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Biostratigraphy and Paleoenvironmental significance of Paleogene foraminiferal assemblages from Dashte Zari area in High Zagros, west Iran

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Abstract

The Paleogene carbonate deposits of Pabdeh and Jahrum formations are widespread in the northwest of the Shahrekord region (Dashte Zari area) in the High Zagros Mountains of Iran and record lateral and upward transition from open marine into shallow water environment within the Zagros foreland basin. The Pabdeh Formation shows a succession of open marine pelagic and hemipelagic limestone, argillaceous limestone, and argillaceous chert. It consists of planktonic wackestone, pellet-planktonic wackestone, mudstone with planktonic foraminifera, and radiolarian siliceous wackestone. The planktonic foraminifera are assigned to the Late Paleocene to Late Eocene, and correspond to subtropical to tropical Zones P4b–E15. Only one planktonic biozone (Zone E12), which corresponds to the high level stand of the Bartonian climate optimum (MECO) was not recognized in likely response to a tectonic event. The Jahrum Formation is represented by bioclast-bearing limestone and calcarenite. It consists of benthic foraminiferal wackestone, benthic foraminiferal-red algal packstone, and bioclast-intraclast packstone

deposited in a shallow platform environment. The Jahrum Formation is inter-fingered in the upper part of the Pabdeh Formation and finally overlies it conformably during the Bartonian-Priabonian. Shallowing and offlap relationships record basin shrinking, while repeated inter-fingering signals moderate tectonic subsidence. Both formations are disconformably covered by the Late Oligocene-Miocene Asmari Formation.

Keywords

Biostratigraphy, Dashte Zari, Pabdeh and Jahrum formations, Zagros foreland basin, Paleogene foraminifera, West Iran

1. INTRODUCTION

The Iranian ranges long have been considered part of the Alpine-Himalayan System (Stöcklin, 1968, 1977, Sengör *et al.*, 1988, Babazadeh, 2003). This orogenic belt, which resulted from the closure of the Mesozoic Neo-Tethys, extends from western Europe (west Neo-Tethys) to Tibet passing through Turkey, Iran, Afghanistan (central Neo-Tethys), and possibly continues to Burma and Indonesia (east Neo-Tethys) (Sengör *et al.* 1988; Ahmad *et al.*, 2014) (Fig. 1A). Multiple continental blocks were amalgamated and are now separated by ophiolitic complexes (Stöcklin, 1977). During the Late Cretaceous, northeastward subduction beneath the Iranian subplate led to the closure of the central Neo-Tethys and ophiolite obduction onto the margin of the Afro-Arabian Plate (Stöcklin, 1977; Berberian & King, 1981; Davoodzadeh & Schmidt, 1981; Stoneley, 1981; Berberian, 1995; Alavi, 2004). Continent-continent collision starting in the Cenozoic led to the formation of the Zagros fold-and-thrust belt and associated Zagros foreland basin, in which Late Cretaceous to Miocene sediments accumulated (Fig. 1B). During the

Paleocene and Eocene, the Pabdeh Formation (pelagic marls and argillaceous limestones) and the Jahrum Formation (shallow marine carbonates) were deposited in the middle part and on both sides of the Zagros basin axis respectively (Motiei, 1993). During the Oligocene–Miocene this basin narrowed gradually and the Asmari Formation, which consists of dolomitized carbonate ramp limestones, calcareous sandstones and evaporites was deposited (e.g. Ehrenberg et al., 2007).

In the study area the lower contact of the Pabdeh Formation with the underlying Upper Cretaceous Gurpi Formation is faulted. The Jahrum Formation is inter-fingered in the upper part of Pabdeh Formation and overlaps it at his top. In the southwestern part of the Zagros basin, the Asmari Formation overlies the Pabdeh Formation, whereas in the Fars and Lurestan regions it covers the Jahrum and Shahbazan formations. Although the lower part of the Asmari Formation is locally interfingered with the Pabdeh Formation, its upper part extends over the entire Zagros basin. The Zagros Mountains include the High Zagros (Internal Zagros), Folded Zagros (Outer Zagros), and Khuzestan plain. In the High Zagros, the Shahrekord region of Chahar-Mahale Bakhtiari Province is subdivided into northeast (Z1), central (Z2), and southwest (Z3) fault-bounded zones. The Central Zone (Z2) is located between the Saman - Fereidoon Shahr thrust (F1) and the Bazoft thrust (F3) (Zahedi & Rahmati Ilkhechi, 2006). This zone is divided into two smaller sub-zones Z2a and Z2b, which are located in the Shahrekord region (Fig. 2A). It consists of the Upper Cretaceous to Paleogene Gurpi, Jahrum, Pabdeh, and Asmari formations. The studied Dashte Zari section (32°25'N; 50°20'E) is located in the sub-zone Z2b of the structural division of northwest Shahrekord city (Fig. 2B).

In the study area, the Pabdeh Formation is subdivided into Lower and Upper units and consists of pelagic carbonate and siliceous sediments, which include a succession of gray thin-bedded limestone, cream argillaceous limestone, and argillaceous chert. In contrast, the Jahrum Formation is composed of shallow marine grey to cream bioclastic limestone and calcarenite (Fig. 3A).

James & Wynd (1965) and Adams & Bourgeois (1967) were pioneers in the study of microfossils and microfacies of the Paleogene carbonate deposits in Zagros basin. They established the benthic foraminiferal biozonation of the Jahrum Formation in southwest and west Iran. Basic works on the Paleogene biostratigraphy of benthic foraminifera in the High Zagros Basin and other basins along the southwestern margin of Iran focused mostly on microfacies and macrofossils (Rahghi, 1976, 1978, 1980, 1983; Kalantari, 1976, 1978, 1980, 1986; Stöcklin & Setudehnia, 1991; Khatibi Mehr & Moalemi, 2009; Babazadeh *et al.*, 2015). The foraminiferal assemblage zones of Jahrum Formation and its equivalents were reported by a few researchers such as James & Wynd (1965) and Hottinger (2007). On the other hand, the Pabdeh Formation was analyzed by several researchers (Kalantari, 1986; Babazadeh *et al.*, 2010; Daneshian *et al.*, 2015; Chegini *et al.*, 2016; Moradian & Baghbani, 2016; Moradian *et al.*, 2017; Hadavandkhani *et al.*, 2018) based on biofacies and stratigraphy of samples from outcrops of the folded Zagros and Khuzestan plain, whereas the analysis of biostratigraphic zonation of planktonic foraminifera are extensively conducted for the first time in the High Zagros of Chahar- Mahale Bakhtiari Province. The purpose of this study is: 1) to document the planktonic and benthic foraminiferal fauna, and 2) to introduce the Paleogene foraminiferal biozonations.

91 **2. MATERIALS AND METHODS**

92 A total of 111 samples of Pabdeh and Jahrum formations from the Dashte Zari section are used
93 in this study. Most of the diagnostic criteria such as the size of the test, the shape of chambers,
94 the thickness of the test, and the number of keels can be recognized in axial and sub-axial
95 sections in thin sections. The thin sections of the specimen samples were prepared in Payame
96 Noor University Laboratory. The Paleogene planktonic zonations were established by many
97 researchers: Toumarkine & Lutertacher (1985); Berggren *et al.* (1995); Olsson *et al.* (1999);
98 Berggren & Pearson (2005), and Wade *et al.* (2011). Besides, the calibration of the first
99 occurrence (FO) and last occurrence (LO) data of planktonic species is based on Berggren *et al.*
100 (1995); and Berggren & Pearson (2005). The identification of Paleogene planktonic
101 foraminiferal species in thin sections is carried out based on the following publications: Postuma
102 (1971); Wernli *et al.* (1997); Konijnenburg *et al.* (1998); Premoli Silva *et al.* (2003); Babazadeh
103 *et al.* (2010); Daneshian *et al.* (2015); Sarigul *et al.* (2017), and Sari (2017) The species
104 identification of benthic foraminifera was made by reference mainly to Ellis & Messina (1940);
105 Le Calvez (1949); Cole & Gravell (1952); Hanzawa (1957); Rahaghi (1980); Loeblich & Tappan
106 (1987); Ozgen (2000); Sirel (2003, 2009); Hottinger (2007); Serra-Kiel *et al.* (2016), and
107 Hayward *et al.* (2021). The biozonal schemes of Berggren *et al.* (1995) and Berggren & Pearson
108 (2005) were correlated with relevant data levels of species found in the study area (Figs. 4A &
109 4B).

