DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

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KRISTJAN URTSON

Stepwise melt transport and accumulation: analogue and numerical modelling approach

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Department of Geology, Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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Supervisors: Prof. Alvar Soesoo, Tallinn University of Technology
Prof. Kalle Kirsimäe, University of Tartu.

Opponent: Prof. O. Tapani Rämö, Helsinki University, Finland

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published papers, which are referred to in the text by their Roman numerals. The papers are reprinted by kind permission of the publishers.

I **Urtson, K.** and Soesoo, A. 2007. An analogue model of melt segregation and accumulation processes in the Earth's crust. Estonian Journal of Earth Sciences, 56, 3–10.

II **Urtson, K.** and Soesoo, A. 2009. Stepwise magma migration and accumulation processes and their effect on extracted melt chemistry. Estonian Journal of Earth Sciences, 58, 246–258.

III Bons, P.D., Becker, J.K., Elburg, M.A. and **Urtson, K.** 2010. Granite formation: Stepwise accumulation of melt or connected networks? Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 100, 105–115.

Author's contribution

Paper I: The author was primarily responsible for performing analogue experiments, field work and preparation of the manuscript.

Paper II: The author was primarily responsible for laboratory work, field work and preparation of the manuscript.

Paper III: The author participated in the field work, analysis and discussion of data and contributed to writing of the manuscript.

1. INTRODUCTION

Partial melting of the crustal rocks and subsequent extraction of generated melt from the source has been widely accepted as the main mechanism of magma formation in the Earth's crust. During the process of magma generation, melt is concentrated from the first microscopical melt droplets into final large, kilometre-scale magma bodies in the upper level of the crust, covering tens of orders of magnitude in the length scale. How the processes of melt segregation, accumulation, transport and final emplacement of magma are involved over this huge range of length scales, however, still remains the matter of debate (e.g. Petford and Koenders 1998; Brown 2004; Bons et al. 2010 − PAPER III).

Past studies of magmatic processes have been mostly focused on a certain process and certain length scale: studies of the first stage of melting by laboratory experiments at the micro-scale (e.g. Bulau et al. 1979; Laporte and Watson 1995; Bagdassarov et al. 1996; Holtzman et al. 2003; Walte et al. 2003), studies of segregation and transport processes at the outcrop scale (Maaløe 1992; Allibone and Norris 1992; Sawyer 1996; Brown et al. 1999; Marchildon and Brown 2003), geophysical modelling of dykes (Emerman and Marrett 1990; Rubin 1995; Mériaux et al. 1999) and studies of pluton emplacement (Zorpi et al. 1989; Paterson and Fowler 1993; Koukouvelas and Kokkolas 2003). The links and transitions between these processes and length scales, unfortunately, tend to be poorly considered.

According to other approaches, one single mechanism acts over the whole range of length scales. Diapirism (e.g. Weinberg and Podladchikov 1994; Paterson and Vernon 1995) and porosity waves (Jackson et al. 2003) are nowadays rejected as non-viable for long-range magma transport in the upper crust and rather account for magma transport in the mantle to the middle crust (Clemens and Mawer 1992; Vigneresse 2004; Bons et al. 2004). The model of connected melt networks (e.g. Weinberg 1999; Olson et al. 2004; Brown et al. 1999) requires the existence of a steady-state pervasive melt-filled network of veins, leucosomes and dykes, which should remain open for a long time in order to accomplish melt segregation and transport. According to this "rivulets-feeding-rivers" model, a number of smaller veinlets supply melt to veins, which in turn feed bigger dykes where magma is transported to the upper levels of the crust. In the model of stepwise melt accumulation (e.g. Maaløe 1987; Bons and van Milligen 2001; Bons et al. 2001, 2004, 2010 − PAPER III) the segregation, transport and accumulation of melt is stepwise and discontinuous and is accomplished in the form of hydrofractures (Bons 2001) or self-propagating dykes (Clemens and Mawer 1992). By this concept, no long-term permeability of the system is needed and melt extraction from the source can occur at low melt fractions.

The present study is focused on the concept of stepwise melt segregation, transport and accumulation that is studied by analogue and numerical modelling and field observations using migmatite vein statistics as well as structural characteristics of leucosomes. The objectives of the study are:

1. to reveal the basic characteristics of a system of liquid phase segregation and extraction from the solid matrix by analogue modelling;
2. to show on the basis of natural examples that magma transport and accumulation processes are stepwise and intermittent and
3. to clarify the effects the stepwise segregation, transport and accumulation may have on the extracted melt chemistry.

In order to reveal the basic characteristics of a system of segregation of the liquid phase (melt) from the solid matrix (host rock), analogue modelling was used with subsequent statistical analysis of experiment results (Urtson and Soesoo 2007, 2009 − PAPERS I and II). Migmatised rocks as one of the manifestations of crustal partial melting were studied in six drill cores from the Estonian Palaeoproterozoic basement and on migmatite terranes in Masku, southwestern Finland, Montemor-o-Novo, central Portugal and Port Navalo, Brittany, France. Leucosome width statistics was recorded and analysed on drill cores and in outcrops (Urtson and Soesoo 2007, 2009 − PAPERS I and II; Bons et al. 2010 − PAPER III). Additionally, in Port Navalo outcrops a structural analysis of migmatites was carried out in order to provide natural examples, which would evaluate the concept of stepwise melt transport and accumulation (Bons et al. 2010 − PAPER III).

Deformation-enhanced stepwise melt segregation and transport will influence the mixing of initial melt batches and melt residence and equilibration times within the source. A simple numerical model was used to reveal resulting effects on the extracted melt chemical composition (Urtson and Soesoo 2009 − PAPER II).

This study includes data from three scientific articles addressing magma segregation, transport and accumulation processes. A brief summary of these studies is given below.

PAPER I

Urtson, K., Soesoo, A. 2007. An analogue model of melt segregation and accumulation processes in the Earth's crust. *Estonian Journal of Earth Sciences* 56(1), 3–10.

An analogue experiment was carried out to model melt segregation from the solid rock matrix and its subsequent transport. Carbon dioxide gas and sand were used as analogue materials of crustal partial melt and host rock, respectively. The analogue model displays the diffusional transport mode at low flux rates and the transition to the ballistical mode as the response of the system to a higher gas flux. The ballistical mode is characterized by discontinuous transport and extraction of the gas phase in separate batches, which leads to the development of power law batch size distribution in the system. The gas is extracted preferentially in large batches and does not influence the state of the system and size distribution of remaining batches. The implications of the analogue model to real magmatic processes are supported by power law leucosome width distributions measured in several migmatite localities. The emergence of fractality and 1/*f* power spectrum of system fluctuations provide evidence of possible self-organized critical nature of melt segregation processes.

PAPER II

Urtson, K., Soesoo, A. 2009. Stepwise magma migration and accumulation processes and their effect on extracted melt chemistry. *Estonian Journal of Earth Sciences* 58(4), 246–258.

