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Pisa, April 27, 2010

Revisions to the Manuscript (SE-2009-12) entitled: "*Rheological control on the dynamics of explosive activity in the 2000 summit eruption of Mt. Etna*".

Dear Prof. Dingwell,

Please find enclosed our reply to reviewer comments for the manuscript entitled: "*Rheological control on the dynamics of explosive activity in the 2000 summit eruption of Mt. Etna*" authored by D. Giordano*, M. Polacci, P. Papale, L. Caricchi.

The manuscript presents an interdisciplinary study where the analysis of textural and rheological features of erupted products were put together with fluid dynamical modelling to understand the role of rheological features on controlling the dynamics of the explosive activity and the factor that might affect the repeated transition from Strombolian and fire-fountaining.

The above is what the paper is devoted to investigate/evaluate and our comments to the reviewer want to remark what the main objectives of the manuscript are. We mostly respected the lines followed in the original manuscript. In revising the text, to accomplish what required from the reviewer (Prof. Melnik) and we believed to be possibly still unclear, we added two additional paragraphs after periods after line 202 and 223 of the original manuscript.

Please also note that my institutional details have been also changed (by adding my new institutional address first and new email address, but also maintaining my previous institutional address) as they follows:

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Luca Caricchi address has also been modified together with the acknowledgemnts.

With kind regards,

Sincerely,

Daniele Giordano

Reply to comments by O. Melnik

General comments

The reviewer outlines the relevance and interest of the data analyzed in the manuscript, adding a comment that our approach of using the latest rheological models for non-Newtonian crystal-rich magmas is doubtful for magmas with up to 65 vol% of bubbles.

It is not easy to reply to this point since the reviewer's comment is not accompanied by further explanation. We assume he refers to additional non-Newtonian behaviour induced by large gas bubble content in magmas, as it is documented in a number of papers (e.g., Llewellin and Manga, JVGR 143, 205-217, 2005).
As a matter of fact, there's insufficient description of the rheological behaviour of crystal-/bubble-rich magmatic suspensions, so, while implementation in the conduit flow code of the constitutive equations in Llewellin and Manga (or others similarly proposed in the literature) is relatively simple, there's no warranty that in the crystal-rich cases that we consider this would result in effective improvements. We have therefore preferred to focus on non-Newtonian behaviour due to solely large crystal volume fractions, which is well described in the literature, and decided to increase the complexity of the rheological description once sufficient data and modelling for crystal-/bubble-rich magmatic suspensions will be available.

Specific (numbered) comments

The reviewer generally comments that the applicability of the code we use to basaltic eruptions "in my opinion still remains doubtful" (quoted from the reviewer). We assume that statement, that is not immediately followed by a motivation, is intended to be substantiated in the subsequent numbered comments. These comments are considered below using the same numbering as from the reviewer. For each comment, the reviewer's statement is first reported (in italic), then followed by our reply.

1. The code assumes relative gas motion only in a form of bubble rise. This is a good assumption for low viscosity, crystal-poor magmas. In crystal-reach magmas this mechanism is not efficient and gas escapes due filtration through the magma or into surrounding rocks.

We note here that the reviewer describes processes never directly observed, apparently with a high degree of self-belief as they were obvious and proven. The processes he describes may be effective in some eruption cases, but not necessarily dominant or relevant in all of them. Our approach is to stick to the observations to constrain the relevant processes, and to define a suitable model based on the first order characteristics of the dynamics under investigation. In the present case, there's no observation substantiating the assumption that gas escape due to filtration through the magma or into the country rocks was a first order process. Efficient gas escape in fact is required to explain eruptive phases characterized by slow lava emission, either in the form of lava flows or as a lava dome. In such cases the erupted magma emerges at the surface with a too low gas volume (and accordingly, low speed) that has been interpreted as due to efficient separation of the gas phase during magma ascent. On the contrary, highly expanded magma is ejected at large speed in lava fountains that are the object of our investigation (reference from the reviewer to simulated Strombolian eruption phases at his comments 3 and 7 is not correct, as explained at the corresponding points below). For these eruptive phases the gas phase is dominant at the vent, not requiring any further process related to gas escape to interpret the observed dynamics. For this reason, gas escape as described by the reviewer is not included in our analysis.

2. Important feature of basaltic eruptions is bubble coalescence that is not accounted in the model.

The reviewer's comment seems to refer again to the development of a permeable gas network via gas bubble coalescence, that would favor gas escape from the magma. As we clarify at point 1 above, there's no evidence that gas escape from the liquid was a major factor during the lava fountain activity at Mount Etna in 2000. Gas bubble coalescence is seen and measured in the products of the eruption (see Polacci et al., J. Volcanol. Geotherm. Res. 2009, 179: 265-269), as it is recorded and dominant in pumice samples from many explosive volcanoes in the world (cfr. Klug and Cashman, Bull. Volcanol. 1996, 58: 87-100; or, Polacci et al., EOS 2005, 86: 333-336); this does not imply that gas escape was the dominant process during the eruption. As a matter of fact, sub-steady lava fountain activity is the equivalent of sub-steady explosive eruptions: in both cases highly expanded magma is discharged at high speed, the major difference being that brittle fragmentation only occurs in the explosive counterparts. Since there's no evidence that bubble coalescence caused any major change in the eruptive dynamics, we do not model it in our approach.

3. The model ignores crystal growth inside the conduit assuming that crystal content is constant along the whole conduit. This might be applicable for the fire-fountain style of eruption but not for the Strombolian where intensive crystal growth occurs only at the upper part of the conduit with a formation of the crystal-reach plug.

