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Abstract

Phonolitic eruptions can erupt either effusively or explosively, and in some cases develop highly energetic events such as caldera-forming eruptions. However, the mechanisms that control the eruptive behaviour of such compositions are not well understood. By combining pre-eruptive data of well studied phonolitic eruptions we show that the explosive-effusive style of the phonolitic magma is controlled by the amount of volatiles, the degree of water-undersaturation and the depth of magma storage, the explosive character generally increasing with pressure depth and water contents. However, external factors, such as ingestion of external water, or latter processes occurring in the conduit, can modify the starting eruptive dynamic acquired at the levels of magma ponding.

1. Introduction

Volcanic eruptions in populated areas represent a major threat to human beings, associated hazard having both regional economic and social impacts and global consequences, as recently illustrated by the eruption of the Eyjafjallajökull volcano in Iceland (e.g., Sigmundsson et al., 2010). Nowadays, the monitoring of active volcanoes allows the prediction of a volcanic eruption with several days or weeks of anticipation. However, the geophysical techniques do not allow predicting the eruptive style of an incipient or on-going eruption.

To improve our capacity of prediction, researchers have put many efforts in studying past-eruptions, as they hold key parameters for understanding future events. Studying the characteristics of the erupted products within an eruptive sequence (ie fall-out, ignimbrites, tephra, lava) indeed allows one to determine the eruptive style of the eruption (explosive, highly explosive, effusive, e.g., Cioni et al., 1999) and, along with laboratory studies, to identify if variations of storage conditions occurred during the eruption or between several events (e.g., Martel et al., 1998; Scaillet et al., 2008). In general, however, the factors that control the explosivity of an eruption and their variations with time are not well constrained.

Special attention has been given to the petrography and geochemistry and to the determination of the storage conditions of magmas as they control the rheological properties of the melt, notably via the solubility of the different species dissolved into the melt. The determination of the pre-eruptive melt viscosity is done by coupling the inferred range of temperature and water content together with available viscosity models, in particular for water. The majority of the highly-explosive and explosive eruptions are associated to highly evolved compositions (ie rhyolites, trachytes, phonolites) which appear to be the most viscous members of their own series.

Despite of not being as abundant as their calc-alkaline counterparts, phonolitic magmas are within the compositions capable to develop highly explosive activity. The very well characterised 79 A.D. Vesuvius eruption which generated pyroclastic flows that destroyed the roman cities of Pomepeii and Hercolano reminds us the high potential explosivity that can be associated to such magma compositions. Phonolitic volcanism occurs in all geological settings: divergent (ie Kenya rift in Africa, Eiffel volcanic complex) and convergent margins (ie Vesuvius, Alban Hills, Tambora), intraplate volcanism (ie Canary Islands, Kerguelen archipelago, Erebus in Antarctica). In general,

phonolitic eruptions are characterised by being volumetrically small (0.01 to a few 1 km³) compared to andesitic-rhyolitic calc-alkaline magmas. However, some events may be highly explosive (ie caldera-forming eruptions), producing fall-out and/or pyroclastic flow deposits with volumes ranging from 5 to 20 km³ Dense Rock Equivalent (DRE; e.g., Edgar et al., 2007, Cioni et al., 1999), or even more (ie the Tambora 1815 eruption).

It is worth noting that several of such potentially dangerous volcanoes are located in highly populated areas (ie Vesuvius, Teide, Tambora volcanoes) which reinforces the need to understand the parameters that control the eruptive dynamic of phonolitic magmas. Several works have determined the rheological properties of phonolitic melts over a wide range of temperatures and water contents (e.g., Giordano et al. 2000; Whittington et al. 2001, 2004; Giordano et al., 2008; Giordano et al., 2009). However, as stressed above, a correct application of such models to volcanic contexts requires that pre-eruption parameters, such as melt H_2O or temperature, are well known. In particular, a precise inference of the depth of magma accumulation is vital in view of the role that pressure exerts on volatile solubilities, hence on the levels of gas exsolution (Larsen and Gardner, 2004; Iacono-Marziano et al., 2007) which greatly affects magma dynamics (e.g., Papale and Polacci, 1999)

In this work we use recently determined phase equilibrium results acquired on phonolitic magmas for determining their viscosity at pre-eruptive conditions and compare them to the pre-eruption melt viscosities of silicic-intermediate extrusive magmas (Scaillet et al., 1998; Takeuchi, 2011). The results show that the selected phonolites have melt viscosities of $10^{3.8\pm0.4}$ Pa·s, being close to magma viscosities owing to their generally low crystal load. In addition, our data show that the explosive or non-explosive character of phonolitic magmas is acquired at storage levels though it can be altered syn-eruptively by external factors (ie intrusion of meteoric water in the system, changes in conduit size, magma mixing in the conduit).

