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1 **New biostratigraphy and microfacies analysis of Eocene Jahrum Formation (Shahrekord**
2 **region, High Zagros, West Iran); A carbonate platform within the Neo-Tethys oceanic**
3 **realm**

4 **Nouvelle biostratigraphie et analyse des microfaciès de la Formation éocène de Jahrum**
5 **(région de Shahrekord, Haut Zagros, Iran occidental). Une plateforme carbonatée au sein**
6 **de la Neo-Tethys**

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15

16 **Abstract**

17 The Eocene Jahrum Formation in High Zagros was studied in Kuh-e-Soukhteh and North
18 Gahrou sections (southwest of Shahrekord region, Chahar-mahal Bakhtiari Province). This
19 formation, composed of limestone, marl, and dolomitic limestone (dolostone), accumulated on a
20 marine platform within the Neo-Tethys ocean realm. It yields a rich foraminiferal fauna, in
21 which three larger benthic foraminiferal assemblage zones were identified. Two assemblage
22 zones in the North Gahrou section were correlated to the Ypresian and Bartonian, and one
23 assemblage zone is represented in the Kuh-e-Soukhteh section and assigned to the Bartonian. In

24 addition, three other groups of benthic foraminiferal associations have been identified based on
25 test wall type (porcellaneous, agglutinate, hyaline) and paleogeographical significance.

26 A discontinuity marked by a hiatus from Cuisian to Lutetian in the North Gahrou section was
27 most probably due to a concealed fault. According to microscopic textures and distribution of
28 benthic foraminifera and other components (peloids, intraclasts, etc.), a gentle depth gradient
29 from the inner ramp to the proximal outer ramp may be reconstructed.

30 **Keywords:** Stratigraphy, Microfacies, larger foraminifera, Jahrum Formation, High Zagros,
31 West Iran

32 **Résumé**

33 La formation éocène de Jahrum dans le Haut Zagros a été étudiée le long de deux coupes, Kuh-e-
34 Soukhteh et Gahrou-nord (sud-ouest de la Région de Shahrekord, Province de Chahar-mahal
35 Bakhtiari) . Cette formation composée de calcaires, marnes et calcaires dolomitiques, s'est
36 déposée en contexte de plateforme au sein du domaine océanique néo-téthysien. La riche faune
37 de foraminifères a permis d'identifier trois biozones de grands foraminifères benthiques. Deux
38 biozones de la coupe de Gahrou-nord sont corrélées respectivement à l'Yprésien et au Bartonien
39 tandis qu'une seule zone assignée au Bartonien a été définie dans la coupe de Kuh-e-Soukhteh.
40 De plus, trois autres groupes d'associations de foraminifères benthiques ont été identifiés selon le
41 type de test (porcellané, agglutiné, hyalin) et leur signification paléogéographique. L'absence du
42 Cuisien et du Lutétien dans la coupe de Gahrou-nord est probablement due à une faille cachée.
43 La distribution des microfaciès, des foraminifères benthiques et autres composants (peletoïdes,
44 intraclastes) permet de reconstituer un gradient modéré de profondeur évoluant depuis la rampe
45 interne jusqu'à la rampe externe proximale.

46 **Mots clés:** Stratigraphie, Microfaciès, grands foraminifères, Formation de Jahrum, Haut Zagros,
47 Iran occidental

48 **1. Introduction**

49 The geological history of Iran recorded several tectonic events related to the Alpine-Himalayan
50 orogeny, which resulted from the collision of the Arabian Platform and several derived
51 microcontinents with Eurasia. Several tectonic phases have contributed to the separation of
52 sedimentary-tectonic basins within the Iran platform, which may be distinguished based on
53 sedimentary facies and benthic foraminiferal communities. After the Paleo-Tethys closure in
54 northern Iran (Alborz margin) during the Middle Triassic, rifting and oceanization (Neo-Tethys
55 Realm) occurred again in southwestern and eastern Iran since the Lower Cretaceous, the traces
56 of which are now distributed along the main Zagros thrust. As a consequence, the ancient
57 Gondwana margin was fragmented into some microcontinents separated by marginal basins.
58 Afterward, the different microcontinents shifted gradually northward and collided with Eurasia
59 during the Late Cretaceous to Upper Eocene period. The closure of marginal basins by
60 subduction formed ophiolitic belts, i.e., assemblages of ultrabasic and basaltic rocks, pelagic
61 sediments (radiolarian cherts and pelagic limestones), and subduction-related (high-pressure low-
62 temperature) metamorphic rocks (Barbarian and King, 1981; Babazadeh, 2003; Babazadeh and
63 De Wever, 2004a, b). The continental collision of the Arabian and Eurasian Plates resulted in the
64 formation of the Zagros mountains (Takin, 1972; Agard *et al.*, 2005). They are located in the
65 middle part of the Alpine-Himalayan Orogenic Belt as a narrow northwest-southeast trending
66 domain, which extends from the Taurus (northeast of Turkey) to the Hormuz Strait (southwest
67 Iran) (Alavi, 2004) (Fig. 1). Owing to the occurrence of several oil formations, detailed research
68 was carried out on the Neo-Tethysian Zagros sedimentary basin. Special attention was paid to its

69 Cenozoic components, which include the Jahrum Formation, a shallow marine carbonate
70 platform unit of special interest because it is one of the important reservoirs in the Zagros and
71 Persian Gulf oil province. However, despite many lithological and paleontological investigations
72 conducted in different parts of Zagros (James and Wind, 1965; Kalantari, 1976, 1978, 1980,
73 1986, 1992; Stocklin and Setudehnia, 1991; Rahghi, 1976, 1978, 1980, 1983; Khatibi Mehr and
74 Moalem, 2009; Babazadeh et al. 2015, Babazadeh and Pazooki Ranginlou, 2015) a precise
75 paleo-environmental framework for Jahrum Formation remains to be established. The purpose of
76 this study is: 1) to provide more data about microfacies and reconstruct the evolution of the
77 depositional environment in a well-constrained stratigraphic framework during the Eocene. 2) to
78 introduce three foraminiferal biozones for correlation with Eocene benthic foraminifera
79 associations of east Iran and neighboring countries (Pakistan and Turkey) and standard
80 biozonation scales of west Tethys.

81

82 **2. Geologic setting**

83 Because of the regional NW-SE structural trend, the Shahrekord region is subdivided into
84 northeast (Z1), central (Z2), and southwest (Z3) fault-bounded zones (Fig. 2A). The Central
85 Zone (Z2) which is the object of the study in this article, consists of the Gurpi, Jahrum, Pabdeh,
86 and Asmari formations composed of Late Cretaceous to Paleogene red clastic rocks, gray to
87 cream limestone, and marl (Zahedi and Rahmati Ilakhchi, 2006).

88 The Jahrum Formation at the type section consists of gray to yellow dolomitic limestone and
89 dolomite with a sugary texture. The basal contact of this formation is conformable with
90 Maastrichtian-Paleocene Sachun Formation but its top is covered by a regional disconformity
91 with Oligo-Miocene Asmari Formation (James and Wynd 1965).

92 Two stratigraphic sections (Kuh-e-Soukhteh and North Gahrou sections) were selected and
93 measured in the southwest of the Shahrekord region from the Gahrou area (Chaharmahal
94 Bakhtiari province). In the studied sections, the Jahrum Formation consists of alternating thick
95 layers of massive limestone interbedded with softer fine-grained limestone, dolomitic limestone
96 (dolostone), and marl. The basal contact of the Jahrum Formation with the underlying Pabdeh
97 Formation is faulted in both sections, while its upper boundary is in faulted contact with the
98 overlying Asmari Formation, or is covered by alluvium. The stratigraphic sections are located in
99 a quadrant limited by N 32° 00' to N 32° 06' Long. and E 50° 55' to E 51° 00' Lat. (Fig. 2B).

100

101 **3. Materials and Methods**

102 The two sections were measured over a thickness of 157 m and 215 m respectively and
103 approximately 165 samples were collected in the field. All specimens were stored and studied at
104 the geological laboratory of Tehran Payame Noor University, Iran. Micro-texture analysis and
105 micro-paleontological determinations were performed under the plane light microscope. Biotic
106 and abiotic components such as foraminifers, bioclasts, peloids, lumps, and intraclasts were
107 determined after Rahaghi (1980); Loeblich and Tappan (1987); Serra-Kiel *et al.* (1998);
108 (Huttinger 2007); Sirel (2003, 2009); Dunham (1962); Embry and Klovan (1971); Buxton and
109 Pedley (1989) and Flugel (2004).

110

111 **4. Regional lithostratigraphy**

112 Three structural zones are documented by the regional NW-SE trend in the Shahrekord region of
113 Chahar-mahal Bakhtiari Province (Zahedi and Rahmati Ilkhechi, 2006). The Northeast Zone
114 (Z1) in the northeast of Zayandehrud consists of metamorphic rocks unconformably overlain by

115 Permian basal conglomerate with metamorphic rock clasts embedded in siliceous cement. In
116 turn, the conglomerate is overlain by Triassic, Jurassic, and Cretaceous marine platform deposits.
117 The Central Zone (Z2) is a part of the High Zagros and is located between the Saman - Fereidoon
118 Shahr thrust (F1) and the Bazoft thrust (F3). Based on the main Zagros thrust fault, this zone is
119 divided into two smaller sub-zones: Z2a and Z2b. These two sub-zones consist of the Gurpi,
120 Jahrum, Pabdeh, and Asmari formations composed of Late Cretaceous to Paleogene red clastic
121 rocks, gray to cream limestone, and marl.

122 The Southwest Zone (Z3) is located southwest of the Karun River and Karun Mountains. It
123 consists of Mesozoic and Cenozoic black shale, siltstone, and thin limestone and forms a large
124 part of the Zagros sedimentary basin. This zone is separated from Z2 by the SW-verging Bazoft
125 thrust (F 3). The study area (Kuh-e-Soukhteh and North Gahrou sections) is exposed on the
126 roadside in the Gahrou area (southwest Shahrekord) and located in sub-zones Z2b of the
127 structural division of Chaharmahal Bakhtiari province. Three groups of rock units with different
128 geological ages are represented on the geological map of Shahrekord. The first group consists of
129 a succession of Cretaceous *Orbitolina*-bearing limestone and *Globotruncana*-bearing
130 argillaceous limestone and shale in the eastern and western parts of the map respectively. The
131 second group corresponds to the Paleocene-Eocene conglomerate that crops out on the western
132 banks of Choghakhor lake and in the northern part of the map. Finally, the third group consists of
133 Eocene limestone, shale, and marl spread over much of the geological map of the region. The
134 third group was the object of the detailed stratigraphic and paleontological work presented in this
135 article.

136

137 **5. Lithostratigraphy**

138 In the study area, the Jahrum Formation consists of three main lithologies: limestone, marl,
139 and dolomitic limestone (dolostone) based on field observation.

140 **5.1. Kuh-e- Soukhteh Section**

141 About 80 samples have been collected from layer 1 to layer 80, over a thickness of 157 m.
142 The index “As” represents the Kuh-e- Soukhteh Section (Fig. 3). The six lithological units of the
143 Jahrum Formation are described as follows:

144 Unit 1 is about 52.5 meters thick and extends from the horizon (bed) 1 to horizon (bed) 34 in
145 stratigraphic order. This unit consists of a sedimentary succession of gray argillaceous limestone,
146 thin layers of green marl, dolostone, and thin dolomitic limestone. These carbonate facies consist
147 of mudstone, dolostone, intraclast packstone, miliolid–pellet wackestone, etc.

148 Unit 2 immediately overlies Unit 1. It is 10 meters thick and extends from bed 35 to bed 40.
149 It mainly consists of medium bedded to thin-bedded gray limestone with intercalation of
150 argillaceous limestone. The carbonate facies is bioclastic grainstone and *Macetadiscus*-miliolid-
151 pellet wackestone.

152 Unit 3, 38.5 m thick, extends from bed 40 to bed 56. It is mainly composed of medium to
153 thick-bedded limestones. The carbonate facies is *Macetadiscus*-miliolid-pellet wackestone,
154 conical porcellaneous-agglutinated foraminifera-miliolid wackestone, and intraclast packstone.

155 Unit 4 consists of thin layers of dolomitic limestone, dolostone, and intercalation of
156 limestone. It is 41 meters thick and extends from bed 57 to bed 74. The carbonate facies is
157 dolomitic wackestone and conical porcellaneous-agglutinated foraminifera-miliolid wackestone.

158 Unit 5, 7.5 meters thick, is composed of medium bedded limestones. It is exposed in the
159 interval between bed 75 and bed 77. The carbonate facies is bioclastic grainstone

160 Unit 6, 7.5 m thick, extends from bed 78 to bed 80. It is composed of gray to cream medium
161 to thin-bedded dolostone and dolomitic limestone. The carbonate facies is dolomitic wackestone.

162

163 **5.2. North Gahrou Section**

164 About 93 samples have been collected from this section 215 m thick, which consists of 93
165 individual beds. The index “GH” represents the Gahrou area (Fig. 3). Seven lithological units
166 have been identified in the field from bottom to top:

167 Unit1, 45 m thick, displays medium layers of gray limestone and thin layers of cream
168 limestone. It extends from bed GH 1 to bed GH 22. The carbonate facies consist of large hyaline
169 foraminifera wackestone and packstone with a variety of benthic foraminiferal fauna.

170 Units 2 consists of cream argillaceous limestone, and gray thin-bedded limestone. It extends
171 from bed GH 23 to bed GH 36. It is 34 meters thick. Most of the biota are small *Nummulites* and
172 thin layer *Assilina*. They are mainly composed of small hyaline foraminifera wackestone and
173 packstone facies.

