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Abstract

Many continental growth models have been proposed over the years to explain geological and geochemical data. Amongst these data, the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates has been used as an argument in favour of delayed continental growth models and of a Neoarchean pulse in continental growth. This interpretation requires that continental freeboard and continental hypsometry have remained constant throughout Earth's history. However, recent studies suggest that Archean sea levels were higher, and Archean relief lower, than present-day ones. To assess the validity of the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates as a proxy for continental growth, we have developed a model that evaluates the co-evolution of mantle temperature, continental hypsometry, sea level, ridge depth, emerged area of continental crust and the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water as a function of continental growth. We show that Archean sea levels were between ~ 500 m and ~ 1800 m higher than present-day ones, that Archean mid-oceanic ridges were between ~ 700 m and ~ 1900 m shallower than present-day ones, and that the Archean emerged land area was less than $\sim 4\%$ of Earth's area. Importantly, the evolution of the area of emerged land, contrary to that of sea level and ridge depth, barely depends on continental growth models. This suggests that the evolution of surface geochemical proxies for felsic lithologies does not constrain continental growth. In particular, the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water predicted for an early continental growth model is in broad agreement with the $^{87}\text{Sr}/^{86}\text{Sr}$ data on marine carbonates when changes in continental freeboard and continental hypsometry are taken into account. We propose that the Neoarchean shift in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates recorded the emergence of the continents rather than a pulse in continental growth. Since the evolution of other geochemical indicators for felsic crust used as proxies for continental growth is equally well explained by continental emergence, we suggest that there could be no need for delayed continental growth models.

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The evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates does not constrain continental growth

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Abstract

Many continental growth models have been proposed over the years to explain geological and geochemical data interpreted as reflecting continental growth. Amongst these data, the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates through time has been used as an argument in favour of delayed continental growth models and of a Neoproterozoic pulse in continental growth. This interpretation requires that continental freeboard and continental hypsometry have remained constant throughout Earth's history. However, recent studies suggest that Archean sea levels were higher, and Archean relief lower, than present-day ones.

To assess the validity of the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates as a proxy for continental growth, we have developed a model that evaluates the co-evolution of mantle temperature, continental hypsometry, sea level, ridge depth, emerged area of continental crust and the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water as a function of continental growth. We show that Archean sea

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levels were between ~ 500 m and ~ 1800 m higher than present-day ones, that Archean mid-oceanic ridges were between ~ 700 m and ~ 1900 m shallower than present-day ones, and that the Archean emerged land area was less than ~ 4 % of Earth's area. Importantly, the evolution of the area of emerged land, contrary to that of sea level and ridge depth, barely depends on continental growth models. This suggests that the evolution of surface geochemical proxies for felsic lithologies does not constrain continental growth. In particular, the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water predicted for an early continental growth model is in broad agreement with the $^{87}\text{Sr}/^{86}\text{Sr}$ data on marine carbonates when changes in continental freeboard and continental hypsometry are taken into account. We propose that the Neoarchean shift in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates recorded the emergence of the continents rather than a pulse in continental growth. Since the evolution of other geochemical indicators for felsic crust used as proxies for continental growth is equally well explained by continental emergence, we suggest that there could be no need for delayed continental growth models.

Keywords: continental growth, continental emergence, continental freeboard, continental hypsometry, thermal evolution, Archean

Highlights

- Evolution of $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates is a proposed proxy for continental growth
- Model evolution of emerged land area and of $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water for contrasted continental growth scenarios

- Emerged land area barely depends on continental growth
- Evolution of $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates is a proxy for continental emergence, not for continental growth
- Surface geochemical proxies for felsic material do not constrain continental growth

1. Introduction

On geological time scales, continental material is produced by the partial melting and differentiation of juvenile material extracted from the mantle, and destructed by being recycled back into the mantle. The tempo of continental growth has received a lot of attention over the past few decades, and many contrasted continental growth scenarios have been proposed (see Rino et al., 2004 and Harrison, 2009, for recent reviews). In these models, the proportion of present-day continental mass at 3.8 Ga ranges between 0% (*e.g* Veizer and Jansen, 1979; Taylor and McLennan, 1985) and 100% (*e.g* Fyfe, 1978; Armstrong, 1981). On one hand, continental growth scenarios based on the secular evolution of surface geochemical proxies for felsic material such as the composition of shales (Taylor and McLennan, 1985), the age distribution of preserved zircons (Condie, 1998, 2000), and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in marine carbonates (Veizer and Jansen, 1979; Taylor and McLennan, 1985) led to delayed continental growth models with no significant continental crust before the Neoproterozoic. On the other hand, continental growth scenarios based on mantle chemical proxies such as the Nb/U signature (*e.g* Campbell, 2003) and the ^{142}Nd anomaly of basaltic suites (*e.g* Boyet et al.,

2003; Caro et al., 2003) suggest an early depletion of the mantle and thus early continental growth.

In this paper, we focus on the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates as a proxy for continental growth. Changes in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates, commonly assumed to represent the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water, reflect changes in the relative contributions of the continental versus mantle chemical reservoirs to the composition of ocean water. Indeed, continents concentrate incompatible elements, including radioactive ^{87}Rb that decays to ^{87}Sr with a half life of 48.81 Gyr. A compilation of the strontium isotopic signature of marine carbonates reveals an increase in $^{87}\text{Sr}/^{86}\text{Sr}$ over time, with a shift from mantle composition at ~ 2.7 Ga (Shields and Veizer, 2002). This increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates reflects the increasing contribution of a radiogenic source to the composition of the oceans, and has been proposed to reflect a Neoproterozoic increase in the production of continental crust (*e.g.* Veizer and Jansen, 1979; Taylor and McLennan, 1985). The input of high radiogenic strontium from the continents to the oceans depends on the sedimentary run-off (Goddris and Franois, 1995) and thus on the area of emerged land and on continental relief (Goddris and Veizer, 2000). As for the input of low radiogenic strontium from the oceanic lithosphere to the ocean, it depends on the efficiency of hydrothermal processes (Goddris and Veizer, 2000).

To date, when using the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates as a proxy for continental growth, it has been implicitly assumed that both continental freeboard and continental relief have been constant through time (Veizer and Jansen, 1979; Godris and Veizer, 2000). However, Rey and

44 Coltice (2008) suggested that a hot continental lithosphere could not support
 45 high elevations in the Archean, and Arndt (1999) and Flament et al. (2008)
 46 suggested that in the Archean the continental crust was both largely flooded
 47 and covered by thick subaqueous continental flood basalts. This would have
 48 resulted in limited weathering and erosion processes, thereby largely isolat-
 49 ing the Archean continental crust from the atmosphere and from the oceans.
 50 Thus, the appearance of the signature of the continental crust in the surface
 51 geochemical record would have been delayed even if large amounts of con-
 52 tinental crust had been extracted from the mantle early in Earth's history.
 53 Thus, the Neoarchean increase in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates could
 54 reflect an important increase in the area of emerged continental crust rather
 55 than an increase in the production of continental crust. This implies that
 56 the suitability of surface geochemical indicators as proxies for continental
 57 growth needs to be reassessed. To this avail, we build an integrated model to
 58 investigate the emerged area of continental crust as a function of continental
 59 growth. This model accounts for the co-evolution of mantle temperature,
 60 continental hypsometry, sea level, ridge depth and emerged area of conti-
 61 nental crust. We then use this model to investigate the effect of contrasted
 62 continental growth scenarios on the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water.
 63 We show that the evolution of the area of emerged land, contrary to that of
 64 sea level and ridge depth, barely depends on continental growth models. We
 65 conclude that the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonate does not
 66 constrain continental growth.

