Estonian J. Earth Sci., 2007, **56**, 1, 3–10 https://doi.org/10.3176/earth.2007.06

An analogue model of melt segregation and accumulation processes in the Earth's crust

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Received 1 June 2006, in revised form 1 November 2006

Abstract. 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.

Key words: analogue modelling, melt segregation, migmatites, fractals, self-organized criticality.

INTRODUCTION

The processes of liquid phase generation, its segregation from the solid matrix and subsequent accumulation and transport occur in many natural systems such as partial melting of different materials including crustal rocks, hydrocarbon formation, etc. Partial melting and melt extraction from its source rock is the main way of magma generation in the Earth's crust. The length scales of magma formation processes cover more than twenty orders of magnitude, starting initially at the micrometre-level deep in the crust and finally forming large magma bodies, several cubic kilometres in volume, near the surface. However, the particular nature of magma accumulation and transport mechanisms and the way they are involved over the whole length range still remain quite unclear.

Migmatites as one of the manifestations of partial melting in the Earth's crust represent just the end product of magma formation or a snapshot of the magmatic system right before solidification. As the traces of previous processes and melt transportation pathways are rare, there is little evidence of the melting stage where the migmatite has been solidified, or of magma volume that has been produced and extracted from the migmatite under observation. These are important aspects in the study of a migmatitic system. Observation of a melting episode in progress could thus provide valuable information for understanding the dynamics of melt generation. However, re-creation of the melting processes at similar extreme physical conditions and long geological time scales as they occur in the crust is quite complicated and sets limits to the experimentation with real crustal rocks. Here the use of analogue materials is an alternative, which allows the experiment to be performed at normal conditions and therefore makes the real-time monitoring of the experiment possible. Certainly, when evaluating the results of the experiment, the somewhat different behaviour of analogue materials must be considered.

The analogue model introduced in this paper is one example of an artificially set up system where natural processes of phase differentiation can be directly observed and which, regardless of the contrasting physical properties of crustal rocks and materials used here, is a good descriptive tool in the studies of the problematic aspects of partial melting and magma formation.

MELT GENERATION IN THE CRUST

Although difficult to apply in real-time studies of mesoscale melt generation processes, melting experiments with crustal rocks have been performed to investigate melt behaviour at the microscale (e.g. Bagdassarov & Dorfman 1998; Knesel & Davidson 1999). As experiments suggest, the initial melt resides at grain junctions in isolated microscopic melt pockets or forms a thin film of liquid along grain boundaries. Melt segregation or draining from the solid fraction will start when a large number of such grain-scale melt domains are connected; this allows the melt to percolate through the rock (Sawyer 2001). The formation of a three-dimensional melt network and overcoming the melt percolation threshold depend mainly on the geometry of melt pockets, which is controlled by surface energy differences between solid and liquid phases, and less on the melt fraction in the rock (Walte et al. 2003). According to the melt composition, percolation thresholds of 3–4% (Laporte & Watson 1995) or 8% of melt (Vigneresse et al. 1996) have been predicted for crustal partial melting. However, the distance of magma transport by percolation through the microscopical melt network is limited due to the interaction of melt with cooler ambient rock. Therefore, this mode of transportation cannot account for the displacement of significant magma volumes.

Melt escape from the local system and magma transfer over larger distances will be possible if the cohesion between mineral grains is lost due to the high melt content in the rock. It has been proposed that 15–20% of melt volume is needed to overcome this melt escape threshold (Vigneresse et al. 1996). Many authors (e.g. Brown et al. 1999; Sawyer 2001; Marchildon & Brown 2003) support the conception of melt migration through connected melt flow networks, where small branching drainage paths feed larger melt channels and which stay conductive over a relatively long time. On the other hand, Bons et al. (2004) argued that neither a connected melt network nor reaching any threshold is required to accomplish magma segregation, and magma extraction and transport can take place at very low bulk melt fractions. According to their conceptual model, magma is transported discontinuously in the melt batches and the accumulation occurs by the stepwise merging of the batches. In this case, melt is rather inhomogeneously distributed in the rock, which allows overcoming melt percolation and escaping thresholds locally in limited space. Compared to percolation, melt transport in batches can be several orders of magnitude faster, which as a result, allows magma displacement over longer distances (Bons & van Millingen 2001).

