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The response of continental silicate rock weathering to the colonization of the continents by vascular plants in the Devonian

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19 ABSTRACT. The first forests appear on the continents during the Givetian stage of the 20 Devonian. The fossil record shows that, by the end of the Devonian, vascular plants and forests 21 were common and widespread in the wet lowlands. Although the impact of this major event on 22 chemical weathering of the continents is reasonably known, the coeval change in physical 23 erosion has never been explored. Here, we built a mathematical description of the coupled 24 response of the physical erosion and chemical weathering on the continents, to the colonization 25 by vascular plants over the course of the Devonian. This spatially-resolved erosion model is 26 coupled to the GEOCLIM model to simulate the response of the global carbon and alkalinity 27 cycles, and of climate, to the colonization phase. A set of simulations is described, assuming an 28 increased weatherability of the continental surface, and a change in physical erosion which can 29 be either a decrease or an increase in response to the spreading of vascular plants. We explore 30 first the initial pre-colonization and the final post-colonization steady states of the surficial 31 Earth system. Then, we simulate the transient states of the Earth system in response to 32 theoretical randomized scenario for the colonization. We found that the pathways of the colonization have a major impact on the CO₂ history through the Devonian. Depending on the 33 magnitude of the change in physical erodibility and chemical weatherability, and on the 34 35 colonization scenario, atmospheric CO₂ evolution may display contrasting behavior: from a 36 uniform CO_2 decrease over the Devonian, to more complex patterns characterized first by a 37 global warming from the end of the Givetian into the Frasnian, and then by a final cooling, in 38 first order agreement with the proxy data for CO₂ and reconstructed climate evolution.

40 41

1. INTRODUCTION

1.1. Devonian Atmospheric CO₂ and Plants

In a seminal paper published in 1998, and following the mechanisms expounded in Algeo et al.
(1995), Berner (1998) linked the atmospheric CO₂ decrease from the Early Devonian to the Late
Carboniferous (Royer and others, 2007; Foster and other, 2017) to the colonization of the continents

by the first vascular plants. Berner suggested that the development of deep roots resulted in a more
 efficient CO₂ consumption by silicate weathering through the mechanical breakdown of rocks and the

- 47 production of respired CO_2 and organic acids in the soils. This activation of weathering would thus be
- 48 driven by an increase in weatherability, which is defined as the product of the factors that affect rock
- chemical weathering other than climatic factors (air temperature and runoff, Kump and Arthur, 1997).This concept of weatherability is at the heart of the numerical models describing the evolution of the
- 51 global carbon cycle at the geological timescale (Kump and Arthur, 1997; Berner, 2004, Lenton and
- 52 others, 2018; Donnadieu and others, 2006; Royer and others, 2014; Joshi and others, 2019). It can be

53 interpreted as a change in the strength of the negative feedback linking the weathering of the

continental silicate rocks to the atmospheric CO_2 level (D'Antonio and others, 2020). Field studies

55 confirm the existence of a weatherability change in the presence of plants (Moulton and others, 2000).

56 The scenario of an enhanced weatherability during the Devonian is now largely accepted by the

57 scientific community. For instance, Porder (2020) states that the spread of vascular plants drove a 40

58 Myr decline in atmospheric CO_2 from 4000 ppmv to about 1000 ppmv.

- 59 Several recent studies raised concerns about the land plant scenario. Indeed, the timing of the
- 60 colonization of the continents by vegetation has been re-evaluated. Molecular clock studies suggest
- 61 that the colonization of the continents by primitive land plants started long before the Devonian, in the
- 62 middle Cambrian or Early Ordovician (Morris and others, 2018), and microfossil evidence for the
- 63 presence of land plants has been discovered in the Middle Ordovician (Rubinstein and others, 2010).
- However, there are no megafossils of bryophytes neither in the Ordovician nor in the Silurian (Drieseand Mora, 2001; Edwards and others, 2015). Pre-Devonian fossil records show the existence of land
- plants limited in size (Edwards and others, 2015). Their potential impact on weathering processes
- remains difficult to assess. Microcosm laboratory experiments conducted on modern mosses suggest
- that bryophytes significantly enhance silicate weathering (Lenton and others, 2012). However, our
- 69 poor knowledge of the spatial cover of Ordovician and Silurian bryophytes renders the extrapolation
- of such results at the global scale uncertain (Porada and others, 2016; Greb and others, 2006). These
- 71 primitive plants were probably restricted to humid areas because of their homosporous reproduction
- 72 necessitating free water for fertilization (Greb and others, 2006).
- 73 Whatever the impact of early bryophytes on the continental weatherability, a step increase in silicate
- 74 rock weatherability must have followed the spread of vascular plants with deep root structures over
- the continents (D'Antonio and others, 2020). Recently, Stein and others (2020) identified the oldest
- 76 forest in the Middle Devonian (Givetian, between 387.7 and 382.7 Ma). Within this forest, some of

the trees displayed a complex, modern-like root system, such as *Archeopteris*. The speed at which

those big trees colonized the continental surfaces is not well constrained. The first forests rose in the
Middle Devonian, and by the late Devonian (around 360 Ma), extensive "Carboniferous-style" forests

- had colonized large continental surfaces (Willis and McElwain, 2002).
- 81 Assuming the base of the Givetian stage as the starting date of the colonization (Stein and others,
- 82 2020) and using the most recent compilation of atmospheric CO_2 proxy estimates (Foster and others,
- 2017), it appears that an increase in atmospheric CO₂ first accompanied the spread of forests on land
- 84 (from the Eifelian into the Givetian, Fig. 1), in agreement with the coeval low-latitude warming
- 85 documented based on sedimentary apatite δ^{18} O (Joachimski and others, 2009). Atmospheric CO₂

subsequently fluctuated around ~1200 ppmv until the middle Frasnian and decreased down to 600

ppm at the end of the Famennian (Foster and others, 2017). Then proxies are missing between 365 Ma

and 345 Ma. At 340 Ma, 20 Myr after trees had become widely represented in the available

- 89 fossil record, atmospheric CO_2 was as low as 300 ppm.
- 90
- 91

1.2. The Importance of Physical Erosion

92

93 Recent studies suggested that the link between the expansion of forests and atmospheric CO_2 (pCO_2)

evolution may be more complex than the monotonic pCO_2 decrease previously considered. New processes have been explored, such as the modification of the water cycle, requiring the development

of process-based models. Lehir and others (2011) showed that the lowering of the continental albedo

97 strongly modified the water cycle and the weathering rates. White and others (2020) have simulated

98 the impact of vegetation on the continental water cycle over the Carboniferous and into the Permian.

99 They showed that the rise in atmospheric oxygen during the late Carboniferous modified the

100 atmospheric pressure, reducing the vegetation evapo-transpiration, ultimately increasing continental

101 runoff rates and modifying the weathering rates. Ibarra and others (2019) built a model linking silicate

102 weathering to a one-dimensional vapor transport model and showed that the growth of forests may

103 have increased the strength of the silicate weathering feedback.

