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4 2 Frasnian (Upper Devonian) of the NW Algerian Sahara
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21 15 **Abstract:** Changes in palaeoenvironment are comparatively investigated in two
22 16 representative Frasnian sections of NW Algerian Sahara integrating sedimentology,
23 17 magnetic susceptibility, and conodont biofacies. The Ben Zireg section is
24 18 characterized by condensed, and ferruginous calcareous deposits, whereas in the
25 19 South Marhouma section the sedimentation rate is high, dominated by muddy
26 20 nodular limestones with several hypoxic shale intervals. In both sections, sediments
27 21 were mostly emplaced on pelagic outer ramps below the limit of storm wave-base,
28 22 evolving in time from proximal to distal setting.

29 23 Investigations on temporal evolution of facies and MS data permits a brought first
30 24 estimate of the local sea-level trends to be made in north-western Algeria. These
31 25 trends match the overall long-term rise of sea-level recognized worldwide from
32 26 Frasnian Zone 5 onward. Outstanding positive excursions of the sea-level curve
33 27 related to the *semichatovae* transgression as well as to the late Frasnian
34 28 transgression prior to the Upper Kellwasser event can be established in this area.
35 29 Whereas the sharp regression of sea-level at the Upper Kellwasser level can be
36 30 confirmed with our data, no particular trend is depicted at the transition of conodont
37 31 zones 11 to 12 where the presence of the Lower Kellwasser level has not been
38 32 clearly recognised so far.
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41 34 **Keywords:** Frasnian, Algerian Sahara, facies, magnetic susceptibility, sea-level
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4 36 **1. Introduction**

5 37 The Frasnian stage in the Late Devonian is outstanding in the occurrence of one of
6 38 the major sea-level rises in the Paleozoic (Haq & Shutter 2008), which culminated in
7 39 spreading of basinal anoxic waters that eventually triggered the global biotic turnover
8 40 at the terminal Frasnian Upper Kellwasser Event (Hallam & Wignall 1999). This long-
9 41 term eustatic rise was documented mainly in Laurussia (e.g. Johnson, Klapper &
10 42 Sandberg, 1985; Johnson & Sandberg, 1988; Alekseev, Konokova & Nikishin, 1996;
11 43 Narkiewicz ,1988), and in South China (Chen & Tucker 2003). On the African
12 44 Gondwana margin, after preliminary records from the Moroccan Anti-Atlas (Wendt &
13 45 Belka 1991), only one accurate sea-level curve was recently provided (Dopieralska,
14 46 Belka, & Walczak, 2016).

15 47 In this contribution we focus on Late Devonian facies and sea level fluctuations in the
16 48 Algerian Sahara, by integrating results from two representative Frasnian sections of
17 49 different marine palaeoenvironmental settings: the South Marhouma section and the
18 50 Ben Zireg section (Fig. 1a). Indeed, this area is still poorly known in comparison to
19 51 time-equivalent North America and European regions. Analyses of lithofacies,
20 52 magnetic susceptibility and conodont biofacies were performed to depict changes in
21 53 the depositional environment and sea level through time. The main objective of this
22 54 study is first to determine whether observed changes and trends occur concomitantly
23 55 in different settings of the region, and, secondly, to propose a first order relative sea-
24 56 level curve through the Frasnian that can be compared with data from other
25 57 continental entities. As such it aims to compare fluctuations in sea level with those
26 58 depicted by Dopieralska, Belka, & Walczak. (2016) in the neighboring Tafilalet region
27 59 and with the global trends in North America (Johnson, Klapper & Sandberg, 1985;
28 60 Johnson & Sandberg,1988).

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47 62 **2. Geological setting**

48 63 The Algerian Sahara is part of the North-Gondwana epicontinental margin between
49 64 the Maghrebian Variscan belt to the North and the West African craton to the South
50 65 (Fig. 1a). This domain was moderately affected by the Variscan deformation. The
51 66 South Marhouma section is located in the intracratonic Ougarta basin that is
52 67 bordered to the south by a Precambrian shield. This basin was a strongly subsiding
53 68 trough filled with continental and marine Ordovician through Carboniferous

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3 69 sediments, up to 10km in thickness and slightly deformed by Variscan compressional
4 70 movements (Donzeau, 1974). In the northern part of the basin Upper Devonian
5 71 deposits are well exposed. At least 75 m of Frasnian sediments are continuously
6 72 outcropping in the South Marhouma section (coordinates: 29°57'31. 6"N,
7 73 002°06'07.8"W) (Fig. 1b). The succession comprises mudrock deposits (shales and
8 74 marls) containing argillaceous micritic nodules, and, at its top, black shales that
9 75 correspond to the Upper Kellwasser horizon. Goniatites from this area were
10 76 described by Petter (1952) & Göddertz (1987), trilobites by Feist, Mahboubi & Girard
11 77 (2016) and ichnological analyses by Bendella & Ouali (2014). The first conodont
12 78 research was conducted by Mahboubi & Gatovsky (2014). It revealed a rather
13 79 moderate yield of often insignificant conodont elements (less than 10 conodonts per
14 80 kg in most samples) preventing a fine-scaled biostratigraphy to be established.
15 81 However, the presence of a restricted number of conodont zones, i.e. FZ 5, 11, 12
16 82 and 13 were recognized with confidence, whereas zones 6-7 and 8-10 remain
17 83 undifferentiated. Many dark shale intervals, notably at the base of the succession (FZ
18 84 1-4?) and in the uppermost part, did not provide any conodonts. Presently we rely on
19 85 these poor data that only permit an incomplete zonation to be established at
20 86 Marhouma.

21 87 In contrast to the high sedimentation rates in the Ougarta trough, these were much
22 88 lower in the Bechar region at some 300 km further to the N. Here, Upper Devonian
23 89 deposits represent condensed carbonate successions punctuated by hiatuses
24 90 (Weyant, 1988). The Frasnian succession is most complete in the Ben Zireg section
25 91 (coordinates: 31° 54'39. 4" N, 001° 47' 58.8" W), on the steep southern flank of an
26 92 acute anticlinal structure. Conodont based biostratigraphy revealed a late Givetian
27 93 through early Frasnian hiatus, superseded by a complete sequence where all
28 94 conodont zones from FZ 5 to the Frasnian-Famennian boundary were recognized
29 95 (Mahboubi *et al.* 2015). At the top of the succession a marker bed of typical
30 96 Kellwasser facies is developed. This zonation is used in in our present study.

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32 98 **3. Material and Methods**

33 99 Samples of hard rock were collected in intervals ranging from 0.2 to 2 m, depending
34 100 on the thickness of the soft shale intercalations. Forty and sixty thin-sections were
35 101 prepared from rock samples both from the South Marhouma and Ben Zireg sections,
36 102 in order to to analyze petrofacies and fabrics. Microfacies descriptions follow Dunham

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3 103 (1962) for carbonate rocks and Schieber (1989) for black shales. The identified facies
4 104 were interpreted and related to a depositional environment setting according to
5 105 Wright & Burchette (1996), Flügel (2004) and Pas *et al.* (2013; 2014). Photographs
6 106 were taken with an integrated Olympus digital camera and with a scanning electron
7 107 microscope (JEOL 5600).

8 108 Magnetic susceptibility measurements were performed on 90 and 54 samples in the
9 109 South Marhouma and Ben Zireg sections, respectively, for preliminary investigation.
10 110 Various lithologies have been measured (shales, arenaceous and carbonate rocks).
11 111 In the laboratory, samples were cleaned from iron coatings prior to weighting with a
12 112 highly accurate balance (precision of 0.01g). Measurements were performed with a
13 113 Bartington susceptibility meter (MS-2). The unit of measure is expressed in $\times 10^{-7} \text{ m}^3$
14 114 kg^{-1} .

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116 **4. Results and interpretations**

117 **4.a. Lithostratigraphy**

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119 **4.a.1. Ben Zireg section**

120 The measured section is 26.6 m thick (Fig. 2). It includes five units (Units 1 – 5)
121 extending from the middle Frasnian to the early Famennian (Mahboubi *et al.*, 2015).
122 The succession is dominated by rhythmic fine-grained carbonates.

123 Unit 1 belongs to Frasnian Zone 5 (FZ 5) just above a depositional hiatus during the
124 early Frasnian. This Unit is characterized by ochre, sometimes brecciated, cherty
125 beds with convolute-lamination (Fig. 3a). Thin iron-hydroxide coatings are displayed
126 at the top of the unit.

127 Unit 2 belongs to FZ 6. It consists of greyish to brownish massive limestone beds,
128 centimeters to decimeters in thickness, intercalated by mm to cm thick argillaceous
129 limestone beds that display discrete nodular structures (Fig. 3b).

130 Unit 3 belongs to the interval ranging from FZ 7 to the top of FZ 11. It is characterized
131 by well-bedded ferruginous and argillaceous limestones frequently coated by
132 hardground films. The limestone beds are often wackstone with abundant pelagic
133 microfauna (tentaculites and entomozoan crustaceans) associated with sparse
134 euhedral pyrites and some phosphate grains. The amount of nodular structures

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3 135 increases progressively upward and they are mostly related to pressure-dissolution
4 136 surfaces.

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6 137 Unit 4 belongs to FZ 12. It is characterized by yellowish, massive, pseudo-nodular,
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8 138 clay-rich limestones sometimes interbedded with thin blackish shales. The limestones
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10 139 are mudstone to wackstone with sparse pelagic bioclasts (Fig. 2). Some of them are
11 140 slightly bioturbated.