The reviewer here appears to have misunderstood the aims and logics of our simulations involving high crystal content. We think we have been clear in the manuscript to stress that we DO NOT simulate the Strombolian phases of the eruption: "While the steady flow model can be applied to the long-lasting fire-fountain phases of the 2000 eruption of Mount Etna, the highly unsteady character of the Strombolian phases prevents its application." (lines 206-208 of the original manuscript). We then continue by stating clearly how we proceed, and which is our aim: "The rheologically updated Conduit4 code has been therefore applied to the fire-fountain phase first, in order to identify a conduit diameter consistent with the observed mass flow-rates." (lines 208-209). "A second set of simulations has been performed by assuming this time a conduit diameter consistent with the fire-fountain phase as determined above, and progressively increasing the crystal content up to that of the Strombolian phase. Here the aim is that of evaluating which would be the net effect on the eruption dynamics of just erupting more crystal-rich magmas." (lines 215-218). We thus clearly state that the model is not applied to Strombolian eruption phases, while our aim is that of evaluating which consequences a much higher crystal content, similar to that in the magma erupted during the Strombolian phases, would produce by itself (the "net effect") on the dynamics of magma flow in a conduit. This same misunderstanding is even more evident at point 7 from the reviewer, where he states that *The model is steady state. Its application to Strombolian activity is not justified.* In fact, we have not applied the model to Strombolian activity.

4. The model assumes a parabolic velocity profile in order to calculate conduit resistance. This approximation is not valid for the case of non-Newtonian liquid where the profile must be a more plug-like.

The statement from the reviewer is correct, but we note here that in a 1D model like the one we use, any assumption on a velocity profile – the calculation of which requires at least a 2D model – does not bring more precision in the calculations, rather, it introduces some arbitrariness that we prefer to avoid. We also note that the simplest assumption of parabolic velocity profile to calculate friction represents a suitable first-order approximation for plug-like flow. In fact, while the effective friction is close to zero in the plug region, it is expected to be substantially larger than for Newtonian flow in the region close to conduit walls as a consequence of larger velocity gradients, thus tending to balance – to a first rough approximation – in the overall friction term. The real world is certainly more complex than our 1D simplification, however, we think we capture the first-order effects by adjusting a local effective Newtonian viscosity to the non-Newtonian value calculated from the new rheological modeling adopted here. This is certainly a progress compared to previous modeling, e.g. Melnik and Sparks 1999 (Nature, 402: 37-41), where very high crystal contents were considered in conduit flow simulations, without including the major effects of non-Newtonian behavior as they are described in our manuscript and implemented in our code. To make the points above clear in the manuscript, we have now added the paragraph below after line 202:

> "Strictly speaking, the introduction of non-Newtonian rheology requires at least 2D flow modeling in order to compute the velocity profile and the internal friction forces at any level in the conduit. Our 1D approach retains instead the simplified assumption of parabolic velocity profile typical of Newtonian fluids, but locally computes an effective viscosity based on non-Newtonian behavior described above. Although 2D modeling can approximate better the true conditions in the conduit, we still capture the major effect of a change of viscosity at any level during magma flow as a consequence of the high crystal content of magma and the locally computed rate of strain."

5. None of the simulations show fragmentation of the magma. This is due to the fact that a strain-rate fragmentation criterion is used as a fragmentation condition. It is justified for silica-reach magmas but can be violated at low viscosity range.

The statement from the reviewer in the last period is not clear to us, mostly because it is not supported by any explanation. We tend to be careful in our approach, and are conscious that any modeling – our modeling as well as those from others – is necessarily a simplification of a much more complex real world, aimed at shading light on some specific first-order aspects, and justified as long as its results are consistent with the observations.

With reference to the fragmentation mechanism quoted by the reviewer, the strain-rate criterion we adopt is found to consistently predict fragmentation of viscous magmas in the observed range of vesicularity, and to explain well the dichotomy between dominant explosive behavior of viscous magmas as opposed to dominant effusive behavior of fluid magmas (see the analysis presented in Papale, Nature 1999: 425-428, and in a number of subsequent papers from the authors).
It is worth noting here that in our manuscript we refer to fragmentation as the brittle process occurring inside a volcanic conduit, not taking into account ductile fragmentation associated with rapid expansion to atmospheric pressure of previously non-fragmented, low-viscosity magma characterizing lava fountain activity. In this sense, lava fountains belong to the non-fragmented family of eruptions, since the discharged magma emerges from the vent in the form of a liquid continuum. To make this point clear in the manuscript, we have now added a period after line 223 of the original manuscript:

> "It is worth noting that for the present purposes, we refer to magma fragmentation as the brittle process occurring in a volcanic conduit, not considering fragmentation upon rapid expansion to atmospheric pressure that results in lava spatters or ash production from the top of lava fountains. In this sense, lava fountains belong to the non-fragmented family of eruptions, since the discharged magma emerges from the vent in the form of a liquid continuum."

6. The presence of simultaneous lava flows during fire-fountain phase requires efficient gas separation from the magma at some depth. This is outside the capabilities of the code.

Once again, it is worth reminding that the application of a model – whatever its sophistication or complexity – is necessarily aimed at exploring some first-order aspects of the dynamics under investigation. This is especially true when studying the underground dynamics of volcanoes, that are outside direct investigation. One may always point out some possible additional complexity, e.g., a volcanic conduit is hardly a constant-diameter cylinder, it is not necessarily vertical, lateral magma intrusions can occur at some level feeding lava flows (very minor in the case under investigation), etc. In our applications the aim, that we clearly state in the manuscript, is that of evaluating the net effects of a possible substantial variation of the crystal content during a basaltic eruption, including the most recent advances on the knowledge of non-Newtonian behavior of crystal-rich magmas. Adding further complexities would not serve our purpose, on the contrary, it would result in the impossibility to extract the simple information that we want. As we do in the manuscript, we can evaluate the consistency of our modeling results with the observations. In the specific case, we simply note that the large magma overpressure predicted immediately below the conduit exit level is consistent with the emergence of (very minor in volume) lava flows at the base of the crater during the Mount Etna eruption that inspires our model applications.

It is also worth noting that the statement from the reviewer that *gas separation from the magma at some depth… is outside the capabilities of the code* does not reflect the truth. There are in the literature simplified methods to account for gas escape through country rocks (assuming the reviewer refers to that process – our model is in fact a multiphase separated flow model, therefore, gas separation along the conduit is explicitly calculated in terms of different gas and liquid or liquid+crystal velocities). The reviewer is a modeler himself, thus, he cannot doubt that the implementation of those methods is easy enough that can be – as a matter of fact it is – included in our modeling. Simply, there is no need to account for that, in the analysis we have carried out and presented in this manuscript.

7. The model is steady state. Its application to Strombolian activity is not justified.

This has been answered at point 3 above. In fact, we have not applied the model to any Strombolian activity.

