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Orbital control on exceptional fossil preservation

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ABSTRACT

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

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).

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

MATERIAL AND METHODS

Mineralogical Signatures

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

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

Sequence Reconstructions

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

Bathymetry and Oxygenation

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

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

RESULTS

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

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

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

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

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

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REFERENCES CITED

- Anderson, R.P., Tosca, N.J., Gaines, R.R., Mongiardino Koch, N., and Briggs, D.E., 2018, A mineralogical signature for Burgess Shale–type fossilization: *Geology*, v. 46, p. 347–350, <https://doi.org/10.1130/G39941.1>.
- Berger, A., Loutre, M.F., and Laskar, J., 1992, Stability of the astronomical frequencies over the Earth’s history for paleoclimate studies: *Science*, v. 255, p. 560–566, <https://doi.org/10.1126/science.255.5044.560>.
- Butterfield, N.J., 1995, Secular distribution of Burgess-Shale-type preservation: *Lethaia*, v. 28, p. 1–13, <https://doi.org/10.1111/j.1502-3931.1995.tb01587.x>.
- Chatelain, M., and Guizien, K., 2010, Modelling coupled turbulence–dissolved oxygen dynamics near the sediment–water interface under wind waves and sea swell: *Water Research*, v. 44, p. 1361–1372, <https://doi.org/10.1016/j.watres.2009.11.010>.
- Curtis, C.D., Hughes, C.R., Whiteman, J.A., and Whittle, C.K., 1985, Compositional variation within some sedimentary chlorites and some comments on their origin:

- 229 Mineralogical Magazine, v. 49, p. 375–386,
230 <https://doi.org/10.1180/minmag.1985.049.352.08>.
- 231 Destombes, J., Hollard, H., and Willefert, S., 1985, Lower Palaeozoic rocks of Morocco,
232 *in* Holland, C.H., ed., Lower Palaeozoic Rocks of the World, volume 4: Lower
233 Palaeozoic rocks of Northwest and West-Central Africa: Chichester, UK, John Wiley
234 and Sons, p. 91–336.
- 235 Elrod, V.A., Berelson, W.M., Coale, K.H., and Johnson, K.S., 2004, The flux of iron
236 from continental shelf sediments: A missing source for global budgets: Geophysical
237 Research Letters, v. 31, L12307, <https://doi.org/10.1029/2004GL020216>.
- 238 Gutiérrez-Marco, J.C., and Martin, E.L.O., 2016, Biostratigraphy and palaeoecology of
239 Lower Ordovician graptolites from the Fezouata Shale (Moroccan Anti-Atlas):
240 Palaeogeography, Palaeoclimatology, Palaeoecology, v. 460, p. 35–49,
241 <https://doi.org/10.1016/j.palaeo.2016.07.026>.
- 242 Hornibrook, E.R.C., and Longstaffe, F.J., 1996, Berthierine from the Lower Cretaceous
243 Clearwater Formation, Alberta, Canada: Clays and Clay Minerals, v. 44, p. 1–21,
244 <https://doi.org/10.1346/CCMN.1996.0440101>.
- 245 Horton, D.E., Poulsen, C.J., Montañez, I.P., and DiMichele, W.A., 2012, Eccentricity-
246 paced late Paleozoic climate change: Palaeogeography, Palaeoclimatology,
247 Palaeoecology, v. 331–332, p. 150–161,
248 <https://doi.org/10.1016/j.palaeo.2012.03.014>.
- 249 Kozłowska, A., and Maliszewska, A., 2015, Berthierine in the Middle Jurassic sideritic
250 rocks from southern Poland: Geological Quarterly, v. 59, p. 551–564.

- 251 Lefebvre, B., et al., 2016, Palaeoecological aspects of the diversification of echinoderms
252 in the Lower Ordovician of central Anti-Atlas, Morocco: *Palaeogeography,*
253 *Palaeoclimatology, Palaeoecology*, v. 460, p. 97–121,
254 <https://doi.org/10.1016/j.palaeo.2016.02.039>.
- 255 Lefebvre, B., Gutiérrez-Marco, J.C., Lehnert, O., Martin, E.L.O., Nowak, H., Akodad,
256 M., El Hariri, K., and Servais, T., 2018, Age calibration of the Lower Ordovician
257 Fezouata Lagerstätte, Morocco: *Lethaia*, v. 51, p. 296–311,
258 <https://doi.org/10.1111/let.12240>.
- 259 Lehnert, O., Nowak, H., Sarmiento, G.N., Gutiérrez-Marco, J.C., Akodad, M., and
260 Servais, T., 2016, Conodonts from the Lower Ordovician of Morocco – contributions
261 to age and faunal diversity of the Fezouata Lagerstätte and peri-Gondwana
262 biogeography: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 460, p. 50–
263 61, <https://doi.org/10.1016/j.palaeo.2016.03.023>.
- 264 Loydell, D.K., 2012, Graptolite biozone correlation charts: *Geological Magazine*, v. 149,
265 p. 124–132, <https://doi.org/10.1017/S0016756811000513>.
- 266 Martin, E.L.O., et al., 2016, The Lower Ordovician Fezouata Konservat-Lagerstätte from
267 Morocco: Age, environment and evolutionary perspectives: *Gondwana Research*,
268 v. 34, p. 274–283, <https://doi.org/10.1016/j.gr.2015.03.009>.
- 269 McMahon, S., Anderson, R.P., Saupe, E.E., and Briggs, D.E., 2016, Experimental
270 evidence that clay inhibits bacterial decomposers: Implications for preservation of
271 organic fossils: *Geology*, v. 44, p. 867–870, <https://doi.org/10.1130/G38454.1>.
- 272 Nichols, G., 2010, *Sedimentology and Stratigraphy*: Chichester, UK, Wiley-Blackwell,
273 432 p.