Numerical and analogue models suggest that melt production, its segregation from the solid matrix and subsequent transport and accumulation are highly dynamic and stepwise processes exhibiting scale invariant patterns in both time and length scales, which is characteristic of self-organized critical systems. This phenomenon is also observed in migmatites at several localities, where the leucosome thickness statistics obey power laws. Stepwise melt transport and deformation-enhanced melt mobility affect melt production dynamics by determining the distribution of extracted melt batch sizes and residence times of melt pockets within the host rock, which in turn would influence the geochemistry of extracted melts. We introduce a numerical approach, which enables qualitative and quantitative assessment of the effects of stress-induced melt migration and accumulation on the chemistry of partial melts. The model suggests that apart from different sources and melting percentages, deformation can be an important factor in producing geochemical variations within and between intrusive/extrusive complexes.

PAPER III

Bons, P.D., Becker, J.K., Elburg, M.A., **Urtson, K.** 2010. Granite formation: Stepwise accumulation of melt or connected networks? *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* 100, 105–115.

Several authors have proposed that granitic melt accumulation and transport from the source region occurs in networks of connected melt-filled veins and dykes. These models envisage the smallest leucosomes as ‘rivulets’ that connect to feed larger dykes that form the ‘rivers’ through which magma ascends through the sub-solidus crust. This paper critically reviews this ‘rivulets-feeding-rivers’ model. It is argued that such melt-filled networks are unlikely to develop in nature, because melt flows and accumulates well before a fully connected network can be established. In the alternative stepwise accumulation model, flow and accumulation is transient in both space and time. Observations on migmatites at Port Navalo, France, that were used to support the existence of melt-filled networks are discussed and reinterpreted. In this interpretation, the structures in these migmatites are consistent with the collapse and draining of individual melt batches, supporting the stepwise accumulation model.

2. THEORETICAL BACKGROUND

2.1. Migmatites

Migmatites as one manifestation of the crustal partial melting represent a magmatic system just before solidification. Migmatites are macroscopically composite prograde metamorphic rocks, which consist of melanocratic and leucocratic parts. In stromatic migmatites or metatexites, the melanocratic and leucocratic parts form a distinct migmatite layering, whereas in diatexites the banding is absent or strongly disrupt (Brown 1973).

The melanocratic part may comprise two distinct units: mesosome that represents either an unmodified protolith or melt-depleted protolith; and melanosome, which is a residual refractory phase concentrated by extraction of partial melt or formed by retrograde back reaction between melt and restite (Maaløe 1992; Brown et al. 1999; Kriegsman 2001a). Leucocratic parts or leucosomes are of igneous origin and represent former melt generated by partial melting of the protolith. By chemical composition, leucosomes may represent also cumulates (Brown et al. 1999; Johannes et al. 2003) or peritectic melts (Kriegsman 2001a). The first generated melt which is concentrated into leucosomes right next to its formation site and has migrated over short distances (few centimetres) is considered as *in situ* melt (Mengel et al. 2001). There is clear structural evidence suggesting higher melt mobility laterally along leucosomes or vertically between leucosomes (Maaløe 1992; Mengel et al. 2001; Sawyer 2001), which indicates that melt may be injected into leucosomes from the adjacent parts of migmatite.

2.2. Melt generation and transport

Partial melting of rocks starts at grain contacts, where initial melt resides in microscopical melt pockets at grain junctions or forms a thin film along grain boundaries (Bulau et al. 1979; Jurewicz and Watson 1984; Laporte and Watson 1995). During progressive melting, these microscopical melt droplets will be interconnected, which allows the melt to percolate through the rock and melt segregation or extraction from the solid matrix can start (Brown 1994; Sawyer 2001).

The formation of three-dimensional grain-scale melt networks and overcome of the melt percolation threshold (Vigneresse et al. 1996) depend on the geometry of initial melt pockets (i.e. dihedral wetting angle), controlled by surface energy differences between liquid and solid fractions which in turn depend on the composition of melt and host rock (Jurewicz and Watson 1984; Laporte and Watson 1995; Walte et al. 2003). For crustal partial melting, percolation thresholds from 3–4% (Laporte and Watson 1995) to 8% (Vigneresse et al. 1996) of melt have been predicted. With progressively increasing melt fraction the cohesion between mineral grains is eventually lost. It has been suggested that 15–20% of melt volume is needed to overcome the melt escape threshold that allows magma (i.e. melt-dominated crystal suspension) to escape from the local system and migrate over larger distances (Vigneresse et al. 1996). Compaction-driven porous flow or "filter pressing" aids melt segregation (McKenzie 1987; Jackson et al. 2003).

Tectonic forces and deformation play a crucial role in driving the melt segregation and transport processes. Coaxial deformation (i.e. pure shear) is effective on concentrating the melt into melt-filled low-stress regions or leucosomes that are oriented parallel or at a high angle to the direction of compression (Bagdassarov et al. 1996; Vigneresse et al. 1996; Vigneresse and Burg 2000). Non-coaxial tectonic forces create gradients in the stress and melt pressure field and strongly promote the mobility of melt and its extraction from the source (Vigneresse and Burg 2000; Marchildon and Brown 2001; Bons et al. 2004). With increasing volumes of accumulated melt batches, density differences between melt and solid fraction (buoyancy of melt) become more dominant as a driving force for melt migration (Bons et al. 2004). Partial melting also induces crustal embrittlement by volume expansion associated with melting as intergranular melt pressure close to the lithostatic pressure may reduce effective normal stress to the point, where failures occur and microfractures form (Vigneresse et al. 1996; Bons et al. 2004). The formed incipient fractures serve as initial accumulation sites for *in situ* melt that has migrated over a limited distance by percolation or porous flow (Mengel et al. 2001). These primary melt batches need to be mobilized in order to accumulate and transport the generated melt through the source area to the upper levels of the crust.

The interconnected melt network or "rivulets-feeding-rivers" (RFR) model (Brown 1994; Weinberg 1999) envisages a tributary network of melt-filled fractures that link the source of melting with feeder dykes that transport melt to the upper levels of the crust. For effective transport of melt in dykes through the sub-solidus crust a sufficient flux of melt must exist at the base of the dyke (Weinberg 1999). The effective supply of melt to the dykes is ensured by hierarchical structure of the network where small fractures feed bigger veins, which are one order of magnitude larger in size but one order less abundant; these veins in turn feed even larger (and fewer) veins and so on (see Figure 1 in Bons et al. 2010 – PAPER III). A fractal structure of such melt networks, similar to the Menger sponge, has been suggested (Tanner 1999). The permeability of the system and melt flow is achieved when melt-filled veins intersect and link up to form a percolating network as the melt fraction increases. Below the critical melt percentage, no flow occurs through the system (Brown 1994; Weinberg 1999). However, localized flow and changes in the developing network may take place below the critical melt fraction (Petford and Koenders 1998; Petford et al. 2000).

On the other hand, it has been argued that due to hydraulic fracturing and ductile flow of the host rock, it is difficult to build and maintain an interconnected melt network that extends through the whole magmatic system over a sufficiently long time period. Theoretical estimate of the vertical stability and sustainability of such an extensive network is given in Bons et al. (2010 – PAPER III).