104 The contrast between the monotonic pCO_2 drop predicted by previous modeling works and the

105 complex pCO_2 evolution based on proxy data suggests that rock weatherability may have been

106 modulated by another factor not yet investigated. The physical erosion of the continents and its

107 response to the expansion of plants might be one of those factors. The relationship between vegetation

cover and landscape erosion is not straightforward, as illustrated by the few following examples.
 Surprisingly, abiotic environments, such as the surface of Mars, show landscape features similar to the

109 Suprisingly, about environments, such as the surface of wars, show fandscape features similar to the vegetated Earth surface (Dietrich and Perron, 2006). But the difference between a biotic and abiotic

111 world may lie in the greater occurrence of some landscape features in the presence of vegetation,

112 compared to non-vegetated environments. On Earth, land plants can accelerate or buffer surface

113 processes. Istanbulluoglu and Bras (2005) suggested that vegetation can change the dominant erosion

114 process from overland flow under abiotic conditions to land sliding in well-vegetated areas. Some

115 case studies show that trees strongly inhibit erosion in mountainous areas (Vanacker and others,

116 2010). In such environments, reforestation may reduce the fluxes of exported sediments by a factor of

up to 45, compared to a barren ground. The presence of an evergreen vegetation in the EcuadorianAndes strongly reduces erodibility (Ochoa and others, 2016). Based on a compilation of data covering

Europe, Panagos and others (2015) calculated that the susceptibility to erosion in forested areas was

120 about 100 times below the mean European value. A similar conclusion was reached by Garcia-Ruiz

and others (2015) based on a worldwide database: forests and shrublands display the lowest erosion

122 rates.

123 The question is why erosion rates are reduced in forested areas. One option could be an enhanced

evapotranspiration and rainfall interception in the presence of trees, generating a decrease in runoff.

However, Carriere and others (2020) challenged this hypothesis: they found that vegetation reduces

the erosion rates by reducing the erodibility (defined as the susceptibility of the continental surfaces to erosion) (table 1), rather than by reducing the surface runoff. It has also been suggested that the

erosion) (table 1), rather than by reducing the surface runoff. It has also been suggested that theimpact of vascular plants on physical erodibility may depend on the considered time scale: vascular

128 Impact of vascular plants on physical elocitomity may depend on the considered time scale. vascular 129 plants may stabilize river banks and promote single-thread channels (Davies and Gibling, 2010),

decreasing erosion on decennial timescales, but potentially foster erosion on longer periods by

131 focusing the river flow. Finally, two recent data compilations (Mishra and others, 2019; Starke and

132 others, 2020} illustrate the variable effect of vegetation on erosion, such as initially proposed by

- 133 Langbein and Schumm (1958). Data from arid area show that the mechanical erosion strongly
- 134 increases with increasing vegetation cover, because erosion is primarily driven by the corresponding
- 135 increase in precipitation rate. Conversely mechanical erosion decreases with increasing vegetation
- 136 cover in wetter areas because the protective role of vegetation dominates.
- 137 In the present contribution, we explore the consequences of the rise of the vascular plants on
- 138 continental silicate weatherability. Although the rise of vascular plants also strongly modified the
- 139 organic carbon cycle and the nutrient cycles (Algeo and Scheckler, 1998), the albedo, the rugosity and
- 140 the evapo-transpiration of the continents, we deliberately focus on the inorganic part of the carbon
- 141 cycle. Our goal is not to simulate all the processes at play, but rather to revisit how silicate weathering
- 142 changed during the colonization when coupled to physical erosion.
- 143 In our modeling framework, we describe by "fully vegetated" continental surfaces upon which can be
- 144 found vascular plants having the ability to change significantly the weatherability and erodibility of
- 145 these surfaces. On the other hand, we qualify as "barren" continental surfaces without those vascular
- 146 plants, though they may contain earlier forms of vegetation. We consider that all continental regions
- 147 can be impacted by this transition from "barren" to "fully vegetated", including very dry areas and
- 148 very cold regions. This simplification is arguable in terms of plant physiology, but from the modeling
- point of view, those regions are characterized by very low CO_2 consumption by silicate weathering
- anyway, because of unfavorable climatic conditions. Their contribution to the global CO₂
- consumption by silicate weathering will remain negligible in any case. The connection between
- vascular plants and the calculated climate occurs only through the impact of plants on the continental
- weatherability and erodibility (table 1), and hence on atmospheric CO_2 concentration.
- 154 We will first simulate the steady-state of the surficial Earth system prior to the colonization of the
- 155 continents by vascular plants, focusing on the impact of changes in weatherability and erodibility of
- 156 the continents. Second, the post-colonization steady-state will be simulated and compared to the pre-
- 157 colonization runs. Finally, the transient state from the pre- to the post-colonization steady-states will
- 158 be explored.
- 159
- 160

2. MODEL DESCRIPTION

We develop a numerical model describing the coupling between physical erosion and chemical
weathering, based on the model of Gabet and Mudd (2009) and West (2012), and we couple it with
the deep time climate-carbon cycle model GEOCLIM (Donnadieu and others, 2006; Goddéris and

- others, 2014; Goddéris and others, 2017). The erosion/weathering model simulates three processes for
 each continental grid cell.
- The regolith production at the interface between the fresh bedrock and the regolith.
 Modeling accurately the early stages of the bedrock weathering is complex. Regolith
 production is dependent on oxidation reactions able to break the bedrock, and releases
 unaltered minerals into the regolith (Navarre-Sitchler and others, 2015). Accordingly, we
 assume that this process does not consume CO₂, and is dependent on temperature and on the
 availability of water at the bedrock interface.
- The removal of materials at the top of the regolith by physical erosion. The physical erosion rate is simulated using a standard mathematical formulation used in most landscape models.
- The dissolution of primary minerals during their travel through the regolith, from their
 release at the bedrock/regolith interface to their removal by physical erosion at the top
 of the regolith. The local chemical reaction rate of this dissolution at a given depth depends

- on the amount of unweathered primary minerals left at that depth, and on climatic conditions.
 This process is the one consuming atmospheric CO₂.
- 180 Introducing a mathematical description of the physical erosion in deep time models has profound
- 181 implications regarding the climate-weathering feedback (Fig. 2). The classical negative feedback
- 182 postulating that CO₂ consumption by weathering is increasing with enhanced greenhouse effect is still
- embedded in the model. But it is now connected too additional loops, generating a feedback either
- 184 positive of negative. The dissolution rate of silicate minerals is made dependent on the physical
- erosion, which modifies the regolith thickness and production, and ultimately the depletion in primaryminerals inside the continental regolith cover. This complexity cannot be unraveled without a
- 187 numerical model.
- 188 The dynamic model is spatially distributed and solves a set of coupled equations for each continental
- grid cell and at each time step. The spatial resolution used for this study is 2.8° (longitude) x 1.4°
- 190 (latitude). The model does not account for the lithology, because it cannot be constrained in the
- 191 Paleozoic. We thus use a mean "bulk" lithology for the complete continental surfaces.
- 192 The first equation describes the time evolution of the regolith thickness:

$$\frac{dh}{dt} = P - E \tag{1}$$

- 194 where P(m/yr) represents the regolith production at the interface between the regolith and the
- unaltered bedrock, and E (m/yr) the removal of materials by physical erosion at the top of the regolith.
- 196 This equation implicitly assumes that the weathering processes have no effect on regolith thickness
- 197 (isovolumetric weathering approximation). P is assumed to be dependent on the regolith thickness h
- 198 through the soil production function f(h).

