Magma chamber formation by periodic dyke intrusions into the Earth's crust

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Abstract

We present a model of magma bodies formation by injection of hot rhyolitic magmatic dikes leading to their incremental accumulation into the plutons and magma chambers in the upper and middle crust. Our 2D model simulates random or organized dike injection into a selected rock volume, calculation of magma and rock displacement based on analytical solution of an elastic problem of elliptical cavity expansion, a realistic melt phase diagrams for country rock and magma. Lagrangian particle transport is calculated in order to reduce numerical dissipation and avoid unphysical mixing. Thermal histories in individual batches of magma and country rocks are recorded. We further combine this model with Bindeman and Melnik (2016) zircon crystallization/dissolution software and compute zircon survival histories in each Lagrangian particle.

The model predicts shapes of realistic T-t histories, zircon age distribution in different portions within a progressively growing reservoir and generates output to estimate crustal vs mantle contributions (e.g. Hf and O isotopes in zircons).

Simulations reveal that the rate of melt production is highly variable in space and time, eruptible magma batches form in clusters, period of initial magmatic incubation is followed by crustal rock melting and formation of a large volume of eruptible magma with high melt fraction.

Zircon survival and host rock eruptibility depends on magma injection duration. After 700 y only ~2 vol % of molten rock can be erupted, but due to slow dissolution most of zircon crystal are preserved. After 1500 years eruptible rock amount reaches 8% but significant number of zircons looses their age information.

Introduction

The main mechanism of magma transport in the Earth's crust is the formation of cracks (dykes) along which magma rises to the surface**?** . Basaltic magmas typically rise from depths of several tens of kilometers {REF}, for kimberlite magmas - up to 150-200 km [**?**]. Dyke widths can vary from centimeters to tens of meters, horizontal extend - from meters to kilometers. Magmaa ascent in dykes is controlled by the buoyancy forces and the tectonic stress field. Most dikes do not reach the surface, but are blocked at the level of neutral buoyancy [4], or with structural barriers in the form of stronger rock layers. As a result of repeated introduction of dikes into the near-surface (first kilometers) region of the earth's crust, it melts with the formation of magma foci, which can reach thousands of cubic kilometers, although usually the volume of foci is much smaller (kilometers-tens of kilometers). Foci of magmatic melt are recorded by seismic tomography using shear wave attenuation. They may have an irregular shape, but most often appear to be flattened bodies with vertical or horizontal strike. Under active volcanoes there can be several foci located at different depths [5].

The formation of magma chambers is simulated both on global geodynamic models [6] and in more detailed local models, where penetration and heat transfer between individual dykes and host rocks are considered [7, 8]. Models of the first type consider regions with a characteristic size of tens of kilometers and a grid spacing of several hundred meters. They cannot resolve the subtle heat exchange processes that occur during the real transport of individual portions of magma, but they allow one to estimate the size and position of magma chambers based on the global distribution of temperatures, rheological properties of rocks and stresses, as well as the consumption of magma between individual chambers.

In the models of the second type, the region into which magma is introduced, as well as the consumption of the latter, is set in advance based on the geological structure of the rocks and estimates of the time of formation of magmatic bodies. An example of the reconstruction of a real magmatic system is [9]. The model assumes horizontal introduction of dikes with lowering the underlying rock layer to the width of the dike. The heat equation is solved taking into account the heat of fusion of the rocks and the real temperature dependence of the concentration of crystals. An explicit scheme for solving the heat equation is used, which imposes a significant limitation on the time step.

In the model [8], the introduction of dikes can occur in an arbitrary direction. To determine the field of displacements, the rocks are considered a viscous fluid and the Navier-Stokes equation is solved. This approach is not justified for low temperatures, at which the behavior of the rocks is described by the relations of the theory of elasticity. In [10], the introduction of dikes is considered vertical. Rock movement is determined solely by kinematic relationships.

Mathematical model

Injection of individual dike leads to displacement of elastic host rocks, heat transfer, rock melting and magma solidification. We model individual dike as an ellipsoid with semi-axes a and b and use analytical solution **?** in order to calculate host rock displacement. Volume of the individual dike and frequency of emplacement is controlled by the specified feeding rate of the magma Q_{in} (km^3/y). We assume that the emplacement occurs in 2D plain geometry and the third spacial dimension is specified and constant. This situation is possible in the extensional tectonic environment, where the local stress field leads to preferentially parallel dyke orientation. We allow random anglo of an individual dike emplacement or change in the dike orientation from vertical at depth to horizontal near the surface.

$$\rho C\left(\frac{\partial T}{\partial t}+\vec{V}grad\left(T\right)\right)=div\left(k\,grad\left(T\right)\right)+\rho L\frac{d\beta}{dt}$$

$$\partial\alpha\frac{}{\partial t+\vec{V}grad(\alpha)=0}$$

$$\rho C=\rho_r C_r\left(1-\alpha\right)+\rho_m C_m\alpha$$

$$\mathrm{k}=\mathrm{k}_r\left(1-\alpha\right)+k_m\alpha$$

$$\beta_r=\beta_r\left(T\right),\ \beta_m=\beta_m\left(T\right).(1)$$

Rock-magma temperature evolution T is governed by heat conduction equation (**??**) that accounts (**??**) for advection due to rock displacement, latent heat of crystallization and heat conduction. Melt fraction depends on temperature according to Annen et al 2006. Injection rate is 0.015 km3/y (0.5 m3/s), initial magma temperature is 950 °C, typical for an island arc system. In order to minimize numerical diffusion PIC/FLIP hybrid method which mixes the perspectives of solving the system from a particle point of view (Lagrangian) and solving the system from a grid point of view (Eulerian) is used. Particle displacement is calculated after each individual dike injection, while heat conduction is solved on a fixed grid.

Acknowledgements

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