2. Pre-eruptive magma viscosity: general considerations

In this work we use the combination of calculated pre-eruptive magma viscosity and recent phase equilibrium results, as a proxy for predicting the potential explosive character of incipient eruptions sourced in phonolite-trachyte reservoirs. The observations and results presented in this study concern primarily the state of magma while still residing in the reservoir. We emphasize that, once the magma starts its ascent

to the surface, its rheological properties will inevitably change due to decompression and accompanying dehydration and its related effects (vesiculation, microlite, crystallization and temperature changes), which all lead to important variations in viscosity that affects in turn the eruptive style of the on-going eruption (e.g., Martel and Schmidt, 2003; Blundy et al., 2006). Hence, critical aspects related to the physics and mechanics of magma ascent (e.g., relaxation timescale of fluid and melt phases, change in conduit diameter, etc…), and syn-eruptive processes that potentially can affect an eruptive event (e.g., degassing, mingling, mixing, decompression, others) are not considered here.

2.1.   Studied eruptions

The calculation of pre-eruptive magma viscosity critically hinges on accurate estimates of pre-eruptive phenocryst, melt composition including its water content, and temperature, in addition to storage pressure (e.g., Papale et al., 2006; Carroll and Blank, 1997; Schmidt and Behrens, 2008). Although numerous studies of phonolite-trachyte volcanic suites are available in the literature, we have only considered those whose pre-eruptive conditions can be rigorously constrained from phase equilibrium experiments, as associated uncertainties on pressure are considerably lower (< 50 MPa; ie Scaillet et al. 2008, Pichavant et al. 2007; Martel et al. 1999, Costa et al. 2004; Andújar et al., 2008, 2010) compared to the application of conventional thermobarometric mineral equilibria (currently +/- 100-200 MPa; Putirka et al., 1996). This is central to the purpose of the present paper, since for a given water content, large uncertainties on pressure translate into large uncertainties with respect to the level at which water-saturation, bubble coalescence, and magma fragmentation occur (e.g., Larsen and Gardner, 2004; Iacono-Marziano et al. 2007).

The selected eruptions and their intensive parameters are shown in Table 1, showing conditions that are representative of the main erupted volume for each event. We note that pre-eruptive parameters of Table 1 may differ from those determined by other authors for the same eruptions, either as a result a different methodology for the parameter determinations (ie mineral-liquid equilibria) or because of the presence of thermally-compositionally zoned magmatic reservoir (ie Montaña Blanca eruption; Ablay et al., 1995; Andújar and Scaillet, in press). The selected eruptions and their main eruptive style are briefly summarised below (Table 1).