$$P = P_0 \cdot f(h) \tag{2}$$

199

200 When the regolith thickness increases, less water can reach the regolith/bedrock interface and the

201 regolith production decreases. Though this formulation was initially proposed for soils (Heimsath and

others, 1997), the distinction between soil and regolith is not always explicit, and it has been widely

- 203 used in numerical models to describe the production of regolith explicitly (e.g. Gabet and Mudd,
- 204 2009; Carretier and others 2014; Braun and others, 2016). Several mathematical definitions of f(h) can 205 be found in the literature (Humphrey and Wilkinson, 2007). We chose an exponential decay with
- thickness (Heimsath and others, 1997; Ferrier and Kirchner, 2008; Gabet and Mudd, 2009; Carretier
- 207 and others, 2014):

$$f(h) = \exp\left(-\frac{h}{h_0}\right) \tag{3}$$

- 209 h_0 is the characteristic decay depth (table 2). The pre-exponential factor P_0 (Eq. 2) is made dependent
- 210 on air temperature T and runoff q, calculated as the difference precipitation minus evaporation
- 211 (Carretier and others, 2014):

$$P_0 = f_W k_{rp} q e^{-(E_a/R)(1/T - 1/T_0)}$$
(4)

213 T_0 is a reference temperature (293.15K), E_a is the apparent activation energy for granitic lithologies (48200 J/mol: Oliva and others, 2003). R is the ideal gas constant and k_{rp} is the regolith production 214 215 calibration constant. The factor f_W simulates the impact of vascular plants on the regolith production rate and on the weathering inside the regolith. This weatherability factor is set to 1 for modern 216 217 conditions (for the purpose of calibration). In the Devonian, its value on fully vegetated grid cell is slightly lower, fixed at 0.87 (based on Berner, 2004, in the absence of angiosperms) in all the 218 219 presented scenarios. Its value prior to the colonization ("barren" grid cell) varies with the considered scenario, but is always lower than 0.87 (Berner, 2004). 220

The physical erosion (m/yr) at the top of the regolith E (eq. 1) can be expressed as follows (Davy and Lague, 2009):

$$E = f_E k_e q^m s^n \tag{5}$$

223

where *s* (m/m) is the prescribed local slope, and *q* (m³/yr) the local water runoff. k_e is a calibration constant. The f_E factor represents the change in the erodibility related to the presence or absence of vascular plants. It is set to 1 for modern conditions (for the purpose of calibration), as well as when

227 grid cells are fully vegetated. The value prior to the colonization by vascular plants is not known and

could be either greater or smaller than 1 as discussed in the previous section, depending on the

erodibility of barren continental surfaces. We refer to section 3 for a detailed discussion about thevalues assigned to this parameter as a function of time.

231 The two other key equations of the dynamic regolith model define the abundance of primary mineral

232 phases within the regolith of each continental grid cell as a function of depth and time:

$$\frac{\partial x}{\partial t} = -P \cdot \frac{\partial x}{\partial z} - K \cdot x \cdot \tau^{\sigma} \tag{6}$$

233

$$\frac{\partial \tau}{\partial t} = -P \cdot \frac{\partial \tau}{\partial z} + 1 \tag{7}$$

234

where z (m) is the depth within the regolith. x (unitless) is the remaining fraction of primary minerals at depth z, that is the density of remaining primary minerals (in kg per m³ of regolith) at depth zdivided by the primary density of minerals (in kg per m³ of rock) in unweathered bedrock. This definition is consistent as the model assumes the weathering to be isovolumetric: the dissolution of primary phases does not affect z. τ is the age of the primary mineral particles, that is the time elapsed since the particles have left the bedrock/regolith interface and started to weather during their journey towards the surface. K is the kinetic constant of the weathering reaction. This kinetic constant is modulated by the age of the particles to the power σ . σ is negative, meaning that the reactivity of the

surfaces is decreasing with time, as secondary minerals progressively precipitate at the surface of the

primary mineral particles, limiting their weatherability. K is also made dependent on the runoff q and

245 on air temperature T (West, 2012):

$$K = f_W k_d \left(1 - e^{-k_w q} \right) e^{-(E_a/R)(1/T - 1/T_0)}$$
(8)

246

247 where k_d is the effective kinetic constant for the weathering of silicate rocks. k_w is a constant

248 describing the impact of the runoff on K. f_W is the same vegetation weatherability factor as in equation 249 4, as we assume that vascular plants have the same effect on mineral dissolution within the regolith

4, as we assume that vascular plants have the same effect on mineral dissolution within the regoliththan on regolith production. Using the two equations (Eq. 6 and 7), it can be demonstrated that the

251 overall weathering rate and associated CO₂ consumption of each grid cell (mol/m²/yr) is equal to:

$$W = [BC]_{bedrock} \int_0^h K \tau^\sigma x dz \tag{9}$$

252

where $[BC]_{bedrock}$ is the content of base cations (Ca and Mg) in bedrock, in mol/m³. Indeed, under the isovolumetric assumption, the integral in equation 9 yields a volumetric weathering rate, in m³ of weathered minerals per m² per yr, that should be multiplied by bedrock density and its content of cations (that boils down in the variable $[BC]_{bedrock}$) to have a weathering rate in mol/m²/yr.

257 The products leaving the regolith no longer interact with the weathering model. Solutes are delivered 258 to the ocean by river systems quasi immediately (with respect to carbon residence time). As for solid 259 eroded products, their potential storage and "remote" weathering in floodplains is neglected by the

260 model.

261 This spatially resolved erosion/weathering model is coupled to the climate-carbon cycle model

262 GEOCLIM (Goddéris and Joachimski, 2004; Donnadieu and others, 2006; Goddéris and others, 2014;

263 Goddéris and others, 2017) (Fig. 2). At each time step of the transient numerical simulation,

264 GEOCLIM calculates the continental temperature and runoff fields based on a look-up table of

climatic fields simulated with a 3D-climate model at various pCO_2 levels. These climatic fields have

266 been calculated using the FOAM ocean-atmosphere general circulation model (Donnadieu and others,

267 2006). These climatic fields are used by the weathering/erosion module to calculate the spatial

distributions of the regolith production rates, regolith weathering rates and physical erosion rates. The regolith mass balance is then solved using the same spatial resolution $(2.8^{\circ} \text{lon x } 1.4^{\circ} \text{lat})$, which allows

270 the calculation of the spatial patterns of regolith thickness changes. The alkalinity generated by

270 the calculation of the spatial patterns of regolith the kness changes. The arkaning generated by271 weathering is released into the oceanic model (9 boxes describing the oceanic chemical composition)

(Godderis and Joachimski, 2004) where carbon is removed through sedimentation. GEOCLIM

273 calculates the new coeval pCO_2 and the model moves towards the next time step. The resulting

coupled numerical model thus describes the coeval evolutions of climate, ocean biogeochemistry and

the erosion/weathering processes. The timestep of the simulations is equal to 0.05 years (about 20

days), a value constrained by the fastest processes simulated in GEOCLIM (the diffusion of CO_2 at

the ocean-atmosphere interface). However, the weathering module is updated only every 100

timesteps (about 5 years), and the timestep of the vascular plant colonization (see section 4.2) is 10

279 000 years.

