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Numerical modeling of the formation and migration of mid-ocean ridges

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Abstract Summary

The planet Earth is unique in the solar system in terms of its geodynamic regime of plate tectonics, in which the Earth's surface is divided into a set of lithospheric plates that move over geological time. An important aspect of this regime is the continuous formation of oceanic plates at mid-ocean ridges — a complex process that involves understanding the behavior of crustal and mantle rocks during magmatic and tectonic processes. The objective of this project is to evaluate how thermal, rheological, and kinematic factors influence the formation of oceanic lithosphere, potentially contributing to the maintenance of the mid-ocean ridge or its abrupt migration to adjacent regions - a phenomenon known as ridge jump. To this end, the software Mandyoc will be used, which simulates the thermo-mechanical evolution of the Earth's crust and mantle over geological time in different geodynamic contexts, allowing the exploration of magmatic phenomena. The numerical results will be compared with natural examples where evidence of ridge jump has been proposed to explain the seafloor evolution pattern.

Introduction

Mid-ocean ridges, such as the Mid-Atlantic Ridge, represent divergent plate boundaries where oceanic lithospheric plates are continuously formed. The plates on either side move in opposite directions, drifting away from the ridge at a rate of a few centimeters per year. The divergent motion of the plates induces upward movement of the mantle beneath the mid-ocean ridge, which, due to a decrease in lithostatic pressure, leads to partial melting of the mantle and consequent magmatism that forms the oceanic crust (Figure 1). Thus, mid-ocean ridges are the sites of the most intense magmatic production on Earth.

Symmetrical patterns relative to the mid-ocean ridge in heat flow, bathymetry, and magnetic anomalies in the oceanic crust indicate that ridges can remain stable over geological time, staying active for tens of millions of years and forming thousands of kilometers of oceanic crust Wessel and Müller (2007). However, in some limited segments of the ocean floor, there is evidence that abrupt migrations of the mid-ocean ridge have occurred, resulting in an abandoned ridge and the formation of a new ridge tens to hundreds of kilometers from the original location — a phenomenon known as a ridge jump.

A possible mechanism behind ridge jumps involves the interaction between mid-ocean ridges and mantle plumes Mittelstaedt et al. (2011). Examples of such ridge jumps have been documented in the Galápagos and Iceland LaFemina et al. (2005); Mammerickx and Sandwell (1986). In the South Atlantic, a bathymetric feature more than 750 km long and 30 km wide, known as the Vema Channel, has an unknown origin, and recent studies suggest that a ridge jump episode during the opening of the South Atlantic created this feature Constantino et al. (2019); Pérez-Díaz and Eagles (2014).

Understanding the interaction between mid-ocean ridges and mantle plumes, and the role of oceanic spreading rates in the occurrence of ridge jumps, remains an open question, especially

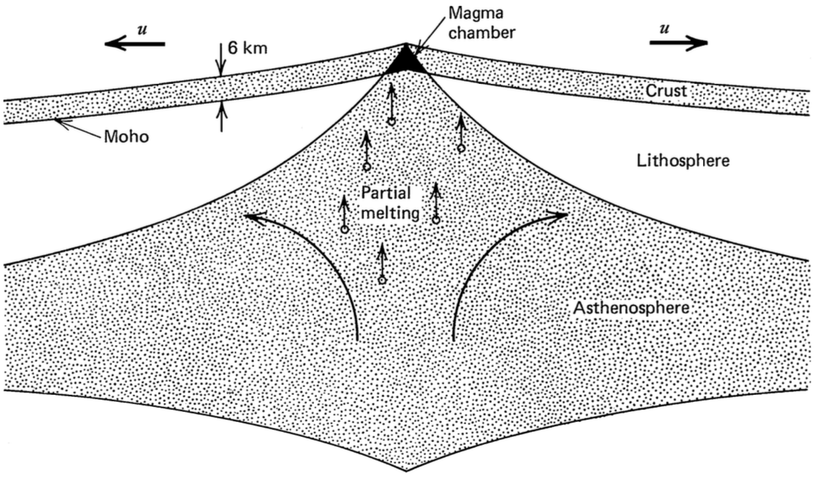

Figure 1: Diagram illustrating the divergent movement of two oceanic lithospheric plates and the upward motion of the asthenospheric mantle, resulting in partial mantle melting and consequent magmatism forming the oceanic crust. Figure adapted from Turcotte and Schubert (2002).

when considering nonlinear rheologies that combine viscoplastic factors and better represent the behavior of the Earth's lithosphere over geological time.

