Short Visit Report

Coupling the decompression dynamics and disequilibrium crystallization: Comparison between laboratory and numerical modeling results

Mattia de' Michieli Vitturi, Caroline Martel

1. Purpose of the visit

In the last decades, magma ascent processes have been increasingly recognized as exerting control on the style and intensity of volcanic activity. In particular, the primary role of the decompression rate on degassing and crystallization has been highlighted by theoretical and experimental studies.

Recent numerical models have contributed to investigate the influence of different parameters (e.g. vesicularity, crystal content, water content) on decompression dynamics during extrusive and explosive eruption regime. To simulate the syn-eruptive processes as close as possible, such numerical models require relevant evolution paths of both, degassing and crystallization during magma ascent in the volcanic conduit. In particular, there is a need to know when syn-eruptive crystallization changes from an equilibrium state to a disequilibrium process as a function of decompression rate. Such data on crystallization kinetics and dynamic can be provided by decompression experiments.

To this aim, the comparison with continuous decompression experiments is crucial and a collaboration between the Institut des Sciences de la Terre d'Orléans (ISTO), Orléans, and the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Pisa, could provide the ideal link to better interpreting natural magma ascent processes.

2. Description of the work carried out during the visit

Since this visit was really the first contact between the two participants, one part of the work was dedicated to (i) the presentation of the numerical model (M. de Michieli Vitturi; INGV Pisa) and (ii) the description of the decompression experiments (C. Martel; ISTO, Orléans).

(i) The numerical model is a new magma ascent model solving the multiphase compressible equations governing magma movement through a subsurface pathway (from chamber to surface, for example), and representing a significant advance in terms of its quantitative description of the magma system in that it: 1) is capable of treating both dilute and dense flow regimes; 2) describes flow above and below the fragmentation level in a coupled and consistent way; 3) quantifies the interaction between two phases forming the magmatic mixture by using two distinct pressures and velocities; and 4) accounts for disequilibrium crystallization and degassing. In particular, the disequilibrium processes are introduced and controlled by equilibrium profiles β^{eq} and x_d^{eq} and two semi-empirical parameters $\tau^{(d)}$ and $\tau^{(c)}$ (that have to be tested and constrained) controlling the degree of disequilibrium. The resulting equation describing the temporal evolution of the crystal volume fraction β and the mass fraction of dissolved gas x_d write as:

$$\frac{\partial}{\partial t}\left(\rho_c \alpha_1 \beta\right)+\frac{\partial}{\partial z}\left(\rho_c \alpha_1 \beta u_1\right)=\frac{1}{\tau^{(c)}}\alpha_1 \rho_c\left(\beta-\beta^{eq}\right)$$

$$\frac{\partial}{\partial t}\left[x_d \alpha_1\left(\rho_1-\beta\rho_c\right)\right]+\frac{\partial}{\partial z}\left[x_d \alpha_1\left(\rho_1-\beta\rho_c\right)u_1\right]=\frac{1}{\tau^{(d)}}\left(x_d-x_d^{eq}\right)\alpha_1\left(\rho_1-\beta\rho_c\right)$$

(ii) The decompression experiments (*Martel, 2012*) were designed to experimentally reproduce the characteristics of the plagioclase microlites (syn-eruptive crystallization) from Plinian, block-and-ash flow, surge, and dome products of Mt Pelée andesite (Martinique, F.W.I.). Indeed, the microlites of the natural pyroclasts show different volume fractions, number densities, crystal lengths, and morphologies depending on the eruption style they were emitted by (*Martel & Poussineau, 2007*). Starting from the hydrated residual melt (rhyolitic) in equilibrium with the phenocrysts in the magma chamber, isothermal (850°C) decompression experiments were performed in high-pressure and high-temperature devices (Figure 1).

Figure 1. Cold-seal pressure-vessel pressurized with argon and equipped with rapid-quench device at ISTO (Orléans, France). Maximum temperature is 875°C and maximum pressure is 200 MPa. The represented autoclave is additionally equipped with a servo-controlled air-driven decompression valve allowing quasi steady-state decompressions over long durations.

The decompressions have been performed from 200 MPa (pre-eruptive pressure; *Martel et al., 1998*) to 5-10 or 30 MPa. Crystallization occurred either during decompression up to 40 days or at final pressure. The experimental plagioclases were analysed by image analysis in terms of fraction, number density, crystal length, and morphology. Diagrams showing the evolution of these parameters as a function of decompression rate (Figure 2) or time spent at final pressure were realized. These experiments highlight the complexity of decompression-induced crystallization, showing nucleation delays and strong chemical disequilibria.

