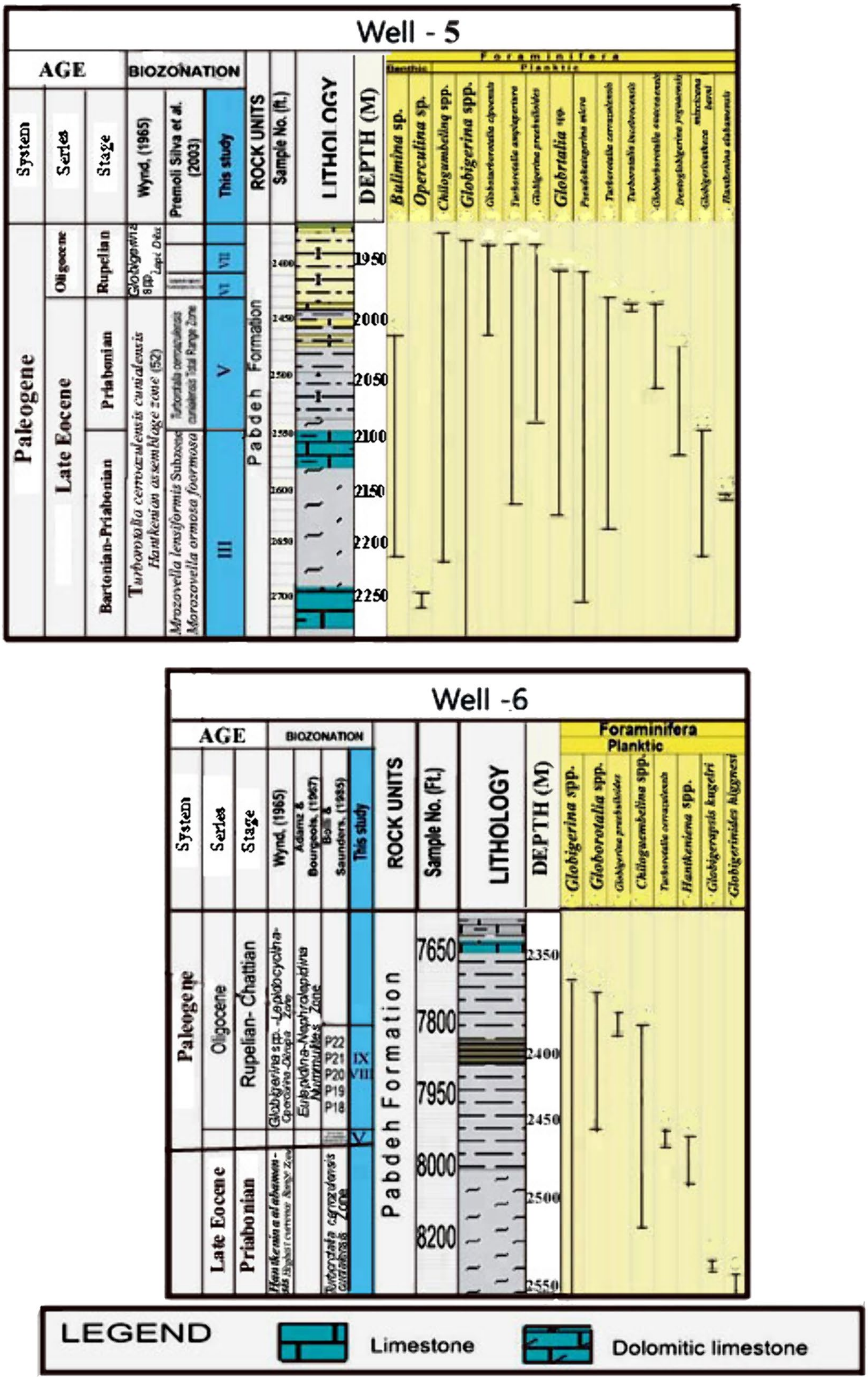


Fig. 8 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene–Oligocene times of the Pabdeh, Jahrum, and Asmari formations in wells 5 and 6