- 274 Nowak, H., Servais, T., Pittet, B., Vaucher, R., Akodad, M., Gaines, R.R., and
275 Vandenbroucke, T.R., 2016, Palynomorphs of the Fezouata Shale (Lower
276 Ordovician, Morocco): Age and environmental constraints of the Fezouata Biota:
277 Palaeogeography, Palaeoclimatology, Palaeoecology, v. 460, p. 62–74,
278 <https://doi.org/10.1016/j.palaeo.2016.03.007>.
- 279 Odin, G.S., and Gupta, B.K.S., 1988, Geological Significance of the Verdine Facies:
280 Developments in Sedimentology, v. 45, p. 205–219, [https://doi.org/10.1016/S0070-](https://doi.org/10.1016/S0070-4571(08)70064-5)
281 [4571\(08\)70064-5](https://doi.org/10.1016/S0070-4571(08)70064-5).
- 282 Odin, G.S., and Matter, A., 1981, De glauconiarum origine: Sedimentology, v. 28,
283 p. 611–641, <https://doi.org/10.1111/j.1365-3091.1981.tb01925.x>.
- 284 Osleger, D., and Read, J.F., 1991, Relation of eustasy to stacking patterns of meter-scale
285 carbonate cycles, Late Cambrian, USA: Journal of Sedimentary Research, v. 61,
286 p. 1225–1252.
- 287 Rampino, M.R., 1979, Possible relationships between changes in global ice volume,
288 geomagnetic excursions, and the eccentricity of the Earth's orbit: Geology, v. 7,
289 p. 584–587, [https://doi.org/10.1130/0091-7613\(1979\)7<584:PRBCIG>2.0.CO;2](https://doi.org/10.1130/0091-7613(1979)7<584:PRBCIG>2.0.CO;2).
- 290 Ruiz, G., Helg, U., Negro, F., Adatte, T., and Burkhard, M., 2008, Illite crystallinity
291 patterns in the Anti-Atlas of Morocco: Swiss Journal of Geosciences, v. 101, p. 387–
292 395, <https://doi.org/10.1007/s00015-008-1267-z>.
- 293 Tang, D., Shi, X., Jiang, G., Zhou, X., and Shi, Q., 2017, Ferruginous seawater facilitates
294 the transformation of glauconite to chamosite: An example from the
295 Mesoproterozoic Xiamaling Formation of North China: American Mineralogist,
296 v. 102, p. 2317–2332, <https://doi.org/10.2138/am-2017-6136>.

- 297 Torsvik, T.H., and Cocks, L.R.M., 2011, The Palaeozoic palaeogeography of central
298 Gondwana: Geological Society of London, Special Publications, v. 357, p. 137–166,
299 <https://doi.org/10.1144/SP357.8>.
- 300 Torsvik, T.H., and Cocks, L.R.M., 2013, New global palaeogeographical reconstructions
301 for the Early Palaeozoic and their generation: Geological Society, London, Memoir
302 38, p. 5–24.
- 303 Van Roy, P., Orr, P.J., Botting, J.P., Muir, L.A., Vinther, J., Lefebvre, B., El Hariri, K.,
304 and Briggs, D.E., 2010, Ordovician faunas of Burgess Shale type: Nature, v. 465,
305 p. 215–218, <https://doi.org/10.1038/nature09038>.
- 306 Van Roy, P., Briggs, D.E.G., and Gaines, R.R., 2015, The Fezouata fossils of Morocco;
307 an extraordinary record of marine life in the Early Ordovician: Journal of the
308 Geological Society, v. 172, p. 541–549, <https://doi.org/10.1144/jgs2015-017>.
- 309 Vaucher, R., Martin, E.L.O., Hormière, H., and Pittet, B., 2016, A genetic link between
310 Konzentrat and Konservat Lagerstätten in the Fezouata Shale (Lower Ordovician,
311 Morocco): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 460, p. 24–34,
312 <https://doi.org/10.1016/j.palaeo.2016.05.020>.
- 313 Vaucher, R., Pittet, B., Hormière, H., Martin, E.L.O., and Lefebvre, B., 2017, A wave-
314 dominated, tide-modulated model for the lower Ordovician of the anti-atlas,
315 Morocco: Sedimentology, v. 64, p. 777–807, <https://doi.org/10.1111/sed.12327>.
- 316 Vorhies, J.S., and Gaines, R.R., 2009, Microbial dissolution of clay minerals as a source
317 of iron and silica in marine sediments: Nature Geoscience, v. 2, p. 221–225,
318 <https://doi.org/10.1038/ngeo441>.

319

FIGURE CAPTIONS

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

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

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

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