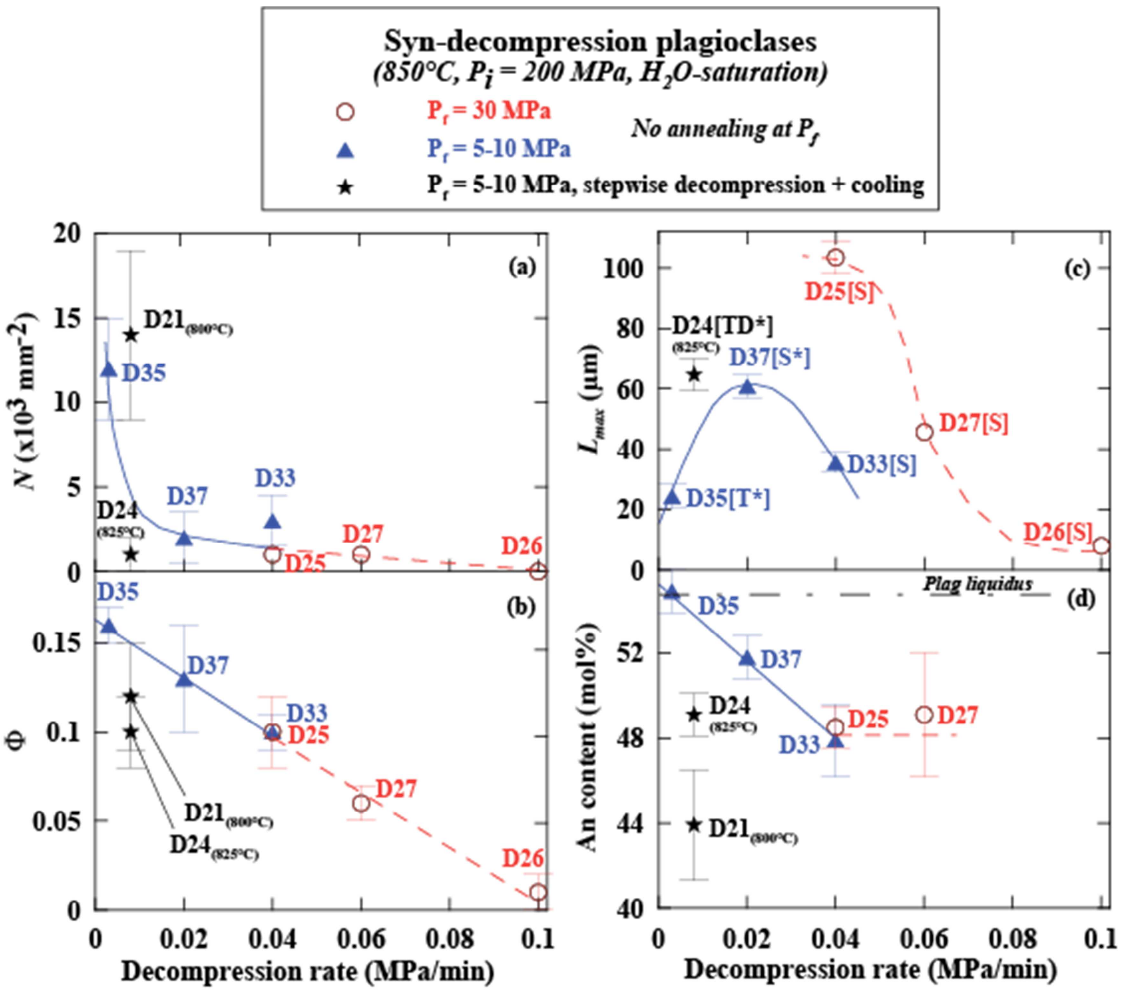

Figure 2. Textural and compositional characteristics of the syn-decompression plagioclases as a function of decompression rate. **(a)** Plagioclase number density, **(b)** area fraction, **(c)** crystal size, and **(d)** composition (*Martel, 2012*).

3. Description of the main results obtained

The numerical model presently considers equilibrium crystallization with decompression, based on the experiments of *Couch et al. (2003)*. However the experimental work described above suggests that equilibrium crystallization, i.e. showing the volume fraction of crystals expected from phase equilibrium at a given pressure, may only be reached for specific conditions of crystallization. In particular, chemical equilibrium may be reached for crystallization occurring at constant (final) pressure after a rapid decompression. In contrast, syn-decompression crystallization does not reach equilibrium, even after 40-days decompression (see run #D35 in Figure 2b, for which phase equilibrium at 5-10 MPa would suggest a crystal volume fraction of 0.45 instead of the 0.16 analysed).

