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## Ordovician stratigraphy and benthic community replacements in the eastern Anti-Atlas, Morocco

J. Javier Alvaro, Mohammed Benharref, Jacques Destombes, Juan Carlos Gutiérrez-Marco, Aaron Hunter, Bertrand Lefebvre, Peter van Roy, Samuel Zamora

### ► To cite this version:

J. Javier Alvaro, Mohammed Benharref, Jacques Destombes, Juan Carlos Gutiérrez-Marco, Aaron Hunter, et al.. Ordovician stratigraphy and benthic community replacements in the eastern Anti-Atlas, Morocco. The Great Ordovician Biodiversification Event: Insights from the Tafilalt Biota, Morocco, 485, The Geological Society of London, pp.SP485.20, In press, Geological Society, London, Special Publication, 10.1144/SP485.20 . hal-02405970

**HAL Id: hal-02405970**

**<https://hal.science/hal-02405970>**

Submitted on 13 Nov 2020

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# The Geological Society Special Publications

## Ordovician stratigraphy and benthic community replacements in the eastern Anti-Atlas, Morocco --Manuscript Draft--

<b>Manuscript Number:</b>	GSLSpecPub2019-17R1
<b>Article Type:</b>	Research article
<b>Full Title:</b>	Ordovician stratigraphy and benthic community replacements in the eastern Anti-Atlas, Morocco
<b>Short Title:</b>	Ordovician stratigraphy of the Anti-Atlas
<b>Corresponding Author:</b>	Javier Alvaro Instituto de Geociencias SPAIN
<b>Corresponding Author E-Mail:</b>	jj.alvaro@csic.es
<b>Other Authors:</b>	MOHAMMED BENHARREF JACQUES DESTOMBES JUAN CARLOS GUTIÉRREZ-MARCO AARON W. HUNTER BERTRAND LEFEBVRE PETER VAN ROY SAMUEL ZAMORA
<b>Order of Authors (with Contributor Roles):</b>	Javier Alvaro (Methodology: Lead; Supervision: Lead; Writing – original draft: Lead; Writing – review & editing: Lead) MOHAMMED BENHARREF (Data curation: Supporting) JACQUES DESTOMBES (Data curation: Supporting; Formal analysis: Supporting; Methodology: Supporting; Project administration: Supporting) JUAN CARLOS GUTIÉRREZ-MARCO (Writing – review & editing: Supporting) AARON W. HUNTER (Visualization: Supporting) BERTRAND LEFEBVRE (Visualization: Supporting) PETER VAN ROY (Writing – review & editing: Supporting) SAMUEL ZAMORA (Visualization: Supporting)
<b>Abstract:</b>	The Anti-Atlas contains a thick, volcanic-free Ordovician succession, originally deposited in a passive-margin basin. Three main sedimentary packages are bounded by major unconformities: (i) the Tremadocian–Floian Lower Fezouata and Upper Fezouata formations, which unconformably overlie a palaeorelief of Cambrian rifting volcanosedimentary complexes, and is subsequently overlain by a Dapingian paraconformable gap; (ii) the Darriwilian–Katian Tachilla Formation and First Bani and Ktaoua groups, the latter unconformably overlain by a Hirnantian glaciogenic succession; (iii) subsequently infilled with deposits of the Second Bani Group. Due to the scarcity of carbonate interbeds for etching analyses, the global Ordovician chart is interpolated on the basis of microphytoplankton (acritarchs and chitinozoans), regional graptolites and brachiopods. The Ordovician counter-clockwise rotation of Gondwana led its Moroccan margin from mid- to high-latitude positions, leading to the onset of a siliciclastic, wave- and storm-dominated platform. Flooding surfaces are marked by shelly silty carbonate interbeds that reflect the episodic development of echinoderm-bryozoan meadows during Katian times; in areas protected from siliciclastic input, they reached massive and bedded bioaccumulations (Khabt-el-Hajar Formation). The Hirnantian glaciation controlled the incision of numerous tunnel channels, infilled with both alluvial-to-fluvial sediments and glaciomarine diacmictites. The Hirnantian

	palaeorelief was definitively sealed during Silurian times.
<b>Section/Category:</b>	The Great Ordovician Biodiversification Event: Insights from the Tafilalt Biota, Morocco
<b>Additional Information:</b>	
<b>Question</b>	<b>Response</b>
Are there any conflicting interests, financial or otherwise?	No
Samples used for data or illustrations in this article have been collected in a responsible manner	Confirmed

1 **Ordovician stratigraphy and benthic community replacements in the eastern Anti-Atlas,**  
2 **Morocco**

3

4 J. JAVIER ÁLVARO<sup>1\*</sup>, MOHAMMED BENHARREF<sup>2</sup>, JACQUES DESTOMBES<sup>†</sup>, JUAN  
5 CARLOS GUTIÉRREZ-MARCO<sup>1</sup>, AARON W. HUNTER<sup>3</sup>, BERTRAND LEFEBVRE<sup>4</sup>,  
6 PETER VAN ROY<sup>5</sup> & SAMUEL ZAMORA<sup>6</sup>

7

8 <sup>1</sup> *Instituto de Geociencias (CSIC-UCM), Dr. Severo Ochoa 7, 28040 Madrid, Spain*

9 <sup>2</sup> *CAP Ressources, 56 El Fourat, Résidence Sanaa, bureau 18, 20330 Casablanca, Morocco*

10 <sup>3</sup> *Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge,*  
11 *Cambridgeshire CB2 3EQ, United Kingdom*

12 <sup>4</sup> *UMR CNRS 5276 LGLTPE, Géode, Université Lyon 1, Villeurbanne Cedex, France*

13 <sup>5</sup> *Department of Geology and Soil Science, Ghent University, Krijgslaan 281 / S8, B-9000*  
14 *Ghent, Belgium*

15 <sup>6</sup> *Instituto Geológico y Minero de España, Manuel Lasala 44–9<sup>o</sup>B, 50006 Zaragoza, Spain*

16

17 **\* Corresponding author:** *jj.alvaro@csic.es*

18

19 **Abstract**

20

21 The Anti-Atlas contains a thick, volcanic-free Ordovician succession, originally deposited in a  
22 passive-margin basin. Three main sedimentary packages are bounded by major unconformities:  
23 (i) the Tremadocian–Floian Lower Fezouata and Upper Fezouata formations, which  
24 unconformably overlie a palaeorelief of Cambrian rifting volcanosedimentary complexes, and is  
25 subsequently overlain by a Dapingian paraconformable gap; (ii) the Darriwilian–Katian Tachilla  
26 Formation and First Bani and Ktaoua groups, the latter unconformably overlain by a Hirnantian  
27 glaciogenic **succession**; (iii) subsequently infilled with deposits of the Second Bani Group. Due  
28 to the scarcity of carbonate interbeds for etching analyses, leading to rare references of  
29 conodonts, the global Ordovician chart is interpolated on the basis of microphytoplankton  
30 (acritarchs and chitinozoans), regional graptolites and brachiopods. The Ordovician counter-  
31 clockwise rotation of Gondwana led its Moroccan margin from mid- to high-latitude positions,  
32 leading to the onset of a siliciclastic, wave- and storm-dominated platform. Flooding surfaces  
33 are marked by shelly silty carbonate interbeds that reflect the episodic development of  
34 echinoderm-bryozoan meadows during Katian times; in areas protected from siliciclastic input,  
35 they reached massive and bedded bioaccumulations (Khabt-el-Hajar Formation). The Hirnantian  
36 glaciation controlled the incision of numerous tunnel channels, infilled with both alluvial-to-

37 fluvial sediments and glaciomarine diamicrites. The Hirnantian palaeorelief was definitively  
38 sealed during Silurian times.

39

## 40 **Introduction**

41

42 In the Anti-Atlas Ranges of Morocco, the Ordovician rocks occupy approximately 24,000 km<sup>2</sup>  
43 of surface exposures (Fig. 1A–B) and host one of the most productive sedimentary metalliferous  
44 deposits in NW Africa (Agard *et al.* 1952; Destombes 1954, 1958, 1959, 1985a; Destombes &  
45 Jeanette 1962; Destombes 1970; Destombes *et al.* 1985; Raddi *et al.* 2011). Largely due to their  
46 economic importance, these ironstones have ceaselessly been the focus of continuing mapping  
47 programs and associated research projects.

48 About three decades ago, Destombes *et al.* (1985) summarized what was known at that  
49 time about the Ordovician stratigraphy (Moroccan Program of Geological Mapping at  
50 1/200,000 scale) and basin evolution history in the Anti-Atlas. Since then, the huge work  
51 fostered by the Moroccan Geological Survey has been progressively improved by the  
52 subsequent programs of geological mapping at 1/100,000 and 1/50,000 scales. Data acquired  
53 during the last decades have provided important information about the Ordovician fossil record  
54 and represent the basis for comparisons with neighbouring margins of Gondwana and other  
55 continents based on chronostratigraphical, biogeographical, sedimentological and sequence-  
56 stratigraphical correlations.

57 The Ordovician of the eastern Anti-Atlas contains three major gap-bounded, volcanic-  
58 free sedimentary packages: (i) the Tremadocian–Floian Lower Fezouata and Upper Fezouata  
59 formations, which unconformably overlie a palaeorelief of Cambrian rifting volcanosedimentary  
60 complexes, and is subsequently overlain by a Dapingian paraconformable gap; (ii) the  
61 Darriwilian–Katian Tachilla Formation and First Bani and Ktaoua groups, the latter  
62 unconformably overlain by a Hirnantian glaciogenic succession; and (iii) the Second Bani  
63 Group that infills the former glaciogenic palaeorelief.

64 Due to the virtual lack of igneous rocks and the scarcity of carbonate interbeds,  
65 mapping and correlation of the Ordovician have traditionally relied on lithostratigraphical  
66 comparisons along a 1,000 km-long transect from Tan-Tan (western edge of the Anti-Atlas) to  
67 Erfoud (eastern edge). It seems timely to review the stratigraphical nomenclature established  
68 over the past three decades in order to provide a convenient synthesis, from which to develop  
69 local and basin-wide correlations. We provide below an overview of the Ordovician strata from  
70 the eastern Anti-Atlas and adjacent areas. Major mappable lithostratigraphical units are  
71 reviewed and placed in a regional geodynamical and sequence context.

72

## 73 **Geological setting and tectonostratigraphical units**

74

75 The Proterozoic basement of the Anti-Atlas lies along the northern margin of the West African  
76 craton (Ennih & Liégeois 2008). The inliers of the High Atlas and the Anti-Atlas inliers are  
77 crosscut by two major fault networks, the so-called South Atlas and Anti-Atlas Major Faults  
78 (SAF and AAMF in Fig. 1B): the former crosscuts longitudinally the High Atlas, whereas the  
79 latter exemplifies a Neoproterozoic ophiolite-bearing transect, representative of the Pan-African  
80 orogenic suture (Michard *et al.* 2008). The end of the Pan-African orogeny was succeeded by  
81 the onset of a latest Ediacaran–Cambrian rift, known as the Cambrian Atlas Rift (Álvaro *et al.*  
82 2014a, b; Pouclet *et al.* 2018), which evolved during Ordovician times into a passive-margin  
83 basin.

84 Geographically speaking, the Anti-Atlas is subdivided into the western, central and  
85 eastern Anti-Atlas, the latter including the Jbel Saghro, the Jbel Ougnate and the Tafilalt district.  
86 In contrast, from a geological point of view, several works suggest distinguishing the eastern  
87 Anti-Atlas as westerly bounded by the Anti-Atlas Major Fault, as a result of which, a part of the  
88 El Graara massif (including the Bou Azzer-El Graara inlier) would be included in the eastern  
89 Anti-Atlas. In this work, we consider the eastern Anti-Atlas as including the Ordovician  
90 exposures flanking the Jbel Saghro, the Jbel Ougnate and the scattered outcrops that punctuate  
91 the Tafilalt district (1/200,000 maps of Destombes 1985b, d, 1987, 2006a; Raddi *et al.* 2006,  
92 2012; Álvaro *et al.* 2014c, d; Benharref *et al.* 2014a, b, c) (Fig. 1B–C). In the eastern Anti-  
93 Atlas, Ordovician rocks are well exposed, easily accessible, fossiliferous and relatively  
94 undisturbed by tectonism. These advantageous attributes make this region a key area for the  
95 study of the Ordovician stratigraphy and fossil record in Northwest Africa.

96

### 97 **A mid-latitude passive-margin basin**

98

99 After the end of the Pan-African Orogeny, a syn-rift megasequence comprises the Cambrian  
100 Taroudant, Tata, Feijas Internes and Tabanite groups. These volcanosedimentary complexes  
101 infilled the accommodation space generated during a ca. 55.6 m.y.-rifting episode, known as the  
102 Cambrian Atlas Rift. A network of narrow, interconnected rifting branches was episodically  
103 generated, bounded by disconnected shoulders that were locally tilted and uplifted during syn-  
104 rifting pulses.

105 The beginning of rift geodynamics is diachronous throughout the Anti-Atlas but  
106 extended across the Ediacaran–Cambrian boundary interval. During Cambrian times, the Atlas  
107 Rift recorded the onset of (half-)grabens and horsts forming a linear SSW-NNE trending belt,  
108 up to 400 km long and interrupted by a series of major en echelon extensional faults  
109 (Soulaimani *et al.* 2003; Pouclet *et al.* 2007, 2018; Álvaro & Debrenne 2010). The resulting  
110 accommodation space was controlled by extensional rift pulses that led to (i) sharp changes in

111 lithology and facies thickness; (ii) episodic deposition of conglomerates and breccias along rift  
 112 flanks; (iii) local tilting and uplift along rift shoulders associated with subaerial exposure,  
 113 development of hydrothermally induced metal ore deposits and local stratigraphic gaps; and (iv)  
 114 deposition of deeper water facies along the axes of rift branches (Álvarez & Clausen 2007, 2008;  
 115 Álvarez 2013, 2014; Álvarez *et al.* 2015). Several major unconformities punctuate the Cambrian  
 116 volcanosedimentary complexes of the Atlas Rift, marking (i) a pre-rift unconformity at the base  
 117 of the Adoudou Formation; (ii) a syn-rift unconformity marking the top of the Taguedit Bed  
 118 (Tabia Member, Adoudou Formation), which represents a sharp change from extensive fault-  
 119 controlled hydrothermal activity, carbonate production and phosphogenesis followed by sealing  
 120 of the palaeorelief by microbial carbonate-dominated platforms (Tifnout Member, Adoudou  
 121 Formation); (iii) the hiatal shell accumulations of the Brèche à Micmacca Member (Jbel  
 122 Wawrmast Formation) overlying a low-angle unconformity locally affected by karstification;  
 123 and (iv) a Furongian break-up unconformity that marks the rift/drift turnover (Álvarez 2013;  
 124 Álvarez *et al.* 2014a, b; Álvarez & Vicaïno 2018) (Fig. 2). The Azlag Formation (Tabanite Group)  
 125 marks the end of Cambrian sedimentation in the Anti-Atlas, excluding a tectonically depressed  
 126 area of the central Anti-Atlas (El Graara massif), where lies the Jbel Lmgaysmat Formation  
 127 (Tabanite Group). The latter comprises a 10 cm-thick shelly siltstone that has yielded Furongian  
 128 trilobites and brachiopods (Destombes *et al.* 1985; Destombes & Feist 1987; Álvarez *et al.*  
 129 2007a).

