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1 Orbital control on exceptional fossil preservation

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8 **ABSTRACT**

9 Exceptional preservation is defined by the preservation of soft to lightly
10 sclerotized organic tissues. The two most abundant types of soft tissues preservation are
11 carbonaceous compressions and replicates in authigenic minerals. In the geological
12 record, exceptionally preserved soft fossils are rare and generally limited to only a few
13 stratigraphic intervals. In the Fezouata Shale (Lower Ordovician), we found that deposits
14 yielding pyritized soft tissues contain iron-rich silicate minerals. These minerals played a
15 crucial role in inhibiting decaying bacteria and are comparable to those found in
16 formations yielding carbonaceous soft parts around the world. Furthermore, we found
17 that iron-rich minerals show a cyclic pattern of occurrence (of ~100 kyrs periodicity)
18 implicating a short eccentricity control through the general oceanic and atmospheric
19 circulations on iron availability. Our results identify, for the first time, an external climate
20 forcing on exceptional preservation and show that orbital forcing may be a level-selective
21 parameter responsible for the discontinuous occurrence of horizons preserving soft parts
22 around the world.

23 **INTRODUCTION**

24 Exceptional preservation consists of the preservation of soft to lightly sclerotized
25 organic tissues (e.g., feathers, guts, skins) in the geological record (Butterfield, 1995).
26 The transfer of such tissues from the biosphere to the lithosphere is the result of a
27 succession of multiple, complex biological and geological mechanisms. Deciphering
28 these mechanisms is essential to understanding why exceptional preservation is limited to
29 specific intervals in the sedimentary record. Recent studies have shown that the
30 absence/presence of carbonaceous soft tissues is strongly correlated with the mineralogy
31 of the depositional environment and most importantly with iron-rich minerals that can
32 inhibit bacterial decay of soft tissues through the oxidative damage of bacterial cells
33 (McMahon et al., 2016; Anderson et al., 2018). However, little attention has been paid so
34 far to discover within which sediment minerals the pyritized soft tissues occur and what
35 are the processes behind the deposition of these minerals.

36 The Fezouata Shale crops out in the Zagora region in southern Morocco. This
37 Lower Ordovician succession consists of blue-green to yellow-green sandy mudstones
38 and siltstones that coarsen upwards. These sediments are up to 900 m thick in the Zagora
39 region (Destombes et al., 1985; Martin et al., 2016; Vaucher et al., 2017). The entire
40 succession was deposited in a marginal basin at high latitude close to the paleo-South
41 pole (Torsvik and Cocks, 2011, 2013). The shallow depositional setting ranges from the
42 foreshore to the upper offshore. It was storm-wave dominated (Martin et al., 2016) and
43 indirectly influenced by tides (Vaucher et al., 2017). The Fezouata Shale has yielded
44 abundant remains of soft-bodied organisms preserved with high fidelity, showing the
45 association of post-Cambrian taxa typical of the Great Ordovician Biodiversification
46 Event along with iconic taxa of the Cambrian Explosion (Van Roy et al., 2010, 2015).

47 Most soft bodied organisms were pyritized and are now preserved in iron oxides.
48 However, this weathering impact is not substantial as numerous fossils still show original
49 framboidal pyrite crystals. The presence of levels yielding both mineralized and soft
50 bodied organisms, as well as the highly constrained stratigraphic framework of this
51 formation (Gutiérrez-Marco and Martin, 2016; Lehnert et al., 2016; Martin et al., 2016;
52 Nowak et al., 2016; Lefebvre et al., 2018), make the Fezouata Shale a good candidate to
53 investigate whether specific sediment minerals are correlated with pyritized soft parts,
54 and if these mineralogical signatures change through time.