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13 141 Unit 5 extends from FZ 13 to the early Famennian stage. It consists of greyish and
14 142 pinkish nodular to pseudo-nodular limestones and interbedded argillaceous micrite
15 143 yielding poor faunas, except some tentaculite and cephalopod fragments. In the
16 144 upper part of the limestones are 30 cm thick laminated blackish shales overlain by 35
17 145 cm thick laminated pinkish calcisiltites without fossils (Fig. 3c). The black shales
18 146 represent the Upper Kellwasser horizon.
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24 148 **4.a.2. Marhouma section**

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26 149 The Frasnian succession is approximately 75 m thick and includes four units (Units 1
27 150 – 4). The base of this section cannot be precisely dated. Details concerning conodont
28 151 contents and their biostratigraphic implications were presented in Mahboubi &
29 152 Gatovsky (2014). In contrast to Ben Zireg, this section is dominated by monotonous
30 153 shale deposits rich in carbonate nodules (Fig. 4).

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32 154 Unit 1 belongs to the FZ 1 – 4 intervals. It consists of dark shales (Fig. 3d) with rare
33 155 nodular limestones.

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35 156 Unit 2 extends from the upper part of FZ 1 – 4 to the lower part of FZ 8 – 10. It is
36 157 characterized by cm to dm thick, greyish to reddish, pseudo-nodular to nodular
37 158 bioclastic limestones (Fig. 3e), which alternate with unfossiliferous greyish to blackish
38 159 shales. The limestones are wackestone with *Styliolina* (tentaculites) coquinas; they
39 160 yield phacopid trilobites and cephalopods (*Mesobeloceras* sp.) on the surface of bed
40 161 MH9 (Feist, Mahboubi & Girard, 2016).

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42 162 Unit 3 belongs to the FZ 8 – 10 to FZ 13 interval. It is characterized by unfossiliferous
43 163 greenish and darkish shales with frequent reddish and greenish argillaceous nodular
44 164 limestones (Fig. 3f). Toward the top, input of siliciclastic material increases, including
45 165 mm thick intercalations of sandstone with planar-laminations. The Upper Kellwasser
46 166 horizon of this section is marked by plane-laminated shales (Fig. 3g).
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3 167 Unit 4 belongs to the early Famennian. It is mainly composed of dm thick diagenetic
4 168 blackish argillaceous nodular limestones displaying large orthoceratids and
5 169 brachiopods, and of unfossiliferous greyish laminated shales (Fig. 3h).
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9 171 **4. b. Facies**

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11 172 On the basis of differences in texture, fossil components, and lithological nature,
12 173 seven sedimentary facies are identified (Figs. 2, 4). The original texture of most rocks
13 174 has been obscured or obliterated during burial diagenesis, tectonic processes, or
14 175 both. Indeed, micro-shear zones and stylolithes are sometimes identified within
15 176 nodular limestones. Moreover, the original texture (micrite) was transformed into
16 177 microsparite.

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18 178 The facies description follows the distal to proximal order, from Facies 1 to Facies 7.
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24 180 **Laminated-black shales (F1):** In both sections, finely laminated black shales are
25 181 interbedded with silty shales, calcareous shales, or both. Bed thicknesses range from
26 182 centimeter to few meters. In the South Marhouma section, thick layers of black
27 183 shales also display *septaria* nodules, whereas such shales are less common at Ben
28 184 Zireg. The faunal content is represented only by poorly preserved shelly pelagic
29 185 organisms (e.g. tentaculites).

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31 186 Shales, such as those at the base of Marhouma section (Fig. 3d), are usually
32 187 interpreted as deposited in deep basin settings (e.g. Boulvain *et al.* 2004), probably
33 188 below the storm wave-base. This facies is very common in North Africa (e.g. Ahnet
34 189 and Mouydir basins (Wendt *et al.* 2006), with a high accumulation of organic matter
35 190 (Boote, Clarke-Lowe & Traut, 1998). They are considered as the deepest facies in the
36 191 Frasnian interval.
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47 193 **Lithoclastic floatstone (F2):** The lithoclasts mainly consist of chaotic, randomly
48 194 organized angular to rounded limestone and cherty clasts (Fig. 5a, b). Carbonate
49 195 clasts are composed of monomict, poorly sorted pelagic mudstones belonging to
50 196 Facies 3 (see below). Lithoclasts are supported by a matrix composed of calcisiltite,
51 197 clay, microsparite, and iron-hydroxide. The fossil components consist of rare pelagic
52 198 ostracods (entomozoans) and tentaculite debris. Inverse grading in the lower part of
53 199 some dm- thick beds are observed.
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3 200 This facies was assigned to seismo-turbidites by Mutti *et al.* (1984) or megaturbidites
4 201 by Cook *et al.* (1972). In our case, this facies is restricted to Unit 1 in association with
5 202 convolute bedding. It corresponds to debris flows into a distal pelagic domain. This
6 203 facies may also correspond to gravitational deposits that formed under low
7 204 sedimentation rates and unstable depositional conditions (Rossetti & Góes, 2000). F2
8 205 is similar to facies described elsewhere in the Upper Devonian successions from the
9 206 Eastern Anti-Atlas (Wendt & Belka 1991). Convolute structures associated with
10 207 reworked lithoclasts can be generated by seismic shocks giving rise to downslope
11 208 movements (Spalletta & Vai 1984).
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20 210 **Poorly fossiliferous mudstone (F3):** In the two sections, this facies is well
21 211 represented. In the Marhouma section F3 is found in Units 1 and 3 consisting of
22 212 greyish nodular cm-thick beds in shales. In the Ben Zireg section it occurs mainly in
23 213 Units 3 and 5 as centimeter-thick fine-grained limestone beds or greyish nodular
24 214 limestones, respectively. The matrix of this facies is micrite or microsparite. Micritic
25 215 limestones lack bioturbation fabrics, whereas burrowing traces are sometimes
26 216 observed in nodular limestones embedded within greyish shales. F3 is characterized
27 217 by poor faunal content that is represented by pelagic organisms such as tentaculites,
28 218 pelagic molluscs, entomozoans, and radiolarians. No current fabrics have been
29 219 macroscopically observed in this facies.

30 220 The fine-grained matrix and rare fossils suggest low energy and open marine
31 221 conditions, remaining probably under the storm wave-base (Pas *et al.*, 2013; 2014a).
32 222 The scarcity of biogenic activities (e.g. borings and burrows) could reflect oxygen-
33 223 depleted waters (Flügel, 2004). Nodules are often of late diagenetic origin, and were
34 224 presumably produced in a deep burial diagenetic environment (James & Choquette
35 225 1990).
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48 227 **Argillaceous pelagic wackstone (F4):** This facies occurs mainly in middle Frasnian
49 228 strata in both sections. It comprises cm- to dm- thick greyish to reddish limestones.
50 229 Pressure solution processes commonly triggered tectonic stylolithisation. The
51 230 common type of texture is wackstone with microbivalves occurring in a patchily
52 231 distribution. Thus, the matrix displays ferruginous blisters organized into isolated or
53 232 grouped, concentric internal structures. The faunal content is commonly high, with
54 233 tentaculites as the dominating organisms followed by entomozoans, radiolarians,
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3 234 cephalopods, and pelagic mollusks (Fig. 5d). Additionally, scarce benthic faunas are
4 235 represented by debris of trilobites, brachiopods, and ostracods. Bioclasts are
5 236 generally poorly sorted; sometimes they are concentrated into mm-thin laminations
6 237 with a random distribution of fossils and they are partially affected by bioturbation.

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8 238 On the basis of the abundance of pelagic assemblages, facies F4 is interpreted as
9 239 deposited in a deep-water environment, likely just below the storm wave-base (*Pas et*
10 240 *al.*, 2013; 2014a). Finely laminated biogenic detritus is interpreted as being deposited
11 241 by turbidity currents or distal tempestites (*sensu* Aigner, 1985).
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18 243 **Diversified mudstone to wackstone (F5):** This facies is mostly found in the
19 244 uppermost part of both sections. In the South Marhouma section, it is composed of
20 245 large dark diagenetic nodules of early *triangularis* Zone age. In the Ben Zireg section,
21 246 the same facies occurs within greyish nodular muddy limestones. Fossil components
22 247 are dominated by nektonic faunas such as cephalopods with *Orthoceras*, mostly
23 248 fragmented and poorly preserved (Fig. 5c). Pelagic organisms, radiolarians,
24 249 entomozoans, and tentaculites, are less frequent. Benthic faunas are more abundant
25 250 compared with Facies 4 (Fig. 5e); they are dominated by ostracods, skeletal debris of
26 251 echinoderms, brachiopods, and trilobites. This facies is locally bioturbated. Early
27 252 diagenetic geopetal fillings are recognized within some rotated ostracods and
28 253 cephalopods coquinas.

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36 254 In light of the increase in benthic faunal diversity, which is a striking feature of zones
37 255 with normal oxygen concentration (Flügel, 2004), the depositional setting of this
38 256 facies might be located above storm wave-base.
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43 258 **Lime ostracod mudstone (F6):** This facies is not frequent in the studied sections
44 259 (samples BZ10a, BZ11, BZ13a, and MH6'). It occurs mostly in FZ 12 in the Ben Zireg
45 260 section. It consists of yellowish thin bedded argillaceous limestones. The matrix is
46 261 microsparite to sparite, rarely containing euhedral replacement of dolomite crystals.
47 262 The bioclastic components of this mudstone consist predominantly of benthic
48 263 ostracods (Fig. 5f) followed by trilobite and brachiopod fragments. Additionally,
49 264 pelagic elements are limited to entomozoans, radiolarians, and unrecognized pelagic
50 265 shell fragments. Micritic geopetal infillings are sometimes observed. The systematic
51 266 study of benthic ostracods from acid residues revealed the presence of the suborders
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3 267 Podocopida and Metacopida that can be related to the Assemblage III of Casier
4 268 (2008).