130 Throughout the Anti-Atlas, the Cambrian/Ordovician or Tabanite/Fezouata contact is  
 131 represented by both paraconformities and angular discordances. The Tremadocian Lower  
 132 Fezouata Formation occurs unconformably overlying either the Jbel Afraou, Bailiella, Azlag or  
 133 Jbel Lmgaysmat formations of the Tabanite Group. As a result, the erosive gap involved at this  
 134 break-up unconformity varies throughout the region from part of the Furongian to the Drumian–  
 135 Guzhangian–Furongian time span. The rift/drift unconformity is marked in the Anti-Atlas by  
 136 generalized uplift, tilting, subaerial exposure and erosion, which led to the sedimentation of the  
 137 breccias and conglomerates that characterize the lower member of the Lower Fezouata  
 138 Formation (Álvarez & Vicaïno 2018) (Fig. 2). The latter may represent a lag interval of latest  
 139 Furongian alluvial-to-fluvial deposition (Destombes *et al.* 1985; Destombes 2006b) before final  
 140 drowning of the entire Atlas Rift and the onset of the Anti-Atlas passive-margin basin.

141 The Cambrian evolution of the Atlas Rift recorded an episodic volcanism, which ranged  
 142 from rift tholeiites to subsidiary sub-alkaline and alkaline magmatism that ended during  
 143 Guzhangian times. The Atlas Rift was somewhat geodynamically connected to the Ossa-  
 144 Morena Rift, which recorded a common (although diachronous) late Ediacaran–Terreneuvian  
 145 arc-rift transition and a late Furongian rift-drift shift (Álvarez *et al.* 2014b; Pouclet *et al.* 2018).

146 During Ordovician times, a SW-NE-trending depositional trough developed in the Anti-  
 147 Atlas that experienced enhanced axial subsidence in a depocentre located close to the Zagora-

148 Fom Zguid area (central Anti-Atlas). Although the Ordovician history of the Anti-Atlas is  
 149 characterized by relative tectonic quiescence, by comparison with the Cambrian rifting history,  
 150 the Ordovician succession is punctuated by two major, laterally extensive gaps, marking a  
 151 Dapingian hiatus and a Hirnantian glaciogenic gap. The Ordovician represents over 41.2 m.y. of  
 152 continuous sedimentation, (i) regionally preceded by major episodes of tilting and shoulder  
 153 uplift of a graben-to-halfgraben framework recording the dynamic geological history from the  
 154 initial (rift-to-drift) breakup unconformity; (ii) punctuated by the Dapingian hiatus related to  
 155 non-deposition and/or erosion; and (iii) the final post-glacial Silurian sealing of an inherited  
 156 glaciogenic palaeorelief (Fig. 2).

157 Palaeomagnetic (Smith 1997; Evans 2003) and palaeoenvironmental (e.g., Destombes  
 158 1968a, b, 1981, 1987, 2006a, b; Destombes *et al.* 1985; Destombes & Willefert 1988; Ouanaimi  
 159 1998; Hamoumi 1999; Álvaro *et al.* 2000, 2004, 2014c, d, 2016a; Sutcliffe *et al.* 2001; Ghienne  
 160 *et al.* 2007a; Le Heron 2007; Le Heron *et al.* 2007, 2008; Le Heron & Craig 2008; Loi *et al.*  
 161 2010; Videt *et al.* 2010; Clerc *et al.* 2013; Benharref *et al.* 2014a, b, c; Ravier *et al.* 2014)  
 162 evidence indicates for the Anti-Atlas a counter-clockwise drift towards South Polar positions  
 163 from a latest Ediacaran–Cambrian Epoch 2 arid subtropical (10–30°) setting to a Late  
 164 Ordovician (50–70°) subpolar palaeolatitude.

165

#### 166 **Lithostratigraphical chart**

167

168 The Ordovician lithostratigraphical units erected by Destombes (1962a, 1963a, b, 1971) and  
 169 Destombes *et al.* (1985) in the vicinity of Zagora (Jbel Bani, central Anti-Atlas) are  
 170 recognisable in the Tafilalt district. Some differences are remarkable, such as the relative  
 171 thickness increase in the Middle–Upper Ordovician sandstone and quartzite interbeds, reflecting  
 172 a palaeogeographical transect from deeper (depocentre in the Zagora-Fom Zguid area) to  
 173 shallower (Ougnate and Tafilalt) settings of the passive-margin basin. Thus the Ordovician is  
 174 comparable formation-by-formation from Zagora to Erfoud. The only significant (at formation  
 175 scale) lateral facies change is the sudden increase in Katian carbonate production (Khabt-el-  
 176 Hajar Formation) recorded in the vicinity of Erfoud, by comparison with the coeval shale-  
 177 dominant Upper Ktaoua Formation (Destombes 1987; Álvaro *et al.* 2007; Jiménez-Sánchez *et*  
 178 *al.*, 2015; Villas & Colmenar, *this vol.*).

179 Four major, laterally extensive, sandstone/quartzite packages can be traced for about  
 180 400 km (Fig. 2). These are the **Darriwilian** Tachilla Formation (a major marker bed for mapping  
 181 due to its dark reddish colour), the **Darriwilian-Sandbian** First Bani **Group** (subdivided in the  
 182 central Anti-Atlas into five formations), the Upper Tiouririne Formation and the Amouktir  
 183 Member (Upper Formation of the Second Bani Group). Between them, shale-dominated  
 184 landscapes form the plains and jbel flanks of the Anti-Atlas orography. The absence of



185 Ordovician fan-shaped aprons and megadebris-flow deposits in the Anti-Atlas led to the  
 186 identification of its exposures as representative of a marine platform with no significant break  
 187 slopes and slope-related deposits, which are incompletely recognized in the High Atlas  
 188 (Destombes *et al.* 1985; Ouanaimi *et al.* 2006).

189

190 *Feijas Externes Group* (Choubert & Termier 1947)

191

192 In the Anti-Atlas, a shale-dominated unit is sandwiched between the weathering-resistant,  
 193 sandstone/quartzite packages of the Cambrian Tabanite and Middle–Ordovician First Bani  
 194 groups. The Feijas Externes Group forms the plains and flanks of jbel between Akka and Alnif,  
 195 and mainly consists of monotonous shales with sandy intercalations exhibiting locally  
 196 glauconitic and ironstone interbeds. The total thickness ranges from a few tens of metres in the  
 197 northern Jbel Ougnate to about 1100 m in the Zagora-Foum Zguid depocentre. Destombes  
 198 (1962a, b, 1963a, b, 1971) and Destombes *et al.* (1985) subdivided the group into four units,  
 199 named Lower Fezouata and Upper Fezouata (grouped in a single formation by Gutiérrez Marco  
 200 & Martín 2016 and Martín *et al.* 2016a, b in the depocentre, **due to their homogeneous**  
 201 **lithological features**, but still used as distinct mappable formations in the geological maps of the  
 202 Tafilalt district by Álvaro *et al.* 2014c, d and Benharref *et al.* 2014a, b, c), Zini (recognized in  
 203 the surroundings of Zagora and in the vicinity of its homonymous jbel, southwestern Anti-  
 204 Atlas) and Tachilla formations.

205

206 *Lower Fezouata Formation.* This unit is a shale-dominated succession, blue-green in colour,  
 207 with sandy and glauconitic interbeds in its upper part. As stated above, it unconformably  
 208 overlies either the Jbel Afraou, Bailiella, Azlag or Jbel Lmgaysmat formations, and ranges in  
 209 thickness from zero (Jbels Tachilla and Ouarzemine in the northwestern Anti-Atlas, and  
 210 northern Saghro, Maïder and northern Jbel Ougnate in the eastern Anti-Atlas) to 400 m (Zagora-  
 211 Foum Zguid depocentre). The base of the formation comprises lag deposits (marking a  
 212 transgressive surface), rich in ferruginous breccia, conglomerate and sandstone, broadly up to 1  
 213 m thick throughout the Anti-Atlas. In the vicinity of Foum Zguid, this unit can reach 10 m of  
 214 thickness and has been mapped as an informal lower member (Destombes 1985c; Destombes &  
 215 Feist 1987) representing the incision of alluvial-to-fluvial sedimentary systems (Álvaro &  
 216 Vizcaïno 2018).

217

218 In the Jbel Ougnate and the Tafilalt district, the Lower Fezouata Formation  
 219 unconformably overlies the Azlag Formation (Destombes 1960a, b). Its contact is both  
 220 paraconformable and discordant, the latter representing onlapping geometries of Ordovician  
 221 shales sealing an inherited palaeorelief topped by Cambrian quartzites (Tazoult n'Ouzina and  
 Jbel Zorg; Álvaro *et al.* 2014c). Throughout the Tafilalt district, two members can be

222 distinguished in the Lower Fezouata Formation, from bottom to top: (i) a set of conglomerates  
223 and sandstones, up to 1 m thick in Tazoult n'Ouzina; and (ii) a monotonous shaly succession, up  
224 to 400 m thick, locally glauconitic and comprising centimetre-to-decimetre sandstone interbeds.

225

226 *Upper Fezouata Formation.* The formation is subdivided into two members: (i) a  
227 cartographically significant greenish package, approximately 20 m thick, composed of  
228 glauconitic and ferruginous conglomerates and sandstones rich in glauconitic peloids, iron-rich  
229 ooids and hematite cement (Fig. 3A–B), and broadly cropping out in the southern Jbel Saghro,  
230 southern Maider and Tafilalt district; and (ii) a package of variegated alternations of shales and  
231 sandstones, 300–400 m thick (Destombes *et al.* 1985). The formation either conformably  
232 overlies the Lower Fezouata Formation (e.g., in the Tafilalt district) or unconformably overlies  
233 the Jbel Afraou and Bailiella formations (e.g., in the northern Jbel Ougnat; Destombes 1962b;  
234 Destombes *et al.* 1985; Choukri *et al.* 2004; Choukri & Hamoumi 2005). Both the Lower  
235 Fezouata and Upper Fezouata formations are absent in the southwestern area of the Anti-Atlas  
236 (Jbels Tachilla and Ouarzemine; Fig. 2), and the latter reaches a thickness maximum (600–700  
237 m) along the Akka-Tata transect.

238

239 *Tachilla Formation.* This unit, up to 1200 m thick in the Jbels Tachilla and Ouarzemine (south  
240 of Agadir), is a key cartographic marker throughout the Ordovician of the Anti-Atlas. It consists  
241 of ochre-to-blackish, ooidal sandstones rich in iron oxyhydroxides (Fig. 3C–D) with subsidiary  
242 green shale interbeds bearing centimetre-thick carbonate nodules. The base of the formation is  
243 represented by an erosive paraconformity, whereas its top is conformable. In the Jbels Tachilla  
244 and Ouarzemine, the Tachilla Formation is paraconformably overlying the Tabanite Group. In  
245 the eastern Anti-Atlas, the formation ranges from 20 m in the northern Tafilalt to 200 m in the  
246 southern Maider district and the Jbel Ougnat.

247

248 *First Bani Group* ('Bani Quartzites' by Choubert & Termier 1947; 'Quartzites of First Bani' by  
249 Choubert 1952)

250

251 The group forms the most extensive Ordovician sandstone package throughout the Anti-Atlas  
252 and accounts for the main relief of the 450 km-long Jbel Bani. It consists of an alternation of  
253 variegated sandstones and shales, with common iron ooidal interbeds in its lower part. The  
254 Tachilla/First Bani transition is gradual and marked by a progressive enrichment in the  
255 sandstone/shale ratio, whereas the top of the group is sharp and marked by the abrupt  
256 occurrence of decametre-thick shales. The formation exhibits a gradual increase in thickness  
257 from the northern Tafilalt district to the Zagora-Foum Zguid depocentre, ranging from 15 to 700  
258 m (Destombes 1987, 2006a, b). Although this group was originally subdivided in the central

259 Anti-Atlas into five formations (Destombes *et al.* 1985), its lithostratigraphical subdivision  
 260 becomes ambiguous northeasternward. Destombes (1985b, 1987, 2006a, b) described it as a  
 261 single unit in the 1/200,000 Tafilalt-Taouz sheet and the eastern margin of the 1/200,000  
 262 Todhra-Ma' der sheet maps. Álvaro *et al.* (2014c) and Benharref *et al.* (2014c) have subdivided  
 263 the group, in the Tafilalt district, into the Taddrist, Guezzart, Bou-Zeroual, Ouine-Inirne and  
 264 Izegguirene formations based on the sandstone/shale ratio characterized by the presence/absence  
 265 of distinct sedimentary structures.

266

267 *Ktaoua Group* (Choubert 1952)

268

269 The **toponymy** originally referred to the shaly plains and jbel flanks cropping out in the  
 270 surroundings of Tagounite, central Anti-Atlas. It is sandwiched between the weathering-  
 271 resistant sandstone-quartzite packages of the First and Second Bani groups. After several  
 272 subdivisions, Destombes (1971) and Destombes *et al.* (1985) finally subdivided the group into  
 273 three formations highlighting the presence of an intermediate sandstone-dominant package  
 274 (Upper Tiouririne Formation) separating two shale-dominant units (Lower Ktaoua and Upper  
 275 Ktaoua formations). Destombes *et al.* (1985) suggested a lateral change of the Upper Tiouririne  
 276 Formation, to the east of Erfoud, into the 'Khabt-el-Hajar bryozoan limestones', which are  
 277 distinguished below as a separate formation. The total thickness of the group attains its  
 278 maximum close to the Ktaoua plain, with about 350 to 400 m.

279

280 *Lower Ktaoua Formation.* This unit is a shale-dominated succession with subsidiary sandstone  
 281 interbeds and carbonate nodules and concretions parallel to stratification (Fig. 4A). In the  
 282 Zagora-Foum Zguid depocentre, the base is marked by the occurrence of conglomeratic  
 283 sandstones rich in ferruginous ooids. The members distinguished by Destombes *et al.* (1985) in  
 284 the type area cannot be followed northeasternwards. In the Tafilalt district, Destombes (1987)  
 285 distinguished three members, in ascending order: (i) the shale-dominated Jbel Bou-Isidane  
 286 Member, (ii) the shale/sandstone alternations of the Jbel Tiberguent Member (Fig. 4B), and (iii)  
 287 the heterolithic (sandstone-dominant) Jbel Tafersikt Member. However, the **latter** was  
 288 exclusively recognized on jbel summits and, in some cases, will be reported below as the Alnif  
 289 Member (Upper Formation of the Second Bani Group). A minor sandstone-dominant member,  
 290 known as the "Middle Tiouririne sandstones" has been used in some maps of the depocentre due  
 291 to its characteristic fossil content. Only the Jbel Bou-Isidane and Jbel Tiberguent members,  
 292 reported as (informal) lower and upper subunits were mapped in the 1/50,000 maps of the  
 293 Tafilalt district (Álvaro *et al.* 2014c, d; Benharref *et al.* 2014a, b, c).

