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Russian Geology and Geophysics 58 (2017) 1317–1332

RUSSIAN GEOLOGY AND GEOPHYSICS

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Numerical modeling of the mechanisms of magma mingling and mixing: A case study of the formation of complex intrusions

A.N. Semenov [a,b,*], O.P. Polyansky [a]

[a] *V.S. Sobolev Institute of Geology and Mineralogy, Siberian Branch of the Russian Academy of Sciences, pr. Akademika Koptyuga 3, Novosibirsk, 630090, Russia*

[b] *S.A. Khristianovich Institute of Theoretical and Applied Mechanics, Russian Academy of Sciences, ul. Institutskaya 4/1, Novosibirsk, 630090, Russia*

Received 28 June 2016; received in revised form 27 December 2016; accepted 30 March 2017

Abstract

This paper describes a thermomechanical mathematical model of magma mingling and mixing during the formation of complex intrusions and presents the first results of numerical modeling. The model considers one-pulse intrusion of mafic or intermediate melts into a granitoid magma chamber. The model is based on literature data on the composition and structure of two polychronous intrusions: the Burgas quartz syenite massif and the Magadan granitoid batholith. The modeling shows that the main parameter controlling the convection regime is the density difference. The density and viscosity contrasts of interacting magmas during mingling and mixing are estimated. Depending on the density difference, one of the possible processes dominates: In the case of a small difference (less than 30–40 kg/m^3), magma mixing and hybridization in a small contact zone takes place; in the case of a large difference (100 kg/m^3 or more), magma mingling predominates. The viscosity contrast, in turn, determines whether interpenetration of melts or fragmentation of melts in the form of drops, spheres, etc. occurs. There is a limiting viscosity of salic magma (10^8 Pa·s) at which the flows freeze in the chamber and further cooling occurs with a slowly moving fluid. The time of formation of mingling structures is estimated to be several days to several hundred years, depending on the initial melt viscosity.

Keywords: magma mingling; mixing; convection; melt; viscosity; crystallization; numerical modeling; intrusion; dike

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Introduction

Numerous complex intrusions are known among the polychronous massifs of Central Asia. A common feature of these intrusions is the presence of net-veined structures containing salic, mafic, and hybrid (intermediate in composition) magmatic phases. Natural examples of complex composition are the quartz syenite Burgas and Ust'-Khilok massifs, western Transbaikalia (Burmakina and Tsygankov, 2013; Litvinovskii et al., 1993, 1995), the Tastau igneous complex, eastern Kazakhstan (Dokukina et al., 2010), the Erzin gabbro-monzodiorite massif, Sangilen (Karmysheva et al., 2015, 2017; Polyansky et al., 2017; Vladimirov et al., 2005), and the Magadan gabbro-granite batholith (Ponomareva et al., 1994).

Mafic enclaves in granitoids are widely distributed in many gabbro-granite series. They are considered as xenoliths of host rocks or earlier intrusion phases (Izokh et al., 1957), segregations of early crystallization phases (Fershtater and Borodina, 1975), refractory restites (Wiebe, 1973) or products of mafic magmas intruded into more acidic melts (Ermolov et al., 1977; Wager and Bailey, 1953). Evidence in favor of the latter point of view has been found, in particular, for the Magadan batholith (Andreeva et al., 1999; Ponomareva et al., 1994) and the Burgas batholith (Burmakina and Tsygankov, 2013). For the aforementioned massifs, there is detailed petrological, structural, and geochronological information; however, the physicochemical and mechanical processes of magma interaction during the formation of complex intrusions are often described only qualitatively. Quantitative evaluation of the parameters of formation of complex intrusions requires developing consistent thermal convection models taking into account the contrasting physicochemical properties of mafic and granitic magmas and hybridization products (Bohrson et al., 2014; Spera et al., 2016). To this end, we have developed a numerical model of the convective flow of a multiphase medium composed of salic and mafic melts.

Geological observations (Frost and Mahood, 1987) and experimental data (Veksler and Charlier, 2015) have shown

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[*] Corresponding author.

E-mail address: semenov@itam.nsc.ru (A.N. Semenov)

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http://dx.doi.org/10.1016/j.rgg.2017.11.001

that subliquidus silicate melts may be immiscible due to significant differences in the thermodynamic properties of the extreme members. According to (Spera et al., 2016), melts with contrasting compositions and rheological properties interact by two mechanisms: magma mingling and magma mixing. The difference between them is as follows. Magma mingling results in a heterogeneous mixture containing separate portions of the initial melts; the derivative magma contains discrete fragments of melts of different composition. Mixing, in contrast to mingling, is thermodynamic equilibration of two or more compositionally different initial melts to form a chemically and physically homogeneous mixture under conditions where the viscosities of the initial components are similar and low (Frost and Mahood, 1987).