174 Unit 3 consists of an alternation of medium to thick layers of cream and gray limestone. This
175 unit extends from bed GH 37 to bed GH 46 and is mainly composed of large hyaline
176 foraminifera wackestone and packstone. This unit is 33 meters thick.

177 Unit 4 consists of thin layers of gray argillaceous limestone. It is exposed in the interval
178 between bed GH 47 to bed GH 56. This unit is 19 meters thick.

179

180

181 Unit 5, 17 m thick, consists of medium to thick layers of cream limestone with many coarse-
182 grained bioclasts. It is mainly composed of porcellaneous foraminifera wackestone facies and is
183 exposed in the interval between bed GH 57 to bed GH 63.

184 Unit 6 consists of a succession of thin layers of gray to cream limestone. It is mainly
185 textured as *Alveolina*- bioclast-pellet wackestone to grainstone facies. This unit is 25 meters
186 thick and extends from bed GH 64 to bed GH 76.

187 Unit 7, 42 m thick, consists of cream limestone with many coarse-grained bioclasts such as
188 *Gypsina* Carter. It is mainly composed of *Gypsina*-lump-bioclast grainstone with inter-layers of
189 bioclast-intraclast packstone facies. This unit extends from bed GH 77 to GH 93.

190

191 **6. Microfacies**

192 According to Burchette and Wright (1992), carbonate ramp environments can be divided into
193 three parts: 1) the internal ramp between the upper part of the coastal surface and the regular
194 surface of the fair-weather wave base, which is affected by the turbulence of waves. 2) the
195 intermediate ramp between the fair-weather wave base and storm-wave base along with the
196 displacement of the sediment during the flood. The water depth varies from a few tens of meters
197 to 100 to 200 m. and 3) the external ramp between underwater effect lines to deep basin.
198 According to the study of about 170 rock samples, eight facies were identified and are described
199 hereafter (Figs. 4 & 5).

200

201 **6.1. Kuh-e- Soukhteh Section**

202 **6.1.1. Tidal flat**

203 **Mudstone Facies (Pl. 3, fig. J)**

204 It consists of light gray argillaceous micritic limestone that contains rare small porcellaneous
205 foraminifera, rare rotaliids and pellets, and in places shows fenestral fabric. In this type of facies
206 microcrystalline calcite is widespread and micritization is controlled by biological and chemical
207 factors. The occurrence of small and scattered porcellaneous foraminifera in the mud-supported
208 facies (micritic textures) represents a near-shore environment (littoral zone) with low energy
209 (Buxton and Pedley, 1989; Romero *et al.* 2002).

210

211 **Dolostone / dolomitic limestone Facies (Pl. 3, fig. K)**

212 This facies consists of yellow to grey thin-bedded, finely crystalline, homogeneous but in
213 places laminated dolomite. As a result of dolomitization, fossil fragments such as miliolids,
214 rotaliids, and small bivalves faded and disappeared so that it is almost impossible to identify
215 them. The dolomite grains are small and rhomboidal in shape. The dolomite is diagenetically
216 recrystallized to coarser crystals. Vuggy porosities are also abundant in dolostone. This
217 dolostone facies can be compared to dolo-mudstone facies of the Jahrum Formation from the Do
218 Kuhak region in the Fars area of south Iran (Babazadeh and Pazooki Ranginlou, 2015).

219

220 **6.1.2. Inner ramp (Lagoon)**

221 **Miliolid – pellet wackestone (Pl. 3, fig. L)**

222 This type of facies is dominated by pellet and small miliolids. It is characterized by the
223 presence of micritic limestone, micrite grains, and small porcellaneous foraminifera. The peloids
224 are structureless, spherical, ellipsoidal, and subrounded micritic grains. They are mostly well
225 preserved and show weak to moderate sorting. Subordinate *Valvulina* sp. and bivalve fragments

226 are present. This facies is equivalent to that of the Kras Plateau in southwest Slovenia (Zamagni
227 *et al.* 2008) and the Campo section in Spain (Rasser *et al.*, 2005).

228

229 ***Macetadiscus*-miliolid-pellet wackestone (Pl. 3, figs. A & M)**

230 This yellow medium-bedded limestone contains miliolids, micritic pellets, and *Macetadiscus*
231 similar to the previous one except for the presence of *Macetadiscus*. This facies shows a lateral
232 paleoenvironmental relationship with the miliolid-pellet wackestone facies. The subordinate
233 fauna consists of conical agglutinated foraminifera (*Coskinolina* Stache) with rare small rotaliids
234 and without *Alveolina*. This facies is presented for the first time in the Zagros Mountains.

235

236 **Conical porcellaneous- agglutinated foraminifera-miliolid wackestone (Pl. 1, fig. A; Pl. 237 3, fig. Q)**

238 This facies has a widespread distribution in this region and occurs in the middle part of the
239 columnar section. It consists of dark grey micritic limestone containing flattened and conical
240 porcellaneous- agglutinated foraminifera (20-30%), and small miliolids (40-50%). The other
241 subordinate bioclasts (bivalves and gastropods) account for 10-20%.

242

243 **6.1.3. Middle ramp (shoal)**

244 **Intraclast packstone (Pl. 3, fig. N)**

245 This facies consists of thin to medium bedded grey limestone and appears as medium-
246 grained (1–2 mm) calcarenites in the field. The intraclasts (up to 50%) and peloids (10 -20%) are
247 the most abundant components of this facies. Smaller foraminifera (miliolids) and other
248 subordinate bioclasts account for 5-20%. The intraclasts consist of silt to sand-sized carbonate

249 grains showing smooth or sub-angular edges displaced and re-deposited by currents within the
250 micritic matrix.

251

252 **Bioclastic grainstone (Pl. 3, fig. O)**

253 This facies is a medium bedded yellow to grey finely crystalline limestone. The dominant
254 bioclasts (benthic foraminifera), as well as bivalve and gastropod fragments, are cemented by
255 calcite. The presence of broken and abraded large benthic foraminifera (*Coskinolina*,
256 *Macetadiscus*, *Haymanella*, etc) and rounded rotaliids (*Medocia* and *Rotalia*) in sparitic cement
257 suggest shallow-water sedimentation in low-relief shoal environment. This facies accumulated in
258 a shoal close to sea level.

259

260 **6.1.4. Middle ramp (back and fore shoal)**

261 **Hyaline-porcellaneous foraminifera wackestone (Pl. 3, fig. P)**

262 This facies is a yellow to grey thin-bedded limestone with a micritic matrix. The
263 components are dominated by porcellaneous or imperforate (e.g. *Haymanella*) and hyaline or
264 perforate foraminifera (semi-conical rotaliids, e.g. *Rotaliconus* and *Medosia*), the other
265 components such as agglutinated foraminifera and bivalve fragments are subordinate.

266

267 **6.2. North Gahrou Section**

268 In this section, eight major facies defined by biota (fossil) and abiotic (non-fossil)
269 components are represented:

270 **6.2.1. Inner ramp (Lagoon)**

271 ***Macetadiscus*-miliolid-pellet wackestone (Pl. 3, fig. A)**

272 This facies consists of grey micritic limestone, in which pellets are the most abundant
273 components (up to 40%), followed by miliolids and *Macetadiscus*. This facies is comparable to
274 the facies number four of the Kuh-e-Soukhteh. The presence of *Macetadiscus* suggests relatively
275 shallower water than *Alveolina* facies. This facies has a lateral paleoenvironmental relationship
276 with the *Alveolina* –pellet wackestone facies.

277

278 **Conical agglutinated foraminifera- *Alveolina* –pellet wackestone (Pl. 3, fig. B)**

279 This facies comprises yellow to grey thin-bedded limestone. The main components are
280 pellets (up to 45 %) and *Alveolina* (15-35%). Subordinate components are miliolid smaller
281 foraminifera, Barattolites and a few rotalids. The *Alveolina* are important elements in the Lower
282 and Middle Eocene shallow-water deposits. They are also abundant in the lagoon or enclosures
283 behind the back shoal as well as in the shoal and are found in relatively deeper water than
284 *Orbitolites*. This facies is comparable to that of the Birjand region in east Iran (Babazadeh 2010;
285 Babazadeh and Alavi, 2013).

286

287 ***Alveolina*- bioclast—pellet wackestone (pl. 3, fig. C)**

288 This facies consists of grey medium bedded limestones. The *Alveolina* and bioclasts (up to
289 50%) are in equal abundance and are bounded by calcite cement. All other components such as
290 miliolids, *Macetadiscus*, and conical agglutinated foraminifera are subordinate and distributed
291 irregularly among the samples. Pellets and bivalve fragments are less abundant. The presence of
292 *Alveolina* indicates a lagoonal condition and occurred in a sheltered depositional environment at
293 a protected shelf (Hottinger, 1983; Beavington-Penney and Racey, 2004).

294

295 **6.2.2. Shoal**

296 **Bioclast – intraclast packstone/grainstone (Pl. 3, fig. D)**

297 This facies consists of yellow medium bedded limestone with coarse crystalline calcite. The
298 intraclasts (up to 80%) and bioclasts (10 %) are the most abundant components in this facies.
299 The miliolid smaller foraminifera and pellets account for 5-10%. Based on the presence of
300 micritic texture and calcite cement, this facies can change from packstone to grainstone. Due to
301 the low abundance of micrite and dominance of bioclasts, this facies represents higher energy
302 than the previous facies.

303 ***Gypsina*-lump-bioclast grainstone (Pl. 3, fig. E)**

304 In this facies, the main components are bioclasts as well as *Gypsina* and lumps (up to 70 %).
305 Subordinate components are small miliolids, a few agglutinated foraminifera (*Barattolites* sp.),
306 and echinoid fragments. Although this facies separates the lagoon from the open sea, it
307 represents a high-energy environment as testified by the abundance of intraclasts and bioclasts
308 and the absence of micrite. This facies is recognized for the first time in the Zagros Mountains.

309

310 **6.2.3. Back shoal**

311 **Small and thin-shelled hyaline foraminifera wackestone (pl. 3, fig. F)**

312 This facies comprises yellow to grey thin-bedded limestones with small *Nummulites* and
313 small *Operculina* as main components. The small *Nummulites* are robust and ovate whilst the
314 small *Operculina* are thin and elongated. The small and robust *Nummulites* occurred in a broad
315 range of open marine environments on both ramp and shelves and are generally absent from
316 more restricted waters.

317

318 **Porcellaneous - Hyaline foraminifera- pellet wackestone (Pl. 3, fig. G)**

319 This facies consists of grey medium bedded limestone, which contains porcellaneous
320 foraminifera (*Alveolina*) outnumbering hyaline foraminifera (small *Nummulites*). It reflects an
321 offshore transport of porcellaneous forms into the hyaline foraminiferal facies. The bioclasts and
322 pellets are more abundant in the micritic matrix. All other components such as agglutinated
323 conical foraminifera are subordinate and distributed irregularly among the samples. This facies is
324 comparable with the Do Kuhak region in the Fars area of south Iran (Babazadeh and Pazooki
325 Ranginlou, 2015).

326

327 **6.2.4. Fore shoal**

328 **Large hyaline foraminifera wackestone/packstone (pl. 3, figs. H-I)**

329 The major fauna of this facies is constituted by large hyaline thin to thick-shelled
330 foraminifera. The densely packed nummulitid tests (*Operculina* and *Assilina*) account for over
331 70% of the rock volume. Other components are *Discocyclina* and small *Nummulites*. This facies
332 is comparable with MFT 4 of the Kaboudeh section in east Iran (Babazadeh, 2010).

333

334 **7. Interpretation and depositional environment**

335 In the North Gahrou Section, during the Early Eocene (Ilerdian), the large hyaline foraminifera
336 wackestone is repeated twice throughout the columnar section and occupies the basal and middle
337 part of the study section. This facies indicates low-energy depositional condition in the proximal
338 outer ramp environment due to the presence of thin and elongated shells of *Operculina*
339 d'Orbigny and *Assilina* d'Orbigny (Racey et al., 2001; Beavington-Penney et al., 2006). It is
340 followed up section by small hyaline foraminifera wackestone and packstone, indicating

341 somewhat shallower water depths than the former facies, interpreted as the external part of the
342 middle ramp.

343 During the Bartonian, large hyaline foraminifera wackestone, overlying the succession of Early
344 Eocene deposits, records the reestablishment of the initial ramp environment. It is overlain by
345 shallow water deposits with porcellaneous-hyaline foraminifera- pellet wackestone facies
346 indicating a shallowing upward trend in the fore shoal environment. It was followed by different
347 shallow-water facies such as *Alveolina*-bioclast-pellet wackestone, conical agglutinated
348 foraminifera-*Alveolina*-pellet wackestone and *Macetadiscus*-miliolid-pellet wackestone. They
349 are equivalent to the inner ramp facies of the Kuh-e- Soukhteh section and occurred in the
350 middle part of the study section (units 3, 4, 5 and 6). The bioclast-intraclast packstone/grainstone
351 and *Gypsina*-lump-bioclast grainstone occupy the upper part of the study section. They record
352 the shoal environment in the middle ramp setting and represent a high-energy deposit above the
353 fair-weather wave base. The lime muds are swept from the grainstone and the bioclasts and
354 intraclast are abundant in the shoal environment.