8. The main driving force for explosive activity is the gas phase. Its balance due to exsolution and escape determines the explosivity of the eruption. Very little attention is paid in the discussion to this balance.

It is not clear to us what the reviewer aims at pointing out here. We assume that he refers to the fact that our results showing no fragmentation in the volcanic conduit may be affected by neglect of gas loss ("escape") through country rocks or by filtration through the magma (gas exsolution and gas separation from the liquid due to different velocity patterns are in fact fully accounted for in our modeling). However, any paper in the literature (including some from the reviewer himself) treating or mentioning gas escape support the conclusion that such process tends to decrease the explosivity of eruptions, or in other words, tends to decrease the likelihood of magma fragmentation in the volcanic conduit. Our results show that even by not accounting for gas loss through country rocks or for gas filtration through the magma – that as explained at point 3 above, is not justified by the observations in the investigated cases – magmatic fragmentation does not take place – a result that is consistent with the effusive character of the fire-fountain eruptive phases considered in the simulations. Thus, magmatic fragmentation does not occur in the real case, it is not predicted to occur in the simulations, and by adding gas escape in the modeling as suggested by the reviewer it would be even less likely. It is therefore unclear to us what the reviewer suggests to discuss more, related to gas escape and the explosivity of the eruption.

As a conclusion: the paper presents very interesting correlation between textures of eruptive products and the style of explosive activity but its interpretation is rather doubtful based on the current numerical model.

The only modeling-based interpretation we provide on the *correlation between textures of eruptive products and the style of explosive activity* rests on our finding that in the range of the explored conditions, very small fluctuations in the crystal content when the crystallinity of magma is as high as that measured in the Strombolian products cause the mass flow-rate to fluctuate largely, thus not favoring the onset of a steady-state phase of the eruption. We therefore suggest that the onset of a new steady-state, fire-fountain phase required the remobilization of the highly crystalline plug previously formed on top of the magmatic column. This view is consistent with our results and with the observations. It is certainly doubtful, as it is any interpretation on the extremely complex and poorly controlled processes subtending magma ascent to the surface. But still, it is consistent with our results and with the observations, and after having read the reviewer's comments and replied to them, we do not find substantial reasons to modify that view.

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Rheological control on the dynamics of explosive activity in the 2000 summit eruption of Mt. Etna

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keywords: Etna, rheological properties, strombolian vs fire fountain activity

7 figures, 3 tables, ca. 3100 words

Abstract

In the period from January to June 2000 Mt Etna exhibited an exceptional explosive activity characterized by a succession of 64 Strombolian and fire-fountaining episodes from the summit South-East crater. Textural analysis of the eruptive products reveals that the magma associated with the Strombolian phases had a much larger crystal content > 55 vol% with respect to the magma discharged during the fire-fountain phases (~35 vol%). Rheological modelling shows that the crystal-rich magma falls in a region beyond a critical crystal content where small addition of solid particles causes an exponential increase of the effective magma viscosity. When implemented into the modelling of steady magma ascent dynamics, the large crystal content of the Strombolian eruption phases results in a one order of magnitude decrease of mass flow-rate, and in the onset of conditions where small heterogeneities in the solid fraction carried by the magma translate into highly unsteady eruption dynamics. We argue therefore that crystallization on top of the magmatic column during the intermediate phases when magma was not discharged caused the conditions to shift from fire-fountain to Strombolian activity. The numerical simulations also provide a consistent interpretation of the association between fire-fountain activity and emergence of lava flows from the crater flanks.

1. Introduction

Persistently active basaltic volcanoes, such as Mt. Etna, Italy, display different styles of volcanic activity including effusion of lava, fire-fountaining and Strombolian explosions. Plinian-like explosive eruptions are rarer events, but they have been also documented (e.g., Coltelli et al., 2000; Branca and Del Carlo, 2004). Because of its hazard implications, basaltic explosive activity is increasingly better monitored (as an example, see the Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania, website at www.ct.ingv.it) and studied (among the others, AL) by the international scientific community. At Mt. Etna, the most common explosive activity spans from mild to moderate Strombolian explosions to violent fire-fountain episodes consisting of vigorous, continuously sustained jets of magma and gas, often accompanied by ash emissions. A spectacular example of this type of activity is represented by the 64 fire-fountain episodes occurred at the Southeast crater (SEC) on the summit of Mt. Etna between January and June 2000 (Alparone et al., 2003) (Fig.1). Characterization of selected products erupted from this paroxysmal activity demonstrated substantial textural and compositional variations relating to the dominant style (either Strombolian- or fire-fountain) of the eruption (Polacci et al., 2006).

Despite compositions and textures are known to control the rheological behaviour of magmas (e.g., Giordano et al., 2009; Pinkerton and Stevenson, 1996; Lejeune and Richet, 1995) a few studies have investigated the rheological properties of specific basaltic liquids (Giordano and Dingwell, 2003) and basaltic magmas at subliquidus conditions (Shaw, 1969; Ryerson, 1988; Pinkerton and Norton, 1995; Ishibashi and Sato, 2007; Sato, 2005; Ishibashi, 2009). However, none of the previous studies allows tracking of the rheological variation associated with crystallization, vesiculation, cooling and straining of a basaltic magma during its rise to the surface. Only recently, the accessibility to modern high temperature, high pressure deformational facilities has allowed Earth scientists to build numerical and experimental predictive models accounting for the evolution of the rheological properties of magmas as they change in the volcanic conduit during magma rise to the surface.