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285 We first calibrate the model on the present-day continental configuration, with an extensive

vegetation cover. The vegetation factors f_W and f_E are set to 1 for present-day conditions, and we

3. BOUNDARY CONDITIONS AND PARAMETERS FOR THE STEADY-STATE

SIMULATIONS

287 choose the set of model parameters generating the best agreement between the calculated weathering

rates for a wide variety of large watersheds and the measured weathering rates from a published

database (Gaillardet and others, 1999, following the method described in Maffre and others (2018),

290 Table 2).

291 The Devonian simulations have been performed using the 350-360 Ma paleogeography from Golonka

292 (2002) (Fig. 3). The paleogeography is held constant during the simulations. The solid Earth

degassing is set to 6.8 Tmol(C)/yr, the value required to equilibrate the present-day CO₂ consumption

by continental silicate weathering. We adopt a constant degassing in the past to limit the number of

parameters, given the discrepancies existing between the various reconstructions available in the
 literature, mainly for more recent periods (Goddéris and Donnadieu, 2019). The altitude is fixed on

296 Interature, manny for more recent periods (Godden's and Domadieu, 2019). The antitude is fixed off297 each grid cell, and the slope is calculated from the present-day correlation between altitude and slope,

following Goddéris and others (2017). The underlying assumption is that tectonic uplift balances

299 erosion in every places.

300

Regarding the evolution of the f_W factor (Eq. 4 and 8) before, during and after the vascular plant

302 colonization, two scenarios are explored. In the first scenario, the local weatherability is multiplied by

303 3 when a grid element shifts from a barren state to fully vegetated conditions. This means that the

local vegetation weatherability factor f_W increases from 0.29 prior to the colonization to 0.87 when the

305 grid cell is colonized by vascular plants (based on Berner, 2004, in the absence of angiosperms) and

the vegetation erodibility factor f_E is fixed at its modern value of 1. The alternative scenario, derived from the results of Ibarra and others (2019), considers that local weatherability is multiplied by 2

308 during that transition (f_W increases from 0.43 to 0.87, Eq. 4 and 8).

309 The change in erodibility is not constrained (Eq. 5). For this reason, we performed a sensitivity study

310 where the erodibility factor f_E is multiplied by 2, 1, 1/2, 1/4, and 1/8 when a grid element switches

from barren to fully vegetated (that is, f_E changes, respectively, from 0.5, 1.0, 2.0, 4.0, and 8.0 to 1).

312 We thus test 3 cases for which the susceptibility of the continents to physical erosion is greater for

barren surfaces, one case study for which it is unchanged, and a last one for which barren continents

are less erodible in the absence of vascular plants.

315 A limitation of our modeling framework is related to the water cycle. The GEOCLIM model

calculates the water cycle using a 3-dimensional general circulation model (GCM) of the atmosphere

317 and the ocean. The water cycle is thus physically resolved. But GEOCLIM cannot capture the changes

318 in evapotranspiration and albedo associated with the expansion of vascular plants. Adding a feedback

of the vegetation cover directly on the evapotranspiration conditions would necessitate the addition of

one dimension to the climatic interpolation procedure, and hence multiply the number of GCM
 simulations. Such a procedure requires excessive computation time. This is the reason why the GCM

321 simulations. Such a procedure requires excessive computation time. This is the reason why the OCK322 runs have been performed assuming a prescribed distribution of the vegetation transpiration as a

function of latitude, in all runs. We cannot account for the direct climatic impact of the vegetation,

and we focus on the weathering and erosion changes. While previous numerical modeling work

325 acknowledged the importance of changes in land surface properties associated with land plant

- 326 expansion, they also demonstrated that results are model-dependent and, consequently, poorly
- 327 constrained (Le Hir and others, 2011; Brugger and others, 2019).
- 328 Finally, we define the Weathering Efficiency Index (WEI) as the ratio of the CO₂ consumption by
- 329 weathering inside the regolith (W, Eq. 9) versus the maximum potential CO₂ consumption by
- 330 weathering. The latter factor is equal to the regolith production (P, Eq. 2) multiplied by the base
- 331 cation (BC) content of the bedrock.

$$WEI = \frac{W}{[BC]_{bedrock} \cdot P} \tag{10}$$

A WEI of 1 means that all primary minerals released from the bedrock through regolith production
are fully weathered inside the regolith. There are no more primary minerals at the top of the regolith.
A WEI of 1 is typical of the "supply-limited" weathering regime. Conversely, WEI values
approaching zero mean that only a small fraction of the minerals released through regolith production
is weathered inside the regolith, and the materials removed by physical erosion contain a lot of fresh
unweathered minerals. "Kinetically-limited" weathering regimes are characterized by a WEI close to
0.

4. RESULTS

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341

- 4.1. Steady-State Simulations
- 343 344

345 We first run two sets of simulations until they reach steady-state, corresponding respectively to the 346 world before the colonization by vascular plants ("barren") and the world when this colonization is 347 complete ("fully vegetated"). Vascular plants are missing in the first series of runs, and they are 348 assumed to have colonized the whole continental surface in the second series of simulations. These 349 steady states are not dependent on the colonization scenario. The pattern of progressive spatial 350 spreading of vascular plants on continental surfaces, whereby those surfaces go from barren everywhere to fully vegetated everywhere, has no impact on the pre- and post-colonization states (Fig. 351 4). Converse, the pre and post colonization steady-states depend on the model parameters: the 352 prescribed solid Earth degassing rate (held constant at the same value before and after the 353 354 colonization) and on the model erodibility and weatherability for barren or fully vegetated conditions. Because the values of the vascular plants' parameters f_W and f_E are fixed in fully vegetated conditions 355 (we only varied the barren conditions values), in our analysis of steady-state simulations, we use the 356 fully vegetated values as the reference. In other words, we compare the pre-colonization "archaic" 357

- 358 values to the post-colonization "modern" value.
- 359

360 4.1.1. *Before the colonization*

Figure 5 shows the calculated steady-state pCO_2 and surface temperature in the barren world as a function of the prescribed erodibility, assuming, over the entire continental surface, a lowering of the weatherability by a factor of 2 with respect to fully vegetated conditions, or by a factor of 3.