As an alternative to the RFR model, the concept of stepwise melt segregation, accumulation and transport has been proposed (e.g. Maaløe 1987; Bons and van Milligen 2001; Bons et al. 2001, 2004). According to this concept, hydraulic fracturing is the key aspect in magma transport through the crust. Magma transport and extraction occur discontinuously and are accomplished via propagating and merging melt-filled cracks and melt batches well below the critical melt fraction without the need for establishing large-scale permeability. The melt is transported over larger distances in the form of hydrofractures (Bons 2001) or self-propagating dykes (Clemens and Mawer 1992), driven by buoyancy forces or gradients in the tectonic stress field.

During hydraulic fracturing a fluid-filled fracture can move by opening at one end of the crack and simultaneous closure at the other end (Weertman 1971; Secor and Pollard 1975; Takada 1990). Hydrofracture mobility occurs when the effective normal stress gradient along the fracture exceeds the threshold value. The effective normal stress gradient can be due to the difference in the density between fluid/melt and wall-rock, and/or due to a stress gradient in the wall-rock. Calculations by using experimentally established and theoretically calculated values of effective normal stress and fracture toughness indicate that a water-filled fracture becomes unstable when it is longer than 5–100 m, while a vertical melt-filled fracture can reach a length of 15–300 m (Secor and Pollard 1975; Bons and van Milligen 2001). Bons and van Milligen (2001) also show that if the stress gradient is in the order of 1–10 MPa/m, fractures as short as 10 cm become unstable and therefore mobile. Hence, decimetre-scale melt-filled fractures can be mobile at tectonically reasonable stress gradients. When mobile melt veins move and merge with the others, a larger new melt vein is formed that needs an even smaller stress gradient to move further. As a consequence, the new melt vein can move more rapidly and more frequently per unit of time, leading to a greater likelihood of merging with other melt veins (Bons et al. 2004). The movement of the melt is thus envisaged as a stepwise movement of different melt batches, rather than a continuous flow of melt through connected conduits.

Analogue experiments (Bons and van Milligen 2001; Urtson and Soesoo 2007 – PAPER I) as well as numerical models (e.g. Vigneresse and Burg 2000; Bons et al. 2004) suggest that a stepwise melt segregation and accumulation may quickly evolve into a self-organized critical state (Bak et al. 1988; Bak 1996) where it exhibits fractal patterns and scale-invariant behaviour in both time and space − $1/f$ (Bak et al. 1987) volume fluctuations and power law (e.g. Bonnet et al. 2001) batch size statistics. The dynamics of such a self-organized critical system cannot be described by linear transport equations but follow more complex rules (Bak 1996; Bons and van Milligen 2001). It has been shown (Bak 1996; Bons and van Milligen 2001) that a self-organized critical transport system, once it has achieved the critical state, is capable of transferring any additional mass without modifying itself and that the structure of the system is maintained regardless of significant volume extraction. The size of leucosomes and their spatial distribution in migmatites can thus still carry information about the dynamic state of the system while it was still partially molten, although probably large volumes of magma have passed through the rock, the traces of extracted melt pools are not retained and the volume of former melt present in the system is difficult to detect (e.g. Sawyer 2001; Bons et al. 2008).

It is evident that the stepwise melt migration and the merging history of melt batches will influence the chemistry of the resulting melts (Bons et al. 2004; Vigneresse 2007). Many granitic intrusives show heterogeneous character, which indicates the origin from multiple sources (Leeman et al. 1990; Poli 1992; Elliott et al. 1997; Soesoo and Nicholls 1999) and complex magmatic processes (Chappell and White 1974; Clemens and Wall 1984; Soesoo 2000, 2006). The melts from different sources may completely mix to form a range of hybrid phases, or they may remain separate mingled phases (Vernon et al. 1988; Poli and Tommasini 1991; Elburg 1996; Flinders and Clemens 1996; Perugini and Poli 2000, 2004; Perugini et al. 2003, 2006). The geochemical features of batholiths have often been explained by heterogeneous occurrences of restite phases and minerals or *in situ* differentiation (Michael 1984; Chappell 1996). A number of researchers (e.g. Wareham et al. 1997; Pressley and Brown 1999; Slater et al. 2001; Perugini et al. 2003; Spiegelman and Kelemen 2003; Bons et al. 2004; Soesoo et al. 2004a) consider the formation of large magmatic bodies by coalescence of distinct melt batches. Each of these batches may have a different chemistry, due to local differences in source rock, differences in the melting time and regime, and accumulation history (Stephens 1992; Hobden et al. 1999; Soesoo 1999; Sobolev et al. 2000). Thus the composition of magmas depends, amongst other factors, on processes of partial melting and mixing of the resulting melts (Brown 2007).

Although it may be evident from the end product that mixing and mingling of melts did take place, it is less clear how and where these processes occurred. Moreover, it is difficult to quantify the relationship between tectonic forces and the composition of the melts generated under a specific tectonic regime. The key ideas for modelling these relationships have been expressed by Soesoo and Bons (1998, 1999) and Urtson and Soesoo (2009 – PAPER II).

3. MATERIAL AND METHODS

3.1. Analogue experiments

Simple analogue experiments have been performed to model liquid phase (melt) segregation from the solid matrix (host rock) and its subsequent transport (Bons and van Milligen 2001; Urtson and Soesoo 2007 – PAPER I). The experiment stage consisted of two 35 cm x 35 cm sealed glass plates with a 6.5 mm space between them (see Figure 1 in Urtson and Soesoo 2007 – PAPER I). The tank was filled with fine-grained quartz sand immersed by sugar, water and yeast mixture. The life activity of yeast results in the formation of alcohol and carbon dioxide gas. The production and redistribution of the gas phase was considered as the analogue of melt generation during crustal anatexis, with gas batches formed by accumulation and transport representing the melt-rich domains or leucosomes in migmatites. The sand column as the solid phase represented the crustal block that undergoes partial melting.

A digital photo camera was used to record the experiment evolution. The frames were acquired by a 5.5-second interval during approximately 1.5 hours and were used afterwards for statistical analysis of the model. The acquired images were analysed on the computer using the ImageJ image processing software (National Institutes of Health). On a threshold image the gas batch sizes were determined by measuring their apparent areas in pixels. The total gas amount in open fractures was derived by the total sum of batch areas. Fluctuations in the total gas amount in the system were analysed by Fourier transform, using the Benoit fractal analysis software (TruSoft Int'l Inc.).

3.2. Migmatite localities and leucosome width measurements

Leucosome widths have been examined in nine different localities. The migmatites under investigation represent rocks with a variety of chemical compositions and metamorphic histories. Six studied drill cores originate from the Estonian Palaeoproterozoic basement (Soesoo et al. 2004b; Kirs et al. 2009) (Figure 1). Drill cores F-265 (59°28.91'N, 26°16.88'E) and F-266 (59°28.19'N, 26°15.37'E) penetrate granulite facies metasediments of the Jõhvi structural zone, drill core F-122 (59°34.43'N, 25°31.83'E) extends through amphibolite facies metavolcanites and metasediments of the Tallinn zone, drill cores F-156 (59°24.46'N, 26°24.61'E) and F-268 (59°26.56'N, 26°13.30'E) penetrate amphibolite facies metasediments of the Alutaguse zone and drill core F-330 (59°9.15'N, 23°32.56'E) ranges through high-temperature amphibolite facies metavolcanites and metasediments of the West Estonian structural zone of the Estonian Proterozoic basement (Kivisilla et al. 1999; Puura et al. 2004; Soesoo et al. 2004b). Peak metamorphic conditions in this area are estimated at 600–700 ºC and 3–5 kbar (Koistinen et al. 1996; Puura et al. 2004).

