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

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A B S T R A C T

Many continental growth models have been proposed over the years to explain geological and geochemical data. Amongst these data, the evolution of the $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ 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 ∼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 $^{87}Sr/^{86}Sr$ of ocean water predicted for an early continental growth model is in broad agreement with the $^{87}Sr/^{86}Sr$ data on marine carbonates when changes in continental freeboard and continental hypsometry are taken into account. We propose that the Neoarchean shift in the $^{87}Sr/^{86}Sr$ 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.

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 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) of the present-day continental mass. 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 $^{87}Sr/^{86}Sr$ 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 Neoarchean. 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 $^{87}Sr/^{86}Sr$ of marine carbonates as a proxy for continental growth. Changes in

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the $^{87}Sr/^{86}Sr$ of marine carbonates, commonly assumed to represent the evolution of the $^{87}Sr/^{86}Sr$ 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 $^{87}Sr/^{86}Sr$ over time, with a shift from mantle composition at ~2.7 Ga (Shields and Veizer, 2002). This increase in the $^{87}Sr/^{86}Sr$ of marine carbonates reflects the increasing contribution of a radiogenic source to the composition of the oceans, and has been proposed to reflect a Neoarchean 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 (Goddéris and François, 1995) and thus on the area of emerged land and on continental relief (Godderis 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 (Godderis and Veizer, 2000).

To date, when using the evolution of the $^{87}Sr/^{86}Sr$ 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; Godderis and Veizer, 2000). However, Rey and Coltice (2008) suggested that a hot continental lithosphere could not support high elevations in the Archean, and Arndt (1999) and Flament et al. (2008) suggested that in the Archean the continental crust was both largely flooded and covered by thick subaqueous continental flood basalts. This would have resulted in limited weathering and erosion processes, thereby largely isolating the Archean continental crust from the atmosphere and from the oceans. Thus, the appearance of the signature of the continental crust in the surface geochemical record would have been delayed even if large amounts of continental crust had been extracted from the mantle early in Earth's history. Therefore, the Neoarchean increase in the $^{87}Sr/^{86}Sr$ of marine carbonates could reflect an important increase in the area of emerged continental crust rather than an increase in the production of continental crust. This implies that the suitability of surface geochemical indicators as proxies for continental growth needs to be reassessed. To this avail, we build an integrated model to investigate the emerged area of continental crust as a function of continental growth. This model accounts for the co-evolution of mantle temperature, continental hypsometry, sea level, ridge depth and emerged area of continental crust. We then use this model to investigate the effect of contrasted continental growth scenarios on the evolution of the $^{87}Sr/^{86}Sr$ of ocean water. We show that the evolution of the area of emerged land, contrary to that of sea level and ridge depth, barely depends on continental growth models. We conclude that the evolution of the $^{87}Sr/^{86}Sr$ of marine carbonate does not constrain continental growth.

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

In order to investigate the effect of continental growth on the evolution of the $^{87}Sr/^{86}Sr$ 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.

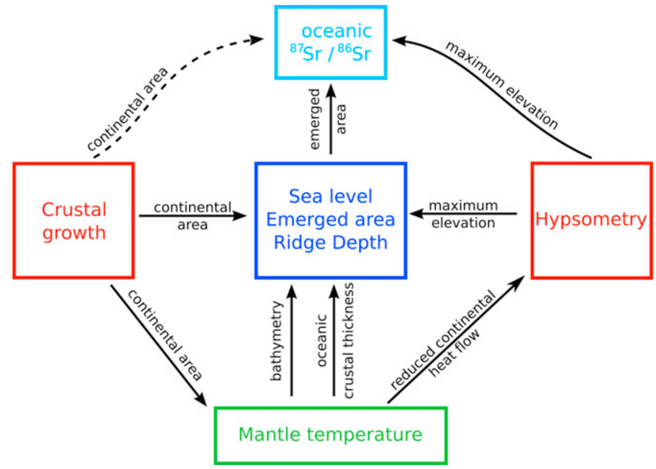

Fig. 1. Flow chart of the model used in this study. Arrows indicate model inputs and boxes indicate the variables and parameters of the model. The temperature of the mantle is calculated as in Labrosse and Jaupart (2007), the continental hypsometry is calculated from the results of Rey and Coltice (2008) and sea level, ridge depth and emerged land area are calculated as in Flament et al. (2008).

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

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

The thermal evolution of the Earth depends on continental growth in several ways. Firstly, the progressive depletion of the mantle in radioactive elements, preferentially concentrated in the continental crust, implies that the early mantle was more radiogenic and thus hotter (Birch, 1965). Calculations by Grigné and Labrosse (2001) suggest that at 4.5 Ga, a non-depleted mantle would have been ~120 °C hotter than a depleted mantle.

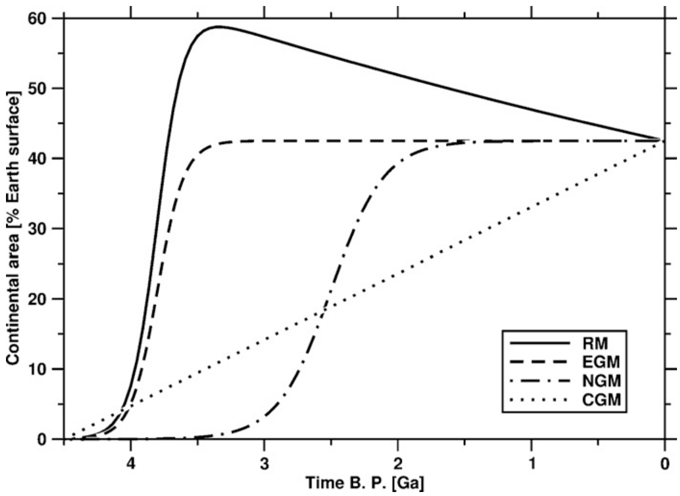

Fig. 2. Continental growth models used in the present study.