For Vesuvius (Italy), we have considered the plinian and sub-plinian eruptions of Mercato, Avellino, Pompeii and Pollena (Scaillet et al. 2008); For the East Eifel volcanic field (Germany), we selected eruptions labelled as LLST, MLST, ULST1060,ULST1088 from the Laacher See volcanic complex (Berndt et al., 2001; Harms et al., 2004); For Kerguelen, we use the work of Freise et al. (2003) carried out the Upper Miocene lavas of the Kerguelen archipelago (K1); For Teide, three eruptions [El Abrigo (EA), Lavas Negras (LN) and Montaña Blanca (MB)] from the phonolitic volcanic complex of Teide volcano (Canary Islands, Spain) were used (Andújar et al., 2008; 2010; Andújar and Scaillet, in press). We also considered the phonolites of the persistent Erebus lava lake as an example of a phonolitic magma containing a low water content with a permanent effusive activity (Kyle et al., 1992, Kelly et al., 2008; Oppenheimer et al., 2011). In addition, the Tambora 1815 eruptions was included. This event ejected ca 33 km^3 of DRE of phonolitic magma (Foden, 1986; Self et al., 2004): although no phase equilibrium experiments have been performed on Tambora, available data (Cioni et al., 1998, 1999; Self et al., 2004; Scaillet et al., 2008) allow us to put precise constraints on key pre-eruptive parameters of this event. Finally, we also included a sligthly Qz-undersaturated trachyte (ie Ne-normative; CI PR38, CI ZAC), with the example of the Phlegrean Fields (Marianelli et al., 2006; Fabbrizio and Carroll, 2008), which is responsible of several large eruptions over the last 100 kyrs, in particular the so-called Campanian Ignimbrite, which erupted more than 100 km^3 some 39 kyrs ago. The selected eruptions span a wide range of eruptive activity from persistent lava lake systems (Erebus), to effusive eruptions (e.g., K1 and Lavas Negras) producing thick lava flows, explosive events (e.g., Laacher See, Vesuvius) with ensuing thick fall-out deposits and pyroclastic flows, caldera-forming eruptions (e.g., El Abrigo; Edgar et al., 2007, Tambora, Self et al., 2004) responsible of the emission of more than 10-100 km^3 DRE of magma, and dome eruptions (e.g., Montaña Blanca).

Studied rocks are mainly phonolites or trachytes (with only one tephri-phonolite composition: the Pollena eruption; Fig.1) according to the classification of Le Bas and Streckeisen (1991) and Le Maitre et al. (1989), with SiO_2 content from 51 to 62 wt% and Na_2O+K_2O between 10 and 18 wt%, being either peralkaline or peraluminous. Although phonolitic in the broad sense, the various magmas differ in their Na_2O/K_2O ratios (between 2 and 0.4), Al_2O_3 (19 to 23 wt%) and CaO contents (5.9 and 0.6 wt %). Such differences in composition affect mineral assemblages and phase diagrams, as

illustrated by several experimental works (e.g., Scaillet et al., 2008; Andújar et al., 2008).

2.2. Pre-eruptive melt and magma viscosity calculations: effect of crystals, bubbles, pressure and volatiles

2.2.1. Method of calculation

We have calculated the melt viscosity at the pre-eruptive conditions and then the magma viscosity. Several works are available in the literature for calculating melt viscosities depending on composition, water content and temperature for phonolites (Whittington et al., 2001, 2004; Giordano et al., 2000; 2008; 2009). In this study, melt viscosities were calculated using the model of Giordano et al. (2008) as this model has been calibrated for a wide range of melt compositions, including trachytes and phonolites, in the temperature interval displayed by the magmas, and it has been applied in the literature for calculating melt viscosities of andesitic to rhyolitic magmas as well (ie Behrens and Zhang, 2009; Gardner and Ketcham, 2011; Takeuchi, 2011). Recent experimental works have demonstrated that this model reproduces measured melt viscosities to within <0.2 log units (ie Vona et al., 2011). The use of the same model for all the considered compositions ensures the self-consistency of the obtained data although we note that the use of other models yields similar viscosities (differences being <1.1 log units; Table 2), and in any case do not alter the basic conclusions reached in this paper.

For calculating magma viscosities we have used the equation of Dingwell et al. (1993):

$$\eta_{magma} = \eta_{melt}(1+0.75((f/f_m)/(1-f/f_m)))^2$$

where η_{magma} and η_{melt} are the viscosities of magma and melt respectively, f is the volume fraction of crystals, and f_m is the concentration of crystal necessary for attaining an "infinite" viscosity. We have chosen a value of 0.6 for f_m, which is that for a monodisperse suspension and relaxed shear viscosity. In addition, such a value was also used for calculating magma viscosities of rhyolitic-intermediate compositions by Scaillet et al. (1998) and Takeuchi (2011; Table 3), whose results are compared with ours for evaluating differences/similarities between these two end-member of evolved compositions. Below we review the role of different parameters on our calculated viscosities, showing that our estimates provide the correct order of magnitude as long as reservoir conditions are considered.