111 **3. STRATIGRAPHY**

The excellent exposures of Paleogene carbonate sedimentary rocks of the High Zagros basin of southwest and west Iran have allowed detailed stratigraphical and micropaleontological investigations of these rocks. The Paleocene-Eocene marine deposits of the Pabdeh and Jahrum formations in the Dashte Zari section contain planktonic and larger benthic foraminifera, which provide the basis for regional biostratigraphy. Due to the presence of faults and discontinuous outcrops of Paleogene successions in the Shahrekord region, the planktonic biostratigraphic research was not conducted until today.

3.1. BIOSTRATIGRAPHY

The planktonic foraminiferal zonations of Berggren *et al.* (195); Berggren & Pearson (2005) and Wade *et al.* (2011), and the benthic foraminiferal zonations of Serra-Kiel *et al.* (1998) and Hottinger (2007) are adopted for comparison and interpretation. However, a brief evaluation of the depositional setting is also explained in terms of Murray (1991), Hottinger (1983, 1997), and Flugel (1982, 2004). The planktonic and benthic foraminiferal assemblages from hemipelagic and neritic successions of the High Zagros provide the first published biostratigraphic data on this area. A total of 46 planktonic foraminiferal species belonging to 14 different genera, and 19 benthic foraminiferal species belonging to 17 different genera have been identified and led to the recognition of 14 planktonic biozones and 3 benthic associations respectively. The columnar stratigraphic sections are summarized in figures 5 and 6, which show the distribution of selected taxa of planktonic and benthic foraminifera. The micrographs of thin sections of Paleogene planktonic and benthic foraminiferal species are shown in plates 1-4 and plate 5 respectively. The planktonic foraminiferal biozonations enable to correlate with other biostratigraphic scales and to make more precise their age determination (Fig. 7).

135

136 **Pabdeh Formation**

137 The planktonic foraminiferal biozones are as follows:

138 **Pp1 - *Acarinina subsphaerica* Zone (TRZ)**

139 **TRZ: Total Range Zone**

140 Estimated age: 59.2–56.5 Ma (Cande & Kent, 1965) ; 60.0– 57.3 Ma (Luterbacher *et al.*, 2004 ;
141 Middle-Late Paleocene (Wade *et al.*, 2011).

142 This zone, characterized by the total range zone of *Acarinina subsphaerica* (Subbotina) has a
143 thickness of 9 meters (bed Pl 1 to bed Pl 7) (Fig. 5). It is equivalent to subzone P4a
144 (*Globanomalina pseudomenardii-Acarinina subsphaerica* CRSZ), subzone P4b (*Ac.*
145 *Subsphaerica-Ac. Soldadensis* ISZ) of Berggren *et al.* (1995), and subzone P4b (*Ac.*
146 *Subsphaerica* PRSZ) of Berggren & Pearson (2005) and Wade *et al.* (2011), thereby indicating
147 Selandian to Thanetian age for the lowermost part of the Pabdeh Formation in the study area.
148 The associated planktonic fauna is *Acarinina decepta* (Martin), *Acarinina mckannai* (White), and
149 *Acarinina* cf. *nitida* (Martin). The associated foraminiferal taxa are well represented throughout
150 the Late Paleocene to Early Eocene. This zone is assigned to the Late Selandian-Thanetian in the
151 study area.

152 **Pp2-*Morozovella velascoensis* Zone (PRZ)**

153 **PRZ: Partial Range Zone**

154 Estimated age: 55.9–55.5 Ma (Cande & Kent, 1995); 56.7– 55.8 Ma (Luterbacher *et al.*, 2004);
155 late Paleocene (Wade *et al.*, 2011).

Biostratigraphic interval characterized by the partial range of the nominate taxon between the LO (Last Occurrence) of *Acarinina mckannai* (White) and the first occurrence (FO) of *Morozovella marginodentata* (Subbotina). This zone has a thickness of 3.5 meters and only appears on horizon Pl 8 (Fig. 5). It is comparable to Zone P4c (*Ac. soldadoensis*-*Gl. pseudomenardii* ISZ); Zone P5 (*M. velascoensis* IZ) of Berggren *et al.* (1995) and subzone P4c (*Ac. soldadoensis*-*Gl. pseudomenardi* CRSZ), Zone P5 (*M. velascoensis* IZ), Zone E1 (*A. sibaiyaensis* LOZ) and Zone E2 (*P. wilcoxensis*-*M. velascoensis* CRZ) of Berggren & Pearson (2005), thereby indicating Late Paleocene (Thanetian) to Early Eocene age in this study. This zone also contains *Acarinina nitida* (Martin).

Pp3- *Morozovella marginodentata*- *Morozovella formosa* Zone (IZ)

IZ: Interval Zone

Estimated age: 54.5–54.0 Ma (Cande & Kent, 1995); 54.9– 54.4 Ma (Luterbacher *et al.*, 2004); Early Eocene (Early Ypresian) (Wade *et al.*, 2011).

This zone, marked by the FO of *Morozovella marginodentata* (Subbotina) and the FO of *Morozovella formosa* (Bolli), extends over a thickness of 2.5 meters (bed Pl 9 to bed Pl 10) (Fig. 5). It corresponds to the *Globorotalia edgari* Zone of Premoli Silva & Bolli, (1973) (in part), the Zone P6a (*Morozovella velascoensis*- *M. formosa*/ *M. lensiformis* ISZ) of Berggren *et al.* (1995), and the Zone E3 (*Morozovella marginodentata* PRZ) of Berggren & Pearson (2005) and Wade *et al.* (2011). The associated planktonic foraminifera of this biozone are *Morozovella edgari* (Premoli Silva & Bolli), *Morozovella velascoensis* (Cushman), *Morozovella acuta* (Toulmin), *Morozovella marginodentata* (Subbotina) and *Acarinina nitida* (Martin). The stratigraphic range of this zone is Early Eocene (Early Ypresian).

Pp4- *Morozovella formosa* - *Guembelitrionoides lozanoi* Zone (IZ)

Estimated age: 54.0–52.3 Ma (Cande & Kent, 1995); 54.4– 52.3 Ma (Luterbacher *et al.*, 2004); Early Eocene (Ypresian) (Wade *et al.*, 2011).

The biostratigraphic interval is characterized by the FO of *Morozovella formosa* (Bolli) and FO of *Guembelitrionoides lozanoi* (Colom). This zone is 5 meters thick (bed Pl 10 to bed Pl 14) (Fig. 5). It corresponds to the Zone P6b (*M. aragonensis*- *M. formosa*) of Berggren *et al.* (1995) and Zone E4 (*Morozovella formosa* LOZ) of Berggren and Pearson (2005) and Wade *et al.* (2011). The associated planktonic foraminifera of this biozone are *Acarinina* cf. *nitida* (Martin), *Igorina* (*Pearsonites*) *broedermanni* (Cushman & Bermudez), *Morozovella velascoensis* (Cushman), *Morozovella marginodentata* (Subbotina), and *Morozovella subbotinae* (Morozova). This associated species ranges within the Early Eocene (Ypresian) age.

