Grain-scale pervasive melt transport through the crust: evidence, mechanism and consequences

Pavlína Hasalová [1,2], Karel Schulmann [2], Ondrej Lexa [2], Pavla Štípská [2] and Vojta Janoušek [3]

[1]IPSG, Charles University, Albertov 6, Prague 2, Czech Republic email: hasalovap@gmail.com [2] Université Louis Pasteur, EOST, 1 rue Blessig, Strasbourg, France [3] Czech Geological Survey, Klárov 3, Prague 2, Czech Republic

General abstract

The general aim of the presented research is to better understand melt transport in the crust and origin of migmatitic rocks. Several authors have recently proposed for transport of felsic magma through hot, mid-crustal rocks a mechanism termed pervasive flow (e.g. Olsen et al., 2004). In their model, foliation-parallel veins/sheets of granitic composition invade hot country rocks, whose low viscosity inhibits hydrofracturing and dyking. Pervasive melt migration controlled by regional deformation in an outcrop scale was also confirmed by a number of field studies. These authors argued that magma intrudes pervasively, parallel to main anisotropy represented by foliation planes, fold hinges and boudin necks (e.g. Brown et al., 1995). Here, we propose a new mechanism of melt migration controlled by **melt infiltration** (porous flow) at grain scale and argue that the large-scale pervasive flow does not require formation of channelized pathways but can also occur penetratively, along grain boundaries. Nevertheless, we are aware that the proposed model still contains several aspects that remain to be clarified.

Technical abstract

The melt extraction from lower crust and its further transport to higher crustal levels are key issues of granite petrogenesis. The melt fraction produced during anatexis originally concentrated mainly at grain boundaries and along microfractures, however the mechanism of the melt segregation is still a controversial issue. It may be drained from the grain boundaries to melt-assisted sites, networks of leucosome-filled structures or dykes (e. g. Petford et al., 1994) responsible for its further transport. The other, arguably more popular model involves pervasive flow through a porous space or fracture network (McKenzie, 1984; Weinberg, 1999) and is strongly controlled by the permeability of the system. Regardless of its exact mechanism, the segregation will be governed by the melt density and viscosity, which in turn reflect its composition, volatile contents and temperature (Brown et al., 1995). Important factor is also the thermal and mechanical state of the crust surrounding the melting zone (Weinberg and Searle, 1998). The efficiency of the melt extraction can be further boosted by active deformation in the source (McKenzie, 1984). At the grain scale, the transport is controlled mainly by the melt geometry (wetting angle) and its amount (e.g. Rushmer, 1995). The grain-scale movement is possible as soon as the melt forms an interconnected network. Even when the wetting angle is low, an important prerequisite for the operation of pervasive porous flow is the lower solidus temperature of the country rock compared to that of the penetrating melt. The other passionately discussed problem is the further transport of the granitic melts. There are three major mechanisms controlling melt migration through the continental crust: (i) diapirism resulting in upward motion of low-density magma through higher density rocks, (ii) dyking that describes melt migration by hydrofracturing of the host rock and transport of melt through narrow dykes (Petford et al., 1994), (iii) and migration of a melt through a network of interconnected pores during deformation or compaction of solid matrix (McKenzie, 1984). As an alternative we propose pervasive magma migration at a grain scale through the whole rock volume (Hasalová et al, 2007).

