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The mechanism of magma ascent through the solid lithosphere and relation between mantle and crustal diapirism: numerical modeling and natural examples

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Abstract

Diapirism can be regarded as the main mechanism of transport through the lithosphere for both felsic and mafic/ultramafic magmas. However, the lack of field observations makes it difficult to identify the key mechanism responsible for the formation of dome-shaped structures. In this study, emplacement of natural diapirs is reconstructed by numerical experiments handling realistic rheological and petrological models for the crust and mantle lithosphere. Three different regimes of diapiric ascent were established depending on the chosen model rheology: (1) single-stage diapir ascent; (2) pulsating ascent of successive batches of mantle-derived magma to the base of the crust with a periodicity of 2–3 Myr; (3) emplacement of extensive magma bodies in the form of sills either beneath the base of the crust (underplating) or to deeper mantle levels. The timescale of 30 Myr for a heat source at the base of the lithosphere is sufficient to initiate the ascent of a diapir through the mantle and crust. The study provides the estimates of rheological properties of the lithosphere and partially molten material at which diapiric ascent through the mantle and crust can occur.

Keywords: diapirs; magma; lithosphere; viscosity; rheology; numerical modeling; continental crust; melting; intrusion

Introduction

Magmatic diapirs are widespread in many of the world's granite-greenstone belts of the Precambrian cratons and are thought to reflect higher than average heat flow in the Precambrian and the ability of ancient crust to undergo plastic deformations. It was recently shown that diapiric structures not only represent essential elements of ancient cratons, but are also developed in younger structures of collision and suprasubduction zones. The classic granitoid diapirs with flanking metabasites and schists were identified in the Archean (3.4–3.3 Ga) Pilbara Craton of Australia (Van Kranendonk et al., 2004) and 2.5 Ga Dharwar Craton of India (Choukroune et al., 1997). These structures define dome-and-basin geometries and are interpreted as the buoyant rise of low-density granitic mass and a complementary sinking of the overlying higher-density supracrustal metabasites and metasedimentary rocks. Other ancient structures developed in collisional or platform settings include the 1.84–1.77 Ga granite-gneiss domes of the Ladoga area (Mints et al., 1996), 1.2–1.0 Ga granite-gneiss domes of the Yenisei Ridge (Nozhkin et al., 1999), and 542 ± 6 Ma granitic diapirs of the Damara orogenic belt, Southwest Africa (Toé et al., 2013).

The mechanism of ascent of granitic magmas remains controversial. According to the review of Brown (2013), transport through fractures (dikes) or conduits in shear zones is the most commonly postulated mechanism. Although discredited in the previous publications (e.g., Petford, 1996), the viability of diapiric ascent of granitoid magmas through the crust under the right circumstances has been demonstrated by Weinberg and Podladchikov (1994), Bittner and Schmeling (1995), and Burov et al. (2003). In addition to theoretical modeling, distinctive features of granitoids diapirism have been studied in detail in many recent papers using a series of natural examples (He et al., 2009; Little et al., 2011; Norlander et al., 2002; Toé et al., 2013; Vanderhaeghe, 2004). In these papers, geologic, structural, microstructural, thermochrono-

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logic, and thermobarometric data were combined to justify diapirism as a viable mechanism of the dome development.

Crustal diapirs have been studied in much more detail than mantle diapirs. This difference in the knowledge of crustal and mantle diapirs can be explained by insufficient erosion of the continental crust and buoyancy of mafic/ultramafic magmas with respect to felsic magmas. For these reasons, only rare examples of buoyant mantle diapiric structures have been reported to date from axial parts of rifting zones. They are usually composed of a core of mantle lherzolite surrounded by lower crustal rocks, as is the case with the metamorphic complex of Zabargad Island, Red Sea rift (Sklyarov et al., 2001). There are some examples showing that the ultramafic magma may reflect melting of an ascending thermochemical diapir beneath the base of the crust (Seiland Igneous Complex, Scandinavian Caledonides (Griffin et al., 2013)).