55 **MATERIAL AND METHODS**

56 **Mineralogical Signatures**

57 Part of the sedimentary succession of the Fezouata Shale (Vaucher et al. 2016)
58 was included in this study. The mineralogy of all fossiliferous levels in this section was
59 investigated. Mineral assemblages of levels yielding exceptional preservation were
60 compared to those in levels bearing only sclerotized remains. Matrix samples from each
61 level were prepared as randomly orientated powdered aggregates ($< 10 \mu\text{m}$), without any
62 specific treatments, on thermoplastic polymer (PMMA) substrates. X-ray diffraction
63 (XRD) was performed using a Bruker D8 Advance diffractometer, employing a $\text{CuK}\alpha$
64 source and Bruker LynxeyeX detector. Peak positions were adjusted for slight variations
65 in sample height displacement error using positions of quartz peaks as internal standards.
66 Mineral phases were then retrieved based on indexation of their diffraction lines, between
67 0 and $75^\circ 2\theta$ values, from the ICDD (International Centre for Diffraction Data) PDF4+
68 2016 reference database. Illite is generally characterized by its basal (001) peak at $\sim 10 \text{ \AA}$.
69 Quartz is characterized by its intense (011) reflection at 3.34 \AA . The differentiation

70 between chlorite minerals is verified based on the lateral variations of their characteristic
71 (001) and (002) peaks, respectively at 14 and 7 Å, as iron enrichment causes an increase
72 in d-spacing that shifts peaks positions toward higher 2θ values (Fig. 1). Phase
73 proportions were estimated from the relative intensity of diffraction lines of each mineral
74 species.

75 **Sequence Reconstructions**

76 The depositional environment of the Fezouata Shale is storm/wave dominated and
77 indirectly influenced by tides (Martin et al. 2016; Vaucher et al., 2016, 2017). In the
78 Fezouata Shale, the interaction of oscillations with surface sediments generated
79 oscillatory structures. The wavelength of these structures decreased from shallow to deep
80 environments (Nichols, 2010; Vaucher et al. 2016). Additionally, coarser sediments
81 indicate a shallower environment, while finer sediments are deposited in deeper settings
82 (Vaucher et al., 2016, 2017). These sediments and structural heterogeneities permitted the
83 establishment of a model of facies for the Fezouata Shale (Vaucher et al. 2017). Based on
84 this model, the alternation of deeper and shallower facies F1, F2 and F4 of Vaucher et al.
85 (2017) allowed us to identify small-, medium- and large-scale sequences. Small-scale
86 sequences correspond to the shortest variations of the sea level (Fig. 2), whereas medium-
87 and large-scale sequences correspond to longer terms sea-level changes.

88 **Bathymetry and Oxygenation**

89 The depth of the water column was estimated accordingly with medium-scale sea
90 level sequences (Lefebvre et al., 2016; Vaucher et al., 2017). Relative oxygen
91 abundances in superficial sediments was reconstructed based on depth variations of the
92 water column. In the Fezouata environment, in deep environments, in shelf settings

93 below storm wave base, rapid burial did not occur, inhibiting the establishment of anoxic
94 conditions in surface sediments (Vaucher et al., 2017). Above storm wave base, where
95 rapid burial during storm events occurred, the establishment of anoxic conditions in
96 surface sediments below the storm deposits was influenced by wave/sediment
97 interactions. Wave/sediment interactions are more pronounced in shallow-most settings
98 (Nichols, 2010), leading to an increase in the oxygen penetration depth from the water
99 column to the sediments (Chatelain and Guizien, 2010). Thus, anoxic/dysoxic conditions
100 occur rarely in the shallowest environments (decimetric wavelength of storm oscillatory
101 structures, high oxygen penetration depth) and may occur only in less shallow deposits
102 (centimetric wavelength of storm structures, limited oxygen penetration depth) just above
103 the storm wave base (Fig. 2) in the Fezouata Shale (Vaucher et al. 2016., 2017).

104 **RESULTS**

105 All samples show a similar composition with an absence of organic matter, a high
106 abundance of illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$ (~60%) and quartz
107 SiO_2 (~30%), and a small portion (<10%) of chlorite minerals (see Table DR1 in the Data
108 Repository for precise percentages). However, the nature of the chlorite phase differs
109 between samples as some specimens show the presence of clinochlore
110 $(Mg_5Al)(AlSi_3)O_{10}(OH)_8$, while others show iron-rich clinochlore
111 $(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$ (iron content ~12%) or chamosite $(Fe_5Al)(AlSi_3)O_{10}(OH)_8$
112 (iron content ~30%) (Fig. 2). In the Fezouata Shale, the occurrence of soft tissues is
113 discontinuous and is limited only to few stratigraphic levels in interval 1 (Fig. 2).

