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Role of random thermal perturbations in the magmatic segmentation of mid-oceanic ridges: Insights from numerical simulations

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ABSTRACT

Using a random thermal perturbation (RTP) model this study investigates the process of magmatic segmentation along mid-oceanic ridge (MOR) axes as a function of the upwelling dynamics, controlled by coupled solidification–melting processes. The RTP model suggests that the variation in along-axis velocity (V_L) fields constitutes the underlying mechanism of segmentation in natural MORs, showing temperature variations within a steady-state range, irrespective of large initial thermal perturbations imposed at the model base. The V_L patterns are initially transient, characterized by multi-order segments, but attain a stable configuration with dominantly large segments (average size ~100 km) within a time scale of 2.3 Ma. Buoyant-melt driven thermal convection explains this transient segmentation. Small scale convection cells are found to be progressively consumed by larger cells, resulting in a stable convection structure over a similar time scale. Slow- and fast-spreading ridges (SSR and FSR) undergo upwelling with contrasting melt flow patterns. SSRs involve melt feeding into the ridge axis by horizontal flows from segment centers, trailing into large-scale conduits at an early stage. With time, vertical upwelling occurs throughout the segment. In the case of FSRs, both melt supply avenues prevail throughout their development. We also evaluate the variation of the across-axis flow velocity (V_T) to investigate the mode of geometric evolution of MORs. Time series V_T maps suggest that a ridge structure develops through localization of discrete axes ($V_T = 0$) with offsets varying up to 15 km, which coalesce with one another to form a single axis. The matured ridge, however, retains higher-order offsets (up to 9 km).

1. Introduction

Mid-oceanic ridge (MOR) systems are one of the most spectacular planetary scale geodynamic manifestations on Earth's surface. The MOR axes are globally discontinuous along the ridge length, showing characteristic magmatic as well as structural segmentation. Despite a significant advancement of the plate tectonic theory over more than five decades, the mechanism of MOR segmentation is still controversial. A number of hypotheses are available in the literature, which diverge widely from one another, leading to no unanimous explanation for the segmentation processes. A group of researchers have argued that the mechanical interactions between active lithosphere segments and seafloor spreading produce fault-like offsets across the ridge axis, resulting in the structural segmentation of MORs (Choi et al., 2008; Gudmundsson, 1995; Wilson, 1965). These studies, however, do not provide any unique mechanism for the structural segmentation process. A parallel line of research is concerned with the origin of magmatic segmentation. It has been proposed that the dynamics of three-dimensional (3D) mantle upwelling can itself drive the process of magmatic segmentation along ridge-axes (Macdonald et al., 1988a). This view has gained much support from recent seismic tomographic evidences and numerical models simulating the mantle dynamics beneath MORs (Beutel et al., 2010; Dunn et al., 2005). Consequently, there has been a general agreement that understanding the process of MOR segmentation must involve the dynamics of mantle upwelling, which is largely governed by large-scale magma chambers localizing beneath the oceanic ridges. Geophysical investigations have reported low-velocity seismic zones (e.g. Detrick et al., 1987), suggesting potential mushy zones (melt admixed with crystals or solids) beneath the ridges. In the fast spreading East Pacific Rise (EPR), magma chambers occur as discrete lenses right beneath the ridge axis and adjoining regions, which are interpreted to be the tips of several large axial magma reservoirs (Sinton and Detrick, 1992). Ophiolite-based oceanic crust models show the occurrence of large magma chambers, in contrast to small chambers with high-degree of melting predicted from seismic and other geophysical evidences. Later deep drilling studies conducted along active spreading centers indicate a dynamic character of the mushy zones (Thy and Dilek, 2003). Seismic and gravity data suggest thinning of the oceanic crust near large scale offsets, and in some cases with small scale offsets of ridge-axes. This phenomenon has been interpreted to have resulted from an axial magma upwelling in mid-segment regions, with very small magma flows along the axis

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(Sinton et al., 1991). Seismic tomography in fact reveals localization of magma upwelling zones away from the active ridge axis (Toomey et al., 2007).

Seismic tomography, multi-beam bathymetry data as well as petrological and geochemical evidences are limited in order to predict an evolutionary model for the 3D structure of ridge-axes and its associated dynamic processes, such as magma upwelling. Experimental and theoretical modeling of the MOR mechanism has thus recently gained its wide acceptance as an effective alternative approach. Analog models have been used extensively, utilizing mainly wax of different variety (Katz et al., 2005; O'bryan et al., 1975; Oldenburg and Brune, 1975; Ragnarsson et al., 1996) and other materials, such as sand–silicone (Dauteuil et al., 2002), sand–PDMS (Marques et al., 2007), and silicone (Tentler and Acocell, 2010). Unfortunately, these analog experiments did not couple the process of magmatic upwelling with the segmentation mechanism. A wide range of numerical models have been employed to account for the magmatic processes (Behn et al., 2004; Katz, 2008; Mittelstaedt et al., 2008; Phipps Morgan, 1987; Scott and Stevenson, 1989; Shen and Forsyth, 1992), emphasizing mainly on the lithospheric interactions and spreading. Some workers dealt with the development of MORs, but mostly as a crustal phenomenon (Choi et al., 2008; Hieronymus, 2004). In contrast, a number of numerical models account for the mantle processes, despite several limitations, such as exclusion of a spatial dimension (Behn et al., 2004; Katz, 2010; Mittelstaedt et al., 2008), structural perturbation (Gerya, 2010), presumption of magma focus (Magde and Sparks, 1997), and imposition of ridge offsets and segmentation on magma processes (Gregg et al., 2009). It follows from the preceding lines that the magmatic segmentation along ridge-axes has never been modeled as a spontaneous geodynamic process in the framework of complex 3D thermo-mechanical upwelling.