- Using both pre-colonization weatherability f_W and erodibility f_E 2 times lower than post-colonization
- 365 values (f_W =0.43, f_E = 0.5), WEI equals 1 at steady-state for most of the continental grid cells (Fig. 6A).
- 366 Because the erodibility is prescribed at a low value in the absence of vascular plants, materials are not
- 367 efficiently removed by physical erosion and the spatially-distributed regolith thickens everywhere on
- Earth, at a rate depending on the local climate conditions. But as the regolith thickens, the soilproduction function decreases. Once reaching steady-state, the continents are covered by thick and
- 370 depleted regolith as a result of the weak erodibility combined with the long residence time of the rock
- 371 particles within the regolith (Fig. 7A). This long residence time allows weathering processes to
- operate at their maximum efficiency (WEI=1), but the CO₂ consumption is low. This setting is close
- to the transport-limited regime as defined by Stallard and Edmond (1983). High CO₂ levels are
- 374 required to allow the global silicate weathering to balance the prescribed solid Earth degassing flux.
- 375 Increasing the prescribed erodibility prior to the advent of the vascular plants generates a decrease in
- the regolith thicknesses (Fig. 7B, 7C, and 7D), which counters the weathering inhibition (Fig. 6B and
- 6C). As weathering reactions are now facilitated by a greater erosion, the balance between the global
- silicate weathering and the prescribed solid Earth degassing is achieved at lower CO₂ levels (Fig. 5).
- 379 A value of 4 for pre-colonization f_E (i.e., erodibility is 4 times above the fully vegetated value) leads
- to a decrease in steady-state CO_2 level down to 1180 ppm (4.2 Pre-industrial Atmospheric Level, or
- 381 PAL).
- 382 The decreasing trend of atmospheric CO_2 with increasing erodibility stops at a f_E of about 4 times the
- fully vegetated value. Above this threshold, the steady-state CO_2 rises with increasing f_E for barren
- lands (Fig. 5), while regolith thickness keeps decreasing (Fig. 7). When a very high erodibility is
- prescribed prior to the colonization ($f_E = 8$), the regolith cover almost disappears (Fig. 7). The bedrock
- particles are removed by intense physical erosion before they are weathered. The calculated WEI
- stabilizes around 0.7 at best in restricted flat areas along the equator (Fig. 6C), corresponding to a
 calculated cation depletion of about 60%. Under such an intense physical erosion, weathering
- becomes inefficient because the fresh primary minerals are being removed before they experience a
- 390 significant weathering. The weathering rates can only balance the prescribed solid Earth degassing
- 391 rate under higher pCO_2 level than when $f_E=4$ (Fig. 5).
- 392 Mean temperatures (global, continental or sea surface), follow a pattern similar to pCO_2 when plotted
- as a function of the pre-colonization erodibility f_E . (fig. 5B and D). Warmest pre-colonization
- temperatures are found for the lowest pre-colonization $f_E(0.5)$, and minimum temperatures are simulated with $f_E = 4$.
- 396 Model simulations using a pre-colonization weatherability factor f_W 3 times lower than the fully
- 397 vegetated conditions mimic the results of the pre-colonization runs with weatherability factor $f_W 2$
- times lower fully vegetated one, but higher CO_2 levels are required to stabilize the global carbon cycle
- 399 (Fig. 5C and 5D).
- 400
- 401 4.1.2. *After the colonization*
- 402
- 403 While we calculate a pre-colonization steady-state for each combination of f_W and f_E parameters, we
- 404 can generate only one post-colonization state given that f_E and f_W are forced to be equal to 0.87 and 1 405 magnetization state given that f_E and f_W are forced to be equal to 0.87 and 1
- 405 respectively once the colonization achieved. The CO_2 level after the colonization stabilizes at 2.7 PAL
- 406 (760 ppm). This CO₂ level is lower than all the tested pre-colonization cases, whether the pre-
- 407 colonization erodibility is higher or lower than the fully vegetated one.

408 A striking difference between the pre-colonization and the post-colonization state is the latitudinal 409 distribution of silicate rock weathering. For a prescribed pre-colonization erodibility equal to or greater than 4 times the post-colonization value, most of the weathering flux and associated CO_2 410 411 consumption is located in the low latitudes (Fig. 8). Indeed, the intense global erodibility makes the bedrock conversion into regolith fast enough for regolith to develop only along the equator where 412 413 climate is warm and humid. In this environment, the model generates a regolith in which weathering reactions can occur. At higher latitudes, the erosion overtakes the weathering reactions. The material 414 415 is removed by physical erosion before being significantly weathered. As discussed below, this behavior has a major impact on the calculated CO₂ and climate evolution during the colonization 416 417 phase. 418 419 420 4.2. During the Colonization: Simulating the Transient State 421 422 4.2.1. Simulation design and sensitivity tests

The transient evolution of climate and carbon cycle once vascular plants start colonizing continents depends on the way the vascular plants spread on continental surfaces, until the continents are fully vegetated. Indeed, the pattern and timing in which continents get colonized affects weathering rates and hence the temporal evolution of pCO_2 . We refer to the pattern and timing of progressive spatial spreading of vascular plants on continental surfaces as the "colonization scenario". Several

427 spreading of vascular plants on continental suffaces as the "colonization scenarios428 colonization scenarios are presented hereinafter.

429 For the sake of clarity, we build our analysis in this section – and the following ones – on the changes

430 in weatherability and erodibility following the transition from barren to fully vegetated. We thus

431 define the vegetation enhancement factors $\Delta f_W = f_W(fully vegetated)/f_W(barren)$, and similarly for Δf_E .

432 One should note that " Δ " is here meant for a ratio, and not a difference.

433 We build a simple cellular automaton to simulate the progressive expansion of the vascular plants on

434 the continents. On each isolated continental block, we first choose arbitrarily a grid element where the

435 colonization starts (Fig. 4). Then the change in weatherability and erodibility propagates according to

the simple following rule: a naked neighbor of a grid element fully vegetated has a probability of 50%

to be fully vegetated during the next time step. A new vegetation map is generated every 10 kyr.

438 As it was the case for the steady-state runs, here we present two sets of simulations, one assuming that

439 vascular plant colonization increases the weatherability by a factor 2 ($\Delta f_W = 2$), and the other by a

440 factor of 3 ($\Delta f_W = 3$). Each set includes three subsets of simulations, where the erodibility is

unchanged ($\Delta f_E = 1$), divided by 4 ($\Delta f_E = 1/4$), and divided by 8 ($\Delta f_E = 1/8$) respectively, when a

442 continental grid element is fully vegetated. Finally, within each subset, three additional simulations443 allow to test the impact of the random propagation of the vascular plants on the continental surfaces,

keeping the seeding points at the same location. This pattern is controlled by the cellular automaton

and differs from one run to the other. Those colonization scenarios are labelled α , β , and γ (Fig. 4).

446 There are still large uncertainties about the colonization of dry uplands. Even if plants already

447 developed the required adaptations for colonization of dry areas in the Silurian (Morris and others,

448 2018), the question of the effective upland occupation by vascular plants remains open (Pawlik and

449 others, 2020) This upland colonization might have occurred around the end of the Devonian (Willis

and McElwain, 2016), or might have been delayed until the Carboniferous (Boyce and Lee, 2016).

- 451 The exact timing and pattern of the colonization will be probably never known, because of the lack of
- 452 fossils from dry areas. In the following, we will assume that the full colonization spans 30 million

453 years (the timespan from the Givetian to the Famennian), a duration that must be considered as a454 parameter.

455

456 4.2.2. Sensitivity of the Earth system to the colonization

457 The following simulations have been performed using the α , β , and γ colonization scenario 458 respectively (FDig. 4). When the weatherability is multiplied by 3 during the colonization ($\Delta f_W = 3$), 459 simulated pCO_2 displays roughly the same temporal evolution whatever the prescribed change in 460 erodibility and whatever the colonization scenario (Fig. 9A). The pCO_2 decreases rapidly from very high values (between 4000 and more than 6000 ppm) down to the post-colonization steady-state value 461 462 of 760 ppm. The change in weatherability is strong enough to overwhelm the effect of changing 463 physical erodibility. This numerical solution, however, is not supported by available pCO_2 proxy data. 464 It implies very large CO_2 levels prior to the colonization, while proxy data suggests a maximum pCO_2 465 of 1900 ppm in the Eifelian (Foster et al., 2017). Previous studies of the effect of the colonization on 466 the carbon cycle are assuming a global decrease of the weatherability by a factor of 3 prior to the colonization (Berner, 2004). Our simulations suggest that this calculated CO₂ decrease might be too 467

468 large.

