LARGE-SCALE PLINIAN ERUPTIONS OF THE COLLI ALBANI AND THE CAMPI FLEGREI VOLCANOES: INSIGHTS FROM TEXTURAL AND RHEOLOGICAL STUDIES

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INTRODUCTION

The objective of this study was to investigate the mechanisms responsible for generating large-scale Plinian eruptions. In particular, the aim was to try to understand the role and the influence of different physical parameters of the magma, with particular reference to its fluid-dynamic, in generating the energies necessary to create and sustain convective columns, with special attention to the analyses of the transitions from sustained to collapsed columns. Eruptions with different compositions, and different viscosities, were chosen: phono-tephrites (Pozzolane Rosse) and tephri-phonites (Pozzolane Nere) from the Colli Albani volcano and trachytes (Agnano Monte Spina) from the Campi Flegrei caldera. All these magmas, despite their variability in chemistry and textural parameters, generated high explosive eruptions accompanied by caldera-forming events.

The research was based on a multidisciplinary approach based on the integration of different methodologies: determination of structural features and main characteristics of the deposit (grain-size, maximum clast size, composition, density); evaluation of eruption parameters (ejected volume, column height and discharge rate); textural analyses (*vesicle and crystal size distribution*); measurement of the rheological properties of the magma (viscosity).

The characterization of the deposit formed the basis of the stratigraphy used throughout this thesis. Selected samples from the type sections were analyzed by scanning electron microscope (SEM) and electron microprobe (EMPA) to reveal further details about the chemical stratigraphy and as a background for textural and rheological analyses. Details of all the methodologies are discussed in the relevant chapters.

Textural analyses were used to reconstruct the physical processes that control the eruptive styles, magma vesiculation, fragmentation and conduit ascent. Vesicles in pyroclasts document the processes of gas exsolution, expansion, and escape that drive most of the volcanic eruptions. Quantification and interpretation of vesicles and crystals were possible in terms of *vesicle and crystal size distributions* measurements.

Rheological measurements were carried out both at liquidus and subliquidus temperatures, in order to quantify the behavior of the pure liquid phases and the effect of crystals and vesicles on the same magmas viscosities.

The combination of all the aforementioned investigation allowed to reconstruct a possible eruptive scenario for both the Colli Albani and Campi Flegrei volcanoes.

CASE STUDIES

Pozzolane Rosse and Pozzolane Nere (Colli Albani, Italy)

After a preliminary part explaining the main features of the Colli Albani volcano (concerning geological setting, geochemical background and volcanic stratigraphy) the following combined investigation were carried out on two of the largest ignimbrites of the Colli Albani volcano, *i.e*., the Pozzolane Rosse (457 ± 4 ka) and the Pozzolane Nere (407 ± 4 ka) ignimbrites: *i)* textural, physical, and chemical characteristics of scoria clasts (density, *vesicle size and crystal size distributions*, viscosity); *ii)* structural features of the deposit (grain-size, maximum clast size, composition); *iii)* eruption parameters (ejected volume, column height, and discharge rate). Field locations and stratigraphic column are reported in Fig. 1. Scoria clasts were analyzed in order to quantify textural features from individual stratigraphic levels and to measure changes in vesicularity and crystallinity during the major shifts in eruptive intensity and style at Colli Albani volcano. Particular attention was given to the Pozzolane Nere fallout phase to reconstruct the main triggering factors and the first phases of the eruption.