In order to quantify the effect of rheology on Mt. Etna eruptive style, in this study we combine two empirical models that allow us to account for the variation of silicate melt viscosity in the T (Temperature)-X (composition)-H_2O space (Giordano et al., 2008) and for the non-Newtonian rheological effects due to the presence of crystals in strained magmas (Costa et al., 2009). These models are applied to calculate the viscosity of volcanic products discharged during selected eruptive episodes of the January-June 2000 Mt. Etna explosive activity. In the following we show that non-Newtonian effects due to straining of crystal-bearing magmas result in substantial differences in the apparent viscosities for the magmas erupted during the Strombolian and fire-fountain phases. The textural and compositional changes observed in scoria clasts erupted during the two different eruptive phases (i.e. Strombolian or fire-fountain) of the 2000 eruption are related to pronounced and relatively sharp changes in rheology. Such changes were initiated by a difference in the crystal content of the erupted magmas, and coincided with a change of the style of eruptions and a shift from Strombolian to fire-fountain activity. A better understanding of the rheology of Etnean magmas and its correlation with the eruptive style provides constraints to models of the dynamics of explosive activity at this volcano, including sudden shifts between eruptive styles that are common at basaltic volcanoes. Ultimately, a thorough comprehension of the rheological properties of magma systems is a valuable tool for improving monitoring and hazard forecasting of active volcanoes.

2. The January-June 2000 Mt. Etna eruption: summary of activity and features of the erupted products

In this study we investigate the evolution of the rheological properties characterizing volcanic products erupted at Mt. Etna during the first semester of 2000. We choose to study this period of activity for the following reasons: first, it represents the most remarkable cyclic explosive activity over a short period of time in the known history of the volcano; second, it allows us to constrain the transition from Strombolian to fire-fountain activity by a rheological point of view; and third, an accurate description of this activity exists in terms of geophysical and geochemical signals (Alparone et al. 2003; Allard et al. 2005), offering a substantial dataset to our rheological modelling.

2.1 Eruption chronology and styles of activity

The eruptive period considered in this study started on 26 January 2000, ended on 24 June of the same year and focussed at SEC, generating 64 paroxysms each consisting of an initial

Strombolian phase that was gradually replaced by a phase of sustained fire-fountain activity. The former activity, usually lasting from a few to tens of minutes, consisted of mild to moderate to increasingly stronger explosions of gas and fragmented magma particles (ash, lapilli and bombs); the latter, so called paroxysmal phase, which also coincided with the peak of the tremor signal, lasted from tens of minutes to a few hours, and consisted of continuous, violent, hundreds-of-metres-high jets of magma and gas and in the formation of ash plumes up to a height of 6 km above the crater. All paroxysmal episodes were preceded and accompanied by lava flows from the flanks of the SEC cone whose peak in volume coincided with the climax of the fire-fountain phase. A detailed descriptions of the eruptive activity is contained in Alparone et al. (2003) and Behncke et al. (2006) and in the papers referenced therein.

2.2 Features of erupted products

Scoria clasts erupted during Strombolian and fire-fountain activity present distinct compositional and textural characteristics, which are respectively summarized in Table 1 and 2. As a general observation, products erupted from both styles of activity are porphyritic rocks (Table 2) that exhibit two vesicle populations: small (<200 μm), generally isolated, rounded to sub-rounded vesicles, and larger (from hundreds of microns to > 1 cm but mostly >0.5 mm), well connected vesicles (Fig. 2). Large vesicles that range from sub-rounded to mostly complex, irregularly-shaped in Strombolian scoriae (Fig. 2 a) are more deformed in products from fire-fountains and may exhibit ellipsoidal to variably elongated shapes (Fig. 2b).

Scoriae from fire-fountains display a less crystallized groundmass (vesicle-free microlite content < ~ 20 vol%) (Table 2 and Fig. 2 c, d), and are more vesicular (crystal-free vesicularity 0.7-0.8, Table 2) in comparison to products erupted during Strombolian activity (microlite cristallinity in the range 30-40 vol%, vesicularity ~0.65). Fire-fountain scoriae also contain a higher number density of small, isolated, vesicles (such vesicles ranging 2-8 mm^{-2} in Strombolian scoriae and 11-23 mm^{-2} in fire-fountain scoriae) and in terms of glass chemistry are less compositionally evolved than Strombolian scoria clasts. Finally, eruptive temperatures calculated via the glass geothermometer of Pompilio et al. (1998) are up to 30 ºC higher for the fire-fountain than for the Strombolian products (Table 1).

3. Rheological model and applications

3.1. The models

As mentioned above, the mixture viscosity is calculated by using two recently published models that account for the continuous description of the Newtonian liquid viscosity in the T - composition - H_2O space (Giordano et al., 2008), and for the non-Newtonian effects of crystals and applied rate of strain (Costa et al., 2009).

The model of Giordano et al. (2008) calculates the Newtonian shear viscosity (η_m) of silicate melts as a function of temperature, 10 major oxides, and volatile content (e. g., H_2O and F). The model is calibrated on ~ 1800 viscosity measurements on dry and hydrous multi-component melts, and accounts for non-Arrhenian temperature dependence. Since a significant dataset used to calibrate the model refers to basaltic compositions (e.g., Giordano and Dingwell, 2003; Sato, 2005; Giordano et al., 2006; Ishibashi and Sato, 2006), this model is particularly suited for calculating magma viscosity of undersaturated basaltic products. The ability of the model of accurately predicting the viscosity of basaltic melts can be appreciated in Fig. 3.

The non-Newtonian rheology of crystal suspensions are accounted for by the Costa et al. (2009) model. This model computes the relative viscosity η_r (viscosity of a crystal-melt mixture divided by the viscosity of the melt phase). Compared to previous models (e.g., Einstein-Roscoe, 1952; Costa, 2005, Caricchi et al., 2007), the Costa et al. (2009) model takes into account the strain-rate dependent rheology of liquid+crystal mixtures up to a higher crystal fraction of 0.80, ensuring consistency with calculations done via the Einstein-Roscoe equation (Roscoe, 1952) for low to vanishing crystal contents.

Major element glass composition, inferred temperatures, and measured crystal contents were implemented in the above rheological modeling to estimate magma viscosity during the Strombolian and fire-fountain phases of the 2000 eruption at Mount Etna (Table 1). Temperature ranges of 1080-1103 °C and of 1106-1129 °C were respectively taken as representative of the Strombolian and fire-fountain phases of the eruption. These estimates (Table 1) are calculated via a glass geothermometer calibrated on Etnean rocks samples (Pompilio et al., 1998).