355 In the Kuh-e- Soukhteh section, during the Bartonian, the facies of mudstone with intercalation
356 of dolomitic limestone consists of small porcellaneous foraminifera (miliolids), rare small
357 hyaline perforate foraminifera (rotaliids), scarce pellets and thin shells of bivalves. This type of
358 association represents a tidal flat in the coastal plain. It gradationally passes over to wackestone
359 with the incorporation of more bioclasts in places. Episodic currents washed peloids onto the
360 lagoonal environment and led to the formation of miliolid-pellet wackestone. Back-stepping is
361 proved by the appearance of the wackestone containing conical porcellaneous forms
362 (spiroliniform such as *Neorhipidionina*), agglutinated forms, and small miliolids. These facies
363 exhibit an alternation of thin layers of mudstone and relatively thicker wackestone beds at the

364 lower part of the section, which typically represent a shallow water environment in the subtidal
365 lagoon to back shoal setting. The transition from tidal flats to lagoonal environment occurred in a
366 shallow subtidal environment. The dominance of micritic sediments indicates a low-energy
367 depositional setting. Further up in the section, the bioclastic grainstone with intraclast packstone
368 and hyaline- porcellaneous foraminifera wackestone can be seen. The intraclast and abraded
369 fauna abound in the shoal setting. These facies typically represent shoal and marginal shoal and
370 extend from the inner ramp to the proximal middle ramp setting, below normal wave agitation
371 depth but occasionally affected by storms. They are followed by the Macetadiscus-miliolid-pellet
372 wackestone and conical porcellaneous-agglutinated-miliolid foraminifera with some rotaliids in
373 the middle part of the section. This part is similar to the lower part of the section, due to the
374 presence of abundant porcellaneous foraminifers. The uppermost part of the section consists of a
375 succession of dolomitic limestone and limestone with subordinate foraminifers (miliolids, small
376 rotaliids, and coskinolinids) associated with inter-bedded of bioclastic grainstone.

377

378

379 **8. Biostratigraphy**

380 The Jahrum Formation is rich in larger benthic foraminifers which were used for establishing the
381 biostratigraphic zonation. This formation, which represents marine strata in the Shahrekord
382 region, was rarely studied and poorly documented. Based on larger benthic foraminifera, the
383 Eocene Assemblage Zones of Jahrum Formation were established by James and Wynd (1965),
384 Adams and Bourgeois (1967), Hottinger (2007), and in the study area (Fig. 6A-B). In the current
385 study 44 species of benthic foraminifera were identified for the first time. The benthic
386 foraminiferal fauna were collected from the gray to cream limestone and argillaceous limestone

387 present throughout the two studied sections (North Gahrou and Kuh-e-Soukhteh sections) (Figs.
388 5 & 6).

389

390

391 **8.1. Assemblage Zones**

392 Three assemblage zones were identified; Assemblage Zone A and Assemblage Zone B, which
393 occurred in the North Gahrou section, and Assemblage Zone C represented in the Kuh-e-
394 Soukhteh section. Selected larger benthic foraminifera are figured in plates 1 and 2.

395

396 **8.1.1. Assemblage Zone A: (Fig. 7)**

397 This zone is exposed in the lower part of the section and extends from bed Gh 1 to bed Gh 77. It
398 is characterized by the presence of the following species:

399 *Assilina* cf. *khorsanica* (Rahaghi), *Assilina* cf. *laminosa* (Gill), *Assilina* cf. *granulosa*
400 (d'Archiac), *Assilina* cf. *subspinosa* (Davies), *Operculina* cf. *patalensis* (Davies), *Nummulites*
401 *globulus* Leymerie, *Nummulites atacicus* Leymerie, and *Nummulites* cf. *fossulata* Cizancourt.

402 This zone was recognized in the lower part of the section and attributed to the Early Eocene
403 (Ypresian). It is equivalent to the foraminiferal association of Lower Eocene deposits in
404 Sahlabad Province (Sistan Suture Zone; east Iran) (Babazadeh 2008, 2010), Eocene beds of
405 Kohat Potowar basin, and Punjab Salt Range in Pakistan as well (Akhtar and Butt 1999; Mirza et
406 al. 2005; Ahmad et al. 2014). This zone can be correlated with SBZ 8 of Serra-Kiel et al. (1998).

407 Stratigraphic range: Early Eocene (Ypresian: Ilerdian).

408

409

410 **8.1.2. Assemblage Zone B: (Fig. 7)**

411 This zone is recognized in the upper part of the section and extended from bed Gh 73 to bed Gh
412 93. It has been characterized by an association of *Nummulites* cf. *perforatus* (de Montfort),
413 *Nummulites ptukhiani* Kacharava, *Nummulites malatyaensis* Sirel, *Alveolina* cf. *fusifformis*
414 Stache, *Alveolina elliptica* (Sowerby), *Gyroidinella magna* Le Calvez, *Macetadiscus* cf.
415 *incolumnatus* Hottinger, Serra-Kiel and Gallardo-Garcia, *Barratolites* sp., *Daviesiconus* cf.
416 *balsilliei* (Davies), *Fabiania cassis* (Oppenheim), *Asterigerina rotula* (Kaufmann), *Gypsina*
417 *marianensis* Hanzawa, *Europertia* sp., *Valvulina* sp., and miliolids.

418 This zone is recognized in the upper part of the section and assigned to the late Middle Eocene
419 (Bartonian). This benthic assemblage is similar to that of the west Tethys (Serra-Kiel et al. 1998)
420 and central Neo-Tethys realm (south, center, and east Turkey) (Sirel 2003; Deveciler 2010,
421 2013). This zone can be correlated with SBZ 17 & 18 of Serra-Kiel et al. (1998).

422 Stratigraphic range: late-Middle Eocene (Bartonian).

423

424 **8.1.3. Assemblage Zone C: (Fig. 8)**

425 In the Kuh-e-Soukhteh section, one single assemblage zone appeared continuously from the base
426 to the top. This zone consists of *Rhabdorites malatyaensis* (Sirel), *Neorhipidionina spiralis*
427 Hottinger, *Archaias operculiniformis* Henson, *Penarchaias glynnjonesi* (Henson),
428 *Praerhapydionina delicate* Henson, *Haymanella huberi* (Henson), *Paraspirolina* cf. *gigantea*
429 Fleury, *Spirolina* cf. *cylindracea* Lamarck, *Macetadiscus* cf. *incolumnatus* Hottinger,
430 *Coskinolina perpera* Hottinger and Drobne, *Coskinolina liburnica* Stache, *Barattolites* sp.,
431 *Daviesiconus* cf. *balsilliei* (Davies), *Medocia blayensis* Parvati, *Rotaliconus persicus* Hottinger,
432 *Rotalia* sp., *Nurdanella* cf. *boluensis* Ozgen, *Biloculina* sp., *Triloculina* sp., *Quinqueloculina* sp.,

433 and *Valvulina* sp. According to Hottinger (2007) and Serra-Kiel et al. (2016), this association is
434 the same as that of central Neo-Tethys (Fars area, south Iran; Dhofar, Oman; Socotra Island,
435 Yemen). The Assemblage Zone C is equivalent to the Assemblage Zone B. The biostratigraphic
436 range of this assemblage may be correlated with SBZ 17 & 18 of Serra-Kiel et al. (1998).
437 Stratigraphic range: late-Middle Eocene (Bartonian).

438

439 **9. Paleontological remarks**

440 Among the reported benthic foraminifera, only the following taxa were selected for structural
441 description and comparison.

442 *Coskinolina perpera* Hottinger and Drobne, *Daviesiconus* cf. *balsilliei* (Davies), *Barattolites* sp.,
443 *Macetadiscus* cf. *incolumnatus* Hottinger, Serra-Kiel and Gallardo-Garcia, *Nummulites globulus*
444 Leymerie, *Nummulites atacicus* Leymerie, *Nummulites* cf. *fossulata* de Cizancourt, *Nummulites*
445 *malatyensis* Sirel, *Nummulites* cf. *perforates* (de Montfort), *Nummulites ptukhiani* Kacharava,
446 *Assilina* cf. *laminosa* Gill, *Assilina* cf. *khorrassanica* Rahaghi and *Assilina* cf. *granulosa*
447 (d'Archiac).

448 The genus *Coskinolina* Stache is characterized by a thick agglutinated conical test with
449 discontinuous pillars in the internal structure and without radial partitions (beams and intercalary
450 beams) and rafters. The genus *Barattolites* Vecchio and Hottinger differs from *Coskinolina*
451 Stache in the presence of beams and intercalary beams.

452 *Coskinolina perpera* Hottinger and Drobne (Pl. 1, figs. A-C) has a thicker wall than all other
453 species of the same genus. The pillars show an irregular pattern and are loosely disposed of in
454 the central part of the cone test. The sutures are depressed and the cone base is slightly convex.
455 The genus *Daviesiconus* Hottinger and Drobne is close to the genus *Barattolites* Vecchio and

456 Hottinger due to the trochospiral nepionic stage in both generations and simple exoskeleton but
457 differs in the presence of marginal apertures, small trochospiral early growth stage and the
458 absence of intercalary beams.

459 In our material, *Daviesiconus cf. balsilliei* (Davies) (Pl. 1, figs. D-E) has an axial cone diameter
460 of 1.25 mm and the basal cone diameter of 1.1- 1.25 mm in megalospheric form. The ratio
461 between basal length and axial length (flattening index, Rb/a) is approximately 1. This specimen
462 shows an isometric form and plots on the normal line of the flattening index diagram. It is similar
463 to the specimens of *Daviesiconus balsilliei* (Davies) collected from former Yugoslavia
464 (Hottinger and Drobne, 1980) but it differs from those of Oman and Yemen (Serra-Kiel et al.,
465 2016) in the smaller size of the test.

466 The *Barattolites cf. trentinarenensis* Vecchio and Hottinger (Pl. 1, fig. F) from the Iranian
467 specimens (our material) has a larger size with respect to the *Barattolites trentinarenensis* Vecchio
468 and Hottinger from the Trentinara Formation of southern Italy.

469 The genus *Macetadiscus* Hottinger, Serra-Kiel, and Gallardo-Garcia was established by Serra-
470 Kiel et al. (2016) and reported by Nafarieh et al. (2019) from the Fars area in southern Iran. It is
471 represented in this paper for the first time in the Shahrekord area. This genus is characterized by
472 the porcellaneous flattened-discoidal test with two or three chambers without skeletal elements in
473 nepionic stage (primary cyclic chambers), discontinuous septula in the annular chambers of the
474 neanic stage, and the presence of foramina in lines with crosswise-oblique axes (Serra-Kiel et al.,
475 2016). *Macetadiscus* Hottinger, Serra-Kiel, and Gallardo-Garcia differs from *Omanodiscus*
476 Hottinger, Serra-Kiel, and Gallardo-Garcia by the presence of discontinuous septula in annular
477 chambers and the absence of pillars. It is also distinguished from *Orbitolites* Lamarck,
478 *Mardinella* Meriç and Coruh and *Azzarolina* Vicedo and Serra-Kiel by the presence of

479 discontinuous septula in annular chambers and the absence of the septula in the primary cyclic
480 chambers and the pillars respectively. The cyclic chambers of *Orbitolites* Lamarck are
481 subdivided into numerous chamberlets by oblique septula (partitions) unlike *Mardinella* Meriç
482 and Coruh with septula perpendicular to the chamber walls.

483 In our samples, *Macetadiscus* cf. *incolumnatus* Hottinger, Serra-Kiel, and Gallardo-Garcia (Pl. 1,
484 figs. G-H) seems to be similar to the materials collected by Nafarieh et al. (2019) from the Fars
485 area (south Iran). The term confer (cf) is used for this specimen due to incomplete skeletal
486 structure and the absence of an equatorial section in our material.

487 The megalospheric test of *Assilina* cf. *laminosa* Gill (Pl. 1, fig. P) is discoidal to lenticular in
488 shape and shows a medium to thick wall with an elongated periphery. It is smooth and
489 characterized by laminations on the surface of the test as ornamentations. The central part of the
490 test is covered by granules. The diameter of the test ranges from 7mm to 10mm and the thickness
491 from 1.5mm to 2mm. This species is characterized by an internally laminated shell wall. This
492 species is accompanied by *Assilina* cf. *granulosa* (d'Archiac), *Nummulites atacicus* Leymerie
493 and *N. globulus* Leymerie. The stratigraphic range is attributed to the Early Eocene.

494 The megalospheric form of *Assilina* cf. *granulosa* (d'Archiac) (Pl. 1, fig. Q) is flattened to
495 lenticular in shape and has a diameter of 5.5-7mm and a thickness of 0.8-1mm. This species
496 shows thin to medium wall with a rounded periphery and a small depression in the central area.
497 The granular ornamentations are well developed on the surface of the test. The spiral cord is thin
498 to medium in thickness. This species is characterized by a heavily granulated surface with
499 distinct septal ridges. It is associated with *Nummulites atacicus* Leymerie, *N. cf. fossulata* de
500 Cizancourt, *N. globulus* Leymerie, and *Assilina* cf. *laminosa* Gill indicating the Ilerdian stage
501 (SBZ 8).

502 The megalospheric test of *Assilina* cf. *khorrassanica* Rahaghi (Pl. 1, fig. R) is lenticular in shape
503 and shows a thick wall with a sharp periphery and elevated central part. The central part of the
504 test is covered by pustules. The diameter of the test ranges from 6mm to 8mm and the thickness
505 from 2.5mm to 3.5mm. The present specimen is similar to Rahaghi's materials but differs by its
506 smaller size. This species is distinguished from *A.* cf. *laminosa* Gill by its thicker wall and more
507 elevated central part of the test. It is found in the Early Eocene limestone of the lower part of the
508 North Gahrou section with the other assilinids and nummulitids such as *Assilina* cf. *granulosa*
509 (d'Archiac), *A.* cf. *laminosa* Gill, *Nummulites globulus* Leymerie and *N. atacicus* Leymerie.