Magma segregation and transport are mainly driven by the deformation of the rock. Pure shear, i.e. compaction of the rock, is effective on melt concentration, which results in melt segregation into low stress regions that are oriented to a plane at a high angle or perpendicular to compression (Vigneresse et al. 1996; Vigneresse & Burg 2000). Gradients in the normal stress field or non-coaxial forces as a simple shear component affect the mobility of melt along melt-rich domains and enhance melt extraction from the rock (Vigneresse & Burg 2000; Bons et al. 2004). The injection of melt from the adjacent areas can create additional gradients in the melt pressure field and cause melt redistribution within the system. High mobility of melt during crustal anatexis becomes evident from the internal structure of leucosomes (Mengel et al. 2001), as well as from the presence of discordant dykes that cross-cut the migmatitic banding (Maaløe 1992; Marchildon & Brown 2003).

THE ANALOGUE EXPERIMENT

The experiment stage consists of two 35 × 35 cm sealed glass plates with a 6.5 mm space between them (Fig. 1). The tank was filled with fine-grained quartz sand and sugar, water, and yeast mixture by settling the sand through the liquid column, so that the pore space between sand grains was completely saturated by the solution. The life activity of yeast bacteria results in the formation of alcohol and carbon dioxide gas. Being included in the sugar solution, the yeast was presumably homogeneously distributed throughout the volume of the tank, therefore the gas generation rate was assumed to be uniform. The production and redistribution of the gas phase was considered as the analogue of magma generation during crustal anatexis, with gas batches formed by the accumulation and transport processes representing the melt-rich domains or leucosomes in migmatites. The sand column as the solid phase represented the crustal block that undergoes partial melting. Extra normal stress or a simple shear component was not introduced in the experiment,

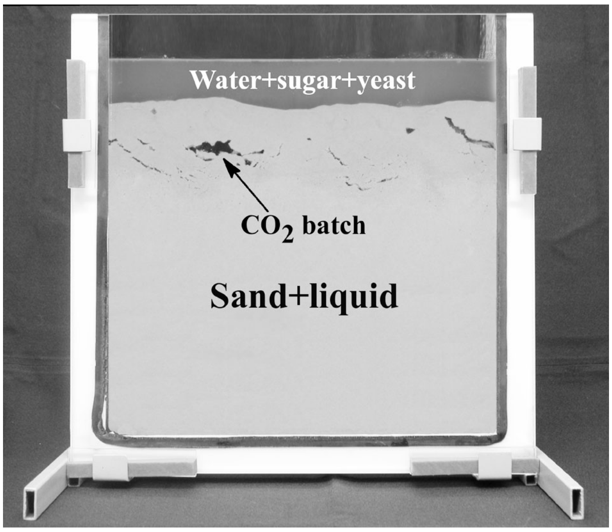

Fig. 1. Set-up of the analogue experiment in a flat glass tank. Carbon dioxide gas is generated by fermentation uniformly throughout the tank and is transported upwards discontinuously in separate batches when the gas flux exceeds the permeability of the intergranular space.

so the compactional stress of the sand column was the only deformational force that could influence gas segregation. The analogue materials used allowed the experiment to be performed at room temperature (20 °C). The original idea of this kind of analogue model is from Bons & van Millingen (2001), although focussed on different aspects at the analysis of the experiment results.

The described semi-flat and transparent tank design is assumed to represent a two-dimensional section through a three-dimensional gas phase segregation system and enables direct tracking of gas accumulation and movements of individual gas batches. The progression of the experiment was recorded in order to enable later analysis of gas behaviour. The authors have performed several analogous experiments with sand and carbon dioxide, with high temporal resolution and long time-range by using a digital video camera. The time resolution of 24 frames per second allowed analysis of the dynamics of gas movements at a very short time scale. In the experiment currently under discussion, a digital photo camera was used to get better spatial resolution. The frames were acquired by a 5.5-s interval during approximately 1.5 h and were used afterwards for statistical analysis of the model.