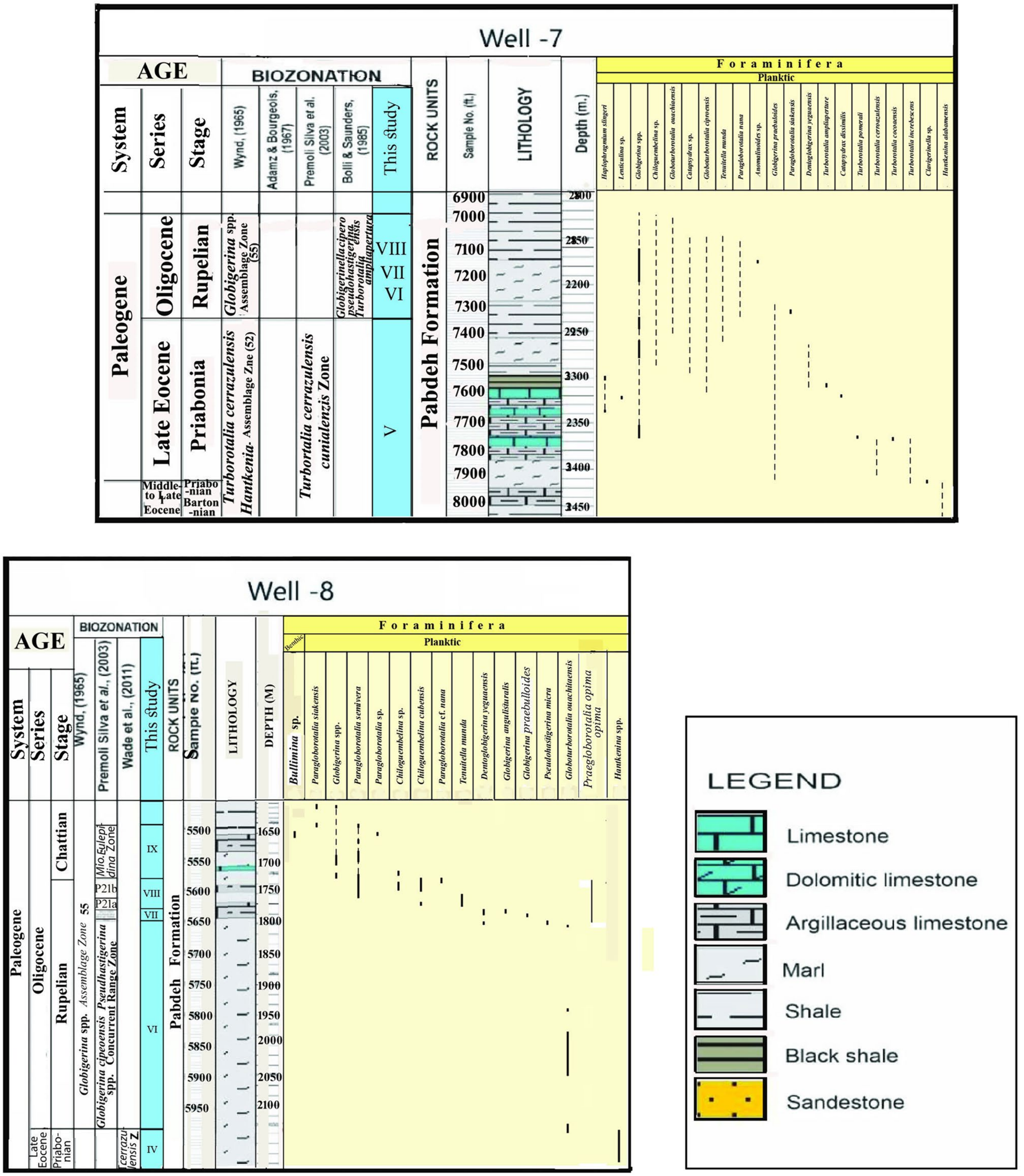


Fig. 9 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene–Oligocene times of the Pabdeh, Jahrum, and Asmari formations in wells 7 and 8

Formation, the thickness of this zone is about 50 m. The most important microfossils in this zone includes: *Operculina* sp., *Elphidium* sp., *Heterostegina* sp., *Triloculina trigonula*, *Neorotalia viennotti*, *Amphistegina* sp., *Quinqueloculina* sp., *Rotalia* spp. Rotaliddae gen. et. sp. indet. *Globorotalina archaeomeandrii*, *Globorotalia praesctiula, Morozovella cf. subbotinae, Morozovella acuta, Morozovella lensiformis, Acarinina soldadoensis*,

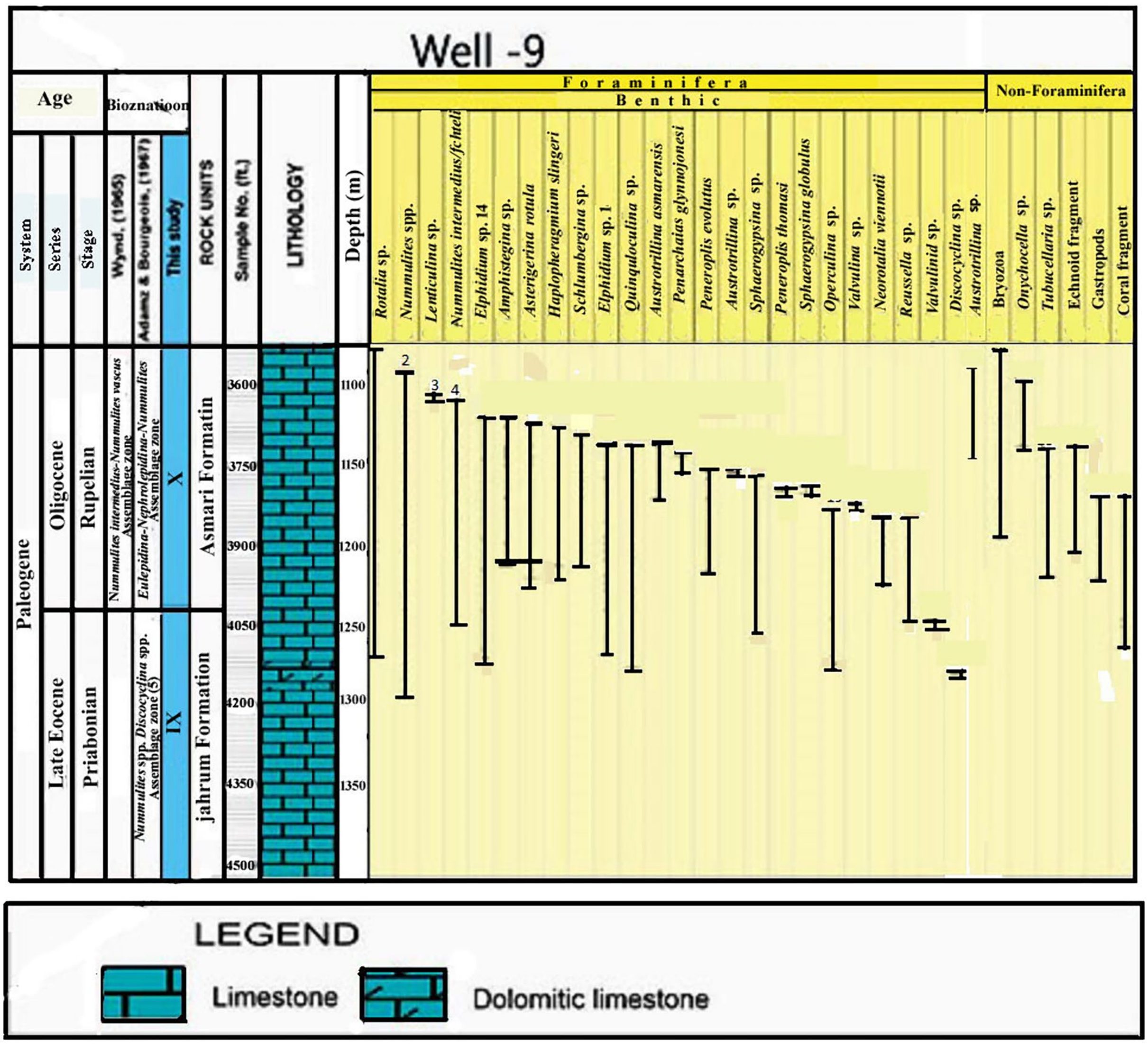


Fig. 10 The occurrence and range of foraminifera, with different biostratigraphic zonation schemes of Eocene–Oligocene times of the Pabdeh, Jahrum, and Asmari formations in well 9

Table 1 Thickness of the Jahrum, Pabdeh, and Asmari formations in the studied wells.