510 *Nummulites globulus* Leymerie (Pl. 2, figs. I-J) is globular to biconical in shape with a diameter
511 ranging from 2.5 mm to 2.9 mm and a thickness from 1 to 1-1.75 mm, for the A form. B-forms
512 were not found in the examined samples. This species shows wedge-shaped chamber cavities
513 with alar prolongations. The pillars are observed in the central part of the test. Septa are almost
514 straight to slightly curved and angular towards the periphery. The chambers are uniformly
515 rectangular to rhombic and increase gradually in size. There are 5 whorls in a radius of 1.375
516 mm in the equatorial section. The spacing of whorls increases slowly. The height of the
517 chambers is larger than the width. The axial section is characterized by its biconvex form with
518 the thick spiral lamina and the thick marginal cord. The *Nummulites globulus* Leymerie is
519 distinguished from other associated *Nummulites* by having a smaller and globular test, a rather
520 smooth surface, thick spiral laminae, and almost straight to slightly curved septa. The present
521 specimen shows some similarities to those described by Blondeau (1972). The *Nummulites*
522 *globulus* Leymerie is associated with *Nummulites atacicus* Leymerie, *Nummulites* cf. *fossulata*
523 de Cizancourt, *Assilina* cf. *laminosa* Gill and *Assilina* cf. *granulosa* (d'Archiac) indicating the
524 Ilerdian stage (SBZ 8). The biometrical data is documented in figure 9.

525 *Nummulites atacicus* Leymerie (Pl. 2, figs. K-L) is lenticular in shape. The diameter of A-forms
526 ranges from 3.3 to 3.5 mm and thickness from 1.7 mm to 2.7 mm. B-forms are not found in the
527 examined samples. The equatorial section shows 5 whorls in a radius of 1.75 mm. The spacing of
528 whorls increases slowly till the end. The septa are arched and inclined towards the periphery.
529 The height of the chambers is larger than the width. The axial section is characterized by regular
530 whorls, narrow spiral cavity, thick spiral lamina, and medium marginal cord. The pillars are
531 observed in the central part of the test.

532 It is closely similar to *Nummulites praecursor* de la Harpe which is distinguished by the slightly
533 larger size of the test with regular septa and more chambers per whorl (Racey, 1995). It is also
534 often confused with *Nummulites globulus* Leymerie and *Nummulites discorbinus* Schlotheim
535 from which it is distinguished by its small proloculus and more chambers per whorl.

536 The co-occurrences of *N. atacicus* Leymerie and *N. globulus* Leymerie represents an excellent
537 global biostratigraphic marker of the Early Eocene (Middle Illerdian). So, the stratigraphic range
538 of this species is considered Illerdian (SBZ 8). The biometrical data is documented in figure 9.

539 *Nummulites cf. fossulata* de Cizancourt (Pl. 2, fig. C) is characterized by the small lenticular test
540 with a central depression and sharp periphery. The shape of the test is an angular "dumb-bell" in
541 an axial section. The biometric data are measured based on the axial section because, in the axial
542 section, this species appears to be very unique. The test has a diameter of 1.75-1.85 mm and a
543 thickness of 0.85-0.9 mm. This species is closely similar to the recorded specimens of Racey
544 (1995). The *Nummulites cf. fossulata* de Cizancourt was originally found in Afghanistan by de
545 Cizancourt (1938) in the Early Eocene. It was reported by Racey (1995) from Late Cuisian to
546 Early Lutetian deposits. This species is reported for the first time from the Jahrum Formation in

547 the study area. It is associated with *N. globulus* Leymerie and *N. atacicus* Leymerie, indicating
548 an Early Eocene age.

549 The megalospheric form of *Nummulites* cf. *perforatus* (de Montfort) (Pl. 2, figs. G-H) shows an
550 inflated test with a rounded periphery. The diameter of the test ranges between 4.5 mm and 7
551 mm and the thickness from 1.58 mm to 2.7 mm. The diameter of proloculus ranges from 0.6 to
552 0.85 mm. The spiral whorls are regular. No microspheric forms were found in our material. The
553 septa are inclined and slightly curved. This species is associated with *Nummulites ptukhiani*
554 Kacharava and *Assilina* cf. *granulosa* (d'Archiac) and its biostratigraphic range is assigned to
555 Bartonian. Due to the absence of centered equatorial sections, we prefer to use the term confer
556 (cf.) to determine the taxa. The biometrical data is documented in figure 9.

557 The megalospheric form of *Nummulites malatyensis* Sirel (Pl. 2, figs. D-F) shows an inflated
558 lenticular test with a strongly rounded periphery. The diameter of the test ranges from 2.2 to 2.6
559 mm and the thickness from 1.6 mm to 1.75 mm. The spherical to sub-spherical proloculus has a
560 diameter of 0.25-0.35 mm. The thickness of the spire is uniform in all whorls. The rate of the
561 spiral opening increases gradually and is constant until the last whorl.

562 *Nummulites malatyensis* Sirel was first reported by Sirel (2003) in Bartonian limestone of the
563 Develi section (Malatya). In this study area, this species was found in the calcareous rocks
564 overlying the carbonate succession containing *Nummulites ptukhiani* Kacharava, *Alveolina* cf.
565 *fusiformis* Stache, *Gyroidinella magna* Le Calvez, and *Fabiania cassis* (Oppenheim). The
566 biometrical data is documented in figure 9.

567 *Nummulites ptukhiani* Kacharava (Pl. 2, figs. A-B) has a diameter of 3.2- 4 mm and a thickness
568 of 1.5-1.9 mm for 4 whorls, in the megalospheric form. The proloculus is 0.25–0,35 mm in
569 diameter. No microspheric forms were found in our material. The spiral laminae are thick, up to

570 half of the height of the chambers in the inner whorls. Chambers are generally higher than wide
571 in each spiral whorl. The pillars are visible and create granules at the surface of the test. The
572 biometrical data is documented in figure 9.

573
574

575 **10- Discussion**

576 The sedimentary model for Tethyan carbonate ramps was proposed by Buxton & Pedley (1989)
577 based on sedimentological and biological characteristics common to depositional environments
578 of present-day ramps (Purser, 1973; Reiss and Hottinger, 1984). Buxton and Pedley (1989)
579 distinguished a succession of facies belts that extends from the protected zone of the inner ramp,
580 characterized by peritidal and lagoonal muddy facies, to deeper zones of the middle and outer
581 ramp.

582 The littoral zone (tidal flat) consists of rare foraminiferal facies, represented by mudstones and
583 dolostone or dolomitic limestones. The mudstones contain thin shells of bivalves, scarce pellets,
584 miliolids, and small rotaliids. This association represents an oligotypic community of epifaunal
585 benthos and indicates a low-energy depositional setting (Zamagni et al., 2008). The dolo-
586 micritization is a diagenetic process in restricted sedimentary environments. The succession of
587 dolostone and dolomitic limestone is usually formed in the low-energy domain of intertidal and
588 subtidal environments in littoral to lagoonal settings (Wilson and Evans, 2002; Al-Saad, 2005;
589 Ivanova *et al.*, 2008; Wilmsen *et al.*, 2010). The main sedimentological characteristic of these
590 facies is a rhythmic alternation of mudstone and dolomitic limestone (dolostone). Therefore, the
591 absence of planktic foraminifera and the presence of small porcellaneous foraminifera (miliolids)
592 indicate low-energy environment with inshore condition in the littoral zone.

593 The lagoonal microfacies consist of miliolid-pellet wackestone facies, *Macetadiscus*-miliolid-
594 pellet wackestone facies, and conical porcellaneous- agglutinated foraminifera-miliolid
595 wackestone facies in Kuh-e-Soukhteh section, and *Macetadiscus*-miliolid-pellet wackestone
596 facies, conical agglutinated foraminifera-*Alveolina*-pellet wackestone facies, and *Alveolina*-
597 bioclastic- pellet wackestone facies in the North Gahrou section. These microfacies generally
598 contain small porcellaneous foraminifera (miliolids), small rotaliids, large discoidal soritids, and
599 agglutinated conical foraminifera. They spread in low-energy environments with relatively slow
600 currents and hint to the restricted environment of the inner ramp (Geel, 2000; Rasser *et al.*, 2005;
601 Badenas and Aurell, 2010). This interpretation is supported by the presence of carbonate mud
602 and the absence of structures indicative of high-energy events.

603 The small porcellaneous foraminifera dominated the shallowest waters in the restricted lagoon in
604 the inner ramp setting, while the large discoidal soritids (*Macetadiscus* Hottinger) and conical
605 porcellaneous (*Neorhipidionina* Hottinger) foraminifera were restricted to the inner and proximal
606 middle ramp. The high diversity of porcellaneous foraminifers was developed in meso- to
607 oligotrophic shallow water environments (Reiss and Hottinger, 1984; Hallock, 1984, 1988;
608 Buxton and Pedley 1989; Romero *et al.*, 2002). The *Macetadiscus* bearing facies has a lateral
609 paleoenvironmental relationship with the *Alveolina* facies. The presence of *Macetadiscus*
610 Hottinger, Serra-Kiel and Gallardo-Garcia suggests relatively shallower water than the *Alveolina*
611 facies. The *Alveolina* d'Orbigny is an important element in Lower and Middle Eocene shallow-
612 water deposits. They are also abundant in the lagoon or enclosure behind the back shoal as well
613 as in the shoal and are found in relatively deeper water than *Orbitolites* Lamarck and
614 *Macetadiscus* Hottinger, Serra-Kiel and Gallardo-Garcia. According to Hottinger (1983), the
615 *Alveolina* facies can occur in protected shelf and higher energy shoal environments.

616 Porcellaneous foraminifera with large conical shapes occurred in tropical carbonate platforms
617 within the upper part of the photic zone (Reiss and Hottinger, 1984; Hohenegger et al., 2000).
618 According to Nebelsick et al (2005) and Barattolo et al (2007), the Middle and Late Eocene
619 larger conical porcellaneous foraminifera were restricted to the proximal middle ramp setting.
620 The recorded facies)conical porcellaneous-agglutinated foraminifera-miliolid wackestone (
621 represents shallow water setting with high light intensity and low substrate stability without
622 turbidity. The conical agglutinated foraminifera are documented as the shallowest association of
623 larger foraminifera, below tidal level, in the upper part of photic zone and indicate a depth of less
624 than 40 m. The distribution of Paleogene conical agglutinated foraminifers depended to the
625 nature of substrate. They seem to prefer the soft substrates and occur wackestone with fine-
626 grained particles and mud. According to Vecchio and Hottinger (2007), the presence of mud
627 level along with conical agglutinated foraminifera wackestone in the stratigraphic section,
628 indicates low water energy environment that can occur in shallow water lagoon setting.

629 The shoal environment is represented by different facies types such as intraclast packstone and
630 bioclastic grainstone in the Kuh-e-Soukhteh section and bioclast-intraclast packstone/grainstone,
631 and *Gypsina*-lump-bioclast grainstone in the North Gahrou section. The shoal area is
632 characterized by a great abundance of rounded bioclasts. The presence of skeletal grains, the
633 high abundance of intraclasts, sparry calcite cement, and lack of lime mud in the shoal facies are
634 also indicative of a high-energy environment.

635 The small and thin shelled hyaline foraminifera wackestone facies, and hyaline-porcellaneous
636 foraminifera wackestone facies could be found in the back and fore shoals in the study area.
637 These facies extend throughout the shallow water inner-middle ramp. The small and robust
638 *Nummulites* Lamarck were spread throughout the Tethyan region from the eastern Alps to the

639 Middle East (eastern Iran) and occurred in a broad range of open marine environments during the
640 Eocene, whereas they are found within the inner ramp during the Paleocene (Rasser *et al.*, 1999;
641 Romero *et al.*, 2002; Bassi *et al.*, 2007; Nebelsick *et al.*, 2005; Babazadeh 2003). The co-
642 occurrence of small *Nummulites* Lamarck and small thin shelled *Operculina* d'Orbigny suggests
643 shallow depth inner and middle ramp settings. It is affected by limiting conditions, such as
644 slightly elevated nutrient levels, favoring the development of a community of r-selection
645 strategists. Meanwhile, the small hyaline and agglutinated foraminifera (*Coskinolina* Stache) are
646 shallow water dwellers and occurred in lagoon and open marine environments, at depth less than
647 40 m. (Ghose, 1977; Geel, 2000; Zamagni *et al.*, 2008). Therefore, the facies of small hyaline
648 foraminifera wackestone can be distributed from the inner ramp to the proximal outer ramp
649 (open marine) and shelves during the Early Paleogene.

650 - The hyaline foraminifera such as *Rotalia* Lamarck, *Rotaliconus* Hottinger, and *Medocia* Parvati
651 are not limited to a specific environment and distributed from the inner ramp to proximal outer
652 ramp (open marine), meanwhile the large hyaline foraminifera (*Assilina* d'Orbigny, *Nummulites*
653 Lamarck, *Operculina* d'Orbigny, etc) appeared in a broad range of open marine environments
654 and occurred in deeper water (middle ramp to proximal outer ramp) and low energy setting
655 during the Eocene. They were spread throughout the Tethyan realm from the eastern Alps to the
656 Middle East (eastern Iran).