2.2.2. Role of crystals

Our method of calculation is clearly an oversimplification of the real rheological behaviour of natural magmas. Recent experimental studies have shown large differences between calculated and measured bulk viscosities (Caricchi et al., 2007; Caricchi et al., 2008; Champallier et al., 2008; Petford, 2009; Costa et al., 2009; Cordonnier et al., 2009; Mueller et al., 2010; Picard et al., 2011; Vona et al., 2011), illustrating in particular that crystal shape and size distribution impart a higher viscosity relative to monodisperse and equant texture fabrics, especially for crystal contents > 30 vol%. The effect of crystals is also highly strain-rate dependent (e.g., Caricchi et al., 2007; Champallier et al., 2008). Yet, at low strain rates, as anticipated to prevail in a convecting reservoir, experiments show that magmas with crystal contents up to 20 vol% behave as Newtonian liquids. In this case, the Einstein-Roscoe equation (ER) faithfully reproduces experimental observations (ie Caricchi et al. 2007; Champallier et al. 2008; Costa et al. 2009; Vona et al., 2011). Furthermore, it appears that the ER is still a good relationships for estimating magma viscosity in the range 20-30 vol% of crystals, measured and calculated viscosities differing by less than 0.5 log units (Champallier et al, 2008; Costa et al., 2009). For suspensions having crystal contents >30 vol%, the magma has a clear non-Newtonian behaviour and differences between ER-based and measured magma viscosities are > 3 log units, hence, specific equations must be used to determine pre-eruptive magma viscosities (Picard et al., 2011; Vona et al., 2011). We note that the majority of the magmas dealt with here have crystal contents in the range 1-30%.

2.2.3. Role of bubbles

In a similar way to crystals, bubbles affect magma viscosity, their effect depending on their size, abundance and strain rate. Figures concerning these parameters at reservoir conditions are difficult to obtain, though valuable information can be retrieved by the study of erupted products (ie analyses of melt inclusions using H_2O-CO_2 and trace element systematics, (Wallace et al., 1995)) or volatile budget combining remote sensing and petrological estimates (Scaillet et al., 2003). These approaches are, however, more or less affected by syn-eruptive processes (ie syn-eruptive degassing, coalescence of bubbles) and require a number of assumptions (closed system behaviour, several melt inclusions genetically related to each other), which make the outputs

model-dependent. Nevertheless, they do suggest that pre-eruptive magmas may coexist with up to 5 wt% fluid phase (e.g., Wallace et al., 1995; Scaillet et al., 2003), equivalent to some 20 % volume of gas at depth. There is no direct information on the size distribution of bubble in evolved magmas at depths, though some works have suggested that, at the storage level, bubbles tend to be small (10 to 100 microns; ie Gualda and Anderson, 2007). For high strain rates, small bubbles behave as rigid undeformable particles during shear motion of the magma, resulting in an increase of the pre-eruptive magma viscosity. In contrast, at slow strain rates (ie in magma chambers), small bubbles will deform viscously, and the pre-eruptive bulk viscosity will decrease due to the low viscosity of the gas phase (e.g., Stein and Spera, 1992; 2002; Manga and Lowenberg, 2001). According to the water-solubility models on phonolitic melts (Carroll and Blank, 1997; Schmidt and Behrens, 2008), only four of the phonolitic magmas were close to water-saturation at the storage levels (CI PR38-ZAC, LLST, Mercato, see below and Table 1) and hence, the presence of bubbles within the magma can be expected. In contrast, the other ten eruptions are clearly water-undersaturated at the storage levels and the occurrence of bubbles in pre-eruptive magma viscosity is less obvious, as stressed above. Altogether, although the occurrence and effect of bubbles at the storage levels of magmas are still under discussion, available data suggest that magma viscosities calculated here are upper bounds.

2.2.4. *Role of pressure*

Several experimental works have studied the effect of pressure on magma rheology at elevated pressures for a range of melt compositions (ie Liebske et al., 2005; Ardia et al., 2008; Hui et al., 2009; Suzuki et al., 2005, 2011). The effect of pressure becomes significant when variations of several GPa occur, and depends on magma composition. (e.g., Liebske et al., 2005; Ardia et al., 2008; Suzuki et al., 2005, 2011). In contrast, these studies have shown that at shallow crustal levels (below 500 MPa), that is, in the range of interest here, the effect of pressure on magma viscosity is trivial, producing variations of about 0.1-0.3 log units at best (Liebske et al., 2003).

