Earth and Planetary Science Letters 383 (2013) 92–100

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Convergence of tectonic reconstructions and mantle convection models for significant fluctuations in seafloor spreading

N. Coltice [a,b,*], M. Seton [c], T. Rolf [d], R.D. Müller [c], P.J. Tackley [d]

[a] Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1, Ecole Normale Supérieure de Lyon, CNRS, France
[b] Institut Universitaire de France, France
[c] EarthByte, School of Geosciences, University of Sydney, Australia
[d] Institute of Geophysics, ETH Zurich, Sonneggstrasse 5, 8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 30 April 2013
Received in revised form 11 September 2013
Accepted 20 September 2013
Available online 17 October 2013
Editor: C. Sotin

Keywords:
mantle convection
plate tectonics
reconstruction
seafloor spreading

ABSTRACT

For 50 years of data collection and kinematic reconstruction efforts, plate models have provided alternative scenarios for plate motions and seafloor spreading for the past 200 My. However, these efforts are naturally limited by the incomplete preservation of very old seafloor, and therefore the time-dependence of the production of new seafloor is controversial. There is no consensus on how much it has varied in the past 200 My, and how it could have fluctuated over longer timescales. We explore how seafloor spreading and continental drift evolve over long geological periods using independently derived models: a recently developed geodynamic modelling approach and state-of-the-art plate reconstructions. Both kinematic reconstructions and geodynamic models converge on variations by a factor of 2 in the rate of production of new seafloor over a Wilson cycle, with concomitant changes of the shape of the area–age distribution of the seafloor between end members of rectangular, triangular and skewed distributions. Convection models show that significant fluctuations over longer periods (∼1 Gy) should exist, involving changes in ridge length and global tectonic reorganisations. Although independent, both convection models and kinematic reconstructions suggest that changes in ridge length are at least as significant as spreading rate fluctuations in driving changes in the seafloor area–age distribution through time.

1. Introduction

The theory of plate tectonics has provided the necessary framework for reconstructing ocean basins, including now subducted seafloor, and paleogeography (Kominz, 1984). Over 50 years of data collection and kinematic reconstruction efforts have led to significant improvements in plate tectonic modelling (Pilger, 1982; Rowley and Lottes, 1988; Scotese et al., 1988; Lithgow-Bertelloni and Richards, 1998; Müller et al., 1997; Seton et al., 2012). Plate tectonic models describing seafloor area–age distributions with relatively small uncertainties exist only for times where geological and geophysical data coverage is sufficient. Challenges remain for reconstructing ancient ocean basins and associated plate boundaries for times earlier than 200 Ma, as they are naturally limited by the preservation of very old seafloor. In addition, only 5% of the history of the planet can be reconstructed using evidence from geological and geophysical data.

However, geodynamic models can now help to evaluate how seafloor spreading evolves over longer time periods. Recent numerical models of mantle convection with pseudo-plasticity can generate long-term solutions producing a form of seafloor spreading (Moresi and Solomatov, 1998; Trompert and Hansen, 1998; Tackley, 2000), although developing a more complete and consistent physical model for the rheology will eventually be required (Bercovici, 2003; Bercovici and Ricard, 2012). These models have a mechanically strong boundary layer at the surface, which becomes weak in regions of higher stresses. Hence, strain localises in relatively narrow regions while rigid body motion dominates elsewhere (van Heck and Tackley, 2008). These models also generate a significant toroidal component in the surface velocity field, as observed on Earth. The introduction of models of continental lithosphere (Yoshida, 2010; Rolf and Tackley, 2011) further improve the quality of such predictions: the computed distribution of seafloor ages reproduces the consumption of young seafloor as observed on the present-day Earth (Coltice et al., 2012).

The time-dependence of the production of new seafloor has long been debated and there is no consensus on how much it has varied in the past 150 My, and how it could have fluctuated over longer timescales. Using plate reconstructions, Parsons (1982)

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[*] Corresponding author at: Laboratoire de Géologie de Lyon, Université Claude Bernard Lyon 1, Ecole Normale Supérieure de Lyon, CNRS, France.
E-mail address: nicolas.coltice@univ-lyon1.fr (N. Coltice).

0012-821X
http://dx.doi.org/10.1016/j.epsl.2013.09.032

and Rowley (2002) proposed that the area–age distribution of the seafloor has experienced limited fluctuations in the past 200 My, while others have suggested that larger variations would fit the observations equally well (Demicco, 2004; Seton et al., 2009). In addition, relatively fast seafloor spreading was proposed for the mid-Cenozoic (Conrad and Lithgow-Bertelloni, 2007). A careful analysis by Becker et al. (2009) concluded that the present-day area vs. age distribution of the seafloor accounts for significant fluctuations of the rate of seafloor production in the past 200 My, an interpretation opposite to that reached by Parsons (1982) and Rowley (2002).

Here we investigate the global dynamics of seafloor spreading using *two independent modelling approaches:* state-of-the-art plate reconstructions and geodynamic models. Both kinematic reconstructions and geodynamic models converge to suggest that the rate of production of new seafloor can vary by a factor of 2 over a Wilson cycle, with concomitant changes of the shape of the area–age distribution of the seafloor.

2. The area–age distribution of the seafloor

The evolution of the area–age distribution of the seafloor through time is of fundamental importance since it impacts on global variations in heat flow, tectonic forces and sea-level. The area–age distribution provides a statistical representation of the state of the seafloor. It can be used to quantitatively compare seafloor spreading states with different continental configurations and plate distributions.