Secondly, the lower average present-day heat flow in continental areas (65 mW m^{-2}) compared to the oceanic areas (~100 mW m^{-2}; Pollack et al., 1993) suggests that oceans are more efficient than continents at evacuating internal heat. Thus, as continents grow, heat loss occurs over an increasingly smaller oceanic area. Considering perfectly insulating continents, Grigné and Labrosse (2001) showed that this continental insulation increases the mantle temperature by 30–100 °C, depending on continental growth models. Thirdly, the presence of continents also has a potential impact on plate tectonics. Indeed, it is not clear whether plate tectonics could operate at all in the absence of continents. Grigné and Tackley (2005) showed that the introduction of rigid continents in mantle convection models that produce plate tectonic-like features stabilises the regime in plate tectonics mode, with no reversal to stagnant-lid regime, and allows more realistic subduction geometries to be obtained. In addition, Labrosse and Jaupart (2007) pointed out that the observed present-day triangular distribution of the ages of the seafloor, which reflects an equal probability of subduction of seafloor of any given age, is possibly imposed by the presence of non-subductable continents.

To calculate the evolution of the temperature of the mantle through time, we follow the approach of Labrosse and Jaupart (2007) that is based on the observed seafloor age distribution. The strengths of this model are that it accounts for the observation that present-day oceanic lithosphere can subduct independently of its age, and that it accounts for the effects of continental growth on mantle temperature. The drawback is that there is no physical model as yet that gives a relationship between mantle temperature and maximum age of the oceanic lithosphere. In contrast, the thermal evolution model of Korenaga (2006) is based on marginal stability analysis of the oceanic lithosphere that gives a relationship between maximum age of the lithosphere and mantle temperature, but fails to reproduce the observation that present-day oceanic lithosphere can subduct independently of its age. Furthermore, the model of Korenaga (2006) assumes a constant continental mass and therefore cannot readily be implemented in an integrated model. Flament et al. (2008) showed that the thermal evolution models of Labrosse and Jaupart (2007) and Korenaga (2006) give broadly similar results in calculations of sea level and area of emerged land.

A prerequisite of both the thermal evolution models of Labrosse and Jaupart (2007) and of Korenaga (2006) is the operation of seafloor spreading. Whilst this is in agreement with numerical models suggesting that Earth could have remained in a mobile-lid regime throughout its thermal evolution (O'Neill et al., 2007), a greater radioactive heat production would most likely have resulted in major differences in the style of tectonics in the Archean (Sleep and Windley, 1982), and the establishment age of modern-style plate tectonics is subject to much debate (e.g. De Wit, 1998; Bédard, 2006; Stern, 2008; Condie and Kröner, 2008).

Keeping this in mind, calculations of the evolution of mantle temperature can be done, based on the global heat balance for the Earth. This balance can be written as

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

where M is the mass of the Earth, C_p is an average heat capacity that accounts for the isentropic temperature gradient and for the thermal evolution of the core, T_m is the potential temperature of the mantle, H_i is the present-day heat generation rate of each radioactive isotope i, exponentially increasing in the past with a decay time scale τ_i, and Q_{tot} is the total heat loss of the Earth that can be separated in an oceanic heat loss Q_{oc} and a continental heat loss Q_{cont}. For a given seafloor age distribution, the oceanic heat loss can be written as (Labrosse and Jaupart, 2007)

$$Q_{oc} = \frac{A_{oc}\,k\,\lambda}{\sqrt{\pi\,\kappa\,t_{max}}}\,T_m \tag{3}$$

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

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

where the present-day radiogenic heat production of the depleted mantle H_{oi} is derived from a bulk silicate Earth model based on the composition of CI chondrites (Labrosse and Jaupart, 2007) and H_{ci} is the present-day radiogenic heat production of the continental crust. In the last two terms of the equation, f is the continental fraction, Q_{cont} is the present-day total continental heat flow below the continents, A_{cc} is the present-day continental area and $\lambda(f) = 2 + 2/3f$ is the seafloor age distribution factor. The thickness of the continental crust is assumed to be constant as in Flament et al. (2008) so that the continental fraction $f \times A_{cc}$ represents the total continental area with respect to the present. Finally, the maximum age of subduction t_{max} is assumed to be constant in the present calculations since a shorter t_{max} would lead to unrealistically high temperatures that would exceed the maximum temperature of 200 ± 100 °C greater than the present-day mantle suggested by petrological (Nisbet et al., 1993; Abbott et al., 1994) and rheological constraints (see Labrosse and Jaupart, 2007; Jaupart et al., 2007 for recent reviews). Values for all the parameters used in the thermal model are listed in Table 1.

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

Table 1
Values of the parameters used in the model.