Pp5- *Guembelitrionoides lozanoi* - *Acarinina pentacamerata* (IZ)

Estimated age: 52.3–50.8 Ma (Cande & Kent, 1995 and Luterbacher *et al.*, 2004); Early Eocene (Ypresian) (Wade *et al.*, 2011).

This zone, characterized by the FO of *Guembelitrionoides lozanoi* (Colom) and the FO of *Acarinina pentacamerata* (Subbotina), extends over a thickness of 2.8 meters (Pl 14 to Pl 18) (Fig. 5). This biozone can be equivalent to the Zone P7 (*M. aragonensis*/ *M. formosa*) and Zone E5 (*M. aragonensis*/ *M. subbotinae* CRZ) of Berggren & Pearson (2005) and Wade *et al.* (2011). The associated fauna of this biozone consists of *Igorina broedermanni* (Cushman and Bermudez), *Morozovella subbotinae* (Morozova), *Guembelitrionoides lozanoi* (Colom), and Radiolaria and extends throughout the Early Eocene (Ypresian).

Remark: the first radiolarian association occurs in the interval from bed 12 to bed 18 (Fig. 5).

Pp6- *Acarinina pentacamerata* - *Planorotalites palmerae* Zone (IZ)

Estimated age: 50.8–50.4 Ma (Cande & Kent, 1995); 50.8– 50.3 Ma (Luterbacher *et al.*, 2004); Early Eocene (Ypresian) (Wade *et al.*, 2011).

This zone, marked by the FO of *Acarinina pentacamerata* (Subbotina) and the FO of *Planorotalites palmerae* Cushman and Bermudez, is 2.5 meters thick (bed Pl 18 to bed Pl 20) (Fig. 5). It is equivalent to Zone P8 (*M. aragonensis* PRZ) of Berggren *et al.* (1995) and Zone E6 (*A. pentacamerata* PRZ) of Berggren & Pearson (2005) and Wade *et al.* (2011). This zone also contains *Guembelitrioides lozanoi* (Colom) and *Turborotalia prolata* (Belfoed). The stratigraphic range of this zone is assigned to the Early Eocene (Early Ypresian).

Pp7- *Planorotalites palmerae* - *Guembelitrioides nuttalli* Zone (IZ)

Guembelitrioides nuttalli is synonymous with *Globigerinoides higginsi*

Estimated age: 50.4–49.0 Ma (Cande & Kent, 1995); 50.3– 48.6 Ma (Luterbacher *et al.*, 2004); Early Eocene (Late Ypresian) (Wade *et al.*, 2011).

This zone, characterized by the FO of *Planorotalites palmerae* Cushman and Bermudez and the FO of *Guembelitrioides nuttalli* (Hamilton), is 2.3 meters thick (bed Pl 20 to bed Pl 22) (Fig. 5). It corresponds to the Zone P9 (*P. palmerae* – *G. nuttalli* IZ) of Berggren *et al.* (1995); Zone E7 (*Acarinina cuneicamerata* LOZ) of Berggren & Pearson (2005) and Zone E7a (*Acarinina cuneicamerata* LOSZ) of Wade *et al.* (2011). This zone also contains *Acarinina collactea*

222 (Finally), *Acarinina pentacamerata* (Subbotina), *Guembelitrionides lozanoi* (Colom),
223 *Planorotalites palmerae* Cushman & Bermudez, *Igorina broedermanni* (Cushman & Bermudez)
224 and *Acarinina pseudotopilensis* Subbotina. This species association is assigned to the late Early
225 Eocene (Late Ypresian).

226

227 **Pp8- *Guembelitrionides nuttalli* - *Globigerinatheka kugleri* Zone (IZ)**

228 Estimated age: 46.4–44.4 Ma (Cande & Kent, 1995); 45.5– 43.4 Ma (Luterbacher *et al.*, 2004);
229 Middle Eocene (Wade *et al.*, 2011).

230 This zone, marked by FO of *Guembelitrionides nuttalli* (Hamilton) and FO of *Globigerinatheka*
231 *kugleri* (Bolli, Loeblich & Tappan 1957), is 14 meters thick (bed Pl 22 to bed Pl 38) (Fig. 5). It
232 corresponds to the Zone P10 (*Hantkenina nuttalli* IZ) of Berggren *et al.* (1995), Zone E8 (*G.*
233 *nuttalli* LOZ) of Berggren & Pearson (2005) and Wade *et al.* (2011). The associated fauna
234 consists of *Dentoglobigerina yeguaensis* (Weinzierl & Applin), *Guembelitrionides lozanoi*
235 (Colom), *Truncorotaloides* sp., *Acarinina bullbrooki* (Bolli), *Turoborotalia frontosa*
236 (Subbotina), *Morozovella caucasica* (Glaessner) and *Morozovella aragonensis* (Nuttall). This
237 zone is assigned to Middle Eocene (Early Lutetian).

238 **Remarks:** the second radiolarian association occurs in the interval from bed Pl 30 to bed Pl 35
239 (Fig. 5).

240

241 **Pp9- *Globigerinatheka kugleri*-*Morozovella aragonensis* Zone (CRZ)**

242 CRZ: Concurrent Range Zone

243 Estimated age: 44.4–43.6 Ma (Cande & Kent, 1995); 43.4–42.6 Ma (Luterbacher *et al.*, 2004);
244 middle Eocene (Wade *et al.*, 2011).

245 This zone, characterized by the concurrent range of the nominate taxa between the FO of
246 *Globigerinatheka kugleri* (Bolli, Loeblich & Tappan) and the LO (last Occurrence) of
247 *Morozovella aragonensis* (Nuttall), is 8.5 meters thick (bed Pl 38 to bed Pl 45) (Fig. 5). This
248 zone is equivalent to P 11 (*G. kugleri*-*M. aragonensis* CRZ) of Berggren *et al.* (1995) and Zone
249 E 9 (*G. kugleri*-*M. aragonensis* CRZ) of Berggren & Pearson (2005) and Wade *et al.* (2011).
250 This zone also contains *Guembelitrioides nuttalli* (Hamilton), *Acarinina bullbrooki* (Bolli),
251 *Dentoglobigerina yeguaensis* (Weinzierl & Applin), *Globigerinatheka senni* (Beckmann),
252 *Globigerinatheka kugleri* (Bolli, Loeblich & Tappan), *Globigerinatheka index* (Finlay),
253 *Turborotalia possagnoensis* (Toumarkine & Bolli), *Turborotalia frontosa* (Subbotina) and
254 *Morozovella aragonensis* (Nuttall). This association corresponds to the Middle Eocene (Middle
255 Lutetian).

256 **Remarks:** the third radiolarian association occurs in the interval from bed Pl 41 to bed Pl 42
257 (Fig. 5).

258 **Pp10- *Acarinina topilensis* Zone (PRZ)**

259 (PRZ): Partial Range Zone

260 Estimated age: 43.6–42.3 Ma (Cande & Kent, 1995); 42.6–41.4 Ma (Luterbacher *et al.*, 2004);
261 middle Eocene (Wade *et al.*, 2011).

262 This zone defined by the LO of *Morozovella aragonensis* (Nuttall) and the LO of
263 *Guembelitrioides nuttalli* (Hamilton), is 5 meters thick (bed Pl 46 to bed Pl 51) (Fig. 5). It is
264 equivalent to the lower part of P 12 (*M. lehneri*, PRZ) of Berggren *et al.* (1995) and Zone E10
265 (*A. topilensis*, PRZ) of Berggren & Pearson (2005) and of Wade *et al.* (2011). This zone also

contains *Acarinina spinuloinflata* (Bandy), *Guembelitrionides nuttalli* (Hamilton),
Globigerinatheka index (Finlay), *Acarinina topilensis* (Cushman), *Acarinina bullbrooki* (Bolli),
Turboroatlia frontosa (Subbotina), *Turboroatlia pomeroli* (Toumarkine & Bolli),
Dentoglobigerina yeguaensis (Weinzierl & Applin), *Morozovella* (*Morozovelloides*) *lehneri*
(Cushman and Jarvis), *Globigerina praebulloides* Blow, and *Globigerinatheka kugleri* (Bolli,
Loeblich & Tappan). Based on planktonic foraminifera, this horizon can be assigned to the
Middle Eocene (Middle Lutetian).