2. An integrated model to calculate the emerged area of continental crust and the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water

In order to investigate the effect of continental growth on the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water, we model the evolution of emerged land area as a function of mantle temperature, continental fraction and continental hypsometry (Flament et al., 2008). To calculate the evolution of the temperature of the mantle, we use the thermal evolution model of Labrosse and Jaupart (2007) because it accounts for the dependance of mantle temperature on continental growth (Birch, 1965; Spohn and Breuer, 1993; Grigné and Labrosse, 2001). The integrated model derived in this study is presented in Fig. 1 and described in detail in this section.

2.1. Continental growth end-members

In order to investigate the effect of contrasted continental growth models on mantle temperature, we adopt the sigmoidal formulation of Grigné and Labrosse (2001) and Labrosse and Jaupart (2007) for the fraction of continents formed with respect to the present-day, hereafter referred to as continental fraction

$$f(t) = \frac{1}{1 + \exp(-(t + t_1)/t_2)} , \quad (1)$$

where the time t is set to 0 at present and is negative in the past, and t_1 and t_2 are two time constants. This model imposes a single continental growth stage centred on time t_1 and of duration t_2 . We propose to use four end-members of continental growth models, including (i) a constant growth model (*i.e* a sigmoid in which steady-state has not been reached yet), hereafter referred to as CGM; (ii) a Neoarchean continental growth model, hereafter referred to as

90 NGM, for which $t_1 = 2.5$ Ga and $t_2 = 200$ Ma - this model is broadly similar
 91 to that of Taylor and McLennan (1985) and of Veizer and Jansen (1979); (iii)
 92 an early continental growth model, hereafter referred to as EGM, for which
 93 $t_1 = 3.8$ Ga and $t_2 = 100$ Ma - this model is similar to that proposed by
 94 Armstrong (1981); (iv) a model in which continental recycling has been more
 95 important than continental additions over the last 3.5 Ga in which $t_1 = 2.5$
 96 Ga and $t_2 = 100$ Ma (Fig. 2) - this last model, hereafter referred to as RM,
 97 is broadly similar to the model of Fyfe (1978). In model RM, we used the
 98 arbitrary function $f_{rec} = f(t) \times \exp(t/\tau)$ with $\tau = 10$ Ga, in order to obtain
 99 larger continental fractions in the past than for the present-day. Together,
 100 the four proposed models reproduce the wide range of published continental
 101 growth curves (Rino et al., 2004; Harrison, 2009).

102 *2.2. Modelling the thermal evolution of the Earth as a function of continental* 103 *growth*

104 The thermal evolution of the Earth depends on continental growth in several
 105 ways. Firstly, the progressive depletion of the mantle in radioactive ele-
 106 ments, preferentially concentrated in the continental crust, implies that the
 107 early mantle was more radiogenic and thus hotter (Birch, 1965). Calculations
 108 by Grigné and Labrosse (2001) suggest that at 4.5 Ga, a non-depleted mantle
 109 would have been $\sim 120^\circ\text{C}$ hotter than a depleted mantle. Secondly, the lower
 110 average present-day heat flow in continental areas (65 mW m^{-2}) compared to
 111 the oceanic areas ($\sim 100 \text{ mW m}^{-2}$; Pollack et al., 1993) suggests that oceans
 112 are more efficient than continents at evacuating internal heat. Thus, as con-
 113 tinents grow, heat loss occurs over an increasingly smaller oceanic area. Con-
 114 sidering perfectly insulating continents, Grigné and Labrosse (2001) showed

115 that this continental insulation increases the mantle temperature by 30 to
116 100°C, depending on continental growth models. Thirdly, the presence of
117 continents also has a potential impact on plate tectonics. Indeed, it is not
118 clear whether plate tectonics could operate at all in the absence of continents.
119 Grigné and Tackley (2005) showed that the introduction of rigid continents
120 in mantle convection models that produce plate tectonic-like features sta-
121 bilises the regime in plate tectonics mode, with no reversal to stagnant-lid
122 regime, and allows more realistic subduction geometries to be obtained. In
123 addition, Labrosse and Jaupart (2007) pointed out that the observed present-
124 day triangular distribution of the ages of the seafloor, which reflects an equal
125 probability of subduction of seafloor of any given age, is possibly imposed by
126 the presence of non-subductable continents.

127 To calculate the evolution of the temperature of the mantle through time,
128 we follow the approach of Labrosse and Jaupart (2007) that is based on the
129 observed seafloor age distribution. The strengths of this model are that it ac-
130 counts for the observation that present-day oceanic lithosphere can subduct
131 independently of its age, and that it accounts for the effects of continental
132 growth on mantle temperature. The drawback is that there is no physi-
133 cal model as yet that gives a relationship between mantle temperature and
134 maximum age of the oceanic lithosphere. In contrast, the thermal evolu-
135 tion model of Korenaga (2006) is based on marginal stability analysis of the
136 oceanic lithosphere that gives a relationship between maximum age of the
137 lithosphere and mantle temperature, but fails to reproduce the observation
138 that present-day oceanic lithosphere can subduct independently of its age.
139 Furthermore, the model of Korenaga (2006) assumes a constant continental

140 mass and therefore cannot readily be implemented in an integrated model.
 141 Flament et al. (2008) showed that the thermal evolution models of Labrosse
 142 and Jaupart (2007) and of Korenaga (2006) give broadly similar results in
 143 calculations of sea level and area of emerged land. One prerequisite of both
 144 these thermal evolution models is the operation of seafloor spreading. Whilst
 145 this is in agreement with numerical models suggesting that Earth could have
 146 remained in a mobile-lid regime throughout its thermal evolution (O’Neill
 147 et al., 2007), a greater radioactive heat production would most likely have
 148 resulted in major differences in the style of tectonics in the Archean (Sleep
 149 and Windley, 1982), and the establishment age of modern-style plate tecton-
 150 ics is subject to much debate (*e.g.* De Wit, 1998; Bédard, 2006; Stern, 2008;
 151 Condie and Kröner, 2008).
 152 Keeping this in mind, calculations of the evolution of mantle temperature
 153 can be done, based on the global heat balance for the Earth. This balance
 154 can be written as

$$MC_p \frac{dT_m}{dt} = \sum_i H_i e^{-t/\tau_i} - Q_{tot}, \quad (2)$$

155 where M is the mass of the Earth, C_p is an average heat capacity that
 156 accounts for the isentropic temperature gradient and for the thermal evolu-
 157 tion of the core, T_m is the potential temperature of the mantle, H_i is the
 158 present-day heat generation rate of each radioactive isotope i , exponentially
 159 increasing in the past with a decay time scale τ_i , and Q_{tot} is the total heat
 160 loss of the Earth that can be separated in an oceanic heat loss Q_{oc} and a
 161 continental heat loss Q_{cont} . For a given seafloor age distribution, the oceanic