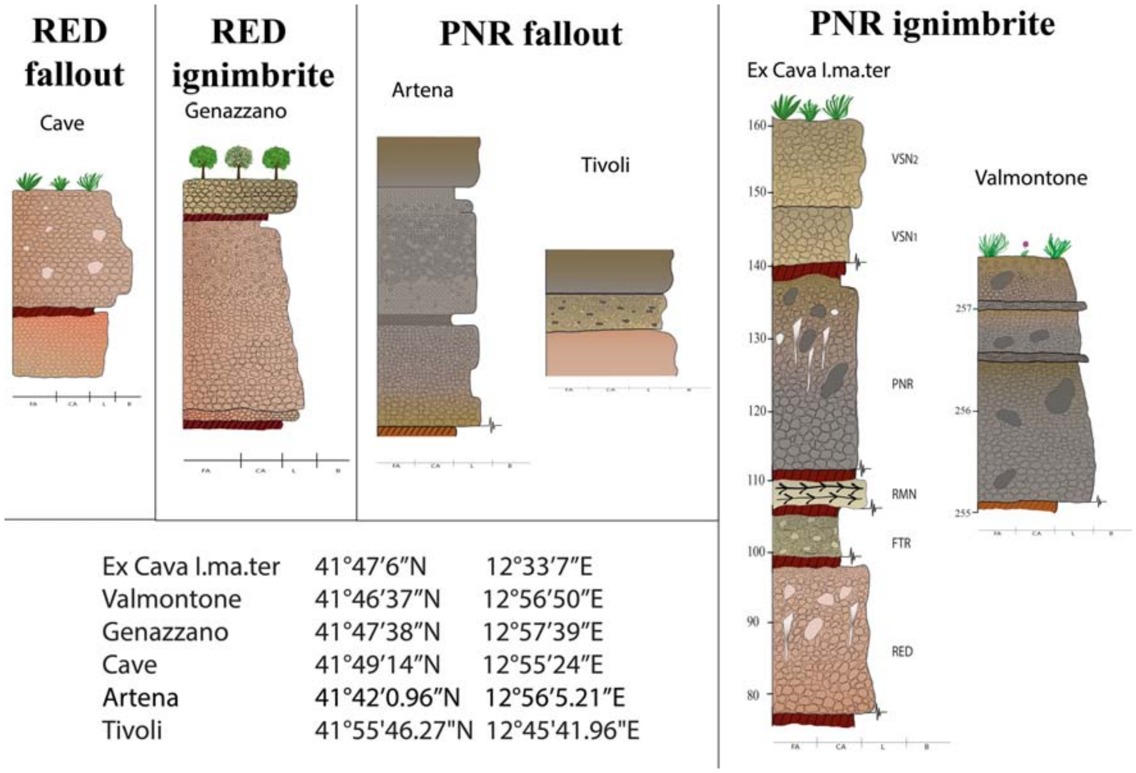

Fig. 1 - Stratigraphic log and geographic coordinates of Pozzolane Rosse (RED) and Pozzolane Nere (PNR) fallouts and ignimbrites analysed.

The results of the textural analysis revealed that both the Pozzolane Rosse and the Pozzolane Nere present characteristics similar to those of the deposits of Plinian acidic eruptions rather than mafic ones, such as VNDs or the vesicle minimum and maximum diameters. By contrast, other characteristics such as porosity are instead typical of mafic explosive deposits. The VNDs are by the order of 10^{10} for the RED and 10^{8}-10^{9} cm^{-3} for the PNR, values 2 or 3 orders of magnitude above the standard of mafic explosive eruptions and entirely comparable with those of the silicic Plinian eruptions. The vesicle maximum diameter varies between 0.4 mm of the PNR fallout and 2 mm of the two ignimbrites. Also in this case, the values are in better agreement with those pertaining to silicic Plinian deposits rather than with those more typical of mafic magmas, which usually far exceeds 5 mm. On the other hand, however, the porosity of both RED and PNR are very low, between 30 and 45%, far lower than the porosity of silicic pumices (70-90%). Throughout the course of the eruptions, from fallouts to ignimbrites, bubbles tend to increase in size and to take always more irregular shapes, thus increasing the coalescence, and also crystal content increase, with a strong intensification at the transition between fallout and ignimbrite.

In order to evaluate the influence of the viscosity during the rise and the effect of crystal on the rheology itself, experiments with the concentric cylinder viscometer on the remelted PNR fallout were carried out. At high temperatures (1100-1225 °C) the viscosity falls within the range $10^{1.04}$ - $10^{3.64}$ Pa·s, whereas at low temperatures (690-800 °C) it ranges between $10^{9.23}$ - $10^{12.15}$ Pa·s. Comparison of our results with other viscosity experiments was presented. From this comparison, it emerged how the analyzed liquid presented higher degree of depolymerization and fragility. The effect of the crystals on the viscosity of melts was evaluated by isothermal crystallization experiments in the region of subliquidus, at T between 1193 and 1240 °C and constant strain rate of 0.1 s^{-1}.