Jahrum formation	Pabdeh formation								Asmari Formation
Well-9	Well-1	Well-2	Well-3	Well-4	Well-5	Well-6	Well-7	Well-8	Well-9
450m	50 m	600 m	725 m	550m	600m	500m	400m	850m	450m

Acarinina intermedia, *Chiloguembelina trintanensis, Parasubbotina varianta*) with *Tubucellaria* sp., and algae. *Globorotalia (Morozovella) velascoensis* has been found in late Paleocene- early Eocene in the well-Tel Hajar-1, Northwestern Iraq (Ghafor 1988; Al-Shaibani et al. 1993). This biozone (P5) was recognized by Bolli and Saunders (1985) and is correlative with biofacies 42 (*Globorotalia velascoensis-Globorotalia pseudomenardii* assemblage zone) of Wynd (1965). Based on the Lowest Occurrence (LO) of *Acarinina intermedia* in the early Eocene age, this zone is restricted to the Early Eocene.

This biozone is herein assigned to the Ypresian (Eocene) that corresponds to 55.4–54.2 Ma, based on Wade et al. 2011).

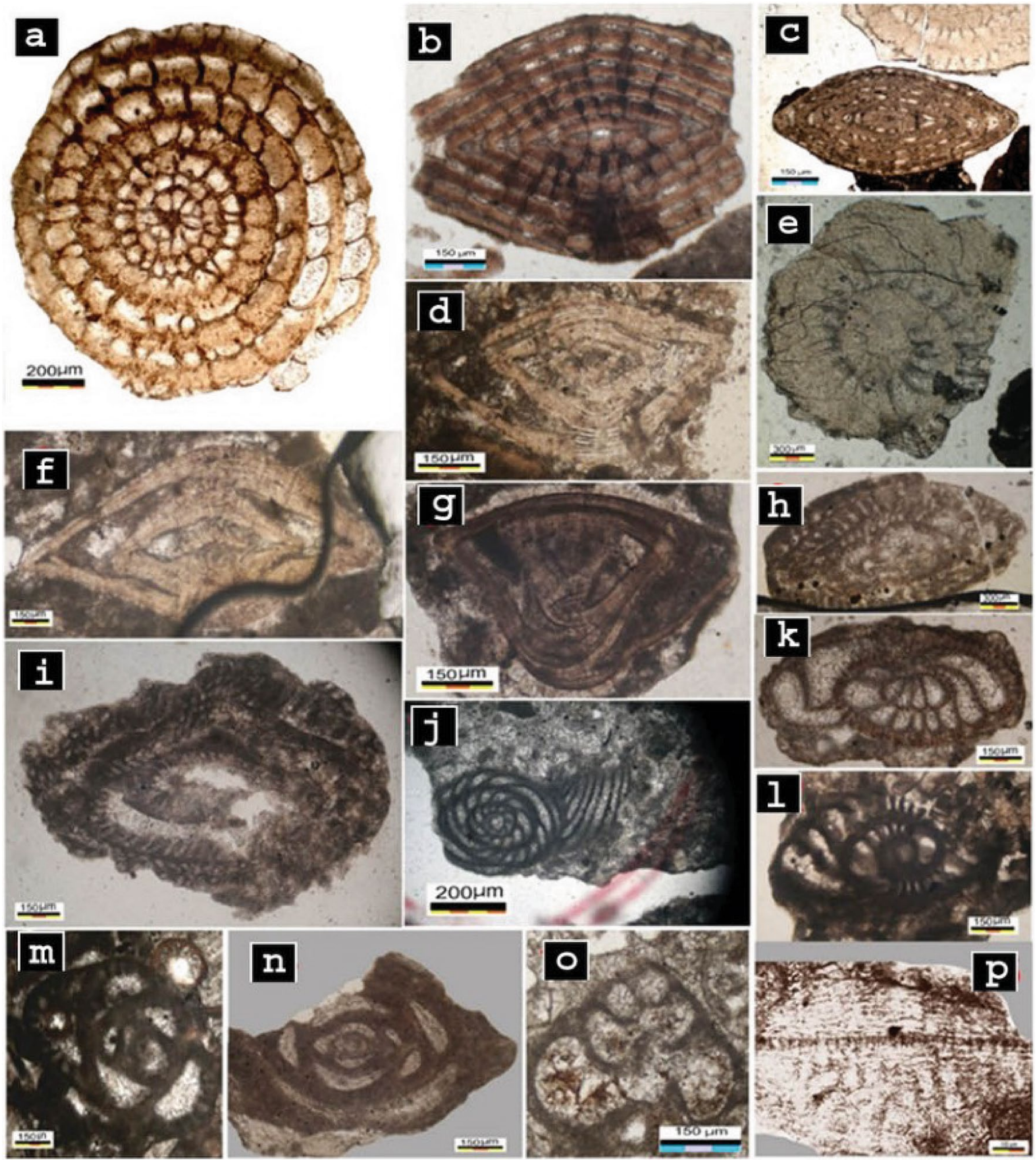
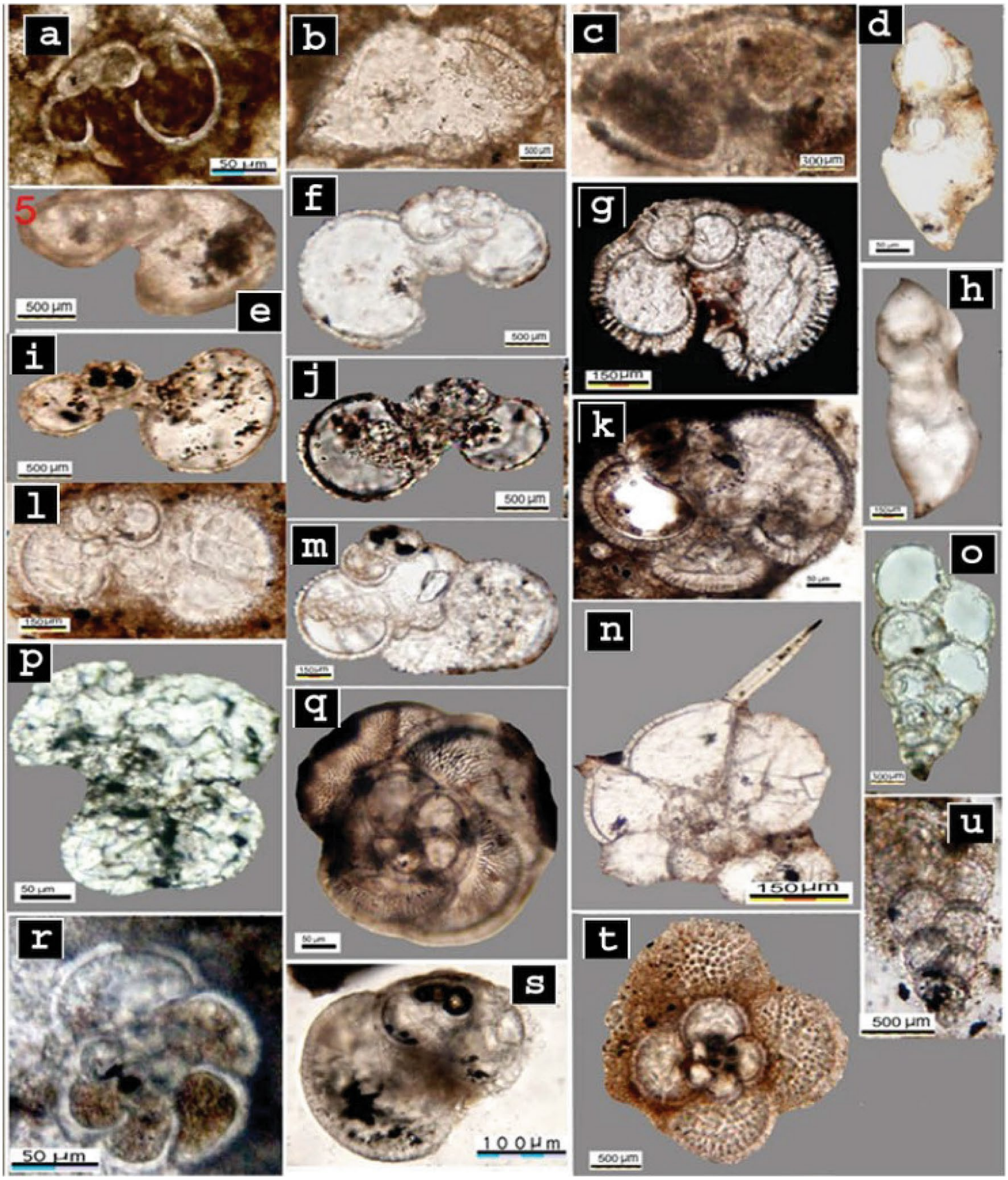