Field and microstructural observations

Based on detail field and microstructural study four types of gneisses and migmatites were described in the Gföhl gneiss complex (Bohemian Massif) (Figs. 1): (i) Banded orthogneiss (Type I) with distinctly separated monomineralic layers of recrystallized plagioclase, K-feldspar and quartz separated by distinct layers of biotite; (ii) Stromatitic migmatite (Type II) composed of plagioclase and K-feldspar aggregates with subordinate quartz and irregular quartz aggregates. The boundaries between individual aggregates are ill-defined and rather diffuse; (iii) Schlieren migmatite (Type III) consists of plagioclase-quartz and K-feldspar-quartz enriched domains and the foliation is marked only by preferred orientation of biotite and sillimanite dispersed in the rock; (iv) nebulitic migmatite (Type IV) with no relicts of gneissosity. It was shown, that they form a continuous sequence developed by melt-present deformation, where the Type I banded orthogneisses and Type IV nebulitic migmatites are considered as end-members (Fig. 1). Progressive disintegration of banded microstructure and development of the nebulitic migmatites are characterized by several systematic textural changes. The grain size of all felsic phases continuously decrease while population density of precipitated phases increases (Fig. 3). The new phases preferentially nucleate along high-energy like-like boundaries causing the development of regular distribution of individual phases. Simultaneously, the modal proportions of felsic phases evolves towards "granitic minimum" composition (Fig. 4). Further this evolutionary trend is accompanied with decrease in grain shape preferred orientation (SPO) of all felsic phases (Fig. 5). To explain all mentioned textural changes together with macroscopic observations and compositional changes we introduced the model of **melt infiltration** from external source where melt passes pervasively along grain boundaries through the whole rock volume. It is suggest that the individual migmatite types represent different degree of equilibration between the host rock and passing melt during retrograde P-T conditions.

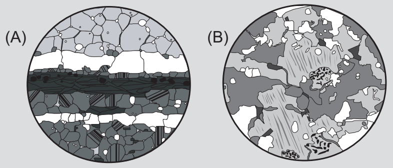


Fig. 2: Detail of microstructure of the two extreme end-members: banded orthogneiss (A) and nebulitic migmatite (B).

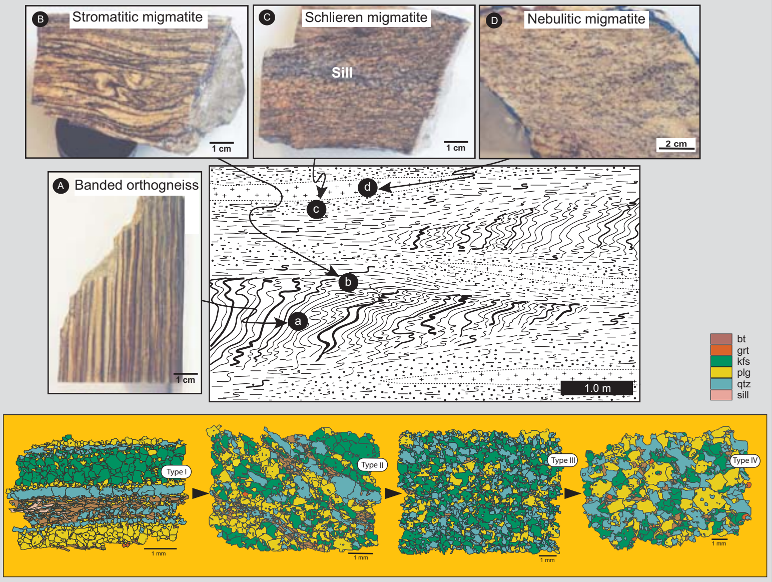
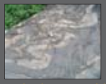


Fig. 1: Sketch showing relationships between individual rock types in an outcrop scale. Banded orthogneiss (A) with S1 monomineral layering is preserved in relics and transposed to a stromatitic migmatite (B) that further passes to schlieren migmatite (C) Macroscopically isotropic nebulitic migmatite (D) forms elongated lbodies in S2 foliation. Rock photos and digitalized thin-sections of studied migmatite sequence show a continuous disintegration of the original high-grade solid state banded orthogneiss (type I) with distinctly separated monomineralic layers to the nebulitic migmatite (type IV) with no relict of gneissosity.

Glossary

Migmatite: a mixed rock involving igneous and metamorphic components (leucosome and mesosome ± melanosome). Migmatite terminology is quite complex, depending on its appearance, origin and amount of molten material.



Restite: the residual material left at the site of melting.