Due to the mathematical complexity involved in studying the various factors that can affect the evolution of mid-ocean ridges — mainly because of the stark differences in rheological behavior between the rigid lithosphere and the more ductile asthenospheric mantle — computational modeling represents a natural approach to this problem.

This project aims to numerically study the formation and evolution of mid-ocean ridges through thermomechanical numerical scenarios that adequately reproduce the rheological behavior of the Earth's crust and mantle in situations where the numerical domain is continuously stretched, mimicking the divergent motion of lithospheric plates.

To achieve this, the Mandyoc software will be used, which is developed and maintained by the Computational Geodynamics Group of the Department of Geophysics at the Institute of Astronomy, Geophysics, and Atmospheric Sciences at the University of São Paulo (USP).

Method and Theory

To simulate the formation and evolution of mid-ocean ridges, this project will use the software Mantle Dynamics Simulator Code - Mandyoc Sacek et al. (2022).

To simulate crustal and mantle dynamics, a non-Newtonian fluid formulation with the Boussinesq approximation is adopted Zhong et al. (2007), solving the following equations for the conservation of mass, momentum, and energy, respectively:

$$u_{i,i} = 0 \tag{1}$$

$$\sigma_{ij,j} + g\rho\delta_{i3} = 0 \tag{2}$$

$$\frac{\partial T}{\partial t} + u_i T_{,i} = \kappa T_{,ii} + H/c_p - \alpha T g u_3/c_p \tag{3}$$

with

$$\rho = \rho_0 \left(1 - \alpha(T - T_0)\right) \tag{4}$$

$$\sigma_{ij} = -P\delta_{ij} + \eta(u_{i,j} + u_{j,i}) \tag{5}$$

where t is time, u_i is the i-th component of velocity, g is the gravitational acceleration, ρ_0 is a reference density, α is the volumetric thermal expansion coefficient, T is temperature, κ is thermal diffusivity, H is radiogenic heat production per unit mass, P is pressure, c_p is specific heat, η is the effective viscosity of the rock, and δ_{ij} is the Kronecker delta. In this notation, repeated indices represent summation and $T_{,i}$ is the partial derivative of T with respect to the coordinate x_i.

In equation 3, the three terms on the right-hand side represent, respectively, the thermal diffusion component, radiogenic heat production, and adiabatic heating.

In the present visco-plastic model, the effective viscosity η follows the formulation described by Moresi and Solomatov (1998), combining viscous rheology with plastic deformation. In this work, the Drucker-Prager yield criterion is adopted for the yield stress (plastic rheology):

$$\sigma_{yield} = c_0 \cdot \cos\phi + P \cdot \phi \tag{6}$$

where ϕ and c_0 are the internal friction angle and cohesion of the rock, respectively. The non-linear effective viscosity for plastic deformation is given by the following expression Moresi and Solomatov (1998):

$$\eta_{plast} = \frac{\sigma_{yield}}{2\dot{\epsilon}_{II}} \tag{7}$$

where $\dot{\epsilon}_{II}$ is the second invariant of the deviatoric strain rate tensor:

$$\dot{\epsilon}_{II} = \left(\frac{\dot{\epsilon}_{ij}\dot{\epsilon}_{ij}}{2}\right)^{1/2} \tag{8}$$

The effective viscosity η, present in equation 5, is then calculated as the minimum between η_{plast} and the viscous drag component η_{visc}:

$$\eta = \min(\eta_{plast}, \eta_{visc}). \tag{9}$$

where

$$\eta_{visc} = C \cdot A^{-1/n} \cdot \dot{\varepsilon_{II}}^{\frac{1-n}{2n}} \cdot \exp\left(\frac{Q + V \cdot P}{nRT}\right) \tag{10}$$

represents the ductile flow component.