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6 269 The abundance of the ostracod assemblage might indicate a more proximal
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8 270 depositional setting compared with the previous environment, likely below the fair
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10 271 weather wave-base. The frequent occurrence of disarticulated ostracods may
11 272 suggest para-autochthonous aggregations produced by episodic storm-induced sea
12 273 floor disturbances (Schülke & Popp, 2005).

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16 275 **“Microbial (?) shale” (F7):** This facies is common in "restricted" environments in the
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18 276 latest Frasnian. It is exhibited in the South Marhouma section as lenticular cm- to dm-
19 277 thick darkly carbonaceous to silty shale. The texture is close to the striped shale
20 278 facies of Schieber (1989), with silt and mud couplets (light) alternating with
21 279 carbonaceous silty shale (dark) (Fig. 6f). In petrographic thin section, the texture
22 280 displays discontinuous wavy-crinkly laminae of kerogenous matter that are widely
23 281 associated with framboïdal pyrites and cubic euhedral crystals (Figs. 6b, c, e). Also,
24 282 terrigenous quartz grains and isolated mud fragments can be found. Imbricated flat
25 283 pebbly conglomerates with argillaceous clasts are observed in bed MH26bas (Fig.
26 284 6a). Characteristic organisms are reworked benthic ostracods, rare brachiopods, and
27 285 undetermined mollusk shells.

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29 286 In the Ben Zireg section, the microbial (?) shale facies is observed in bed BZ15D
30 287 (Uppermost FZ 13). It consists of pink laminated calcareous silty shale. The thin
31 288 sections display a fine-grained matrix with abundant dolomite crystals and rare mica
32 289 crystals. The wavy-crinkly laminae described above are less common (Fig. 6e) and
33 290 organized into fine kerogenous units alternating with fine-grained calcareous
34 291 laminae. SEM observations display tube-like shapes (Fig. 6d) occasionally forming
35 292 ramiform structures and sometimes associated with rare framboïdal pyrites. Fossils
36 293 are very sparse, with brachiopods, benthic ostracods and tentaculite fragments.

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38 294 Framboïdal pyrite is commonly present in hypoxic to anoxic environments (e.g. Li
39 295 Tian *et al.* 2014; Peckmann & Thiel 2004; Wignall, Newton & Brookfield, 2005) where
40 296 crystallization is partly controlled by bacterial activity (e.g. Folk, 2005; Mac Lean *et*
41 297 *al.*, 2008). The association of wavy to wavy-crinkly structures with kerogen laminae
42 298 has been considered resulting from the occurrence of benthic microbial
43 299 (cyanobacterial?) mats (e.g. Schieber, 1986, 1989; Sur *et al.*, 2006; Deb, Schieber &
44 300 Chaudhuri, 2007) and coccoidal bacteria have been identified within such deposits

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3 301 (Kaźmierczak, Kremer & Racki, 2012). Even if no obvious diagnostic feature of
4 302 primary cyanobacterial mats (e.g. web-like texture indicator of benthic coccoidal
5 303 remnants, Kremer & Kaźmierczak, 2005) were found in the studied sections, the
6 304 presence of organic matter, framboidal pyrite, wavy lamination, wavy lenticular
7 305 lamination with shale fragments, wavy crinkly structure and tubular structures (SEM)
8 306 are strongly suggestive of the presence of microbial mats acting during the deposition
9 307 of the black shales in the two sections. The presence of mud and silt couplets with
10 308 locally reworked fossils and mixing of conodont assemblages indicate episodic high
11 309 energy episodes attributed to storms. Such an interpretation is compatible with that of
12 310 Schieber (1986, 1989) who located the depositional environment of similar shales
13 311 between fair weather wave-base and average storm wave-base.
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23 313 **4.c. Magnetic susceptibility trends**

24 314 First application of the magnetic susceptibility (MS) technique (Figs. 8, 9) provided
25 315 extremely low MS values for the Frasnian and basal Famennian strata. These vary
26 316 between $0.1 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ and $8 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ at the south Marhouma section with an
27 317 empirical average value of $1.9 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. They are even lower in the Ben Zireg
28 318 anticline where they fluctuate between $3.7 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ and $0.4 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$ with
29 319 an average of $1.3 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. Even if the reliability of the MS measures should be
30 320 tested by additional magnetic techniques (Da Silva *et al.*, 2013) to appreciate
31 321 problems of re-magnetization or diagenesis, the mean values are compatible with
32 322 those from other Frasnian sites. In both Algerian sections the averages of MS values
33 323 are lower than those for the $\text{MS}_{\text{marine standard}}$ ($5.5 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$) of Ellwood *et al.* (2011)
34 324 and (Da Silva, Mabile & Boulvain, 2009). This was also observed in the Carnic Alps
35 325 (Pas *et al.*, 2014a) and in the Dinant Synclinorium (Pas *et al.*, 2014b) where mean
36 326 values range from 0.1 to $1 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$.

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46 327 Qualitative analysis of the magnetic susceptibility suggests the same global trend
47 328 with shared peaks, which are considered as isochronous (Crick *et al.* 2002), in the
48 329 South Marhouma and in Ben Zireg sections (Figs. 8, 9). At Marhouma, the lower part
49 330 of the section from FZ1-4 to FZ6-7 shows important fluctuation of MS value from 0 to
50 331 $8 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. The upper part of the section, from FZ8-10 to Famennian, shows low
51 332 values between 0 and $3 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. At Ben Zireg, the lower part of the section
52 333 from FZ5 to FZ7 shows little fluctuation, between 0 and $3 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$. In the upper
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3 334 part of the section, from FZ8-10 to Famennian, the MS value remains low, between 0
4 335 and $1 \times 10^{-7} \text{ m}^3 \text{ kg}^{-1}$.

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7 8 337 **5. Discussion**

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10 339 **5.a. Local depositional environment**

11 340 Paleoenvironmental interpretations of depositional settings of Facies 1 and 3 to 7
12 341 observed in both sections (plus F2 at Ben Zireg only) allow proposing that the
13 342 sediments were deposited along a low angle, mid to outer ramp profile *sensu* Wright
14 343 & Burchette (1996) at regional scale (Fig. 7).
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16 345 **5.a.1. Ben Zireg section**

17 346 The section is dominated by fine grained carbonates above a major gap in the lower
18 347 Frasnian. This gap corresponds to a non-deposition and erosion? in submarine
19 348 setting and was related elsewhere to bottom currents (Hüneke, 2006). The presence
20 349 of such currents has not been evidenced at Ben Zireg. An outer ramp model is
21 350 suggested for this area at the northern margin of Algerian Sahara (Fig. 7). In this
22 351 model the deepest deposits are represented by some black shale intervals (Facies 1,
23 352 Fig. 2 and 3d) and siliceous deposits with convolutes and breccias (Facies 2; Figs.
24 353 3a, 5a, b). In our model (Fig. 7), Facies 4 and 5 were emplaced below storm wave-
25 354 base, as no current features were found. In Facies 4 the presence of submicrometric
26 355 hydroxides may result from iron - bacteria activity (Mamet & Préat 2006). Common
27 356 hardgrounds point to repeated episodes of cementation on the sea floor. The
28 357 proximal part of the ramp displays accumulations of fragmented bioclasts from both
29 358 benthic and pelagic communities. This is interpreted as indicating a deposition
30 359 between storm wave-base and fair-weather wave-base, with an increasing amount of
31 360 benthic fauna upward from Facies 5 to Facies 7 indicative of a shallowing upward
32 361 trend.
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34 363 **5.a.2. South Marhouma section**

35 364 The section is dominated by mudrocks (e.g. shales) and fine-grained carbonate
36 365 deposits with open marine fauna.
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3 366 From FZ 1 to 4 sedimentation resumed in autochthonous facies 1 and 3 which are the
4 367 deepest facies. Facies 1 (black shales) probably indicates dysoxic to anoxic bottom
5 368 conditions. Facies 2 was not found (Fig. 8). From FZ5 to FZ13 the nodular
6 369 argillaceous limestones (Facies 3) with mudstone texture and rare fauna suggest
7 370 distal depositional setting under quiet depositional conditions. The fine-grained
8 371 bioclastic mudstone and wackstone (Facies 4 and Facies 5) with overwhelming
9 372 abundance of open marine fauna (Facies 4) attest depositional setting similar to F1
10 373 and F3 but with some influence of shallow-water. Frequent occurrences of dark
11 374 shales in this setting may reflect confined conditions when only organic matter was
12 375 deposited upon the substrate. A shallower ramp is recognized during FZ6 – 7 and
13 376 FZ12 by the increase of benthic faunal components (Facies 5). The shallowest facies
14 377 herein is depicted by the occurrence of microbial (?) benthic mats (Facies 7) that are
15 378 affected by storm action below the fair weather wave-base.

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27 380 **5.a.3. Comparison between both sections**

28 381 Stratigraphic correlation between Ben Zireg and Marhouma was documented in
29 382 Mahboubi *et al.* (2015). The Frasnian deposits of the South Marhouma section are
30 383 nearly three times thicker than those of Ben Zireg, though mostly represented by
31 384 distal shaly deposits (Facies1). We conclude in a higher sedimentation rate under
32 385 subsiding basinal conditions at Marhouma. In contrast, distal carbonate deposits with
33 386 minor shaly interbeds characterize Ben Zireg where Facies 3 to Facies 5 dominate.
34 387 We suggest a discrete submarine rise setting on an outer ramp under low
35 388 sedimentation rates. Such a depositional setting results either from submarine rise
36 389 topography, or from enhanced current activity, or from a more distant location to the
37 390 source areas of detrital inputs.