2.2.5. *Volatiles other than H_2O*

Thermodynamic (ie Papale et al., 2006) and experimental solubility models (ie Morizet et al., 2002) predict low CO_2 concentrations in phonolitic melts at shallow levels (< 6 km), in agreement with the low amounts of CO_2 found in melt inclusions in

the selected eruptions (< 500ppm; Oppenheimer et al., 2011; Gertisser et al. 2012; Wörner and Schmincke, 1984; Signorelli et al., 1999; Marianelli et al., 2006). If CO_2 was present in the phonolitic-trachytic eruptions considered in this work, the most likely situation is to have it stored in CO_2-rich exsolved fluid phase that could affect magma rheology, as discussed previousy, but, also affect phase equilibria through the reduction of H_2O activity (Holloway, 1976), and the magma eruptive dynamics (see Papale and Polacci, 1999). Concerning F and Cl, these two species may either decrease (F) or increase (Cl) melt viscosity though their effect remains relatively low compared to that of H_2O (ie Lange, 1994). We have checked the effect of both F and Cl on pre-eruptive melt viscosity by adding (when possible) to the model of Giordano et al. (2008) the amounts found in MI for the different eruptions to our pre-eruptive melt calculations (ie Cioni, 2000; Ablay et al., 1995,1998; Signorelli et al., 1999; Harms and Schmincke, 2000). The results show that pre-eruptive melt viscosity is affected by about ±0.3 log units when F and Cl are taken into account. Considering the small effects that these volatile species have in modifying pre-eruptive melt viscosities, though we do not have F and Cl contents for all the eruptions, we conclude that the role of such volatiles is of second order importance relative to that of water.

2.2.6. Summary

From the above considerations, it is clear that differences between calculated and real pre-eruptive magma viscosities can be expected if the amount and shape of phenocrysts, bubbles, strain rate and pressure effects are ignored. However, except for one eruption (ULST), the pre-eruptive crystal content of the studied phonolitic-trachytic magmas varies between 1 to ca. 30 vol%, falling in the range where ER equation used here performs well. Hence, the majority of magmas will have pre-eruptive viscosities close to melt viscosities, and only for magmas whose crystal content is about 30 vol% (Lavas Negras and Erebus) will pre-eruptive magma viscosities be 0.3-0.5 log units higher than that of melt. Although the effect of bubbles cannot be rigorously evaluated, we anticipate that their role under reservoir conditions (slow strain rates and less than 20% of small bubbles) is not essential (ie estimated magma viscosities being possibly overestimated by <0.5 log unit). Similarly, considering the range of storage depths for the phonolite-trachyte eruptions (50 to 225 MPa; Table 1), predicted variations on pre-eruptive magma viscosity due to changes in this parameter would be <0.3 log units and hence, the effect of pressure can be also neglected.

The only exception is the ULST magma which contains 55 vol% of phenocrysts (Table 1). In this case, we are aware of the limitations of our pre-eruptive viscosity calculations, which could underestimate the real pre-eruptive viscosity by up to 3 log units. However, for the time being, the rheology of three-phase suspensions (bubbles+crystals+melt) is poorly understood and, the available data does not permit to develop a general predictive model for the role of crystals on magma rheology, which is why we have refrained on further elaborating on this topic.

3. Phonolitic-trachytic versus andesitic-rhyolitic melt/magma viscosities

In Table 1 the petrological features and intensive parameters of the phonolitic rocks necessary for the calculations and the obtained values for the pre-eruptive melt and magma viscosities are listed. For eruptions lacking direct experimental constraints (e.g., Tambora), we use existing experiments performed on similar compositions (e.g., Scaillet et al., 2008) and models (Cioni et al., 1999) in combination to petrological data (ie phenocrysts content and/or pre-eruptive water content) to infer the most likely pre-eruptive conditions (see below).