The chemical composition for the experimental products was determined by microprobe analyses and the textures were investigated by optical microscopy and SEM imaging. The mineralogical assembly is constituted by the constant presence of leucite and iron oxides. The total percentage of the crystalline phases varies between about 6 and 22 vol% depending on the experimental temperature. On the basis of chemical and textural analysis, a model was developed to predict the variation of the viscosity of the suspension liquid + crystals + bubbles for different water contents along the entire eruptive sequence of PNR. In the fallout phase, the combined effect of crystals and vesicles tends to decrease the viscosity up to a maximum of one order of magnitude, whereas in the ignimbrite, presenting much higher concentration in crystals and lower vesicularities, the viscosity is higher. In general, however, the three-phase mixture viscosity increased by about 0.5 logPa s from the base to the top of the fallout then undergo an abrupt increase of 0.8 logPa s during ignimbrite phase.

The relative influence of magma internal dynamic (viscosity changes) versus external factors (*i.e.*, the vent diameter) responsible for the fall out-flow transition was also discussed. Based on the investigations and on *Confort15* simulations, a model for the volcanological evolution of the Colli Albani ignimbrite eruptions was then presented. We calculated the decompression rates, considering VNDs and some peculiar properties of the magma (*e.g.*, diffusivity, density of the magma, surface tension) using Toramaru (1995, 2006) formulations. The decompression rates for the PNR are very high and tend to decrease along the eruption. Then, an implemented version of Conflow model (Mastin & Ghiorso, 2000) called *Confort15* was presented. The main modifications concern the liquid viscosity and crystal-bearing rheology determination, as well as the fragmentation criteria. This Fortran modified version *Confort15* was applied on the Pozzolane Nere eruption. Model simulations were performed at different vent diameters for PNR fallout and, because of the uncertainty due to the absence in literature of experiments with a similar chemical composition, two different surface tensions were investigated (σ = 0.01 and 0.035 N/m). Results indicated that velocities reach very high values (up to 280 and 600 m/s respectively) and the fragmentation depth depends mainly by the inferred decompression rate (very different for the two surface tensions), varying from 750-800 m and 2400-4000 m. Moreover, results showed that the magma ascent is very much influenced by the conduit geometry, describing really dissimilar patterns at fixed 40, 60 and 80 m vent diameter.

Finally, the transition between fallout and ignimbrite was investigated. Inferring the decompression rates derived from the textural analysis, the ignimbrite reaches the fragmentation only in the last meters close to the surface, reaching viscosities of 10^5 Pa·s and exit velocities of 120 m/s. The high decrease in velocities from up to 600 m/s of the fallout phase to 120 m/s could explain the collapse of the column. The cause for such decrease in velocity is probably related not to a change in intrinsic properties of the magma but to a change in the vent/conduit geometry, as also testified by field evidences.

Agnano Monte Spina (Campi Flegrei, Italy)

The textural characteristics and physical properties of the three major fallouts (A1, B1 bottom and top, and D1) and on the respective pyroclastic flows and surges (A2, B2, D2) of the Agnano Monte Spina eruption were also analyzed. The aim of this part of the study was to relate the textural features of the deposit to intrinsic parameters of the magma during ascent along the conduit and to understand to what extent, if any, changes in the intrinsic properties of the magma may have affected the course of the eruption for the Agnano Monte Spina case. A combination of field, grain-size, density, *vesicle and crystal size distributions*, fine-ash morphologies and experimental viscosity investigations was carried out. The results lead us to propose an eruptive scenario, taking particularly into account the role of volatiles into the different transitions between sustained and collapsed column. An important assumption for this scenario is that pumices acquire their final texture during fragmentation and are thus representative of the last state of the magma before quenching. FTIR analyses show an initial water content for A, B and D members of 1.77, 2.12 and 2.72 wt.% (MIs, Arienzo, pers. comm.) and residual water content of 0.88-0.75 wt.% (A1-A2), 0.72-0.60 wt.% (B1-B2), 0.81-0.74 wt.% (D1-D2). Low temperature-high viscosity experiments were carried out using the micropenetration technique in the viscosity range of $10^{9.23}$ to $10^{11.56}$ Pa·s, and T ranging from 660 to 790 °C. High temperature-low viscosity experiments were investigated using the concentric cylinder apparatus at T between 975 and 1600 °C, in the viscosity interval from $10^{1.68}$ to $10^{6.08}$ Pa·s. Results were in good agreement with both Giordano *et al.* (2008) and Misiti *et al.* (2011) models (Fig. 2).