3.2. Viscosity calculations

Average crystal contents of 0.57 for the Strombolian phase and 0.37 for the fire-fountain phase, both referred to a bubble-free magma, were adopted in most calculations (see Table 2). Fig. 4 shows the strain-rate dependence of the relative viscosity at varying crystal volume fractions. As shown in Fig. 4a, the relative viscosity of two-phase mixture increases following a sigmoid curve with exponential increase above a critical solid fraction. Variations of crystal content cause orders of magnitude changes in viscosity. The critical crystal volume fraction depends on crystal shape, size distribution and crystal orientation, decreasing with randomness in object orientation and particle shape anisotropy (i.e., equant vs elongated) and increasing with dispersion in object size (Chong 1971; Lejeune and Richet, 1995; Saar, 2001; Caricchi et al., 2007; Caricchi et al., 2008; Costa et al., 2009).

As a first order approximation, calculations with the model of Costa et al. (2009) are shown for the simple case of equally sized, mono-distributed spheres. A huge effect on the magmatic mixture viscosity is observed when moving from a crystal volume fraction of 0.37 to 0.57 (Fig. 4b), representative of the two magma types erupted during the fire fountain and Strombolian phases, respectively, of the 2000 Mt. Etna activity. This effect is maximum at low strain rates ($<10^{-5}$ s^{-1}) where the rheology is approximately Newtonian, and it is reduced at higher strain-rates where non-Newtonian behaviour becomes substantial for large crystal contents.

Figure 5 shows calculations at constant H_2O contents of 0.3 wt% and 0.7 wt%, corresponding to the residual water content in the magma discharged during the Strombolian and fire-fountain phases, respectively (Metrich et al., 2004; Spilliaert et al., 2006). The calculations are shown for two different low and high rates of strain. To consider the effect of crystals on the viscosity of the erupted magmas, the relative viscosity of the Strombolian and fire-fountain products were first calculated using the Costa et al. (2009) model with crystal contents reported above and representative of those in Table 2. Relative viscosities were then multiplied by melt viscosities calculated through the Giordano et al. (2008) model. The plots in figure 5 clearly show that the viscosities of the two different crystal-rich and crystal-poor magmas plot in two well distinct fields, with the magma from the Strombolian activity displaying values >2 to 4 orders of magnitude higher.

3.2. Application to conduit flow dynamics

The rheological models described above have been implemented in the Conduit4 code for the 1D steady multiphase dynamics of conduit flow (Papale, 2001). With this update, the code embodies non-Newtonian rheology as due to strain-rate dependent viscosity of magmatic crystal suspensions as described by the Costa et al. (2009) model. Additionally, the recent model of Giordano et al. (2008) for silicate liquid viscosity as a function of temperature, liquid composition, and dissolved water has been implemented. For any condition in terms of locally-defined silicate liquid composition, dissolved volatiles, temperature, and rate of strain encountered in the flow dynamics calculations, the viscosity of the liquid-crystal magmatic mixture is the one implied by the two rheological models referenced above.

Strictly speaking, the introduction of non-Newtonian rheology requires at least 2D flow modeling in order to compute the velocity profile and the internal friction forces at any level in the conduit. Our 1D approach retains instead the simplified assumption of parabolic velocity profile typical of Newtonian fluids, but locally computes an effective viscosity based on non-Newtonian behavior described above. Although 2D modeling can approximate better the true conditions in the conduit, we still capture the major effect of a change of viscosity at any level during magma flow as a consequence of the high crystal content of magma and the locally computed rate of strain.

For the present purposes, the particles (crystals) dispersed in the liquid magma have been assumed to have a spherical shape, after having verified that elongated shapes with aspect ratio up to 10 involve variations in the calculated mass flow-rate of less than 5% on a log scale.

While the steady flow model can be applied to the long-lasting fire-fountain phases of the 2000 eruption of Mount Etna, the highly unsteady character of the Strombolian phases prevents its application. The rheologically updated Conduit4 code has been therefore applied to the fire-fountain phase first, in order to identify a conduit diameter consistent with the observed mass flow-rates. Besides the mass flow-rate, the eruptive conditions have been constrained by the silicate liquid composition (10 major oxides), magma temperature, total volatiles H_2O and CO_2, and total crystal content assumed to correspond to 0.35 volume fraction (referred to bubble-free magma). The code then computes a conduit diameter and the corresponding vertical distribution of flow quantities and magma properties corresponding to the assumed mass flow-rate.

A second set of simulations has been performed by assuming this time a conduit diameter consistent with the fire-fountain phase as determined above, and progressively increasing the crystal content up to that of the Strombolian phase. Here the aim is that of evaluating what would be the net effect on the eruption dynamics of just erupting more crystal-rich magmas. Figure 6 shows the set of pressure distributions along the conduit obtained as described above, for crystal contents from .35 to .59. For this set of simulations, the ascending magma is never found to reach the conditions for fragmentation, apart from the most crystal-rich cases, and at a level corresponding to the conduit exit. The pressure is larger than lithostatic everywhere, increasing with decreasing crystal content of the erupted magma.

It is worth noting that for the present purposes, we refer to magma fragmentation as the brittle process occurring in a volcanic conduit, not considering fragmentation upon rapid expansion to atmospheric pressure that results in lava spatters or ash production from the top of lava fountains. In this sense, lava fountains belong to the non-fragmented family of eruptions, since the discharged magma emerges from the vent in the form of a liquid continuum.

Figure 7 illustrates the effect on mass flow-rate of the discharge of progressively crystal-richer magma. Comparing the conditions at the lowest and highest employed crystal contents, representative of the fire-fountain and Strombolian phases, respectively, reveals that such an increase of the crystal content at equally other conditions produces a decrease of the mass flow-rate by one order of magnitude. If the total water content decreases when the crystal content is increased, the decrease in mass flow-rate is even more dramatic.

Figures 6 and 7 also show that small variations of the crystal content in the erupted magma have an effect which is comparably small if the crystal content is relatively small, but it can be substantial if the crystal content is sufficiently high. At the large crystal contents comparable with that of the Strombolian phases at Mount Etna, small variations of the crystal content are expected to result in large fluctuations of the mass flow-rate (Fig. 7), suggesting a tendency towards unsteady eruption dynamics.