469

470 If weatherability is multiplied by 2 during the colonization phase ($\Delta f_W = 2$), the global amplitude of 471 the *p*CO₂ changes is considerably reduced, in closer agreement with proxy data (Fig. 9B). Conversely 472 to the previous results, changes in continental erodibility during the colonization lead to contrasting 473 *p*CO₂ evolutions. The simulation with an unchanged erodibility during the colonization ($\Delta f_E = 1$) 474 shows an overall decrease in atmospheric CO₂. In simulations $\Delta f_E = 1/4$ and $\Delta f_E = 1/8$, *p*CO₂ increases 475 during the early stages of the colonization, reaching a maximum just after the Givetian/Frasnian 476 boundary, and subsequently decreases. The *p*CO₂ simulated in all runs $\Delta f_E = 1/4$ and $\Delta f_E = 1/8$ (i.e.,

477 using the colonization scenarios α , β or γ) falls within the range of uncertainty of the CO₂ proxy

478 estimates. Consequently, these simulations are all equally plausible (Fig. 9B).

479

4.2.3. *Analysis of the simulations with constant erodibility*

481

480

482 To decipher the respective influence of each parameters considered in this study, we first explore the 483 dynamics of a simulation where erodibility does not change during the colonization ($\Delta f_E = 1$, $\Delta f_W = 2$ 484 with the β colonization scenario). Such run is somewhat similar to the simulations previously 485 performed with the GEOCARB model family (e.g., Zhang et al., 2018), given that vascular plants 486 generate a change in weatherability only, without impacting the physical erosion, with the notable

487 differences that we account for the spatial distribution of the weathering rates, and we simulate the

488 time evolution of the regolith thickness.

489

490 Simulation $\Delta f_E = 1$, $\Delta f_W = 2$ with the β colonization scenarios shows a general decrease in *p*CO₂.

491 Starting a few hundred thousand years after the beginning of the colonization (Fig. 10A) and

492 promoted by the increase in weatherability propagating on the continents in response to the expansion

493 of vascular plants, the global CO₂ consumption by weathering remains higher than the CO₂ release by

494 solid Earth degassing (Fig. 10B). The departure from equilibrium, however, is small (never exceeding

- 495 0.2 Tmol/yr), which means that the weathering feedback is operating efficiently. The evolution of the
- 496 CO₂ consumption by silicate weathering on each individual continent shows contrasting behaviors

497 (fig. 10C). Given their size, the two most important contributors to the global weathering flux are the498 Euramerica and Gondwana continents.

499 The silicate weathering CO₂ consumption stays remarkably constant over Euramerica for 7 million

500 years after the start of the colonization (Fig. 10C). Then the colonization reaches the mountain range

501 located close to the equator. The combination of more intense erosion linked to greater slopes with

502 enhanced weatherability generates a marked increase in the Euramerica weathering flux (fig. 10C).

503 The subsequent decrease in atmospheric CO_2 further cools the planet, forcing weathering on

504 Gondwana to decrease.

505 Ten million years after the start of the colonization, Euramerica is fully vegetated in scenario β (Fig.

4). The overall weatherability cannot increase anymore, and the growth of the regolith progressivelyinhibits weathering over Euramerica (Fig. 10C). The weathering of Euramerica shifts to a transport-

508 limited mode. Conversely, weathering fluxes over Gondwana increase (Fig. 10C), because the

509 continuous spreading of the vascular plants overcomes the effect of climate cooling on weathering

510 fluxes. The contribution of each continent to the global weathering flux eventually converges towards

511 the pre-perturbation spatial distribution, but at a much lower CO_2 .

512

513 4.2.4. *Analysis of the simulations with a decreasing erodibility through the colonization*

514

515 We compare now the behavior of the carbon cycle in simulation ($\Delta f_E = 1$, $\Delta f_W = 2$), with erodibility 516 insensitive to the colonization, with simulation where erodibility decreases by a factor of 4 on 517 colonized grid cells ($\Delta f_E = 1/4$, $\Delta f_W = 2$). The colonization scenario β is used in each case.

518 The decrease in erodibility generates a positive excursion in pCO_2 during the colonization phase. To 519 provide an explanation for this puzzling behavior, we separated the general trend into three distincts 520 phases.

521	• Phase 1. During the first ca. 2 to 3 million years of the colonization, pCO_2 stays constant
522	(Fig.10A, run $\Delta f_E = 1/4$, $\Delta f_W = 2$). Responding to the expansion of the vascular plants, the
523	weathering rates (the flux per unit of land area) in the model grid cells instantaneously
524	increase when the cells are colonized. In the equatorial band, hot spots of weathering appear
525	as spikes in the silicate weathering curve of Euramerica (Fig. 10C, dashed lines). These
526	hotspots vanish rapidly, within a few hundred thousand years after their colonization. During
527	this time span, the regolith acts as a reservoir of cation-bearing minerals, but this reservoir is
528	rapidly exhausted owing to the increased weatherability. This depletion of the regolith limits
529	the weathering rates. As long as the fraction of the equatorial belt fully vegetated remains
530	small, the overall weathering rates are not significantly affected, and so does pCO_2 .

Phase 2 As colonization proceeds and reduces the erodibility over increasing areas of
 Euramerica, the regolith thickness increases. The weathering rates are consequently
 progressively inhibited in the warm and humid equatorial belt, and after 2 to 3 million years,
 pCO₂ starts to rise.

Phase 3. While this rise in CO₂ warms the climate, further inhibiting weathering in the equatorial region, it accelerates the weathering at higher latitudes together with the decrease in erosion associated with the colonization (Fig.11). As a consequence, the weathering at higher latitudes (around 40°S to 60°S) intensifies. Atmospheric CO₂ starts to decrease down to the post-colonization steady-state value of 760 ppm.

541 Figure 12 and 13 summarize the temporal evolution of the regolith thickness simulated in the ($\Delta f_E = 1$,

542 $\Delta f_W = 2$) and $(\Delta f_E = 1/4, \Delta f_W = 2)$ simulations (both with colonization scenario β). If erodibility does 543 not change, the spatio-temporal pattern of the regolith thickness remains virtually unchanged: the

equatorial region is covered by thick regoliths before, during and after the colonization, with a peak in

regolith thickness at 10 million years (Fig. 12). After 10 million years, the regolith thickness starts to

546 decrease, because the decrease in atmospheric CO₂ generates cooler and dryer conditions, reducing

547 the efficiency of the regolith production. In the run ($\Delta f_E = 1/4$, $\Delta f_W = 2$), the flux of CO₂ consumption

548 by silicate weathering is first located mainly along the equator, promoted by an intense weathering

- 549 driven by a strong erosion, until ca. 3 million years after the start of the colonization. At that time, the
- regolith thickness starts to increase along the equator, and the weathering system shifts towards the
- 551 modern geographic distribution (fig. 13).