Parameter	Meaning	Value	Unit (model)
Thermal parameters			
κ	Thermal diffusivity	8×10^{-7} [a]	$m^2\,s^{-1}$
ρ_{cc}	Density of the continental crust	2820	$kg\,m^{-3}$
A_{cc}	Area of continents	2.01×10^{14} [a]	m^2
A_{oc}	Area of oceans	3.09×10^{14} [a]	m^2
C_p	Heat capacity	1200 [a]	$J\,kg^{-1}\,K^{-1}$
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	$W\,m^{-1}\,K^{-1}$
M	Mass of the Earth	6×10^{24}	kg
Q_{cont}	Reduced continental heat flow	7 [b]	TW
T_0	Surface temperature	20	°C
t_{max}	Maximum age of subduction	180 [a]	Ma
z_{cc}	Thickness of the continental crust	40	km
Chemical parameters			
f_{recy}	Fraction of recycled continental crust	0.57	(NGM)
	1.09	(EGM)	
$K^{Rb}_{M\rightarrow CC}$		Enrichment factor of rubidium	215
$K^{Sr}_{M\rightarrow CC}$	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^{Sr}_{hy}	Present-day strontium hydrothermal flux	1.5×10^{9} [c]	$kg\,yr^{-1}$
Q^{Sr}_{r}	Present-day river strontium flux to the oceans	2.5×10^{9} [c]	$kg\,yr^{-1}$

[a] Labrosse and Jaupart (2007).
[b] Jaupart et al. (2007).
[c] Goddéris and François (1995).

the first effect; (iv) the mantle becomes depleted in radioactive elements with continental growth.

2.3. Modelling the evolution of continental hypsometry

Rey and Coltice (2008) suggested that the maximum elevation of orogenic plateaux would have been lesser in the Archean, when the continental crust was hotter than at present (Mareschal and Jaupart, 2006). Using thin sheet modelling, Rey and Coltice (2008) showed that the plateau elevation of a continental lithosphere in convergent regime is limited to ~2000 m for Archean Moho temperatures greater than ~700 °C, compared to 5500 m for present-day Tibet (Molnar et al., 1993). The relationship between plateau elevation and Moho temperature is non-linear, with a marked increase in plateau elevation for temperatures lower than ~700 °C due to the rapid strengthening of the lithospheric mantle (Rey and Coltice, 2008). We fit the results of the most conservative model of Rey and Coltice (2008), which assumes a strain rate of $1 \times 10^{-14}\,s^{-1}$, using the power-law

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

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

To compute the evolution of continental hypsometry, we derive the Moho temperature using a one-dimensional steady-state heat conduction model for which the energy conversation is

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

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

$$H(z) = H_0 \exp\left(\frac{-z}{h_r}\right), \tag{7}$$

where H_0 is the surface heat production, z is the depth and h_r is the characteristic thickness of a layer enriched in heat producing elements. The thickness of the enriched heat producing layer h_r is assumed to linearly decrease with time from 20 km at 4.5 Ga to 9 km at 2 Ga. Whilst the use of a linear law is arbitrary, this change in the thickness of the heat producing layer reflects the re-distribution of radiogenic elements from a more homogeneous early continental crust (Jaupart and Mareschal, 1999; Mareschal and Jaupart, 2006).

Solving Eq. (6) for the Moho temperature with knowledge of the mantle heat flux at the base of the continental crust $q_m = Q_{cont}/fA_{cc}$ and of the surface temperature T_0 gives

$$T_{Moho} = T_0 + \frac{q_m}{k}z_{cc} + \frac{\rho_{cc}H_0h_r^2}{k}(1 - e^{-z_{cc}/h_r})\,. \tag{8}$$

The evolution of the Moho temperature of cratons calculated using this thermal model is shown in Fig. 3a. The calculated present-day Moho temperature is ~460 °C, in agreement with the temperature at 50 km depth of ~430 ± 98 °C inferred from surface