294

295 *Upper Tiouririne Formation*. The presence of significant sandstone-dominated packages  
296 marking the middle part of the Ktaoua Group is not clear in the Ktaoua plain and westwards. In  
297 contrast, it is distinguishable in the Maider and Tafilalt districts and, to the west of Tagounite,  
298 these sandstone packages served to Destombes (1985) to define the Rouïd Aïssa Formation.  
299 There, this mappable sedimentary package is represented by a thick succession (150–300 m) of  
300 sandstone beds and interbedded shales, calcareous siltites and carbonate nodules parallel to  
301 stratification. Due to changes in the sandstone/shale ratio from Zagora to Tafilalt, the base is not  
302 clearly distinguished northeasternwards. In the vicinity of Alnif, Álvaro *et al.* (2007b) suggested  
303 the presence of a phosphatic limestone infested with the brachiopod *Rafinesquina pomoides* to  
304 mark the base of the formation (Fig. 4C). This horizon can be followed in the Tafilalt district,  
305 where the formation contains common cobble- to pebble-sized conglomeratic intervals rich in  
306 shelly accumulations (Fig. 4D–G); its top is characterized by the presence of sandstone  
307 packages with sigmoidal cross-stratified sets, episodically encrusted by ooidal hardgrounds rich  
308 in iron oxyhydroxides (e.g., summit of Jbel Adrar; Álvaro *et al.* 2014b; Colmenar & Álvaro  
309 2015: fig. 5a–b).

310  
311 *Upper Ktaoua Formation*. This unit is incompletely preserved in the Tafilalt district due to its  
312 upper erosive contact with the Second Bani Group. Where present, it can reach up to 80 m of  
313 thickness and consists of monotonous shales episodically punctuated by decimetre-thick,  
314 orthoceratid-rich calcareous siltstones (Fig. 4H) and sandstones, and scattered centimetre-thick  
315 carbonate and phosphatic nodules, parallel to stratification and rich in orthoconic nautiloids.  
316 One marker bed is recognizable close to the top of the formation, the so-called “Ouzregui bed”,  
317 whose name is derived from the abundance of the trilobite species *Flexicalymene ouzregui*.

318  
319 *Khabt-el-Hajar Formation*. To the North-East of Erfoud, some limestone/shale alternations  
320 (Fig. 5A), informally named ‘Bryozoan Limestones’ and up to 40 m thick, were reported by  
321 Termier & Termier (1950a, b) and Destombes (1962a). They were mapped and formally erected  
322 by Destombes *et al.* (1985) as the Khabt-el-Hajar Formation. Several logs were reported by  
323 Destombes (2006a) illustrating the presence of some angular discordances and ‘ravinement  
324 surfaces’ representing, in fact, erosive surfaces (one of them marking the base of the formation)  
325 and onlapping geometries of bryozoan- and echinoderm-rich limestone lenses (Fig. 5B–C). The  
326 top of the formation is marked, in its northeasternmost outcrop (Destombes 2006a), by a barren  
327 ironstone interval, 3 m thick, which may represent either the Second Bani Group or a Silurian  
328 basal lag. Geometrically, the Khabt-el-Hajar Formation unconformably overlies a sandstone  
329 package assigned to the Upper Tiouririne Formation by Destombes (2006a), and is  
330 unconformably overlain by the above-reported, condensed ironstone level, which is  
331 subsequently onlapped by Silurian shales (Destombes 1987, 2006a).

332

333 *Second Bani Group* ('Sandstones of the Second Bani' by Choubert & Termier 1947;

334 'Sandstones of the Second Bani or Beni Selmane' by Choubert 1952)

335

336 Although originally erected in the vicinity of Zagora, where a Lower Formation was  
 337 distinguished, the Second Bani Group is only represented in the eastern Anti-Atlas by its upper  
 338 formation (Destombes *et al.* 1985).

339

340 *Lower Formation.* In the Zagora-Foum Zguid depocentre, the heterolithic Lower Formation, up  
 341 to 120 m thick, consists of conglomerates, sandstones and shales commonly separated by  
 342 scouring surfaces. According to Destombes *et al.* (1985), its base is conformable and located at  
 343 the occurrence of ooidal limestone nodules and centimetre-thick layers, whereas its top is  
 344 marked by the glaciogenic unconformity that marks the base of the Upper Formation (Loi *et al.*  
 345 2010).

346

347 *Upper Formation.* This formation was formally subdivided close to Alnif by Villas *et al.* (2006)  
 348 and Álvaro *et al.* (2007b). Its three-fold subdivision (Alnif, Tamekhardt and Amouktir members)  
 349 has been followed in the 1/50,000 geological sheets of the Tafilalt district (Álvaro *et al.* 2014c,  
 350 d).

351 Several apparently diachronous unconformities had been traditionally recognized at the  
 352 top of some jbel of the Ktaoua Group marking the base of variegated conglomerates.

353 According to their scouring position, these conglomerates received different lithostratigraphical  
 354 names, such as 'Conglomérat d'Alnif' or 'Conglomérat d'Amessoui' (incising the Lower  
 355 Ktaoua Formation in the vicinity of the eponymous village and jbel, respectively; Destombes  
 356 1985b, c, d, 2006b; Hamoumi 1999; Choukri *et al.* 2004); 'Conglomérat d'Imzizoui' (incising  
 357 the Upper Tiouririne Formation at the homonymous jbel; Destombes 2006a, b; El Maazouz &  
 358 Hamoumi 2007); some conglomeratic beds forming the top of the Jbel Tafersikt Member  
 359 (Lower Ktaoua Formation; Destombes 2006a), and the 'Argiles microconglomératiques'  
 360 (Destombes *et al.* 1985) or glaciomarine diamictites (Villas *et al.* 2006). All these apparently  
 361 diachronous unconformities represent indeed one single glaciogenic erosive unconformity that  
 362 can be laterally correlated. After mapping in detail this unconformity and its stratigraphical  
 363 contacts, the overlying Upper Formation (Second Bani Group) is clearly recognizable, on the  
 364 basis of its deeply erosive lower boundary and the distinct glaciogenic features of its lower part  
 365 (Álvaro *et al.* 2007b, 2014c, d; Benharref *et al.* 2014a, b, c).

366 The Alnif Member of the eastern Anti-Atlas represents a discontinuous unit, which  
 367 comprises the Alnif Conglomerate *sensu* Destombes (1985b), up to 80 m thick, conformably  
 368 overlain by an upper package of lenticular sandstones, up to 10 m thick (Fig. 5D–G). The Alnif

369 Member is overlain by a claystone-dominant diamictite, named ‘argiles microconglomératiques’  
 370 by Destombes *et al.* (1985) owing to the presence of scattered quartz granules and pebbles  
 371 ‘floating’ in a clayey matrix (Fig. 5H), and Tamekhtart Member by Villas *et al.* (2006); its  
 372 thickness is highly variable (up to 100 m) and influenced by the bedrock palaeorelief inherited  
 373 from the aforementioned erosive unconformity. Finally, the uppermost Amouktir Member, 30–  
 374 60 m thick, is a stratigraphical unit resistant to weathering, composed of sandstone/shale  
 375 alternations that pass upward into conglomerates (Fig. 5I), and ends at the occurrence of  
 376 Silurian graptolite-bearing black shales.

377

### 378 **Biostratigraphical scale**

379

380 The global chronostratigraphical subdivisions defined by the *International Subcommission on*  
 381 *Ordovician Stratigraphy* (ISOS) are mainly based on the first occurrence datum (FAD) of  
 382 particular species of graptolites and conodonts. Due to the unsuitable environments for the **life**  
 383 **and** preservation of key graptolites and the scarcity of carbonate interbeds for **dissolution to**  
 384 **yield conodont elements**, leading to rare references of Ordovician conodonts in the Anti-Atlas  
 385 (El Bourkhissi & Sarmiento 1997; Lehnert *et al.* 2016), the global chronostratigraphy of the  
 386 Ordovician chart erected by the ISOS is interpolated in the Anti-Atlas on the basis of (i)  
 387 microphytoplankton (acritarchs and chitinozoans; Elaouad-Debbaj 1984a, b, 1986, 1988a, b;  
 388 Soufiane & Achab 1993; Paris 1990, 1996, 1999; Paris *et al.* 1995, 1999, 2007; Bourahrouh *et*  
 389 *al.* 2004; Nowak *et al.* 2016; Tessitore 2016; Lefebvre *et al.* 2018), graptolites (Gutiérrez-Marco  
 390 *et al.* 2003, Gutiérrez-Marco & Martin 2016; Lefebvre *et al.* 2018), brachiopods (Havlíček  
 391 1970, 1971; Villas *et al.* 2006; Colmenar & Álvaro 2015) and, in its Katian part, by bryozoans  
 392 (Jiménez-Sánchez *et al.* 2015a, b, 2016). The finest Ordovician zonation of the **N African-SW**  
 393 **European margin of** Gondwana, based on chitinozoans, includes 26 biozones with an average  
 394 duration close to 2 m.y. per zone. This biozonation can be tentatively correlated to the South  
 395 Polar regional scale erected for the Ordovician, which includes several stages defined in  
 396 Bohemia and Iberia (Gutiérrez-Marco *et al.* 2015, 2017b) (Fig. 6).

397

### 398 *Tremadocian–Floian*

399

400 The Lower Fezouata and Upper Fezouata formations are highly fossiliferous and have yielded  
 401 acritarchs (Deunff 1968a, b), graptolites (Destombes & Willefert 1959), trilobites (Choubert *et*  
 402 *al.* 1955; Destombes 1985b, c, d; Destombes *et al.* 1985) and echinoderms (Ubaghs 1963;  
 403 Lefebvre & Fatka 2003). The scarcity of conodonts precluded any direct correlation with global  
 404 Tremadocian horizons, but the presence of acritarchs and the graptolite *Rhabdinopora*  
 405 *flabelliformis* has traditionally allowed the identification of the Tremadocian in the Anti-Atlas.

406 Destombes *et al.* (1985) and Destombes (2006a, b) reported an assemblage of  
 407 graptolites sampled in the Upper Fezouata Formation cropping out in the Jbel Bou Legroun  
 408 (NW Rissani), Taklimt, Aroudane and Zorg. Subsequently, based on graptolites, Gutiérrez-  
 409 Marco & Martin (2016) recognized throughout the central and eastern Anti-Atlas the  
 410 *Anisograptus matanensis*–*Rhabdinopora flabelliformis anglica*, ‘*Adelograptus*’ *tenellus*,  
 411 *Aorograptus victoriae*, *Araneograptus murrayi*, *Hunnegraptus copiosus*, ?*Cymatograptus*  
 412 *protobalticus*, ?*Baltograptus jacksoni* and *Baltograptus minutus* zones plus the ‘*Azygograptus*  
 413 *interval*’, the succession of which represents the Tremadocian (Tr2–Tr3) and Floian (Fl1–Fl3)  
 414 stage slices of Bergström *et al.* (2009). According to these authors, the base of the Lower  
 415 Fezouata Formation does not coincide with the base of the Tremadocian, despite earlier studies  
 416 reporting a Cambrian–Ordovician boundary age (Destombes 1971).

417 Recently, some strata of the Fezouata Konservat-Lagerstätte in the Tizig Zaouine  
 418 section (north of Zagora) and the Adrar-Zouggar borehole (about 3 km SW of Zagora) have  
 419 yielded a Tremadocian (Tr3 stage slice of Bergström *et al.* 2009) age, including the  
 420 *messaoudensis*–*trifidum* acritarch assemblage of the upper Tremadocian–lower Floian (Cooper  
 421 *et al.* 1995; Servais & Molyneux 1997), and the *paschaensis*–*symmetrica* and *brevis*  
 422 chitinozoan-based zones (Nowak *et al.* 2015, 2016). Based on conodonts, Lehnert *et al.* (2016)  
 423 recognized the Tremadocian (Tr3 stage slice) *Paraoistodus proteus* and the Floian (Fl1 slice)  
 424 *Prioniodus oepiki* zones. A recent biostratigraphical reappraisal for the oldest Fezouata Biota by  
 425 Lefebvre *et al.* (2018) clearly confirms the late Tremadocian age of the Lagerstätte strata, being  
 426 mainly correlated with the *Paraoistodus proteus* biozone of conodonts, and with the 1–2 sub-  
 427 assemblage of the *messaoudensis*–*trifidum* acritarch assemblage.

428

429 *Darriwilian*

430

431 Destombes *et al.* (1985) initially proposed four trilobite, two brachiopod and one echinoderm-  
 432 based zones for the Tachilla Formation and the First Bani Group, which were subsequently  
 433 assigned to the Fennian (*pars*), Oretanian and Drobotivian stages of the Mediterranean Province  
 434 by Gutiérrez-Marco *et al.* (2003, 2017b). The regional stages represent the global Darriwilian  
 435 Stage. These authors tentatively located the Middle–Upper Ordovician boundary below the  
 436 FAD of the trilobite *Marrolithus cf. bureaui* Oehlert, about 20 m above the base of the  
 437 Izegguirene Formation of the First Bani Group.

438 The chitinozoan *clavata (pars)*, *pissotensis* and *ponceti* zones have been recognized in  
 439 the First Bani Group (Paris 1990), ranging as a whole from the early late Darriwilian to the  
 440 earliest Sandbian (less than 3 m.y.; Videt *et al.* 2010).

441

442 *Sandbian–Katian*

443

444 In the central Anti-Atlas, the *deunffi* and *dalbyensis* chitinozoan zones were reported by  
 445 Elaouad-Debbaj (1986) in the Assif bou Zeggarh Member of the Lower Ktaoua Formation,  
 446 whereas, in the Amouguer Member of the same formation, the author recognized the  
 447 *fistulosa/barbata* zones. As a result, the Lower Ktaoua Formation ranges in age from the early  
 448 Sandbian to the mid Katian. The Upper Tiouririne Formation has yielded chitinozoans  
 449 (Bourahrouh *et al.* 2004) of the *fistulosa/barbata* and *nigerica (pars)* zones, pointing to a mid-  
 450 early late Katian age. The overlying Upper Ktaoua Formation has been assigned, based on  
 451 chitinozoans, to the *nigerica (pars)* Zone (Elaouad-Debbaj 1984a; Destombes *et al.* 1985; Paris  
 452 1990; Samuelsson *et al.* 2001; Bourahrouh *et al.* 2004), and correlated with the well J1-81A of  
 453 NE **Lybia** (Molyneux & Paris 1985; Paris 1988).

454 In the vicinity of Alnif and in Tizi-n'Rsas (Al Atrous sheet, Tafilalt district), some  
 455 calcareous siltstones marking the Lower Ktaoua/Upper Tiouririne transition are rich in  
 456 brachiopods, which have allowed recognition of the *Tafilaltia destombesi*, *Drabovinella*,  
 457 *Svobodaina feisti* and *Heterorthis alternata* brachiopod biostratigraphically significant  
 458 associations (Villas *et al.* 2006; Álvaro *et al.* 2007b; Colmenar & Álvaro 2015).