657 The hyaline-porcellaneous foraminifera wackestone facies is very heterogeneous due to the
658 presence of two different types of foraminifera and is considered to occur in shallow water
659 middle ramp setting. The small rotaliids and large soritids are representative of hyaline and
660 porcellaneous foraminifera respectively. They are major contributors to Eocene carbonate
661 sediments and present a wide geographic distribution. On the other hand, the co-occurrence of

662 hyaline and porcellaneous foraminifera represents an open shelf platform or low relief with the
663 connection between the front and behind relief. This suggests that no effective barrier existed
664 (Romero et al., 2002, Rasser et al., 2005) and/or that porcellaneous foraminifera were transported
665 from the shallow environment to deeper areas (Hohengger *et al.*, 1999). A similar facies was
666 reported from Paleogene carbonate ramp in western Cephalonia, Greece (Accordi *et al.*, 1998),
667 Early Oligocene deposits of Lower Inn Valley (Nebelsick *et al.*, 2001), and Early Eocene
668 deposits of Minerve section, France (Rasser *et al.*, 2005).

669 The fossil assemblage consisting of large foraminifera (k- strategist foraminifera, long life span)
670 such as *Assilina* d'Orbigny and *Operculina* d'Orbigny with subordinate agglutinated foraminifera
671 (*Valvulina* d'Orbigny), are thought to be restricted to stable, slightly nutrient-depleted
672 environments, normal marine salinity values, and lower limit of the photic zone (Hallock and
673 Glenn, 1986). Therefore, *Assilina* d'Orbigny and *Operculina* d'Orbigny in the large hyaline
674 foraminifera wackestone/packstone facies were adapted to a reduced light condition in an open
675 platform (ramp) and occurred in deeper water (proximal outer ramp) and low energy setting
676 (Buxton and Pedley, 1989).

677 In the study section, all of the recorded shallow water benthic foraminiferal associations could be
678 classified by the composition and morphology of the test in three groups: 1) porcellaneous, 2)
679 agglutinated, and 3) hyaline. The Porcellaneous foraminiferal group is subdivided into three
680 categories: a) simple forms, b) fusiform/ discoidal forms, and c) planispiral/conical-fan forms.

681 The simple Porcellaneous foraminiferal forms have a small test with an imperforate wall. They
682 consist of *Nurdanella* cf. *boluensis* Ozgen, *Biloculina* sp., *Triloculina* sp., and *Quinqueloculina*
683 sp. *Alveolina fusiformis* Stache and *Alveolina elliptica* (Sowerby) are porcellaneous foraminifers
684 with fusiform shape. While *Macetadiscus* cf. *incolumnatus* Hottinger, and *Orbitolites*

685 *complanatus* Lamarck are porcellaneous foraminifers with discoidal shape. The planispiral-
686 conical-fan shape forms consist of *Penearchaias glynnjonesi* (Henson), *Archaias*
687 *operculiniformis* Henson, *Rhabdorites malatyaensis* (Sirel), *Praerhapydionina delicate* Henson,
688 *Haymanella huberi* (Henson), *Paraspirolina gigantea* Fleury, *Spirolina cylindracea* Lamarck,
689 and *Neorhipidionina spiralis* Hottinger.

690 Three taxa including *Coskinolina perpera* Hottinger and Drobne, *Daviesiconus* cf. *balsilliei*
691 (Davies), *Barattolites* sp., and *Valvulina* sp. are related to the agglutinated foraminiferal group.

692 The hyaline foraminiferal group is characterized by an association composed of nummulitids
693 (*Nummulites* Lamarck, *Assilina* d'Orbigny and *Operculina* d'Orbigny) and rotalids such as
694 *Medocia blayensis* Parvati, *Rotaliconus persicus* Hottinger, *Gyroidinella magna* Le Calvez and
695 *Fabiania cassis* (Oppenheim), *Asterigerina rotula* (Kaufmann), *Gypsina marianensis* Hanzawa,
696 *Europertia* sp., and *Rotalia* sp.

697 The Early Eocene (Ypresian) age is indicated by the foraminiferal Assemblage A in the lower
698 part of the North Gahrou section. Whereas typical late Middle Eocene (Bartonian) species related
699 to Assemblages B and Assemblage C, are present in the upper part of North Gahrou and
700 throughout Kuh-e-Soukhteh sections as well. The absence of Cuisian and Lutetian benthic
701 foraminifera in the North Gahrou section is most probably due to a concealed fault unnoticed
702 during fieldwork. At last, the stratigraphic studies improve the resolution of Eocene carbonate
703 microfacies and benthic foraminiferal biozonation, which were poorly established in this region

704 **11- Conclusions**

705 - In the study area, the Jahrum Formation consists of three main lithofacies: limestone, marl and
706 dolostone/ dolomitic limestone. It yields a rich benthic foraminiferal fauna that took place in the
707 Tethyan carbonate ramp environment.

708 - Based on the stratigraphic range of index benthic foraminifera, three assemblage zones are
709 recognized for the Jahrum Formation in the two studied sections: Assemblage A of the Gahrou
710 section is assigned to the Early Eocene (Ypresian), while the Assemblage B of the Gahrou
711 section and the Assemblage C of Kuh-e-Soukhteh section are considered late Middle Eocene
712 (Bartonian) in age. These assemblages are comparable with the benthic foraminifera assemblages
713 of west Tethys and neighboring countries in the Middle East and indicated an extension of the
714 Neo-Tethys realm from the Zagros passive margin (west Iran) to the Sistan Suture Zone (east
715 Iran).

716 - The absence of Cuisian and Lutetian benthic foraminifera between two assemblage zones in the
717 North Gahrou section is related to fault disruption.

718 - The pattern of foraminiferal distribution in the Kuh-e- Soukhteh section shows a shallow water
719 environment with relative deepening through time. Whereas, the distribution of microfacies in
720 the North Gahrou section, indicates shallowing upward.

721 - The Jahrum Formation corresponds to the progressive onset of a carbonate ramp characterized
722 by protected low-energy environments with scarce influence of tidal waves. The analysis of
723 carbonate facies suggests a homoclinal ramp setting with the transition from inner ramp to
724 proximal outer ramp on the gently seaward-sloping morphology.

725 - There was no evidence of re-sedimentation or turbidite sediments indicating breakage in the
726 carbonate platform. Also, there are no reef-making fossil structures or large and important reefs
727 that separate the open sea from the restricted and semi-restricted parts of the basin.

728

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735

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913

914

915 **Figure captions**

916 Fig. 1: Iran map showing the different geological zones of Iran (Alavi, 2004).

917 Fig. 2: A) Location of the study area in the High Zagros on the Chaharmahal Bakhtiari Province
918 (Zahedi and Rahmati Ilkhechi, 2006); B) Location of the study area in Ardal geological map
919 (1:250000).

920 Fig. 3: Correlation between Kuh-e-Soukhteh and North Gahrou columnar sections which
921 showing the different lithological units in the study area.

922 Fig. 4: Distribution of main microfacies in the Kuh-e-Soukhteh columnar section.

923 Fig. 5: Distribution of main microfacies in the North Gahrou columnar section.

924 Fig. 6: A) Benthic foraminifera biozones of Wynd (1965) and Adams and Bourgeois (1967); B)
925 Benthic foraminifera biozones of Hottinger (2007) and the study area.

926 Fig. 7: Distribution of benthic foraminifera in the North Gahrou columnar section.

927 Fig. 8: Distribution of the benthic foraminifera in the Kuh-e-Soukhteh columnar section.

928 Fig. 9: Comparison of small A- forms based on biometrical data between *Nummulites* taxa of the
929 study area and the specimens of Blondeau (1975), Schaub (1981), Abdulsamad (2000), Sirel
930 (2003), and Deveciler (2013).

931 Plate 1: Fig. A: A1) *Coskinolina perpera* Hottinger and Drobne, axial section, Kuh-e- Soukhteh
932 section, As 46, A2) *Coskinolina liburnica* Stache, axial section, As 46; Fig. B: *Coskinolina*

933 *perpera* Hottinger and Drobne, equatorial section, Kuh-e- Soukhteh section, As 38; Fig. C:
934 *Coskinolina perpera* Hottinger and Drobne, oblique section, Kuh-e- Soukhteh section, As 80;
935 Fig. D: *Daviesiconus* cf. *balsilliei* (Davies), subaxial section, Gahrou section, GH 64; Fig. E:
936 *Daviesiconus* cf. *balsilliei* (Davies), equatorial section, Gahrou section, GH 63. Fig. F:
937 *Barattolites* cf. *trentinarensis* Vecchio and Hottinger equatorial section, Kuh-e- Soukhteh
938 section, As 80; Fig. G: *Macetadiscus* cf. *incolumnatus* Hottinger, axial section, Gahrou section,
939 GH 75; Fig. H: *Macetadiscus* cf. *incolumnatus* Hottinger, subaxial section, Kuh-e- Soukhteh
940 section, As 41; Fig. I: *Alveolina* cf. *fusiformis* Stache, axial section, Gahrou section, GH 60; Fig.
941 J: *Gyroidinella magna* Le Calvez, equatorial section, Gahrou section, GH 69; Fig. K: *Fabiania*
942 *cassis* (Oppenheim), axial section, Gahrou section, GH 63; Fig. L: *Medocia blayensis* Parvati,
943 subaxial section, Kuh-e- Soukhteh section, As 42; Fig. M: *Rhabdorites malatyaensis* (Sirel),
944 subaxial section, Kuh-e- Soukhteh section, As 42; Fig. N: *Gypsina marianensis* Hanzawa, axial
945 section, Gahrou section, GH 77; Fig. O1: *Archaias operculiniformis* Henson, oblique (nearly
946 axial section), Kuh-e- Soukhteh section, As 77, Fig. O2: *Penarchaias glynnjonesi* (Henson),
947 transverse section parallel to the axis of coiling, Kuh-e- Soukhteh section, As 77; Fig. P: *Assilina*
948 cf. *laminosa* (Gill), axial section, Gahrou section, GH 1; Fig. Q: *Assilina* cf. *granulosa*
949 (d'Archiac), axial section, Gahrou section, GH 38; Fig. R: *Assilina* cf. *khorsanica* (Rahaghi),
950 sub axial section, Gahrou section, GH 3, Scale bars:1mm.

951 b: beam, ch: chamber, f: foramen, p: pillar, s: septum, sl: septulum, ma: marginal aperture

952

953 Plate 2: Fig. A: *Nummulites ptukhiani* Kacharava, equatorial section, Gahrou section, GH 51;
954 Fig. B: *Nummulites ptukhiani* Kacharava, axial section, Gahrou section, GH 47; Fig. C:
955 *Nummulites* cf. *fossulata* Cizancourt, axial section, Gahrou section, GH 11; Fig. D: *Nummulites*

956 *malatyaensis* Sirel, axial section, Gahrou section, GH 90; Fig. E: *Nummulites* cf. *malatyaensis*
957 Sirel, axial section, Gahrou section, GH 93; Fig. F: *Nummulites malatyaensis* Sirel, equatorial
958 section, Gahrou section, GH 90; Fig. G: *Nummulites* cf. *perforatus* (de Montfort), equatorial
959 section, Gahrou section, GH 37; Fig. H: *Nummulites* cf. *perforatus* (de Montfort), axial section,
960 Gahrou section, GH 43; Fig. I: *Nummulites globulus* Leymerie, equatorial section, Gahrou
961 section, GH 21; Fig. J: *Nummulites globulus* Leymerie, axial section, Gahrou section, GH 21;
962 Fig. K: *Nummulites atacicus* Leymerie, equatorial section, Gahrou section, GH 25; Fig. L:
963 *Nummulites atacicus* Leymerie, semi axial section, Gahrou section, GH 25. Scale bars: 1mm.

964
965 Plate 3: Figs. A: *Macetadiscus*-miliolid-Pellet wackestone, A1: Kuh-e- Soukhteh section, As 45
966 and A2: Gahrou section, GH 62; Fig. B: *Alveolina*-pellet wackestone, Gahrou section, GH 63;
967 Fig. C: *Alveolina*-bioclast-pellet wackestone/grainstone, Gahrou section, GH 72; Fig. D:
968 Bioclast-intraclast packstone/grainstone, Gahrou section, GH 76; Fig. E: *Gypsina*-lump- bioclast
969 grainstone, Gahrou section, GH 77; Fig. F: Hyaline foraminifera (*Nummulites* sp.) wackestone,
970 Gahrou section, GH 25; Fig. G: Porcellaneous-hyaline-foraminifera- Pellet wackestone, Gahrou
971 section, GH 58; Fig. H: Large hyaline foraminifera (*Assilina* sp.) wackestone/packstone, Gahrou
972 section, GH 1; Fig. I: Large hyaline foraminifera [(*Operculina* cf. *patalensis* (Davies)]
973 wackestone, Gahrou section, GH 5; Fig. J: Mudstone with miliolids, Kuh-e- Soukhteh section,
974 As 11; Fig. K: Dolostone or dolomitic limestone without fossils, Kuh-e- Soukhteh section, As
975 26; Fig. L: Miliolid-Pellet wackestone, Kuh-e- Soukhteh section, As 40; Fig. M: *Macetadiscus*-
976 miliolid-Pellet wackestone, Kuh-e- Soukhteh section, As 41; Fig. N: Intraclast packstone with
977 gastropods fragments, Kuh-e- Soukhteh section, As 19; Fig. O: Bioclastic grainstone, Kuh-e-
978 Soukhteh section, As 75; Fig. P: Hyaline-porcellaneous foraminifera wackestone, Kuh-e-

979 Soukhteh section, As 38; Fig. Q: Conical porcellaneous foraminifera-miliolid wackestone, Kuh-
980 e- Soukhteh section, As 14; All scale bars= 1mm, except A2= 0.5 mm.