Some principal outlines of the gas behaviour during the experiment, characteristic of this phase segregation model, can be drawn here. During the first half-hour, the gas production increased; the gas still resided between the sand grains in the form of small bubbles but was progressively filling the pore space as inferred from the expansion of the liquid in the tank. At this stage, the gas bubbles were transported upwards in the gravity field by slow diffusion through the pore space. This transport mode was sufficient to accommodate the low but increasing gas flux. No visible changes were observed in the structure of the sand column at this stage of the experiment.

In half an hour, a notable change occurred in the gas transport mode and velocity when the gas flux exceeded the permeability of the sand column. The gas pressure in the pore space increased rapidly and caused the loss of cohesion between the sand grains, resulting in the formation of gas-filled voids. As some compactional stress due to the weight of the sand was present, the first gas accumulation batches and flow paths appeared as sub-horizontal cracks. In this way, the system in the tank modified itself for transmitting a larger volume of gas by opening the cracks and voids as additional gas escape pathways and temporary accumulation sites.

This more dynamical stage of experiment is characterized by stepwise and intermittent migration and accumulation of the gas. The redistribution and transport of the gas phase was managed by the merging of the batches, as the voids grew bigger and became connected, as well as by draining the gas from one part of the tank into another. The resulting batch grew until the critical volume was achieved, which created enough buoyancy for the batch to rise to the surface and escape from the system. The displacement and escape occurred as sudden gas bursts and subsequent collapse of the voids without leaving any apparent traces in the sand. Although the escaped gas volume is on average equal to the production rate, the transport is highly intermittent and large gas volumes are transported out of the system rapidly in separate escape events. Due to its highly dynamic nature, such a transport mode has also been called ballistical (Bons & van Millingen 2001).

Stepwise accumulation and transport of gas in the crack-shaped voids dominated during about one hour. At later stages, a static network of the bubble-shaped voids was developed, providing a steady open escape path for the gas over a long time period, probably due to the cohesion between the grains and limited compression effect of the overlying sand that avoided the complete closure of the drained voids but also due to thorough mixing of the system during the continuous gas production and transport.

Quantitative analysis of the results obtained included the estimation of the gas amount in the tank during the experiment and evaluation of the gas batch size statistics at different time steps. The pictures were analysed on the computer using the ImageJ image processing software (available as freeware on the website rsb.info.nih.gov/ij/). The batch sizes were determined by measuring their apparent areas in pixels on a thresholded image. In this way, the amount of the gas phase in the 2D section was estimated. Such a two-dimensional cut through the three-dimensional space can suffer from sectioning effects (see Bonnet et al. 2001), which influence correct estimation of the number of objects in the system – the number of small batches may be underestimated as they have less chance to be exposed in the front of the tank. However, in the current case the character of the representative cut and the possible influence of sectioning effects are still the matter of debate. Besides, as the resolution of the images of 96 pixels per inch sets the measuring limit to approximately 0.25 mm, only the areas of visible gas batches were recorded, most of the gas residing in the pore space was therefore excluded from the data set.

The measurements of gas batch areas suggest that their size distribution is not random. On the log-log diagram, the cumulative distribution of the gas batch sizes defines a straight line and therefore obeys the power law in the form

$$N_A = A^{-D},$$

where A is the batch size, N_A is the number of the batches greater than the specified size, and D is the fractal dimension or distribution exponent (Bonnet et al. 2001). The above expression is also known as Zipf's law. The power law with an exponent about 0.6 is defined over almost three orders of magnitude (Fig. 2).