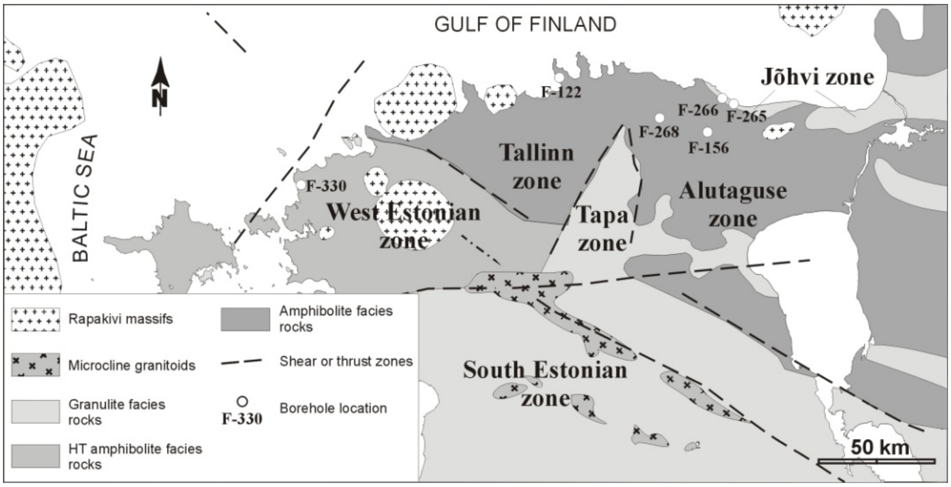

Figure 1. Geological sketch map showing major structural zones of the Estonian Proterozoic basement and locations of studied drill cores (modified after Puura et al. 2004).

The Masku migmatite outcrop (60°32.52'N, 22°08.00'E) near the town of Turku in southwestern Finland belongs to the Turku Migmatite Complex of the southern Svecofennian Shist Belt (Figure 2). Metapelitic migmatites have undergone Proterozoic granulite facies metamorphism with peak metamorphic conditions at 800 ºC and 6 kbar (Mengel et al. 2001; Johannes et al. 2003).

Migmatites of the Montemor-o-Novo outcrop (38°38.12'N, 8°12.54'W) in central Portugal belong to the Evora massif in the Ossa Morena zone of the Iberian terrane, accreted to the Hesperian massif during Variscan orogeny (Figure 3). The high-grade metamorphism of the Seria Negra Group pre-orogenic metasediments is probably of Variscan or Cadomian age (Pereira and Silva 2002).

The study area at Port Navalo (47°32.56'N, 2°54.74'W) is located in the Southern Brittany Metamorphic Belt (Figure 4), which is part of the Variscan Armorican arc (Bons et al., 2010 – PAPER III). The area was deformed and metamorphosed during the Palaeozoic Variscan orogeny, reflecting interaction between Laurasia and Gondwana (Matte 2001). The study area is dominated by migmatized metapelites and amphibolites. Peak metamorphic conditions associated with the first phase of melting have been estimated at 8 kbar and 800 ºC, followed by the second phase of melting resulting from near isothermal decompression at 700ºC and ~4 kbar (Johnson and Brown 2004). Three deformation phases have been recognized in the area (Marchildon and Brown 2003).

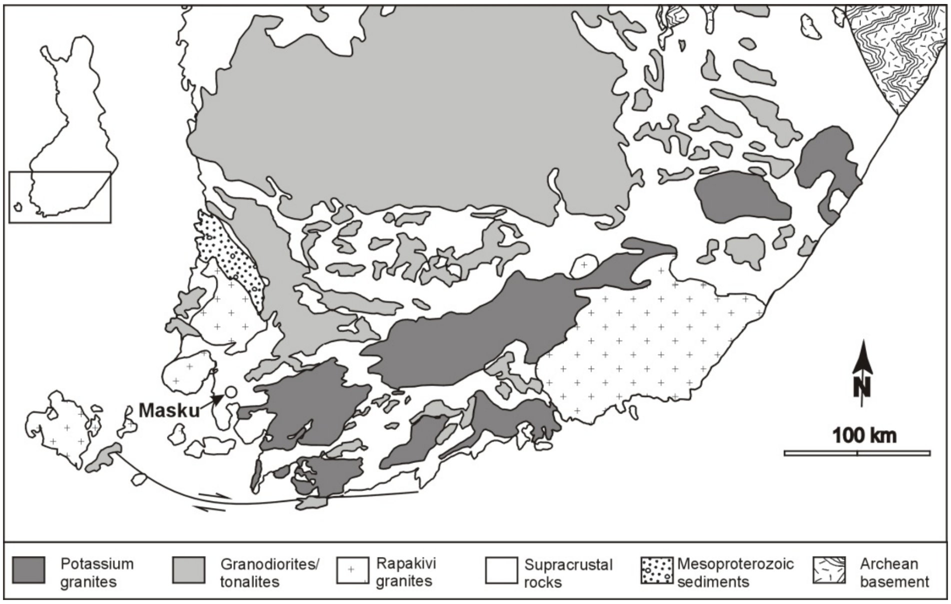

Figure 2. Geological map of southern Finland (after Johannes et al. 2003).

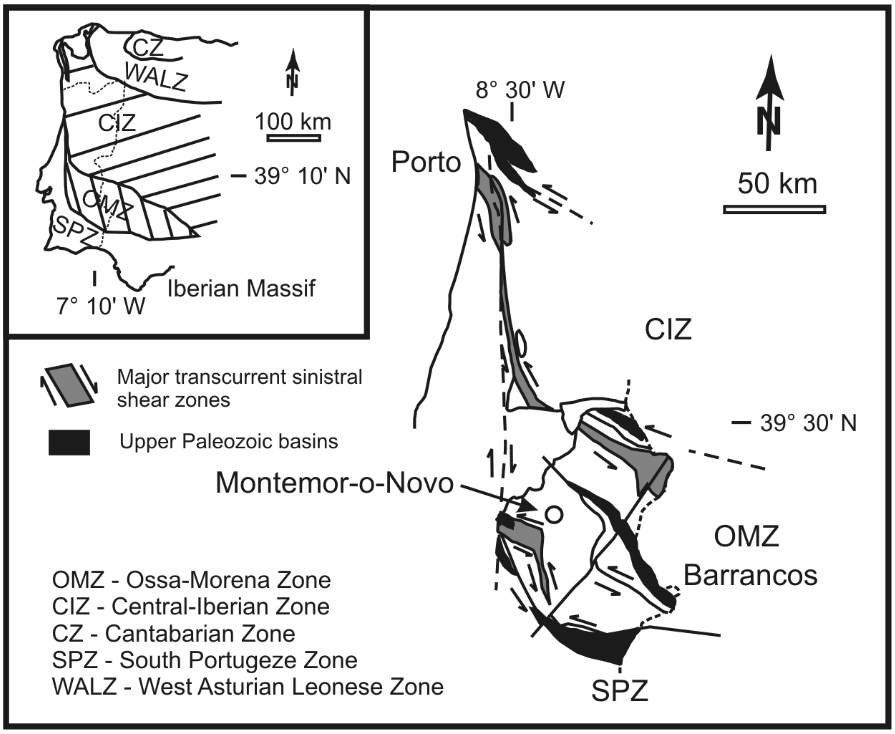

Figure 3. Geological sketch map of Portugal showing major structural zones and location of Montemor-o-Novo migmatite outcrop (after Silva and Pereira 2004).