38 391 As a whole, the Frasnian interval at Marhouma is punctuated by several
39 392 developments of hypoxic facies (black and grey shales) that are not identified in the
40 393 Ben Zireg section. The absence of such facies is presumably due to the submarine
41 394 rise topography or to currents activity or to a far distant location regarding the
42 395 sources of detrital and biogenic materials magnetic susceptibility values are low, see
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55 398 **5.b. Sea-level fluctuations**

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3 399 Integrating both lithofacies and MS data (Figs. 8 and 9), as well as data of conodont
4 400 biofacies (Seddon & Sweet, 1971; Sandberg, 1976; Klapper & Barrick, 1978;
5 401 Sandberg & Ziegler 1979) 'recently published in both studied sections (Mahboubi &
6 402 Gatowsky, 2014; Mahboubi *et al.*, 2015), we tentatively interpret environmental
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8 403 changes through middle and late Frasnian times in terms of bathymetrical variation.
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10 404 However, we are aware that changes in bathymetry might not be the sole cause of
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12 405 fluctuations in the percentage of conodont genera in succeeding populations (Belka
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14 406 & Wendt 1992).
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17 18 408 **5.b.1. Early Frasnian**

19 409 During the early Frasnian (FZ1 – 4), the Marhouma section displays a regressive
20 410 trend with an upward change from facies 1 to 3 and fluctuating MS values (Fig. 8).
21 411 This trend is in contradiction to the transgressive trend recorded in North America
22 412 (Fig. 10) at that time. It could be related to the specific location of the Marhouma
23 413 section where abundant fine-grained siliciclastic inputs from the emerging West
24 414 African Shield might have obscured the eustatic signal.
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27 28 416 **5.b.2. Middle Frasnian**

29 417 Between FZ 5 and the beginning of FZ 8/10, both sections display instabilities of MS
30 418 and lithofacies values (Fig. 8 and 9). During this interval, at Marhouma, slight shifts of
31 419 MS values roughly reflect concomitant shifts in lithofacies. In contrast, at Ben Zireg,
32 420 shifts in both MS and lithofacies values, though discernible, are less pronounced with
33 421 lower amplitudes in their maximum excursions. MS values, in particular, that vary
34 422 between 0 and 8 units at Marhouma, are much lower at Ben Zireg with a shift from 1
35 423 to 3 units and as such being almost insignificant. In parallel, variations in succeeding
36 424 lithofacies are more vigorous with shifts from F1 to F6 at Marhouma, whereas these
37 425 are restricted to F2+3 and F4 at Ben Zireg. Mean prevalence of F4 in both sections
38 426 along with a poorly documented decrease in MS values coincide with biofacies
39 427 indicators available at Ben Zireg that shift temporarily from shallower Po-Ic
40 428 (*Polygnathus-Icriodus*) in FZ 6 to deeper Po between FZ 7 and the beginning of
41 429 FZ8/10 before returning to Po-Ic thereafter (Mahboubi *et al.*, 2015).
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44 431 During the middle Frasnian the global trend is transgressive (Johnson & Sandberg,
45 432 1988; Sandberg *et al.*, 1992). In the nearby Tafilalt region this trend is perceptible
46 433 since FZ8 (Dopieralska, Belka, & Walczak, 2016) and culminates at the end of FZ 10
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3 433 (Fig. 10). This trend is likewise to be observed at Ben Zireg. At Marhouma, the
4 434 global transgressive trend begins in the lower part of FZ6 to FZ10 but a marked
5 435 regressive event occurred at the transition from during FZ6-7.
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10 437 **5.b.3. Late Frasnian**

11 438 MS values remain constantly very low throughout the late Frasnian without any
12 439 significant changes at the Upper Kellwasser level in particular.

13 440 During the early FZ11 there is a regressive event followed by a transgressive peak in
14 441 the late FZ 11. This transgressive peak is characterized by a significant extension of
15 442 deep sea lithofacies, associated with biofacies Po-Pa (*Polygnathus-Palmatolepis*)
16 443 dominated conodont associations. This signal is most obvious at Ben Zireg
17 444 (Mahboubi *et al.*, 2015), whereas, at Marhouma, the paucity of available conodont
18 445 record prevents to confirm the slight deepening of the sedimentary setting there
19 446 (Mahoubi & Gatowsky, 2014). The curve of Ben Zireg remarkably coincides with the
20 447 curves obtained in Euramerica and in the Tafilalt (Fig. 10). At Marhouma, only the
21 448 transgressive peak is clearly recorded. Dopieralska, Belka, & Walczak (2016)
22 449 emphasize the importance of the *semichatovae* transgression with the highest
23 450 positive shift in ϵNd values within FZ 11. This event has earlier been described from
24 451 Euramerica where it is characterized by the sudden spread of *Palmatolepis*
25 452 *semichatovae* in FZ 11 (Sandberg *et al.* 1992; Sandberg, Morrow & Ziegler, 2002).
26 453 This species has not been established in the studied sections, but the obvious
27 454 transgressive episode recorded within FZ 11 at both Marhouma and Ben Zireg may
28 455 most likely correspond to this event. As a whole, the *semichatovae* transgression is
29 456 evidenced in the Saharian Platform.

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38 457 During FZ 12 shallower environments reappear between Facies 5 and Facies 6 at
39 458 Ben Zireg, and between Facies 1 and Facies 7 at Marhouma. Biofacies in both
40 459 sections clearly indicate a shallowing trend with predominance of Po-An (*Polygnathus-*
41 460 *Ancyrodella*) (Mahoubi & Gatowsky, 2014; Mahboubi *et al.*, 2015). This regressive
42 461 trend was also identified in Euramerica and in the Tafilalt (Fig. 10).

43 462 At the top of FZ 12 and the transition between FZ 12 and FZ 13 the hypoxic Lower
44 463 Kellwasser horizon (LKW), usually occurring elsewhere, is not developed in its typical
45 464 shale facies in our sections. Litho- and biofacies indicate a sudden increase in
46 465 bathymetry followed up by fluctuations of lithofacies that average increase of water
47 466 depth up to the Upper Kellwasser (UKW) horizon. Indicators of concomitant biofacies
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3 467 appear to be somewhat contradictory, as they remain constant in prevalence of Pa-
4 468 Po and Pa at Ben Zireg but return to shallower signals at Marhouma (Mahboubi &
5 469 Gatovsky 2014, Mahboubi *et al.* 2015). The increase in bathymetry observed in our
6 470 sections is in accordance with that of Euramerica and Tafilalt (Fig. 10). Dopieralska,
7 471 Belka, & Walczak (2016) also identified regressive trends coinciding in particular with
8 472 the Lower and Upper Kellwasser extinction events at the FZ 12/13 transition and at
9 473 the top of FZ 13 respectively. At Ben Zireg and Marhouma the LKW deposits are not
10 474 lithologically recognized and precisely located; any regressive trend occurs slightly
11 475 earlier, still within FZ12 when biofacies Po-An (*Polygnathus-Ancyrodella*) biofacies
12 476 dominates. This anomaly might perhaps be introduced by local palaeoecological
13 477 factors, in relation to the absence of the Lower Kellwasser horizon, as thereafter
14 478 “normal” transgressive conditions are progressively emplaced matching the global
15 479 sea-level trend.

16 480 The Upper Kellwasser horizon is characterized by its typical hypoxic facies at Ben
17 481 Zireg. Bathymetric criteria point to a relative highstand of sea-level at the beginning of
18 482 the event followed up by a marked decrease of water depth until its top with
19 483 development of Pa-An biofacies (Mahboubi *et al.*, 2015) and occurrence of possible
20 484 “microbial shales” (F7). In contrast, at Marhouma, the drop in sea level seems to start
21 485 earlier when F7 and Po-Ic (*Polygnathus-Icriodus*) are present at the beginning of the
22 486 presumed Upper Kellwasser (Mahboubi & Gatovsky, 2014). Consequently, it cannot
23 487 be excluded that the equivalent of the Upper Kellwasser event starts a little earlier at
24 488 Marhouma than considered by Mahboubi & Gatovsky (2014). At top of FZ 13 the
25 489 major regression during the UKW event occurs both at Ben Zireg and Marhouma and
26 490 is in accordance with the results of Dopieralska, Belka, & Walczak (2016) and
27 491 Johnson & Sandberg (1988).

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29 493 **5.b.4. Summary**

30 494 The bathymetric curves in the Saharian Platform display a continuing sea-level rise
31 495 through the middle Frasnian punctuated by a first regression at the base of FZ11,
32 496 but with a minor regression at FZ6 at Marhouma. During the late Frasnian in
33 497 Euramerica, this global transgressive event achieves its highest stand from the top of
34 498 FZ 11 to FZ 13, intercalated by two regressions prior to and succeeding the Lower
35 499 Kellwasser (LKW) event. This is matched by the recently established curve based on
36 500 Nd isotopic data presented by Dopieralska, Belka, & Walczak (2016). Coincident

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3 501 results on bathymetric evolution obtained by an independent method, data gathered
4 502 from neighboring southeastern Moroccan terrains, are of importance for the
5 503 comparative interpretation of the curve established in SW Algeria (Fig. 10).