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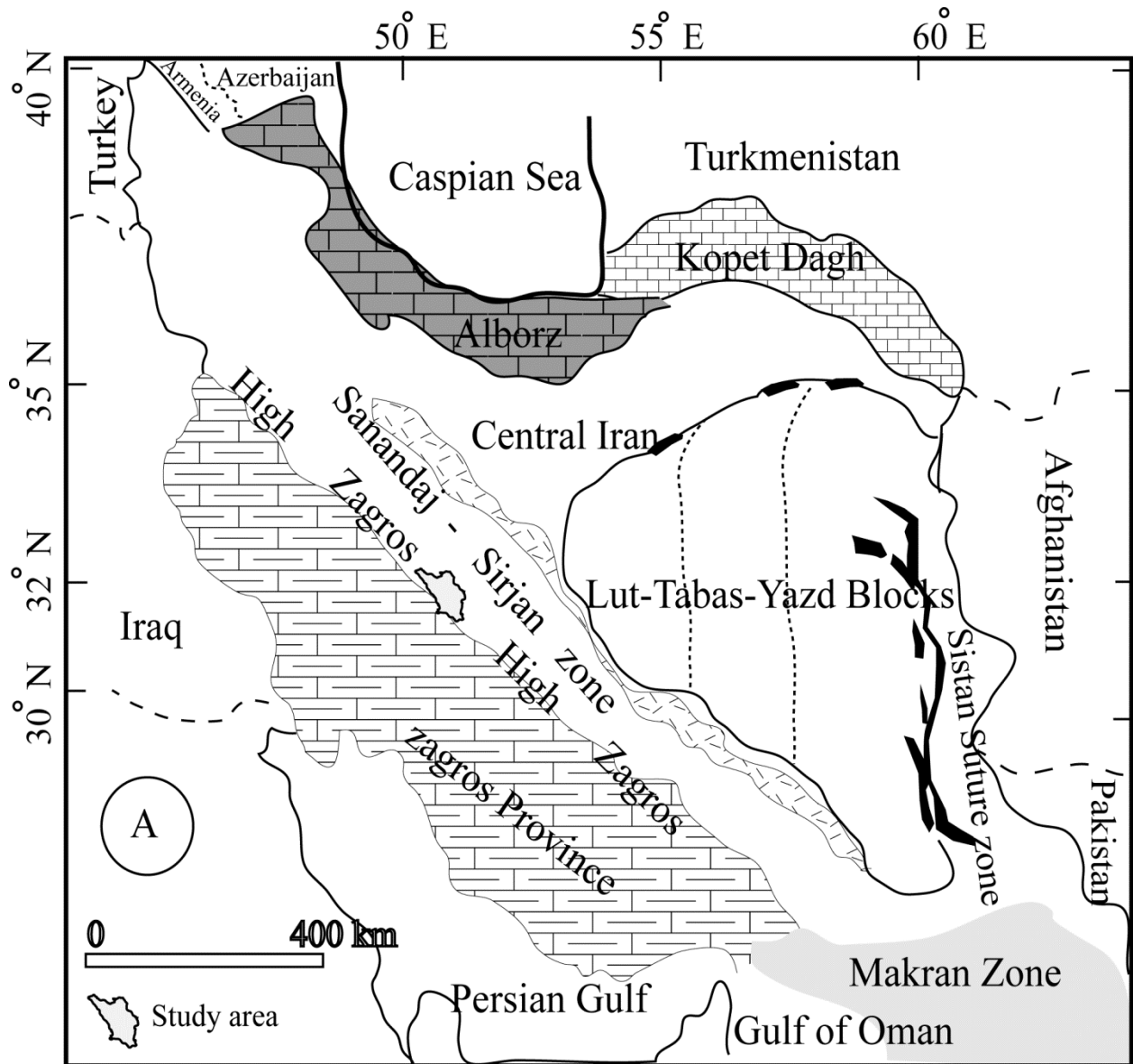


Fig. 1

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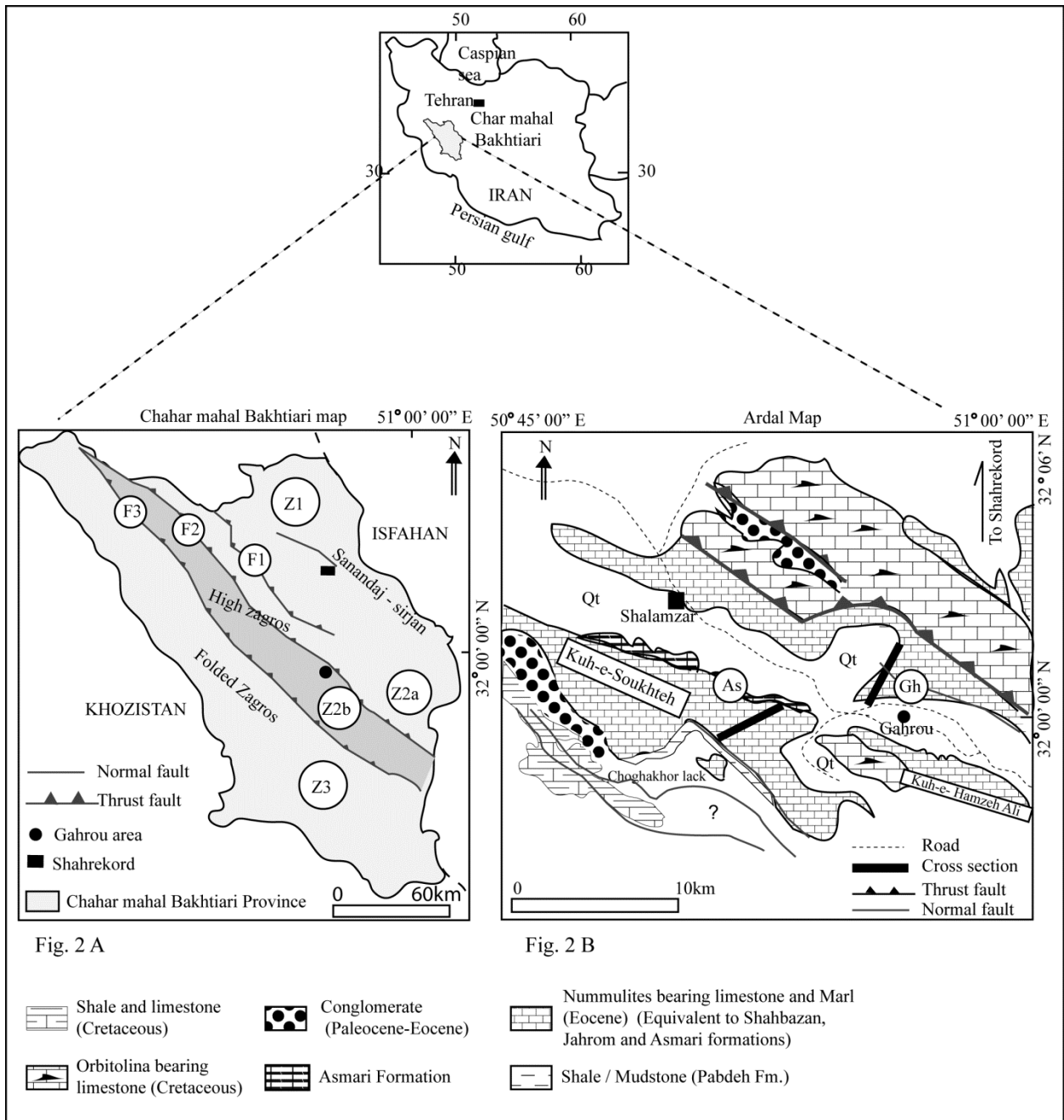
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Kuh-e-Soukhteh section