A is the pre-exponential factor, n is the power-law exponent, Q is the activation energy, V is the activation volume, P is pressure, T is temperature, and R is the universal gas constant.

Equations 1-2 are solved numerically using the finite element method Zhong et al. (2007) on a 3D mesh with hexahedral Q_1P_0 elements or on a 2D mesh using quadrilateral Q_1P_0 elements Hughes (2012). Equation 3 is also solved on the same finite element mesh using the implicit formulation presented by Braun (2003).

For the numerical simulation (Figure 2), the user initially specifies the initial and boundary conditions for temperature T and velocity u, along with the reference density field ρ_0, radiogenic heat production H, and other physical properties of each lithology. At each time step, η_{visc} and η_{plast} are calculated. Then, the effective viscosity η is determined. Given the effective viscosity field, the Uzawa method Zhong et al. (2007) is used for the iterative solution of the mass and momentum conservation equations, obtaining updated fields for u and P. The updated velocity field modifies the effective viscosity η, which in turn perturbs the velocity field u again.

The code is capable of simulating complex rheological behavior, accounting for different tectonic pulses, such as the formation of divergent and convergent margins, allowing for simulation of the

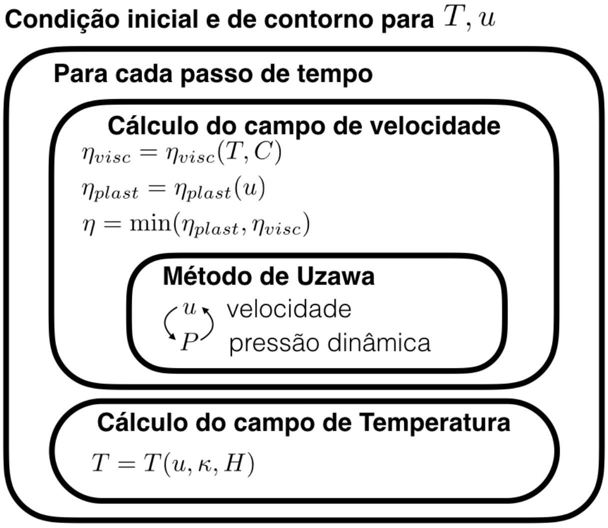

Figure 2: Flowchart for the numerical solution of the equations related to the conservation of mass, momentum, and energy.

non-linear deformation behavior of the Earth's mantle and crust. In the numerical simulations of the present project, we also aim to explore numerical scenarios using rheologies with parameters derived from experimental data Gleason and Tullis (1995); Karato and Wu (1993), an aspect not explored in the models of Moresi and Solomatov (1998).

Results

Although we do not yet have a large set of results at this stage of the project, ongoing simulations (Figure 3) are actively being conducted and preliminary analyses are already showing promising behavior of the implemented rheological models. We expect to obtain a comprehensive set of results well before the conference date in November, which will allow us to present detailed insights into the formation and evolution of mid-ocean ridges under different tectonic and rheological scenarios.