The evolution of the area–age distribution has been the subject of intense debate in the past 30 years. The present-day distribution displays a linear decrease of the area for increasing age. Young seafloor dominates, but areas with ages as old as 180 Ma exist. The shape of this distribution is called triangular. The physics behind this distribution has been questioned by Labrosse and Jaupart (2007), particularly because it suggests that lithosphere of young age (hot) is subducted with the same probability as that of older ages (cold). Indeed, a principle of convection is that when a material at the surface of a thermal boundary layer of convecting fluid has cooled sufficiently its buoyancy becomes large enough to start sinking into the viscous interior. The onset of the downwellings corresponds to a critical value of the local Rayleigh number, which in dimensional values can be converted to a critical age. As a consequence, convection appears to favour the sinking of lithosphere only when a critical age is attained, implying that a rectangular distribution is expected.

Two effects can be proposed to force a convective system to adopt a distribution that is skewed (or triangular): continent configuration and time-dependence of the flow. Continents are relatively unsinkable and conductive, therefore the entire continental area cannot participate in seafloor spreading and subduction. As observed on Earth today, subduction zones tend to locate themselves at the continent–ocean boundary. As shown in Fig. 1, the orientation and shape of the subduction zone along a continent, relative to the opening ridge governs the shape of the area–age distribution.

The time-dependence of seafloor spreading also implies modifications of the area–age distribution, as proposed earlier by Demicco (2004). Indeed, since the integral of the distribution is the total seafloor area, a conserved quantity in recent geological time, increasing the rate of production of new seafloor necessarily involves the sinking of older seafloor. As shown in Fig. 2, fluctuations of seafloor production can lead to triangular-like shape. The more time-dependent the system is, the more variable the area–age distribution can be. However, the time-dependence of the rate of production of new seafloor has been challenged by Parsons (1982) and Rowley (2002), who propose that the fluctuations in the past 150 My do not exceed 30% of the present-day value. In the following we will address the extent of the time-dependence with the most recent plate reconstructions and mantle convection models.

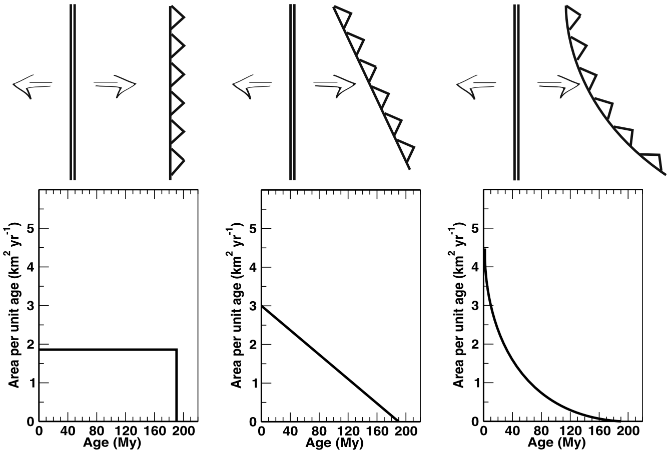

Fig. 1. The shape of the area–age distribution depends on the geometry of plate boundaries.

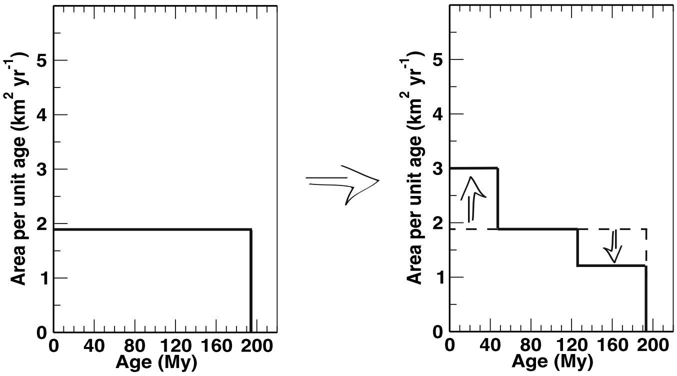

Fig. 2. The time-dependence of the production of new seafloor implies changes of shape of the area–age distribution.

3. Reconstructed seafloor history since 200 Ma

We reconstruct the seafloor spreading history for the past 200 million years based on a merged absolute reference frame (O'Neill et al., 2005 and Steinberger and Torsvik, 2009) with relative plate motions based on Seton et al. (2012). The plate reconstructions are underpinned by over 70,000 magnetic anomaly and fracture zone identifications for currently preserved crust. For crust that has been subducted, we use simple assumptions of spreading symmetry, adherence to the rules of plate tectonics and onshore geological data to constrain our plate reconstructions (Müller et al., 2008; Seton et al., 2012). We extend the model back to the Triassic (250 Ma) by incorporating a longer history of seafloor spreading between the three major plates that form Panthalassa (Izanagi, Farallon, Phoenix plates) similar to its Jurassic–Cretaceous opening history, the closure of the Mongol–Okhotsk Ocean based on Van der Voo et al. (1999) and a more extensive paleo-Tethys ocean largely consistent with Stampfli and Borel (2002) and Golonka (2007). Our plate reconstructions also include an accompanying set of continuously closed plate polygons (CPP) and plate boundaries (Gurnis et al., 2012) allowing us to track the properties of the plates themselves through time.

In the Triassic, the vast Panthalassic and the smaller Tethys Ocean surrounded the supercontinent, Pangaea. Panthalassa, modelled as a simple three plate spreading system between the Izanagi,