162 heat loss can be written as (Labrosse and Jaupart, 2007)

$$Q_{oc} = \frac{A_{oc} k \lambda}{\sqrt{\pi \kappa t_{max}}} T_m \quad (3)$$

163 where A_{oc} is the total oceanic area, k is the thermal conductivity, λ is a
 164 seafloor age distribution factor, κ is the thermal diffusivity and t_{max} is the
 165 maximum age of subduction of the oceanic lithosphere. To take continental
 166 growth into account, the heat balance of the mantle can be written from Eqs.
 167 2 and 3 as

$$MC_p \frac{dT_m}{dt} = \sum_i (H_{oi} + (1 - f) H_{ci}) e^{-t/\tau_i} - f Q_{cont} - \frac{(A_{oc} + A_{cc}(1 - f)) k \lambda(f)}{\sqrt{\pi \kappa t_{max}}} T_m, \quad (4)$$

168 where the present-day radiogenic heat production of the depleted mantle
 169 H_{oi} is derived from a bulk silicate Earth model based on the composition
 170 of CI chondrites (Labrosse and Jaupart, 2007) and H_{ci} is the present-day
 171 radiogenic heat production of the continental crust. In the last two terms
 172 of the equation, f is the continental fraction, Q_{cont} is the present-day total
 173 continental heat flow below the continents, A_{cc} is the present-day continental
 174 area and $\lambda(f) = 2 + 2/3 f$ is the seafloor age distribution factor. The thickness
 175 of the continental crust is assumed to be constant as in Flament et al. (2008)
 176 so that the continental fraction $f \times A_{cc}$ represents the total continental area
 177 with respect to the present. Finally, the maximum age of subduction t_{max} is
 178 assumed to be constant in the present calculations since a shorter t_{max} would
 179 lead to unrealistically high temperatures that would exceed the maximum
 180 temperature of $200 \pm 100^\circ\text{C}$ greater than the present-day mantle suggested
 181 by petrological (Nisbet et al., 1993; Abbott et al., 1994) and rheological

182 constraints (see Labrosse and Jaupart, 2007 and Jaupart et al., 2007 for
183 recent reviews). Values for all the parameters used in the thermal model are
184 listed in Tab. 1.

185 It appears from Eq. 4 that continental growth affects the thermal evolution
186 of the mantle in four ways: (i) it imposes changes in oceanic area so that
187 the greater oceanic heat flow occurred over a larger area in the past; (ii)
188 continents are not considered perfect thermal insulators but account for a
189 total non-radiogenic heat flow Q_{cont} . Following Lenardic and Kaula (1995),
190 we assume the reduced continental heat flow to be constant through time
191 as expressed by the term $f Q_{cont}$; (iii) the seafloor age distribution factor
192 varies with continental fraction so that the age distribution is rectangular
193 when there are no continents and triangular for present-day continental area.
194 This effect implies a lesser oceanic heat loss for small continental fractions
195 and is thus opposite to the first effect; (iv) the mantle becomes depleted in
196 radioactive elements with continental growth.

197 *2.3. Modelling the evolution of continental hypsometry*

198 Rey and Coltice (2008) suggested that the maximum elevation of orogenic
199 plateaux would have been lesser in the Archean, when the continental crust
200 was hotter than at present (Mareschal and Jaupart, 2006). Using thin sheet
201 modelling, Rey and Coltice (2008) showed that the plateau elevation of a con-
202 tinental lithosphere in convergent regime is limited to ~ 2000 m for Archean
203 Moho temperatures greater than $\sim 700^\circ\text{C}$, compared to 5500 m for present-
204 day Tibet (Molnar et al., 1993). The relationship between plateau elevation
205 and Moho temperature is non-linear, with a marked increase in plateau ele-
206 vation for temperatures lower than $\sim 700^\circ\text{C}$ due to the rapid strengthening

207 of the lithospheric mantle (Rey and Coltice, 2008). We fit the results of the
 208 most conservative model of Rey and Coltice (2008), which assumes a strain
 209 rate of $1 \times 10^{-14} \text{ s}^{-1}$, using the power-law

$$h_p = 1.1296 \times 10^{13} \times T_{Moho}^{-3.3807}, \quad (5)$$

210 where h_p is the elevation of the orogenic plateau and T_{Moho} is the Moho tem-
 211 perature. In addition, we assume the elevation of the Tibetan plateau to be
 212 the maximum plateau elevation at all times. This elevation is reached for
 213 $T_{Moho} \approx 570^\circ\text{C}$ in Eq. 5. We calculate the dynamically supported maximum
 214 elevation from the orogenic plateau elevation using the shape of the hypso-
 215 metric curve given in Flament et al. (2008). In doing this, we assume that
 216 mountain building constantly affects the elevation of continents. However,
 217 in periods marked by the absence of orogenies, such as the break-up of a
 218 supercontinent, mountain belts would be eroded down so that the maximum
 219 elevation would be lower. Thus, the calculated maximum elevation is an up-
 220 per limit at any given time. On the other hand, the model of Rey and Coltice
 221 (2008) is based on the solid-state flow of a hot continental crust in thermal
 222 equilibrium, and does not account for the increased efficiency of crustal flow
 223 due to the presence of partial melt in the lower crust, nor for the transiently
 224 hot continental geotherms associated with the large-scale eruption of basalts
 225 abundant in the Archean. In this respect, the calculated maximum elevation
 226 is conservative.

227 To compute the evolution of continental hypsometry, we derive the Moho
 228 temperature using a one-dimensional steady-state heat conduction model for

229 which the energy conversation is

$$0 = k \frac{d^2 T}{dz^2} + \rho_{cc} H, \quad (6)$$

230 where k is the thermal conductivity, T is the temperature, z is the depth,
 231 ρ_{cc} is the density of the continental crust and $H = H_{ci}/(f A_{cc} z_{cc} \rho_{cc})$ is
 232 the time-dependent heat production per unit mass with f the continental
 233 fraction, A_{cc} the area and z_{cc} the thickness of the continental crust. Values
 234 for these parameters are listed in Tab. 1. We use the concentrations in U, Th
 235 and K of present-day Archean cratons given by Taylor and McLennan (1995)
 236 and we assume heat producing elements to be distributed in the continental
 237 crust according to

$$H(z) = H_0 \exp(-z/h_r), \quad (7)$$

238 where H_0 is the surface heat production, z is the depth and h_r is the char-
 239 acteristic thickness of a layer enriched in heat producing elements. The
 240 thickness of the enriched heat producing layer h_r is assumed to linearly de-
 241 crease with time from 20 km at 4.5 Ga to 9 km at 2 Ga. Whilst the use of
 242 a linear law is arbitrary, this change in the thickness of the heat producing
 243 layer reflects the re-distribution of radiogenic elements from a more homoge-
 244 neous early continental crust (Jaupart and Mareschal, 1999; Mareschal and
 245 Jaupart, 2006).