The phenocryst contents of K1 and Mercato phonolites is either low (< 5 to 1 vol%) or at trace levels (< 1 vol%) (e.g., Weis et al., 1993; Santacroce, 1987) hence, for these two cases, we have used for our calculations a phenocryst content of 1% (note that varying the crystal content from 1 to 5 vol % increases the viscosity of the magma of about 0.2 Pa·s log units). For ULST phonolites the water content for the melt was roughly determined by Berndt et al. (2001). In this case, for calculating the melt and magma viscosities we have used the temperature and pressure constraints provided by Berndt et al. (2001) along with the water content of glass inclusions analysed by Harms and Schmincke (2000). For Tambora, petrological attributes are from Foden (1986) and Self et al. (2004). The pre-eruptive melt composition was taken from Self et al. (2004), who also inferred a pre-eruptive temperature range between 930-980°C and a pressure of storage of 100 MPa, using mineral thermobarometry. The pre-eruptive temperature was refined using the melt thermometer of Cioni et al. (1998, 1999), which yields 935±10°C (using the melt composition of Self et al. (2004)). There are no determinations of pre-eruptive melt H_2O content: however, melt inclusion analyses performed by Self et al. (2004) yield a total of 97.3 wt%, suggesting dissolved water contents in the range 2-3 wt%. Comparison of these T-H_2O values with phase equilibria

established on the similar composition of 472 AD Pollena eruption of Vesuvius (Scaillet et al., 2008), shows that they indeed correspond to near liquidus conditions, in agreement with the crystal poor-content of Tambora phonolites (10 wt%, Self et al., 2004). Pre-eruptive conditions for the Phlegrean Fields trachyte are those of Fabbrizio and Carroll (2008), in addition to melt inclusion data from Marianelli et al. (2006).

In this work we directly compare the calculated pre-eruptive melt and magma viscosities of phonolite-trachyte magmas with those of Takeuchi (2011), which were obtained for rhyolitic-andesitic compositions (Table 3). This author used the same calculation method outlined above for estimating the pre-eruptive magma viscosities, considering also the effects of phenocrysts, bubbles, pressure, volatiles, and strain rate. In doing so, we minimize discrepancies between the two data sets resulting from applying different calculation models and ensure that observed differences in pre-eruptive viscosities are primarily due to differences in magma composition and petrological charateristics.

The calculated melt and magma viscosities for both phonolitic-trachytic and rhyolitic-dacitic (Tables 1 and 3) rocks are plotted as a function of pre-eruptive temperature, crystal load and water content dissolved in the melt (Fig. 2 and 3). Phonolitic melts have an average viscosity of $10^{3.8\pm0.4}$ (Pa·s), being one log unit lower than the average viscosity value of rhyolites-andesites (4.8±0.8 (Pa·s) log units). Such a difference in viscosity is due to difference in melt composition (e.g., Giordano et al. 2008). Yet, both composition types display the same pattern against pre-eruptive water content ie, the hottest the magma the lowest its water content (Fig.2b). However, in detail the higher values of viscosity of the phonolitic melts overlap the lowest values of those rhyolitic. This illustrates that rhyolitic melts needs as much as twice the water content of phonolitic melts in order to have the same viscosity (Fig. 2 b and Fig.3 a). The decrease in temperature slightly increases the viscosity of rhyolitic melts whereas it does not affect phonolitic magmas which remain clustered around the average value of $10^{3.8}$ (Pa·s).

When the crystallinity of the rocks are considered the emerging general pattern is as anticipated, i.e. a decrease of the pre-eruptive magma viscosity with decreasing crystallinity though, for the rhyolite-andesite compositions this trend is enhanced for phenocrysts contents >25 vol% and less remarkable at lower crystallinities (Fig., 3c). For a given crystal content phonolites generally plot at lower viscosity than rhyolites except for the highly crystallized ULST phonolite which plots close to the maximum

reached by rhyolitic-andesitic magmas ($10^{6.8}$ Pa·s, Fig. 2c and 3c). The presence of crystals in the rhyolitic compositions increases the viscosity by 1 log units (from 4.8±0.8 to 5.7±1.1 Pa·s) whereas for phonolites, the increase is smaller (from 3.8 to 4.3 Pa·s log unit). The variation of water content has the same effect on magma viscosity than that observed for the melts: phonolites slightly increase their magma viscosity from 3.2 to 6.5 Pa·s log units, and rhyolites from 3.3 to 7.2 Pa·s log units (with an extremely high value of 9.7, Tables 1 and 3) with decreasing water content.

Except for the most crystallized samples, both rhyolites and phonolites have melt viscosities close to magma viscosities. One remarkable point of this study is that phonolitic magmas have viscosities at pre-eruptive conditions that are 1 log unit lower than rhyolitic magmas (Figs. 2 and 3). Phonolitic magmas can reach the maximum viscosity values of rhyolites at higher degrees of crystallization (>50 vol%) whereas the crystal content of rhyolitic magmas at such viscosity value is ~10 vol% lower (Tables 1 and 3).