273

274 **Pp11- *Morozovelloides lehneri* Partial-Range Zone (PRZ)**

275 Estimated age: 42.3–40.5 Ma (as per Cande & Kent, 1995); 41.4– 39.8 Ma (as per Luterbacher *et*
276 *al.*, 2004); middle Eocene (Lutetian-Bartonian) (Wade *et al.*, 2011).

277 This zone, characterized by the LO of *Guembelitrionides nuttalli* (Hamilton) and LO of *Acarinina*
278 *bullbrooki* (Bolli), is 4 meters thick (bed Pl 52 to bed Pl 58) (Fig. 5). It is equivalent to the upper
279 part of P12 (*M. lehneri*, PRZ) of Berggren *et al.* (1995) and E11 (*M. lehneri*, PRZ) of Berggren
280 & Pearson (2005) and Wade *et al.* (2011). The associated planktonic fauna contains
281 *Globigerinatheka kugleri* (Bolli, Loeblich and Tappan), *Acarinina topilensis* (Cushman),
282 *Turboroatlia frontosa* (Subbotina), *Dentoglobigerina yeguaensis* (Weinzierl and Applin),
283 *Acarinina bullbrooki* (Bolli), *Globigerinatheka senni* (Beckmann) and *Hantkenina* sp. This
284 association extends through the Late Lutetian-Bartonian age.

285 **Remarks:** The Zone E12 (*Orbulinoides beckmanni* Taxon-range Zone) of Berggren & Pearson
286 (2005) and Wade *et al.* (2011) is absent due to lateral facies change. There, pelagic carbonates of
287 the Pabdeh Fm. corresponding to the planktonic biozone E12, are replaced by an inter-fingered

lens of the Jahrum Formation (with benthic foraminifera). This interval has a thickness of 2.5 meters (bed Pl 59 to bed Pl 60) (Fig. 5). The benthic foraminifera consist of *Gyrodinella magna* (Le Calvez), *Neorotalia* spp., *Asterigerina rotula* (Kaufmann), and *Discocyclina* sp. and are assigned to the Bartonian.

Pp12: *Morozovella crassata*- *Globigerinatheka kugleri* (IZ)

Estimated age: 40.0–38.0 Ma (Cande & Kent, 1995); 39.4– 37.7 Ma (Luterbacher *et al.*, 2004); 40.0–38.1 Ma (Pälike *et al.*, 20006) ; Middle Eocene (Bartonian) (Wade *et al.*, 2011).

This zone, marked by the FO of *Morozovella crassata* (Cushman) and the LO of *Globigerinatheka kugleri* (Bolli, Loeblich & Tappan), has a thickness of 14 meters (bed Pl 61 to bed Pl 76) (Fig. 5). This zone is equivalent to P14 (*Tr. rohri*-*M. spinulosa* PRZ) of Berggren *et al.* (1995), Zone E13 (*M. crassata* HOZ) of Berggren & Pearson (2005) and Zone E13 (*Morozovelloides crassatus* HOZ) of Wade *et al.* (2011). The biostratigraphic range is assigned to the Bartonian.

The planktonic fauna is as follows: *Globigerinatheka kugleri* (Bolli, Loeblich & Tappan), *Morozovella crassata* (Cushman), *Catapsydrax dissimilis* Cushman & Bermudez, *Dentoglobigerina yeguaensis* (Weinzierl & Applin), *Subbotina eocaenica* (Guembel), *Turborotalia pomeroli* Toumarkine & Bolli, *Turborotalia griffinae* Blow, *Pseudohastigerina micra* (Cole), *Turborotalia increbescens* Bandy, *Globigerinatheka index* (Finlay), *Globigerinatheka Mexicana* (Cushman), *Globigerinatheka lutherbacheri* Bolli, *Turborotalia cerroazulensis* (Cole), *Pseudohastigerina* sp. and *Hantkenina* sp.

In this interval (from bed Pl 61 to bed Pl 76), two inter-fingered lenses of Jahrum Formation containing benthic foraminifera are observed. The first lens contains *Gyrodinella magna* (Le Calvez), *Asterigerina rotula* (Kaufmann), *Gypsina marianensis* Hanzawa, *Nummulites fossulata* De Cizancourt, and *Discocyclina* sp. It has a thickness of 3.5 meters and extends from bed Pl 64 to bed 68 (Fig. 6). The second horizon contains *Neorotalia* spp., *Discocyclina* sp., *Gyroidinella magna* (Le Calvez), *Gypsina marianensis* Hanzawa, and *Asterocyclina sireli* Özcan & Less. It presents a thickness of 3.5 meters and extends from bed Pl 72 to Pl 74 (Fig. 6). Based on benthic foraminiferal association, the biostratigraphic range of both lenses is considered Bartonian.

Pp13- *Cribrohantkenina inflata*- *Globigerinatheka Mexicana* Zone (IZ)

Estimated age: 38.0–35.8 Ma (Cande & Kent, 1995); 37.7– 35.8 Ma (Luterbacher *et al.*, 2004); 38.1–35.8 Ma (Pälike *et al.*, 2006); Middle-Late Eocene (Bartonian-Priabonian) (Wade *et al.*, 2011).

This zone, characterized by FO of *Cribrohantkenina inflata* Howe to LO of *Globigerinatheka Mexicana* (Cushman) is 4.5 meters thick (bed Pl 75 to bed Pl 83) (Fig. 5). It is equivalent to Zone P15 (*Po. semiinvoluta* IZ) of Berggren *et al.* (1995) and Zone E14 (*G. semiinvoluta* HOZ) of Berggren & Pearson (2005) and Wade *et al.* (2011). The associated planktonic fauna contains *Turborotalia cerroazulensis* (Cole), *Turborotalia pomeroli* (Toumarkine & Bolli), *Catapsydrax dissimilis* Cushman & Bermudez, *Globigerinatheka index* (Finlay), *Turborotalia increbescens* Bandy, *Globigerina venezuelana* (Hedberg), and *Cribrohantkenina inflata* Howe.

Pp14: *Globigerinatheka index* Zone (PRZ)

331 **PRZ: Partial Range Zone**

332 This zone, characterized by the partial range of the nominate taxa between the LO of
333 *Globigerinatheka Mexicana* (Cushman) and the LO of *Globigerinatheka lutherbacheri* Bolli,
334 extends over a thickness of 10 meters (bed Pl 83 to bed Pl 99) (Fig. 5). The associated
335 planktonic fauna is *Pseudohastigerina naguewichiensis* (Myatliuk), *Cribrohantkenina inflata*
336 Howe, *Turborotalia cocoaensis* (Cushman), *Turborotalia cerroazulensis* (Cole), *Globigerina*
337 (*Dentoglobigerina*) *venezuelana* (Hedberg), *Pseudohastigerina micra* (Cole), *Turborotalia*
338 *pomeroli* (Toumarkine and Bolli), *Catapsydrax dissimilis* Cushman and Bermudez, *Turborotalia*
339 *increbescens* Bandy, *Globigerinatheka Mexicana* (Cushman) and *Globigerinatheka*
340 *lutherbacheri* Bolli.