459 Regarding the bryozoan-rich Khabt-el-Hajar Formation, Havlíček (1970, 1971),  
 460 Termier & Termier (1970), Destombes (1985c, 2006a, b) and Le Menn & Spjeldnaes (1986)  
 461 reported the presence of endemic trilobites, brachiopods and echinoderms, associated with  
 462 undetermined conulariids, nautiloids, gastropods and bivalves. The **authors** claimed that the  
 463 presence of some Telychian graptolites in marlstone interbeds, reported in older papers, should  
 464 be ruled out. In addition, the record of the upper Katian brachiopods *Paucicrura catalanica*,  
 465 *Drabovia* sp. and *Streptis?* sp. (Jiménez-Sánchez *et al.* 2015a; Villas & Colmenar this vol.), as  
 466 well as of some **biostratigraphically significant** trilobites (such as *Brongniartella platynota*  
 467 *marocana*, *Mucronaspis termieri*) and bryozoan species in the formation, have recently  
 468 constrained the duration of episodes of carbonate productivity. Fenestrates (e.g., *Enallopora*  
 469 *lineata*), cryptostomates (e.g., *Graptodictya meneghinii*, *Ptilodictya exilis*, *Stellatodictya*  
 470 *valentinae* and *Ulrichostylus radiatus*) and trepostomates (e.g., *Anaphragma mirabile*,  
 471 *Cyphotrypa magna*, *Dekayia minima*, *Diplotrypa languedociana*, *Homotrypa miqueli*,  
 472 *Monotrypa jewensis*, *Prasopora falesi* and *Trematopora sardoa*) of the Khabt-el-Hajar  
 473 Formation, also occur in the Glauzy and Gabian formations of the Montagne Noire, the  
 474 Maciurru and Punta S'Argiola Members of the Domusnovas Formation and the units *c* and *e* of  
 475 Sardinia, the La Peña Member (Cystoid Limestone **Formation**) of the Iberian Chains, and the  
 476 Uggwa Formation of the Carnic Alps. Outside the Mediterranean margin, some of these species  
 477 also occur in the Jövi and Oandu stages (D<sub>I-III</sub>) and the Kegel Limestone of Estonia, the horizons  
 478 B<sub>I</sub> and B<sub>II</sub> of the Volkhov and horizons B<sub>I</sub> to B<sub>III</sub> of the Lynna Formation in the Leningrad  
 479 region (Russia); and in the Richmondian and Mohawkian Series of USA. This biostratigraphic



480 control and that provided by the Kralodvorian brachiopod and trilobite species listed above  
 481 allowed Havlíček (1970, 1971), Destombes (1985c, 2006a, b), Jiménez-Sánchez *et al.* (2015a,  
 482 b, 2016) and Villas & Colmenar (this vol.) to date the Khabt-el-Hajar Formation as late Katian.

483

484 *Hirnantian*

485

486 The Jbel Bou Ingarf section of east Zagora provides a complete Late Ordovician chitinozoan  
 487 succession (Elaouad-Debbaj 1987; Paris *et al.* 1995) of the Katian–Hirnantian boundary interval  
 488 and the Hirnantian. Some taxa, such as *Armoricochitina nigerica*, *Calpichitina lenticularis*,  
 489 *Jenkinochitina lepta*, *Lagenochitina prussica* and *Ancyrochitina longispira*, occur both in the  
 490 Upper Ktaoua and the Lower Second Bani formations, whereas other taxa (such as  
 491 *Ancyrochitina merga*, *Plectochitina sylvanica*, *Spilachitina debbajae*) are restricted to the Upper  
 492 Ktaoua Formation. The latter assemblage is characteristic of the *merga* Zone (Paris 1990).

493 Based on the presence of **an indeterminate species** of the brachiopod genus *Hirnantia* in the  
 494 Lower Formation (Second Bani Group) of **the laterally equivalent Aït Issioul section, West of**  
 495 **Tagounite**, Destombes (1985c, 2006b), Destombes *et al.* (1985), Loi *et al.* (2010) and Videt *et*  
 496 *al.* (2010) placed **tentatively** the Katian–Hirnantian boundary within this formation. **However,**  
 497 **Colmenar *et al.* (this vol.) has noted the presence of late Katian trilobites in the lower part of**  
 498 **this formation at the Aït issoul section, some metres below an undoubtely Hirnantian**  
 499 **brachiopod assemblage.**

500 The Tamekhtart and Amouktir members of the Upper Formation have yielded *A.*  
 501 *nigerica*, *C. lenticularis*, *Spinachitina cf. fragilis* and *Tanuchitina elongata* (Elouad-Debbaj  
 502 1984), which Paris *et al.* (1995) referred to the *elongata* Zone. In addition, the *Eostropheodonta*  
 503 *jebiletensis* brachiopod association has been reported in the Amouktir Member, which  
 504 represents the *Aphanomena (=Eostropheodonta)-Hirnantia* Community (Rong 1986; Wang *et*  
 505 *al.* 1987; Colmenar & Álvaro 2005).

506

### 507 **Control of sequence framework on the replacement of benthic communities**

508

509 The Ordovician of the Anti-Atlas comprises the sedimentation of a siliciclastic-dominant  
 510 platform with subsidiary episodes of reefal-free carbonate productivity. The distal slope-apron  
 511 and deep basinal deposits of this platform are absent in the Anti-Atlas, and may be placed  
 512 throughout the northern High Atlas and Coastal meseta outcrops. The Ordovician exhibits the  
 513 superposition of several orders of sea-level fluctuations. Changes in the rate of subsidence,  
 514 driven by thermal cooling, global eustatism, sediment loading and/or local tilting were probably  
 515 responsible for sequence and cyclic sedimentation. Tilting led to the record of low-angle  
 516 discordances and onlapping features, which change laterally into paraconformities over larger

517 areas. The recorded sequence stratigraphic architecture exerted a primary control on the fossil  
 518 record, mainly as a result of the onset of sharp environmental changes on flooding surfaces and  
 519 the erosive role played by scouring surfaces capped by shoaling complexes.

520 In the Zagora-Foum Zguid depocentre, six Tremadocian–Floian third-order sequences  
 521 were recognized by Loi *et al.* (2010) and Videt *et al.* (2010) (O1 to O6 in Fig. 7). Although a  
 522 direct correlation of these six sequences with other Ordovician sequence frameworks is not  
 523 available (for comparison, see e.g., Ross & Ross 1992, 1995 for Laurentia; Nielsen 2004 for  
 524 Baltica; Ghienne *et al.* 2007b for the Ougarta Range of Algeria; Videt *et al.* 2010 for the  
 525 Armorican Massif), some of them can be identified in the Anti-Atlas, such as the *Ceratopyge*  
 526 Regressive Event of Baltica (*tenellus* graptolite Zone), identified in the Anti-Atlas by the O2  
 527 sequence boundary. In the Tafilalt district, the Lower Fezouata/Upper Fezouata contact is well  
 528 marked by the abundance of glauconitic ironstones, separating two successions of four-order  
 529 shoaling-upward parasequences (O6 in Fig. 7) in a wave-dominant tide-modulated platform  
 530 with predominance of offshore clayey substrates (Álvarez *et al.* 2014c, d; Vaucher *et al.* 2017;  
 531 Saleh *et al.* 2018). About 200 taxa have been reported from these two formations, mainly  
 532 controlled by the exceptional preservation conditions of the Fezouata Biota (Gaines *et al.* 2012;  
 533 Lefebvre *et al.* 2016a, b, 2018; see list in Annex 1), the taphonomic conditions of which were  
 534 virtually controlled by external climatic forcing (Saleh *et al.* 2019). The most representative  
 535 benthic communities include non-reefal algae, bryozoans, cnidarians, echinoderms (Crinoidea,  
 536 Diploporita, Edrioasteroidea, Eocrinoidea, Rhombifera, Soluta, Somasteroidea and Stylophora)  
 537 and sponges, which are associated with brachiopods, molluscs (bivalves, rostroconchs,  
 538 paragastropods, gastropods and tergomyans), hyoliths, annelids, cycloneuralia, lobopodians,  
 539 arthropods (agnostoids, radiodonts, trilobites and other euarthropods) and problematica.

540 The Dapingian gap is marked by the absence of representative fossils in the Anti-Atlas.  
 541 This paraconformity is sealed by the Darriwilian–Sandbian–Katian First Bani and Ktaoua  
 542 groups. In some areas of the Anti-Atlas, such as in the Tachilla and Ouarzemine jbelles of the  
 543 western Anti-Atlas, the Darriwilian sedimentation occurs directly sealing an inherited  
 544 palaeorelief formed by Miaolingian strata; the corresponding Miaolingian–Dapingian gap  
 545 should be associated with a Dapingian event responsible of uplift, tilting and erosion (Fig. 2).  
 546 Although no geodynamic explanation has yet been advanced for this gap, a possible distal  
 547 influence of the Mid–Late Ordovician Sardic Phase may be recorded in this margin of  
 548 Gondwana. The Sardic Phase has been reported in the eastern branch of the Variscan Ibero-  
 549 Armorican Arc (Sardinia, Pyrenees, Montagne Noire and Mouthoumet massif of Occitan  
 550 Domain in South France, and Briançonnais in the Alps), but is virtually absent in the western  
 551 branch or Iberian Massif (e.g., Stampfli *et al.* 2002; Casas 2010; Oggiano *et al.* 2010; Minzoni  
 552 2011; Zubriggen 2015; Álvarez *et al.* 2016b).

553 The Darriwilian–Katian sedimentary package of the Anti-Atlas comprises the  
 554 conformable Tachilla Formation and the First Bani and Ktaoua groups, which represent seven  
 555 (O8 to O15 in Fig. 7) third-order sequences. They consist of interfingering sandstone- and  
 556 shale-dominant rock packages, subdivisible into four-order parasequences dominated by  
 557 shallowing-upward trends from deeper water (offshore) sediments shoaling, through  
 558 aggradation and progradation, to shoreface/foreshore deposits. Some tops show evidence of  
 559 fluvial point-bar migration and subaerial exposure and widespread precipitation of hematite  
 560 crusts (Colmenar & Álvaro 2015). Carbonate production was not laterally persistent in the  
 561 eastern Anti-Atlas (Álvaro *et al.* 2007b; El Maazouz & Hamoumi 2007), except in an area  
 562 protected from persistent siliciclastic input. To the north of Erfoud, the Khabt-el-Hajar  
 563 Formation consists of two successive marlstone-limestone units shallowing upward into mixed  
 564 siliciclastic-limestone packages (Destombes *et al.* 1985).

565 Most of the sandstone/shale alternations and sandstone packages reported in the  
 566 Tachilla Formation and the First Bani and Ktaoua groups form coarsening-upwards  
 567 parasequences indicative of shoaling and/or upwards increase in energy level. They reflect the  
 568 interplay and feedback between (i) changes in third-order accommodation potential, (ii) episodic  
 569 progradation of terrigenous wedges, and (iii) distal production of temperate-water (bryonoderm)  
 570 carbonate shelly factories rich in trepostomate and fenestrate bryozoans. The carbonate  
 571 production during the HST was less resilient to terrigenous poisoning and was susceptible to  
 572 localized nucleation of bryozoan–pelmatozoan meadows and thickets. Nearly all the silty and  
 573 skeletal limestones that occur as decimetre-scale interbeds are inferred to represent stacking of  
 574 mineralized hardgrounds and increased content of reworked phosphate nodules and crusts,  
 575 indicating increased sediment starvation.

576 Darriwilian–Katian benthic communities comprise arthropods (aglaspidid and  
 577 chelionellid euarthropods, ostracods and trilobites), brachiopods, echinoderms (Asteroidea,  
 578 Coronata, Crinoidea, Diploporita, Edrioasteroidea, Eocrinoidea, Ophiuroidea, Rhombifera,  
 579 Soluta and Stylophora), hyoliths, molluscs (bivalves, gastropods, rostroconchs and tergomyans),  
 580 conulariids, paleoscolecidans, cornulitids, paropsonemid eldonioids, machaeridians and  
 581 agglutinated problematic tubes (see list in Annex 1). Colmenar & Álvaro (2015) recognized in  
 582 the Katian of the Tafilalt district, four types of brachiopod-dominant shell accumulations: (i) lag  
 583 concentrations, interpreted as indicators of erosive surfaces; (ii) event concentrations  
 584 representing either single or amalgamation of multiple reworking pulses; (iii) hydraulic simple  
 585 and composite concentrations marking the top of shoal complexes; and (iv) hiatal or condensed  
 586 concentrations on maximum flooding surfaces.

587 As stated above, major flooding surfaces reflect the episodic development of  
 588 echinoderm-bryozoan meadows in outer-platform settings. In the eastern Atlas Basin, some  
 589 bryozoan thickets flourished locally on Katian silty carbonates of the Ktaoua Group (Álvaro *et*

590 *al.* 2007b, 2014a, b; Benharref *et al.* 2014a, b, c). The onset of echinoderm-bryozoan meadows  
 591 and mud-mounds had been previously reported in Libya (Buttler & Massa 1996; Buttler *et al.*  
 592 2007), the Iberian Peninsula (Vennin *et al.* 1998; Jiménez-Sánchez 2009, 2010; Jiménez-  
 593 Sánchez & Villas 2010; Jiménez-Sánchez *et al.* 2013) and Sardinia (Conti 1990). The bryozoan  
 594 assemblages of the upper Katian Khabt-el-Hajar Formation display a diversity close to that  
 595 documented in the Iberian Chains (Jiménez-Sánchez 2009, 2010; Jiménez-Sánchez & Villas  
 596 2010) and Sardinia (Conti 1990), only surpassed in the southwestern Mediterranean region in  
 597 the southern Montagne Noire (Ernst & Key 2007). Recent taxonomic studies on the bryozoans  
 598 of the Khabt-el-Hajar Formation (Jiménez-Sánchez *et al.* 2015a, b) have identified 21 species of  
 599 12 trepostomate genera and 15 species of 13 cryptostomate, fenestrate and trepostomate genera  
 600 (Jiménez-Sánchez *et al.* 2016) adapted to offshore-dominated, marly substrates. Many of these  
 601 species exhibit significantly larger body sizes than congeneric species from lower latitudes.  
 602 Based on autozoocial sizes, many of them may be examples of subpolar gigantism (Jiménez-  
 603 Sánchez *et al.* 2016). A complete biogeographical study of mid-high latitude bryozoans from  
 604 the Mediterranean region (Carnic Alps, Iberian Chains, Libya, Montagne Noire, Morocco and  
 605 Sardinia) was made by Jiménez-Sánchez & Villas (2010) and Jiménez-Sánchez *et al.* (2016),  
 606 who concluded that the Moroccan-Libyan transect plot close to the remaining high-latitude  
 607 Mediterranean assemblages. Bryozoans that invaded the Mediterranean margin of Gondwana,  
 608 during the late Katian transgression, although preserving Baltic affinities, developed an  
 609 independent faunal signal, denoting clear environmental differences from those in subtropical  
 610 palaeocontinents, from which they came.

611 **A distinct Mediterranean biogeographic unit** (extending from what is now Syria to NW  
 612 Argentina; **see original definition by Spjeldnaes 1961**), **postdating the Boda Event and**  
 613 **characterized by Avalonian-Baltic affinities with low diversity and marked endemism**, emerged  
 614 at subpolar latitudes. The extinction of several bryozoan genera in tropical seas, simultaneously  
 615 with their immigration into the Mediterranean cool waters, is consistent with the onset of a late  
 616 Katian global warming (Boda event) (Taylor & Ernst 2004; Fortey & Cocks 2005; Jiménez-  
 617 Sánchez & Villas 2010).

618 The benthic communities that characterize the Katian-Hirnantian transition cannot be  
 619 studied in the eastern Anti-Atlas due to the absence of the Lower Formation of the Second Bani  
 620 Group. In the eastern Anti-Atlas, the Upper Ktaoua Formation is unconformably overlain by the  
 621 Upper Formation of the Second Bani Group, locally forming distinct tunnel channels  
 622 (Destombes 2006a, b; Álvaro *et al.* 2007b, 2014a, b; Loi *et al.* 2010; Videt *et al.* 2010;  
 623 Benharref *et al.* 2014a, b, c; Colmenar & Álvaro 2015) (Fig. 2).