246 Solving Eq. 6 for the Moho temperature with knowledge of the mantle heat
 247 flux at the base of the continental crust $q_m = Q_{cont}/f A_{cc}$ and of the surface
 248 temperature T_0 gives

$$T_{Moho} = T_0 + \frac{q_m}{k} z_{cc} + \frac{\rho_{cc} H_0 h_r^2}{k} (1 - e^{-z_{cc}/h_r}). \quad (8)$$

249 The evolution of the Moho temperature of cratons calculated using this ther-
 250 mal model is shown in Fig. 3a. The calculated present-day Moho temper-
 251 ature is $\sim 460^\circ\text{C}$, in agreement with the temperature at 50 km depth of
 252 $\sim 430 \pm 98^\circ\text{C}$ inferred from surface heat flow data for Neoarchean cra-
 253 tons (Artemieva, 2006), and the calculated Moho temperature at 2.7 Ga is
 254 $\sim 640^\circ\text{C}$. The secular evolution of the plateau and maximum elevations are
 255 shown in Fig. 3b. Comparison with the modelling results of Rey and Coltice
 256 (2008) shows that the model used in the present study is conservative. An
 257 Archean craton in a context of ongoing convergence would imply a plateau
 258 elevation similar to that of present-day Tibet at ~ 2 Ga, and we assume that
 259 the elevation has been constant since then (Fig. 3b).

260 *2.4. Modelling the evolution of sea level and area of emerged land*

261 We use the model described in Flament et al. (2008) to calculate the evolu-
 262 tion of sea level and area of emerged land as a function of mantle temper-
 263 ature, continental fraction and hypsometry. The two main assumptions of
 264 this model are a constant oceanic volume and a constant thickness of the
 265 continental crust.

266 *2.5. Modelling the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water*

267 In order to estimate the evolution of $^{87}\text{Sr}/^{86}\text{Sr}$ in the mantle, the oceans
 268 and the continental crust for different continental growth models, we use a
 269 box model formulation that is a simplified representation of complex natu-
 270 ral geochemical cycles (Coltice et al., 2000). In this formulation, the mass
 271 conservation of a reservoir i is written as

$$\frac{dM_i}{dt} = \sum_{j \neq i} Q_{j \rightarrow i} - \sum_{j \neq i} Q_{i \rightarrow j}, \quad (9)$$

where M_i is the mass of box i , t is the time and $Q_{i \rightarrow j}$ is the mass flux from box i to box j . The concentration C_i^k of the element k in the box i can vary by (a) output or input fluxes, (b) dilution, (c) radioactive decay and (d) production from parent element. The elemental balance is expressed by

$$\begin{aligned} \frac{dC_i^k}{dt} = & - \left(\lambda^k + \frac{\sum_{j \neq i} Q_{j \rightarrow i} - \sum_{j \neq i} Q_{i \rightarrow j}}{M_i} + \frac{\sum_{j \neq i} Q_{i \rightarrow j} K_{i \rightarrow j}^k}{M_i} \right) C_i^k \\ & + \frac{\sum_{j \neq i} Q_{j \rightarrow i} K_{j \rightarrow i}^k}{M_i} C_j^k + \lambda^{k-1} C_i^{k-1}, \end{aligned} \quad (10)$$

where $K_{i \rightarrow j}^k$ is the enrichment factor due to the fractionation of element k upon transfer from box i to j . The element k is produced by the parent $k-1$ and produces the daughter isotope $k+1$ with radioactive decay constants respectively λ^{k-1} and λ^k . We consider the isotopic system that includes the stable isotope ^{86}Sr and the radioactive isotope ^{87}Rb , which decays to the daughter isotope ^{87}Sr with a constant $\lambda^{87\text{Rb}} = 1.42 \times 10^{-11} \text{ yr}^{-1}$. We consider three reservoirs, namely the mantle (M), the continental crust (CC) and the ocean water (OW) (Fig. 4). The composition of the oceanic crust in $^{87}\text{Sr}/^{86}\text{Sr}$ is assumed to be identical to that of the mantle as in Godderis and Veizer (2000), because oceanic crust is directly extracted from the mantle and subsequently not modified by radiogenic ingrowth, since the residence time of oceanic crust at the surface of the Earth is much shorter than the radioactive decay of ^{87}Rb . The initial isotopic ratios of rubidium and strontium in the mantle ($^{87}\text{Rb}/^{86}\text{Sr} = 0.085$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.699$) are taken from Zindler and Hart (1986).

To follow is the formulation of the fluxes between the three reservoirs of

our box model. The mass flux from the mantle to the continental crust is described by continental accretion. This can be written as

$$Q_{M \rightarrow CC} = M_{CC}(t) = M_{CC}^* f(t),$$

291 where $f(t)$ is the continental fraction given by Eq. 1 and M_{CC}^* is the present-
 292 day continental mass (Tab. 1). Rb and Sr are incompatible elements that
 293 are preferentially concentrated into the the continental crust upon partial
 294 melting and differentiation of material extracted from the mantle, which is
 295 expressed by two enrichment factors $K_{M \rightarrow CC}^{Rb}$ and $K_{M \rightarrow CC}^{Sr}$. We adjust both
 296 of these enrichment factors (values are given in Tab. 1) in order to obtain
 297 the present-day concentration of Sr in the continental crust (320 ± 46 ppm;
 298 Rudnick and Gao, 2003). In doing this, we assume that the concentration of
 299 the mantle in Sr is 70% of that of the primitive undepleted mantle (19.9 ppm;
 300 McDonough and Sun, 1995) to account for a deep enriched mantle reservoir
 301 (Hofmann, 1997) which could contain up to a third of Earth's radiogenic
 302 elements (Coltice and Ricard, 1999).

The flux opposite to continental accretion is the recycling of continental crust back into the mantle, expressed as a fraction of recycled continental crust f_{recy} with respect to total extracted continental crust, so that

$$Q_{CC \rightarrow M} = M_{CC}(t) f_{recy}.$$

303 The total amount of continental crust extracted from the mantle over Earth's
 304 history is the sum of $f(0)$ and f_{recy} . We adjust f_{recy} to obtain the present-day
 305 $^{87}\text{Sr}/^{86}\text{Sr}$ of the oceans (0.709; Shields and Veizer, 2002), of the continents
 306 (~ 0.712) and that of the depleted mantle (~ 0.7025 ; Workman and Hart,
 307 2005). Values for adjusted parameters are shown in Tab. 1.

308 The flux of strontium between the mantle and the oceans is assumed to be
 309 in steady-state, and is written as

$$Q_{M \rightarrow OW}^{Sr} = Q_{OW \rightarrow M}^{Sr} = Q_{hy}^{Sr}, \quad (11)$$

310 where Q_{hy}^{Sr} is the present-day total strontium hydrothermal flux affecting
 311 the oceanic lithosphere, including high-temperature hydrothermal exchange
 312 at mid-oceanic ridges and low-temperature seafloor weathering away from
 313 ridges.

314 The flux of strontium from the continents to the oceans can be written as

$$Q_{CC \rightarrow OW}^{Sr} \propto Q_r^{Sr} \times A \times Y, \quad (12)$$

315 where Q_r^{Sr} is the present-day river strontium flux to the oceans and the
 316 term $A \times Y$ varies between 0 and 1. A is the emerged area of continents
 317 relative to present-day (A is 1 today) and Y is the continental sedimentary
 318 yield, or run-off, with respect to present-day. Following the empirical model
 319 of Hay (1998), we write $Y = e^{\alpha (h_{max} - h_{eve})}$, where $\alpha = 0.002$, h_{max} is the
 320 maximum elevation in the hypsometric curve and h_{eve} is the elevation of
 321 Mount Everest. Finally, we assume a constant concentration of strontium in
 322 ocean water, which implies that the sedimentary flux of strontium onto the
 323 seafloor is equal to the river flux of strontium to the oceans.