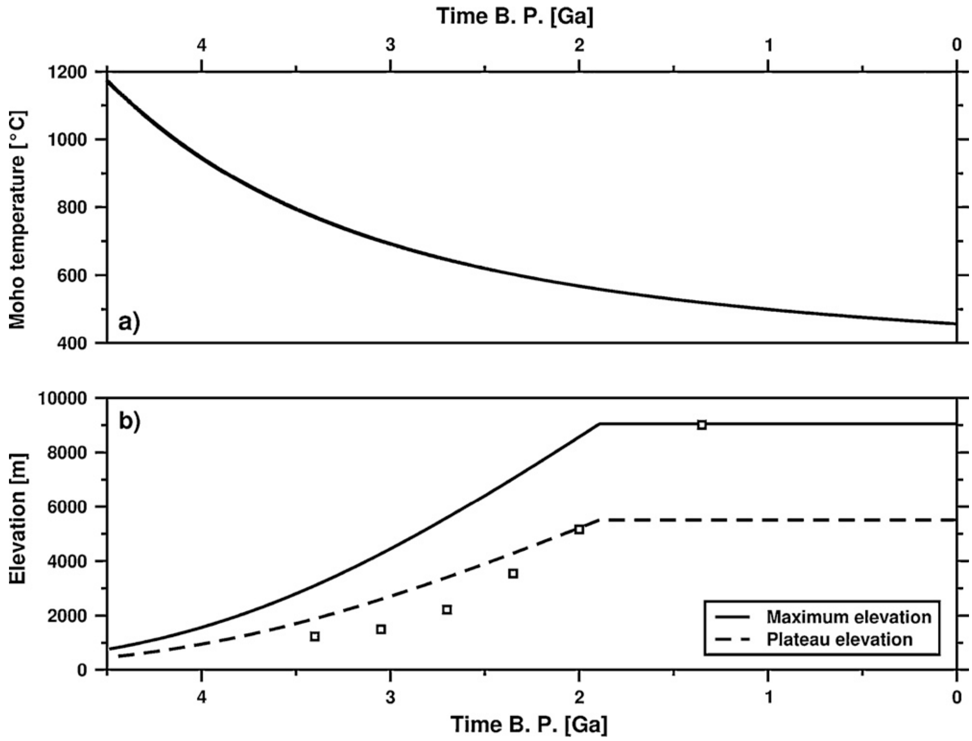

Fig. 3. (a) Typical secular evolution of Moho temperature. (b) Secular evolution of the plateau elevation (dashed curve) and maximum elevation (plain curve). Plateau elevation values from Rey and Coltice (2008) are shown as empty black squares for comparison.

heat flow data for Neoarchean cratons (Artemieva, 2006), and the calculated Moho temperature at 2.7 Ga is ∼640 °C. The secular evolution of the plateau and maximum elevations are shown in Fig. 3b. Comparison with the modelling results of Rey and Coltice (2008) shows that the model used in the present study is conservative. An Archean craton in a context of ongoing convergence would imply a plateau elevation similar to that of present-day Tibet at ∼2 Ga, and we assume that the elevation has been constant since then (Fig. 3b).

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

We use the model described in Flament et al. (2008) to calculate the evolution of sea level and area of emerged land as a function of mantle temperature, continental fraction and hypsometry. The two main assumptions of this model are a constant oceanic volume and a constant thickness of the continental crust.

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

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

$$\frac{dM_i}{dt} = \sum^{j \neq i} Q_{j \to i} - \sum^{j \neq i} Q_{i \to j}, \tag{9}$$

where M_i is the mass of box i, t is the time and $Q_{i \to j}$ 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 (i) output or input fluxes, (ii) dilution, (iii) radioactive decay and (iv) production from parent element. The elemental balance is expressed by

$$\frac{dC_i^k}{dt} = -\left(\lambda^k + \frac{\sum^{j \neq i} Q_{j \to i} - \sum^{j \neq i} Q_{i \to j}}{M_i} + \frac{\sum^{j \neq i} Q_{i \to j} K_{i \to j}^k}{M_i}\right) C_i^k + \frac{\sum^{j \neq i} Q_{j \to i} K_{j \to i}^k}{M_i} C_j^k + \lambda^{k-1} C_i^{k-1}, \tag{10}$$

where $K_{i \to j}^k$ 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 yr^{-1}. We consider three reservoirs (Fig. 4), namely the mantle (M), the continental crust (CC) and the ocean water

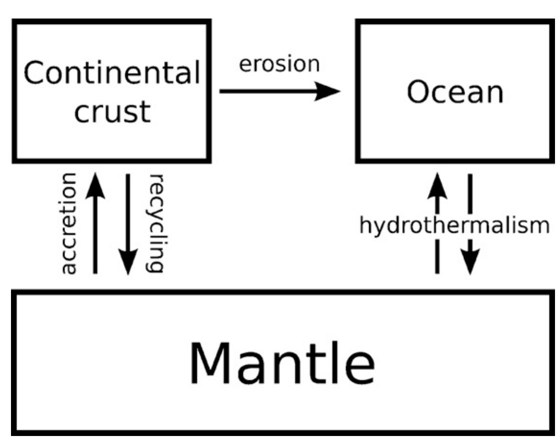

Fig. 4. Schematic description of the geochemical box model use in this study. Each box represents a reservoir and each arrow represents a flux.

(OW). The composition of the oceanic crust in $^{87}Sr/^{86}Sr$ 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 ($^{87}Rb/^{86}Sr = 0.085$ and $^{87}Sr/^{86}Sr = 0.699$) 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

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

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

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

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

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

$$Q_{M\to OW}^{Sr} = Q_{OW\to M}^{Sr} = Q_{hy}^{Sr}, \tag{11}$$

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

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

$$Q_{CC\to OW}^{Sr} \propto Q_{r}^{Sr} \times A \times Y, \tag{12}$$

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

3. Results

In this section, we investigate the dependency of mantle temperature, sea level, ridge depth, area of emerged land and $^{87}Sr/^{86}Sr$ of ocean water on 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; 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 270–300 °C greater than present, whereas delayed continental growth models (models CGM and NGM) predict Archean mantle temperatures 220–230 °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 greater for early continental growth models.