Plate 1 (**a**–**c**) *Nummulites fichteli/intermedius* (D'Archiac, 1846), (Zone IX, Chattian), (**a**) Sample 4410, Well-9, X4, (**b**) Sample 3850, Well-9, X4, (**c**) Sample 3830, Well-9, X4 (**d**) *Asterigerina* sp., d' Orbigny, 1839), (Zone X, Chattian), Sample 4130, Well-9, X10; (**e**) *Operculina complanata* (De France in Blainville, 1822), (Zone X, Chattian) Sample 6930, Well-9, X4; (**f**) *Amphistegina* sp., d' Orbigny, 1826, (Zone IX, Chattian) Sample. 3750, Well-9, X10; (**g**) *Asterigerina rotula* (Kaufmann, 1867), (Zone X, Chattian), Sample 3870, Well-9, X10; (**h**, **i**) *Austrotrillina asmariensis* Adams, 1968, (Zone IX, Chattian) (**h**) Sample 3830, Well-9, X10, (**i**) Sample 3670-75, Well-3, X10; (**j**) *Peneroplis thomasi*, (Henson, 1950), (Zone IX, Chattian) Sample. 3960, Well-9, X4; (**k**, **l**) *Elphidium* sp.1, Montfort, 1808, (Zone IX, Chattian), (**k**) Sample 4190, Well-9, (**l**) Sample no. 4330, Well-9, X10; (**m**) *Quinqueloculina* sp. (d' Orbigny, 1826), (Zone IX, Chattian) Sample 4190, Well-9, X10; (**n**) *Schlumbergina* sp., (Chalmas, 1882) (Zone IX, Chattian) Sample 4190, Well-9, X10; (**o**) *Valvulinid* sp. 1, Sample 4370, Well-9, X10; (**p**) *Discocyclina* sp., Gumbel, 1870, (Zone X, Chattian) Sample 4520, Well-9, X

Morozovella edgari Zone (II)

This zone is initially defined by Premoli Silva and Bolli (1973). Biostratigraphic interval of this zone is characterized by the co-occurrent range of the nominate taxa of *Igorina tadjikistanensis* and *Chiloguembelina trinitatensis*. This zone appears above the *Morozovella velascoensis* zone. This zone occurs only in well 1, the thickness of this zone is about



40 m, the most diagnostic species in this zone include: *Heterostegina* sp., *Neorotalia viennotti*, *Amphistegina* sp., *Quinqueloculina* sp., *Rotalia* spp. Nummulitidae gen. et. sp. indet. *Morozovella cf. subbotinae, Morozovella acuta, Morozovella cf. acuta, Morozovella* sp., *Acarinina soldadoensis*, *Aarinina intermedia*, *Globanmalina* sp., *Chiloguembelina trintanensis, Igornia tadjikistanensis, Parasubbotina varianta*) with *Tubucellaria* sp., and algae. It is equivalent to *Morozovella edgari* Subzone proposed by Premoli Silva et al. (2003), in Italy country., and This biozone is defined by the biostratigraphic interval between the Highest Occurrence (HO) of *Morozovella velascoensis* and the simultaneous Lowest Occurrence (LO) of *Morozovella formosa formosa* and/or *Morozovella lensiformis* and is correlative with biofacies 42 (*Globorotalia velascoensis-Globorotalia pseudomenardii* assemblage zone) of Wynd (1965). This zone is restricted to the early Eocene.

This biozone is herein assigned to the Ypresian (Eocene) that corresponds to 34.3–33.7 Ma (54.2–54 Ma, based on Wade et al. 2011).