The total gas amount in open fractures was derived by the total sum of batch areas. The gas amount fluctuated in the range from 7000 to 17 000 pixels (Fig. 3a). Compared to the image area, it corresponds to 1–2.6% of the gas fraction residing in the open cracks. The Benoit fractal analysis software from TruSoft Int'l Inc. was used to analyse the gas level fluctuation signal with Fourier transform, suggesting its $1/f$ power spectrum where the amplitude of fluctuations is inversely proportional to their frequency f (Fig. 3b).

The measurements of the batch sizes at different time steps show that the data fit the power law continuously throughout the experiment. However, the distribution exponent is not constant and increases gradually, probably due to the development of the system towards the static structure described above, where the contribution of smaller bubbles is more significant. Compared to this slowly increasing trend, the changes in the exponent value due to the short-time gas accumulation and escape processes are negligible, as suggests the closer study of the batch size distribution evolution (Fig. 3c,d). The power law nature of gas batch size distribution is characteristic of the experimental sand/carbon dioxide phase segregation system. This observation is also supported by former analogous experiments performed by the authors (not published).

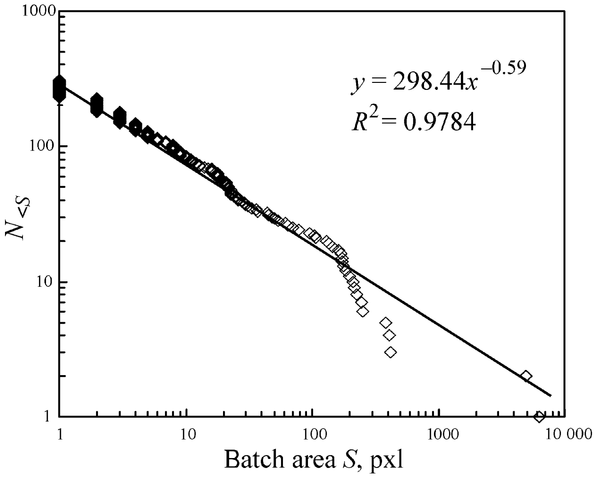

Fig. 2. Cumulative distribution of the gas batch sizes in the tank about 25 min after the transition to the ballistical transport mode. The data define a straight line, where the slope of the power law trend or distribution exponent represents the relative significance of smaller or larger batches.

DISCUSSION

The analogue experiment described here illustrates well the liquid phase segregation and transportation processes and the response of the system to increasing flux through it. However, the model should be treated just as a general example in a broader sense and not as a direct analogue of a natural magmatic system in detail. As the physical properties of crustal and experimental materials are not proportional, as well as the applied physical conditions, the rheology of materials in both systems is somewhat different. Distinct density contrasts between liquid and solid phases which control the buoyancy of the gas or crustal melt, contrasting viscosities of carbon dioxide gas and silicate melt, non-proportional differences in phase surface energies and incomparable applied stresses are the aspects that influence the behaviour of the liquid phase in details.

Generally speaking, the analogue model exhibits different modes of liquid phase transport in operation. The diffusional transport is controlled by the permeability of the rock, which depends on the porosity of the sand in the analogue model and on the presence and configuration of the microscopical melt network in partially molten crustal rocks. The model displays the transition from the diffusional to the ballistical mode where the system reorganizes itself to higher transport rates. In natural magmatic systems, this corresponds to the overcoming of the melt escape threshold, when the melt escape from the local space is permitted and which results in the redistribution and accumulation of melt into separate batches and leucosomes. As the analysis of the experiment suggests, the stepwise merging of batches and intermittent transport of the liquid phase leads to the state, where only a few largest batches contribute to most of the escaped liquid volume; the batches in the system have no characteristic size and their size distribution is best described by the power law. In that way, most of the melt resides in a few largest batches, whereas the overall distribution exponent is determined by numerous smaller batches. Removal of the largest batches from the system does not markedly influence the trend of size distribution of remaining batches. Therefore, the system can discharge a large amount of gas without leaving any traces in the sand and changing the topology of gas batches.