3.2. Influence of continental growth on sea level

We calculate the evolution of sea level, ridge depth and emerged land area from the evolution of mantle temperature and of continental fraction using the model of Flament et al. (2008). In this model, four situations can occur for a given set of parameters in

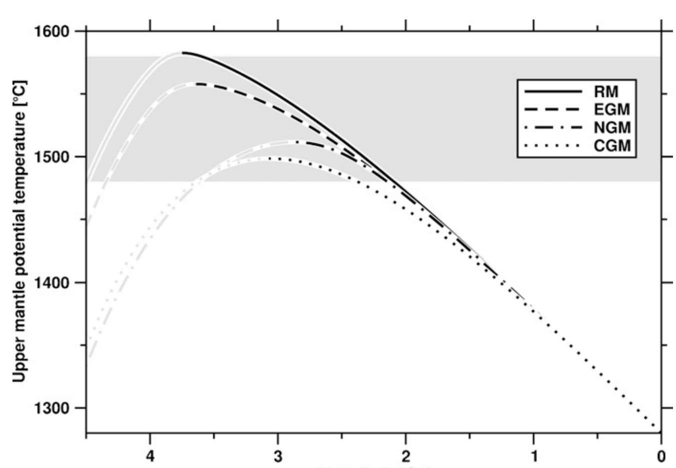

Fig. 5. Thermal evolution models computed for the four continental growth models shown in Fig. 2. The shaded area denotes mantle temperatures 200–300 °C hotter than present. Curves are grey before the temperature maximum to denote that results are hypothetical – see text for details.

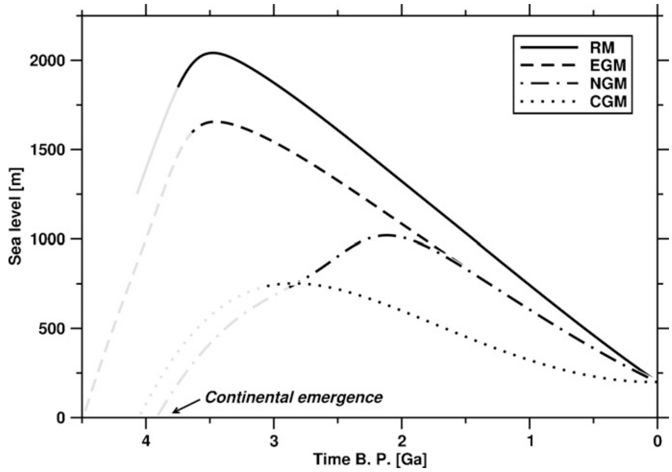

Fig. 6. Secular evolution of sea level for the four proposed continental growth models. The reference (zero-depth) is the edge of present-day continental shelves, with respect to which present-day sea level is 200 m. Grey segments of curves denote hypothetical results.

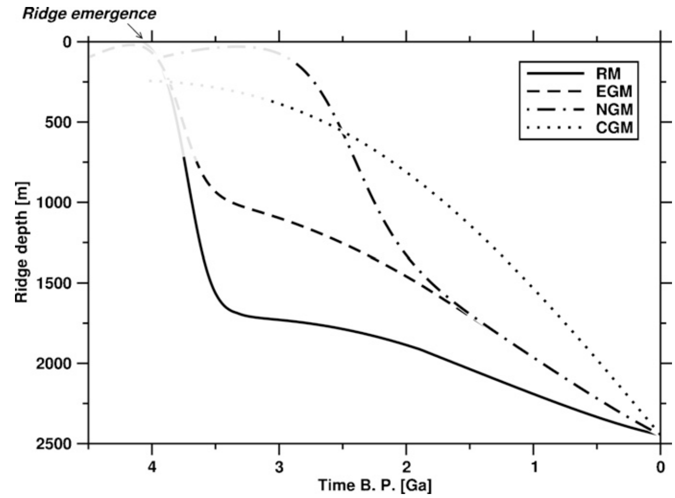

Fig. 7. Secular evolution of the depth of ridge crests for the four proposed continental growth models. Grey segments of curves denote hypothetical results.

which (i) the continents are partially flooded; (ii) the continents are entirely flooded; (iii) the continents are entirely emerged; and (iv) the mid-oceanic ridges emerge. Model calculations are only valid for partially flooded continents. Situations (ii), (iii) and (iv) constitute limits to the model and the calculation stops if any of these situations occurs. For this reason, some of the evolution models discussed in the following do not span the whole of Earth's history.

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

The calculated amplitudes of Archean sea level change range between ~550 m and ~1850 m. Even the lower end of this range is approximately twice the amplitude of Phanerozoic sea level change (Müller et al., 2008). Therefore, the hypothesis of constant continental freeboard is difficult to reconcile with any of the proposed continental growth end-members that cover most of the range of published continental growth models (Rino et al., 2004; Harrison, 2009). In addition, early continental growth models predict a maximum amplitude of sea level change between ~1450 m and ~1850 m, significantly larger than the sea level change of between ~550 m and ~800 m predicted for delayed continental growth models (Fig. 6). This is because larger past continental areas not only impose a higher sea levels (Flament et al., 2008) but also greater mantle temperature, which themselves impose higher sea levels. Our models also suggest that continents could have been entirely emerged before ~4 Ga for delayed continental growth models that predict large oceanic reservoirs and relatively low mantle temperatures (~150 °C greater than present). This emergence of small continental fractions ($f < 0.1$) is hypothetical since it occurs during the early warming period of the thermal evolution model (Fig. 5). Nevertheless, the occurrence of detrital zircons as old as ~4.4 Ga in the clastic sedimentary rocks of the Jack Hills, Narryer Gneiss Terrane, Yilgarn Craton (Wilde et al., 2001) and older than 4.1 Ga in the Youanmi Terrane, Yilgarn Craton (Wyche, 2007), suggests that small areas of continental crust were emerged early in Earth's history.