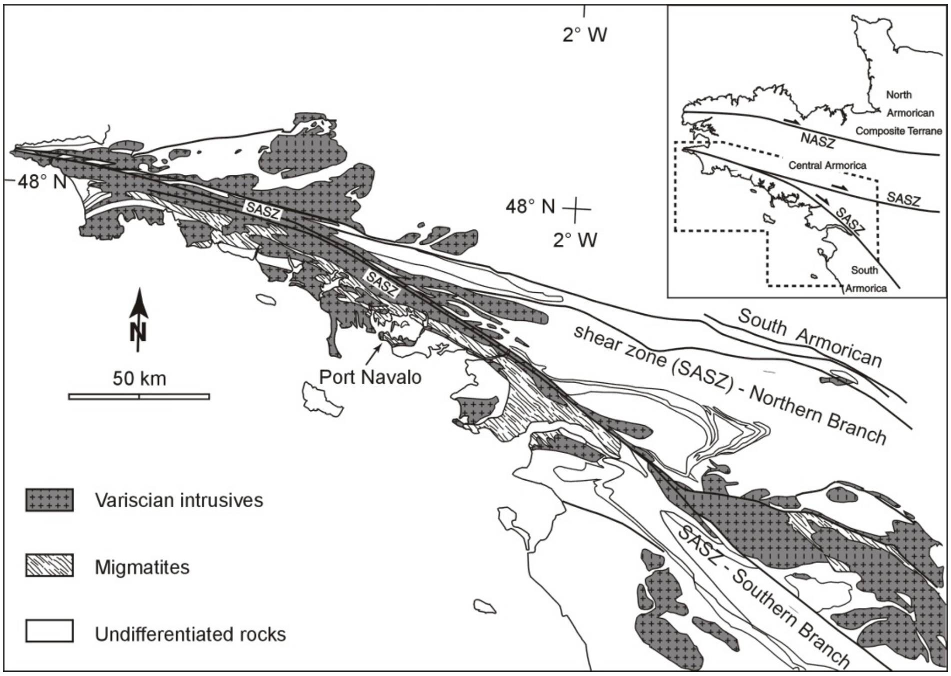

Figure 4. General geologic map of southern Brittany showing distribution of Variscan granite and migmatite rocks (modified after Marchildon and Brown 2003).

The thickness of leucosomes and their spacing were measured along the axis of drill cores or along line traverses on outcrops using a tape ruler (see Figure 7b in Bons et al. 2010 – PAPER III). The resolution of measurements was limited to 2 mm; leucosomes with thicknesses below this value were not counted as their number would very likely be underestimated and thus should not be included in the data. In several cases where the placement of the measuring traverse was dictated by the orientation of the drill core or the erosional surface of the outcrop at some angle with respect to leucosome layering, apparent leucosome thicknesses were recorded, which, however, does not affect their distribution trend.

Measured leucosome thickness data were plotted on a bi-logarithmic graph with the measured thickness on the x-axis and the number of leucosomes of that thickness on the y-axis. The power law data are defined by a straight line with the distribution exponent being equal to its slope. Different methods of plotting – cumulative frequency distribution and density distribution with logarithmic binning were used for comparison, as it helps to evaluate the quality of the data (Davy 1993). The cumulative distribution represents the number of leucosomes N with a thickness greater than the given thickness h: $N(>h) = h^{-D}$, where D is the distribution exponent. Density distribution represents the number of leucosomes belonging to an interval (or bin), divided by the interval length dh as $N(h) = h^{-D}/ dh$ (Bonnet et al. 2001). In addition to leucosome thickness data, the total melt fraction in the section was estimated by integration of leucosome thicknesses along the traverse.

3.3. Numerical modelling of extracted melt chemistry

The numerical model was developed to investigate the effect of stepwise segregation and accumulation of melt during progressive melting of the source. The model is based on the assumption that melt resides and moves solely in the form of mobile hydrofractures or melt-filled veins.

In the model, melt batches are modelled as discrete spheres placed in the space of a cube. Bons et al. (2004) have shown that the simplified shape of the melt batch will not significantly change the results of the modelling. Progressive melting is simulated in 0.01% increments by creating randomly placed initial melt batches in discrete time steps; typically 5000–10 000 time steps are used in the run. The movement of melt batches, i.e. the mobility of hydrofractures due to tectonic stress gradients, is simulated by moving all spheres each step in the x-, y- and z-direction. The distance of movement depends on the mobility factor E that exemplifies the strain rate and which is ranging between 0 and 1000 in the simulation, i.e. over three orders of magnitude; for moving each sphere, the value is chosen randomly between $\pm E$. A preferred direction of movement, for example upward propagation of melt by buoyancy forces, was not included in the model which implies that the model applies to the region and scale where tectonic forces dominate over buoyancy-driven melt transport.

Merging of the melt batches is performed by merging all pairs of overlapping or touching spheres where the new position of the sphere (melt batch) is taken as the volume-weighted average of the centres of the merged spheres. The extraction of melt batches is related to the batch volume: any sphere that exceeds a set threshold in volume (usually V_{ext} = 2000 or 1–1.5% of partial melt) is removed from the cube, simulating the escape of a melt batch from the source region. Statistics (e.g. volume and age) of the batches in the system and the extruded batches are recorded at every time step.

The chemistry of each melt batch is recorded for the major elements and complementary trace element concentration (partition) at certain temperature. The major element chemical composition of the melts generated at different stages of partial melting is calculated, using the existing modelling package MELTS developed by Ghiorso and Sack (1995). While knowing liquid/solid proportions during the melting steps at certain pressure–temperature conditions, the trace element distribution between solid and liquid phases are calculated with conventional batch and fractional melting equations. By merging batches with different composition, the composition of the resulting batch is calculated as volume-weighted average of the compositions of the merging batches.

4. RESULTS AND DISCUSSION

4.1. Analogue modelling

The experimental system with analogue materials has proved itself as a useful tool to study melt segregation, transport and accumulation processes at conceptual level. At the early stage of the experiment the CO_2 gas production rate is low and the gas percolates through the interconnected pore space between sand grains. At this stage the system is capable of accommodating all the produced gas in the pore space and transferring the low flux of excess gas. At increasing rates of gas production, the system adapts to higher transport rates and switches to the ballistic transport mode (term by Bons and van Milligen 2001) where open cracks and gas batches appear. In this mode the transport of the gas is intermittent and stepwise and occurs as discrete events by merging of gas batches, draining the gas into adjacent parts of the tank or escaping from the system (see Figure 3d in Urtson and Soesoo 2007 – PAPER I). Stepwise merging, draining and escaping of melt batches redistributes the gas in the system and modifies the gas pressure field in the tank, which may then trigger new merging and escaping events. In such a way a line of interaction exists between gas batches in the tank. The system has reached a state of dynamic equilibrium, where continuous production of the gas and escape in short bursts are in balance, but only on long-term average.