341 Two horizons with benthic foraminifera are observed in this biozone. They can be correlated
342 with the zone E15 of Berggren & Pearson (2005) and Wade *et al.* (2011). The first horizon 4.5
343 meters thick, extends from bed Pl 85 to bed 90 (Fig. 6). It consists of *Fabiania cubensis*
344 (Cushman & Bermudez), *Chapmanina gassinensis* (Silvestri), *Penarchaias* cf. *glynnjonesi*
345 (Henson), *Praebullalveolina afyonica* Sirel & Acar, *Halkyardia* sp., *Silvestriella* cf. *tetraedra*
346 Gumbel, *Discocyclina nandori* Less, *Nummulites* cf. *fabianii* (Prever), *Borelis* sp., *Gyroidinella*
347 *magna* (Le Calvez), *Neortalia* spp., *Praerhapydionina* sp., and *Discocyclina* sp. The second
348 horizon presents a thickness of 1.5 meters and extends from bed 94 to bed 97. It contains
349 *Chapmanina gassinensis* (Silvestri), *Nummulites* cf. *fabianii* (Prever), and *Neorotalia* spp. (Fig.
350 6). This association is equivalent to E15 of Berggren & Pearson (2005) and Wade *et al.* (2011)
351 and can be assigned to the Priabonian due to the presence of *Nummulites* cf. *fabianii* (Prever).

The rest of the columnar section (top of section) with a thickness of 22.5 meters (bed 100 to bed 111) is formed by the Jahrum Formation. It contains *Alveolina nuttalli* (Davies), *Discocyclina nandori* Less, *Asterigerina rotula* (Kaufmann), *Macetadiscus incolumnatus* Hottinger, and *Discocyclina* sp. This benthic foraminiferal association is equivalent to E16 of Berggren & Pearson (2005) and Wade et al. (2011). The range of this association is assigned to the Priabonian.

4. PALEOENVIRONMENT REMARKS

The lithologic units may change laterally from a continuous to abrupt fashion (Boggs (2006). Facies changes may occur as lateral gradation, pinch out, or inter-tonguing/inter-fingering. The abrupt contacts (inter-tonguing), which are commonly very sharp can distinctly separate two formations with different lithologies a result of fast changes in local depositional conditions. The pelagic and hemipelagic facies of the Pabdeh Formation are deposited in deep-sea (open ocean) environment. They consist of argillaceous limestones, mudstones, and radiolarian cherts. The argillaceous limestones mostly contain planktonic foraminifera such as *Acarinia*, *Morozovella*, *Globigerinatheka*, *Turborotalia*, etc. The stratigraphical analysis of the Pabdeh Formation showed the presence of some inter-fingering layers of the Jahrum Formation containing benthic foraminifera only, which correspond to shallow marine neritic deposits. The occurrence of inter-fingered tongues of benthic facies (Jahrum Formation) within the pelagic facies (Pabdeh Formation) suggests repeated sharp depth changes (Fig. 3B). In addition, the appearance of medium to coarse grain bioclastic limestone with larger benthic foraminifera and large-sized red algae in the top of the section (Jahrum Fm.) suggests shallowing. Hence, the overlapping benthic facies on top of the section recorded regression that could be due to progressive shrinking of the

basin and sea-level drop as well. The gradual decline of micrite observed in the Jahrum Formation is likely due to decreasing water depth and increasing energy, which led to the development of bioclastic limestone. Concomitantly, the benthic foraminifers are mainly limited to rotaliids (*Gyroidinella*, *Fabiania*, etc.), orthophragminids (*Discocyclina*), and alveolinids, which indicate restricted platform conditions (Murray 1991; Hottinger 1983, 1997; Flugel 1982, 2004).

5. DISCUSSION

The studied section mainly consists of Pabdeh Formation with some inter-fingered tongues of Jahrum Formation. Based on lithological features, the Pabdeh Formation is subdivided into two lithological units (Lower and Upper Units). The Lower Unit is dominated by pelagic limestone and radiolarian chert, whereas the Upper Unit consists of pelagic limestone, mudstone, and some inter-fingered lenses of bioclastic limestone, which are attributed to the Jahrum Formation. Further up, toward the top of the section, the Pabdeh formation is overlain by the Jahrum Formation represented by a carbonate succession of packstone with abundant red algae, bioclasts, and hyaline/porcellaneous foraminifers.

The presence of marker planktonic foraminifera such as *Acarinina subsphaerica* (Subbotina) confirms the Late Paleocene age of Zone Pp1, because the last occurrence of this species falls in the upper part of Zone Pp1. The species *Morozovella velascoensis* (Cushman) occurs across the Late Paleocene-Early Eocene boundary, therefore its presence help to distinguish the Zone Pp2. During the Early Eocene from the upper part of Zone Pp2 to Zone Pp7, some taxa such as

396 *Morozovella* and *Turborotalia* were rare but *Igorina broedermanni* (Cushman and Bermudez)
397 was only sporadic during the Early Eocene (Ypresian).

398 The Lutetian stage (from Zone Pp8 to Zone Pp10) coincides with the extinction of some species
399 such as *Planorotalites palmerae* Cushman and Bermudez, *Acarinina pseudotopilensis* Subbotina,
400 *Turborotalia prolata* (Belford), and *Acarinina pentacamerata* (Subbotina). In contrast, the
401 association of *Acarinina bullbrooki* (Bolli), *Globigerinatheka kugleri* (Bolli, Loeblich &
402 Tappan), *Turborotalia possagnoensis* (Toumarkine & Bolli), *Acarinina topilensis* (Cushman),
403 *Dentoglobigerina yeguaensis* (Weinzierl & Applin), *Globigerinatheka senni* (Beckmann),
404 *Guembelitrioides nuttalli* (Hamilton), *Turborotalia frontosa* (Subbotina), *Turborotalia*
405 *possagnoensis* (Toumarkine & Bolli), and *Morozovella aragonensis* (Nuttall) are abundant.

406 The time interval Lutetian-Bartonian is equivalent to Zone Pp11, which is consistent with Zone
407 E11 of Berggren & Pearson (2005). It is characterized by the partial range zone of *Morozovella*
408 *lehneri* (Cushman & Jarvis).

409 Abundant Bartonian planktonic foraminifers are represented in the Zone Pp12 of this study, but
410 some species such as *Turborotalia griffinae* Blow, *Pseudohastigerina micra* (Cole),
411 *Globigerinatheka Mexicana* (Cushman), *Globigerinatheka lutherbacheri* Bolli, *Turborotalia*
412 *increbescens* Bandy, *Turborotalia cerroazulensis* (Cole), *Pseudohastigerina* sp. and *Hantkenina*
413 sp. are rare in this biozone. In contrast, they are abundant in the Zone Pp13 for the Bartonian-
414 Priabonian time interval. The species *Globigerinatheka kugleri* (Bolli, Loeblich & Tappan)
415 becomes extinct in this biozone, whereas the species *Globigerina* (*Dentoglobigerina*)
416 *venezuelana* (Hedberg), and *Cribohantkenina inflata* Howe are reported for the first time.

Three associations of benthic foraminifera (Fig. 6) are distinguished in the middle and upper parts of the stratigraphic section. They are assigned to the Bartonian and Priabonian stages and can be equivalent with Zone Pp 12 –Zone Pp14.

5. CONCLUSION

- The Pabdeh Formation is mainly composed of hemipelagic and pelagic sediments with intercalations of radiolarian chert, whereas the Jahrum Formation consists of neritic deposits accumulated on a shallow marine platform. Both formations are disconformably covered by the Late Oligocene-Miocene Asmari Formation.

-The Pabdeh Formation consists of Late-Paleocene to Late Eocene planktonic foraminifera (Zone Pp1–Pp14) which correlate mainly to the subtropical to tropical Zones P4b-E15 of Berggren & Pearson (2005). This Formation passes upwards and laterally into the Jahrum Formation and up section. Hence, the abrupt disappearance of the planktonic foraminifera in the Pabdeh Formation coincides with the presence of larger benthic foraminifera (orthophragminids, rotaliids) in the Jahrum Formation.