Therefore, the numerical model had to be modified in order to incorporate a relevant evolution of crystallization fraction as a function of decompression rate, for the whole spectrum of decompression rates that may be associated to dome-forming and Plinian eruptions of silicic magmas. To this aim, we determined some parameters that must be modified in the crystallization equations previously used and validated some results for the case of the eruption of the 1929 block-and-ash flows of Mt Pelée. The numerical model has been tested with a conduit of 8 km length and different values of the radius, in order to obtain different ascent velocities and thus different decompression rates. The pressure at the conduit inlet and outlet are fixed respectively at 200 MPa and 10 MPa, in order to mimic the experimental conditions. The solutions for a conduit radius of 20 m and 75 m are plotted in Figures 3 and 4, while the corresponding decompression and crystallization plots are presented in Figures 5 and 6.

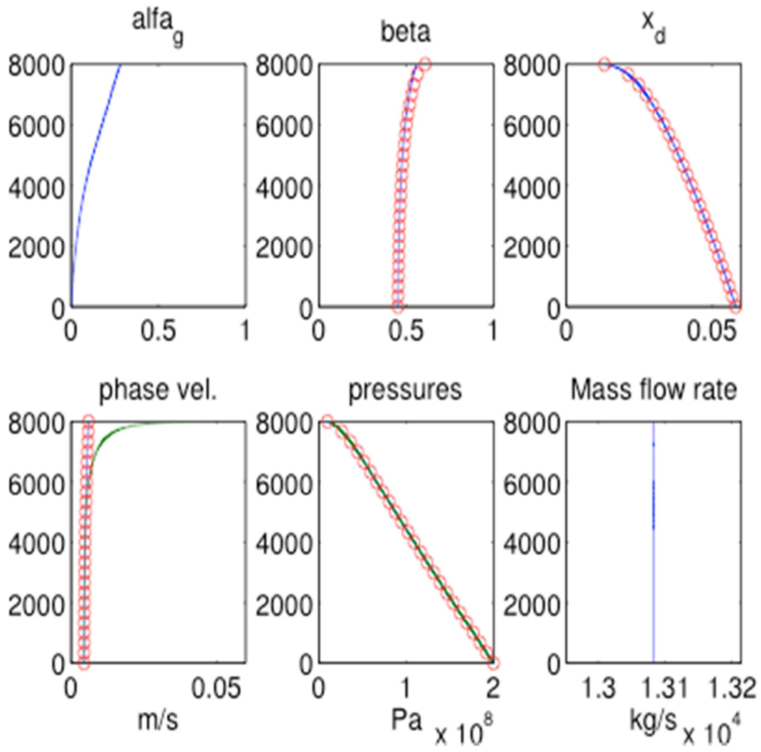

Figure 1. Vertical profiles for the solution of a numerical simulation done with conditions representative of Mt Pelée and a radius of 20 m. The blue lines represent the solutions of the model, while the red dots represent equilibrium values.

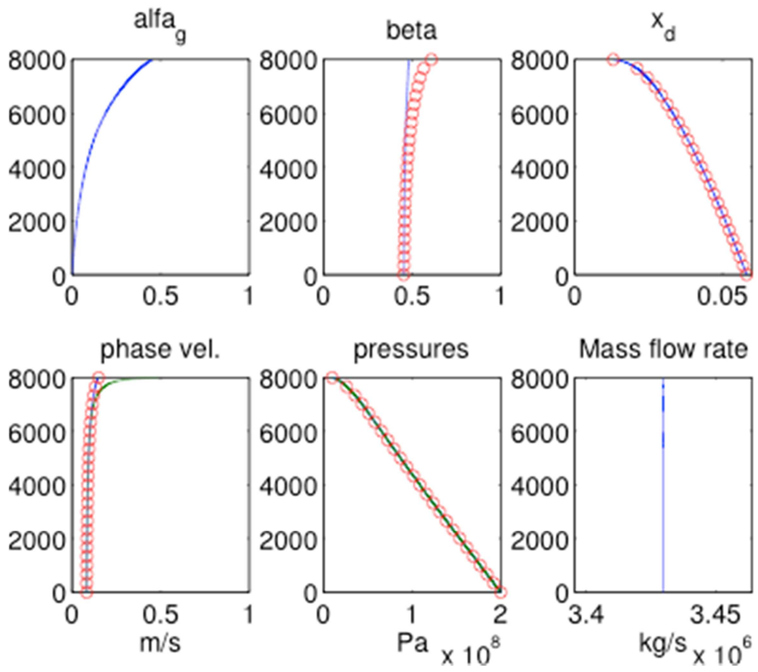

Figure 2. Vertical profiles for the solution of a numerical simulation done with conditions representative of Mt Pelée and a radius of 75 m. The blue lines represent the solutions of the model, while the red dots represent equilibrium values.