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8 504 As expected, Frasnian sections of SW Algeria display a similar sea-level evolution
9 505 through mid- and late Frasnian times than in neighboring parts of Gondwana
10 506 (Morocco). Differences in deposits (absence or presence of LKW), in timing (changes
11 507 in sea-level occurring later in SW Algeria than elsewhere) and amplitude of changes
12 508 in both litho- and biofacies between sites might result from effects of locally different,
13 509 tectonically driven rates in subsidence. In addition, sampling bias cannot be excluded
14 510 in highly condensed portions such as in the lower part of the Ben Zireg section, or, on
15 511 the contrary, when conodonts are rather scarce in deposits with high sedimentation
16 512 rates as occur in the early through middle Frasnian in the Marhouma trough
17 513 (Mahboubi *et al.*, 2015).

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27 515 **6. Conclusions**

28 516 The investigated sections through the middle and late Frasnian are composed of
29 517 seven marine lithofacies that vary in time and duration throughout the successions.
30 518 These lithofacies are organized along a very low angle, mid to outer ramp at the
31 519 scale of the western part of the Saharian platform. Condensed carbonate
32 520 sedimentation on discrete highs prevail in the North (Ben Zireg) whereas abundant
33 521 shaly deposits occur in the South (Marhouma). Vertical facies changes are most
34 522 perceptible at Marhouma both during the early middle and the latest Frasnian where
35 523 rapid shifts between deep and shallow lithofacies occur. During the late middle and
36 524 early upper Frasnian more stable conditions with the deposition of bioclastic mud-
37 525 and wackstones prevail. Conversely, at Ben Zireg, these latter conditions
38 526 characterize the condensed middle and earliest late Frasnian succession. A
39 527 deepening occurred in the upper part of FZ 11, followed up by a marked shallowing
40 528 at the beginning of FZ 12 and an average deepening up to the Upper Kellwasser.
41 529 The latter is marked in both sections by a regressive-transgressive cycle.

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51 530 Provisional measurements of magnetic susceptibility provided very low values. Shifts
52 531 are more pronounced with rapid variations in the lower part of the middle Frasnian,
53 532 remaining constantly rather low thereafter up to the Frasnian/Famennian boundary in
54 533 both sections. In particular, no significant shift is available at the equivalent levels of
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3 534 the Kellwasser event. Further, more detailed and bed-by-bed measurements are
4 535 necessary to reconsider MS trends comparatively.

5 536 A sea-level curve, tentatively established mainly on data from Ben Zireg matches the
6 537 “standard” curves already provided at a world scale. Especially, the middle Frasnian
7 538 transgression, the lower FZ11 regression, the *semichatovae* transgression within FZ
8 539 11, the lower FZ12 regression, the upper FZ13 transgression and Upper Kellwasser
9 540 regression are clearly evidenced in the Saharian platform.

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741 **Figure captions**

742 **Fig. 1.** (a) Location of South Marhouma section (Ougarta basin) and Ben Zireg
743 section (Bechar basin) in NW Algeria (photograph from Google Earth). (b)
744 Investigated section in the Saoura region (after Petter, 1959). (c) Investigated section
745 in the Ben Zireg anticline (after Pareyn, 1961).

746

747 **Fig. 2.** Lithological column with relative abundance of fossil components and facies
748 fabrics of the Ben Zireg section. Conodont zones from Mahboubi et al. (2015).
749 Lithostratigraphic units: (Unit 1) ochre cherty limestones with soft-deformations, (Unit
750 2) massive micritic limestones, (Unit 3) ferruginous limestones, (Unit 4) pseudo
751 nodular argillaceous limestones, (Unit 5) nodular limestones. Abbreviations: Hg, Hard
752 ground; M, Mudstone; W, Wackestone; P, Packstone; F, Floatstone; FZ, Frasnian
753 Zone (after Klapper & Kirchgasser, 2016).

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755 **Fig. 3.** Lithofacies. (a) Convolute laminations (Ben Zireg). (b) Thin-bedded, upper
756 Frasnian micritic limestones (Ben Zireg). (c) Detail of the Upper Kellwasser bed in the
757 Ben Zireg section with a thin layer of black shales (red arrow) superseded by
758 laminated pinkish calcisiltic shale (black arrow). (d) Black shales (Marhouma). (e)
759 Alternating pseudonodular limestone beds and grey shales (Marhouma section). (f)
760 Interbedded argillaceous micritic nodules (Marhouma Formation). (g) Upper
761 Kellwasser bed in the South Marhouma section with laminated black to pinky shales.
762 (h) Dm-thick diagenetic limestones and black shales from early Famennian strata of
763 the Marhouma section.

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765 **Fig. 4.** Lithological column with relative abundance of fossil components and facies
766 fabrics of the South Marhouma section. Conodont zones from Mahboubi & Gatovsky
767 (2014). Lithostratigraphic units: (Unit1) dark shales, (Unit 2) bioclastic
768 nodular/pseudonodular limestones-grey shales, (Unit 3) nodular muddy limestones-
769 greenish/darkish shales, (Unit 4) Diagenetic limestones/black shales. Abbreviations:
770 Hg, Hard ground; M, Mudstone; W, Wackestone; P, Packstone, *L.tr.*, Lower
771 *triangularis*; FAM, Famennian; FZ, Frasnian Zone.

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3 773 **Fig. 5.** Facies of the depositional environments of the South Marhouma section and
4 the Ben Zireg section. Scale (yellow bar) is 1mm. (a) Facies F2, outer ramp deposit:
5 774 reworked mudstone layers in the Ben Zireg section (bed BZ2B). (b)) Facies F2,
6 775 outer ramp deposit: microscopic view (bed BZ1C). (c) Facies F6, mid-outer ramp
7 776 deposit: lime mudstone with cephalopod bioclasts (bed MH34. (d) Facies F4, outer
8 777 ramp deposit: pelagic argillaceous wackstone displaying distinct lamination by
9 778 parallel arrangement of tentaculite coquinas (bed MH10). (e) Facies F6, outer ramp
10 779 deposit: diversified wackestone with bioclasts consisting of abundant brachiopod
11 780 shells (bed MH32). (f)) Facies F6, mid ramp deposit: fine-grained mudstone with
12 781 benthic ostracods (bed BZ10B). Abbreviations: br, brachiopod; go, goniatite; ort,
13 782 orthoceras; os, ostracod; pa, parabreccia; ra, radiolarian; tr, trilobite; te, tentaculite
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23 785 **Fig. 6.** Facies F7, mid ramp deposits, latest Frasnian at South Marhouma and Ben
24 786 Zireg sections. (a) Flat-pebble conglomerate fabric (bed MH26bas). (b) SEM image
25 787 of kerogenous laminae (wavy-crinkly structures) (bed MH29). (c, e) Kerogenous
26 788 laminae. Note that these structures are more abundant in the South Marhouma
27 789 samples (picture b, bed MH29) compared to the Ben Zireg sample (picture e, bed
28 790 BZ15D). (d) SEM image of tube-like structures (black arrows, bed BZ15D) associated
29 791 with framboidal pyrite (white arrow). (f) Finely-laminated striped shale displaying
30 792 graded silt-mud couplets (bed MH30).
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33 795 **Fig. 7.** Sedimentary model in NW Algeria during the Frasnian period (South
34 796 Marhouma and Ben Zireg sections). This model shows a mid to outer ramp setting
35 797 with lateral distribution of facies from the most proximal setting (F7) to the the most
36 798 distal (F1). SWB, Storm Wave-Base; FWWB, Fair Weather Wave-Base.
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39 801 **Fig. 8.** Magnetic susceptibility evolution, facies change, and sea-level fluctuations
40 802 through the Frasnian in the South Marhouma section. FZ: Frasnian Zones, LKW:
41 803 Lower Kellwasser, UKW: Upper Kellwasser.
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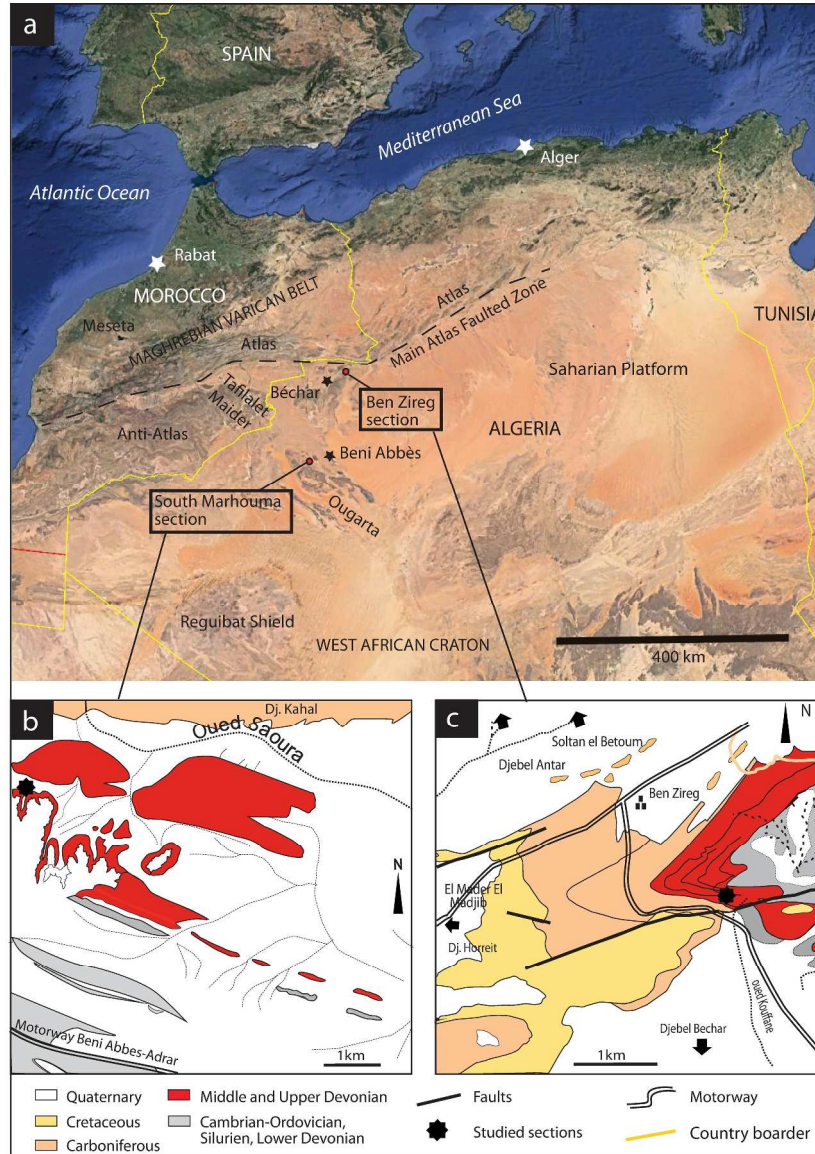
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3 804 **Fig. 9.** Magnetic susceptibility evolution, facies change, and sea-level fluctuations
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5 805 through the Frasnian in the Ben Zireg section. FZ: Frasnian Zones, LKW: Lower
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7 806 Kellwasser, UKW: Upper Kellwasser.
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12 809 **Fig. 10.** Comparison of sea-level fluctuations from Euramerica and North Africa
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14 through the Frasnian stage. FZ (Frasnian Zones) after Klapper & Kirchgasser (2016),
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16 810 relative duration of conodont Zones are from Becker, Gradstein & Hammer (2012). In
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18 811 grey anoxic events. UKW: Upper Kellwasser; LKW: Lower Kellwasser; FAM:
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Mahboubi et al., Fig. 1

