Gondwana Research 42 (2017) 151–162

Contents lists available at ScienceDirect

Gondwana Research

journal homepage: www.elsevier.com/locate/gr

Paleogeographic forcing of the strontium isotopic cycle in the Neoproterozoic

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ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form 19 September 2016
Accepted 19 September 2016
Available online 20 October 2016

Handling Editor: R.D. Nance

Keywords:
Neoproterozoic
Paleogeography
Strontium isotopes
Carbon cycle
Modeling

ABSTRACT

The period spanning from 825 to 540 Ma is characterized by major changes in the surficial Earth system. This extraordinary interval starts with the breakup of the Rodinia supercontinent and eruption of a series of large igneous provinces and ends with the assembly of Gondwana, giving rise to the Pan-African orogenies. This paleogeographic reorganization is accompanied by a global climatic cooling, including the paroxysmal Cryogenian "snowball" glacial events. The $^{87}Sr/^{86}Sr$ of seawater displays a major long-term rise over this interval that is punctuated by episodic, smaller declines and inflections. We use a coupled deep time climate-carbon numerical model to explore the complex role of tectonics and climate on this distinct evolution in seawater $^{87}Sr/^{86}Sr$. We show that the modulation of the weathering of the erupted large igneous provinces by continental drift explains the changes in seawater $^{87}Sr/^{86}Sr$ from 800 to 635 Ma. The subsequent sharp rise in seawater $^{87}Sr/^{86}Sr$ from 635 to 580 Ma is the result of erosion of radiogenic crust exposed in the Pan-African orogens. Coeval evolution of atmospheric CO_2 displays a decrease from about 80 times the pre-industrial level around 800 Ma to 5 times just before the beginning of the Phanerozoic.

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1. Introduction

The strontium isotopic composition of seawater over the last 850 million years, as recorded in carbonate minerals, reveals three major long-term trends (Fig. 1). First, between ca. 850 and 500 Ma, $^{87}Sr/^{86}Sr$ rises in two broad steps from 0.706 to 0.709 (Halverson et al., 2007). This Neoproterozoic increase in $^{87}Sr/^{86}Sr$ is followed by a long-term (> 300 m.y.), net decrease from the late Cambrian to the Jurassic (Veizer et al., 1999; McArthur et al., 2012). Finally, $^{87}Sr/^{86}Sr$ increases from 0.707 in the Jurassic to 0.709 at present day, with an inflection to a much steeper slope beginning ca. 40 Myr ago (De Paolo and Ingram, 1985).

The causes of trends in seawater Sr isotope ratios have been intensely debated over the last 30 years, with most models emphasizing the relative contributions of hydrothermal versus continental Sr fluxes to seawater. Many papers have focused on the rise over the last 40 Myr, for which the record is most complete (De Paolo and Ingram, 1985). The dominant interpretation for this abrupt increase is that it records the influence of the Himalayan orogeny in exposing large volumes of highly radiogenic (i.e. high $^{87}Sr/^{86}Sr$) rocks to continental weathering (Edmond, 1992; Galy et al., 2002; Myrow et al., 2015). However, alternative models have been proposed. Zachos et al. (1999) proposed that the increased flux of radiogenic Sr to seawater instead reflects the onset of Antarctic glaciation and its role in physical breakdown of radiogenic rocks, thus facilitating chemical weathering. Focusing instead on the hydrothermal Sr source to seawater, Coogan and Dosso (2015) argued that the Cenozoic rise in $^{87}Sr/^{86}Sr$ can be explained by a decrease in the off-axis Sr flux due to lower bottom-water temperatures attending global cooling at this time.

Less attention has been paid to the longer-term changes in seawater $^{87}Sr/^{86}Sr$. By analogy to the late Cenozoic, the Neoproterozoic rise, or at least the steep increase in the Ediacaran Period, has been related to the impact of the Pan-African orogenies on the strontium isotopic cycle (Derry et al., 1989). But the mechanism behind the earlier Neoproterozoic, longer-term changes (>100 Myr) remains obscure, in particular because it contradicts traditional models that would imply that continental break-up (i.e. of Rodinia) should increase the hydrothermal Sr.