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

The predicted evolution of the depth of ridge crests through time is shown in Fig. 7. We find that ridge crests were shallower in the past than at present, which is in agreement with the results of Galer (1991). Interestingly, the evolution of the depth of ridge crests appears to be anti-correlated to continental growth (Figs. 2 and 7). Therefore, the depth of ridge crests closely depends on continental growth, contrary to the evolution of sea level that mainly reflects the evolution of mantle temperature. This is because changes in mantle temperature affect the depth of ridge crests through relatively minor changes in bathymetry whereas they affect sea level through large amplitude changes in oceanic crustal thickness (Flament et al., 2008).

Early continental growth models predict ridge crests significantly less shallow than delayed continental growth models mainly because larger continental areas result in higher sea levels. Our model predicts that at 2.5 Ga ridge crests were between ~660 m (model RM) and ~1200 m (model EGM) shallower than the present-day ridge crest depth of 2500 m. In comparison, delayed continental growth models result in ridge crests ~1900 m shallower at 2.5 Ga than at present. In addition, ridge crest emergence is predicted at ~4.1 Ga for model RM, time at which the thermal model is not realistic any more.

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

Fig. 8 shows that the Archean area of emerged land does not significantly depend on the continental growth model, despite large differences in continental area and in calculated sea level (Fig. 6). This is because the area of emerged land depends on mantle temperature, continental fraction and continental hypsometry. Thus, the Archean area of emerged land is intrinsically small for delayed continental growth models that predict small Archean continental areas. It is also small for early continental growth models that predict high Archean sea levels and thus largely flooded continents. The predicted Archean emerged land area is less than ~4% of Earth's

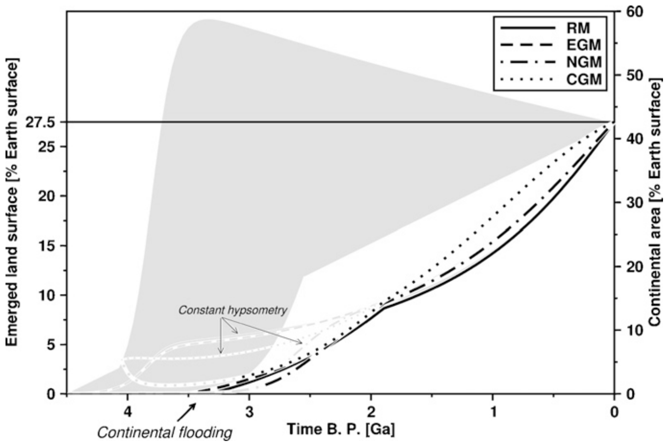

Fig. 8. Secular evolution of the area of emerged land for the four proposed continental growth models. The grey shaded area and the right-hand side axis of the figure indicate the range of predicted continental areas (see Fig. 2). Thick grey segments of curves denote hypothetical results, and thin grey curve indicate constant hypsometry. Despite large differences in continental area, all models predict similar emerged land surfaces, especially when changes in continental hypsometry are taken into account.

area in all models, with differences between models ⩽1.5%. For constant continental hypsometry, the area of emerged land is less than ~7% of Earth's area, and models differ by up to ~5% of Earth's area earlier than ~3 Ga. Note that these differences in area of emerged land remain small with respect to the large range of predicted continental areas for the same period (between 0 and ~57% of Earth's area, Fig. 8). The results for emerged area are in agreement with that of Flament et al. (2008) who proposed an Archean emerged land area of less than 3% of Earth's area (<12% of Earth's area for constant continental hypsometry). Estimates slightly differ because the feedback between continental growth and mantle temperature is taken into account in the present study whereas it was not in Flament et al. (2008).

Focusing on the results for non-constant hypsometry, the predicted Archean emerged land area is slightly larger in model CGM than in other models (Fig. 8). This is because the small continental area predicted by model CGM results in lesser mantle temperatures and lower sea levels. In contrast, model RM predicts larger continental areas than other models, which results in greater mantle temperatures and higher sea levels, and thus in a relatively small area of emerged land. The smallest Archean emerged land areas are predicted for model NGM in which mantle temperatures are significantly lower than in early continental growth models, and continental fractions are significantly larger than in model CGM. Near-complete continental flooding is predicted between ~3.3 and 3.5 Ga for all models because of high sea levels for early continental growth models and because of small continental areas for delayed continental growth models. It is worth noting that the progressive continental emergence from ~3.5 Ga predicted by our models fits nicely with the oldest angular unconformity (Buick et al., 1995) reported in the 3458–3426-Ma Panorama Formation, East Pilbara Craton (van Kranendonk et al., 2007). It is also consistent with the occurrence of shallow water quartz-rich sandstones in the *ca.* 3.4 Ga Strelley Pool Formation, East Pilbara Craton (van Kranendonk et al., 2007) and with the abundance of post-3.5 Ga clastic metasedimentary rocks in the Youanmi Terrane, Yilgarn Craton (Wyche, 2007).

