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The evolution of the $^{87}Sr/^{86}Sr$ 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. 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.

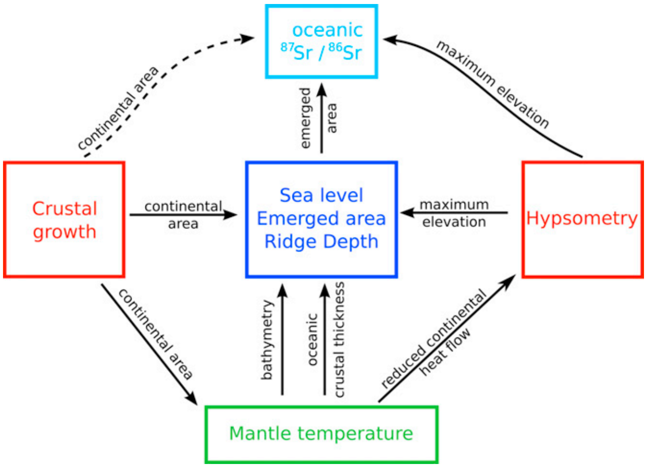

Fig. 1. Flow chart of the model used in this study. Arrows indicate model inputs and boxes indicate the variables and parameters of the model. The temperature of the mantle is calculated as in Labrosse and Jaupart (2007), the continental hypsometry is calculated from the results of Rey and Coltice (2008) 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

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

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.