5. Discussion and Conclusions

The analysis and modelling carried out in this paper demonstrates that the phases characterized by Strombolian and fire-fountain activity during the 2000 summit eruption cycle at Mt. Etna were characterized by the emission of magma having bulk or multiphase viscosity differing by orders of magnitude. Higher viscosity was associated with the Strombolian phases as a consequence of larger crystal content of magma trespassing a critical value at around 50 vol%, above which the slope of the viscosity vs. crystal content curve rapidly increases. Numerical modelling of steady magma flow performed here suggests that at such large crystal contents small heterogeneities in the solid particles carried by the magma may imply large fluctuations of the flow conditions, effectively hampering the onset of steady flow conditions.

We propose here that the large crystal content > 50 vol% of the Strombolian eruption phases represented a rheological barrier for the onset of a sub-steady fire-fountain phase like those characterizing instead the discharge of magma with 30-40 vol% crystal content. According to this view, when the deep forces sustaining efficient magma discharge waned, the magma residing at shallow levels in the conduit had sufficient time to crystallize under degassed and cooling conditions. Addition of about 20 vol% crystals to the original magma resulted in 2 to 3 orders of magnitude increase in viscosity, and in the formation of a plug of scarcely mobile magma on top of the magmatic column. Remobilization occurred then through a sequence of strongly unsteady Strombolian pulses until the viscous plug was eliminated and a new fire-fountain phase discharging less crystal-rich and less viscous magma took place.

The numerical simulations presented in Figs. 6 and 7 provide also a physical interpretation for the association between fire-fountaining and accompanying lava flows, often observed during the eruptive sequence. In fact, steady magma discharge turns out to be associated with large overpressure in the volcanic conduits (Fig. 6), with maxima around 10 MPa in correspondence of the upper portion of the conduit. Such a conduit region corresponds to the cone of SEC, mainly formed by the accumulation of tephra during last 30 years of activity of Mt. Etna and therefore characterized by a minimum in mechanical resistance. It is therefore expected that during the fire-fountain phases of the eruption dyke intrusion occurs at the level of the cone due to the favourable combination of highest magmatic overpressure and lowest mechanical resistence of surrounding rocks. Dyke intrusion at this shallow level would therefore cause lava flows to emerge from the flanks of the SEC during the fire-fountain phases of the eruption, as it was in fact repeatedly observed.

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Figure captions

Fig. 1 Fire-fountain activity at the South-East crater of Mt. Etna on 8 June 2000. Horizontal edge of photo ~ 700 m. Courtesy of D. Andronico.

Fig. 2 Backscattered scanning electron images of bulk (top images) and groundmass (bottom images) textures in scoria clasts from Strombolian (a, c) and fire-fountain activity (b, d) at Mt. Etna in 2000. Black voids are vesicles, white, dark grey and light grey features are crystals, groundmass glass is in intermediate grey. Scale bar is 1 mm in a and b and 20 μm in c and d.

Figure 3. Calculated vs measured viscosities for SiO_2-undersaturated natural melts (SiO_2 in the 40-50 wt% range): (Witthington et al., 2000, 2001 (basanitic (NIQ) and tephritic compositions); Giordano and Dingwell, 2003a, b (Eifel basanite; Etna trachybasalt; Vesuvius phonotephrite); Dingwell et al., 2004 (Balmuccia peridotite); Bouhifd et al., 2004 (Stein Frenz tephrite and phonotephrite); Sato, 2005; Ishibashi and Sato, 2007; Giordano et al., 2006, 2007, 2008, 2009 (Slapany basanite, Nyiragongo phoidite, Stromboli materials, 1906 Vesuvius eruption tephrite); Villeneuve et al. 2009; Ishibashi, 2009. The calculations are based on the Giordano et al. (2008) (GRD) model and reproduce high temperature (close to eruptive temperature) and low temperature (close to glass transition) data with less than 0.35 log units RMSE (Root Mean Standard Error). Accuracy of the predictions at close to eruptive temperature is significantly higher, with RMSE less than 0.2 log units.

Figure 4. a) Relative viscosity as a function of crystal volume fraction at different strain-rates; (b) relative viscosity as a function of strain-rate for two crystal volume fractions of 0.37and 0.57, adopted for fire-fountain and Strombolian phases of the Etna 2000 activity, respectively. Calculations made with the model in Costa et al. (2009).

Figure 5. Calculated liquid-crystal viscosity as a function of temperature for the magmas erupted during the Strombolian (open symbols) and fire-fountain (solid symbols) phases of the 2000 Mt. Etna activity. The calculations assume a crystal volume fraction of 0.37 for the fire-fountain phase and 0.57 for the Strombolian phase (see text and Table 2). The viscosity of pure liquids at anhydrous and dissolved water contents (reported in the figure) of 0.3 and 0.7 wt%, calculated with the GRD model, are also shown as lines in the figure.

Figure 6. Calculated pressure distribution along the conduit for magmas from 35 to 59 vol% of crystals relative to the liquid-crystal phase. Assumed total water content: 4 wt%. All other conditions reported in Table 3. The calculations are performed with the Conduit4 code (Papale, 2001), assuming a fixed conduit diameter of 4.5 m, corresponding to the conduit diameter required (from the simulations) to produce an observed mass flow-rate of 2.5 x 10^5 kg/s for the fire-fountain eruption phase with 35 vol% crystals.

Figure 7. Calculated mass flow-rate as a function of the crystal content, for the simulations in Fig. 6 plus a few others with assumed total water content of 2 wt%.