114 The entire sedimentary succession was deposited around the storm wave base.
115 Both intervals 1 and 3 (Fig. 2), were deposited under anoxic/dysoxic conditions. The
116 largest part of interval 2 was deposited under oxic conditions (Fig. 2).

117 The studied section contains ~2 medium-scale and 9 small-scale sequences. The
118 occurrence of 4 small-scale sequences per medium-scale sequence deduced from facies
119 changes (Fig. 2) in the entire sedimentary succession suggests an eccentricity control on
120 sequence formation through its 100 and 400 kyrs periodicities. The studied sediments
121 were deposited during the Tremadocian (duration of 7.7 ± 3.3 Ma). In the Tremadocian,
122 10 main graptolites subdivisions (biozones) of ~0,7 Ma have been identified (Loydell,
123 2012). In the Fezouata Shale, the first three biozones of the Tremadocian are missing
124 (Gutiérrez-Marco and Martin, 2016; Lefebvre et al., 2018). This suggests that the
125 Tremadocian sediments (450 m) of the Fezouata Shale were deposited over 5.7 ± 2.4 Ma.
126 In addition, the sedimentation of the Fezouata Shale appears to be uniform (i.e.,
127 monotonous sequence dominated by siltstones) and formed by the stacking of storm
128 deposits (mm- to cm-thick sandstone or coarse siltstone levels separated by mm-thick
129 argillaceous siltstone or fine-grained siltstone layers) (Vaucher et al., 2016, 2017). This
130 homogeneity of the sediments and the absence of observed long or short-term
131 sedimentary hiatus (Vaucher et al., 2017) both suggest a relatively stable accumulation
132 rate of ~79 m/Ma. Thus, the studied 67 m-thick section was deposited over $\sim 0.84 \pm 0.35$
133 Ma. One medium-scale sequence would then represent a time interval of $\sim 0.42 \pm 0.17$
134 Ma, and one small-scale sequence of 0.09 ± 0.03 Ma. These estimated durations are in
135 accordance with the durations of eccentricity cycles.

136 **DISCUSSION**

137 The sediment in the Fezouata Shale has a relatively simple composition
138 comparable to other Paleozoic sites with exceptional preservation (Anderson et al., 2018).
139 In this formation, chamosite appears to be correlated with levels recording exceptional
140 preservation (Fig. 2). Chamosite can be formed directly from the transformation of
141 primary clay minerals (kaolinite, glauconite) at high temperatures ($T > 175$ °C) or from the
142 transformation of berthierine, an iron rich serpentine phyllosilicate, in less extreme
143 conditions ($T < 100$ °C; Tang et al., 2017). In the Fezouata Shale, sediments did not
144 endure extreme temperatures and burial conditions, and only 2–3 km (i.e., equivalent of
145 burial temperatures between 70 and 100 °C using a mean geothermal gradient of 30° per
146 km in passive margins) of sediments were deposited over these shales (Ruiz et al., 2008).
147 Thus, berthierine is the most probable precursor for chamosite in the Fezouata Shale. In
148 addition to that, chamosite occurrences appear to be correlated with an intermediate
149 bathymetry, as it occurs only in intervals 1 and 3 (Fig. 2). In the Fezouata Shale, specific
150 parameters (e.g. bathymetry, oxygenation) controlled the precipitation of berthierine in
151 the depositional environment and were thus indirectly responsible of the selective
152 presence of chamosite.

153 In a depositional environment, the presence of a significant amount of iron under
154 reducing conditions leads to the precipitation of berthierine (Tang et al., 2017), a mineral
155 which can inhibit decay bacteria (McMahon et al., 2016). Afterward, during a deeper
156 burial, most of the berthierine is transformed to chamosite (Hornibrook and Longstaffe,
157 1996). In some levels of intervals 1 and 3, reducing conditions and abundant iron were
158 available, leading to berthierine precipitation in sediments in addition to the pyritization
159 of decaying soft parts. In interval 1, some levels, deposited under similar bathymetry (i.e.,

160 fast burial and sedimentary anoxia), yield mostly clinochlore instead of chamosite.
161 Clinochlore and chamosite belong to the same chlorite mineral group, and lie on its
162 magnesium-rich and iron-rich poles respectively (Curtis et al., 1985). The occurrence of
163 both chamosite and clinochlore in intervals with different porosities suggests that the
164 formation of these minerals is independent from the physical parameters in the sediments.
165 Instead, the presence of clinochlore is likely related to iron deficiencies in these levels
166 during early diagenesis.