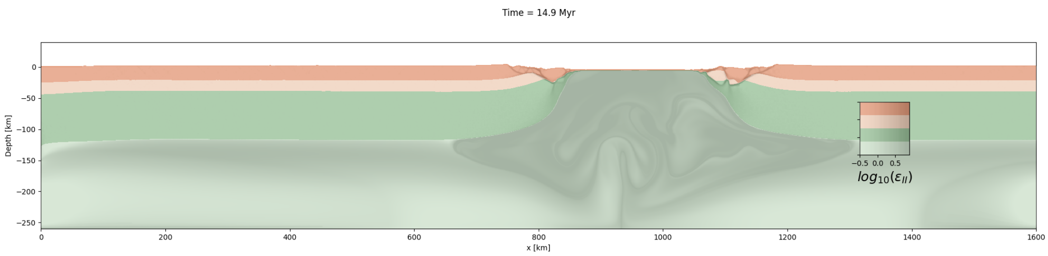

Figure 3: Numerical simulation result at 14.9 Myr, showing the formation of oceanic lithosphere at a mid-ocean ridge. In the central part of the model, a plume-like upwelling of asthenospheric mantle induces partial melting and crustal accretion.

Conclusions

In this work, we presented the numerical framework and methodology for simulating the formation and evolution of mid-ocean ridges using the Mandyoc software. The visco-plastic rheological formulation adopted allows for realistic modeling of lithospheric and mantle behavior under divergent tectonic settings. While comprehensive results are still under development, the current modeling approach (Figure 4) has demonstrated consistency with geological processes such as magmatism, thermal diffusion, and lithospheric deformation. Future simulations will focus on exploring the influence of variable spreading rates and plume-ridge interactions, with a complete set of results expected to be available for presentation at the upcoming conference in November.

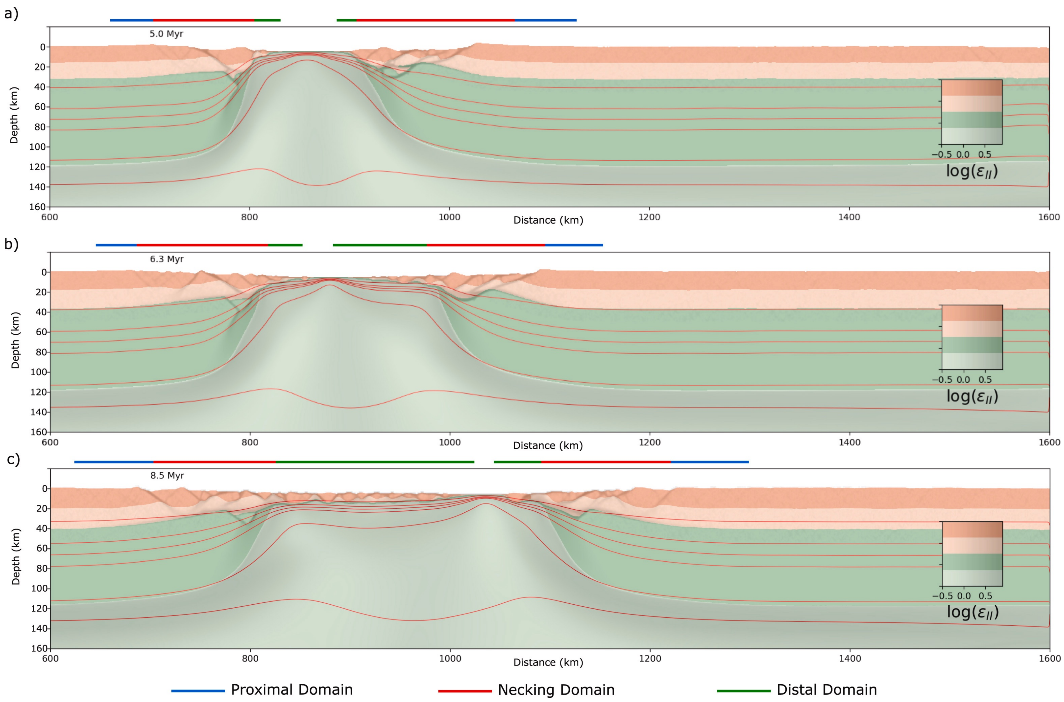

Figure 4: Example of numerical scenarios illustrating the final configuration of divergent continental margins, showing the margin architecture and the formation of a mid-ocean ridge where isotherms in the mantle shift toward the surface. Figure adapted from dos Santos Souza et al. (2025).

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