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

As for the thickness of the continental crust, seismic studies suggest that the average present-day Archean continental crust is ~10 km thinner than the average present-day Proterozoic and Phanerozoic continental crust (Durrheim and Mooney, 1994; Christensen and Mooney, 1995). However, the regional metamorphic grade of exposed Archean cratons suggests a long term uplift and erosion of 5 ± 2 km due to the secular cooling of the mantle, initially in isostatic equilibrium with the depleted sub-continental lithospheric mantle underlying cratons (Galer and Mezger, 1998). The original thickness of the average Archean continental crust would thus have been undistinguishable from that of the average post-Archean continental crust. Nevertheless, the ~2.7 Ga peak in global magmatic activity that resulted in thickening of the continental crust through the eruption of greenstone suites 5–15 km thick covering a total area larger than 10^7 km^2 over most, if not all, Archaean cratons (De Wit and Ashwal, 1997) could have significantly contributed to the Neoarchean increase in the area of emerged land.

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

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

Fig. 9a shows the results obtained for both continental growth models assuming constant continental freeboard and hypsometry, which are the conventional assumption in models of the evolution of the $^{87}Sr/^{86}Sr$ of ocean water (e.g. Veizer and Jansen, 1979; Godderis and Veizer, 2000). The delayed continental growth model produces a better fit of the $^{87}Sr/^{86}Sr$ of marine carbonates (Shields and Veizer, 2002; Kuznetsov et al., 2010) and barites (Perry et al., 1971; McCulloch, 1994) than for the early continental growth model (Fig. 9a). In particular, the delayed continental growth model reproduces the shift of the oceanic reservoir from the mantle reservoir at ~2.7 Ga, whereas the early continental growth model predicts an oceanic reservoir significantly more radiogenic than suggested by the data, and a shift between oceanic and mantle reservoirs at ~4 Ga that is not observed in the data. This argument has been used repeatedly in favour of delayed continental growth models (Veizer and Jansen, 1979; Taylor and McLennan, 1985; Godderis and Veizer, 2000).

Fig. 9b shows the $^{87}Sr/^{86}Sr$ of the mantle and of the oceans calculated for both continental growth models, taking changes in emerged land area into account. The reduced area of emerged land and lower maximum continental elevation predicted by our models result in a reduced flux from the continents to the oceans (Eq. (12)) in the Archean, which results in less radiogenic oceans. In our models, the contribution of the continental strontium flux to the

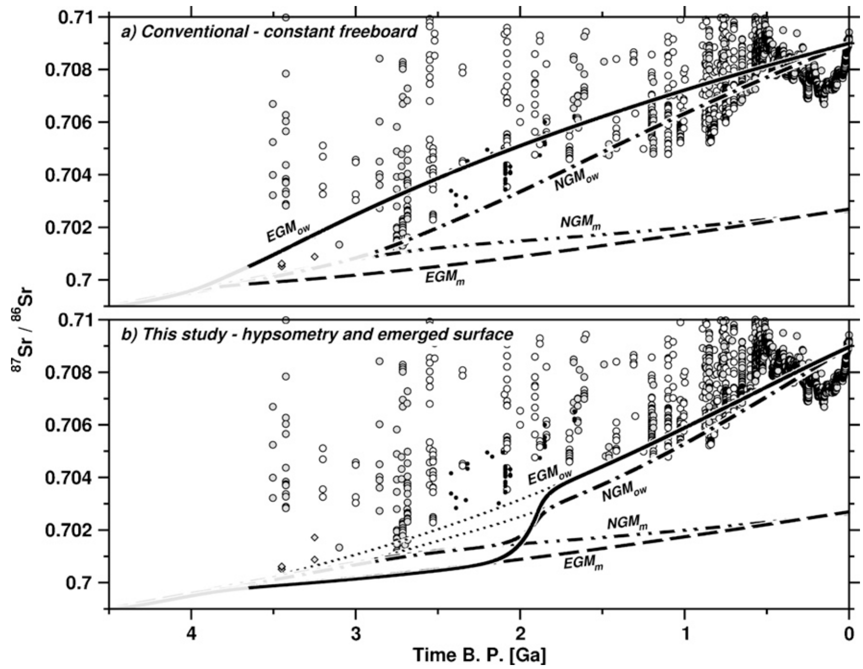

Fig. 9. Evolution of the $^{87}Sr/^{86}Sr$ of ocean water (OW) and of the mantle (M) for the Neoarchean (NGM) and early (EGM) continental growth models, (a) for constant hypsometry and constant freeboard and (b) taking changes in emerged area and continental hypsometry into account. The grey segments of curves denote hypothetical results, and the dotted black curves in (b) denote constant maximum elevation (see also Fig. 8). Grey and white circles are respectively well and poorly dated $^{87}Sr/^{86}Sr$ 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).

composition of ocean waters increases from 0% for entirely flooded Archean continents to ~61% for the present-day; the contribution of the complementary hydrothermal strontium flux decreases from 100% to ~39% for the present-day. It is clear from Fig. 9b that secular changes in continental hypsometry and in area of emerged land delay the contribution of the continents to the composition of the oceans. This effect is most important for model EGM that predicts larger continental areas in the Archean. However, the shift in the $^{87}Sr/^{86}Sr$ of ocean water at ~2.1 Ga predicted by for both models is delayed by ~600 Myr compared to the shift at ~2.7 Ga interpreted from the data on marine carbonates (Fig. 9b; Shields and Veizer, 2002). This time lag could reflect the fact that our steady-state thermal model for the continental crust (Section 2.3) does not account for variability in continental geotherms. Indeed, the present-day continental crust, for which surface heat flow varies between 50 and 120 mW m^{-2} depending on tectonic setting (Artemieva, 2009), cannot be described by a single steady-state or average continental geotherm. Similarly, a large range of continental geotherms were probably represented in the Archean, as suggested by the observed differences in crustal and lithospheric thickness of Archean cratons (Artemieva, 2009). Locally and/or transiently low Moho temperatures could have resulted in higher elevations and in an earlier shift of the predicted $^{87}Sr/^{86}Sr$ of ocean water. To further investigate this hypothesis, we carry out calculations for changing sea level and constant continental hypsometry (dotted curves in Fig. 9b). This gives a predicted $^{87}Sr/^{86}Sr$ of ocean water for model EGM that is very similar to that for model NGM assuming constant freeboard (Fig. 9a), confirming that changes in emerged land area account for the evolution of the $^{87}Sr/^{86}Sr$ of ocean water.

