Earth-Science Reviews 105 (2011) 1–24

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Supercontinents, mantle dynamics and plate tectonics: A perspective based on conceptual vs. numerical models

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ARTICLE INFO

Article history:
Received 1 June 2010
Accepted 7 December 2010
Available online 14 December 2010

Keywords:
supercontinents
mantle dynamics
plate tectonics
Wilson Cycle
supercontinent cycle
numerical model

ABSTRACT

The periodic assembly and dispersal of supercontinents through the history of the Earth had considerable impact on mantle dynamics and surface processes. Here we synthesize some of the conceptual models on supercontinent amalgamation and disruption and combine it with recent information from numerical studies to provide a unified approach in understanding Wilson Cycle and supercontinent cycle. Plate tectonic models predict that superdownwelling along multiple subduction zones might provide an effective mechanism to pull together dispersed continental fragments into a closely packed assembly. The recycled subducted material that accumulates at the mantle transition zone and sinks down into the core–mantle boundary (CMB) provides the potential fuel for the generation of plumes and superplumes which ultimately fragment the supercontinent. Geological evidence related to the disruption of two major supercontinents (Columbia and Gondwana) attest to the involvement of plumes. The re-assembly of dispersed continental fragments after the breakup of a supercontinent occurs through complex processes involving ‘introversion’, ‘extroversion’ or a combination of both, with the closure of the intervening ocean occurring through Pacific-type or Atlantic-type processes. The timescales of the assembly and dispersion of supercontinents have varied through the Earth history, and appear to be closely linked with the processes and duration of superplume genesis. The widely held view that the volume of continental crust has increased over time has been challenged in recent works and current models propose that plate tectonics creates and destroys Earth's continental crust with more crust being destroyed than created. The creation–destruction balance changes over a supercontinent cycle, with a higher crustal growth through magmatic influx during supercontinent break-up as compared to the tectonic erosion and sediment-trapped subduction in convergent margins associated with supercontinent assembly which erodes the continental crust. Ongoing subduction erosion also occurs at the leading edges of dispersing plates, which also contributes to crustal destruction, although this is only a temporary process. The previous numerical studies of mantle convection suggested that there is a significant feedback between mantle convection and continental drift. The process of assembly of supercontinents induces a temperature increase beneath the supercontinent due to the thermal insulating effect. Such thermal insulation leads to a planetary-scale reorganization of mantle flow and results in longest-wavelength thermal heterogeneity in the mantle, i.e., degree-one convection in three-dimensional spherical geometry. The formation of degree-one convection seems to be integral to the emergence of periodic supercontinent cycles. The rifting and breakup of supercontinental assemblies may be caused by either tensional stress due to the thermal insulating effect, or large-scale partial melting resulting from the flow reorganization and consequent temperature increase beneath the supercontinent. Supercontinent breakup has also been correlated with the temperature increase due to upwelling plumes originating from the deeper lower mantle or CMB as a return flow of plate subduction occurring at supercontinental margins. The active mantle plumes from the CMB may disrupt the regularity of supercontinent cycles. Two end-member scenarios can be envisaged for the mantle convection cycle. One is that mantle convection with dispersing continental blocks has a short-wavelength structure, or close to degree-two structure as the present Earth, and when a supercontinent forms, mantle convection evolves into degree-one structure. Another is that mantle convection with dispersing continental blocks has a degree-one structure, and when a supercontinent forms, mantle convection evolves into degree-two structure. In the case of the former model, it would take longer time to form a supercontinent, because continental blocks would be trapped by different downwellings thus inhibiting collision. Although most of the numerical studies have assumed the continent/supercontinent

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0012-8252/$ – see front matter
doi:10.1016/j.earscirev.2010.12.002

to be rigid or nondeformable body mainly because of numerical limitations as well as a simplification of models, a more recent numerical study allows the modeling of mobile, deformable continents, including oceanic plates, and successfully reproduces continental drift similar to the processes and timescales envisaged in Wilson Cycle.