624 Finally, the Hirnantian glaciation has developed two incisions in the Anti-Atlas, (i) the  
 625 onset of glacial channels from Alnif to the Tafilalt district, subsequently infilled by the alluvial-  
 626 to-fluvial Alnif Conglomerate and the Tamekhtart glaciomarine diamictites, and (ii) a second

627 erosive (Amouktir Member) capped by marine, fossiliferous strata rich in brachiopods  
628 (sequence O16 in Fig. 7). The subsequent palaeorelief was finally sealed by Silurian strata  
629 (Álvaro *et al.* 2014c, d; Benharref *et al.* 2014a, b, c).

630

### 631 **Concluding Remarks**

632

633 The Ordovician sediments of the eastern Anti-Atlas are punctuated by three major  
634 unconformities: (i) a Furongian break-up unconformity marking the end of the Cambrian Atlas  
635 Rift and the development of a passive margin devoid of volcanism; (ii) a Dapingian  
636 unconformity that separates a Tremadocian–Floian sedimentary package (Lower and Upper  
637 Fezouata formations) from a Darriwilian–Katian sedimentary package (Tachilla Formation and  
638 First Bani and Ktaoua groups); and (iii) the Hirnantian incision of tunnel channels and  
639 glaciogenic (both continental and glaciomarine) imprint. The final sealing of the Hirnantian  
640 palaeorelief was achieved during Silurian times.

641 Except the Katian Khabt-el-Hajar Formation, erected in the vicinity of Erfoud, the  
642 Ordovician lithostratigraphy was originally defined in the Zagora-Foum Zguid depocenter. The  
643 Ordovician is dominated by terrigenous deposits sedimented at mid- to high latitudes. Despite  
644 the presence of scattered episodes of shelly carbonate production, only a proximal area close to  
645 Erfoud has recorded the onset of bryozoan-echinoderm meadows and thickets (Khabt-el-Hajar  
646 Formation) that allow identification of the Katian Boda event in this segment of the Gondwanan  
647 margin.

648 Due to the palaeolatitudinal position of the Anti-Atlas Basin during Ordovician times,  
649 carbonate production was scattered and mainly associated with the record of shelly pavements.  
650 Key conodonts and graptolites have not been recovered to recognize the global  
651 chronostratigraphic subdivision erected by the *International Subcommission on Ordovician*  
652 *Stratigraphy*. The **thinnest** Ordovician zonation of the **N African-SW European margin of**  
653 **Gondwana**, based on chitinozoans, includes 26 biozones with an average duration close to 2  
654 m.y. per biozone. This chitinozoan scale is the standard in Morocco, to which the stratigraphic  
655 ranges of graptolites, trilobites, brachiopods and other taxa are referred. The  
656 chronostratigraphical regional South Polar scale, defined in Bohemia and Iberia, is applicable in  
657 the Anti-Atlas.

658

### 659 **Acknowledgements**

660

661 **The authors thanks the useful and detailed revisions made by J. Colmenar, T. Servais and one**  
662 **anonymous referee.** This work is dedicated to the memory of Jacques Destombes who left us  
663 during the redaction of this synthesis. This paper is a contribution to Spanish project CGL2017-

664 87631-P from Spanish Ministry of Science, Innovation and Universities and IGCP 653 (IUGS-  
665 UNESCO) project ‘The Onset of the Great Ordovician Biodiversification Event’.

666

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- 1553

1554 **FIGURE CAPTIONS**

1555

1556 Figure 1. A. Sketch of main geographical units in NW Africa. B. Geological sketch showing the  
 1557 geographical distribution of Ordovician exposures throughout the Anti-Atlas, High Atlas and  
 1558 Ouagarta massif; modified from Destombes *et al.* (1985); abbreviations: Ar- Aroudane jbel, BI-  
 1559 Bou Ingarf jbel, BK- Bou el-Khoualb, BR- Bou Rdim, OU- Ouzina jbel, Ti- Timzizouit jbel and  
 1560 TR- Tizi n'Rsas.

1561

1562 Figure 2. Stratigraphical chart of the Miaolingian-Hirnantian in the Anti-Atlas with setting of  
 1563 main gaps; abbreviations of Hirnantian glacial tunnels: Ad- Adrar (Merzouga sheet), Am-  
 1564 Amessoui, Ar- Aroudane, Im-Ti- Imzizoui-Timzizouit, Ti- Taouirt n'Irjdelen, TR: Tizi n'Rsas;  
 1565 modified from Álvaro *et al.* (2014c, d), Benharref *et al.* (2014a, b, c) and Álvaro & Vizcaíno  
 1566 (2018).

1567

1568 Figure 3. Field aspect of the Feijas Externes Group in the Tafilalt district. A. Centimetre-scale  
 1569 glauconitic sandstone/siltstone alternations rich in hematite cement, forming the basal part of  
 1570 the Upper Fezouata Formation, South of Jbel Ouzina. B. Thin-section photomicrograph (parallel  
 1571 light) of clast-supported glauconitic-quartz sandstone cemented with hematite; detail of  
 1572 previous picture; scale = 1 mm. C. Three shallowing-upward cycles (tops arrowed) forming the  
 1573 Tachilla Formation, North of Jbel Ouzina. D. Thin-section photomicrograph of a clast- to  
 1574 cement-supported ironstone with scattered ooids from the Tachilla Formation; detail of previous  
 1575 image; scale = 1 mm.

1576

1577 Figure 4. Field aspect of the Ktaoua Group in the Maider-Tafilalt district. A. Claystone-  
 1578 dominated succession with scattered metre-scale carbonate concretions of the Lower Ktaoua  
 1579 Formation, close to Alnif; scale = 1 m. B. Channels interbedded in the shales of the Lower  
 1580 Ktaoua Formation showing angular cobble clasts embedded in a brachiopod shell matrix,  
 1581 reflecting high-energy episodes, close to Alnif. C. Phosphatic layer marking the Lower  
 1582 Ktaoua/Upper Tiouririne contact at Alnif. D. Coquina on a silty carbonate surface with  
 1583 branching bryozoans (b), orthoceratids (o), tentaculitids (te) and trilobites (tr), from the Upper  
 1584 Tiouririne Formation at Jbel Aroudane; scale = 4 cm. E. Channel interbeds of the Upper  
 1585 Tiouririne Formation with superposed scouring surfaces and granule-to-boulder clasts, close to  
 1586 Alnif. F. Thin-section photomicrograph (parallel light) of a bryozoan floatstone with  
 1587 disarticulated echinodermossicles and brachiopods, embedded in a silty carbonate matrix; Upper  
 1588 Tiouririne Formation at Jbel Aroudane; scale = 1 mm. G. Coquina of disarticulated echinoderm  
 1589 plates from the top of the Upper Tiouririne Formation at Tizi n'Rsas. H. Thin-section  
 1590 photomicrograph (parallel light) illustrating the traditional orthoceratid-rich carbonate siltstone

1591 that punctuate the monotonous shales of the Upper Ktaoua Formation, Jbel Aroudane; scale = 1  
1592 mm.

1593

1594 Figure 5. Field aspect of the Khabt-el-Hajar Formation and the Upper Formation of the Second  
1595 Bani Group in the Maider-Tafilalt district. A. Second shallowing-upward trend of marlstone-to-  
1596 limestone rich in echinoderm-bryozoan debris from the northwestern edge exposure of the  
1597 formation, north of Erfoud. B. Destombes' (1987) "ravinement surface" (arrowed) separating  
1598 two packages of echinoderm-bryozoan limestones, reinterpreted as an onlapping geometry of a  
1599 palaeorelief formed by skeletal shoals, north of Erfoud. C. Aspect of bryozoan meadows from  
1600 the upper part of the Khabt-el-Hajar Formation exhibiting parautochthonous robust and fragile  
1601 branching and dendroid bryozoans, north of Erfoud. D. Alluvial channel (scouring base  
1602 arrowed) infilled with clast-supported conglomerates of the Alnif Member, subsequently capped  
1603 by fluvial sandstone bars at the base of Jbel Boulakoualeb. E. Western contact (arrowed) of the  
1604 Hirnantian Alnif tunnel channel, incised in the Upper Tiouririne Formation (subhorizontal beds  
1605 on the left). F. Alternating conglomerate and sandstone beds with subparallel and low-angle  
1606 laminae reflecting pulsations in the infill of the Hirnantian Alnif tunnel channel. G. Clast-  
1607 supported conglomerate highlighted by the orange colour of the silty carbonate clasts eroded  
1608 from the Lower Ktaoua and Upper Tiouririne formations; Alnif Member at Tizi n'Rsas tunnel  
1609 channel. H. Outsized sandstone clasts embedded in a homogeneous claystone of the Tamekhar  
1610 Member; glaciogenic diamictite at Jbel Imzizoui. I. Overlying cross-stratified sandstones of the  
1611 Amouktir Member at Jbel Imzizoui.

1612

1613 Figure 6. Updated litho-and chronostratigraphical charts of the Ordovician in the Anti-Atlas,  
1614 Morocco. [Global chronostratigraphic scale subdivisions according to Bergström \*et al.\* \(2009\);](#)  
1615 [regional scale updated by Gutiérrez-Marco \*et al.\* \(2017\) and Colmenar \*et al.\* \(2017\).](#)  
1616 [Lithostratigraphy after Destombes \(in Destombes \*et al.\* 1985\). Chitinozoan zonation updated](#)  
1617 [from Paris \*et al.\* \(1990, 1999\) in Gutiérrez-Marco \*et al.\* \(2015, 2017b\). Graptolite zones after](#)  
1618 [Gutiérrez-Marco & Martin \(2016\) and Gutiérrez Marco \*et al.\* \(2017b\).](#)

1619

1620 Figure 7. Chronostratigraphical distribution of third-order sequences described in the Zagora-  
1621 Fom Zguid depocentre and the Maider-Tafilalt districts, central and eastern Anti-Atlas; based  
1622 on Destombes *et al.* (1985), Álvaro *et al.* (2007b, 2014c, d), Ghienne *et al.* (2007a), Loi *et al.*  
1623 (2010), Benharref *et al.* (2014a, b, c), Colmenar & Álvaro (2015), and Álvaro & Vizcaïno  
1624 (2018).

1625



1626 **ANNEX 1. Updated Ordovician fossil record**

1627

1628 In the Anti-Atlas, taxonomic works have been focusing on trilobites (Choubert *et al.* 1955;  
1629 Destombes 1963c, 1966, 1967a, b, 1972, 1985a, b, c, d, 1987, 2000, 2006a-j; Destombes &  
1630 Henry 1987; Rábano 1990; Henry 1991; Henry & Destombes 1991; Henry *et al.* 1992; Vidal  
1631 1998a, b; Bruton 2008; Fortey 2009, 2011a, b; Rábano *et al.* 2010, 2014; Martin *et al.* 2016b;  
1632 Fortey & Edgecombe 2017; Pereira *et al.* 2017; Gutiérrez-Marco *et al.* 2017, 2019; Drage *et al.*  
1633 2019), radiodonts (Van Roy & Tetlie 2006; Van Roy & Briggs 2011; Van Roy *et al.* 2015a),  
1634 aglaspids (Van Roy 2006a, b; Ortega-Hernández *et al.* 2016), cheloniellid arthropods  
1635 (Alessandrello & Bracchi 2006, Van Roy 2006a), echinoderms (Termier & Termier 1950a, b,  
1636 1970; Ubaghs 1963, 1968, 1969; Choubert *et al.* 1953; Chauvel 1966a, b, 1969a, b, 1971a, b,  
1637 1977, 1978; Paul 1968; Chauvel & Régnault 1986; Donovan & Savill 1988; Cripps 1990;  
1638 Beisswenger 1994; Le Menn & Spjeldnaes 1996; Ruta 1999; Lefebvre & Fatka 2003; Parsley &  
1639 Gutiérrez Marco 2005; Lefebvre 2007; Lefebvre & Botting 2007; Lefebvre *et al.* 2007, 2008,  
1640 2010, 2016c, 2019; Nardin 2007; Régnault 2007; Ware & Lefebvre 2007; Lefebvre & Roch  
1641 2009; Noailles *et al.* 2010; Sumrall & Zamora 2011; Allaire *et al.* 2015, 2017; Martin *et al.*  
1642 2015; Nardin & Régnault 2015; Zamora *et al.* 2015; Reich *et al.* 2017; Hunter & Ortega-  
1643 Hernández 2017), brachiopods (Havliček 1970, 1971; Mergl 1981, 1983; Villas *et al.* 2006;  
1644 Colmenar & Álvaro 2015; Candela & Harper 2016; Colmenar 2016), hyoliths (Marek 1983;  
1645 Valent & Corbacho 2015; Martí Mus 2016), sachtids (Vinther *et al.* 2017), bivalves and  
1646 rostroconchs (Termier & Termier 1950b; Babin & Destombes 1990; Polechová 2016),  
1647 gastropods, paragastropods and tergomiids (Horný 1997a, b, c; Ebbestad & Lefebvre 2015;  
1648 Ebbestad 2016), graptolites (Destombes & Willefert 1959; Martin *et al.* 2016a; Gutiérrez-Marco  
1649 & Martin 2016), conodonts (El Bourkhissi & Sarmiento 1997; Lehnert *et al.* 2016), ostracods  
1650 (Gutiérrez-Marco *et al.* 1997), sponges (Botting 2007, 2016), conulariids (Van Iten *et al.* 2016),  
1651 cephalopods (Kröger & Lefebvre 2012), machaeridians (Chauvel 1966c; Vinther *et al.* 2007),  
1652 palaeoscolecid and soft-bodied metazoans (Samuelsson *et al.* 2001; Alessandrello & Bracchi  
1653 2003; Van Roy 2006a; Gaines *et al.* 2012; McGabhan 2012; Gutiérrez-Marco & García-Bellido  
1654 2015; Martin *et al.* 2016c; Gutiérrez Marco *et al.* 2017a; Kouraiss *et al.* 2018; McGabhan *et al.*  
1655 2019), cornulitids (Gutiérrez-Marco & Vinn 2018), bryozoans (Destombes *et al.* 1971; Ernst *et al.*  
1656 2015; Jiménez-Sánchez *et al.* 2015a, b, 2016), organic-walled microfossils (Deunff 1968a, b,  
1657 1977; Elaouad-Debbaj, 1984a, b, 1986, 1988a, b; Paris 1990; Nowak *et al.* 2015, 2016) and  
1658 some ichnofossils (Gibb *et al.* 2010; Azizi *et al.* 2017). To these fossil associations are added  
1659 the palaeontological contributions reported in this special volume, which include conulariids  
1660 (Van Iten *et al.*), brachiopods (Colmenar *et al.*; Villas & Colmenar), echinoderms (crinoids by  
1661 Botting *this vol.*; stylophorans by Lefebvre *et al.*; edrioasteroids by Sumrall & Zamora;  
1662 coronates and *Hexedriocystis* by Zamora & Sumrall; and rhombiferans by Zamora *et al.*),

1663 graptolites (Gutiérrez-Marco *et al.*), molluscs (Ebbestad *et al.*), trilobites (Gutiérrez-Marco *et al.*  
 1664 this vol.), and problematica (agglutinated tubes by Muir *et al.*).