324 **3. Results**

325 In this section, we investigate the dependency of mantle temperature, sea
 326 level, ridge depth, area of emerged land and $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water on
 327 continental growth.

3.1. Influence of continental growth on mantle temperature

The thermal evolution models computed for the four proposed continental growth end-members are shown in Fig. 5 along with the range of acceptable Archean mantle temperatures 200 ± 100 °C greater than present derived from geochemical, petrological and rheological constraints (see Labrosse and Jaupart, 2007, and Jaupart et al., 2007, for reviews). All four models are in agreement with the available constraints on Archean mantle temperature (Fig. 5). Early continental growth models (models EGM and RM) predict Archean mantle temperatures 270°C to 300°C greater than present, whereas delayed continental growth models (models CGM and NGM) predict Archean mantle temperatures 220°C to 230°C hotter than present. Indeed, larger Archean continental areas would result in greater continental insulation, thus in smaller heat loss and in greater mantle temperatures.

The computed thermal evolution models display an early warming period (Fig. 5) because heat loss is smaller than heat production for the young Earth in the thermal model of Labrosse and Jaupart (2007). This early warming period is unrealistic, since the gravitational energy liberated by the accretion of the Earth could have been large enough to melt the outer 1000 km of the mantle (Kaula, 1979), which would likely have resulted in an early magma ocean stage. Whilst we primarily focus on our modelling results between the present-day and the maximum in predicted mantle temperature, results for earlier periods are mentioned for the sake of completeness. The temperature maximum is reached at ~ 3.7 Ga for early continental growth models, and at ~ 3 Ga for delayed continental growth models. This difference of 700 Myr is mainly controlled by the seafloor age distribution factor λ (Eq. 3) that is

353 greater for early continental growth models.

354 *3.2. Influence of continental growth on sea level*

355 We calculate the evolution of sea level, ridge depth and emerged land area
356 from the evolution of mantle temperature and of continental fraction using
357 the model of Flament et al. (2008). In this model, four situations can oc-
358 cur for a given set of parameters in which (i) the continents are partially
359 flooded; (ii) the continents are entirely flooded; (iii) the continents are en-
360 tirely emerged; and (iv) the mid-oceanic ridges emerge. Model calculations
361 are only valid for partially flooded continents. Situations ii), iii) and iv)
362 constitute limits to the model and the calculation stops if any of these situ-
363 ations occurs. For this reason, some of the evolution models discussed in the
364 following do not span the whole of Earth's history.

365 Galer (1991) and Flament et al. (2008) pointed out that the evolution of
366 sea level is primarily controlled by mantle temperature. A greater mantle
367 temperature in the Archean would result in a thicker oceanic crust (Sleep
368 and Windley, 1982) that would be more buoyant than the underlying mantle
369 and would thus impose high sea levels (Galer, 1991; Flament et al., 2008).
370 Indeed, the calculated sea levels are maximum at ~ 3.5 Ga for models EGM
371 and RM, and at ~ 2.9 Ga for model CGM (Fig. 6), which coincides with the
372 respective maxima of mantle temperature (Fig. 5). The offset of ~ 800 Myr
373 between the maxima in sea level (at ~ 2.1 Ga, Fig. 6) and in temperature
374 (at ~ 2.9 Ga, Fig. 5) for model NGM is due to the Neoproterozoic pulse in
375 continental growth for this model. This illustrates that for small continental
376 fractions, sea level closely depends on continental area (Flament et al., 2008).
377 The calculated amplitudes of Archean sea level change range between ~ 550 m

378 and ~ 1850 m. Even the lower end of this range is approximately twice the
 379 amplitude of Phanerozoic sea level change (Müller et al., 2008). Therefore,
 380 the hypothesis of constant continental freeboard is difficult to reconcile with
 381 any of the proposed continental growth end-members that cover most of the
 382 range of published continental growth models (Rino et al., 2004; Harrison,
 383 2009). In addition, early continental growth models predict a maximum am-
 384 plitude of sea level change between ~ 1450 m and ~ 1850 m, significantly
 385 larger than the sea level change of between ~ 550 m and ~ 800 m predicted for
 386 delayed continental growth models (Fig. 6). This is because larger past con-
 387 tinental areas not only impose a higher sea levels (Flament et al., 2008) but
 388 also greater mantle temperature, which themselves impose higher sea levels.
 389 Our models also suggest that continents could have been entirely emerged be-
 390 fore ~ 4 Ga for delayed continental growth models that predict large oceanic
 391 reservoirs and relatively low mantle temperatures ($\sim 150^\circ\text{C}$ greater than
 392 present). This emergence of small continental fractions ($f < 0.1$) is hy-
 393 pothetical since it occurs during the early warming period of the thermal
 394 evolution model (Fig. 5). Nevertheless, the occurrence of detrital zircons as
 395 old as ~ 4.4 Ga in the clastic sedimentary rocks of the Jack Hills, Narryer
 396 Gneiss Terrane, Yilgarn Craton (Wilde et al., 2001) and older than 4.1 Ga
 397 in the Youanmi Terrane, Yilgarn Craton (Wyche, 2007), suggests that small
 398 areas of continental crust were emerged early in Earth’s history.

399 *3.3. Influence of continental growth on the depth of mid-oceanic ridges*

400 The predicted evolution of the depth of ridge crests through time is shown
 401 in Fig. 7. We find that ridge crests were shallower in the past than at
 402 present, which is in agreement with the results of Galer (1991). Interestingly,

403 the evolution of the depth of ridge crests appears to be anti-correlated to
 404 continental growth (Figs. 2 and 7). Therefore, the depth of ridge crests closely
 405 depends on continental growth, contrary to the evolution of sea level that
 406 mainly reflects the evolution of mantle temperature. This is because changes
 407 in mantle temperature affect the depth of ridge crests through relatively
 408 minor changes in bathymetry whereas they affect sea level through large
 409 amplitude changes in oceanic crustal thickness (Flament et al., 2008).
 410 Early continental growth models predict ridge crests significantly less shallow
 411 than delayed continental growth models mainly because larger continental
 412 areas result in higher sea levels. Our model predicts that at 2.5 Ga ridge
 413 crests were between ~ 660 m (model RM) and ~ 1200 m (model EGM)
 414 shallower than the present-day ridge crest depth of 2500m. In comparison,
 415 delayed continental growth models result in ridge crests ~ 1900 m shallower
 416 at 2.5 Ga than at present. In addition, ridge crest emergence is predicted
 417 at ~ 4.1 Ga for model RM, time at which the thermal model is not realistic
 418 any more.