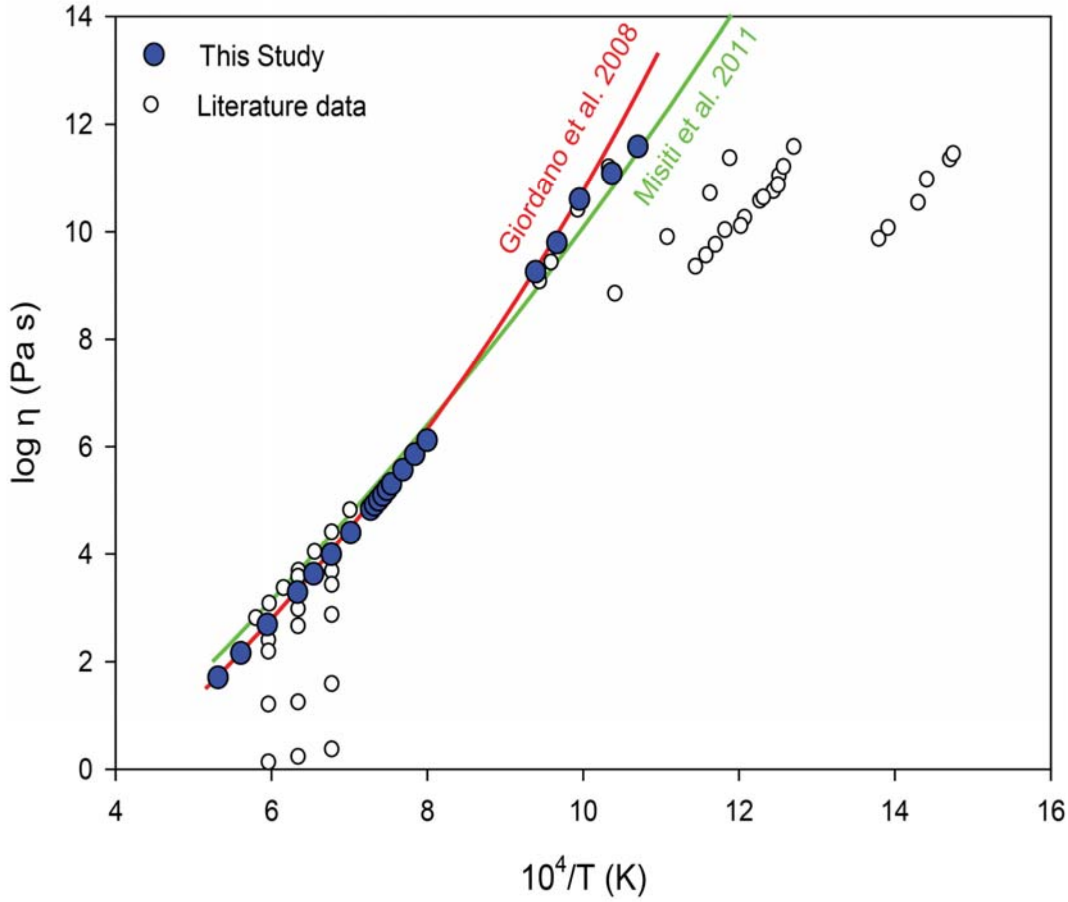

Fig. 2 – Viscosities versus reciprocal temperature for AMS samples investigated in this study (blue circles) and literature data (white circles). The viscosity calculated using the Giordano *et al*. (2008) model (red line) and the Misiti *et al*. (2011) model (green line) are reported.

Isothermal viscosity measurements in the *subliquidus* region and their extrapolation at the eruptive temperature of 827 °C and 945 °C under different water contents, allowed us to estimate the effect of crystals and vesicles on the AMS magmas. At estimated eruptive conditions and water content, viscosity of AMS magma reaches very high values compatible with the eruptive style of the eruption. Fragile fragmentation can be expected to occur. A reconstruction of the eruptive sequence of the AMS eruption was then performed based on all textural, stratigraphic and rheological analyses.

