Unraveling the Complexity of Magma Mixing Processes and its Petrologic Implications: an Experimental and Numerical Approach

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A new experimental apparatus has been developed to perform chaotic magma mixing experiments in systems of melts with high temperature and viscosity contrast. The apparatus consists of an outer and an inner cylinder, independently rotating at definite strain rate to generate chaotic streamlines. The two cylinders axes are offset. Two end-member silicate melt compositions were synthesized: 1) a peralkaline haplogranite and 2) a haplobasalt. The viscosity ratio between these two melts was of the order of 10^3. Experiments have been performed for approximately two hours, at $1400°C$ under laminar fluid dynamic conditions [Re $\sim 10^{(-7)}$]. Initial proportions of the peralkaline haplogranite and haplobasalt were 95% and 5%, respectively.

Results show that the two melts mixed very efficiently producing patterns that are topologically identical to magma mixing structures observed in volcanic rocks. In particular, in both experiments and natural rocks, a scale-invariant (i.e. fractal) distribution of alternate filaments of the two melts is observed down to the micrometric scale. Such an intimate mechanical mixing is the prerequisite for the onset of efficient mass transfer between the interacting melts via chemical diffusion.

Chemical analysis by electron microprobe have been performed along several transects crossing the filament-like structures. Results show that the combination of advection (mechanical mixing) and diffusion produces extremely variable compositional patterns, both in space and time. Compositional fields are differently modulated depending on the local amounts of the two melts and their spatial distribution. A first remarkable result is that, contrary to common thinking, inter-elemental binary plots do not show linear variations, as it should be expected from a pure two end-member mixing process. This result is related to different diffusivities for different chemical elements triggering diffusive fractionation processes, which are responsible for the deviation of compositional patterns from simple linear trends.

The homogenization time along different transects has been estimated using the numerical solution of the diffusion equation for an infinite medium with an initial concentration being a periodic function in time. To this aim the variation of concentration through the filaments has been fitted by means of the Fourier series technique whose polynomial expansion is used as the periodic function. Results show that time-scales for homogenization are variable for the different chemical elements due to their different diffusivities. In addition, it is shown that the time required to erase compositional diversity is also different for the different filaments. Homogenization time is then strongly dependent on the relative amount of melts that locally interact in the mixing system. This strong modulation of compositional fields in space and time is responsible for the production of a virtually infinite number of transient end-members that are continuously generated with progression of the mixing process in time.

Results presented in this work offer new insights into the complexity of processes expected to be operating during magma mixing and may have important petrological implications. In particular: i) it is shown that, in contrast with current thinking, rheologically contrasting magmas can mix (i.e. with large proportions of felsic magmas and high viscosity ratios), thus extending significantly the spectrum of geological conditions under which magma mixing processes can occur efficiently; ii) the mixing process cannot be modeled using the classical linear two-end-member mixing model; and iii) the chemical compositions on short length-scales represent only snapshots within the process of mixing and therefore, if used in classic petrologic models, may provide misleading information on the composition of parental magmas.