The dynamic structure inside the tank is continuously rearranged but remains statistically unchanged. The analysis of the data recorded during the experiment reveal power law size statistics of gas batches present in the system at a chosen time step (Urtson and Soesoo 2007 – PAPER I) and the volumes of the escaping batches (Bons and van Milligen 2001). Due to discrete escape events, the total amount of the gas in the system fluctuates, producing a signal with a $1/f$ power spectrum (Bons and van Milligen 2001; Urtson and Soesoo 2007 – PAPER I).

The study of gas batch size distribution at selected time steps shows that regardless of the extraction of large gas volumes, the batch size statistics remain unaffected. As most of the extracted gas volume is included in the few largest batches, removing of them does not affect the overall trend of the data and the fit to a power law (see Figure 1b,c in Urtson and Soesoo 2007 – PAPER I). As a result, the distribution exponent remains constant even when a large fraction of gas is extracted. The dynamic structure of the system is then characterized by only one number – the distribution exponent D.

As the experiment suggests, the transport of large gas volumes can be accomplished without the need for a steady-state open network of drainage paths. The liquid escape threshold (Vigneresse et al. 1996) can be overcome locally and temporarily, a high bulk fraction of the melt phase is not needed. The process of gas transport in the tank is a continuous rearrangement of local migration channels and accumulation pools, which disappear when the gas is extracted.

The analogue experiments described in Urtson and Soesoo (2007 – PAPER I) contribute to the idea that melt segregation, transport and subsequent accumulation is a highly dynamic stepwise and intermittent process. The observed phenomena, such as a large number of interacting members ("communicating" gas batches in the experiments), adaptation of the system to higher transport rates and the emergence of power law statistics and $1/f$ fluctuations, are characteristic of a self-organized critical system (Bak 1996; Bons and van Milligen 2001).

4.2. Migmatite data

As plotted on the bi-logarithmic graph, leucosome thickness data follow a power law (Figure 2 in Urtson and Soesoo 2009 – PAPER II; see subsection 4.3 for Port Navalo data, Bons et al. 2010 − PAPER III). The slope of the distribution trend line is defined by the distribution exponent D, which ranges between 0.64 and 1.4 for cumulative frequency distributions among localities.

In theory, the value of the distribution exponent m (denoted as D for leucosome data) describes the relationship between the number of large and small leucosomes and distribution of mass between them. In case of the exponent $m = 2/3$, up to 50% of mass is residing in the largest leucosome, indicating effective accumulation of melt, whereas a higher exponent value shows a higher significance of smaller leucosomes and therefore, poorer accumulation. The exponent value $m = 1$ can be considered as the boundary between accumulation and dispersion (Bons et al. 2004; Soesoo et al. 2004a).

However, the distribution of leucosome widths recorded in migmatites represent one-dimensional cut through a three-dimensional migmatite system and is not directly comparable with the volume distribution of leucosomes. Soesoo et al. (2004a) have derived the relationship between the distribution exponents of magmatic leucosome widths and corresponding melt batch volumes, where the expected range of the volume distribution exponents m between good accumulation and the limit of dispersion $2/3 < m < 1$ translates into $0 < D < 1$ for leucosome width distributions.

On the basis of the above expression, the accumulation efficiency of melt in the studied migmatites can be estimated as moderate to poor. Despite the variability among different localities there is no correlation between the distribution exponent and host rock composition/metamorphic history (i.e. melting conditions and reactions) of the studied migmatites. It has been shown by numerical modelling that the mobility of melt is a critical factor in magmatic systems, determining the accumulation and extraction efficiency (Bons et al. 2004; Urtson and Soesoo 2009 – PAPER II). Besides other factors, such as composition of the host rock, melting reactions or the presence of fluids, melt mobility is controlled by the deformation rate and temperature. Therefore, the evolution and state of a magmatic system right before solidification, as well as final melt batch size distribution within the system, may be determined by the tectono-thermal conditions at late stages of melting.

4.3. Stepwise transport and accumulation of melt – field observations

Expected field evidence for the stepwise melt accumulation and transport model include power law distribution of leucosomes and structures representing collapsed former melt volumes that indicate melt loss. The observations were made in migmatite outcrops near Port Navalo on the South Brittany coast, France (Bons et al. 2010 – PAPER III). These outcrops have been formerly studied in detail by Marchildon and Brown (2003) and Brown (2004, 2005) and used as proof for the RFR model. Their key evidence included layer-parallel leucosomes, discordant dykes and dilatant sites that form an interconnected melt-filled network with petrographic continuity and without discordant structural relationships.

However, the observations presented in Bons et al. (2010 – PAPER III) show that this evidence should be re-examined and re-interpreted. Contrary to former statements, granitic and aplitic dykes clearly cross-cut the bedding-parallel leucosomes and are petrographically distinct having a different grain size and colour (see Figure 4a,b,c in Bons et al. 2010 – PAPER III). Furthermore, dykes cross-cut isoclinally folded leucosomes without being folded themselves, which indicates that the dykes and the leucosomes belong to different generations and were not filled with melt at the same time. Different generations of dykes intersect each other with sharp and straight boundaries, suggesting that older dykes were already solidified when cut by younger ones (see Figure 5 in Bons et al. 2010 – PAPER III). The observations revealed no evidence of the existence of melt-filled interconnected vein network in Port Navalo migmatite outcrops, as would be expected for the RFR model.

Discordant leucosomes studied in Port Navalo outcrops typically form boudin- and shear band-like structures, where the primary foliation is deflected. Boudins show typical fish-mouth structures where the foliation pinches in towards the boudin neck. The foliation bends into shear band-like leucosomes with both normal or reverse drag direction (see Figure 4d,e in Bons et al. 2010 – PAPER III). Such structures are commonly interpreted as dilational, inducing pressure gradients that lead the melt to flow towards them (Hollister and Crawford 1986; Sleep 1988; Allibone and Norris 1992; Oliver and Barr 1997; Brown 2004). However, another possibility is to consider them as contraction structures, formed by converging of the surrounding rock when melt has escaped from the accumulated volume. Depending on the original shape of the initial melt batch, a variety of structures may develop, ranging from shear band-like leucosomes to apparent boudins (Bons 1999; Kriegsman 2001b). The combination of both normal and reverse drag at the tips and centre of shear band-type leucosomes, respectively, is commonly observed in migmatites; analogue experiments suggest that this effect is enhanced by deformation (Druguet and Carreras 2006). Yet, unambiguous distinction of collapse and dilatant structures needs detailed investigation of the formation of these structures considering the consistency of the amount of deflection with either model. In the present case, the strong deflections for relatively short shear band-like leucosomes lead to favouring melt loss and contraction as origin of these structures (Bons et al. 2010 – PAPER III).