The entire AMS eruption evidenced textural characteristic typical of very explosive silicic magmas. In particular, *vesicle number densities* (VNDs) range from 10^7 to 10^8 cm^{-3}, *i.e.* the usual values for powerful Plinian activity, with the exception of the episode that emplaced the welded scoriae (B2-WS) in the upper part of B2 sub-member (10^5 cm^{-3}). Also porosities and minima vesicle sizes were well in agreement with common values of highly explosive acidic eruptions (> 75% and 0.003 - 0.005 mm). We noted a repetitive behavior for each main eruptive phase, characterized by the alternation of magmatic and phreatomagmatic events, at times even concurring. In particular, each event starts with an efficient water-magma interaction, resulting in A0-B1bottom-D0 deposits. These phreatomagmatic explosions initiate the eruption and we suggest that also trigger the transition to magmatic explosivity, leading to the formation of magmatic pulsating Plinian eruption columns (A1-B1top-D1). All these three fallout events show a residual of the magma-water interaction, recognizable by the presence in the finer fraction of blocky ash-shards with stepped surfaces, grooves, pitting, and adhered particles, all indicative of a phreatomagmatic contribution to the fragmentation process. The subsequent transitions Plinian column/column collapse is texturally noticeable by vesicles number densities drop of about one order of magnitude (from 10^8 to 10^7 cm^{-3}), indicating a remarkable decrease in ascent rates. Moreover, also porosities show a reduction, slight (2-3%) in A1-A2 and D1-D2, and moderate in B1-B2 (5-6 %) cases.

We identified similar differences between the phases following the column collapse (A2-B2-D2). A2 and D2 deposits present several similarities, such as the contemporaneous presence of pure magmatic (the majority) and phreatomagmatic grains and a maxima vesicle sizes completely comparable to that of the corresponding fallout (2.66 mm for A1-A2 and 1.68 mm for D1-D2). However, the B1-B2 transition shows a more complex behavior. First of all, B2-F1 presents maxima vesicle sizes lower than the corresponding fallout (1.31 mm and 2.11 mm, respectively) and the finer fractions suggest only magmatic activity. This was thought to be due to the gradual water depletion favored by the escape along the former fractures that anticipate the caldera collapse. However, B2-F1 is stratigraphically overlaid by the B2-S pyroclastic surge, probably generated by a water renewal or by the contemporaneous presence of more vents within the Agnano plain. Another peculiarity of the B2 member is the presence of a welded scoria deposit in the upper part (B2-WS) associated to a lag-breccia deposit, indicating the weakening of the eruption and the evidences of the volcano-tectonic collapse.

We also calculated the decompression rates, which present a non-linear behavior. In particular, each PDC phase presents much slower dP/dt than the respective fallout. Furthermore, the decompression rates increase from A to B to D members (1.56, 2.20, 2.68 MPa/s), in good agreement with each corresponding column height (5, 23, 27 km). *Confort15* simulations on the AMS eruption showed that the Papale (1999) criterion is sufficient to reach the fragmentation criterion for these magmas and the generation of the column sustained activity. For AMS, the conduit shape seems not to be so relevant on the magma ascent rate, but rather on the fragmentation depths. A, B and D members present different mass discharges, velocities, viscosities, and fragmentation depth, corresponding to their initial magma intrinsic properties, such as water content or chemical composition. We demonstrate that distinctive decompression rates, initial water content (1.77, 2.12 and 2.73% for A, B and D respectively) and minor changes in compositions are able to explain the different column height and volume erupted through the A1, B1, and D1 sequence of the eruption. In various occasion during the AMS eruption, column collapse episodes occurred (A1-A2, B1-B2, D1-D2). From the results of *Confort15* simulation, the decrease in ascent velocities responsible for the column collapse and the generation of the pyroclastic density current could be generated both by a change in the geometry of the vent/conduit system and/or by a change in intrinsic properties (volatile content) of the magma itself.

CONCLUDING REMARKS

The combination of methods described in this study represents a powerful tool to gain detailed insights into the complex eruption dynamics that take place during mafic Plinian eruptions as the Pozzolane Nere one. Furthermore, the combination of existing data, including melt inclusion and isotope analyses, with the detailed investigation of the corresponding deposit and magma characteristics provided in this study, helped to unravel the processes influencing the dynamics and the change in styles of standard acidic Plinian eruptions, such as the Agnano Monte Spina eruption. The detailed datasets of both eruptions described in this study allowed a comparison of the processes responsible for generating large-scale Plinian eruptions and the variation from different eruptive styles. The major properties affecting the eruption dynamics, next to the dynamic changes of both eruptions are summarized below and in Table 1.