-The orthophragminids (*Discocyclina*) are mainly associated with rotaliids (*Gyroidinella*, *Asterigerina*, etc), while alveolinids and nummulitids are locally relatively common in the bioclastic facies of Jahrum Formation. The low frequency of *Nummulites* and major changes in the composition of benthic foraminifera with increasing rotalides recorded a change of sedimentary environment.

-The occurrence of Jahrum Formation (bearing benthic foraminifera) within the Pabdeh Formation (bearing planktonic foraminifera) enables benthic foraminifera ranges to be tied to

local planktonic foraminiferal biostratigraphy. Therefore, the stratigraphic range of benthic foraminiferal associations in the upper part of the study section is Bartonian-Priabonian.

-Late Paleocene planktonic foraminifera are sparse in the Pabdeh Formation, whereas the Eocene planktonic foraminifers are more abundant and widespread.

-During the Early Eocene, the two genera *Acarinina* and *Morozovella* are abundant but other genera such as *Globigerinatheca*, *Turborotalia*, etc. gradually become predominant.

-The absence of open marine planktonic foraminifera such as *Orbulinoides beckmanni*, which corresponds to Zone E12 of Berggren and Pearson (2005) in the upper unit of Pabdeh Formation, coincides with the sudden appearance of larger benthic foraminifera coeval with coarsening upwards trend. As this interval coincides with the Middle Eocene Climate Optimum (ca. 40 Ma), which corresponds to a sea level rise of ca. 50 m (e.g. Miller et al., 2020 and references therein), such abrupt shallowing recorded by the absence of planktonic foraminifers must be due to tectonic causes.

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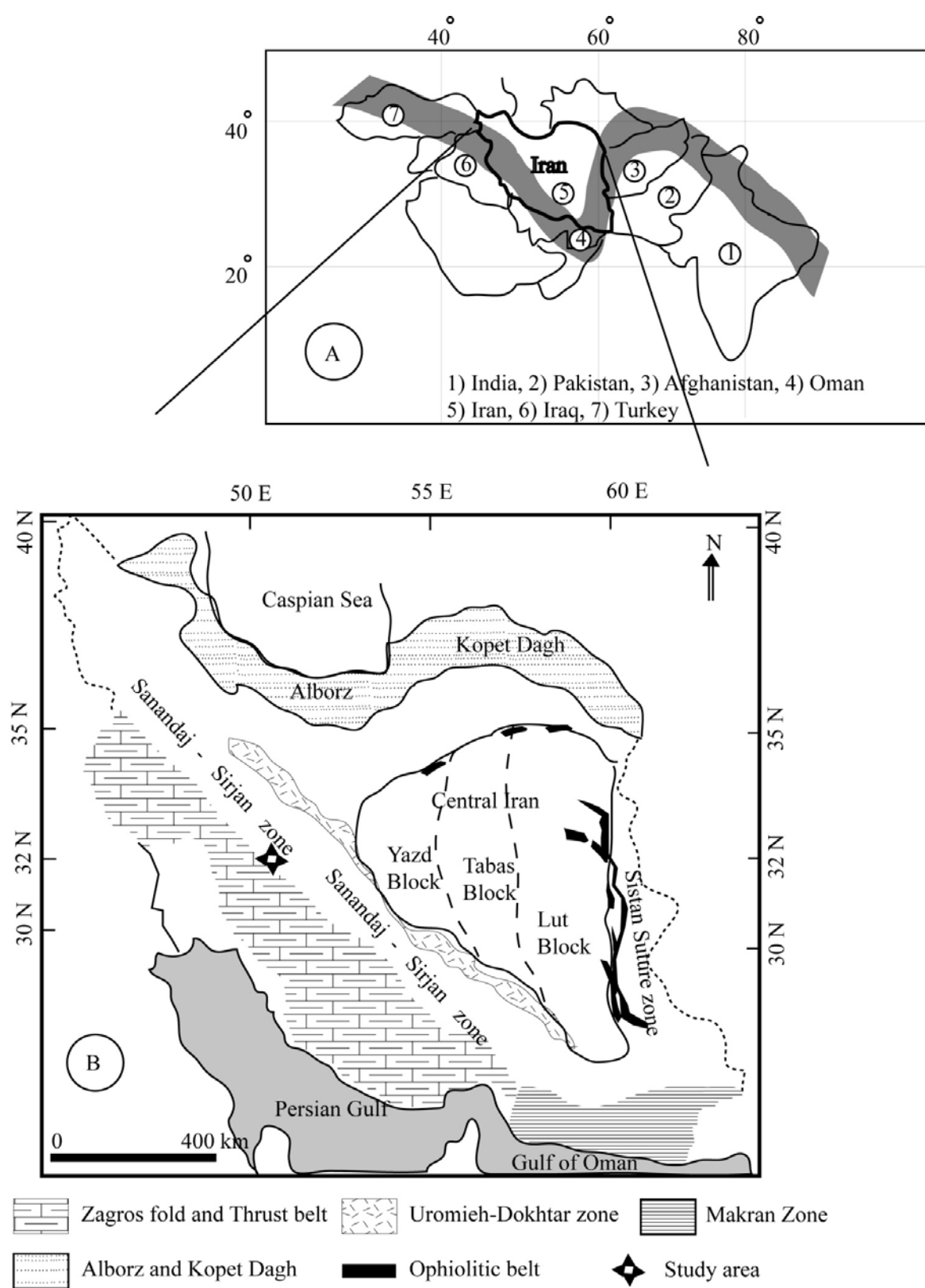