PolyLX: Matlab toolbox (Lexa, 2003) for fabric quantification. Freeware to download at: http://petrol.natur.cuni.cz/~ondro.

Anatexis: refers to the differential, or partial, melting of rocks, especially in the forming of metamorphic rocks such as migmatites. Each mineral in a rock has its own melting temperature, which is decreased to varying degrees by its close association with other minerals.

Metasomatism: the process by which the chemical composition of a rock is changed by interaction with fluids; replacement of one mineral by another without melting.

Melt infiltration: the process where melt from external source passes pervasively along grain boundaries through the whole rock volume.

Myrmekite: irregular, wormy penetration by quartz in plagioclase feldspar; these wormlike, or fingerlike bodies may develop during the late stages of crystallization of igneous rocks if the two minerals (quartz and feldspar) grow simultaneously in the presence of a volatile phase.

Schlieren: irregular dark or light streaks in rock that differ in composition from the principal mass. The origin of schlieren are not always clear, but may be produced by differential magma flow or disaggregation of xenoliths, among other mechanisms.

Mass balance: is an accounting of material entering and leaving a system. Fundamental to the balance is the conservation of mass principle, i.e. that matter can not disappear or be created.

Quantitative Textural Analysis

Textural parameters such as grain size, aspect ratio, grain boundary (GBPO) and shape preferred orientation (SPO) combined with other data as AMS and crystallographic preferred orientation help us to quantified the fabric midifications connected to disintegration of parental banded orthogneiss and development of random mineral microstructure. The quantification was done using Matlab PolyLX Toolbox (Lexa, 2003).

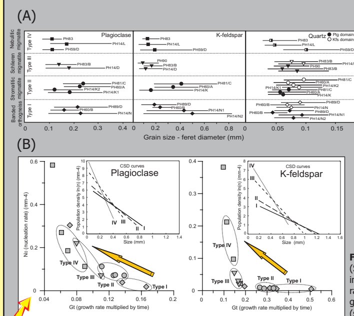


Fig. 3: Grain size statistic. (A) Calculated average grain size and standard deviation for plagioclase, K-feldspar and quartz. (B) Plots of crystal size distribution parameters N0 (corresponding to the nucleation density per size per volume) and Gt (non-dimensional value dependent on the growth rate).

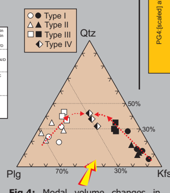


Fig.4: Modal volume changes in both plagioclase (open symbols) and K-feldspar (closed symbols) domains throughout the studied sequence.

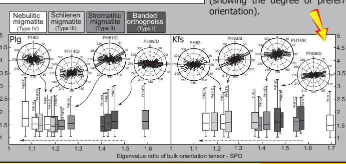
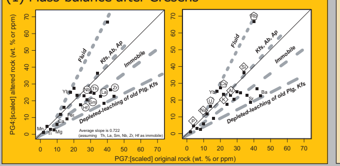


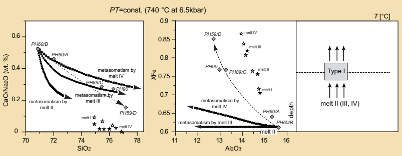
Fig. 5: Shape preffered orientation (SPO). The results are summarized in a boxplot-type diagram of aspect ratios (characterizing the shape of grains) vs. eigenvalue ratios (showing the degree of preferred orientation).