The mechanism of formation of crustal granite-gneiss diapirs for thermoelastic-viscoplastic rheologies was described in previous works (Polyansky et al., 2009, 2010). The same approach was used to study diapiric ascent of ultramafic/mafic magmas through the lithospheric mantle (Polyansky et al., 2012, 2014). The objective of this paper is to explore further the possibility of modeling mantle diapirism—magmatic underplating—crustal diapirism as sequential processes. However, the remaining problem is to prove the possibility and evaluate the parameters for sequential ascent of diapirs through mantle and crust. A similar model for sequential stages of diapir ascent was first calculated by Weinberg and Podladchikov (1994) using the Hadamard–Rybczynski equation for the velocity of viscous spherical drops rising through Newtonian ambient fluids. The analytical approach alone is insufficient to calculate the ascent time, depth and shapes of the rising magmatic bodies. The capability of 2D numerical simulation in MSC.MARC (2012) software package allows calculations using the temperature-dependent nonlinear rheology of rocks and an arbitrary (unknown) shape of the rising bodies. This numerical method was used in the present study to answer the following questions:

1. What is the mechanism that allows the diapiric ascent of partially molten material through a superviscous but deformable lithosphere?

2. What will be the duration of action of a sublithospheric heat source to ensure thermal softening and ascent of magma through the cratonic lithosphere and what will be the time interval between the occurrence of bimodal mantle (mafic) and crustal (felsic) magmatism?

3. What degree of melting of lithospheric mantle and crust would be responsible for generating partially molten masses that can effectively rise as diapirs through mantle and crust?

4. What are the physical processes that govern interaction between rising mantle diapirs and the crust: thermomechanical erosion and thinning or magma underplating and subsequent crustal melting? In the case of crustal melting, under what conditions secondary (crustal) diapirism is likely?

Geological objects

Each particular dome has been attributed to various mechanisms because geological observations do not provide an answer to the question of what was the governing process. Among possible mechanisms in producing dome-shaped (drop-like) structures are:

(1) diapirism first proposed by Eskola (1949) was thought to be driven by inversion of the rocks densitites with depth due to partial melting or reactions involving an increase in the specific volume;

(2) the mechanism that combines ballooning and intrusion of granitic magmas into country rocks, i.e., what Pitcher and Berger (1972) called piercement diapir with respect to the Ardara pluton in Ireland;

(3) isostatic unloading due to tectonic extension and unroofing leading to the formation of metamorphic core complexes (Buck, 1991; Rey et al., 2009; Sklyarov, 2006).

A realistic model for diapir formation would require data on the structure, composition, thermophysical properties and the timing of formation of natural structures. Data on particular structures provided in this section are based on the literature and the results of our own studies.

Examples of mantle diapirs. As noted above, because mantle diapirs are inaccessible to direct observation, their effect is determined from indirect evidence. The Vilyui Igneous Province in the eastern part of the Siberian platform is an example of a mantle diapir (superplume) (Kuzmin et al., 2010). It is assumed that a superplume rising under the Vilyui rift in the Middle Paleozoic may have transported significant amounts of molten material to the base of the lithosphere, which was in part (320 thousand km^3) extruded to the surface or intruded into the sedimentary successions (Kiselev et al., 2014). Indirect evidence of the existence of a mantle diapir beneath the Vilyui province comes from plutons of alkaline-ultramafic rocks, flood basalt eruptions at 380–350 Ma, formation of rift zones and mafic dike belts (Kuzmin et al., 2010; Polyansky et al., 2013).

The formation of ultramafic plutons making up the Caledonian Seiland complex of Norway was explained by Griffin et al. (2013) using a model of multistage melting and ascent of a lherzolite thermochemical plume similar to that proposed by Dobretsov (2010), Kirdyashkin and Kirdyashkin (2013). It was suggested that when the lherzolite diapir rising from a transition zone 200–250 °C hotter than the mantle adiabat impinges on the base of a 65 km thick lithosphere, it is expected to spread out horizontally. The second stage represented by the contact aureole of the plume may reflect melting of the asthenosphere and intrusion of the late picrite, mafic and ultramafic dikes into the igneous complex.

Examples of granite-gneiss diapirs. Diapiric domes of the Archean Pilbara craton (Western Australia) are interpreted as isolated steep-sided granitoid-cored complexes flanked by greenstones. These granitic diapirs are extrapolated as 35–120 km diameter subvertical cylinders to depths of 14 km (Van Kranendonk et al., 2004). The authors ascribe the diapiric rise of tonalite-trondjemite-granodiorite (TTG) suites to the