The stepwise accumulation model predicts a power law distribution of the accumulated melt volumes. The corresponding leucosome widths that are analysed in the field are also expected to follow power law distribution (Soesoo et al. 2004a). In Port Navalo outcrops, leucosome widths were measured on two profiles with lengths of 3 and 4 m. Power law leucosome width distributions with the exponent $n = 1.3$ were observed for leucosome widths in the range of 5 to 100 mm (see Figure 7a in Bons et al. 2010 – PAPER III). Brown (2005) has reported power law width distribution with the exponent $n = 1.11$ for leucosomes wider than 100 mm measured approximately in the same location. Synthesis of these two data sets allows extending the power law distribution over a wider range of leucosome widths in this area. It is, however, unclear whether the veins and dykes in these two data sets belong to the same generation.

4.4. Sustainability of the RFR model vein networks

The time scale of melt generation, controlled by the duration of tectono-metamorphic events, is in the order of 1–10 million years (Harris et al. 2000), which is much larger than needed for pluton emplacement (Petford et al. 2000). Thus, the episodes of magma extraction and pluton filling are separated by long periods of melt formation without significant flow through the network. The tributary melt network must therefore remain sustainable over a prolonged period of time.

In order to collect the melt from the source and transport it to the base of dykes, the melt network must vertically extend through the whole height of the partially molten zone, which can be about 1 km or greater. However, vertical fluid-filled fractures will eventually reach the critical length, above which hydraulic fracturing occurs; they start to propagate upwards and drained fractures will be closed by ductile flow of the matrix (Weertman 1971; Secor and Pollard 1975; Takada 1990). Thus, the network comes unstable well before it reaches the full height; clusters of interconnected veins start to propagate upwards and the permeability is destroyed. Theoretical estimate of the vertical stability of such a tall melt network given in Bons et al. (2010 – PAPER III) suggests that the time frame for draining the melt-filled veins and closing the local network is in the order of years to hundreds of years. This means that it is difficult to create and maintain a vertically extensive interconnected vein network over longer periods of time, needed for melt extraction from the source and pluton emplacement (Bons et al. 2010 – PAPER III).

4.5. Geochemical evolution of generated melt composition

The results of numerical modelling show that to produce escaping melt batches, smaller percentages of melt are needed at a high strain rate than at a low strain rate (Urtson and Soesoo 2009 – PAPER II). The mobility factor *E* has a distinct effect on the character of the population of extruded spheres and their chemistry. With increasing *E* the average size and age of the extracted batches decrease, but the variability of ages increases. In geological terms this implies that a high deformation rate within the source would favour many but smaller batches to leave the source, and a high variability in melt chemistry, reflecting the relatively short residence time within the source. Deformation distinctly facilitates the accumulation of melt batches that initially formed at different melting events during progressive melting and in different source sub-regions with variations in chemical composition. The early melts produced at a high strain rate are enriched in incompatible elements. The abundances of most incompatible elements may vary by two to three orders of magnitude between the early and late magma batches (Urtson and Soesoo 2009 – PAPER II). As melting proceeds, the extracted partial melts may show a large variation in chemical composition. At low strain rates the residence time of the initial melt batches is longer, enabling the melt batches to become equilibrated with residual solids, and the chemical variation in extracted melts is small. At a high strain rate (*E* = 1000) the trace element compositions of extracted melt batches match well with the theoretical incremental melting curve, while at a low strain rate (*E* = 2–10) the majority of melt batches are compositionally similar to those of theoretical batch melting. At a very high degree of partial melting (40–50% of source melting) the resulting melts are compositionally between these two end-member cases (see Figures 3–5 in Urtson and Soesoo 2009 – PAPER II).

Therefore, it can be shown by numerical modelling that a relatively large change and variability in the major and trace element compositions may be related to differences in strain rates. Apart from pressure, temperature, source composition and partial melt percentage, differences in the deformation history and related differences in melt accumulation and extraction can result in a large spread in geochemical characteristics of partial melts within the crust. Chemical variation within intrusive or extrusive complexes can readily be caused by variation in tectonic stresses in the area.

One of the conclusions of the modelling experiment is that the interactions between melt and source may not be simple and might not be described meaningfully by average values. Some melt batches have a long residence time, while others may quickly become entrained and have little time to interact with restite or other melt. Melt chemistry may be variable from one extracted batch to another where trace element as well as major element chemistry can show large variations. Since in our model melt escapes from the source before a critical melt percentage (Arzi 1978; Vigneresse et al. 1996) has been reached, melt extraction starts at an earlier stage than in conventional models of granite petrogenesis. This will reduce the time for equilibration with restite or source rock, which in turn may cause disequilibrium partitioning of trace elements and isotopic ratios (Harris et al. 1995; Tommasini and Davies 1997; Perugini et al. 2006). For granitology it may indicate that granite geochemistry does not image their sources (Chappell and White 1984) and attempts to model the composition of the source by equilibrium partitioning between melts and restite would also be doomed to fail (Sawyer 1991). However, this approach may lead to better explanations on the heterogeneous chemistry of some batholiths. The results derived from this model are likely to approach reality better than those from more conventional geochemical models (e.g. trace element modelling).

5. CONCLUSIONS

The present study gives several arguments for favouring the concept of stepwise melt segregation, transport and accumulation as a viable mechanism for magma transport in the Earth's crust:

1) Experiments with carbon dioxide and sand as analogues of crustal partial melt and host rock, respectively, show that liquid segregation from the solid matrix and subsequent transport are highly dynamical and intermittent processes and exhibit scale invariant patterns in both time and space, characteristic of a self-organized critical system – power law batch size statistics and $1/f$ volume fluctuations. The experiment suggests that similar to the analogue system, melt segregation and transport is likely a stepwise and intermittent process and is accomplished in the form of melt-filled hydrofractures.

2) Power law leucosome thickness statistics recorded at nine migmatite localities support the implications of analogue and theoretical approaches to real magmatic systems. The emergence of power law statistics in migmatites is predicted by the stepwise accumulation model.

3) Detailed field observations in migmatite outcrops reveal the evidence for the stepwise accumulation model – collapsing structures that indicate melt escape from the accumulated volumes and power law size distributions of accumulated melt volumes. Evidence for the "rivulets-feeding-rivers" (RFR) model proposed by earlier studies was discussed and reinterpreted. The conclusions do not support the existence of a melt-filled interconnected network, which is one of the basic assumptions of the RFR model.

4) Theoretical estimates of the vertical stability of extensive melt-filled networks, a prerequisite for the RFR model, show that such networks are difficult to create and maintain in nature over prolonged time periods, sufficient for melt extraction from the source and pluton emplacement.

5) Stepwise melt transport and deformation-enhanced melt mobility affect melt production dynamics by determining the distribution of extracted melt batch sizes and residence times of melt pockets within the host rock, which in turn would influence the geochemistry of extracted melts. The numerical model of melt chemistry evolution suggests that apart from different sources and melting percentages, deformation can be an important factor in producing geochemical variations within and between intrusive/extrusive complexes.