Fig. 1. (a) Location of South Marhouma section (Ougarta basin) and Ben Zireg section (Bechar basin) in NW Algeria (photograph from Google Earth). (b) Investigated section in the Saoura region (after Petter, 1959). (c) Investigated section in the Ben Zireg anticline (after Pareyn, 1961).

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Mahboubi_et_al_Fig 2

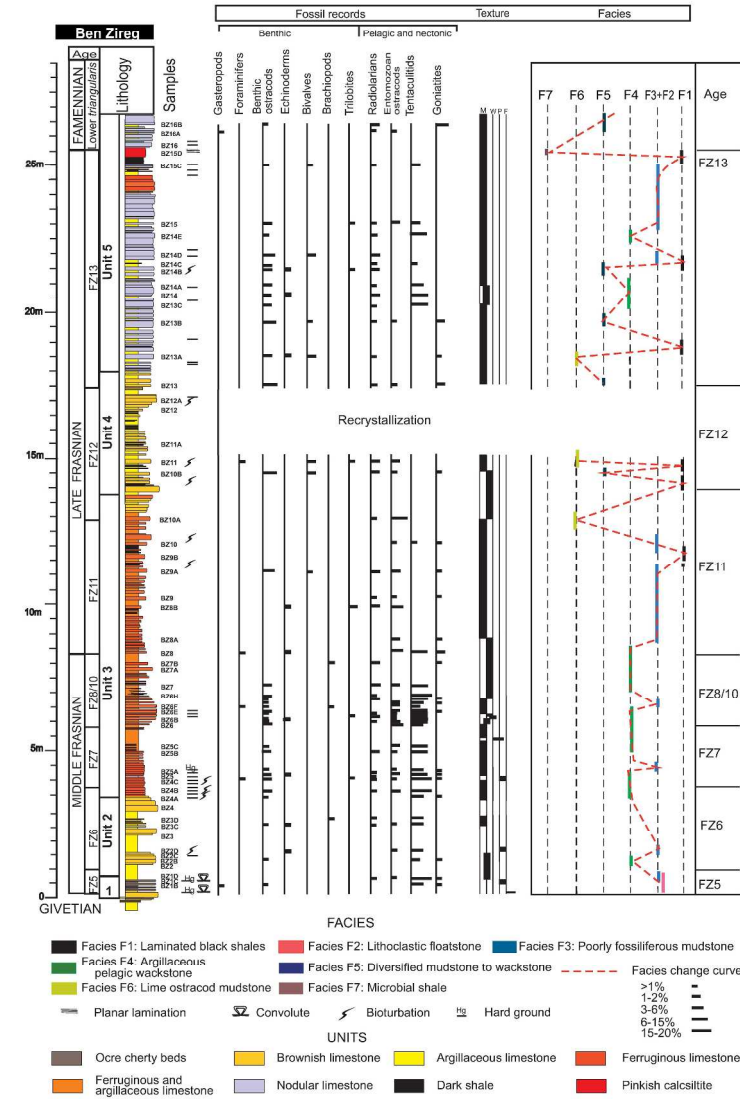


Fig. 2. Lithological column with relative abundance of fossil components and facies fabrics of the Ben Zireg section. Conodont zones from Mahboubi et al. (2015). Lithostratigraphic units: (Unit 1) ochre cherty limestones with soft-deformations, (Unit 2) massive micritic limestones, (Unit 3) ferruginous limestones, (Unit 4) pseudo nodular argillaceous limestones, (Unit 5) nodular limestones. Abbreviations: Hg, Hard ground; M, Mudstone; W, Wackestone; P, Packstone; F, Floatstone; FZ, Frasnian Zone (after Klapper & Kirchgasser, 2016).

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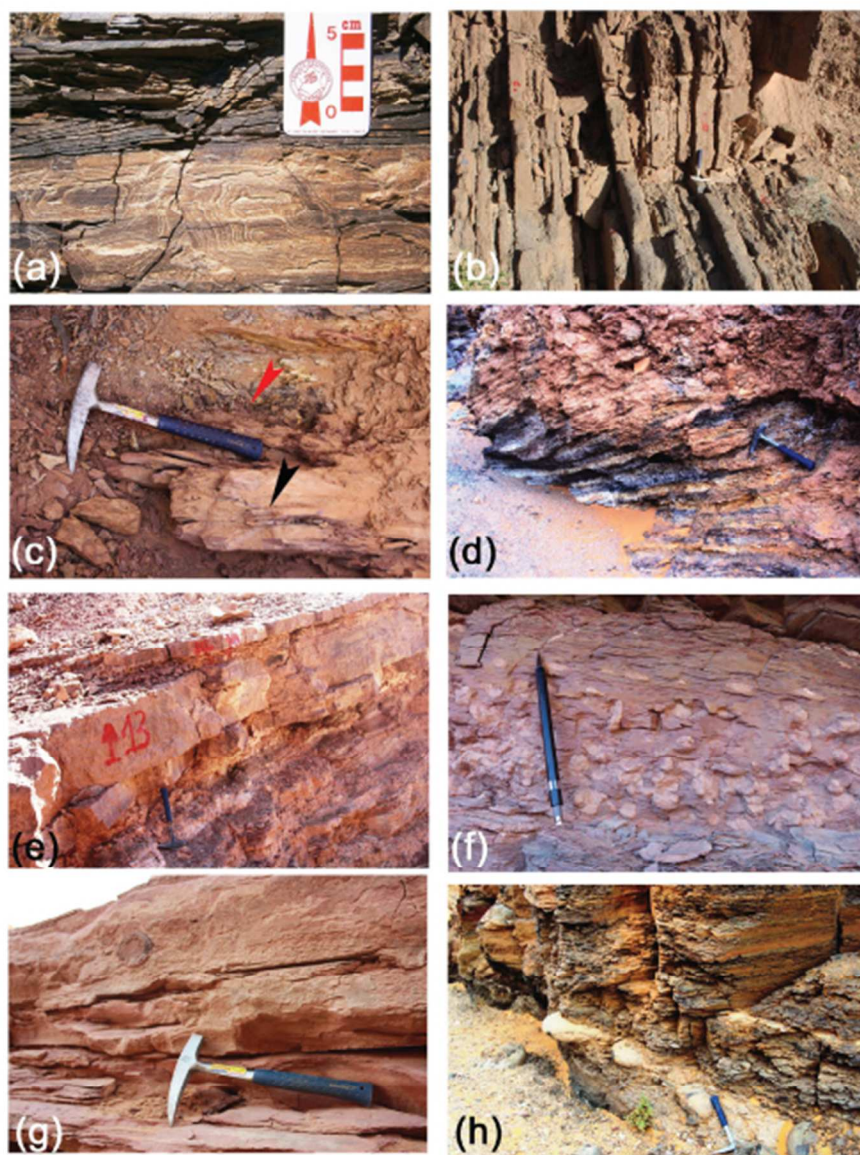
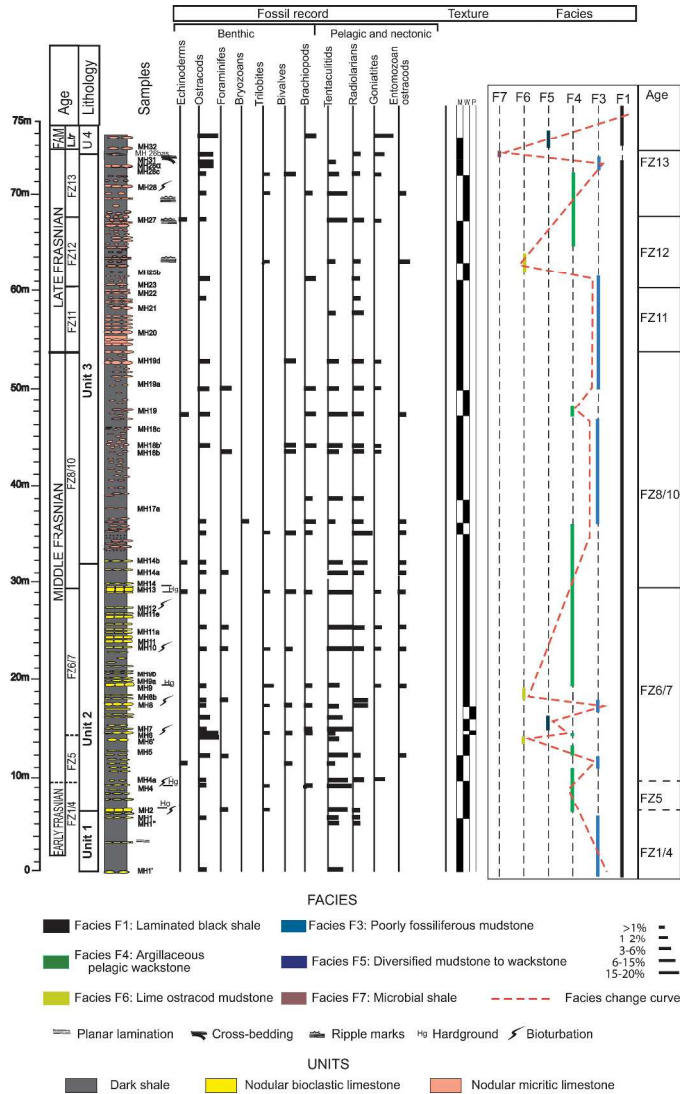