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http://dx.doi.org/10.1016/j.gr.2016.09.013
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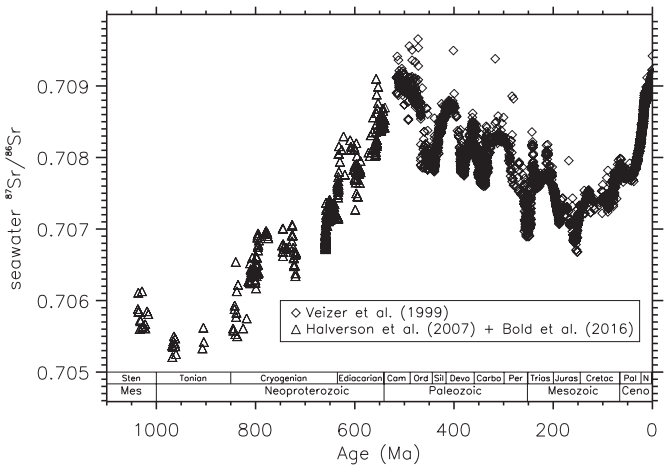

Fig. 1. The measured evolution of the seawater $^{87}Sr/^{86}Sr$ over the last 825 million years. Data collated from Bold et al. (2016), Halverson et al. (2007) and Veizer et al. (1999).

Recent studies have offered new perspectives on the strontium cycle. The role of island arc weathering has been identified as an important driver of the oceanic strontium isotope budget, potentially accounting for 60% of the low radiogenic Sr input into seawater (Allègre et al., 2010). Van Der Meer et al. (2014) proposed that the length of subduction zones, if used for scaling the input of mantle strontium into the ocean, can explain the main features of the seawater $^{87}Sr/^{86}Sr$ over the last 250 million years. Young et al. (2009) and Nardin et al. (2011) argued that the general decline in the seawater $^{87}Sr/^{86}Sr$ during the early Paleozoic, and specifically during the Ordovician, might be related to the enhanced weathering of young volcanic rocks with time. In this scenario, the engine driving secular evolution in seawater $^{87}Sr/^{86}Sr$ is a change in lithology at the earth's surface.

Another potential source of seawater $^{87}Sr/^{86}Sr$ modulation is evolving paleogeography (Worsley and Nance, 1986) due to the role of climate in continental weathering. Given the spatial heterogeneity of continental lithologies and global climatic zonation, ongoing continental drift should drive secular evolution in the global discharge of dissolved elements to the ocean. As a result, continental drift modulates the average $^{87}Sr/^{86}Sr$ signature of continental runoff and hence the ocean. For instance, during the existence of supercontinental phases, the continents are encircled by volcanic arcs, which provide an easily weathered source of young, unradiogenic basalt and andesite. In contrast, as break-up proceeds, the margins of old continental shields are uplifted and their interiors increasingly exposed to precipitation, potentially elevating the flux of radiogenic strontium to the oceans. Based on this qualitative reasoning, Halverson et al. (2007) suggested that the seawater $^{87}Sr/^{86}Sr$ should increase during the break-up of a supercontinent as the relative importance of continental weathering increases at the expense of arc weathering.

Such a scenario has not been tested quantitatively. Nor did this conceptual model account for the role of emplacement of mafic large igneous provinces (LIPs), which are associated with supercontinental break-up (Courtillot et al., 1999), or subsequent Himalayan-style orogenesis, which follows continental break-up. In this contribution, we explore the relative role of paleogeography and these other processes related to the supercontinental cycle on the long-term evolution (10^7 years) of seawater $^{87}Sr/^{86}Sr$ during the Neoproterozoic using the Earth System Model for the deep time GEOCLIM.