◂**Plate 2** (**a**) *Acarinina intermedia* Subbotina, 1953, (Zone I, Ypressian), Sample 7040-50, Well-1, X40; (**b**)*Morozovella lensiformis* (Subbotina, 1953), (Zone I, Ypressian), Sample 7040-50, Well-1, X40; (**c**) *Igorinatadjikistanensis* (Bykova, 1953), (Zone I, Ypressian), Sample 7050-60, Well-1, X40; (**d**, **h**) *Clavigerinella* sp., Bolli, Loeblich&Tappan, 1957, (Zone V, Priabonian), (**d**) Sample 7920, Well-7, X10, (**h**) Sample 5790, Well-8, X10; (**e**) *Globanomalina* sp., Haque, 1956, (Zone I, Ypressian), Sample 7030-35, Well-1, X40; (**f**) *Globigerina praebulloides* (Blow, 1959), (Zone IV, Priabonian), Sample 5720-30, Well-2, X40; (**g**) *Turborotalia ampliapertura*, (Bolli, 1957), (Zone IV, Priabonian), Sample 5770-80, Well-3, X40 ; (**i**) *Parasubbotina varianata*, (Subbotina, 1953), (Zone III, Ypressian) Sample 7050-60, Well-1, X40; (**j**) *Acarinina soldadoensis* (Bronnimann, 1952), (Zone III, Ypressian) Sample 7020-30, Well-1, X40; (**k**) *Catapsydrax dissimilis* (Subbotina, 1953), (Zone V, Priabonian), Sample 7670, Well-7, X10; (**l**) *Dentoglobigerina yeguaensis* (Weinzierl & Aprplin, 1929), (Zone V, Priabonian), Sample. 7530,Well-7, X40; (**m**) *Globoturborotalia ouachitaensis* (Howe & Wallace, 1932), (Zone VII, Rupelian), Sample 7600, Well-8, X40; (**n**) *Hantkenina alabamensis* (Cushman, 1925a), (Zone V, Piabonian), Sample 8000, Well-7, X10; (**o**) *Chiloguembelina cubensis* (Palmer, 1934), (Zone V, Priabonian), Sample 5690, Well-6, X40; (**p**) *Paragloborotalia opima* (Bolli, 1957), (Zone III, Rupelian), Sample 5690, Well-8, X10; (**q**) *Turborotalia cerroazulensis* (Cole, 1928), (Zone V, Priabonian), Sample 7890, Well-7, X40; (**r**) *Pseudohastigerina micra* (Cole, 1927), (Zone V, Priabonian), Sample 5770, Well-5, X40; (**s**) *Turborotalia pomeroli* (Toumarkin & Bolli, 1970), (Zone V, Priabonian), Sample 7770, Well-7, X40; (**t**) *Globoturborotalia ciproensis* (Bolli, 1957), (Zone V, Rupelian), Sample 5810, Well-3, X40; (**u**) *Chiloguembelina trinitatensis* (Kushman & Renz, 1942), (Zone III, Ypressian), Sample 7050-60, Well-1, X40

Morozovella formosa formosa Zone (III)

This zone is initially defined by Bolli, (1957), Biostratigraphic interval of this zone is characterized by the co-occurrent range of the nominate taxa of *Chiloguembelina trinitatensis* and *Acarinina soldadoensis*. This zone is established only in well-5 and is restricted to the Early Eocene, the thickness of this zone is about 150m. The most diagnostic species in this zone includes: *Heterostegina* sp., *Neorotalia viennotti*, *Amphistegina* sp., *Quinqueloculina* sp., *Rotalia* spp. Nummulitidae gen. et. sp. indet. *Morozovella cf. subbotinae, Morozovella acuta, Morozovella formosa formosa, Morozovella cf. acuta, Morozovella* sp., *Acarinina soldadoensis*, *Aarinina intermedia*, *Globanmalina* sp., *Chiloguembelina trintanensis, Igornia tadjikistanensis, Parasubbotina varianta*, with *Tubucellaria* sp., and algae. This zone is not disintegrated and is equivalent to biozones P6b-P7 (*Morozovella lensiformis* Subzone and *Morozovella formosa formosa* Zone) of Premoli Silva et al. (2003). The subzone P6b (*Morozovella lensiformis* Subzone) is defined by the biostratigraphic interval between the LO of *Morozovella formosa formosa* and/or *Morozovella lensiformis* and the LO of *Morozovella aragonensis.* The subzone P7 (*Morozovella formosa formosa* Zone) is defined by biostratigraphic interval between the LO of *Morozovella aragonensis* and the LO of *Morozovella formosa formosa.* These two biozones are correlative with biofacies 42 (*Globorotalia velascoensis-Globorotalia pseudomenardii* assemblage zone) of Wynd (1965).

This biozone is herein assigned to the Ypresian (Eocene) that corresponds to (54–52.3 Ma, based on Wade et al. **2011).**

Hantkenina alabamensis Zone (IV)

This zone is marked only with LO of *Hantkenina alabamensis* at the top borders. It is Highest-Occurrence-Range. The thickness of this zone is about 25 m in well 2, 31 m in well 3, and 80 m in well 8. The most diagnostic species in this zone are *Reucella* sp., *Globigerina* sp., *Globigerina praebulloides*, *Hantkenina alabamensis*, *Globoturbortalia quachiatensis*, *Pseudohastigerina micra*, have been recognized in this zone. This zone is equivalent to biozone E16 (*Hantkenina alabamensis* Highest-Occurrence Zone) of Wade et al. (2011). This biozone is characterized by a partial range of nominate taxons between the LO of *Globigerinatheka index* and the LO of *Hantkenina alabamensis*. This biozone is characterized by wells 2, 3, and 8. This biozone is correlative with biozone 52 (*Globorotalia cerroazulensis-Hantkenina* assemblage zone) of Wynd (1965) and is restricted to the late Eocene.

This biozone is herein assigned to the Priabonian (Eocene) that corresponds to 34.3–33.7 Ma, based on Wade et al. 2011).

Turborotalia cerroazulensis cunialensis Zone (V)

Biostratigraphic interval of this zone characterized by the total range of ***Turborotalia cerroazulensis cunialensis***.

The thickness of this zone is about 60 m in well 4, 90 m in well 5, 7 m in well 6, and 400 m, in well 7.

The most important fauna in this zone are: *Hantkenina* spp., *Turborotalia cerroazulensis cunialensis, Globigerina* spp., *Globoturborotalia ouachitaensis, Globrotalia praebulloides, Globortalia* spp., *Pseudohastigerina micra*, *Turborotalia crreazulensis, Turborotalia pomeradli*, *Turborotalia cocaensis, Turborotalia increbescensis*, *Chiloguembelina cubensis, Chiloguembelina* sp., *Hantkenina alabamensis*, *Dentoglobigerina yeguaensis, Globanomalina* sp., *Bulimina* sp., *Operculina* sp., *Globigerapsis kugleri, Globorotalia* spp., *Haplofragmium sliengeri, Lenticulina* sp., *Chiloguembelina* sp., *Catapsydrax dissimilis, Globoturborotalia ciproensis, Tenuitella munda, Paragloborotalia nana, Paragloborotalia siakensis, Turborotalia ampliapertura, Clavigerinella* sp. This zone is corresponding to biozone P17 (*Turborotalia cerroazulensis cunialensis* Total Range Zone) of Toumarkine and Bolli (1970). This biozone is characterized by the LO of *Turborotalia cerroazulensis* in wells 4 to 7. *Turborotalia cerroazulensis* has been found in middle-Late Eocene sediments (Ghafor and Al-Qayim 2021). The *Hantkenina* spp. is present in this zone. The biozone P17 (*Turborotalia cerroazulensis* Total Range Zone) is correlative with biofacies 52 (*Globorotalia cerroazulensis-Hantkenina* assemblage zone) of Wynd (1965) and restricted to the late Eocene. It is equivalent to the *Acarinina bullbrooki* and *Morozovelloides lehneri* biozone of Ghafor and Al-Qayim (2021) and to the upper part of *Assilina spira- Lokharatia hunti* zone by Al-Qayim and Ghafor (2022). The associated fauna in well 7 is consisting of *Turborotalia cerroazulensis., Turborotalia pomeroli, Turborotalia ampliapertura. Catapsydrax dissimilis* and *Dentoglobigerina yguaensis.*

This biozone is herein assigned to the Priabonian (Eocene) that corresponds to 35.5–33.7 Ma, based on Wade et al. 2011).