4. Discussion

Previous authors have separately investigated the role of continental growth on mantle temperature (e.g. Spohn and Breuer, 1993; Grigné and Labrosse, 2001; Labrosse and Jaupart, 2007) and on the composition of the oceans and of the atmosphere (e.g. Godderis and Veizer, 2000; Sleep and Zahnle, 2001), but to our knowledge this study is the first to simultaneously investigate the effect of continental growth on mantle temperature and sea water composition. Our approach is guided by the intrinsic inter-dependency between continental growth, thermal evolution of the Earth, continental hypsometry, sea level and $^{87}Sr/^{86}Sr$ of ocean water. Its strength is to allow us to investigate the effect of one parameter, the growth of the continents, on both interior and surface processes (Fig. 1). Its limitation is that hypotheses have to be made at different levels. Nevertheless, the structure of the proposed integrated model requires that hypotheses must be consistent at all levels.

In the present study, we have identified contrasted dependencies of sea level, ridge depth and emerged land area on continental growth. Sea level closely depends on mantle temperature that itself depends on continental growth, and the depth of mid-oceanic ridges is directly correlated to continental growth. In contrast, the area of emerged land does not significantly depend on continental growth. This is the key result of the present contribution. The weak dependency of emerged land on continental growth model suggests that surface geochemical indicators are inappropriate to constrain continental growth. In addition, using surface geochemical indicators as proxies for continental growth is based on the implicit assumptions of constant continental freeboard and constant continental elevation (e.g. Veizer and Jansen, 1979; Taylor and McLennan, 1985). However, these assumptions fail to explain the preponderance of subaqueous flood volcanism in the Archean (Arndt, 1999; Kump and Barley, 2007) that suggests high Archean sea levels (Flament et al., 2008). Our calculations reconcile the preponderance of subaqueous flood volcanism in the Archean with the evolution of the $^{87}Sr/^{86}Sr$ of marine carbonates by showing that early continental growth models are consistent with the evolution of the $^{87}Sr/^{86}Sr$ of ocean water when a reduced area of emerged land and a lower continental elevations are taken into account (Fig. 9). The evolution of the $^{87}Sr/^{86}Sr$ of marine carbonates is not a geochemical proxy for continental growth but rather a tracer of the efficiency of the flux from the felsic continents to the oceans. We propose that the evolution of $^{87}Sr/^{86}Sr$ of marine carbonates does not reflect an increase in continental volume, but an increase in weathering and erosion processes (Rey and Coltice, 2008; Flament et al., 2008).

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

Interestingly, the correlation between the depth of ridge crests and continental area suggests that ridge depth could be used as a proxy for continental growth, if a preserved Archean mid-oceanic ridge were 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 $\delta^{18}O$ 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, 2004), 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 oxidation state of the atmosphere, we speculate that the Neoarchean emergence of the continents could have contributed to the great oxidation event dated at ~2.45 Ga (Bekker et al., 2004). Finally, the quantification of the area of emerged land is of importance to models of the Archean climate and atmospheric composition. Indeed, the emerged land area affects the albedo of the Earth (Rosing et al., 2010) and the intensity of weathering processes that regulate the composition of the atmosphere in CO_2 (Sleep and Zahnle, 2001) and in O_2 (Godderis and Veizer, 2000). To date, models of the Archean climate have used the conventional hypothesis of constant continental freeboard, therefore over-estimating the efficiency of erosion and weathering processes. Future models of the Archean climate should take the effect of an area of emerged land of less than ~4% of Earth's area into account.

5. Conclusion

The integrated model developed in this study allows us to investigate the influence of continental growth models on mantle temperature, sea level, ridge depth, emerged land area and $^{87}Sr/^{86}Sr$ of ocean water. Our results suggest that because of the thermal insulation imposed by continents on the mantle, early continental models result in higher Archean mantle temperature. Since both elevated mantle temperatures and large continental fractions impose high sea levels, early continental growth models predict higher Archean sea levels than delayed continental growth models. We find that mid-oceanic ridges were shallower in the past, and that the evolution of the depth of ridge crests is anti-correlated to continental growth. We calculate that less than ~4% of Earth's area was emerged in the Archean and we show that the evolution of the area of emerged land does not significantly depend on continental growth. Therefore, we suggest that geochemical proxies for felsic crust do not constrain continental growth. For instance, the evolution of the $^{87}Sr/^{86}Sr$ of marine carbonates is a tracer of the flux of radiogenic strontium from the emerged continents to the oceans, but is not an appropriate proxy for continental growth.

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

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