1665           The Lower Fezouata and Upper Fezouata formations contain about 200 taxa that have  
 1666 been reported in the so-called Fezouata Biota (Van Roy *et al.* 2010, 2015b; Lefebvre *et al.*  
 1667 2016b, c; Vaucher *et al.* 2016, 2017; Saleh *et al.* 2018, 2019), many of which still remain  
 1668 undescribed. The biota includes algae (such as chaetocladids); sponges (*Choia*, *Choiaella*,  
 1669 *Hamptonia*, *Pirania*, *Valospongia* and other demosponges, hexactinellids, leptomitids and  
 1670 wapkiiids); cnidarians (*Archaeoconularia*, *Eoconularia* and *Sphenothallus*); brachiopods  
 1671 (*Angusticardinia*, *Celdobolus*, *Elliptoglossa*, *Monobolina*, *Orbithele*, *Paurorhis*, *Plectorthis*,  
 1672 *Ranorthis*, *Tarfaya* and *Wosekella*); undetermined bryozoans; molluscs such as bivalves  
 1673 (*Alococoncha?*, *Babinka*, *Cardiolaria?*, *Cienagomya?*, *Coxiconchia*, *Ekaterodonta*, *Glyptarca*,  
 1674 *Praenucula?* and *Redonia*), rostroconchs (*Ribeiria*, *Tolmachovia?*), paragastropods  
 1675 (*Pelecogyra*), gastropods (*Lesueurilla* and *Sinuities*), tergomyans (*Carcassonnella* and  
 1676 *Thoralispira*), cephalopods (a.o. *Bactroceras*, *Bathmoceras*, *Destombesiceras*, *Polymeres*,  
 1677 *Protocryptendoceras* and *Rioceras*) and other stem mollusc groups (sachitids such as  
 1678 *Calvapilosa*, halkieriids, helcionellids and wiwaxiids); hyoliths (*Cavernolites*, *Gompholites*,  
 1679 *Elegantilites*, *Gamalites?*, *Nephrotheca?* and *Pauxilites*); annelids (*Plumulites*, different  
 1680 polychaetes and isolated scolecodonts), cycloneuralia (*Palaeoscolex?* and priapulids),  
 1681 lobopodians, radiodonts (*Aegirocassis* and other hurdiids, and amplexobeluids), euarthropods  
 1682 (*Brachyaglaspis*, *Mollisonia*, *Pseudoangustidontus*, *Thelxiope*, *Tremaglaspis*, canadaspidids,  
 1683 leanchoiliids, aglaspidids, cheloniellids, basal chelicerates, xiphosurids, chasmataspidids,  
 1684 eurypterids, liwiids, naraoiids, marrellid and acercostracan marrellomorphs, and possible  
 1685 helmetiids, pycnogonids and retifaciids); trilobites (*Agerina*, *Ampyx*, *Anacheirurus*,  
 1686 *Apatokephalus*, *Asaphellus*, *Asaphopsis*, *Basilicus*, *Bathycheilus*, *Bavarilla*, *Cnemidopyge*,  
 1687 *Colpocoryphe*, *Dikelokephalina*, *Eoharpes*, *Euloma*, *Harpides*, *Foulonia*, *Kierarges*,  
 1688 *Lichakephalus*, *Megistaspis*, *Neseuretus*, *Nileus*, *Orometopus*, *Ogyginus*, *Parabathycheilus*,  
 1689 *Platycoryphe*, *Platypeltoides*, *Pharostomina*, *Pradoella*, *Prionocheilus*, *Selenopeltis*,  
 1690 *Symphysurus*, *Toletanaspis* and *Uralichas*) and agnostoids (*Geragnostus*), phyllocarids,  
 1691 ostracods, angustidontids and lepadomorph barnacles; echinoderms such as Crinoidea (*Iocrinus*  
 1692 and *Ramseyocrinus*), Diploporita (*Aristocystites* and *Palaeosphaer***on**ites), Edrioasteroidea  
 1693 (*Anedriophus*, *Argodiscus* and *Rhenopyrgidae*), Eocrinoidea (*Balantiocystis*, *Lingulocystis*,  
 1694 *Pareocrinus?* and *Rhopalocystis*), Rhombifera (*Macrocystella*), Soluta (*Plasiacystis*),  
 1695 Somasteroidea (*Cantabrigiaster*, a.o.), Stylophora (*Ampelocarpus*, *Amygdalotheca*, *Anatifopsis*,  
 1696 *Aspidocarpus*, *Balanocystites*, *Bohemiaecystis*, *Chauvelicystis*, *Chinianocarpus*, *Flabelllicarpus*,  
 1697 *Galliaecystis*, *Hanusia*, *Lagynocystis*, *Nanocarpus*, *Peltocystis*, *Phyllocystis*, *Procothurnocystis*,  
 1698 *Prokopicystis* and *Vizcainocarpus*); graptolites (*Adelograptus?*, *Ancoragraptus*, *Araneograptus*,  
 1699 *Azygograptus*, *Baltograptus*, *Choristograptus*, *Clonograptus*, *Cymatograptus?*, *Dictyonema*,

1700 ‘*Didymograptus*’, *Hunnegraptus*, ‘*Kiaerograptus*’, *Koremagraptus*, *Paradelograptus*,  
 1701 *Paratemnograptus*, *Rhabdinopora*, *Schizograptus*?, ‘*Tetragraptus*’ and ?tuboids); conodonts  
 1702 (*Acodus*, *Cornuodus*, *Drepanodus*, *Drepanoistodus*, *Paltodus*, *Parapaltodus*, *Paroistodus*,  
 1703 *Periodon*, *Prioniodus*, *Scalpellodus*, *Scolopodus*, *Semiacontiodus*, *Stolodus*, *Tripodus* and  
 1704 *Tropodus*); chordates (dermal plates) and problematica (e.g., Van Roy *et al.* 2010, 2015b;  
 1705 Martin *et al.* 2016a, b).

1706 The Tachilla Formation has yielded trilobites (*Bathycheilus*, *Colpocoryphe*, *Dionide*,  
 1707 *Ectillaenus*, *Eohomalonotus*, *Morgatia*, *Neseuretus*, *Ormathops*, *Placoparia*, *Plaesiacomia*,  
 1708 *Selenopeltis* and ‘*Zeliszella*’), brachiopods (*Euorthisina* and ‘*Orthambonites*’), ostracods  
 1709 (*Brephocharieis*), echinoderms [Diploporita (*Calix*), Stylophora (*Bohemiaecystis*)], hyoliths  
 1710 (*Elegantilites*, *Gompholites* and *Pauxillites*), bivalves (*Praenucula* and *Redonia*), tergomyans  
 1711 (*Cyrtodiscus*, *Tachillanella* and *Thoralispira*?), gastropods (*Lesueurilla*, *Ptychonema*, *Sinuities*,  
 1712 *Selesinuities* and *Tropidodiscus*), graptolites (*Aulograptus*?, *Corymbograptus*, *Didymograptus*,  
 1713 *Hustedograptus*?, *Jenkinsograptus* and *Xiphograptus*?) and undetermined lingulaceans,  
 1714 orthoconic nautiloids and conulariids.

1715 The First Bani Group contains trilobites (such as *Basilicus*, *Bathycheilus*, *Caudillaenus*,  
 1716 *Cekovia*, *Colpocoryphe*, *Crozonaspis*, *Degamella*, *Eccoptochile*, *Ectillaenus*, *Eoharpes*,  
 1717 *Eohomalonotus*, *Iberocoryphe*, *Isabelinia*, *Kerfornella*, *Marrolithus*, *Morgatia*, *Mytocephala*,  
 1718 *Neseuretus*, *Nobiliasaphus*, *Parabarrandia*, *Phacopidina*, *Placoparia*, *Plaesiacomia*,  
 1719 *Selenopeltis* and *Uralichas*), cheloniellid euarthropods (*Duslia* and possibly *Triopus*),  
 1720 brachiopods (*Atlantida*, *Euorthisina*, *Mimella*, ‘*Orthambonites*’, *Paterorthis*, *Tafilaltia* and  
 1721 *Tissintia*); echinoderms including Crinoidea (*Iocrinus* and *Trichinocrinus*?), Diploporita  
 1722 (*Aristocystites*, *Calix*, *Oretanocalix*, *Isidalocystis*, *Phlyctocystis* and *Sphaeronites*?),  
 1723 Edrioasteroidea (*Belochthus*?, *Isorophus* and *Moroccodiscus*), Eocrinoidea (*Ascocystites*),  
 1724 Ophiuroidea, Stylophora (*Anatifopsis*, *Aspidocarpus*, *Bohemiaecystis*, *Destombesicarpus*,  
 1725 *Diamphidiocystis*, *Eumitrocystella*, *Milonicystis*, *Nanocarpus*, *Procothurnocystis* and  
 1726 *Scotiaecystis*) and incertae sedis (*Hexedriocystis*); molluscs such as tergomyans (*Quasisinuities*),  
 1727 bivalves (*Cardiolaria*, *Coxiconchia*, *Cyrtodontula*?, *Hemiprionodonta* and *Redonia*) and  
 1728 rostroconchs (*Ribeiria*); hyoliths (*Elegantilites* and *Gompholites*), graptolites (*Didymograptus*,  
 1729 *Dendrograptus* and *Ptilograptus*), conulariids (*Archaeoconularia*), paleoscolecidans  
 1730 (*Gamascolex*), conodonts (*Coleocerodontus*?, *Distomodus*?, *Drepanoistodus*?,  
 1731 *Paraprioniodus*?, *Phragmodus*?, *Plectodina* and ‘*Scandodus*’), ostracods (‘*Dilobella*’,  
 1732 ‘*Piretopsis*’, *Quadrijugator*?, *Reuentalina* and *Sigmoopsis*?), paropsonemid eldonioids  
 1733 (*Discophyllum*), agglutinated problematic tubes (*Onuphionella*) and undetermined lingulaceans,  
 1734 asterozoans, nautiloids, and bryozoans.

1735 The Lower Ktaoua Formation has yielded trilobites (*Actinopeltis*, *Calymenella*,  
 1736 *Colpocoryphe*, *Crozonaspis*, *Dalmanitina*, *Deanaspis*, *Eccoptochile*, *Eohomalonotus*,

1737 *Eudolatites*, *Flexicalymene*, *Kloucekia*, *Mucronaspis*, ‘*Ogmasaphus*’, *Onnia*, *Ormathops*,  
 1738 *Placoparia*, *Plaesiacomia*, *Primaspis*, *Prionocheilus*, ‘*Scotiella*’, *Selenopeltis*, *Sokhretia* and  
 1739 *Stenopareia*), brachiopods (*Aegiromena*, *Bicuspina*, *Dalmanella*, *Drabovia*, *Drabovinella*,  
 1740 *Eostropheodonta*, *Gelidorthis*, *Heterorthis*, *Howellites*, *Irhirea*, *Mimella*, *Onniella*,  
 1741 *Protomendacella*, *Rafinesquina*, *Rostricellula*, *Schizocrania*, *Svobodaina*, *Tafilaltia*, *Tazzarina*  
 1742 *Triplesia*), echinoderms such as Diploporita (*Calix*, *Codiacystis*, *Destombesia*, *Maghrebocystis*  
 1743 and *Phlyctocystis*), Edrioasteroidea (*Isorophusella*, *Spinadiscus* and *Streptaster*), Eocrinoidea  
 1744 (*Cardiocystites*), Ophiuroidea, Rhombifera (*Arachnocystites*, *Deutocystites*, *Echinosphaerites*,  
 1745 *Heliocrinites* and *Homocystites*), Soluta (*Dendrocystites*) and Stylophora (*Anatifopsis*,  
 1746 *Aspidocarpus*, *Barrandeocarpus* and *Eumitrocystella*?); molluscs such as tergomyans  
 1747 (*Sinuitopsis*), gastropods (*Atlantophon*, *Bucanopsina*, *Deaechospira*, *Nonorios*, *Radvanospira*  
 1748 and *Tritonophon*) and bivalves (*Myoplusia*, *Phestia*?, *Pseudarca*? and *Praenucula*); hyoliths  
 1749 (*Elegantilites*, *Joachimilites*?, *Leolites*, *Nephroteca*, *Panitheca* and *Sololites*?), machaeridians  
 1750 (*Plumulites*), graptolites (*Climacograptus*, *Dictyonema* and *Ptilograptus*), paropsonemid  
 1751 eldonioids (*Discophyllum* and *Praeclarus*), agglutinated problematic tubes (*Onuphionella*) and  
 1752 undetermined conulariids, bivalves, ostracods, asterozoans, and bryozoans.

1753           The Upper Tiouririne Formation contains trilobites (*Actinopeltis*, *Baniaspis*,  
 1754 *Calymenella*, *Cyclopyge*, *Declivolithus*, *Delgadoa*, *Eudolatites*, *Flexicalymene*,  
 1755 *Heterocyclopyge*, *Kloucekia*, *Mucronaspis*, *Nobiliasaphus*, *Onnia*, *Pricyclopyge*, *Prionocheilus*,  
 1756 *Selenopeltis* and *Sokhretia*), agnostoids (*Corrugatagnostus*), aglaspimid and chelionellid  
 1757 arthropods (*Chlupacaris* and *Triopus*), brachiopods (*Aegiromena*, *Cliftonia*, *Destombesium*,  
 1758 *Drabovia*, *Drabovinella*, *Eostropheodonta*, *Hirnantia*, *Heterorthis*, *Eostropheodonta*,  
 1759 *Heterorthis*, *Kiaeromena*?, *Orbiculoidea*, *Rafinesquina*, *Rostricellula*, *Svobodaina*,  
 1760 *Schizocrania* and *Tafilaltia*), echinoderms such as Asteroidea, Coronata (*Mespilocystites*),  
 1761 Crinoidea (*Euptychocrinus*?, *Isthlocrinus* and *Rosfacrinus*), Diploporita (*Codiacystis*,  
 1762 *Destombesia* and *Maghrebocystis*), Edrioasteroidea (*Euryeschatia*, *Hemicystites*,  
 1763 *Moroccopyrgus*, *Panidiscus* and *Streptaster*), Ophiuroidea, Rhombifera (*Echinosphaerites*),  
 1764 Stylophora (*Aspidocarpus*, *Barrandeocarpus*? and *Eumitrocystella*?), and incertae sedis  
 1765 (*Hexedriocystis*); molluscs such as tergomyans (*Sinuitopsis*), gastropods (*Sinuites*,  
 1766 *Deaechospira* and *Radvanospira*), bivalves (*Praenucula*) and cephalopods (*Tafadnatoceras*),  
 1767 conulariids (*Archaeoconularia* and *Pseudoconularia*), cornulitids, paropsonemid eldonioids  
 1768 (*Discophyllum*), biserial graptolites (*Neodiplograptus*? and *Normalograptus*?) and agglutinated  
 1769 problematic tubes (*Onuphionella*).