North Gahrou section

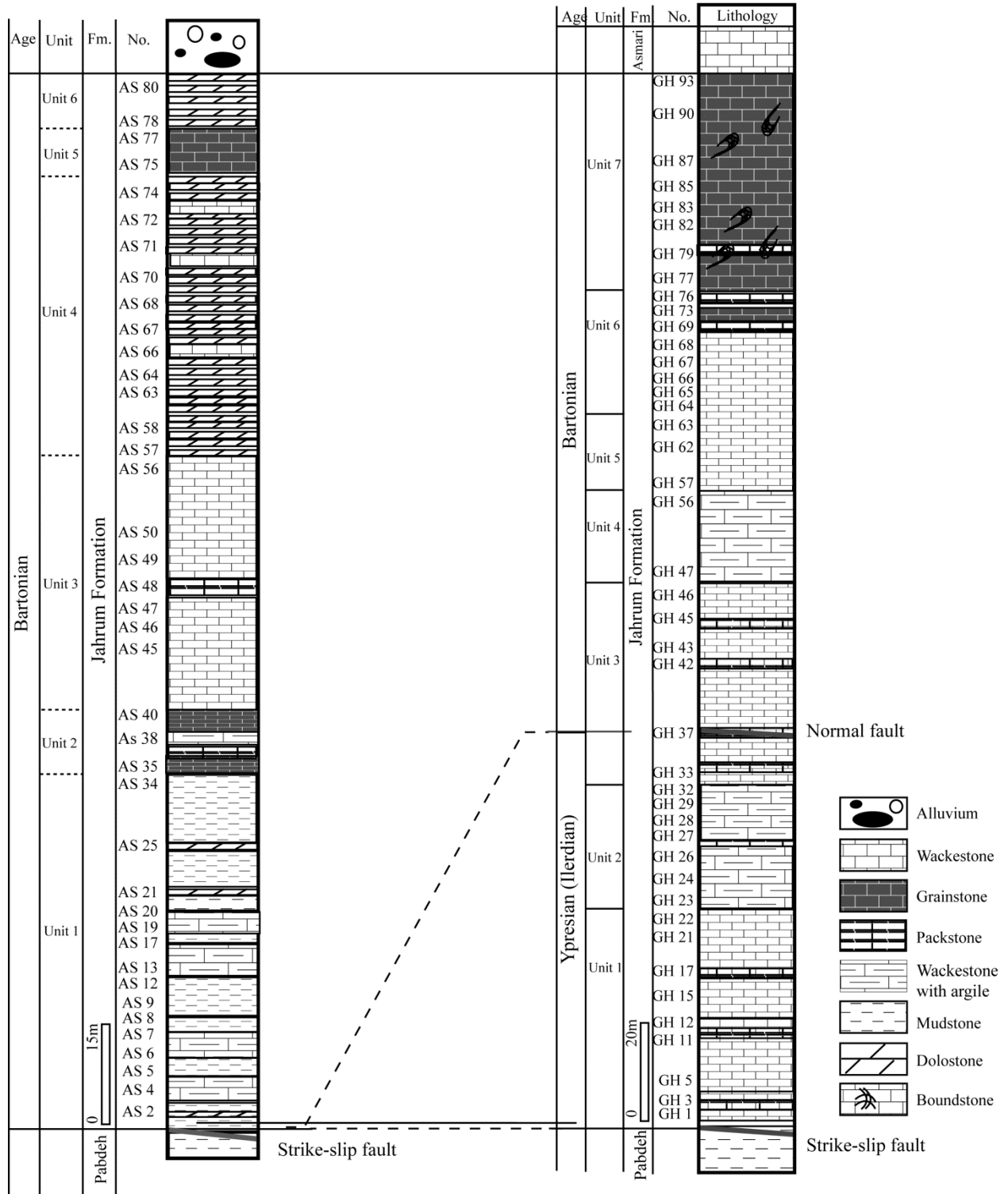


Fig. 3

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Kuh-e-Soukhteh section

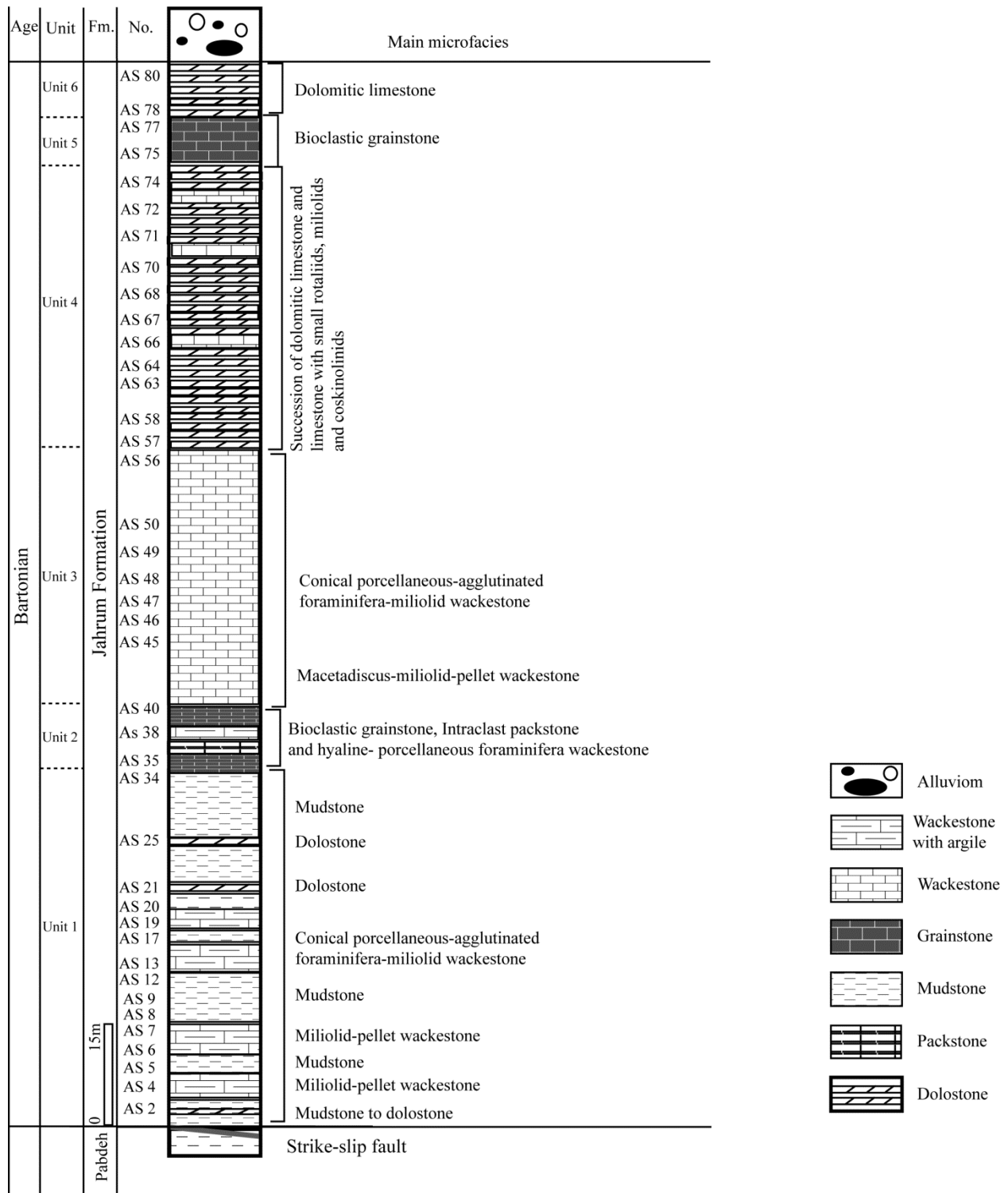


Fig. 4

North Gahrou section

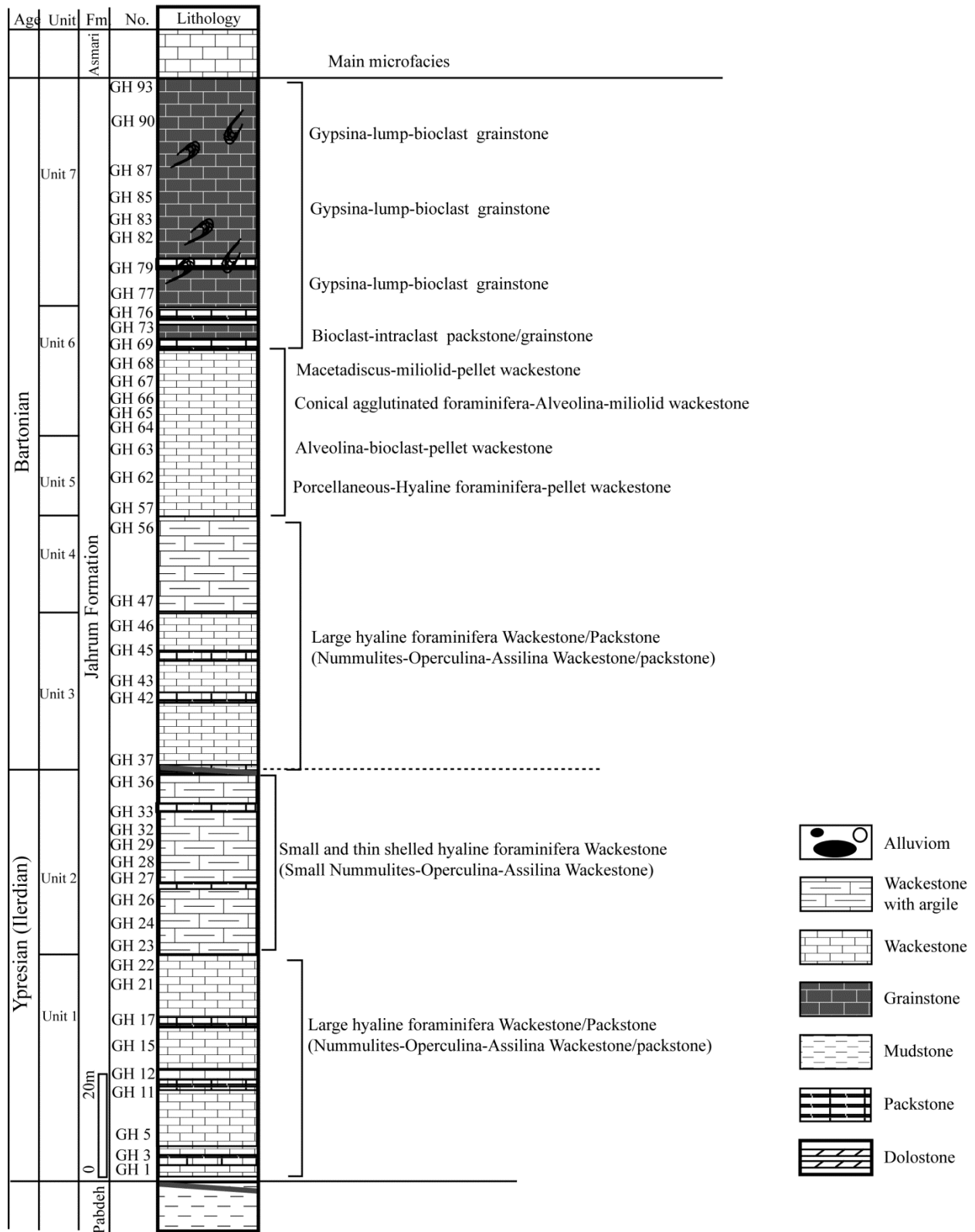


Fig. 5

Formation	Age	Wynd (1965)	Adams & Bourgeois (1967)
Jahrum Formation	Late Eocene	Chapmanina-Pellatispira-Baculogypsinoides Assemblage Zone (Zone 53)	Nummulites spp.-Discocyclina spp. Assemblage Zone
		Nummulites-Alveolina Assemblage Subzone (51)	Coskinolina-Rhapydionina Assemblage Zone
	Dicyoconus-Coskinolina-Orbitolites complanatus Assemblage Subzone (50)		
	Middle Eocene	Linderina Subzone (49)	
E. Eocene	Opertorbitolites Zone (44)		
	Miscellanea- Kathina Assemblage Zone (Zone 43)		

Fig. 6A

Biozones (Serra)	Fars area (Hottinger 2007)	In this study	
		North Gahrou section	Kuh-e-Soukhteh section
Bartonian	SBZ 17 - 18	Assemblage B	Assemblage C
		<p><i>Globoreticulina iranica</i> <i>Austrotrillina paucialveolata</i> <i>Austrotrillina eocaenica</i> <i>Neorhapydionina spiralis</i> <i>Hymanella huberi</i> <i>Praerhapydionina delicata</i> <i>Rhabdorites malatyaensis</i> <i>Neotaberina neaniconica</i> <i>Orbitolites minimus</i> <i>Penarchaias glyyijonesi</i> <i>Archaias operculiniformis</i> <i>Archaias diyarbakirensis</i> <i>Coskinolina perpera</i> <i>Coskinolina liburnica</i> <i>Dicyoconus indicus</i> <i>Medocia blayensis</i> <i>Rotaliconus persicus</i></p>	<p><i>Austrotrillina eocaenica</i> <i>Neorhapydionina spiralis</i> <i>Hymanella huberi</i> <i>Praerhapydionina delicata</i> <i>Rhabdorites malatyaensis</i> <i>Macetadiscus cf. incolummatus</i> <i>Nurdanella bolhiensis</i> <i>Archaias operculiniformis</i> <i>Penarchaias glyyijonesi</i> <i>Coskinolina perpera</i> <i>Coskinolina liburnica</i> <i>Medocia blayensis</i> <i>Rotaliconus persicus</i> <i>Barattolites sp.</i></p>
Ypresian (Ilerdian)	SBZ 8	Assemblage A	
		<p><i>Assilina cf. khorasanica</i> <i>Assilina cf. laminosa</i> <i>Assilina cf. granulosa</i> <i>Assilina cf. subspinosa</i> <i>Operculina cf. patalensis</i> <i>Nummulites atacicus</i> <i>Nummulites cf. fossulata</i> <i>Nummulites globulus</i></p>	