In this study we develop a fluid-based 3D, thermo-mechanical model to simulate spontaneous magmatic processes, and explore the mode of evolution of large-scale MOR geometries. This model involves thermal perturbations at a deeper (28 km) level with a mathematically defined randomness factor, which drives the coupled solidification–melting process and form magma upwelling patterns, as reported in the current literature. For example, Ganguly (2005) has shown from a thermodynamic analysis that the mantle upwelling can involve either increasing or decreasing temperatures depending upon their density contrast. Our model simulations indicate that the random thermal perturbations (RTP) can be a potential mechanism of magmatic segmentation occurring globally along MORs. Using the same RTP model we provide a detailed account of the spatial and temporal variations of thermal convection patterns associated with the upwelling process beneath ridge axes. The mechanics of ridge offsetting is a long standing, unresolved issue, which has been discussed at length. From our RTP model we show structural ridge offsetting as a complementary process coupled with the magmatic segmentation.

2. Model description

2.1. Initial setup

The modeling has been implemented within a framework of computational fluid dynamics (CFD) using the commercial finite volume code of Fluent® (Fluent, 2009). Our computational models are designed as a 150 km × 500 km × 28 km thermo-mechanical box (Fig. 1) with a characteristic fluid environment, subjected to a condition of temperature-dependent solidification. We have chosen the ridge along the box length (500 km), where its height (28 km) covered the uppermost mantle with the crustal layer at the top. The crustal part has been modeled mechanically as a high-viscosity layer with a thickness of 4 km at the ridge, varying linearly to 8 km at a distance of 75 km away from the ridge axis (White et al., 1992). The model has a rectangular belt (30 km × 500 km) at the base right below the MOR line, considering magma eruption at randomly distributed points, termed henceforth as *magma points*.

At the model base the rectangular inlet area (covering a width of 15 km on either side of the central axis of the model) contains magma

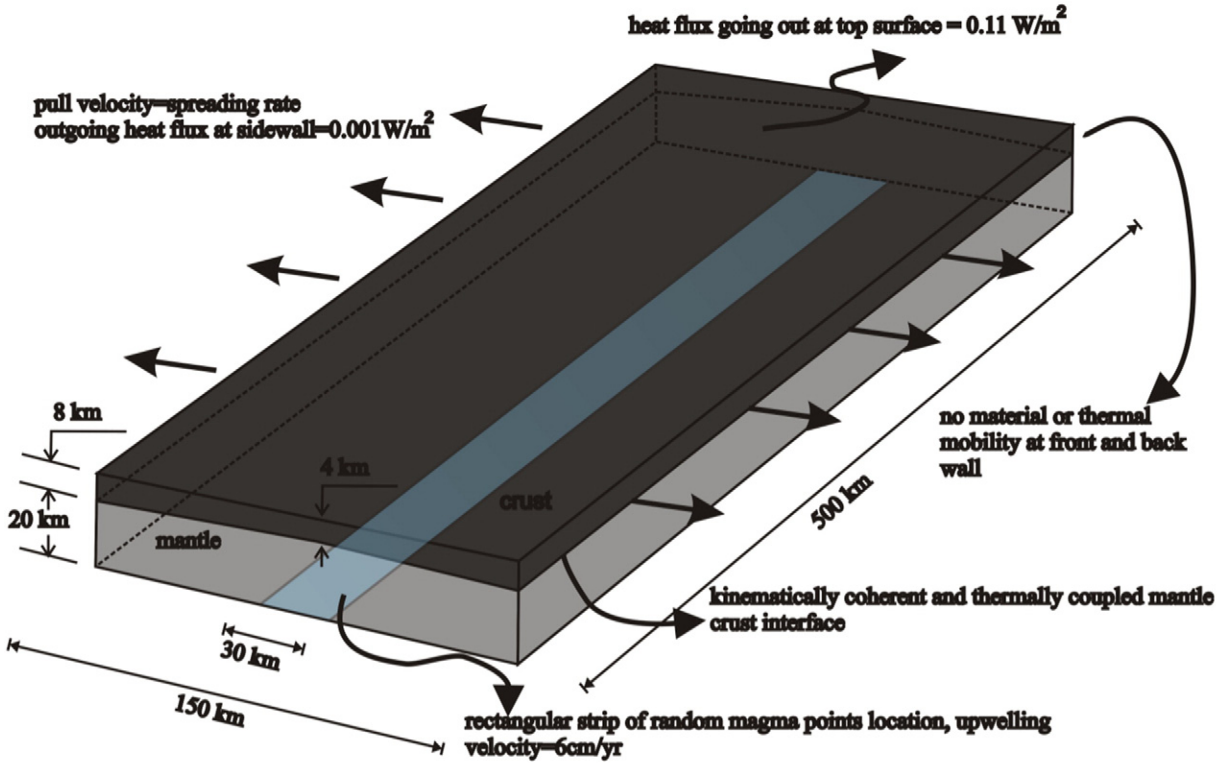

Fig. 1. Schematic presentation of the initial model setup used for simulation experiments. The computational model has a cell resolution of 1 km. Each of the 165 transient models has been simulated for 8 Ma in average computer time of 72 h in quad core workstations, utilizing pressure based Fluent® solver and adaptive time stepping (Fluent, 2009).