419 *3.4. Influence of continental growth on the area of emerged land*

420 Fig. 8 shows that the Archean area of emerged land does not significantly de-
 421 pend on the continental growth model, despite large differences in continental
 422 area and in calculated sea level (Fig. 6). This is because the area of emerged
 423 land depends on mantle temperature, continental fraction and continental
 424 hypsometry. Thus, the Archean area of emerged land is intrinsically small
 425 for delayed continental growth models that predict small Archean continen-
 426 tal areas. It is also small for early continental growth models that predict
 427 high Archean sea levels and thus largely flooded continents. The predicted

428 Archean emerged land area is less than $\sim 4\%$ of Earth's area in all models,
 429 with differences between models $\leq 1.5\%$. For constant continental hypsom-
 430 etry, the area of emerged land is less than $\sim 7\%$ of Earth's area, and models
 431 differ by up to $\sim 5\%$ of Earth's area earlier than ~ 3 Ga. Note that these
 432 differences in area of emerged land remain small with respect to the large
 433 range of predicted continental areas for this period (between 0 and $\sim 57\%$
 434 of Earth's area, Fig. 8). The results for emerged area are in agreement with
 435 that of Flament et al. (2008) who proposed an Archean emerged land area of
 436 less than 3% of Earth's area ($< 12\%$ of Earth's area for constant continental
 437 hypsometry). Estimates slightly differ because the feedback between conti-
 438 nental growth and mantle temperature is taken into account in the present
 439 study whereas it was not in Flament et al. (2008).
 440 Focussing on the results for non-constant hypsometry, the predicted Archean
 441 emerged land area is slightly larger in model CGM than in other models
 442 (Fig. 8). This is because the small continental area predicted by model
 443 CGM results in lesser mantle temperatures and lower sea levels. In con-
 444 trast, model RM predicts larger continental areas than other models, which
 445 results in greater mantle temperatures and higher sea levels, and thus in a
 446 relatively small area of emerged land. The smallest Archean emerged land
 447 areas are predicted for model NGM in which mantle temperatures are sig-
 448 nificantly lower than in early continental growth models, and continental
 449 fractions are significantly larger than in model CGM. Near-complete conti-
 450 nental flooding is predicted between ~ 3.3 and 3.5 Ga for all models because
 451 of high sea levels for early continental growth models and because of small
 452 continental areas for delayed continental growth models. It is worth noting

453 that the progressive continental emergence from ~ 3.5 Ga predicted by our
454 models fits nicely with the oldest angular unconformity (Buick et al., 1995)
455 reported in the 3458-3426-Ma Panorama Formation, East Pilbara Craton
456 (Van Kranendonk et al., 2007). It is also consistent with the occurrence of
457 shallow water quartz-rich sandstones *c.*-3.4-Ga Strelley Pool Formation, East
458 Pilbara Craton (Van Kranendonk et al., 2007) and with the abundance of
459 post-3.5 Ga clastic metasedimentary rocks in the Youanmi Terrane, Yilgarn
460 Craton (Wyche, 2007).

461 In the above calculations of the evolution of sea level, depth of oceanic ridges
462 and of area of emerged land, we have assumed a constant volume of oceans
463 and a constant thickness of continental crust. Whilst Flament et al. (2008)
464 assessed the sensitivity of their models to these two parameters using a Monte
465 Carlo analysis, we further discuss the main model assumptions below. The
466 amount of water at the surface of the Earth primarily depends on the effi-
467 ciency of the recycling of water to the mantle at subduction zones. Numerical
468 models of the water cycle at subduction zones by Rüpke et al. (2004) sug-
469 gest that the loss of water of a hot subducting slab to the mantle wedge is
470 greater than that of a cold subducting slab. In addition, an array of geo-
471 chemical indicators suggests that water accumulated at the surface of the
472 Earth ~ 100 Myr after its formation, and that the equivalent of the present-
473 day volume of oceans has been progressively incorporated into the mantle
474 over the history of the Earth (Albarède, 2009). Whilst these arguments do
475 not constrain the volume of Archean oceans, they suggest that there was
476 abundant water at the surface of the Archean Earth. If the volume of oceans
477 was greater in the Archean, the emerged land area would have been smaller

478 than predicted by our models.

479 As for the thickness of the continental crust, seismic studies suggest that
480 the average present-day Archean continental crust is ~ 10 km thinner than
481 the average present-day Proterozoic and Phanerozoic continental crust (Dur-
482 rheim and Mooney, 1994; Christensen and Mooney, 1995). However, the re-
483 gional metamorphic grade of exposed Archean cratons suggests a long term
484 uplift and erosion of 5 ± 2 km due to the secular cooling of the mantle, ini-
485 tially in isostatic equilibrium with the depleted sub-continental lithospheric
486 mantle underlying cratons (Galer and Mezger, 1998). The original thickness
487 of the average Archean continental crust would thus have been undistinguish-
488 able from that of the average post-Archean continental crust. Nevertheless,
489 the ~ 2.7 Ga peak in global magmatic activity that resulted in thickening
490 of the continental crust through the eruption of greenstone suites 5-15 km
491 thick covering a total area larger than 10^7 km² over most, if not all, Archaean
492 cratons (De Wit and Ashwal, 1997) could have significantly contributed to
493 the Neoarchean increase in the area of emerged land.

494 *3.5. Influence of continental growth models on the calculated evolution of the*
495 *$^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water*

496 We now compare the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of the oceans and of the
497 mantle predicted for the delayed continental growth model NGM, which is
498 similar to that of Taylor and McLennan (1985) and of Veizer and Jansen
499 (1979), and for the early continental growth model EGM, which is similar to
500 that of Armstrong (1981, 1991).

501 Fig. 9a shows the results obtained for both continental growth models as-
502 suming constant continental freeboard and hypsometry, which are the con-

503 ventional assumption in models of the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean wa-
 504 ter (*e.g.* Veizer and Jansen, 1979; Godderis and Veizer, 2000). The delayed
 505 continental growth model produces a better fit of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine car-
 506 bonates (Shields and Veizer, 2002; Kuznetsov et al., 2010) and barites (Perry
 507 et al., 1971; McCulloch, 1994) than for the early continental growth model
 508 (Fig. 9a). In particular, the delayed continental growth model reproduces the
 509 shift of the oceanic reservoir from the mantle reservoir at ~ 2.7 Ga, whereas
 510 the early continental growth model predicts an oceanic reservoir significantly
 511 more radiogenic than suggested by the data, and a shift between oceanic and
 512 mantle reservoirs at ~ 4 Ga that is not observed in the data. This argument
 513 has been used repeatedly in favour of delayed continental growth models
 514 (Veizer and Jansen, 1979; Taylor and McLennan, 1985; Godderis and Veizer,
 515 2000).