The leucosome width statistics in migmatites supports the evaluation of the model as a good analogue of crustal partial melting and magma accumulation. The leucosome widths measured in drill cores of the Estonian crystalline basement (Soesoo et al. 2004a), in outcrops of the Masku area, southwestern Finland (Johannes et al. 2003), and Montemor-o-Novo, central Portugal (Silva & Pereira 2004), obey generally the power law with exponents in the range D = 0.83–1.9 (Fig. 4; Soesoo et al. 2004b;

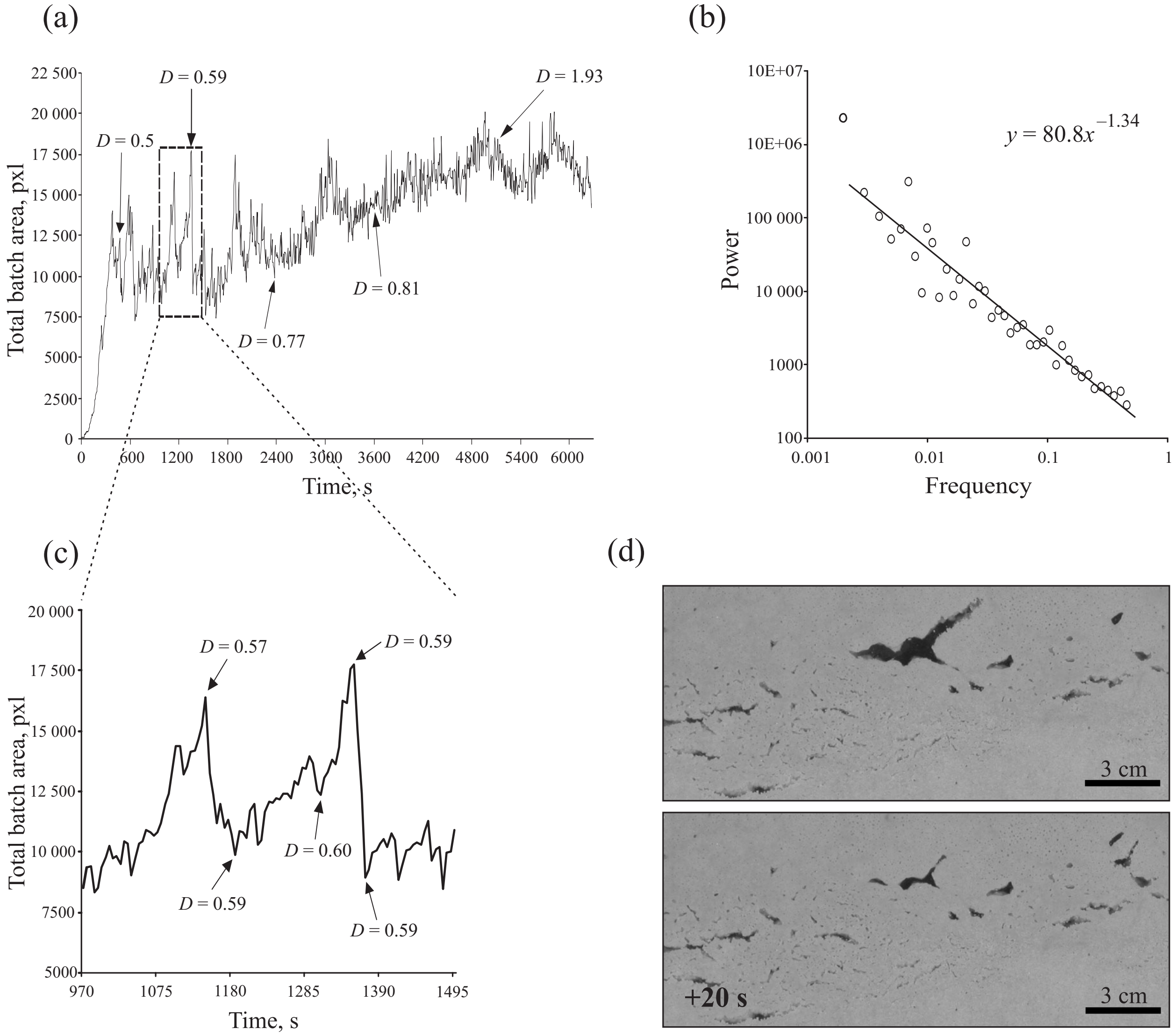

Fig. 3. (a) Fluctuation of the gas level during the experiment. Estimated gas batch size distribution exponents *D* show a continuous increasing trend due to the increasing number of small batches. The dashed rectangle specifies the time interval presented in Fig. 3c. (b) The 1/*f* power spectrum of the gas volume fluctuation signal where low-frequency fluctuations have larger amplitudes. (c) Close-up of the gas level fluctuation in the chosen 9-min interval and batch size distribution exponents in some selected time steps. Changes in the exponent are negligible, even if almost half of the gas escapes within a few seconds. (d) A gas escape event at about 23 min. The gas is drained from large batches; it does not influence the size distribution of the batches remaining in the system.

unpublished data of the authors). Other authors have reported both scale-invariant (fractal) (e.g. Tanner 1999) and non-fractal (Marchildon & Brown 2003) nature of leucosome thickness distributions.

Despite the variability of distribution exponents, which may be the result of particular melting conditions in different localities, the general common feature and resemblance with the experimental system is the overall definition of the power law trend. This allows us to assume the similar mechanisms and, as referred from the analogue model, stepwise and discontinuous nature of crustal melt transport and accumulation.