Cassigerinella chiploensis-Pseudohastigerina micra Zone (VI)

Biostratigraphic interval of this zone was characterized by the concurrent range zone of the nominate taxa between the LO of ***Cassigerinella chiploensis*** to the LO of *Pseudohastigerina micra.* The thickness of this zone is about 95m in well 3, 163 m, in well-4, and about 24 m in the well-5, 56m in well 7, and 300m in well 8. This zone includes these planktic foraminifera: *Globorotalia opima opima, Turborotalia increbcenus, Turborotalia cerroazulensis, Hantkenina* spp., *Globigerina praebulloides, Globoturborotalia cipreoensis, Globigerina cips, angustimblicata, Bullimina* sp. This stratigraphic interval encompasses Zones P18 and P19 of Blow (1969), Zone P18 and P19 (*Cassigerinella chiploensis-Pseudohastigerina micra* Concurrent Range Zone) of Bolli and Saunders (1985), Zones P17 and P18 of Berggren et al. (1995), and Iaccarino and Premoli Silva (2005). This biozone in well-2 is characterized by a biostratigraphic interval between the LO of *Hantkenina alabamensis* to the LO of *Pseudohastigerina micra*. The association fauna in this interval encompasses *Reussella* sp., *Chiloguembelina* sp., *Globigerina* spp., *Globigerina praebulloides*. The biozone P18-P19 is also identified and characterized in well-8 by the biostratigraphic interval between the LO of *Hantkenina* spp. to the LO of *Pseudohastigerina micra*. The Oligocene biozonation is not disintegrated in the other wells and has been reported to form a compound, except in wells- 4 and 5. The biozone P18-P19 in well-4 is characterized by a biostratigraphic interval between the LO of *Hantkenina* spp. to the LO of *Turborotalia increbescens*. This biozone in well- 5 is marked from the LO of *Turborotalia cerroazulensis* to the LO of *Pseudohastigerina micra*. The biozone P18-P19 of (Bolli and Saunders 1985, and Iaccarino and Premoli Silva 2005) is correlative with the Oligocene biozonation of Wynd (1965) and Adams and Bourgeois (1967). This zone is restricted to the Early Oligocene.

This biozone is herein assigned to the to the Rupelian (Oligocene) that corresponds to 33.8–30.3 Ma, based on Wade et al. 2011).

Turborotalia ampliapertura Zone (VII).

This zone is initially defined by Berggren et al. (1995), Biostratigraphic interval of this zone is characterized by the co-occurrent range of the nominate taxa of *Pseudohastigerina* and *Turborotalia ampliapertura*. The thickness of this zone is about 95m in well 3, 54 m, in well 5, and, 66m in well 7, and 18m in well 8. This biozone includes these planktic foraminifera: *Nummulites* spp., *Operculina* sp., *Triloculina* sp., *Reussella* sp., *Chiloguembelina cubensis*, *Chiloguembelina* sp., *Globigerina* spp., *Turborotalia ampliapertura*, *Dentoglobigerina yguaensis*, *Globoturborotalia ouachitaensis*, *Globigerina angulisuturalis, Globigerina praebulloides, Pseudohastigerina micra, Globoturborotalia ouachitaensis, Praegloborotalia opima opima, Praegloborotalia nana, Anomaniloides* sp., *Tenutella munda*, and *Globigerina praebulloides*. This biozone corresponds to the P19 Interval Zone of Berggren et al. (1995). The zone is re-defined concerning the original zone of Bolli (1957) and coinciding with biozone P20 (*Turborotalia ampliapertura* Interval Range Zone) of Iaccarino and Premoli Silva (2005), it is exactly correlative with the biozone P20 of Iaccarino and Premoli Silva (2005) except in well-8. The biostratigraphy interval at the top boundary of well-8 is marked from the LO of *Dentoglobigerina yeguaensis*.. This biozone is equivalent to the *Turborotalia ampliapertura* zone *(*Sajadi et al. 2016) in southeastern Persian Gulf. The stratigraphy interval in well-4 is equivalent to biozone P20 (*Tuborotalia ampliapertura* Interval Zone) of Bolli and Saunders (1985) which is characterized by biostratigraphic interval between the LO of *Turborotalia increbescens* to the LO of *Globorotalia opima opima*. The Oligocene biozonation is not disintegrated in the other wells and has been reported to form a compound. This biozone is correlative with the Oligocene biozonation of Wynd (1965), Adams and Bourgeois (1967).

This biozone is herein assigned to the to the Rupelian (Oligocene) that corresponds to 30.3–29.4 Ma, based on.

Wade et al. 2011).

Paragloborotalia opima opima Zone (VIII).

This zone is initially defined by Berggren et al. (1995), **the** biostratigraphic interval of this zone is characterized by the total range of *Paragloborotalia opima opima*, the thickness of this zone is about 60 m. in well 4, 300m in well 3, 65m in well 6, 213m in well 7, and 70m in well 8. This zone includes these species of planktic and benthic foraminifera:, *Globoturborotalia ciproensis ciproensis* and