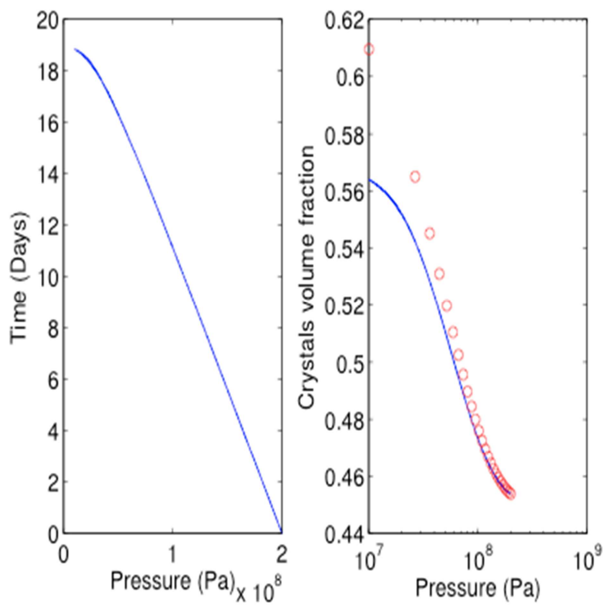

Figure 5. Time (left) and Crystal Volume Fraction (right) vs Pressure for a numerical simulation done with conditions representative of Mt Pelée and a radius of 20 m. The magma decompress from 200 MPa to 10 MPa with an average decompression rate of $7x10^{-3}$ MPa/min.

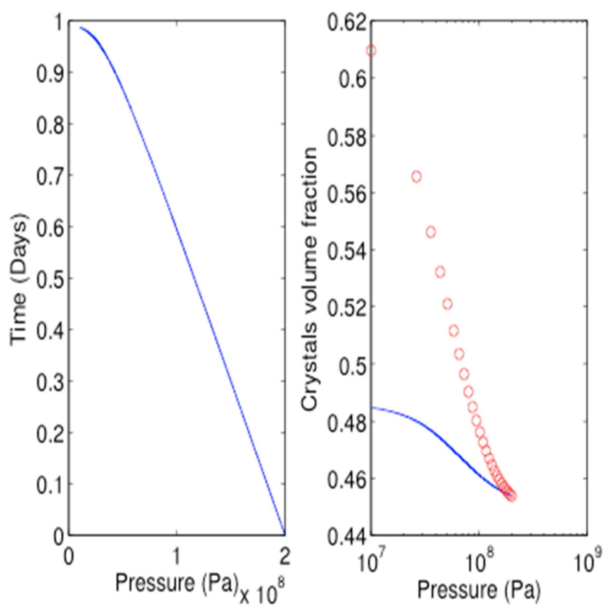

Figure 6. Time (left) and Crystal Volume Fraction (right) vs Pressure for a numerical simulation done with conduit conditions representative of Mt Pelée and a radius of 75 m. The magma decompress from 200 MPa to 10 MPa with an average decompression rate of $1.3x10^{-1}$ MPa/min.

4. Future collaboration with host institution

The changes of the parameters and equations of crystallization in the numerical code will require a consequent amount of time. Therefore, we planned to visit again as soon as these changes will be done, first in order to validate the new code with the experimental and natural data of Mt Pelée, and second, because we would also like to take into account the evolution of the number density of crystals as a function of decompression rate. Indeed, the experiments provide the evolution of the number of crystals with decompression rate (Figure 2a), which could be incorporated into the numerical model.

5. Projected publications / articles resulting or to result from the grant (ESF must be acknowledged in publications resulting from the grantee's work in relation with the grant)

Once validations between the numerical and empirical (experimental) models will be performed, there will be solid material for publication.

References

Couch S., Sparks, R.S.J. & Carroll M.R. (2003) The kinetics of degassing-induced crystallization at Soufrière Hills volcano, Montserrat. J. Petrol. 44, 1477-1502.

Martel C. (2012) Eruption dynamics inferred from microlite crystallization experiments: Application to Plinian and dome-forming eruptions of Mt. Pelée (Martinique, Lesser Antilles). J. Petrol. 53, 699-725.

Martel C., Pichavant M., Bourdier J.-L., Traineau H., Holtz F. & Scaillet B. (1998) Magma storage conditions and control of eruption regime in silicic volcanoes: experimental evidence from Mt. Pelée. Earth Planet. Sci. Lett. 156, 89-99.

Martel C. & Poussineau S. (2007) Diversity of eruptive style inferred from the microlites of Mt. Pelée andesite (Martinique, Lesser Antilles). J. Volcanol. Geotherm. Res. 166, 233-254.