Fig. 3. Lithofacies. (a) Convolute laminations (Ben Zireg). (b) Thin-bedded, upper Frasnian micritic limestones (Ben Zireg). (c) Detail of the Upper Kellwasser bed in the Ben Zireg section with a thin layer of black shales (red arrow) superseded by laminated pinkish calcisiltic shale (black arrow). (d) Black shales (Marhouma). (e) Alternating pseudonodular limestone beds and grey shales (Marhouma section). (f) Interbedded argillaceous micritic nodules (Marhouma Formation). (g) Upper Kellwasser bed in the South Marhouma section with laminated black to pinky shales. (h) Dm-thick diagenetic limestones and black shales from early Famennian strata of the Marhouma section.

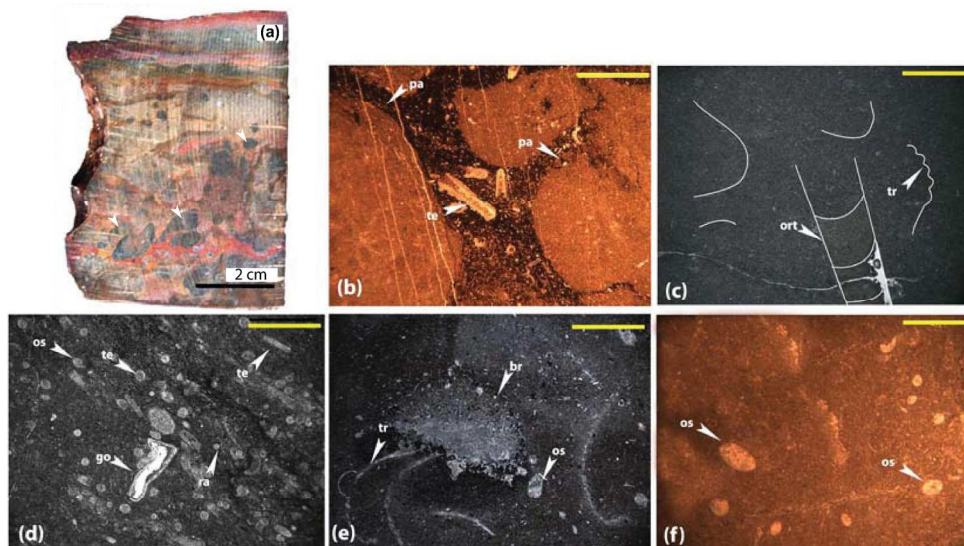
190x239mm (72 x 72 DPI)



Mahboubi et al., Fig. 4

Fig. 4. Lithological column with relative abundance of fossil components and facies fabrics of the South Marhouma section. Conodont zones from Mahboubi & Gatovsky (2014). Lithostratigraphic units: (Unit1) dark shales, (Unit 2) bioclastic nodular/pseudonodular limestones-grey shales, (Unit 3) nodular muddy limestones-greenish/darkish shales, (Unit 4) Diagenetic limestones/black shales. Abbreviations: Hg, Hard ground; M, Mudstone; W, Wackestone; P, Packstone, L.tr., Lower triangularis; FAM, Famennian; FZ, Frasnian Zone.

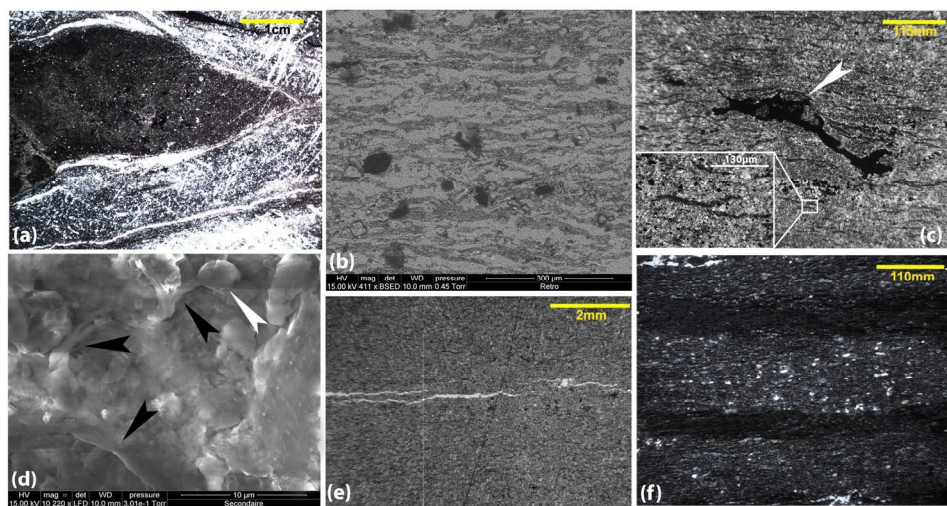
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Mahboubi et al. Fig. 5

Fig. 5. Facies of the depositional environments of the South Marhouma section and the Ben Zireg section. Scale (yellow bar) is 1mm. (a) Facies F2, outer ramp deposit: reworked mudstone layers in the Ben Zireg section (bed BZ2B). (b) Facies F2, outer ramp deposit: microscopic view (bed BZ1C). (c) Facies F6, mid-outer ramp deposit: lime mudstone with cephalopod bioclasts (bed MH34). (d) Facies F4, outer ramp deposit: pelagic argillaceous wackestone displaying distinct lamination by parallel arrangement of tentaculite coquinas (bed MH10). (e) Facies F6, outer ramp deposit: diversified wackestone with bioclasts consisting of abundant brachiopod shells (bed MH32). (f) Facies F6, mid ramp deposit: fine-grained mudstone with benthic ostracods (bed BZ10B). Abbreviations: br, brachiopod; go, goniatite; ort, orthoceras; os, ostracod; pa, parabraconia; ra, radiolarian; tr, trilobite; te, tentaculite

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Mahboubi et al., fig. 6

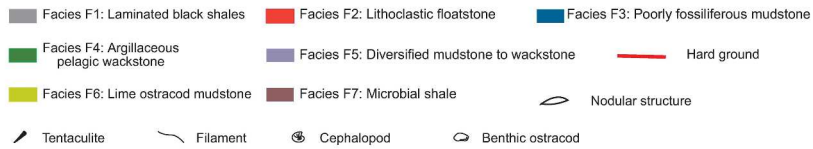
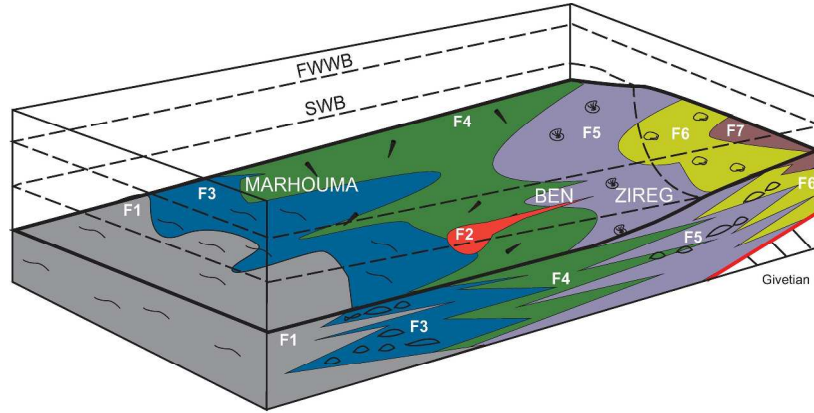
Fig. 6. Facies F7, mid ramp deposits, latest Frasnian at South Marhouma and Ben Zireg sections. (a) Flat-pebble conglomerate fabric (bed MH26bas). (b) SEM image of kerogenous laminae (wavy-crenulate structures) (bed MH29). (c, e) Kerogenous laminae. Note that these structures are more abundant in the South Marhouma samples (picture b, bed MH29) compared to the Ben Zireg sample (picture e, bed BZ15D). (d) SEM image of tube-like structures (black arrows, bed BZ15D) associated with framboidal pyrite (white arrow). (f) Finely-laminated striped shale displaying graded silt-mud couplets (bed MH30).