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SUMMARY IN ESTONIAN

ASTMELINE MAGMA TRANSPORT JA AKUMULATSIOON: ANALOOG- JA NUMBRILINE MODELLEERIMINE

Käesolev doktoritöö uurib maakoores aset leidvate magmatekkeprotsesside dünaamikat. Magma teket algkivimite osalisel ülessulamisel, järgnevat magma transporti maakoore ülemistesse kihtidesse ning lõplikku kogunemist, näiteks graniitsetesse plutoonidesse, on senistes uuringutes käsitletud enamasti eraldiseisvate protsessidena mille vahel puudub selge põhjuslik sidusus. Samas on välja pakutud magmatekke mehhanisme, mis integreerivad iseendas kõiki neid magma moodustumise etappe. Leukosoomvõrgustiku mudeli kohaselt moodustub sulamise algetapil tekkinud sulatilkade ühinemisel kivimsulaga täidetud leukosoomidest ja daikidest ühendatud võrgustik, mille kaudu toimub magma segregeerumine algkivimist ning edasine transport läbi maakoore. Võrgustiku moodustumine ja läbilaskevõime tekkimine toimub maakoore teatud ülessulamisastme juures, millest allpool magma transporti ei toimu. Lisaks on vajalik võrgustiku läbilaskevõime püsimine pika aja jooksul, mis kulub magma genereerimiseks, transpordiks ning magmakehade täitmiseks maakoore ülemises osas. Alternatiivina magma transpordi pidevprotsessile on välja pakutud astmelise magma transpordi ja akumulatsiooni mudel, kus magma eraldumine algkivimist algab oluliselt madalama sulamiprotsendi juures, magma transport läbi maakoore toimub üksikute magmakogumitena kivimite hüdraulilise lõhenemise teel ning magmasüsteemi pikaajalise läbilaskevõime tagamine pole vajalik. Käesolev doktoritöö käsitlebki astmelise magma transpordi ja akumuleerumise mudeli erinevaid aspekte ning toob esile ülalnimetatud leukosoomvõrgustiku mudeli olulisemad puudused.

Magma segregeerumist ja transporti modelleeriti analoogmaterjalide abil, kasutades magma ja maakoore kivimite analoogidena vastavalt süsihappegaasi ja liiva. Analoogmudel näitab, et gaasi kogunemine ja liikumine süsteemis pole ühtlane vaid dünaamiline ja katkendlik, kusjuures gaasi ümberpaigutumine ja eraldumine toimub üksikute piiritletud kogumitena. Astmelise gaasi akumulatsiooni ja transpordi tulemuseks on gaasikogumite suuruste astmejaotus ja gaasinivoo fluktuatsioonide $1/f$ spekter, mis on iseloomulikud iseorganiseerunud kriitilistele süsteemidele.

Sarnane fenomen on jälgitav ka looduslikes magmasüsteemides, kus migmatiitide leukosoomide laiused järgivad astmejaotust. Leukosoomide laiused väga erineva vanuse, geneesi ja geograafilise asukohaga kivimkompleksides (kuus puursüdamikku Eesti kristalsest aluskorrast, migmatiitide paljandid Maskus, Soome; Montemor-o-Novo, Portugal ja Port Navalo, Prantsusmaa) näitavad astmejaotust eksponendiga vahemikus 0.64 kuni 1.4, mis viitab mõõdukale magma akumulatsiooni efektiivsusele nendes kivimites. Port Navalo migmatiitidel, mida varasemates uuringutes on kasutatud just leukosoomvõrgustiku mudeli tõestuseks, viidi läbi ka leukosoomide strukturaalne analüüs, mis näitab et ühtset leukosoomide võrgustikku pole nendes kivimites eksisteerinud ning viitab vajadusele varasemad tõendid ümber hinnata. Port Navalo migmatiitides vaadeldud leukosoomide struktuur, magma lahkumisele viitavad leukosoomide kollapseerumise tunnused ning leukosoomide laiuste astmejaotus on tõendiks astmelisele magma akumulatsioonile nendes kivimites.

Teoreetiline hinnang leukosoomvõrgustiku vertikaalsele stabiilsusele näitab, et võrgustik, mis peab läbima kogu osaliselt ülessulanud maakooreplokki vertikaalse ulatusega 1 km ja rohkem, muutub ebapüsivaks magma voolamise tõttu raskusjõu toimel ja ümbriskivimi plastilise käitumise tõttu ning tema juhtivus seeläbi katkeb. Läbilaskevõimelise võrgustiku käigushoidmine piisavalt pika aja jooksul, mis on vajalik magma kogumiseks algkivimist ühe tektoonilis-termaalse sündmuse jooksul (sada tuhat kuni miljon aastat) on seetõttu äärmiselt keeruline.

Astmeline transport ja akumuleerumine omavad mõju magma keemilise koostise kujunemisele. Deformatsiooniliselt soodustatud magma mobiilsus mõjutab magma produktsiooni dünaamikat, määrates väljunud magmakogumite suuruste jaotuse ja sulami viibeaja algkivimis, mis omakorda mõjutavad süsteemist väljunud magma keemilist koostist. Nõrga deformatsiooni puhul on magma viibeaeg kivimis pikk võimaldades magmal keemiliselt tasakaalustuda ümbriskivimiga, väljunud magmakogumite keemilise koostise variatsioonid on seetõttu väikesed ning järgivad portsjonsulamise (*batch melting*) mudeli kõverat. Deformatsiooni intensiivistumine lühendab magma viibeaega, põhjustab väljunud magmakogumite keemilises koostises suuri variatsioone ning need järgivad teoreetilist fraktsioneeruva sulamise mudelit. Astmelise transpordi ja akumuleerumise numbriline mudel näitab seega deformatsiooni olulist rolli geokeemiliste variatsioonide tekkimisel magmalistes kivimkompleksides.

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PUBLICATIONS

CURRICULUM VITAE

Kristjan Urtson

Date of birth: 06.09.1974
Address: Institute of Geology at Tallinn University of Technology,
Ehitajate tee 5, 19086, Tallinn
Contact: Phone +372 620 3034
E-mail: urtson@gi.ee

Education

2005–...	University of Tartu, PhD studies in geology
2003–2005	University of Tartu, MSc in geology
1999–2003	University of Tartu, BSc in geology

Professional employment

2003–...	engineer at the Institute of Geology at Tallinn University of Technology

Research activity

Field of research:
Dynamics of magmatic processes, analogue and numerical modelling of geological processes

Publications

Bons, P.D., Becker, J.K., Elburg, M.A. and Urtson, K. 2010. Granite formation: Stepwise accumulation of melt or connected networks? Earth and Environmental Science Transactions of the Royal Society of Edinburgh, 100, 105–115.

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ELULOOKIRJELDUS

Kristjan Urtson

Sünniaeg: 06.09.1974
Aadress: Tallinna Tehnikaülikooli Geoloogia Instituut,
Ehitajate tee 5, 19086 Tallinn
Kontakt: Tel. +372 620 3034
E-mail: urtson@gi.ee

Haridus

2005–...	Tartu Ülikool, geoloogia doktorant
2003–2005	Tartu Ülikool, MSc geoloogias
1999–2003	Tartu ülikool, BSc geoloogias

Teenistuskäik

2003–...	Tallinna Tehnikaülikooli Geoloogia Instituut, insener

Teadustegevus

Teadustöö põhisuunad: Magmaprotsesside dünaamika, geoprotsesside analoog- ja numbriline modelleerimine

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