552

The prescribed erodibility change Δf_E has important implications for the silicate weathering feedback (Walker and others, 1981). Indeed, the ($\Delta f_E = 1/4$, $\Delta f_W = 2$) simulation emphasizes the weakness of the

555 silicate weathering negative feedback in the tropics, when the role of the regolith thickness is

accounted for. Lower erosion rate due to lower erodibility ($\Delta f_E = 1/4$) dramatically reduces chemical

557 weathering rates in the tropics despite the increased weatherability ($\Delta f_W = 2$). Hence, while

558 Euramerican CO₂ consumption by silicate weathering rises during the colonization in simulation (Δf_E

559 = 1, $\Delta f_W = 2$), it decreases by 20% in the simulation ($\Delta f_E = 1/4$, $\Delta f_W = 2$) (with colonization scenario β)

560 between 0 and 10 million years (Fig. 10C). During a few million years, the tropics act as a powerful

561 warming engine for Earth's climate. Without the presence of continents at higher latitude, the silicate

562 weathering system may drive Earth's climate into a runaway greenhouse.

563

The behavior of weathering within equatorial Euramerica, where CO₂ consumption decreases with 564 increasing CO₂, is further investigated hereafter by comparing results obtained in simulation (Δf_E = 565 1/4, $\Delta f_W = 2$) using the colonization scenario α , on the one hand, and colonization scenarios β and γ , 566 on the other hand. The biggest contribution to the global CO_2 sink is located in Euramerica, especially 567 568 prior to the colonization and during the early phases of the colonization. This implies that the global 569 weathering CO_2 consumption is largely driven by Euramerica weathering. The pCO_2 evolution 570 simulated in scenarios α , β and γ are similar during the early stages of the colonization (Fig. 14). 571 pCO_2 first stays constant, and then rises after 2 to 3 million years, for the reason exposed previously. Then, scenario α generates a divergent story. After 4 million years, the rate of the CO₂ rise weakens, 572 573 and after about 7 million years of colonization, pCO_2 goes down in the α run, while pCO_2 still rises in 574 scenarios β and γ . The only difference between these simulations is the pattern of the colonization in 575 space and time. The colonization starts from the same seeding locations in each colonization scenario (on Euramerica, located on its Eastern equatorial border, Fig. 4) but the expansion is subsequently 576 577 proceeding randomly. In scenarios β and γ , the colonization reaches the western border of equatorial 578 Euramerica sooner than in scenario α . At 8 million years, the warm and humid equatorial zone of 579 Euramerica is almost wholly colonized in scenarios β and γ . Consequently, the weathering processes 580 in this region (which is the main contributor to weathering) are strongly inhibited by the increasing regolith thickness. Conversely, in scenario a, part of Euramerica is not fully vegetated at 8 million 581 582 years as the colonization did not reach yet the western border of Euramerica. This region is thus still able to respond to climate change, with an unchanged erodibility factor f_E of 4 times the post-583 584 colonization efficiency. Owing to the global warming generated by the inhibition of weathering in the 585 colonized equatorial grid cells outside of this region, the western part of Euramerica increases its 586 consumption of atmospheric CO₂ under warmer and more humid climate. CO₂ is thus progressively 587 removed from the atmosphere.

- 588 From a global perspective, the relationship between the total CO₂ consumption by silicate rock
- 589 weathering and the change in atmospheric CO_2 is complex when physical erosion is accounted for. 590 Indeed, when we assume that the colonization of the continents by vascular plants does not change the
- 590 Indeed, when we assume that the colonization of the continents by vascular plants does not change the 591 physical erodibility ($\Delta f_E = 1$, $\Delta f_W = 2$), the silicate weathering versus atmospheric CO₂ function
- displays an overall positive correlation between both variable (Fig. 15). But when we account for a
- 593 decrease in erodibility through the colonization event ($\Delta f_E < 1$), the correlation is lost. During the
- early phases of the colonization, the global silicate weathering decreases with increasing CO₂ (Fig.
- 595 15) because the shielding of the equatorial area limits the silicate weathering flux. But when the
- 596 colonization starts to increase significantly the weathering at higher latitude, silicate weathering rises
- 597 again with atmospheric CO₂. Two tipping points can be identified. First, an inflexion in the silicate
- weathering vs CO₂ curve is calculated 5 million years after the beginning of the colonization event.
 This tipping point corresponds to the moment when silicate weathering become efficient at mid-
- 600 latitude in response to the progressive expansion of vascular plants. The second tipping point occurs
- 601 when the colonization is completed, 25 million years after the first tipping point. At that moment,
- 602 weatherability (f_W) and erodibility (f_E) are held constant for all the continental grid cells, silicate
- 603 weathering is not more forced and the model predicts the restoration of a classical weathering/CO₂
- 604 relationship.
- 605

606 Our numerical simulations thus strongly suggest that the colonization of the continents by vascular

plants during most of the Devonian did not monotonically remove CO₂ from the atmosphere, in

response to an enhanced weatherability. Simulations accounting for a decrease in erodibility of the

- 609 continental surface show that pCO_2 might have first risen, or oscillated, before starting to decrease.
- 610

611

5. LIMITATION AND ADDITIONAL THOUGHTS

612

613 Many studies have focused on the role played by mountain ranges on the evolution of the global carbon cycle. In the 90s, it has been repeatedly argued that the uplift of the Himalayan range was a 614 powerful driver of the carbon cycle, by promoting physical erosion. The subsequent increase in 615 regional silicate weathering rates was proposed as the culprit for the late Cenozoic cooling (Raymo, 616 1991). Then Kump ad Arthur (1997) defined the concept of weatherability. Mountain ranges are not 617 618 boosting weathering fluxes, but they enhance the weatherability, forcing CO_2 to go down while the 619 global carbon mass balance stays close to equilibrium. But this weatherability change is in fact a 620 change in erodibility, which removes the regoliths and facilitates the dissolution of the fresh bedrock. Goddéris and others (2017) explored the role of erodibility change during the uplift and demise of the 621 622 Central Pangean Mountains. It has also been suggested that mountainous regions reinforce the negative weathering feedback (West, 2012; Maher and Chamberlain, 2014). Recently, the role of 623 624 mountain ranges on the global evolution of the carbon cycle has been repeatedly questioned. The 625 burial of organic carbon exported from the ranges might be a powerful CO₂ sink (France-Lanord and Derry, 1997; Galy and others, 2007). Similarly, the release of sulfuric acid by the oxidation of 626 sedimentary sulfur exposed in mountain ranges raises the importance of carbonate weathering, the 627 mountains becoming a source of carbon at a timescale below the residence time of sulfur in the ocean-628 atmosphere system (Calmels and others, 2007; Torres and others, 2016). But all those processes are 629 630 driven by the physical erosion in the specific case of active mountain ranges. The erodibility of the mountainous areas becomes the central piece of the climatic evolution of the Earth. For instance, 631 using the formalism described here to simulate the physical erosion, Maffre and others (2021) have 632 633 quantified the role played by the oxidation of sedimentary pyrite on the carbon cycle. Erodibility

being partly a function of climate, it paves the way for the integration of new feedback processes inglobal scale models.