In the originally performed experiment, Bons & van Millingen (2001) measured the volumes of escaping gas batches and reported their power law size distribution as well as the 1/*f* power spectrum of the gas amount fluctuations in the tank. The emergence of fractality, power law statistics, and 1/*f* noise have been stated as the

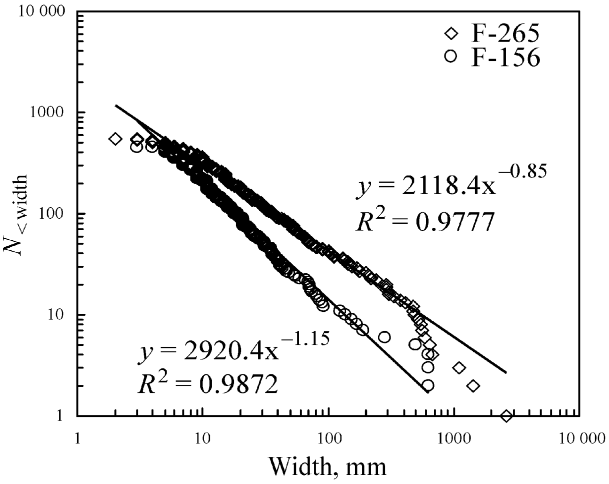

Fig. 4. Cumulative distributions of leucosome widths measured in two drill cores from the Estonian crystalline basement.

indicator of the incorporation of self-organized criticality (Bak et al. 1987). This phenomenon occurs in complex dynamic systems with a large number of interacting members and many degrees of freedom. Such systems may independently evolve into a critical state with self-similar behaviour and without characteristic time or length scales – into a self-organized critical state (Bak et al. 1988; Bak 1996). The self-organized critical state is characterized by the minimal stability, where the smallest disturbances may cause rearrangements of the system at all time and length scales. A classical example of a self-organized critical system is the sand pile, which consists of a large number of interacting sand particles (Bak 1996). Adding one single grain to the critical slope may result in the reposition of just a few grains or cause a large avalanche that involves the whole pile. The sand is transported downwards discontinuously in the form of avalanches. The numerical and analogue constructions of the sand pile model imply the power law statistics of the avalanche sizes (Bak 1996). Bons & van Millingen (2001) introduced a cellular automaton model where the fluid transport along the row of fluid-filled cells is carried out via diffusive channels or, alternatively, by opening valves in the ballistical transport channels to accommodate higher flux. At high flux rates when the ballistical transport is activated, the system reaches quickly the self-organized critical state where the transport of the fluid occurs as intermittent bursts with a wide range of amplitudes and which is characterized by the fluctuating pressure with the 1/*f* power spectrum.