Figure 1. Giordano et al., 2009

434 Figure 2. Giordano et al., 2009

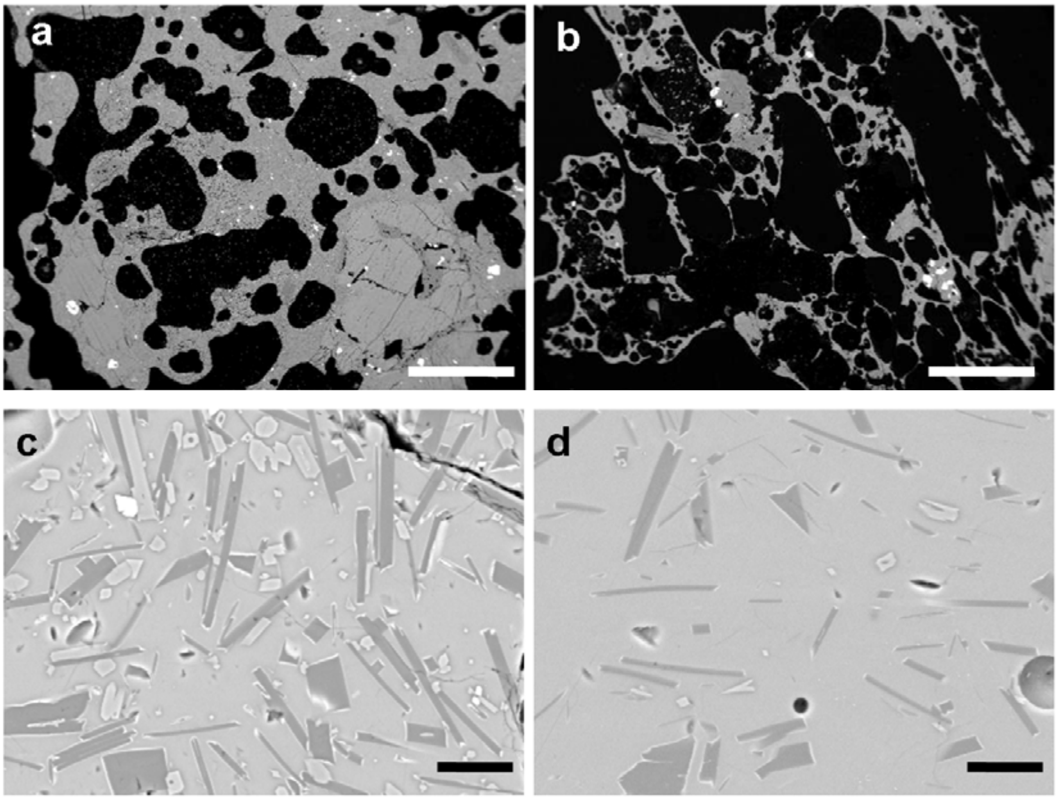

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Figure 3. Giordano et al., 2009