2. Methods

We test the impact of Rodinia break-up, of the weathering of young volcanic arcs and LIPs, and of the Pan African orogen on the Neoproterozoic seawater $^{87}Sr/^{86}Sr$ through the application of the spatially resolved numerical model, GEOCLIM, which we summarize here. A complete description of GEOCLIM can be found in Donnadieu et al. (2006) and in Goddéris et al. (2014).

2.1. The GEOCLIM model

GEOCLIM couples a 10-box model describing the biogeochemical cycles of carbon, oxygen, alkalinity, phosphorus, strontium, and its isotopic budget to a spatially resolved climate model. The continental weathering fluxes are calculated with a spatial resolution of 7.5° longitude by 4.5° latitude. The boundary conditions are the amount of energy received from the sun by the Earth, the continental configuration, the solid Earth degassing, the continental topography, and the spatial distribution of different continental lithologies. Continental weathering is calculated for each continental grid cell as a function of mean annual local temperature and runoff (Dessert et al., 2003; Oliva et al., 2003). Here, GEOCLIM is run in a steady-state mode. This means that we calculate the level of atmospheric CO_2 and associated spatially resolved climate at which CO_2 consumption by continental silicate weathering balances the prescribed solid Earth CO_2 degassing flux (Walker et al., 1981). In other words, we calculate the steady-state CO_2 and climate for each set of boundary conditions. We then calculate seawater $^{87}Sr/^{86}Sr$ assuming that the strontium cycle is in steady-state, a reasonable assumption for the temporal resolution of our simulations (one simulation every 30 to 50 million years).

The spatial resolution of the climate model is 7.5° long × 4.5° lat. Continental weathering fluxes are calculated at the same resolution. The model accounts for four lithologies: shield rocks (i.e. old continental crust), fresh basaltic surfaces (LIPs), volcanic arcs, and carbonate rocks. LIPs and volcanic arcs are located on each map according to geological constraints (see boundary conditions). The remaining spaces on the continental surfaces are filled by shield and carbonate rocks. The weathering flux for LIPs is calculated as follows (assuming a basaltic lithology) (Dessert et al., 2003):

$$F_{weath}^{LIP} = \sum_{j=1}^{n_{grid}} \varphi_{LIP}^{j} \times area_j \times f_{LIP}^{j} \quad (1)$$

where n_{grid} is the number of continental grid elements, $area_j$ the area of the grid element j, and φ^j_{LIP} is the fraction of the grid element covered by basalts. f^j_{LIP} is the climatic dependence of basaltic rock weathering:

$$f_{LIP}^{j} = k_{BAS} \times run_j \times e^{-\frac{42300}{r_{gas}}\left(\frac{1}{T_j}-\frac{1}{298}\right)} \quad (2)$$

where r_{gas} is the ideal gas constant, T_j the mean annual temperature calculated by the climate model for grid element j, and run_j is the local mean annual runoff from the climate model. k_{BAS} is a calibration constant (see below). The same formulation is used for the weathering of active volcanic arcs, assuming a basaltic lithology. This simplification maximizes the contribution of arc to the global weathering flux.

The weathering of continental shield rock is calculated using the same formalism:

$$F_{weath}^{shield} = \sum_{j=1}^{n_{grid}} \varphi_{shield}^{j} \times area_j \times f_{shield}^{j} \quad (3)$$

with (Oliva et al., 2003):

$$f_{shield}^{j} = k_{shield} \times run_j \times e^{-\frac{48200}{r_{gas}}\left(\frac{1}{T_j}-\frac{1}{298}\right)} \quad (4)$$

k_{shield} and k_{bas} are calibrated so that the total silicate weathering consumes 6.8 Tmol CO_2/yr, with basaltic weathering contributing to 30% of the total for a present day configuration (Gaillardet et al., 1999; Dessert et al., 2003). Carbonate weathering is so fast that it is assumed

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