The magma mixing/mingling efficiency depends on several factors, including the chemical composition, density, viscosity, temperature, crystallization temperature, and degree of crystallization of each component. The viscosity of each of the phases and their difference (contrast) are important parameters, but the question of their relationship still remains unresolved (Perugini and Poli, 2005). According to one view, the rheological characteristics of interacting magmas are determined by the large difference in viscosity between hydrous granitic melt and dry basaltic melt (Sklyarov and Fedorov, 2006). On the other hand, according to (Weidendorfer et al., 2014), mixing of two magmas is possible if the effective viscosities of the hydrous melt + crystal mixtures are very close.

The pioneering paper dealing with the generation of granitic magmas due to the intrusion of mafic rocks into the continental crust was perhaps that by Huppert and Sparks (1988), where the authors describe the interaction of magmas by simultaneous melting of the roof, fractional crystallization, and precipitation of crystals in the chamber. This paper and the paper Martin and Nokes (1989) were the first to analytically describe the interaction of two phases: convecting magma and precipitating solid crystals. These studies have shown that the fluid dynamics in magma chambers is determined by changes in magma density due to variations in temperature, material composition, and degree of crystallization. It has been found that the buoyancy of magma is influenced (in order of importance) by temperature changes, changes in magma composition during degassing and crystallization, and melting/crystallization phase transitions. The effect of temperature on the melt density occurs through heat transfer to the surrounding rock and the release of the latent heat of crystallization. The composition change during crystallization increases the buoyancy of the residual melt due to the removal of heavy components from the system and reduces the buoyancy of melts upon loss of volatiles during decompression.

Starting from these works, models describing the interaction between the melt and crystallizing phases have become progressively more complicated from conductive models using analytical methods of description to models of thermochemical multiphase convection based on numerical methods. Models describing the material zoning of magma reservoirs have been developed in a number of works in which the phases are determined by the mineral or chemical composition. Gutierrez and Parada (2010) reconstructed the evolution of the material composition during cooling in stock- and sill-like magma chambers by 2D thermohydrodynamic and mass-balance modeling. The results show how mineral phases in a 2D chamber cross-section are redistributed at different stages of the evolution of the multiphase medium. It is found that convective dynamics is characterized by three different types of flows during cooling of the chamber: (1) flows in convective cells, (2) mass transfer in the form of plumes, and (3) flows in the boundary layers along the chamber walls. As shown by the modeling, the silica content and the magnesium number of magma have a continuous zonal distribution without any inhomogeneities characteristic of magma mingling processes.

Simakin and Bindeman (2012) have modeled the eutectic melting of the roof of a volcanic caldera (phase 1) with repeated intrusion of superheated rhyolitic melt (phase 2). Melting is examined using the melting diagram of the Ab–Qz–Qr system in the feldspar–quartz pseudobinary section. In this approach, the differentiation and contamination of the intruded melt is determined from the change in the SiO_2 content. The modeling results suggest the following conclusions: (1) convection leads to mixing of the material and temperature anomalies; (2) descending plumes initiate convection currents within the near-roof layer; melting is accompanied by erosion of the roof, i.e., separation of fragments of the roof material and their involvement in the assimilation process; (3) the convective regime is slightly influenced by variations in the magma composition (SiO_2 content), but the degree of crystallization in different parts of the chamber is a more important factor. Maximum crystallinity is observed in the tops of descending plumes and reduces up to complete dissolution in the central part of the magma chamber.

In the papers cited above and in reviews of current approaches to modeling the evolution of magma chambers (Bohrson et al., 2014; Spera et al., 2016), there are no models describing magma mingling and mixing processes. To switch from qualitative to quantitative characteristics of magmas, it is necessary to use numerical models that take into account experimental dependences of properties on temperature, pressure, composition, and volatile content.

The purpose of this study was to develop a model for the interaction of two or more types of melts assuming the presence of two or more fluids in the magmatic source. The study had the following objectives: (1) to model the mechanism of interaction of melts of contrasting compositions, leading to the formation of rocks with a magma mingling structure; (2) to determine the ranges of melt rheological parameters such as viscosity and density contrasts and volumetric ratios at which mingling and mixing processes occur in nature; (3) to propose a mechanism for the ascent of mafic enclaves surrounded by less dense salic magma in an intrusive chamber.