1770           The Upper Ktaoua Formation has yielded trilobites (*Actinopeltis*, *Amphitryon*,  
 1771 *Baniaspis*, *Brogniartella*, *Calymenella*, *Chlustinia*, *Dionide*, *Dreyfussina*, *Eccoptychile*,  
 1772 *Eudolatites*, *Flexicalymene*, *Kloucekia*, *Lichas*, *Mucronaspis*, *Octillaenus*, *Onnia* and  
 1773 *Selenopeltis*), brachiopods (*Chonetoidea*, *Comatopoma*, *Eochonetes* and *Eostropheodonta*),

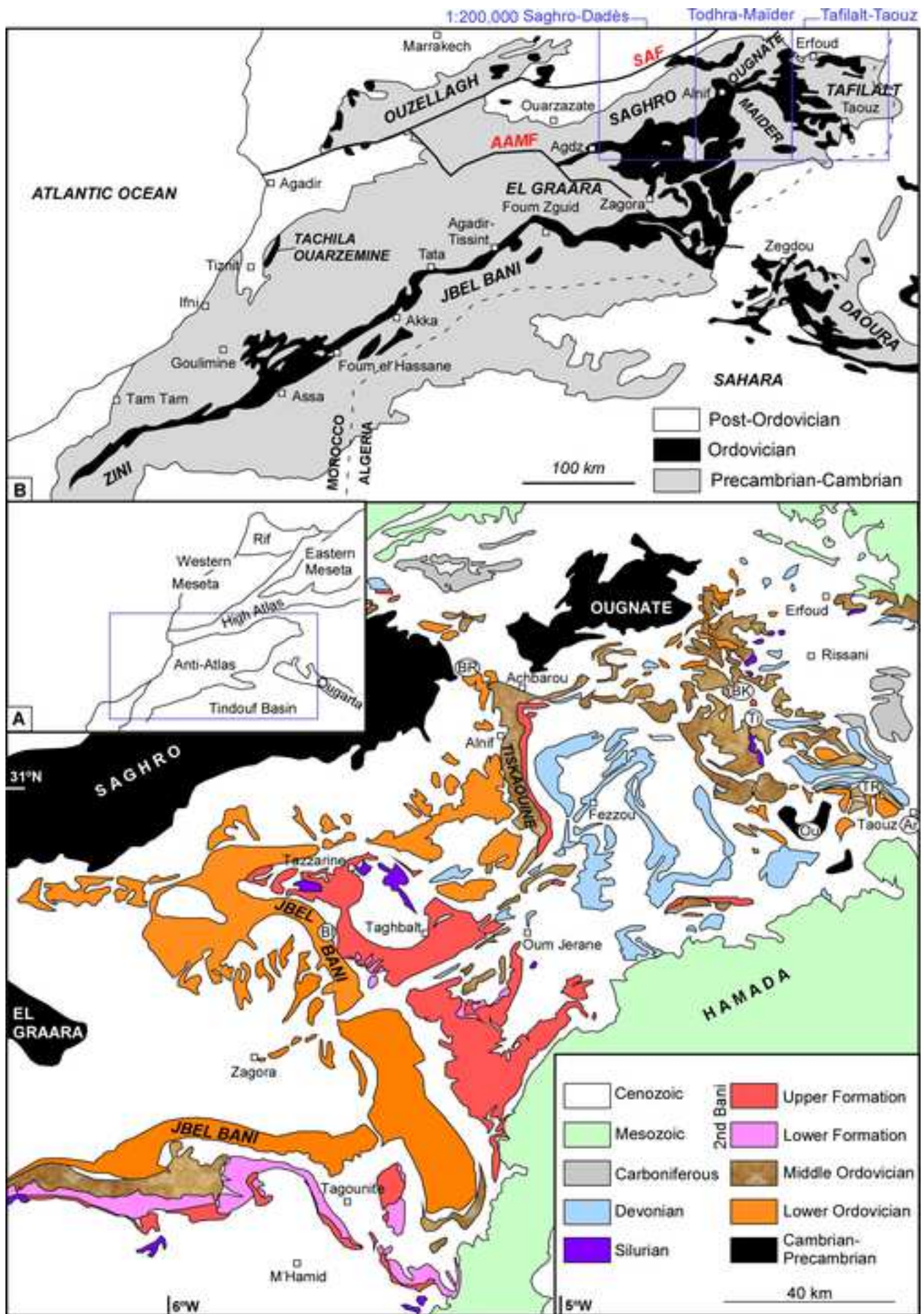
1774 echinoderms such as Diploporita (*Destombesia* and *Maghrebocystis*), Rhombifera  
 1775 (*Arachnocystites*, *Echinosphaerites* and *Heliocrinites*) and Stylophora (*Barrandeocarpus*?);  
 1776 molluscs, including cephalopods (*Armenoceras*, *Wadema* and ormoceratids), gastropods  
 1777 (*Allossospira*, *Lophospira* and *Sinuites*) and bivalves (*Sluha*, *Cleionychia* and *Praenucula*);  
 1778 hyoliths (*Elegantilites*), conularids (*Archaeoconularia*, *Pseudoconularia*), machaeridians  
 1779 (*Plumulites*) and undetermined ostracods, rostroconch molluscs, and biserial graptolites  
 1780 (*Normalograptus*?).

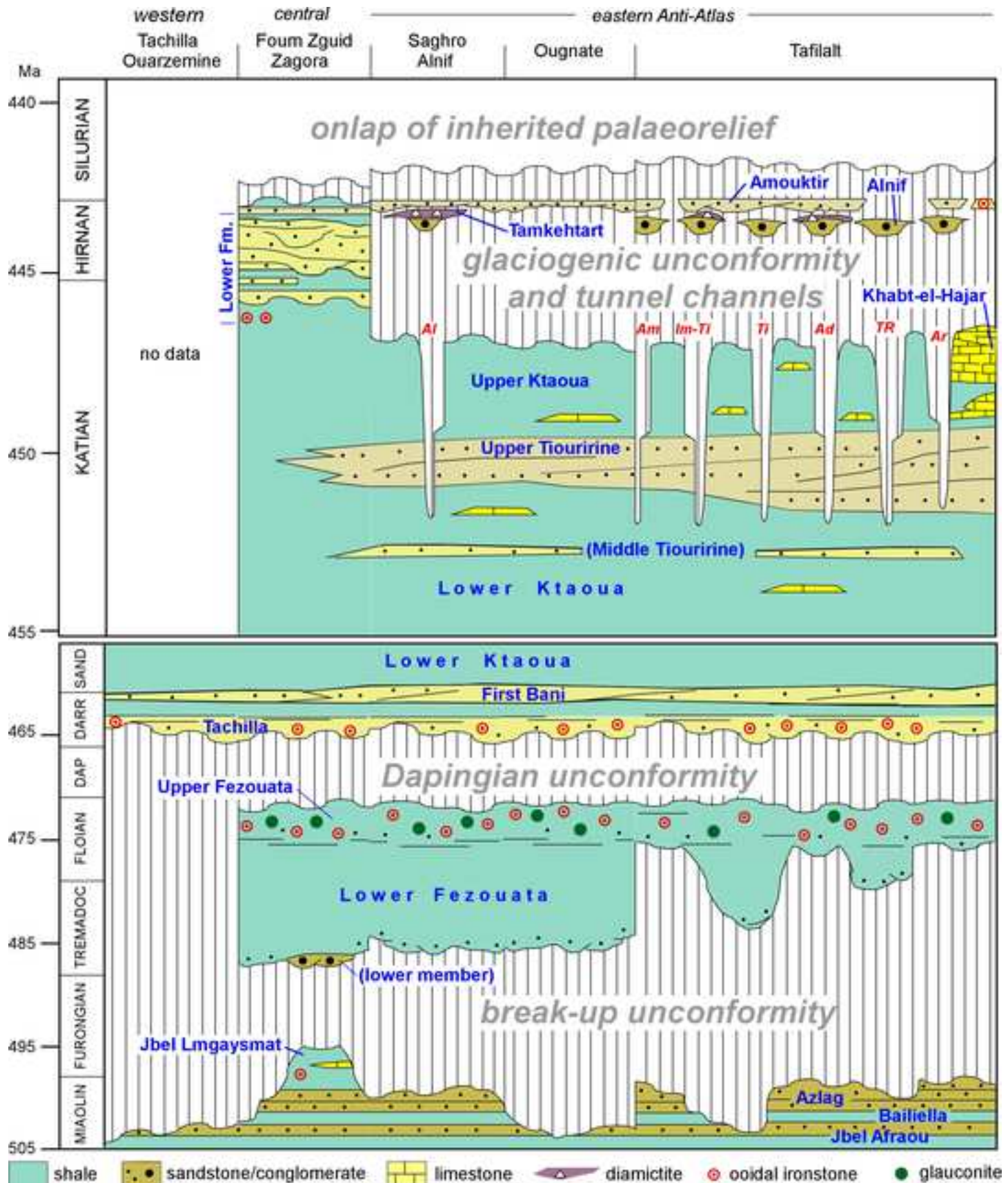
1781 In the Khabt-el-Hajar Formation, a complete assemblage of bryozoans has been  
 1782 described by Jiménez-Sánchez *et al.* (2015a, b, 2016), including cryptostomates (*Graptodictya*,  
 1783 *Ptilodictya*, *Staliodictya* and *Ulrichostylus*), fenestrates (*Enallopora*) and trepostomates  
 1784 (*Anaphragma*, *Aostipora*, *Atactoporella*, *Calloporella*, *Cyphotrypa*, *Decayia*, *Diplotrypa*,  
 1785 *Eridotrypa*, *Heterotrypa*, *Homotrypa*, *Monotrypa*, *Monticulipora*, *Parvohallopora*, *Prasopora*,  
 1786 *Radiotrypa* and *Trematopora*); associated with trilobites (*Brogniartella* and *Mucronaspis*;  
 1787 Destombes 1985c, 2006a, b; Le Menn & Spjeldnaes 1986) and brachiopods (*Drabovia* and  
 1788 *Paucicrura*; Havlíček 1970, 1971; Villas & Colmenar this vol.)

1789 The Katian-Hirnantian boundary lies within the Lower Formation of the Second Bani  
 1790 Formation. Its latest Katian part has yielded brachiopods (*Dalejina*, *Destombesium*,  
 1791 *Eostropheodonta* and *Hirnantia*), trilobites (*Actinopeltis*, *Cekovia*, *Dreyfussina*, *Mucronaspis*  
 1792 and *Onnia*) and diploporite echinoderms (*Herpetocystis* and *Magrebocystis*). In contrast, the  
 1793 Hirnantian part contains a diversified Hirnantia fauna including brachiopods (*Arenorthis*,  
 1794 *Clarkeia*, *Dalejina*, *Destombesium*, *Eostropheodonta*, *Fehamya*, *Hirnantia*, *Holderleyella*,  
 1795 *Kinnella*, *Plectothyrella* and ‘*Resserella*’), trilobites (*Calymenella* and *Mucronaspis*),  
 1796 gastropods (*Tritonophon*, *Radvanospira* and *Sinuites*), bivalves (*Ambonychia*, *Cleionychia*,  
 1797 *Cyrtodonta*, *Dzeruska*, *Modiolopsis* and *Nuculites*); echinoderms including Diploporita  
 1798 (*Magrebocystis*), Stylophora (*Anatifopsis*, *Barrandeocarpus*?, *Enoploura*? and *Nanocarpus*) and  
 1799 undetermined asterozoans and crinoids; cornulitids (*Cornulites*) and some bryozoans  
 1800 (Destombes 2006a, b; Álvaro *et al.* 2014a, b; Colmenar & Álvaro 2015; Gutiérrez-Marco &  
 1801 Vinn 2018; Ebbestad *et al.* this vol.; Colmenar *et al.* this vol.).

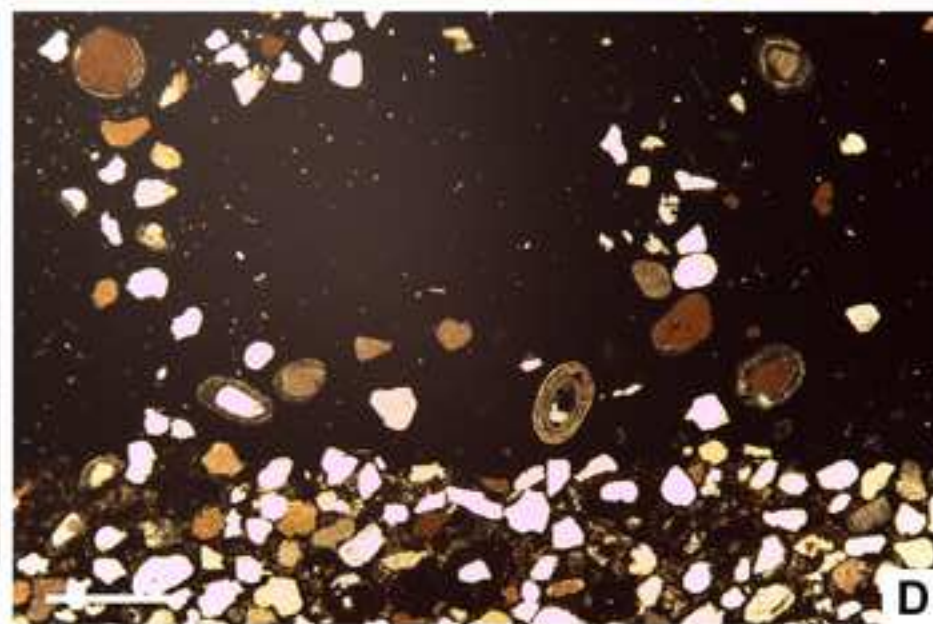
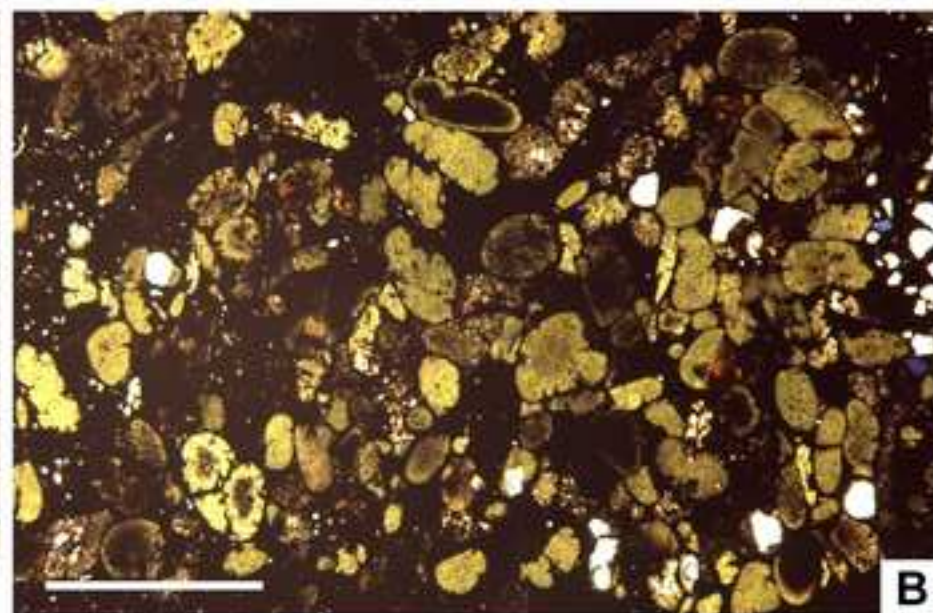
1802 Boulders included in the glaciogenic sediments of the Alnif Member have yielded a  
 1803 redeposited fauna from the underlying Ktaoua Group, including allochthonous esthonioprine,  
 1804 trepostome and rhabdosemine bryozoans (Ernst *et al.* 2015), brachiopods (e.g., *Destombesium*  
 1805 *akkaensis* and *Eostropheodonta? tafilaltensis*; Colmenar & Álvaro 2015), bivalves, gastropods,  
 1806 echinoderms, cornulitids and orthoconic nautiloids mainly sourced from the Upper Tiouririne  
 1807 Formation. Finally, the Tamekhtart Member of the Upper Second Bani Formation has yielded  
 1808 brachiopods (*Arenorthis*, *Destombesium* and *Eostropheodonta*) and undetermined bryozoans,  
 1809 bivalves and trilobites. Sandstone interbeds of the Amouktir Member are locally rich in the  
 1810 brachiopods *Eostropheodonta*, *Hirnantia*, *Kinnella* and *Plectothyrella*; the latter represents the