Despite their variability in chemistry and textural parameters, the PNR and the AMS eruptions were both very high explosive eruptions accompanied by caldera-forming events. In particular, tephri-phonolitic and trachytic compositions characterize the PNR and the AMS eruptions respectively. Porosity and crystallinity are very different from one another, with a bubble content of 25-45 vol% for the PNR and of 75-85 vol% for the AMS.

Table 1 – Comparison of the physico-chemical parameters and eruption dynamics of the PNR and the AMS eruptions.

	Colli Albani		**Campi Flegrei**	
Eruption	**Pozzolane Nere**		**Agnano Monte Spina**	
	Fallout	***PDC***	***Fallout***	***PDC***
Age (ka)	407		4.1	
VEI	6		5/6	
Volume (Km^3)	15		1.2	
Composition	Tephri-phonolite		Trachyte	
Porosity (vol%)	31-48	24-34	79-82	76-81 (38 B2-WS)
VND (cm^{-3})	10^9 (10^8 ash layer)	10^9	10^8	10^7 (10^5 B2-WS)
Crystallinity (vol%)	2-30	35-40	2-13	3-12
Vesicle maximum diameter (mm)	0.13-0.7	2.19	1.33-2.66	1.31-2.66
Max viscosity at eruptive conditions (Pa s)	10^4	$10^{4.5}$	$10^{8.39}$	$10^{8.5}$
Fragmentation	Decompressive event		brittle (high porosity and viscosity)	
External factors	trigger magma-water interaction, calderic collapse		alternation phreatomagmatic-magmatic, opening of the vent	

The main crystal assemblage varies from leucite + clinopyroxene (with an average content of 30-40 vol% for the basic PNR eruption with an extensive microlitization in the juvenile of the ignimbrite phase) to K-feldspar + clinopyroxene + plagioclase (2-13 vol%) for the acidic counterpart. Notwithstanding these chemical and textural disparities, both eruptions present very elevated VNDs, with those of the PNR (10^9 cm^{-3}) even higher than those related to the AMS eruption (10^7-10^8 cm^{-3}). High VNDs correspond to rapid magma ascent and bubble nucleation (*e.g.*, Cashman & Mangan, 1994; Toramaru, 2006). In both cases, VNDs are on the range of typical silicic Plinian eruptions, which fit perfectly with the AMS silicic pumices but are apparently in contrast with the mafic nature of the PNR scoria clasts. Generally, the anomalous values pertaining the mafic compositions are attributed to heterogeneous nucleation of bubbles on submicroscopic crystals or to post-fragmentation processes due to the microlitization. The diffuse microlitization would in fact decrease the overall melt referenced porosity and artificially increase the number of bubbles, especially those of low sizes. As stated into the section dedicated to the PNR, in order to take this phenomenon into account, we discarded all sizes smaller than 0.017 mm in the calculation, as the BSD showed that small vesicles obey to a different distribution law that we interpreted to be strongly affected and arising from the presence of secondary microlites. Even after correcting for the presence of small bubbles, the VNDs of our PNR liquids were very high, in the order of 10^9 cm^{-3}. This confirmed that the high vesicles numbers that we measured were related to the extremely high energy of the eruption and not to the post-eruptive microlitization process.

In order to understand the dynamics of these eruption and the role of the magma properties on the energy and style of the eruptions, we investigated the viscosity variation during the course of the eruptions testing the effect exerted by the crystallization and the degassing. The AMS was in accord with the acidic Plinian behaviors, recording at eruptive temperatures viscosity values (up to 10^6 Pa.s), which allow to satisfy the brittle fragmentation criterion. On the contrary, the PNR viscosities at eruptive temperatures never reached high values (up to $10^{4.5}$ Pa.s), seemingly suggesting that the internal properties of the magma do not control strongly the conduit dynamics and external factors to fragment explosively the magma have to be invoked.

The style of fragmentation is quite easy to deduce for the AMS eruption. In fact, the high porosities, the high viscosities and the presence, even if limited, of tube pumices that represent the part of the magma that was exposed to higher elongational strain rates close to the conduit walls, indicate that the magma fragmented in a brittle manner (Papale, 1999). For the PNR eruption, the dynamics and the fragmentation style were more complex to interpret. We calculated for the two eruptions the decompression rates, on the basis of the VNDs and of some peculiar properties of the magma (*e.g.*, diffusivity, density of the magma, and surface tension). The decompression rates for the PNR were very fast and tend to decrease arising along the eruption, whereas the AMS ones presented a non-linear behavior. From *Confort15* simulations we demonstrated that, inferring these very high decompression rates, the PNR eruption could fragment following the Spieler *et al*. (2004) criterion.