- This period of Earth history is critical because erodibility and weatherability are altered by two
- 637 distinct, yet not independent processes. On the one hand, the release of organic acids and the below
- 638 ground CO₂ release by the roots increases the weatherability, on the other, roots modify the erodibility
- by stabilizing the regolith. The coupling between the two processes occurs through the presence of
- 640 vascular plants, but the relative amplitude of weatherability and erodibility changes are not precisely
- 641 known, even for the present-day environment. This present uncertainty is even higher in the Devonian
- 642 context, with extinct tree species (Pawlik and others, 2020). Nevertheless, we demonstrate that the
- Earth climate history from the middle to the late Devonian is heavily dependent on the relative
- 644 importance of these two processes, and on vegetation colonization scenario.
- 645 Our results are also dependent on the positions of the "seeding" points. In the experiments, we
- 646 prescribe arbitrarily one seeding point on each continent. Given that the three colonization scenarios
- 647 (all with the same seeding point on each continent) have a strong impact on the atmospheric CO_2
- evolution, the choice of the position of the seeding points will impact the time evolution of
- 649 atmospheric CO₂, because it modifies drastically the pattern of the colonization with time. This effect
- should be tested by multiplying the number of simulations to generate an ensemble of results that canbe explored with adequate statistical methods. At this stage, this is beyond the objective of this study.
- be explored with adequate statistical methods. At this stage, this is beyond the objective of this study.But we perform a sensitivity analysis where we moved the seeding on the Gondwana continent from a
- 653 tropical location to a high latitude site. We choose the Gondwana continent because its size will
- 654 generate the maximum impact of the seeding point location (scenario δ). We re-run the simulations
- 655 $(\Delta f_E = 1, \Delta f_W = 2), (\Delta f_E = 1/4, \Delta f_W = 2), \text{ and } (\Delta f_E = 1/8, \Delta f_W = 2).$ When erodibility does not change $(\Delta f_E = 1/8, \Delta f_W = 2)$.
- 656 = 1, $\Delta f_W = 2$), the impact on the calculated atmospheric CO₂ evolution remains marginal. But when
- 657 Δf_E equals 1/4 or 1/8, the CO₂ shows a great sensitivity to the Gondwana seeding point (Fig. 16). We
- are a still generating rather constant CO₂ during the early phase of the colonization, and then a rise
- triggering a warmer climate later in the Frasnian, compared to the previous simulations.

660

661 Lastly, this is a theoretical study. We are not attempting at reproducing precisely the real evolution of the surficial environment during the colonization of the continents by vascular plants. Such an 662 663 objective cannot be achieved for the following reasons: the timing is not well constrained, the 664 scenario of the colonization is unknown, the position of the continents and their relief are held constant in the present work, the plants do not have a direct impact on the climate, and last but not 665 666 least, our numerical model misses some key processes and feedbacks, despite its complexity. But we 667 show that the colonization of the continental surfaces by vascular plants was probably not a long and quiet river, bringing the CO₂ from the high early Paleozoic levels down to the low Carboniferous level 668 monotonically. And our study also highlights the importance of accounting for the spatial distribution 669 670 of the weathering fluxes.

- 671
- 672

6. CONCLUSIONS

673

We used a modified version of the GEOCLIM climate-carbon cycle model to simulate the impact of the colonization of the continents by vascular plants during the Middle and Late Devonian. We

- accounted for the associated changes in weatherability and erodibility of the continental surfaces. This
- 677 is the first attempt to simulate the coupled changes in the global carbon cycle including pCO_2 ,
- 678 climate, weathering processes (with a spatial resolution).

- A first conclusion is that, whatever the change in erodibility, all simulations considering a 3-fold
- 680 increase in weatherability due to the colonization by vascular plants, lead to a marked decrease in
- atmospheric CO_2 in response to the expansion of vascular plants in the Devonian. Such results align
- 682 well with previous modeling studies (e.g., Berner, 2004). However, the amplitude of the simulated
- 683 pCO_2 decrease is generally outside the range permitted by pCO_2 proxy data.
- 684 When considering a weaker increase in weatherability with colonization (i.e. a doubling), the
- temporal evolution of simulated pCO_2 becomes highly dependent on considered changes in physical
- erosion. If erodibility is kept the same, the pCO_2 decreases during the colonization. When a decrease
- 687 in erodibility with colonization is considered, however, all simulations first generate a constant pCO_2
- for about 3 million years after the beginning of the colonization, followed by a positive excursion. For
- 689 instance, when erodibility is reduced by a factor of 4 or more, an ample positive excursion in pCO_2 is 690 simulated. Assuming a colonization lasting 30Myrs, this pCO_2 excursion generally lasts about 10
- 691 million years but its duration depends on the colonization scenario.
- million years but its duration depends on the colonization scenario.
- 692 Whatever the change in erodibility considered, pCO_2 after the colonization is systematically lower
- than before the colonization. This is true for the range of change in erodibility tested here: from a
- decrease by a factor of 8 to an increase by a factor of 2 when continental areas transition from naked
- 695 to fully vegetated.
- A decreasing erodibility of the continental surface from barren to fully vegetated deeply alters the
- 697 latitudinal distribution of weathering. Prior to the colonization, silicate weathering mostly takes place
- at equatorial latitudes (between 15°S to 15°N). During the colonization, this equatorial band shifts
- towards a transport limited mode, facilitated by the decrease in physical erodibility, the increase in
 weatherability, and a warm and humid climate. This induces decrease in CO₂ consumption by silicate
- weathering in the equatorial region, promoting atmospheric CO₂ rise. After a few million years, this
- inhibition of equatorial weathering is counteracted by the progressive increase in weathering at the
- 703 mid-latitudes triggered by global climate warming. It is possible that this new spatial pattern of
- 704 weathering impacted the efficiency of the weathering negative feedback stabilizing the Earth climate
- 705 at the geological timescale.
- 706 In conclusion, the impact of vascular plants on the CO_2 consumption by silicate weathering cannot be 707 described as a monotonic decrease in pCO_2 forced by an increasing weatherability. It appears that the 708 concomitant change in erodibility is critical. The paleogeographic configuration is also a major 709 controlling parameter, as is the sequence by which the environmental occupation of vascular plants
- expanded. All those three factors are not well constrained, and there is a possibility that they will
- never be known at the degree of confidence required to understand physically the Devonian evolution
- 712 of the surficial Earth system.
- 713
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- 714 715

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949 APPENDIX 1: THE COLONIZATION SCENARIOS

- 950 Figure 16. Colonization of the continents by vascular plants (in each grid element turning green, the
- 951 erodibility and weatherability is shifting from its pre-colonization value to its post-colonization value
 952 (see main text). These maps stand for scenario α.
- 953 forest scenario vegdyn.pdf
- 954
- Figure 17. Colonization of the continents by vascular plants (in each grid element turning green, the
- erodibility and weatherability is shifting from its pre-colonization value to its post-colonization value(see main text). These maps stand for scenario β.
- 958 forest_scenario_vegdyn2.pdf

959

- 960 Figure 18. Colonization of the continents by vascular plants (in each grid element turning green, the
- 961 erodibility and weatherability is shifting from its pre-colonization value to its post-colonization value 962 (see main text). These maps stand for scenario γ .
- 963 forest_scenario_vegdyn3.pdf

964

- 965 Figure 19. Colonization of the continents by vascular plants (in each grid element turning green, the
- 966 erodibility and weatherability is shifting from its pre-colonization value to its post-colonization value
- 967 (see main text). These maps stand for scenario HL (same scenario that β except that the position of the
- 968 seeding points on Gondwana has been shifted to a higher latitude).
- 969 forest_scenario_vegdyn_hl.pdf
- 970