Globoturborotalia ciproensis angulisuturalis, *Globigerina praebulloides*, *Globigerina* cip. *angustiumblicata, Globigerina* sp., *Paragloborotalia opima opima*, *Paragloborotalia nana, Paragloborotalia* cf. *nana, Paragloborotalia sikaensis, Paragloborotalia semivera, Chiloguembelina* sp., *Anomaniloides* sp., *Catapsydrax dissimilina,., Catapsydrax* sp., *Globigerina officlnolis, Globigerina praebulloides*, *Globigerina angulisturalis, Globorotalia ouachitaensis, Globorotalia ciproensis, Tenuitella munda, Chiloguembelina* sp, *Chiloguembelina cubensis, Anomaniloides* sp., *Dentoglobigerina yeguaensis, Pseudohastigerina micra,Operculina* spp., *Numulites* spp., *Textularia* spp., *Trilocullina trigonula.* This biostratigraphy interval of this zone coincides with biozone P21 (*Globorotalia opima opima* Taxon Range Zone) of Bolli (1957). This biozone in wells- 3 and 4 is characterized by the total range of the nominate taxon. In addition to the restriction of the nominate taxon, based on Bolli (1957). This stratigraphy interval in well-8 is equivalent to two subzones P21a and P21b of Iaccarino and Premoli Silva (2005). The subzone P21a in well-8 is marked from the LO of *Dentoglobigerina yeguaensis* to the LO of *Paragloborotalia semivera* and subzone P21b is marked from biostratigraphy interval between the LO of *Paragloborotalia semivera* to the LO of *Chiloguembelina cubensis*. The Oligocene biozonation is not disintegrated in the other wells and has been reported to form the compound. This biozone is equivalent to the *Globorotalia opima opima* zone by (Sajadi et al. 2016) in the southeastern Persian Gulf. The biozone P21 of Bolli and Saunders (1985) and Iaccarino and Premoli Silva (2005) is correlative with the Oligocene biozonation of Wynd (1965) and Adams and Bourgeois (1967). This zone is restricted to the Early Oligocene.

This biozone is herein assigned to the to the Rupelian (Oligocene) that corresponds to 29.4–28.4 Ma, based on.

Wade et al. 2011).

Nummulites intermedius – Nummulites vascus Zone (IX)

The biostratigraphic interval of this zone was characterized by the assemblage of the nominate taxa (*Nummulites intermedius-Nummulites vascus*). The thickness of this zone is 100 m in well 6, 90 m. in well 8, 100 m in well 9, this zone involves these species of benthic and planktic foraminifera: *Rotalia* sp., *Bullimina* sp., *Nummulites* spp., *Nummulites intermedius/fichteli*, *Nummulites* spp., *Lenticulina* sp., *Elphidium* sp., *Amphistegina* sp., *Haplofrugmina slingeri*, *Schlumbergina* sp., *Elphidium* sp1., *Quinqueloculina*, *Austrotrillina asmariensis, Penarchiaus glynogonesi, Peneroplis evolutus, Austrotrillina* sp., *Valvulina* sp., *Sphaerogypsina* sp., *Sphaerogypsina globulus, Valvulinid* sp., *Operculina* sp., *Neorotalia viennotti, Reussella* sp., *Discocyclina* sp., *Globogerina* spp., *Praegloborotalia semivera, Praegloborotalia* sp., *Chilohuembelina cubensis*, *Chiloguembelina* sp., and other microfossils such as echinoid fragments, coral fragments, *Onychosella* sp., *Tubucellaria* sp., Bryozoa, and gastropods. This zone is equivalent to biozone 5 (*Nummulites* spp. *Discocyclina* spp. Assemblage Zone) of Adams and Bourgeois (1967).

This biozone is herein assigned to the to the Chattian (Oligocene) Based on Adams and Bourgeois (1967).

Nummulites spp. *Discocyclina* spp. Zone (X)

The biostratigraphic interval of this zone was characterized by the assemblage of the nominate taxa *Nummulites* spp. *Discocyclina* spp. This zone occurs in well-9 with a thickness about 142 m, it includes: *Nummulites fichteli/intermedius*, *Amphistegina* sp., *Asterigerina rotula., Schlumbergerina* sp., *Quinqueloculina* sp., *Austrotrillina* sp., *Valvulinid* sp., *Elphidium* sp. 1, *Elphidium* sp. 14, *Rotalia* sp., *Lenticulina* sp., *Haplofragmina slingeri*, *Austrotrillina asmariensis, Austrotrillina* sp., *Quinqueloculina* sp., *Penarchaias glynnjonesi, Peneroplis oevolutus*, *Peneroplis thomasi, Spharegypsina* sp., *Operculina* sp., *Neorotalia viennotti, Reusella* sp., Discocycllina sp., *Onychocella* sp., *Tubucellaria* sp coral fragments, bryozoa, gastropods,,., and echinoid fragments. This zone is equivalent to biozone 3 (*Eulepidina-Nephrolepidina-Nummulite* assemblage Zone) of Adams and Bourgeois (1967). This zone is equivalent to the *Globoturborotalia ciproensis* zone by (Sajadi et al. 2016) in the southeastern of the Persian Gulf. This biozone is equivalent to the Lower Asmari (Thomas 1949). It is equivalent to *Nummulitic vascus-Nummulitic fichteli* zone by Ghafor and Najaflo (2021), to the *Nummulitic fichteli -Nummulitic vascus* zone of Ghafor and Ahmad (2021).

This biozone is herein assigned to the to the Chattian (Oligocene) Based on Adams and Bourgeois (1967).

Discussion

Based on the latest biozonation, ten biozones have been recognized. These biozones are considered to be Eocene–Oligocene in age. These established biozones have been correlated very well in the studied transect. Upper Eocene through Lower Oligocene deposits, at the study transect, contains abundant planktic and benthic foraminifera. According to Toumarkine and Bolli (1970), the LO for each of three subspecies (*Turborotalia cerroazulensis cerroazulensis*, *Turborotalia cerroazulensis cocoaensis, Turborotalia cerroazulensis cunialensis*) marks the Eocene–Oligocene transition and *Hantkenina* spp., showing the biostratigraphy range of Late Eocene time. The simultaneous extinctions of *Hantkenina* spp. and *Turborotalia cerroazolensis* lineage are now widely accepted as a biostratigraphic datum that marks the