516 Fig. 9b shows the $^{87}\text{Sr}/^{86}\text{Sr}$ of the mantle and of the oceans calculated for
 517 both continental growth models, taking changes in emerged land area into
 518 account. The reduced area of emerged land and lower maximum continental
 519 elevation predicted by our models result in a reduced flux from the continents
 520 to the oceans (Eq. 12) in the Archean, so that the oceans are less radiogenic.
 521 It is clear from Fig. 9b that secular changes in continental hypsometry and
 522 in area of emerged land delay the contribution of the continents to the com-
 523 position of the oceans. This effect is most important for model EGM that
 524 predicts larger continental areas in the Archean. However, the shift in the
 525 $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water at ~ 2.1 Ga predicted by for both models is de-
 526 layed by ~ 600 Myr compared to the shift at ~ 2.7 Ga interpreted from
 527 the data on marine carbonates (Fig. 9b; Shields and Veizer, 2002). This

528 time lag could reflect the fact that our steady-state thermal model for the
 529 continental crust (section 2.3) does not account for variability in continen-
 530 tal geotherms. Indeed, the present-day continental crust, for which surface
 531 heat flow varies between 50 and 120 mW m⁻² depending on tectonic setting
 532 (Artemieva, 2009), cannot be described by a single steady-state or average
 533 continental geotherm. Similarly, a large range of continental geotherms were
 534 probably represented in the Archean, as suggested by the observed differ-
 535 ences in crustal and lithospheric thickness of Archean cratons (Artemieva,
 536 2009). Locally and/or transiently low Moho temperatures could have re-
 537 sulted in higher elevations and in an earlier shift of the predicted ⁸⁷Sr/⁸⁶Sr of
 538 ocean water. To further investigate this hypothesis, we carry out calculations
 539 for changing sea level and constant continental hypsometry (dotted curves in
 540 Fig. 9b). This gives a predicted ⁸⁷Sr/⁸⁶Sr of ocean water for model EGM that
 541 is very similar to that for model NGM assuming constant freeboard (Fig. 9a),
 542 confirming that changes in emerged land area account for the evolution of
 543 the ⁸⁷Sr/⁸⁶Sr of ocean water.

544 4. Discussion

545 Previous authors have separately investigated the role of continental growth
 546 on mantle temperature (*e.g.* Spohn and Breuer, 1993; Grigné and Labrosse,
 547 2001; Labrosse and Jaupart, 2007) and on the composition of the oceans and
 548 of the atmosphere (*e.g.* Godderis and Veizer, 2000; Sleep and Zahnle, 2001),
 549 but to our knowledge this study is the first to simultaneously investigate the
 550 effect of continental growth on mantle temperature and sea water compo-
 551 sition. Our approach is guided by the intrinsic inter-dependency between

552 continental growth, thermal evolution of the Earth, continental hypsometry,
 553 sea level and $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water. Its strength is to allow us to inves-
 554 tigate the effect of one parameter, the growth of the continents, on both
 555 interior and surface processes (Fig. 1). Its limitation is that hypotheses have
 556 to be made at different levels. Nevertheless, the structure of the proposed
 557 integrated model requires that hypotheses must be consistent at all levels.
 558 In the present study, we have identified contrasted dependencies of sea level,
 559 ridge depth and emerged land area on continental growth. Sea level closely
 560 depends on mantle temperature that itself depends on continental growth,
 561 and the depth of mid-oceanic ridges is directly correlated to continental
 562 growth. In contrast, the area of emerged land does not significantly depend
 563 on continental growth. This is the key result of the present contribution.
 564 The weak dependency of emerged land on continental growth model suggests
 565 that surface geochemical indicators are inappropriate to constrain continental
 566 growth. In addition, using surface geochemical indicators as proxies for con-
 567 tinental growth is based on the implicit assumptions of constant continental
 568 freeboard and constant continental elevation (*e.g.* Veizer and Jansen, 1979;
 569 Taylor and McLennan, 1985). However, these assumptions fail to explain the
 570 preponderance of subaqueous flood volcanism in the Archean (Arndt, 1999;
 571 Kump and Barley, 2007) that suggests high Archean sea levels (Flament
 572 et al., 2008). Our calculations reconcile the preponderance of subaqueous
 573 flood volcanism in the Archean with the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ma-
 574 rine carbonates by showing that early continental growth models are consis-
 575 tent with the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water when a reduced area
 576 of emerged land and a lower continental elevations are taken into account

577 (Fig. 9). Therefore, the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates is
578 not a geochemical proxy for continental growth but rather a tracer of the ef-
579 ficiency of the flux from the felsic continents to the oceans. We propose that
580 the evolution of $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates does not reflect an increase
581 in continental volume, but an increase in weathering and erosion processes
582 (Rey and Coltice, 2008; Flament et al., 2008).

583 Similarly, we suggest that the changes observed at the Archean/Proterozoic
584 boundary in the composition of black shales (Taylor and McLennan, 1985)
585 could reflect the emergence of the continents rather than a pulse in conti-
586 nental growth. Finally, the episodicity in the U-Pb age of preserved zircons
587 was originally interpreted to reflect continental growth pulses (Condie, 1998,
588 2000). However, in situ measurements of oxygen and hafnium isotopes on
589 precisely dated zircons revealed that significant reworking over several hun-
590 dred million years (Kemp et al., 2006). This has led to the conclusion that
591 the peaks in the U-Pb age distribution of preserved zircons are preservation
592 peaks (Kemp et al., 2006; Lancaster et al., 2011; Condie et al., 2011) possibly
593 associated with the formation of supercontinents (Campbell and Allen, 2008;
594 Lancaster et al., 2011; Condie et al., 2011). Therefore, there could be no
595 need for delayed continental growth models derived from surface geochemi-
596 cal proxies for felsic crust. Mantle-derived proxies, such as the evolution of
597 Nb/U in basaltic series (*e.g.* Campbell, 2003) seem more suitable to constrain
598 continental growth.

599 Interestingly, the correlation between the depth of ridge crests and continen-
600 tal area suggests that ridge depth could be used as a proxy for continental
601 growth, if a preserved Archean mid-oceanic ridge was identified. Kitajima

et al. (2001) proposed from a petrographic study and thermodynamic calculations that the ~ 3.5 Ga greenstone complex at North Pole in the Pilbara Craton was emplaced under a water column of ~ 1.6 km, which is in agreement with the abundance of subaqueous flood volcanism in the Archean (Arndt, 1999; Kump and Barley, 2007) and strengthens the view that Archean continents were largely flooded.

Our results have important implications for the evolution of Earth's external envelopes. For instance, our models supports the hypothesis of Kasting et al. (2006) and Jaffrés et al. (2007) who argued that a secular deepening of ridge crests rather than decreasing ocean temperatures (Knauth and Lowe, 2003) would explain the observed secular increase in the $\delta^{18}\text{O}$ of marine carbonates. Furthermore, we suggest that the evolution of the area of emerged land possibly played a central role in the oxygenation of the atmosphere. Indeed, a reduced area of emerged land implies a limited supply of the nutrient phosphorus, preferentially concentrated in the continents, to the oceans and thus limits the global biomass. An increase in the area of emerged land towards the Archean/Proterozoic boundary would increase the supply of phosphorus to the oceans, thus increasing the primary productivity of cyanobacteria that produce O_2 (Campbell and Allen, 2008). The synchronous enlargement of shallow epereic seas (Eriksson et al., 2005) would favour the burial of reduced carbon (Bjerrum and Canfield, 2005), contributing to the increase in atmospheric oxygen levels. On the other hand, an increase in emerged land area would enhance silicate weathering processes, thus buffering the rise of atmospheric oxygen imposed by the two processes listed above. Whilst further work is needed to quantify the effect of the emergence of the continents on the

627 oxidation state of the atmosphere, we speculate that the Neoarchean emer-
 628 gence of the continents could have contributed to the great oxidation event
 629 dated at ~ 2.45 Ga (Bekker et al., 2004). Finally, the quantification of the
 630 area of emerged land is of importance to models of the Archean climate and
 631 atmospheric composition. Indeed, the emerged land area affects the albedo of
 632 the Earth (Rosing et al., 2010) and the intensity of weathering processes that
 633 regulate the composition of the atmosphere in CO_2 (Sleep and Zahnle, 2001)
 634 and in O_2 (Godderis and Veizer, 2000). To date, Archean climate have used
 635 the conventional hypothesis of constant continental freeboard, therefore over-
 636 estimating the efficiency of erosion and weathering processes. Future models
 637 of the Archean climate should take the effect of an area of emerged land of
 638 less than ~ 4 % of Earth’s area into account.