Fig. 1

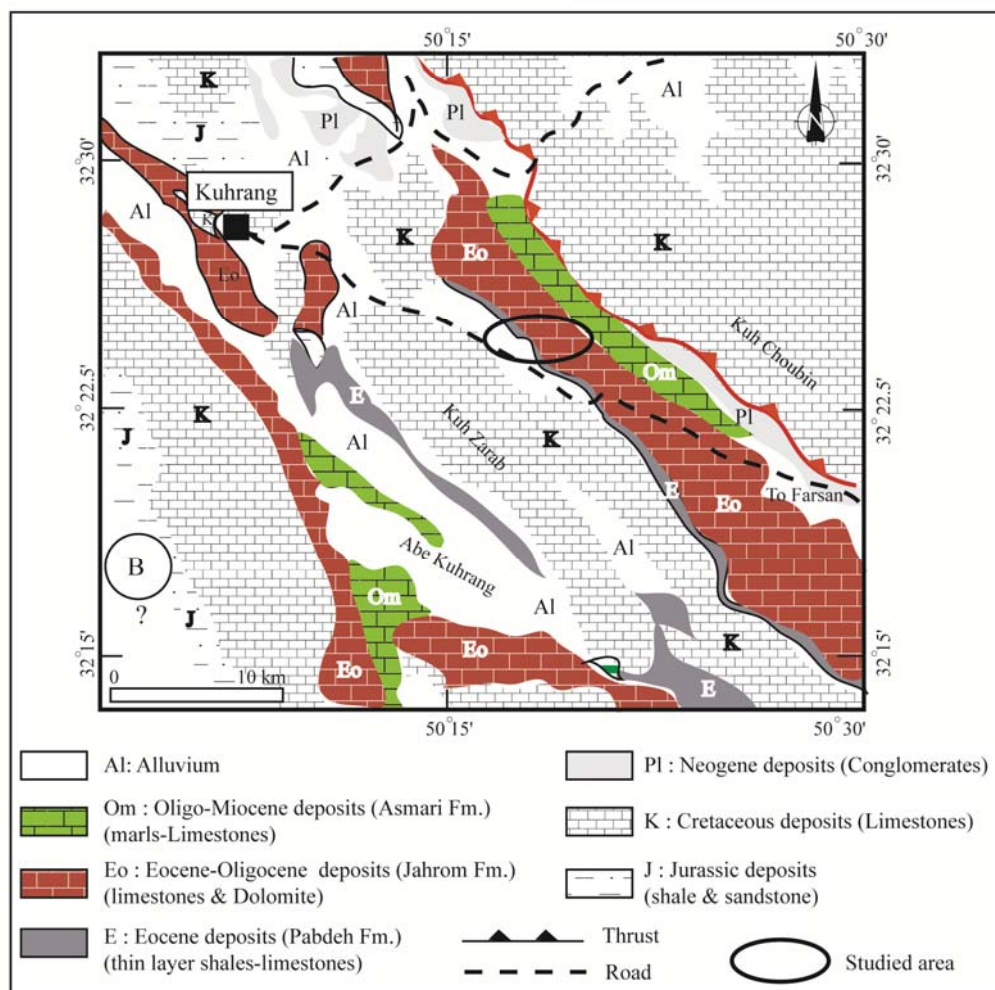
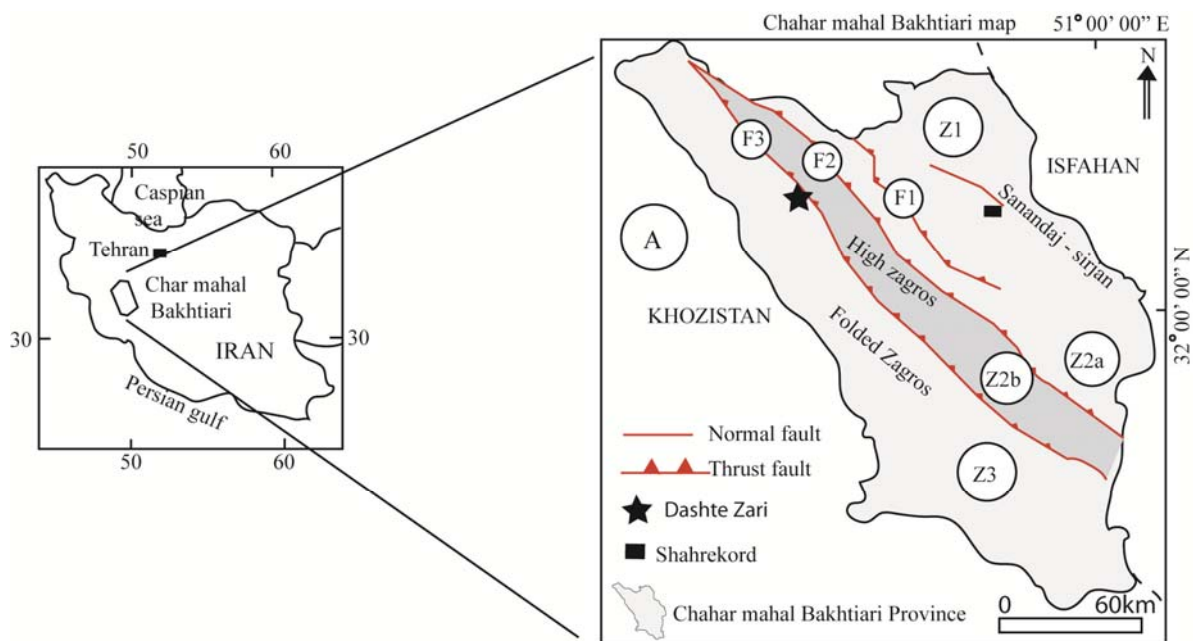
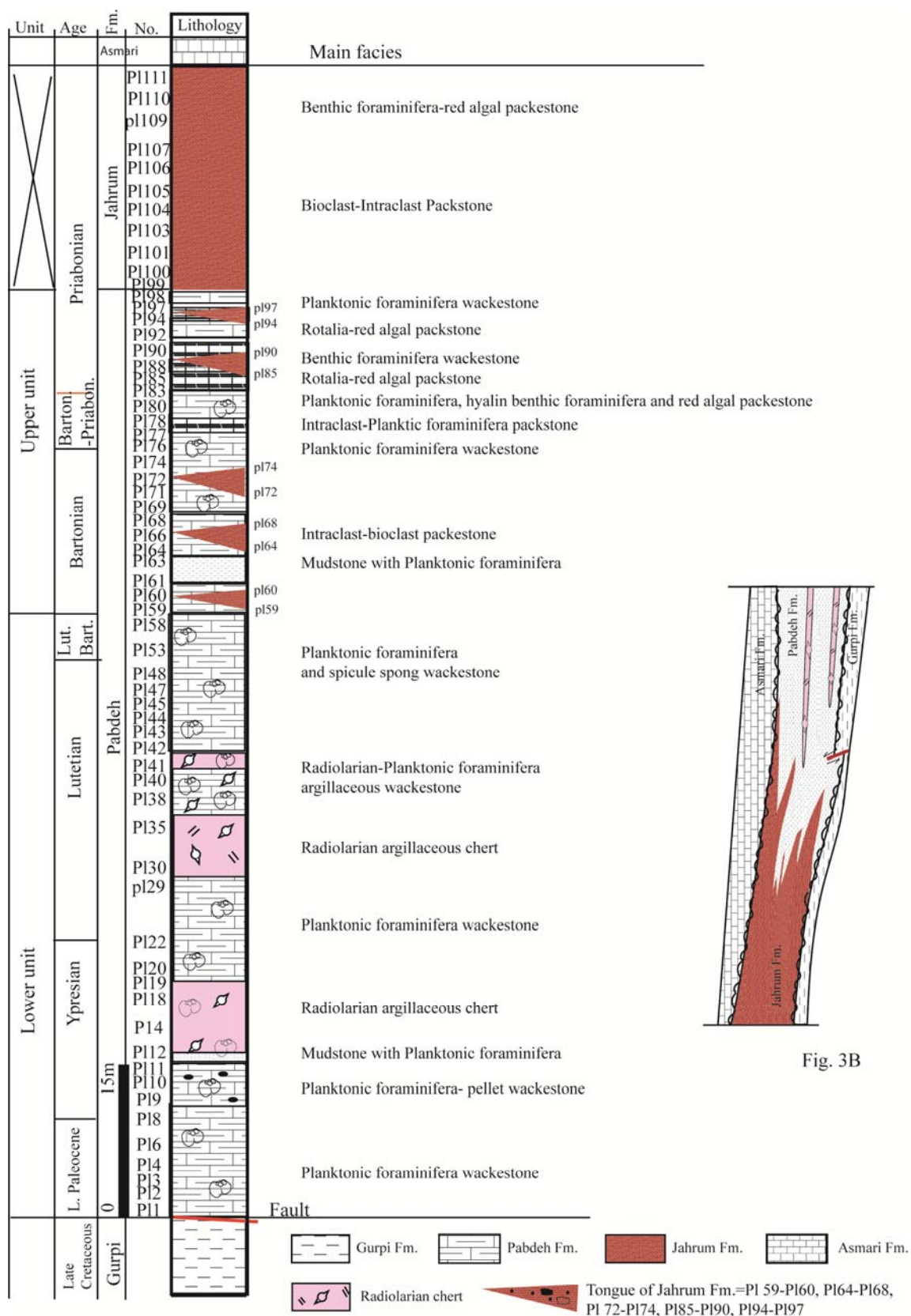