Eocene–Oligocene transition (Snyder et al. 1984). Those microfossils most useful for recognition of the Eocene–Oligocene transition are subspecies of *Turborotalia cerroazulensis* (Premoli Silva et al. 2003). The rapid evolution of *Hantkenina* from *Clavigerinella* was via a previously undescribed intermediate form (Pearson et al. 2006a, b, c). Based on Isotope records, the ranges of *Turborotalia cerroazulensis* and *Turborotalia pomeroli* are near the middle/late Eocene boundary (Premec-Fucek 2006; Pearson 2006). Based on the new study of Wade et al. (2011), the LO for *Hantkenina alabamensis* marks the Eocene/Oligocene boundary. The Eocene–Oligocene transition in the Adriatic Sea is clearly defined by the extinction of all hantkeninids, the *Turborotalia cerroazulensis* group, and the last globigerinathekid species *Globigerinatheka tropicalis* (Fucek and Kucenjak 2013). Molina et al. (2016), show that the Integrated biostratigraphy by means of planktic foraminifera, calcareous nannofossils, and larger benthic foraminifera from a continuous marine section at Noroña (Cuba) the extinction of orthophragminids lies in the Rupelian (early Oligocene). Rapid mass extinction event in planktic foraminifera occurred at the Eocene–Oligocene transition, in northeastern Tunisia, including the extinction of the Turborotalids (*Turborotalia cerroazulensis, Turborotalia cocoaensis* and *Turborotalia cunialensis*) followed by a significant size reduction of the genus *Pseudohastigerina* and the extinction of the hantkeninids (*Hantkenina alabamensis, Hantkenina brevispina*, *Hantkenina nanggulanensis* and *Cribrohantkenina lazzarii*), which mark the Eocene–Oligocene transition. (Karoui-Yaakoub et al. 2017). In the current study three lithostratigraphic units have been recognized which are Pabdeh, Jahrum and asmari formations that corresponds to the lithostratigraphic units in Iraq, that Jahrum Formation is equivalent to the Kolosh, Aaliji, and Sinjar formations in Iraq (Ghafor 1988; Sharbazheri et al. 2009, 2011; Al Fattah et al. 2017, 2018, 2020a, 2020b; Al-Nuaimy et al. 2020; Al-Taee et al. 2024a,b,c), and the upper part of the Pabdeh Formation is equivalent to the Tarjil, Shurau, Baba, and Bajwan formations in Iraq (Ghafor 2022; Ghafor and Najaflo 2022), and the lower part of the Pabdeh Formation is equivalent to the Avanah and Jaddala formations in Iraq (Asaad 2022; Al-Sultan 2018), finally the Asmari Formation is equivalent to the Azkand, Baba, Anah, Serikagni, Ibrahim, Jerebi, and Euphrates formations in Iraq (Buday 1980; Ghafor 2004; Ghafor and Najaflo 2022). The microscopic investigation revealed the presence of common planktic foraminifera, i.e., *Turborotalia cerroazulensis, Turborotalia pomeroli, Turborotalia cocoaensis*, *Clavigerinella* sp., *Dentoglobigerina*

Table 2 Correlation chart showing the biostratigraphic zones of this study with the other studies in Iraq.

Eratheme	System	Series	Stage	Ghafor, 2011	Ghafor & Al-Qayim 2021	Ghafor & Ahmad 2021	Al-Qayim & Ghafor 2022	Ghafor 2022	Ghafor & Najaflo 2022	Ghafor et al., 2023	Al-Taee et al. 2024	This Study
Cenozoic	Paleogene	Oligocene	Chattian	*Lepidocyclina-Nummulites* Zone		*Praehapydomina delicata Penerooplis evolutus* Zone		*Preahapydmina delicata Atchaias kirkunesis* Zone	*Lepidocyclina(Eulepidina) dilatat* *Nummulites vascus Nummulites fichteli* Zone	*Meandrospina anahensis-Austrotrillina asmariensi* Zone		X, IX, VIII
			Rupelian			*Eulepidina dilata Nephrlepidina marginata* Zone		*Preahapydmina delicata peneroplis evolutus* Zone	*Nummulites vascus Nummulites fichteli* Zone			VII, VI
		Eocene	Priabonian		*Globugerinatheca semiinvoluta Hantkenina alabamensis* Zone; *Morozovelloides lehneri* Zone; *Acarinina bullbroki* Zone		*Assilina spiri Lokharatia hunti* Zone; *Nummulites ginehensis-Nummulites moculatus* Zone					V, IV
			Ypressian								*Idalina sinjarica Alveoolina globosa Alvelina pastisilata* Zone	III, II, I

yeguaensis, *Globoturborotalia ouachitaensis*, *Turborotalia increbescens*, *Pseudohastigerina micra*, *Globigerina praebulloides*, *Turborotalia ampliapertura*, *Globoturborotalia ciproensis*, *Chiloguembelina trinitatensis*, *Chiloguemblina cubensis*, *Paragloborotalia opima opima* and *Paragloborotalia nana,* with variable percentages of benthic foraminifera mainly belonging to the *Nummulites fichteli/intermedius*, *Nummulites* spp., *Elphidium* sp. 14, *Amphistegina* sp., *Asterigerina rotula*, *Schlumbergerina* sp., *Quinqueloculina* sp., Valvulinid sp., *Peneroplis evolutus*, *Neorotalia viennoti*, *Reussella* sp., *Haplophragmium slingeri*. The recognized biozones (Zone I—Zone X) in the current study were correlated with the biozones established in Iraq (Table 2). The distributions of larger benthic foraminifera in the well-9 section are determined by the Eocene–Oligocene transition and age of the Jahrum and Asmari formations. Based on above mentioned well-known planktic and benthic zonal scheme, the Eocene–Oligocene transition continues and occurs in open marine deposits of the Pabdeh Formation and finally leads to the shallow marine carbonates of the Jahrum and Asmari formations in the nine wells of the studied area, (Plates 1, 2). The Eocene–Oligocene transition is identified and integrated throughout the study transect, except in well-1, which exposes a biostratigraphy gap (Wynd 1965). According to micropaleontological data, the Eocene–Oligocene transition is continuing. The integrated biostratigraphy (planktic and benthic foraminifera) shows that the Eocene–Oligocene transition of this region have 10 biozones).

Conclusions

Three formations have been recognized in this study:- (1) the Jahrum Formation (Proabonian), (2) Pabdeh Formation (Priabonian-Chattian), and (3) the Asmari Formation (Rupelian-Chattian). The proposed biozonation and age determinations is based on planktic and benthic foraminifera and compared with biozones from the tethyan and realms. The Eocene–Oligocene transition characterized biostratigraphically. More than 50 species of planktic and benthic foraminifera have been identified in the studied wells, among the recorded index species markers of this work, we considier *Turborotalia* and *Hantekenina* (LO as reliable proxies/ indicators of the Eocene–Oligocene boundary. Based on these results the Eocene–Oligocene transition at the study area is continuing and conformable throughout the NE-SW transection, except in well-1, where an unconformity (or hiatus) is supposed to occur spanning the middle Eocene to late Oligocene. Depending on the results the Jahrum Formation extended from the Ypresian to Priabonian (Eocene) age, the Pabdeh Formation to the Priabonia (Eocene) age, and the Asmari Formation from Rupelian to Chattian (Oligocene) age.

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Author contributions All the authors participated in this manuscript, that Dr Roya fanati write all the sections from the abstract to the conclusion, Dr sajadi draw all the figures and wrote the suggestions on all the sections, and Ghafor read the manuscript carefully and made the corrections and preparing the plates and figures, references and discussions.

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Declarations

Conflict of interest Authors have no competing interests and no interest declaration.

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