639 **5. Conclusion**

640 The integrated model developed in this study allows us to investigate the in-
 641 fluence of continental growth models on mantle temperature, sea level, ridge
 642 depth, emerged land area and $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water. Our results suggest
 643 that because of the thermal insulation imposed by continents on the mantle,
 644 early continental models result in higher Archean mantle temperature. Since
 645 both elevated mantle temperatures and large continental fractions impose
 646 high sea levels, early continental growth models predict higher Archean sea
 647 levels than delayed continental growth models. We find that mid-oceanic
 648 ridges were shallower in the past, and that the evolution of the depth of
 649 ridge crests is correlated to continental growth. We calculate that less than
 650 ~ 4 % of Earth’s area was emerged in the Archean and we show that the

651 evolution of the area of emerged land does not significantly depend on con-
652 tinental growth. Therefore, we suggest that geochemical proxies for felsic
653 crust do not constrain continental growth. For instance, the evolution of the
654 $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates is a tracer of the flux of radiogenic strontium
655 from the emerged continents to the oceans, but is not an appropriate proxy
656 for continental growth.

657 Our results show that early continental growth models are consistent with
658 the evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water as recorded by marine car-
659 bonates when a reduced emerged area and a lower continental elevation are
660 taken into account. Thus, a delayed continental growth model is not needed
661 to explain the observed trend in the $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonates. We
662 suggest that the delayed appearance of the differentiated crust in the sur-
663 face geochemical record reflects the emergence of the continental crust rather
664 than its extraction from the mantle. Until the Neoarchean, the continental
665 crust was largely covered by thick subaqueous greenstone covers and was
666 thus an isolated geochemical reservoir. The Neoarchean strengthening of the
667 continental lithosphere, together with the secular increase in emerged land
668 area, resulted in the appearance of the differentiated continental crust in
669 the sedimentological record, with first order consequences for the evolution
670 of Earth's exogenic envelopes. The effect of a smaller emerged land area
671 should be included in future models of the Archean climate and atmospheric
672 composition.

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Table 1: Values of the parameters used in the model.

Parameter	Meaning	Value	Unit (model)
<i>Thermal parameters</i>			
κ	thermal diffusivity	$8 \times 10^{-7} \text{ }^a$	$\text{m}^2 \text{ s}^{-1}$
ρ_{cc}	density of the continental crust	2820	kg m^{-3}
A_{cc}	area of continents	$2.01 \times 10^{14} \text{ }^a$	m^2
A_{oc}	area of oceans	$3.09 \times 10^{14} \text{ }^a$	m^2
C_P	heat capacity	1200 a	$\text{J kg}^{-1} \text{ K}^{-1}$
H_{ci}	present-day continental radiogenic heat production	7 b	TW
H_{oi}	present-day mantle radiogenic heat production	12.4 a	TW
k	thermal conductivity	2.5	$\text{W m}^{-1} \text{ K}^{-1}$
M	mass of the Earth	6×10^{24}	kg
Q_{cont}	reduced continental heat flow	7 b	TW
T_0	surface temperature	20	$^{\circ}\text{C}$
t_{max}	maximum age of subduction	180 a	Ma
z_{cc}	thickness of the continental crust	40	km
<i>Chemical parameters</i>			
f_{recy}	fraction of recycled continental crust	0.57	(NGM)
		1.09	(EGM)
$K_{M \rightarrow CC}^{Rb}$	enrichment factor of rubidium	215	
$K_{M \rightarrow CC}^{Sr}$	enrichment factor of strontium	27	
M_M	mass of the mantle	4×10^{24}	kg
M_{CC}	present-day mass of the continents	2.6×10^{22}	kg
M_{OW}	mass of the oceans	1.4×10^{21}	kg
Q_{hy}^{Sr}	present-day strontium hydrothermal flux	$1.5 \times 10^9 \text{ }^c$	kg yr^{-1}
Q_r^{Sr}	present-day river strontium flux to the oceans	$2.5 \times 10^9 \text{ }^c$	kg yr^{-1}

^aLabrosse and Jaupart (2007)^bJaupart et al. (2007)^cGoddris and Franois (1995)

Figure 1: Workflow of the model used in this study. Arrows indicate model inputs and boxes indicate the variables and parameters of the model. The temperature of the mantle is calculated as in Labrosse and Jaupart (2007), the continental hypsometry is calculated from the results of Rey and Coltice (2008) and sea level, ridge depth and emerged land area are calculated as in Flament et al. (2008). A colour version of this figure is available online at [doixxx](#).

Figure 2: Continental growth models used in the present study. See text for details. A colour version of this figure is available online at [doixxx](#).

Figure 3: a) Typical secular evolution of Moho temperature. b) Secular evolution of the plateau elevation (dashed curve) and maximum elevation (plain curve). Plateau elevation values from Rey and Coltice (2008) are shown as empty black squares for comparison.

Figure 4: Schematic description of the geochemical box model use in this study. Each box represents a reservoir and each arrow represents a flux. A colour version of this figure is available online at [doixxx](#).

Figure 5: Thermal evolution models computed for the four continental growth models shown in Fig. 2. The shaded area denotes mantle temperatures 200-300°C hotter than present. Each curve is grey before the temperature maximum to denote that results are hypothetical - see text for details. A colour version of this figure is available online at [doi:10.1017/S0007122617000000](#).

Figure 6: Secular evolution of sea level for the four proposed continental growth models. The reference (zero-depth) is the edge of present-day continental shelves, with respect to which present-day sea level is 200 m. A colour version of this figure is available online at [doi:10.1016/j.tectonophysics.2015.04.011](#).

Figure 7: Secular evolution of the depth of ridge crests for the four proposed continental growth models. A colour version of this figure is available online at [doixxx](#).

Figure 8: Secular evolution of the area of emerged land for the four proposed continental growth models. The grey shaded area and the right-hand side axis of the figure indicate the range of predicted continental areas (see Fig. 2). Despite large differences in continental area, all models predict similar emerged land surfaces, especially when changes in continental hypsometry are taken into account. A colour version of this figure is available online at [doi:10.1016/j.epsl.2015.05.011](#).

Figure 9: Evolution of the $^{87}\text{Sr}/^{86}\text{Sr}$ of ocean water (ow) and of the mantle (m) for the Neoproterozoic (NGM) and early (EGM) continental growth models, a) for constant hypsometry and constant freeboard; and b) taking changes in emerged area and continental hypsometry into account. The dotted black curves in b) denote constant maximum elevation (see also Fig. 8). Grey and white circles are respectively well- and poorly-dated $^{87}\text{Sr}/^{86}\text{Sr}$ data on marine carbonates from Shields and Veizer (2002). Black dots are data from Kuznetsov et al. (2010), and grey diamonds are data on barites from Perry et al. (1971) and McCulloch (1994). A colour version of this figure is available online at [doi:10.1016/j.epsl.2016.05.011](#).