We postulated that the initial magma-water interaction generated a decompression wave over the rising magma able to propagate inward and downward within the conduit such as to provide the pressure gradient necessary to initiate the fragmentation. The transition between fallout and ignimbrite was characterized by very low decompression rates (0.02 MPa/s), as calculated through *Confort15* simulations, and a consequent drop in exit velocities (100 m/s against up to 600 m/s of the fallout phase). The very low values of dP/dt and the significant increase in vesicle maximum diameter from the fallout to the ignimbrite phase suggest that the growth and the coalescence clearly predominated over the nucleation process. The *Confort15* simulations obtained changing the water content showed a small variation in exit velocities, probably not sufficient to generate the transition between fallout and ignimbrite. Moreover, decompression rates simulations were not at all compatible with values resulting from textural analysis, both for the fallout and the fallout-ignimbrite transition. This suggested that the magma itself did not have internal properties in terms of speed and mass to produce a Plinian eruption, and both the generation of a column sustained activity and the transition fall-ignimbrite must therefore be ascribed to external factors, such as change in vent/conduit geometry.

On the contrary, the internal properties of the AMS eruption were sufficient to achieve the fragmentation in a brittle manner, following the Papale (1999) criterion. In fact, directly simulating decompression rates that satisfy the properties of the magma and of the system, resulting dP/dt are close to those obtained with the textural analysis and Toramaru formulations. In general, for the AMS eruption, were lower compared to those relative to the PNR eruption (up to 120 m/s for D member), closer to the standard values for Plinian eruptions and mass discharges rates were comparable with those expected with this type of eruptions, ranging between 10^7-10^8 kg/s. The distinctive decompression rates, initial water content (1.77, 2.12 and 2.73 % for A, B and D respectively) and minor changes in compositions were able to explain the different column height and volume erupted through the A1, B1, and D1 sequence of the eruption. Moreover, column collapse episodes occurred during the AMS eruptions (A1-A2, B1-B2, D1-D2) were accompanied by distinctive change in textural properties of the magma (VNDs). Numerical simulations, taking into account decompression rates derived from textural analyses, were able to reproduce the strong decreases in exit velocities responsible for such transitions in eruptive styles. Both a change in intrinsic properties of the magma (water content decrease) and/or a change in conduit/vent geometry, could be responsible for the sudden drop in magma ascent rate.

REFERENCES

Cashman, K.V & Mangan, M. (1994): Physical aspects of magmatic degassing; II, Constraints on vesiculation processes from textural studies of eruptive products. *Rev. Mineral. Geochem.*, **30**, 447-478.

Giordano, D., Russell, J.K., Dingwell, D.B. (2008): Viscosity of magmatic liquids: A model. *Earth Planet. Sci. Lett*., **271**, 123-134, doi:10.1016/j.epsl.2008.03.038.

Mastin, L.G. & Ghiorso, M. (2000): A numerical program for steady-state flow of magma- gas mixtures through vertical eruptive conduits. *U. S. Geological Survey Open File Report* **00-209**, 56 p.

Misiti, V., Vetere, F., Freda, C., Scarlato, P., Behrens, H., Mangiacapra, A., Dingwell, D.B. (2011): A general viscosity model of Campi Flegrei (Italy) melts. *Chem. Geol*., **290**, 50-59, doi:10.1016/j.chemgeo.2011.08.010.

Papale, P. (1999): Strain-induced magma fragmentation in explosive eruptions. *Nature*, **397**, 425-428.

Spieler, O., Kennedy, B., Kueppers, U., Dingwell, D.B., Scheu, B., Taddeucci, J. (2004): The fragmentation threshold of pyroclastic rocks. *Earth Planet. Sci. Lett.*, **226**, 139-148.

Toramaru, A. (1995): Numerical study of nucleation and growth of bubbles in viscous magmas. *J. Geophys. Res.*, **100**, 1913-1931.

Toramaru, A. (2006): BND (bubble number density) decompression rate meter for explosive volcanic eruptions. *J. Volcanol. Geotherm. Res*., **154**, 303-316, doi:10.1016/j.jvolgeores.2006.03.027.