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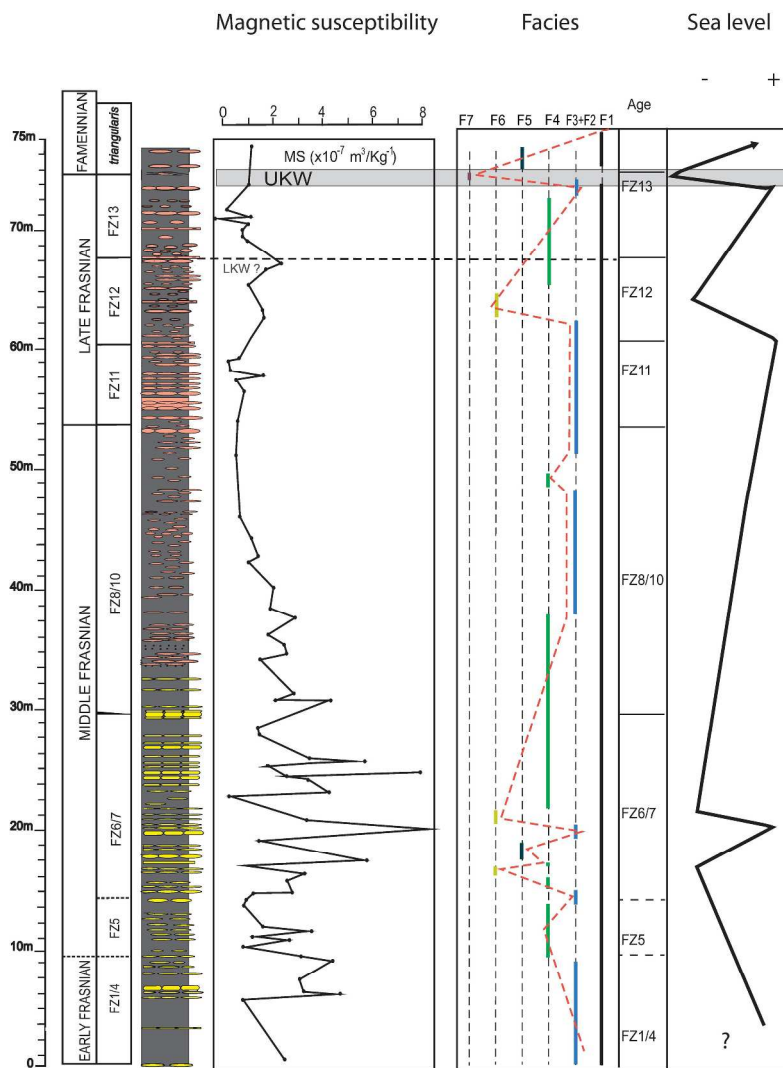


Mahboubi et al. Fig. 7

Mahboubi et al. Fig. 7

Fig. 7. Sedimentary model in NW Algeria during the Frasnian period (South Marhouma and Ben Zireg sections). This model shows a mid to outer ramp setting with lateral distribution of facies from the most proximal setting (F7) to the the most distal (F1). SWB, Storm Wave-Base; FWWB, Fair Weather Wave-Base.

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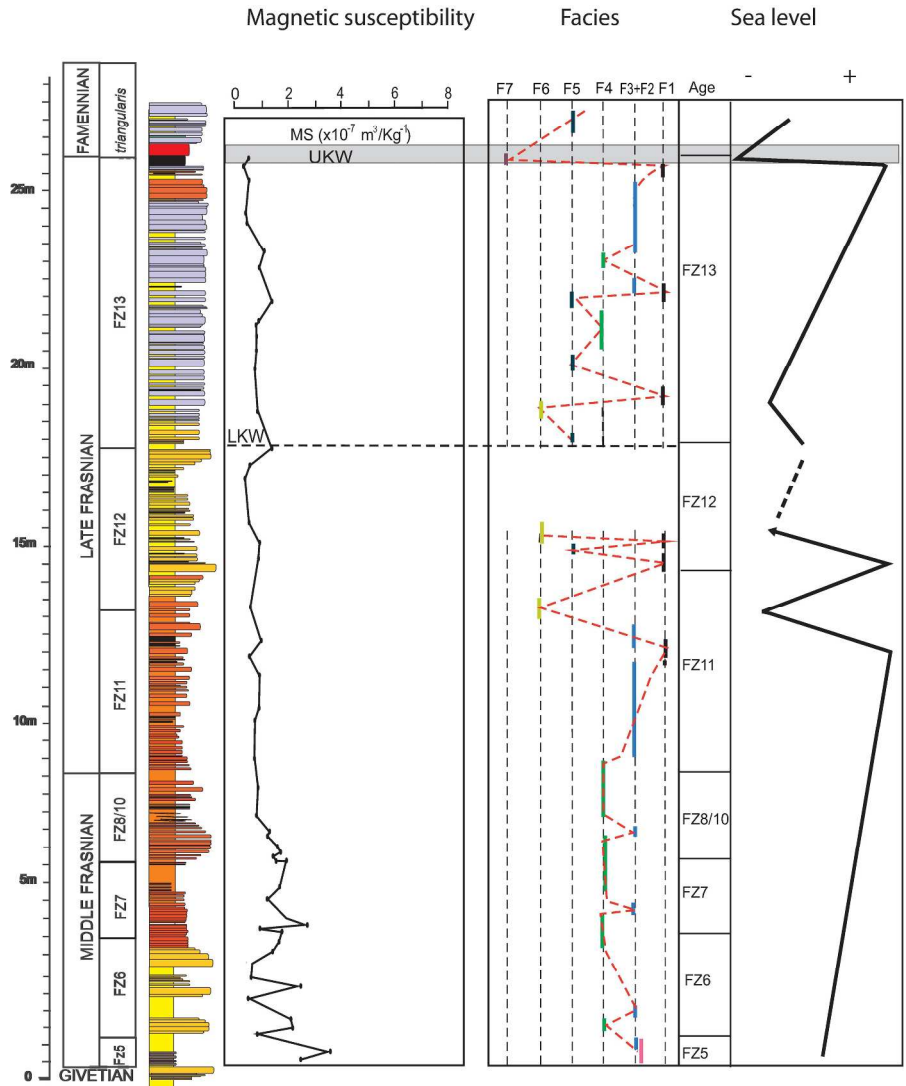


Mahboubi et al., Fig. 8

Fig. 8. Magnetic susceptibility evolution, facies change, and sea-level fluctuations through the Frasnian in the South Marhouma section. FZ: Frasnian Zones, LKW: Lower Kellwasser, UKW: Upper Kellwasser.

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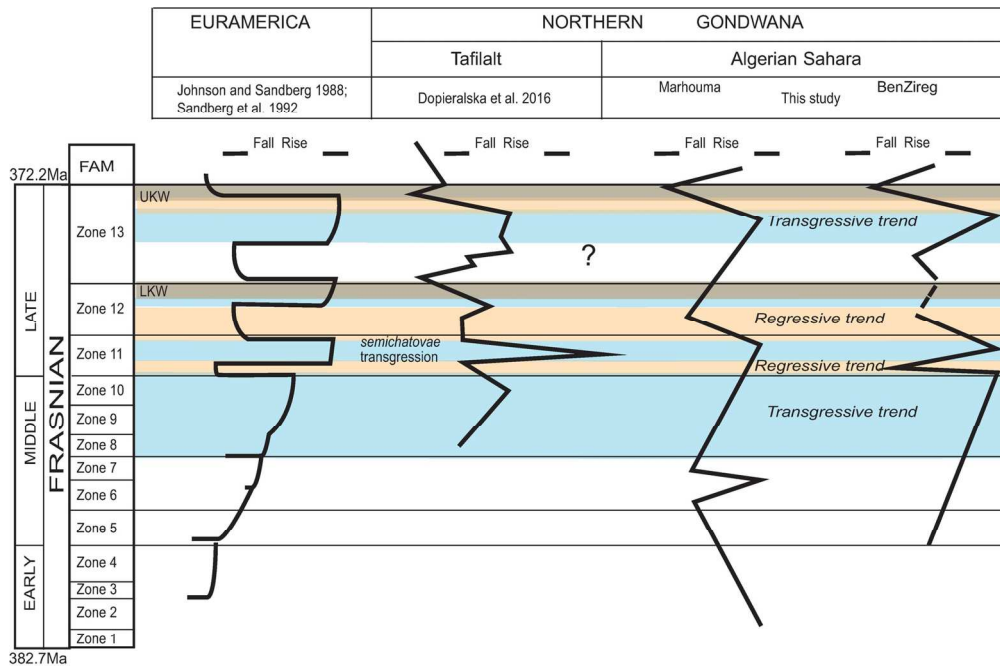
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Mahboubietal.Fig.9

Fig. 9. Magnetic susceptibility evolution, facies change, and sea-level fluctuations through the Frasnian in the Ben Zireg section. FZ: Frasnian Zones, LKW: Lower Kellwasser, UKW: Upper Kellwasser.

238x320mm (300 x 300 DPI)



Mahboubi et al., Fig.10

Fig. 10. Comparison of sea-level fluctuations from Euramerica and North Africa through the Frasnian stage. FZ (Frasnian Zones) after Klapper & Kirchgasser (2016), relative duration of conodont Zones are from Becker, Gradstein & Hammer (2012). In grey anoxic events. UKW: Upper Kellwasser; LKW: Lower Kellwasser; FAM: Famennian.

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