167 In interval 2, chamosite is absent, and was mainly replaced by iron rich
168 clinochlore indicating the presence of iron. The absence of chamosite and exceptional
169 preservation in this interval were due to the absence of favorable reducing conditions
170 (Fig. 2).

171 Iron, an important element for the formation of both berthierine and pyrite, may
172 have different sources such as (i) circulation of iron-rich hydrothermal fluids (Tang et al.,
173 2017), (ii) microbial extraction of iron from clay minerals after their deposition in marine
174 sediments (Vorhies and Gaines, 2009) or (iii) iron inputs to the sea from other marine or
175 continental sources (Odin and Matter, 1981). In the Fezouata Shale, illite, which is the
176 main clay mineral in sedimentary basins (Ruiz et al. 2008), is present in all intervals.
177 However, chamosite does not occur in all levels showing a different distribution than
178 illite. This implies that the scenario considering microbial iron extraction from clay
179 minerals is not parsimonious. In addition, the occurrence of chamosite at the end of a
180 regression/ beginning of a transgression of a small-scale sequence (Fig. 2) rules out
181 hydrothermal fluids as the main source of iron and favors marine and/or continental
182 inputs. The Fezouata Shale was deposited in a shallow sea near the South Pole with a

183 limited oceanic circulation (Martin et al., 2016, Vaucher et al., 2017). Thus, the
184 enrichment of iron is considered as continental in origin.

185 According to duration estimations based on graptolite biostratigraphy, any two
186 consecutive iron rich intervals in interval 1 were deposited with an average delay of ~100
187 kyrs in pace with eccentricity-controlled sea-level cycles (Fig. 2). Astronomic
188 calculations confirmed that even if the periodicity of the obliquity and precession
189 decreased with time, eccentricity frequency was stable over the last 500 million years
190 (Berger et al., 1992). These calculations were validated through robust responses of
191 different sedimentary systems to astronomically controlled climate forcing from recent
192 times to the Cambrian (Osleger and Read, 1991). Every 100 kyrs, eccentricity transitions
193 from a circular to an elliptic orbit, or vice versa, influencing precession and thus,
194 insolation and seasonal variations (Fig. 3). Consequently, these variations influence the
195 evaporation/precipitation cycle, ice volume (Rampino, 1979), if any, as well as river
196 fluxes and continental weathering (Horton et al., 2012), and thus the inputs of iron to the
197 sea (Fig. 3). These inputs constitute a major contributor to iron abundances in oceans
198 (Elrod et al., 2004), and lead to berthierine formation in shallow environments at the
199 water/sediment interface (Odin and Gupta, 1988; Kozłowska and Maliszewska, 2015)
200 when anoxic conditions are present (Tang et al. 2010).

201 For the first time, our results (1) provide detailed information on the
202 mineralogical context in which pyritized soft tissues occur, (2) identify a temporal
203 variation of minerals in a sedimentary succession with soft tissue preservation, and (3)
204 evidence an orbital control on soft tissue fossilization. This external climate forcing may
205 be responsible for the discontinuous occurrence of soft tissues in numerous formations

206 around the world in which iron discrepancies between levels yielding exceptional
207 preservation and those with only skeletal remains are evidenced (Anderson et al., 2018).

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- 319

320 **FIGURE CAPTIONS**

321

322 Figure 1. Minerals identification in samples from the Fezouata Shale from X-ray powder
323 diffraction. The box with red margins is an expansion of the area indicated in the main
324 plot.

325

326 Figure 2. From left to right: sequences of various scales translating sea-level cycles at
327 different timescales, part of the sedimentary succession of Fezouata Shale with location
328 of samples, facies F1, F2 and F4 as described in Vaucher et al. (2017) used to identify the
329 sequences, relative bathymetry changes and oxygen fluctuations.

330

331 Figure 3. Model explaining the effect of orbital forcing on seasonality, and thus on soft
332 tissues preservation.

333

334 1GSA Data Repository item 2018xxx, xxxxxxxxxxxxxxxxxx, is available online at
335 <http://www.geosociety.org/datarepository/2018/>, or on request from
336 editing@geosociety.org.