Fig. 6 B

North Gahrou section

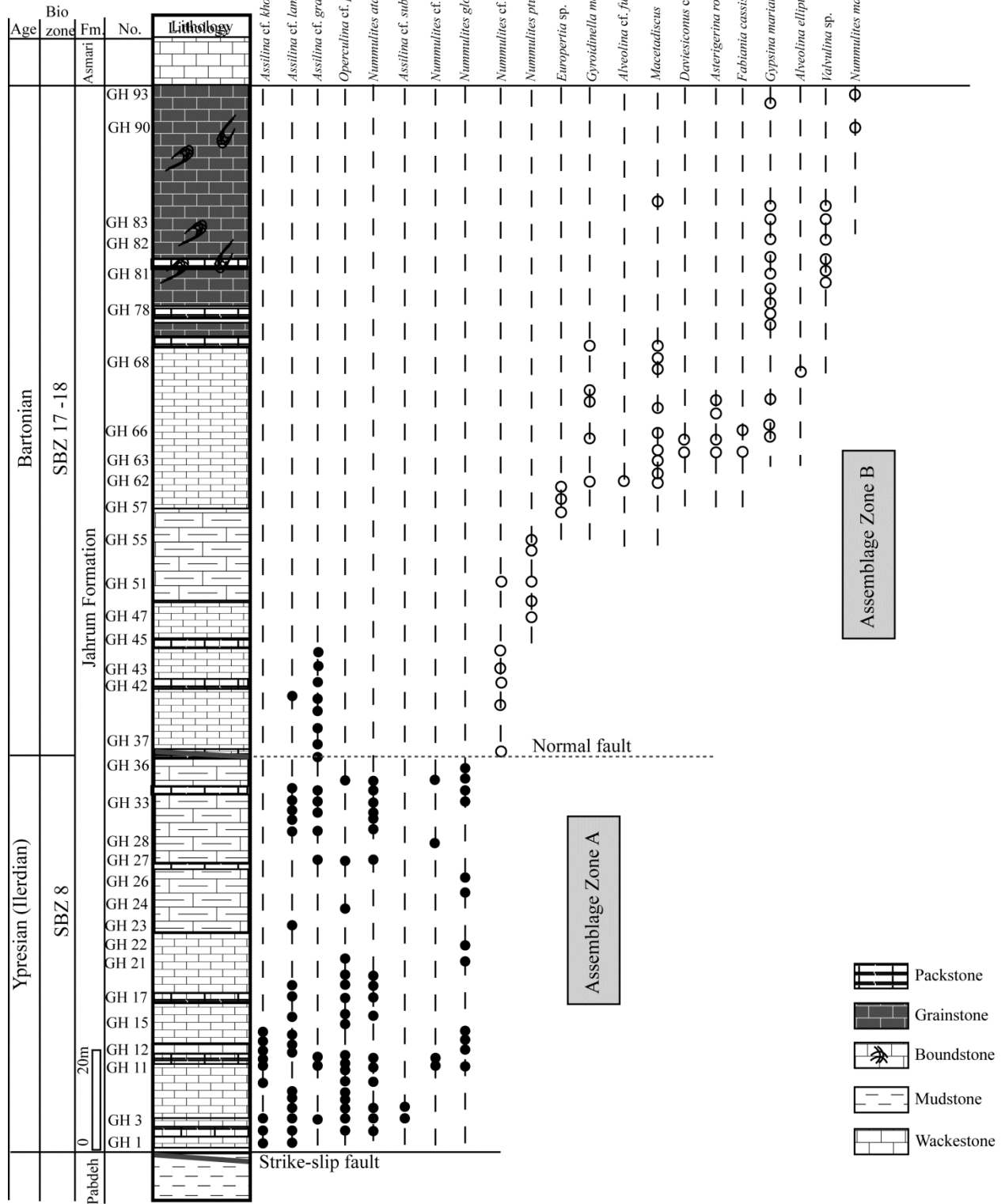


Fig. 7

Kuh-e-Soukhteh section

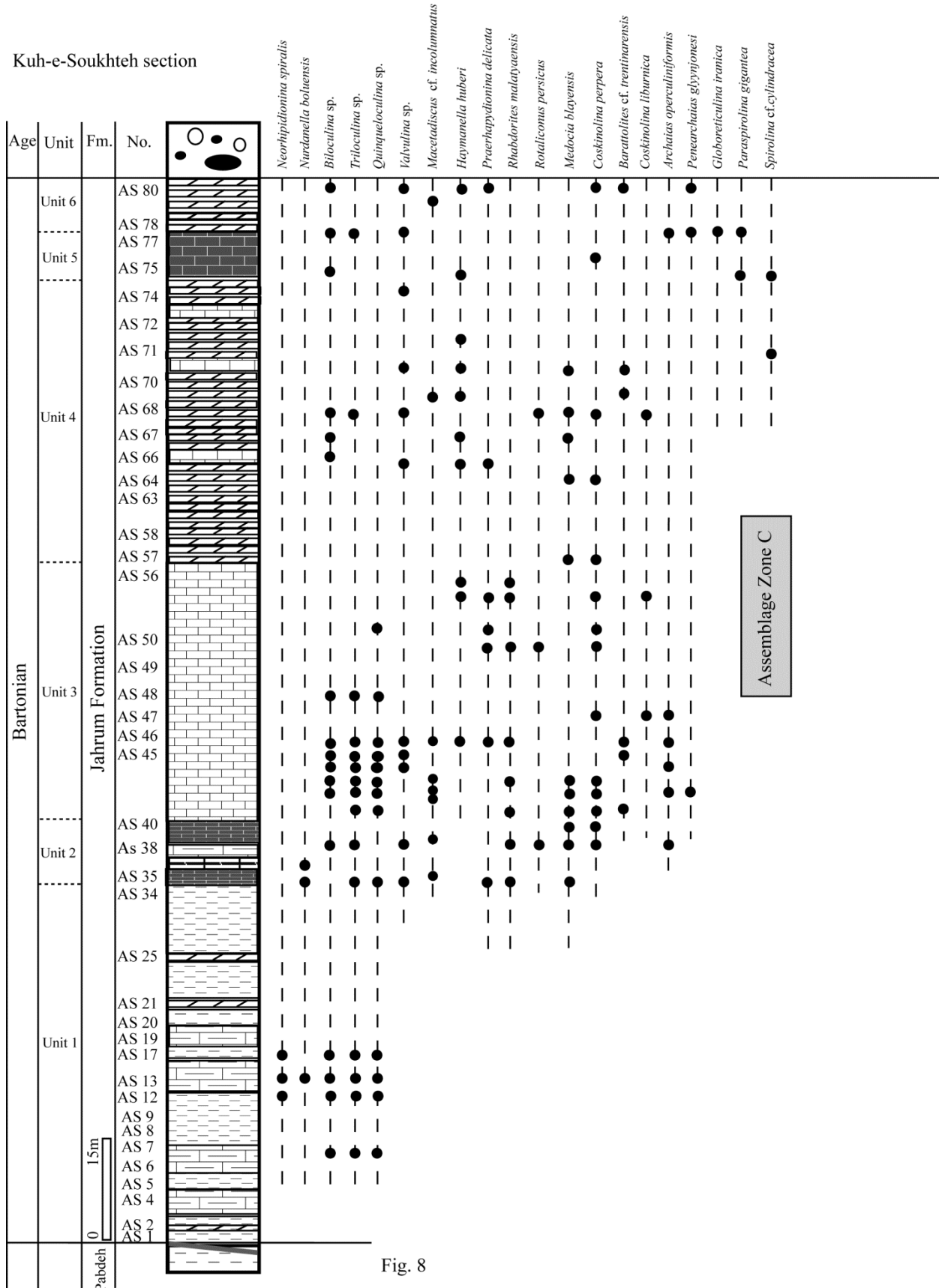


Fig. 8

Species \ A-form	D (mm)	T (mm)	W4th/R	(C) in 1/4 third whorl	H-L	Proloculus	Age
<i>Nummulites globulus</i> (after Blondeau, 1972)	2-3.5	1-1.8	4/1.3	5-6	H> L	————	Ilerdian (SBZ 8)
<i>N. globulus</i> (after Schaub, 1981)	2-3	1-1.5	4/1.2-1.7	————	H> L	0.15-1.3	Ilerdian (SBZ 8)
<i>N. globulus</i> (after Abdulsamad, 2000)	2.8	1.8	4/1.11	4-5	H> L	0.15-0.25	Ilerdian (SBZ 8)
<i>N. globulus</i> (in this study)	2.5-2.9	1-1.75	4/1.2	5-6	H> L	0.2-0.25	Ilerdian (SBZ 8)
<i>N. atacicus</i> (after Blondeau, 1972)	3-5	1.2-2.3	4/1.4	6-7	H> L	————	Ilerdian (SBZ 8)
<i>N. atacicus</i> (after Schaub, 1981)	3-5.5	1.3-2.5	4/1.8-2	————	H> L	0.4-0.65	Ilerdian (SBZ 8)
<i>N. atacicus</i> (in this study)	3.3-3.5	1.7-2.7	4/1.37	7	H> L	0.45-0.5	Ilerdian (SBZ 8)
<i>N. ptukhiani</i> (after Schaub, 1981)	2.8-4	1-1.8	——	————	——	0.15-0.22	Bartonian
<i>N. ptukhiani</i> (after Boukhari et al. 2005)	2.7-2.9	1.25-1.4	4/1.32	4-5	H=L	0.1-0.15	Priabonian
<i>N. ptukhiani</i> (after Cotton et al. 2019)	3.23	1.74	4/1.4	5-6	H> L H< L	——	Bartonian
<i>N. ptukhiani</i> (in this study)	3.2-4	1.5-1.9	4/1.38	5-6	H≈ L	0.25-0.35	Bartonian
<i>N. malatyensis</i> (after sirel, 2003)	0.9-2.7	0.7-1.7	——	7-8	H=L	0.1-0.275	Bartonian
<i>N. malatyensis</i> (after Deveciler, 2013),	2.4-3.4	1.5-1.75	4/1.4	8-9	H> L	0.25-0.3	Bartonian
<i>N. malatyensis</i> (in this study)	2.2-2.6	1.6-1.75	4/0.9	————	H=L	0.25-0.35	Bartonian
<i>N. perforatus</i> (after Blondeau, 1972)	4-6	2-2.5- 3.2	6/2.1	5-6	H< L	——	Bartonian
<i>N. perforatus</i> (after Schaub, 1981)	3-5-6-7-9	1.5-2.5-3-4	5/2.5	————	H< L	0.75-1.25	Bartonian
<i>N. cf. perforatus</i> (in this study)	4.5-7	1.58-2.7	4/1.3-1.85	5-6	H< L	0.6-0.85	Bartonian

Fig. 9

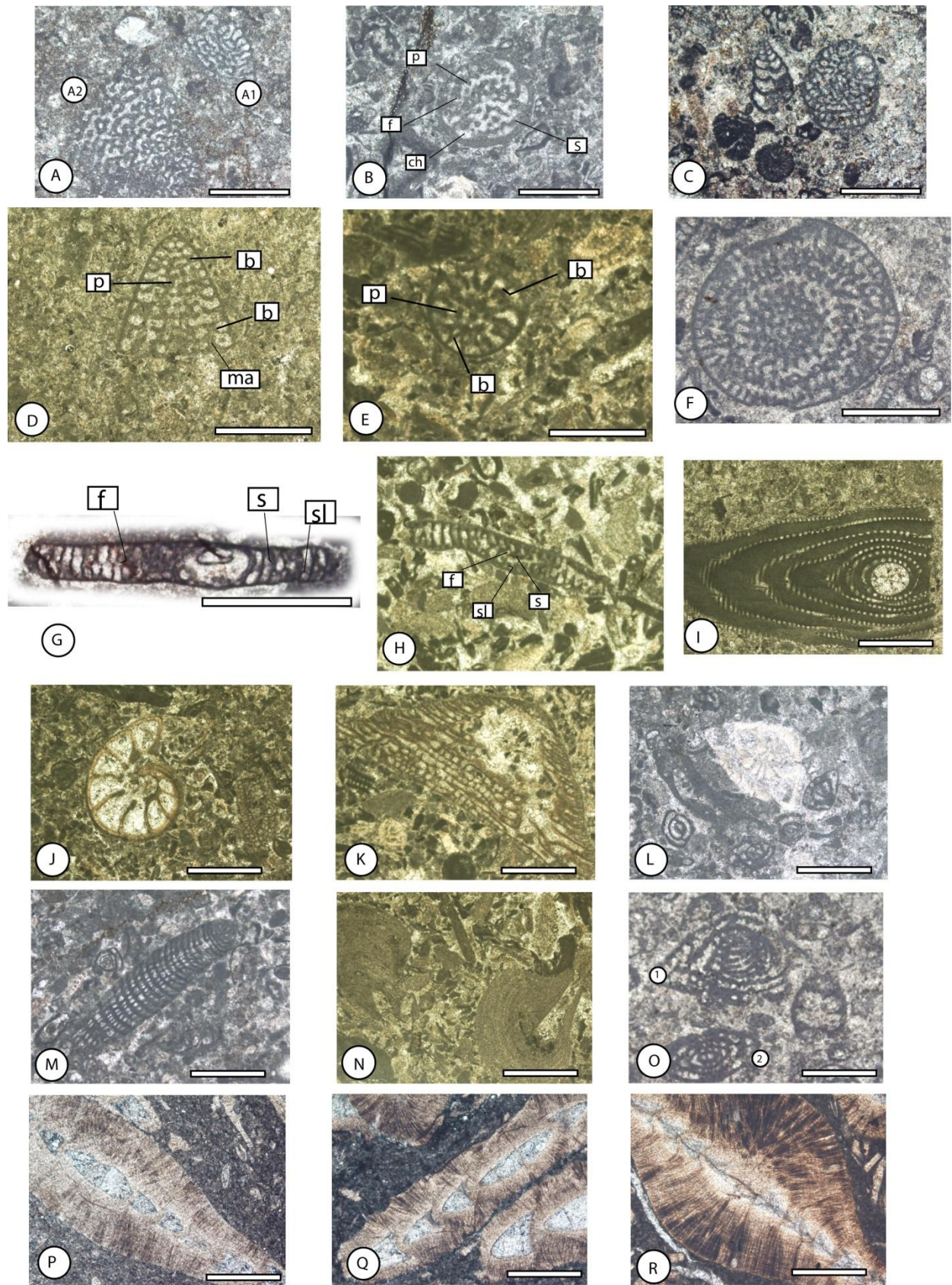
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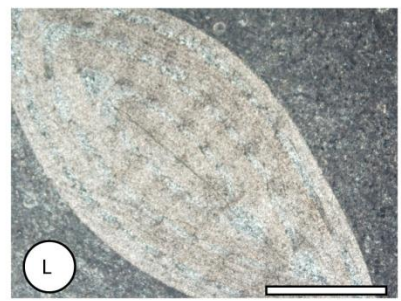
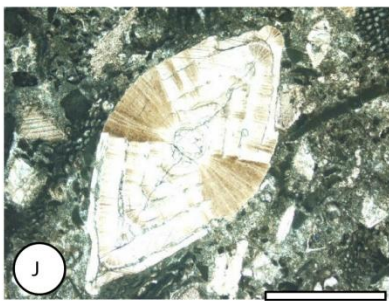
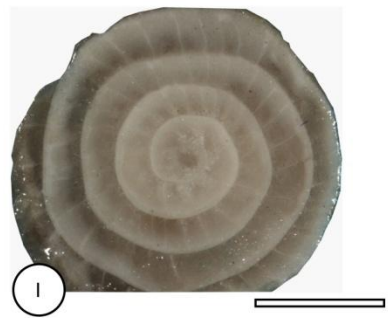
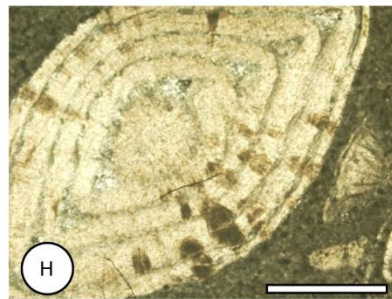
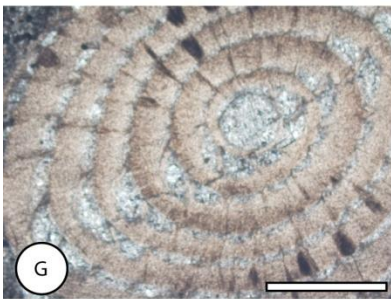
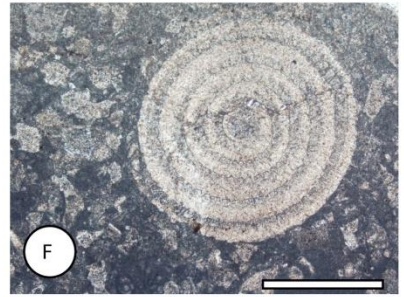
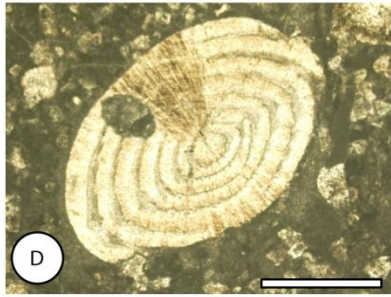
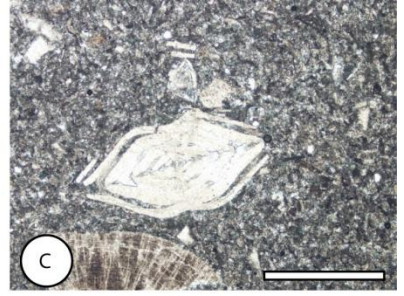
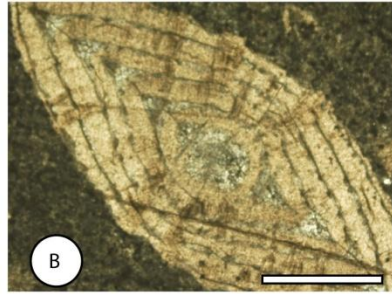
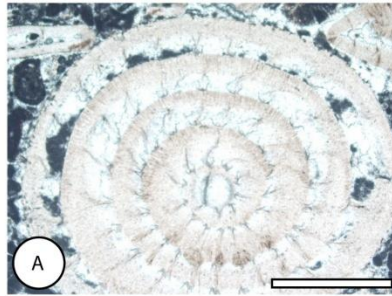


Plate 2

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