Fig. 2



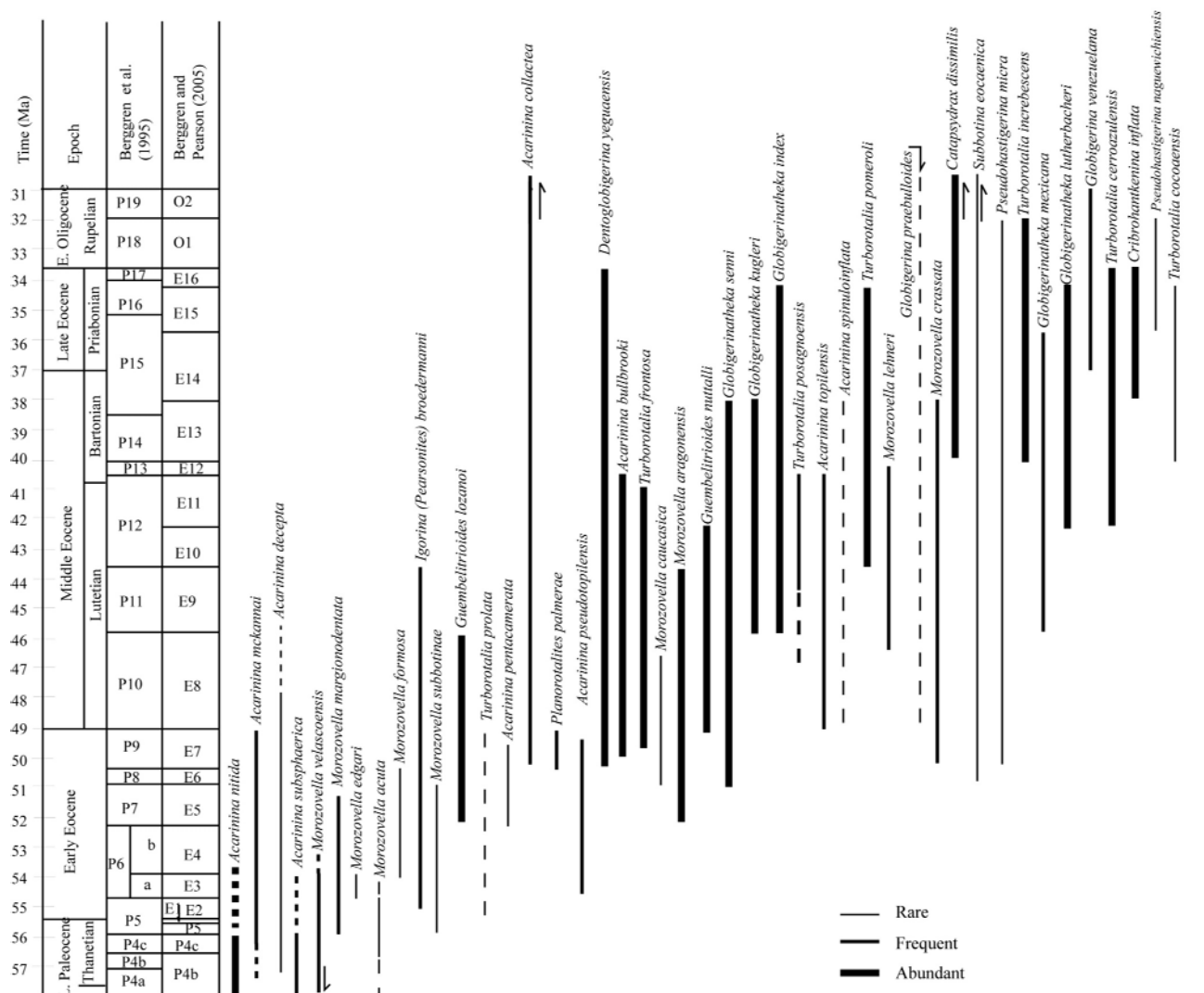


Fig. 4 A



Time (Ma)	Epoch	Berggren et al. (1995)	Planktonic biozones	Berggren and Pearson (2005)	Planktonic biozones	Planktonic / benthic biozones in this study		Shallow benthic zone (SBZ) Serra-Kiel et al (1998)									
31	E. Oligocene	Rupelian	P19	<i>Turborotalia ampliapertura</i> IZ	O2	<i>Turborotalia ampliapertura</i> HOZ											
32			P18	<i>Chiloguembelina cubensis</i> - <i>Pseudohastigerina</i> spp. IZ	O1	<i>Pseudohastigerina nagewichiensis</i> HOZ											
33	Late Eocene	Priabonian	P17	<i>Turborotalia cerroazulensis</i> IZ	E16	<i>Hantkenina alabamensis</i> HOZ			Benthic assemblage zone III	SBZ 19 - 20							
34			P16	<i>Turborotalia cunialensis</i> / <i>Cr. inflata</i> CRZ	E15	<i>Globigerinatheka index</i> HOZ	Pb15 <i>Globigerinatheka index</i> PRZ	Benthic assemblage zone II									
35			P15	<i>Po. semiinvoluta</i> IZ	E14	<i>Globigerinatheka semiinvoluta</i> HOZ					Pb14	<i>Cribrohantkenina inflata</i> - <i>Globigerinatheka mexicana</i> IRZ					
36	Middle Eocene	Bartonian					P14	<i>Turborotalia rohri</i> - <i>M. spinulosa</i> PRZ	E13	<i>Morozovella crassata</i> HOZ			Pb13	<i>M. crassata</i> - <i>Gl. kugleri</i> IRZ	Benthic assemblage zone I	SBZ 17 - 18	
37			P13	<i>Globigerinatheka beckmanni</i> TRZ	E12	<i>Orbulinoides beckmanni</i> TRZ					Pb12						
38			Lutetian	P12	<i>Morozovella lehneri</i> PRZ	E11					<i>Morozovella lehneri</i> PRZ	Pb11					<i>Morozovella lehneri</i> PRZ
39	P11	<i>Globigerinatheka kugleri</i> / <i>Morozovella aragonensis</i> CRZ					E9	<i>Globigerinatheka kugleri</i> / <i>Morozovella aragonensis</i> CRZ	Pb9	<i>Globigerinatheka kugleri</i> / <i>Morozovella aragonensis</i> CRZ							
40															P10	<i>Hantkenina nuttalli</i> IZ	
41			Early Eocene	P9	<i>Pt. palmerae</i> - <i>H. nuttalli</i> IZ	E7					<i>Ac. cuneicamerata</i> LOZ	Pb7					<i>P. palmerae</i> - <i>Gu. nuttalli</i> IRZ
42	P8	<i>Morozovella aragonensis</i> PRZ					E6	<i>Ac. pentacamerata</i> PRZ	Pb6	<i>Ac. pentacamerata</i> - <i>P. palmerae</i> IRZ							
43															P7	<i>Morozovella aragonensis</i> / <i>M. formosa</i> CRZ	
44			P6	b <i>Morozovella formosa</i> / <i>M. lensiformis</i> <i>Morozovella aragonensis</i> ISZ	E4	<i>Morozovella formosa</i> LOZ					Pb4	<i>M. formosa</i> - <i>Guembeltrioides lozanoi</i> IRZ					
45	a <i>Morozovella velascoensis</i> - <i>M. formosa</i> / <i>M. lensiformis</i> ISZ	E3					<i>M. marginodentata</i> PRZ	Pb3	<i>M. marginodentata</i> / <i>M. formosa</i> IRZ								
46														P5	<i>Morozovella velascoensis</i> IZ	E2	
47			P4c	<i>Ac. soldadoensis</i> - <i>Gl. pseudomenardii</i> ISZ	E1	<i>A. sibayensis</i> LOZ											
48	P4b	<i>Ac. subsphaerica</i> - <i>Ac. soldadoensis</i> - ISZ					P5	<i>Morozovella velascoensis</i> IZ									
49														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ	P4c	
50			Paleocene	Thanetian	P4b	<i>Ac. subsphaerica</i> PRSZ					Pb1	<i>Acarinina subsphaerica</i> TZ					
51	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
52														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
53			P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ													
54	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
55														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
56			P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ													
57	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
			P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ													
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	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
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	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
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	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
			P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ													
	P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ															
														P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ		
			P4a	<i>Gl. pseudomenardii</i> - <i>Ac. subsphaerica</i> CRSZ													

Fig. 7

Ac: Acarinina, Gl: Globigerinatheka, Gu: Guembelirioides, M: Morozovella, P: Planorotalites, Ps: Pseudohastigerina