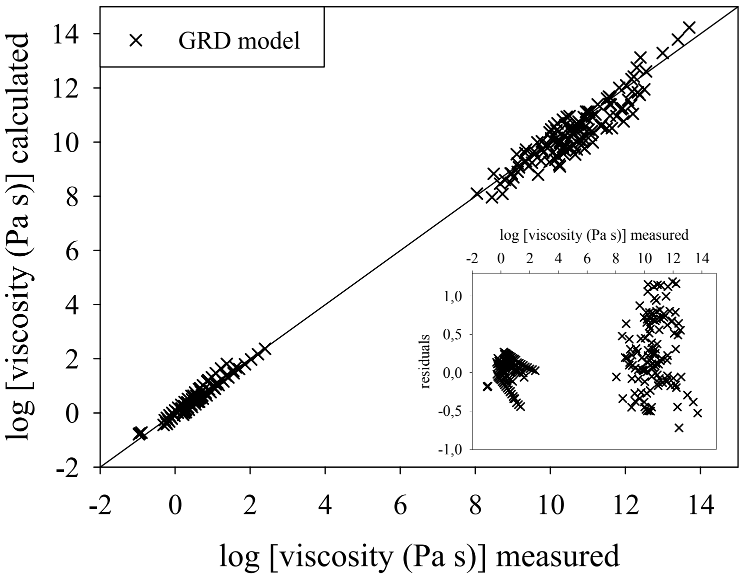

Figure 4. Giordano et al., 2009

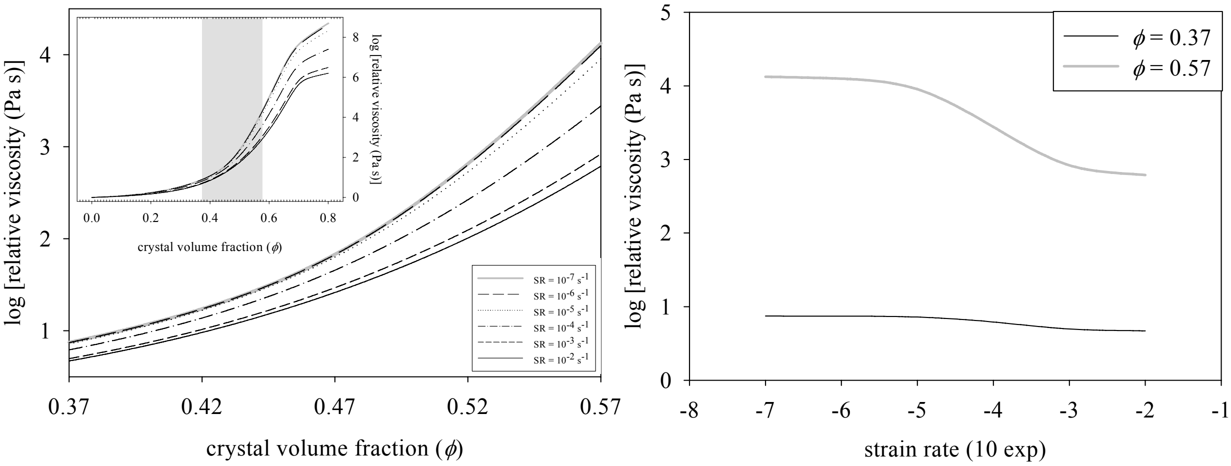

Figure 5. Giordano et al., 2009

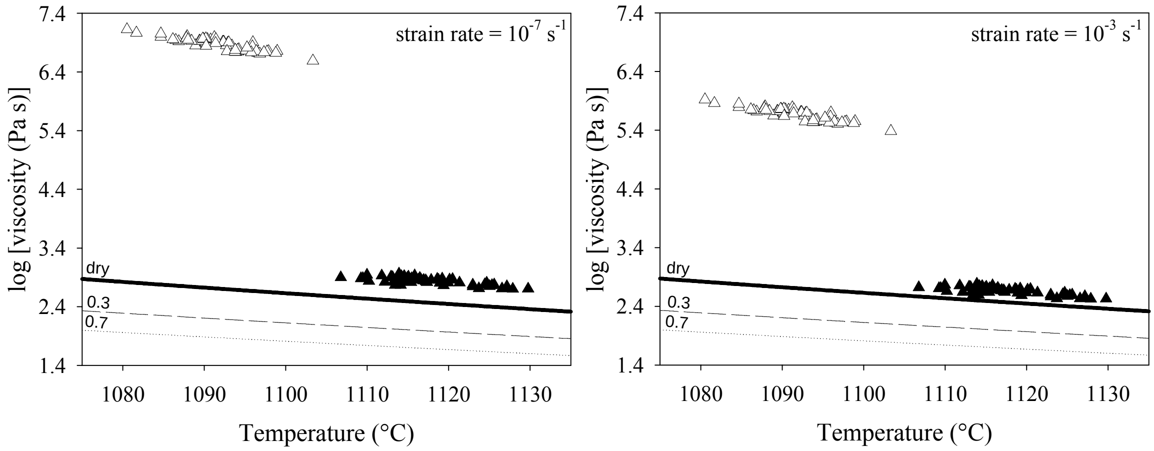

Figure 6. Giordano et al., 2009

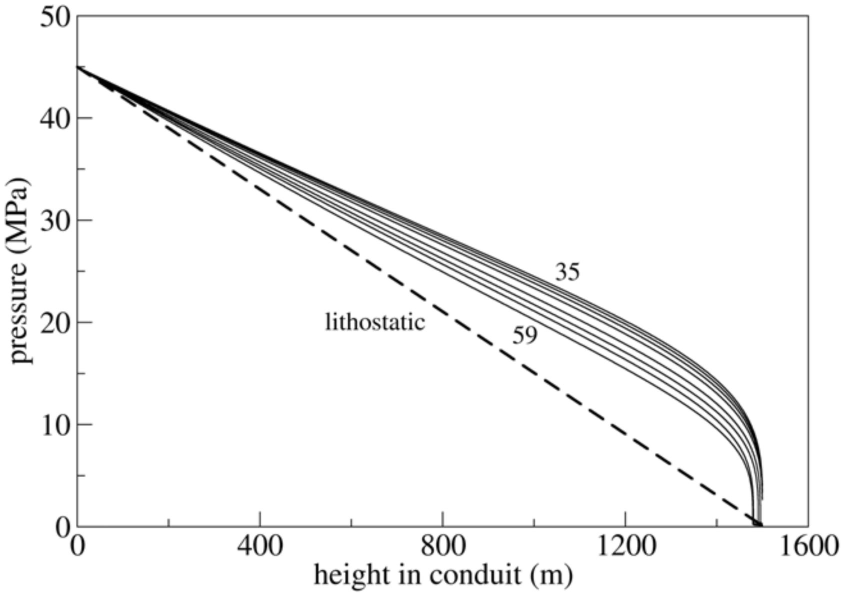

Figure 7. Giordano et al., 2009

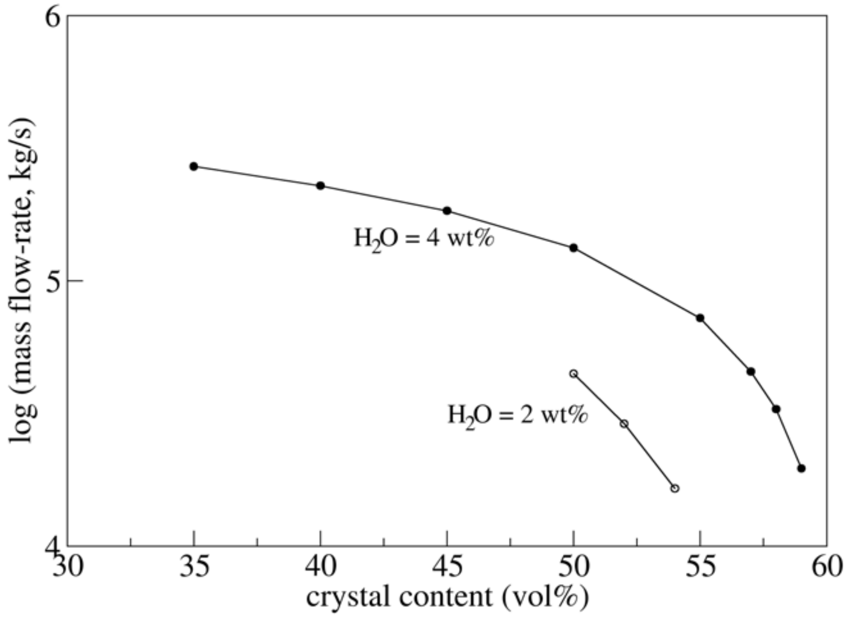

Table 1. Eruptive temperatures and CaO/MgO content in products from explosive activity at Etna in 2000

	Strombolian	Fire-fountain
T(°C)		
Average	1091.9	1117.6
Minimum	1080.5	1106.8
Maximum	1103.3	1129.8
CaO/MgO (wt%)		
Average	2.29	2.13
Minimum	2.04	1.88
Maximum	2.48	2.30

Table 2. Summary of textural features of scoriae erupted from the explosive activity at Etna in 2000

Sample	Type of activity	[a]Vesicularity	[a]Microlite crystallinity	Tot crystallinity
040300B	Strombolian	0.66	0.36	0.58
040300B1	Strombolian	0.64	0.30	0.59
160400D	Strombolian	0.63	0.40	0.55
150500B	Fire fountain	0.80	0.12	0.39
150500Ea	Fire fountain	0.72	0.17	0.39
150500Eb	Fire fountain	0.68	0.23	0.43
170500	Fire fountain	0.78	0.12	0.30

[a]Vesicularity and microlite crystallinity from Polacci et al. (2006)

Table 3. Input data for the numerical simulations

		ff 150500
conduit length (m)[a]		1500
pressure at conduit base (Pa)		4.5×10^7
magma temperature (K)		1390
average crystal density (kg/m^3)		2800
magma composition (wt %)	*SiO_2*	48.55
	TiO_2	2.07
	Al_2O_3	16.77
	Fe_2O_3	1.86
	FeO	8.00
	MnO	0.20
	MgO	4.31
	CaO	9.08
	Na_2O	4.14
	K_2O	3.07

[a]*Vergniolle et al., 2008*