Geochemical and thermodynamic modelling

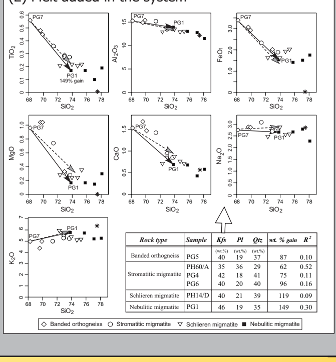
(1) Mass-balance after Gresens



(3) Metasomatism by melt



(2) Melt added in the system



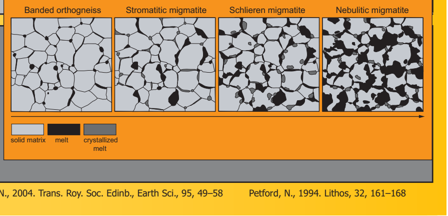
Rock type	*Sample*	*Kfs* (wt.%)	*Pl* (wt.%)	*Qtz* (wt.%)	*wt. % gain*	*R^2*
Banded orthogneiss	PG5	40	19	37	87	0.10
Stromatitic migmatite	PH60/A	35	36	29	62	0.52
	PG4	42	18	41	75	0.11
	PG6	40	20	40	96	0.16
Schlieren migmatite	PH14/D	40	21	39	119	0.09
Nebulitic migmatite	PG1	46	19	35	149	0.30

We have attempted to model the process of melt infiltration as an open-system process by three possible approaches. All of them are using whole-rock geochemical data and mineral chemistry:

(1) For assessment of the mass balance in individual major- and trace-elements during the orthogneiss transformation was used the approach of Gresens (1967) in the form of isocon plots. The results of individual isocon analyses were pulled together into binary plots of an immobile element vs. relative gains/losses (%) of individual elements. Slopes of the isocons fitted to these HFS elements are lower than unity in all cases, pointing to an increase in the overall mass of the system. This approach resulted in identification of component added to the original orthogneiss, resulting from a heterogeneous nucleation of feldspars, quartz and apatite from the passing melt. This is in line with the observed presence of new albitic Plg, Kfs and Qtz coatings as well as resorption of relict feldspars in the matrix.

(2) As an addition of K-feldspar, plagioclase and quartz crystallized from the melt passing through the banded orthogneiss. The whole compositional spectrum from the banded orthogneisses to the nebulitic migmatite can be explained by a relative gain up to 60 % of K-feldspar, plagioclase and quartz. The proportion of the three minerals changes from roughly balanced to a strong prevalence of K-feldspar (~40 %) and quartz (~40 %) over plagioclase (~20 %).

(3) Metasomatism by melt, where melt moves through and equilibrates with the host rock and leaves it with slightly different composition, the rock also changing composition. The infiltrating melt may have been lost from similar protoliths at any point on the P-T path, moving up through the rock pile, or it can be of foreign derivation, for example from granulitic migmatites outside the Gföhl orthogneiss migmatite body. Using this modelling we tried to evaluate the change of rock composition that such a continuing equilibration with infiltrating melt produces.



Conclusions

- We introduce the concept of melt infiltration from external source where melt passes pervasively along grain boundaries through the whole rock volume and changes macroscopic (Fig.1) and microscopic (Fig. 2) appearance of the rock. This process is characterised by resorption of old phases, nucleation of new ones along high energy like-like grain boundaries and modification of mineral and whole-rock composition. It should be emphasized, that all these processes occur along retrograde path during the exhumation of the Gföhl unit.
- We argue that the large-scale pervasive flow does not require formation of channelized pathways but can also occur penetratively, along grain boundaries.
- And if true such a large quantity of melt penetrative passing through rock would have profound implications for melt transport in a migmatitic crust and would be a crucial process for crustal differentiation and also for crustal rheology during orogeny.

References: Brown, M. et al. , 1995. Journal of Geophysical Research, 100, 15655-15679
Rushmer, T., 1995. Journal of Geophysical Research, 100, 15681–15695
Lexa, O., 2003. Unpublished PhD thesis, Charles University, Prague
Weinberg, R., 1999. Lithos, 46, 393–410
McKenzie, D., 1984. Journal of Petrology, 25, 713-765
Weinberg, R. and Searle, M.P., 1998. Journal of Geological Society, 155, 883–891
Olsen, S.N., 2004. Trans. Roy. Soc. Edinb., Earth Sci., 95, 49–58
Petford, N., 1994. Lithos, 32, 161–168