The numerical valve model of Bons & van Millingen (2001) has a straightforward analogy with the sand–carbon dioxide experimental system, where the formation of gas-filled cracks and voids in the sand due to the increased gas flux resembles the opening of ballistical transport channels. Moreover, there exists interaction and "communication" between different parts of the tank, as the gas is continuously redistributed due to the merging and escaping of the batches. The draining of one batch into another or escaping from the system reorganizes the gas pressure gradient pattern within the tank and can trigger the merging or escaping of new batches. The stepwise transport of the gas as sudden bursts is comparable to the avalanches on the sand pile or fluid bursts between cells in the valve model. The experimental sand–carbon dioxide model thus holds the characteristics of a self-organized critical system – a large number of interacting members and degrees of freedom to adapt to higher transport rates, which results in a scale-free and self-similar behaviour over three orders of magnitude at the length and time scales, inferred from the power law size distribution of the gas batches in the system and volumes escaped, as well as from the 1/*f* power spectrum of the gas level fluctuations in the tank.

The behaviour of the gas, considered as an analogue of the crustal silicate melt, allows us to assume that similar mechanisms are also involved in real crustal partial melting processes. The stepwise and discontinuous transport of magma has certain influences, for example, on the chemical composition of magma at variable equilibration times of separate magma batches, as well as at the mixing of magma batches with different chemical compositions and should, therefore, be taken into consideration in studies of the evolution of magmatic systems.

In addition to the application in partial melting studies, the analogue experiment described here can also be a useful tool in other research fields, for example, in petroleum geology, where the probable stepwise and dynamic nature of the extraction of hydrocarbons from their source, upward movement of hydrocarbons and their accumulation in oil and gas reservoirs at higher levels should be considered. In the same way, the ballistical style of hydrothermal fluid movement through sediments can have a significant influence on the concentration of ore minerals.

CONCLUSIONS

A liquid phase segregation model using carbon dioxide gas and sand as analogues of crustal partial melt and host rock, respectively, displays liquid transport and accumulation mechanisms, which should be important also in natural magmatic systems. At low flux rates, the diffusion through the pore space is sufficient to accommodate all of the needed transport. If the flux exceeds the permeability of the intergranular space, the rock structure is modified to permit higher transport rates. The fluid transport becomes highly dynamic, being characterized by intermittent and stepwise merging and escape of fluid batches. The ballistical transport results in the emergence of power law statistics of fluid batch sizes and 1/*f* noise of fluid fraction fluctuations, which give evidence of a possible self-organized critical nature of fluid segregation processes. In that state, the system can discharge a large amount of fluid without modifying itself and leaving traces of escape events. Implications of analogue and theoretical models to real magmatic systems are supported by power law leucosome width distributions measured in migmatites from several localities.

ACKNOWLEDGEMENTS

The research was financially supported by the Estonian target funding programme No. 0332652s04 and the Estonian Science Foundation (grant No. 6749).

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Maakoore osalise ülessulamise protsesside modelleerimine analoogmaterjalide abil

Kristjan Urtson ja Alvar Soesoo

Magma segregeerumist ja transporti maakoores on modelleeritud analoogmaterjalide abil, kasutades magma ja maakoore kivimite analoogidena vastavalt süsihappegaasi ja liiva. Analoogmudel näitab, et transpordivoogude kasvamisel toimub üleminek difusiooniliselt transpordilt ballistilisele, mida iseloomustab astmeline gaasi ümberpaigutumine ja lahkumine süsteemist üksikute piiritletud kogumitena. Astmelise gaasi akumulatsiooni ja transpordi tulemuseks on gaasikogumite suuruste astmejaotus ja gaasinivoo fluktuatsioonide 1/*f* spekter, mis tõendavad segregatsiooniprotsesside tõenäoliselt iseorganiseeruvat kriitilist olemust. Analoogmudeli võrreldavust reaalsete magmaprotsessidega toetavad migmatiitides mõõdetud leukosoomide laiuste astmejaotused.