Contents

1. Introduction

The history of growth, evolution and dispersion of supercontinents on the globe through time has received considerable attention in the recent years, particularly with respect to the impact of the assembly and dispersion of continental fragments on mantle dynamics, surface processes and life evolution (for a recent compilation, see Santosh and Zhao, 2009, and papers therein). A recent synthesis of the various conceptual models suggests that supercontinent tectonics in relation to mantle dynamics provides a key to evaluate the history of evolution and destruction of the continental crust, to understand the history of life, and to trace the major surface environmental changes of our planet (Santosh, 2010b). The postulated Neo-Archean continental assemblies (e.g., Rogers and Santosh, 2004; Eriksson et al., 2009) and the increasing evidence for the Paleo-Mesoproterozoic supercontinent Columbia (Meert, 2002; Rogers and Santosh, 2002; Zhao et al., 2002; Rogers and Santosh, 2009), Neoproterozoic Rodinia (Dalziel, 1991; Hoffman, 1991; Z.X. Li et al., 2008) and Late Neoproterozoic–Cambrian Gondwana (Collins and Pisarevsky, 2005; Meert and Lieberman, 2008), among other proposed supercontinents, support the notion that global cycles of continental reorganization have occurred throughout Earth's history (Worsley et al., 1984; Nance et al., 1986).

Seismic tomographic images suggest that the Earth's mantle structure is characterized by different modes of flow: (1) Subducting plates mainly beneath the Circum-Pacific region, some of which are stagnated at the 660 km phase boundary (i.e., spinel to perovskite + magnesiowüstite phase transition boundary), whereas others penetrate into the deeper lower mantle (e.g., Fukao, 1992; van der Hilst et al., 1997; Fukao et al., 2001; Zhao, 2004); (2) Large-scale, broad upwelling-plumes beneath the South Africa–South Atlantic and South Pacific regions (e.g., Fukao, 1992; Masters et al., 2000; Mégnin and Romanowicz, 2000; Ritsema and van Heijst, 2000); (3) Small-scale, localized upwelling-plumes originating from the core–mantle boundary (CMB) or 660 km phase boundary, which were detected mainly by the recent highly-resolved tomographic model (e.g., Wolfe et al., 1997; Montelli et al., 2004, 2006; Wolfe et al., 2009). Geochemical evidence and geodynamic models support this global view of mantle structure, although several models with various compositional heterogeneities have also been proposed (see review by Tackley, 2000a, 2007). On the other hand, a continent/supercontinent is isolated from the convecting mantle in terms of the rheology, composition, large radiogenic internal heating production (e.g., Schubert et al., 2001), and the longevity over geologic time (e.g., Carlson et al., 2005). The thermal and mechanical interaction between the continental drift and mantle convection has not been, however, fully resolved.

The numerical studies of mantle convection have markedly progressed toward the realization of seismic tomography images of mantle structure and a better understanding of geodynamic mechanisms in accordance with the advancement in numerical modeling techniques as well as the increase of computational power and resource. The mantle convection theory is comprehensively summarized by several papers and textbooks (e.g., McKenzie et al., 1974; Jarvis and McKenzie, 1980; Christensen, 1984; Busse, 1989; Schmeling, 1989; Davies, 1999; Schubert et al., 2001; Turcotte and Schubert, 2002; Ricard, 2007). A review of mantle convection studies and the numerical simulation techniques used are beyond the scope of this paper, and can be found in the several textbooks and papers with broader view and perspective (e.g., Richards and Davies, 1992; Tackley, 2000a; Schubert et al., 2001; Ricard, 2007; Zhong et al., 2007b; Ismail-Zadeh and Tackley, 2010). In particular, numerical studies performed in the 80s–90s mainly by using two-dimensional (2-D) model with continents/supercontinents are carefully reviewed in the textbook by Schubert et al. (2001). The relationship between the supercontinent and mantle convection processes is clarified in a review by Condie (2001) from the viewpoint of geology and geochronology. However, there have been very little attempts so far to link the geophysical numerical models and the geological and tectonic conceptual models to understand the history of plate tectonics, Wilson Cycle and supercontinent cycle. Furthermore, it is important to link these models with the actual surface geological records, and the quantitative geophysical data from various types of geophysical surveys. In the recent years, several numerical models of mantle convection have addressed the assembly and breakup of supercontinents using three-dimensional (3-D) models. This paper