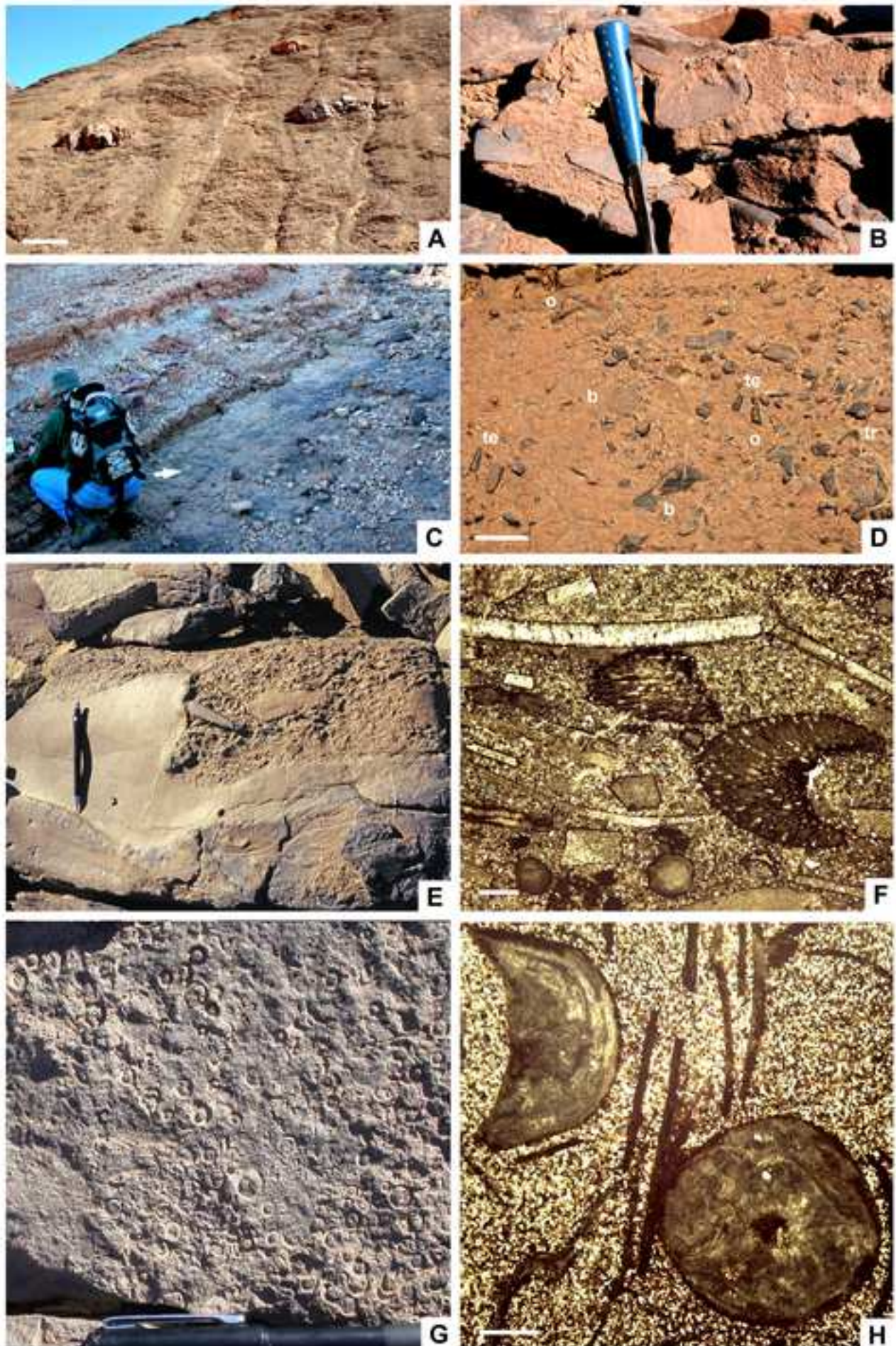
1811 so-called *E. jebiletensis* association (Colmenar & Álvaro 2015), typical of the *Aphanomena*  
1812 (= *Eostropheodonta*)-*Hirnantia* Community (Rong 1984, 1986; Wang *et al.* 1987).  
1813  
1814

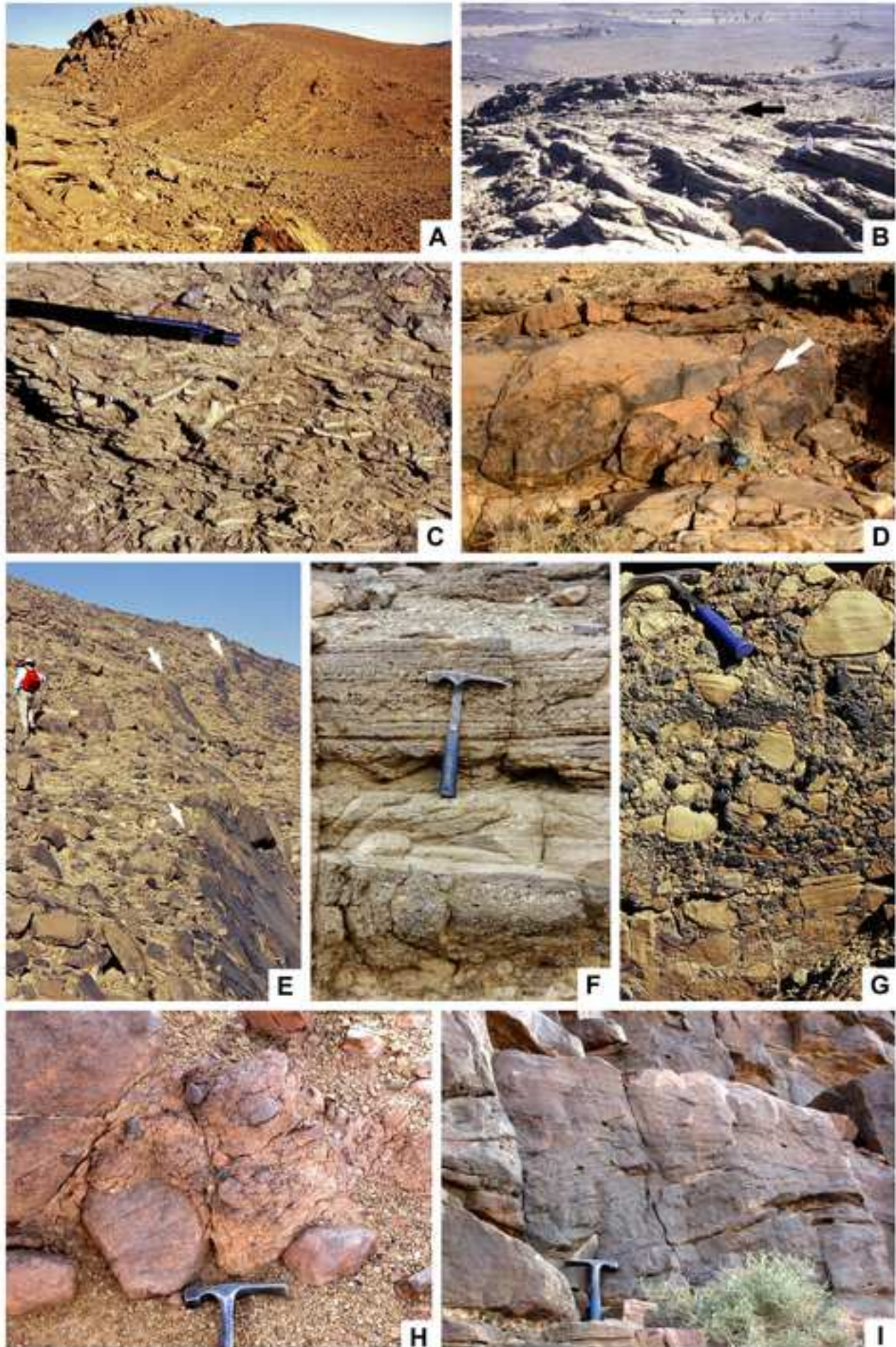






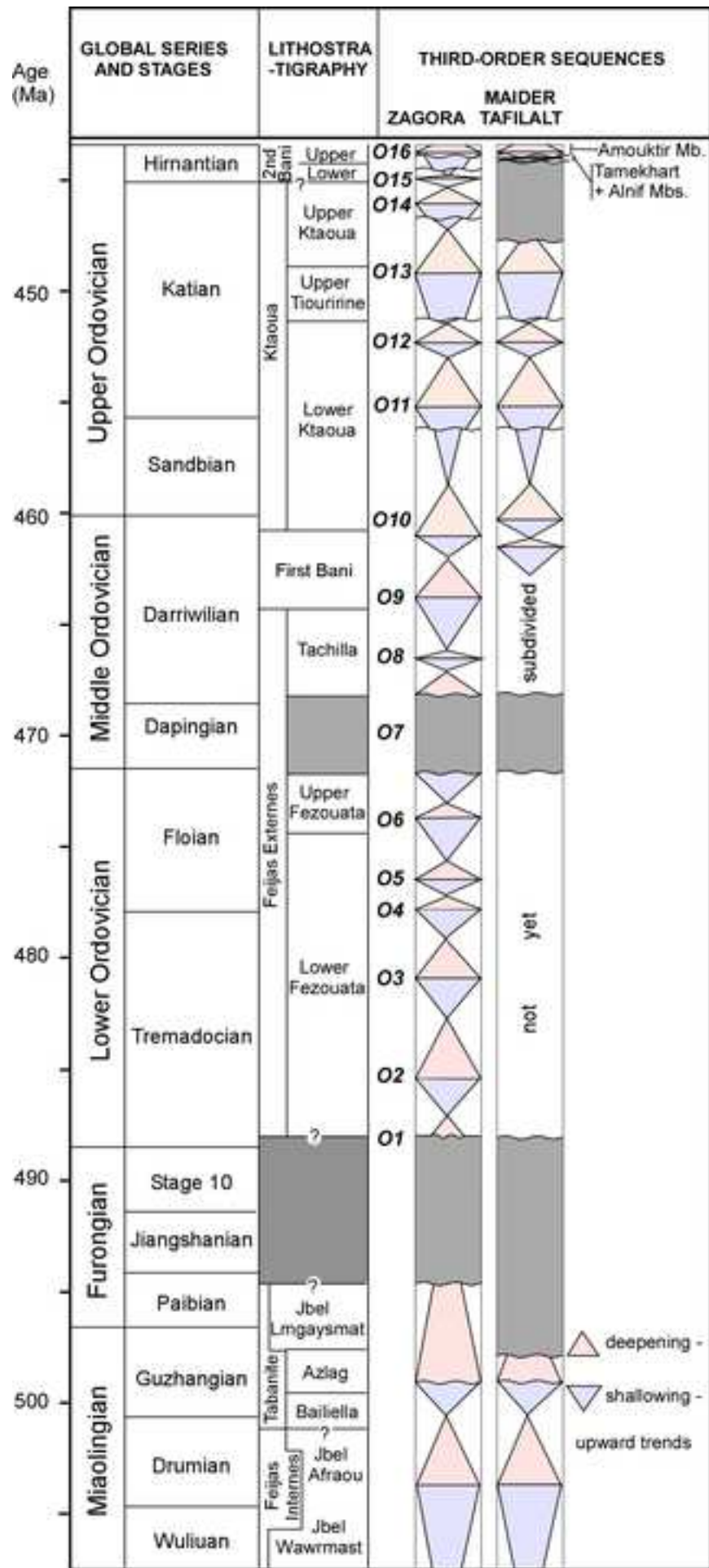






GLOBAL		REGIONAL		ANTI-ATLAS	REGIONAL	REGIONAL		
CHRONOSTRATIGRAPHIC		CHRONOSTRATIGRAPHIC		FORMATIONS	CHITINOZOAN	GRAPTOLITE		
SCALES		SCALES		AND GROUPS	ZONES	ZONES		
UPPER ORDOVICIAN	Hirnantian	Hi2	HIRNANTIAN	Upper Second Bani	2nd Bani	<i>oulebsiri</i>	<i>persculptus</i>	
		-?		Lower Second Bani		<i>elongata</i>	<i>ojsuensis</i> - <i>extraord.</i> <i>charis</i>	
	Katian	Ka4	KRALODVORIAN	Upper Ktaoua	Ktaoua	<i>merga</i>	<i>laticeps</i> <i>complanatus</i>	
		Ka3		Upper Tiouririne		<i>nigerica</i>	<i>teres / lobatus</i>	
		Ka2	BEROUNIAN	Lower		<i>barbata</i>	<i>bohdalecensis</i>	
		Ka1		middle Tiouririne		<i>fistulosa</i> <i>robusta</i>		
	Sandbian	Sa2		Ktaoua	<i>tanvillensis</i>	<i>trubinensis</i>		
		Sa1			<i>dalbyensis</i> <i>deunffi</i>	<i>bekkeri</i>		
	MIDDLE ORDOVICIAN	Darnwilfian	Dw3	DOBROTIVIAN	Izeggourene	First Bani	<i>ponceti</i>	
					Ouine-Inirne		<i>pissotensis</i>	<i>'eretiusculus' -</i> <i>Proclimacograptus</i> n. sp.
Guezzart					<i>clavata</i>		<i>distichus</i>	
Bou-Zeroual					<i>jenkinsi</i> <i>armoricana</i>		<i>murchisoni</i>	
Daping.		Dw2	ORETANIAN	Taddrist	<i>formosa</i>	<i>artus</i>		
				Tachilla	<i>calix</i> <i>protocalix</i> <i>bulla</i> <i>lebrayi</i>	<i>retroflexus</i> <i>austrodentatus</i>		
Daping.		Dw1	'ARENIGIAN'	Zini	Feijas Externes (pars)	<i>omensis</i>	<i>hirundo</i>	
						<i>?</i>	<i>suecicus</i>	
						<i>brevis</i>	<i>?</i> <i>minutus</i>	
						<i>paschaensis -</i> <i>symmetrica</i> <i>?</i>	<i>vicinaria</i> <i>tenellus</i> <i>anglica</i> <i>malanensis</i> <i>praepar./parabola</i>	
Floian	F13	TREMADO-CIAN	Lower Fezouata	<i>destombesi</i>	<i>?</i>			
				<i>?</i>				
				<i>destombesi</i>				
				<i>?</i>				

figure 7





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**supplementary material (not datasets)**  
APPENDIX.docx