4. Factors controlling the eruptive dynamic of phonolite-trachyte magmas

Proposed factors that control eruptive style of magmas are numerous, and include variations in ascent rate of the magmas within the volcanic conduit (Jaupart and Allègre, 1991; Woods and Koyaguchi, 1994) that affects bubble connectivity, permeability and hence gas loss in a vesiculating magma (Sparks, 1997), changes of magma rheology owing to changes in intensive parameters (i.e, temperature; Blundy et al., 2006). In silicic magmas high water contents are generally considered as responsible of high explosive activity (e.g., Sparks et al., 1997), but detailed experimental investigations on well documented eruptions show this to be not always true (see for instance Martel et al., 1998 for the Mt Pelée).

To shed further light on this issue, phase equilibrium experiments have been combined with decompression experiments carried on explosive and effusive volcanic products (e.g, Couch et al. 2003; Martel and Poussineau, 2007). Decompression experiments on phonolitic compositions have shown that they differ significantly in their behaviour during decompression as compared to rhyolite products in terms of water-oversaturation rates and bubble densities for a given ΔP (Larsen and Gardner, 2004; Iacono-Marziano et al. 2007). Such parameters are directly linked to differences in viscosity and diffusion of water in phonolite versus rhyolite magmas, which give rise

to contrasted rates of magma degassing, bubble growth and coalescence. However, the systematic application of such results to natural systems is difficult since the explored conditions do not necessarily match those prevailing in magmatic reservoir(s) (Table 1 and 3), as documented here. In particular, decompression experiments are often carried at water-saturated as well as super-liquidus conditions (e.g., Larsen and Gardner, 2004). In such experiments, both the crystal content and phase assemblage are different from those of many natural magmas considered in our study (Table 1). This may lead to contrasted behaviour of the magma during eruption, owing to heterogeneity/homogeneity in the bubble nucleation process (e.g., Iacono-Marziano et al., 2007). Altogether, this seriously hampers direct use of the decompression experiments, hence, in the following we will not consider in any detail the role of this parameter on eruptive dynamics, though it is admittedly an important factor.

Below we evaluate the role of pre-eruptive conditions and rheological properties on controlling the future eruptive dynamic of phonolitic magmas at the storage levels.

5. Pre-eruptive conditions vs. pre-eruptive magma viscosity

Our results show that phonolites are stored at various crustal levels, from very shallow conditions (1 atmosphere for Erebus lava lake to 50 MPa of Montaña Blanca) up to 225 MPa, under a wide range of temperatures (700 to 900ºC) and with water contents dissolved in the melt ranging from 0.5 to up to 7 wt%. In Figure 4 we have plotted the storage depth of the phonolitic magmas versus the pre-eruptive melt water content along with different water-saturation curves from solubility models obtained for Na- phonolites (Carroll and Blank 1997; Schmidt and Behrens, 2008). For Na-phonolites the different models predict similar water contents for pressures up to 125 MPa, whereas at higher pressures differences reach ~0.6-0.8 wt% (Schmidt and Behrens, 2008). According to these authors, the model of Carroll and Blank, (1997) over-estimates the water content due to errors in the analytical method and to differences between the starting material used in these works. However, differences in water content between these models overlap within errors of water determination obtained from melt inclusions and experimental works reported in Table 1. We thus conclude that this will not affect the main findings of this paper. The systematic investigation of Schmidt and Behrens (2008) on the role of Na/K also shows that this chemical parameter has a trivial effect on water solubility of phonolites. Thus, in this

study, for simplicity we have considered that the water-saturation curve determined for Na-phonolites is also valid for K-phonolites.

From Fig. 4 two important observations can be made. Firstly, regardless of the pre-eruptive magma viscosity, the considered eruptions can be clearly divided in two different fields (explosive and non-explosive) according to their storage pressure, pre-eruptive water content and their subsequent eruptive dynamic (dashed line in Fig.4). Secondly, most of these phonolitic magmas are water-undersaturated. In detail, in five of the eruptions the water contents of the magmas lie at or near saturation whilst nine are clearly far away from saturation. However, some highly water-undersaturated magmas were able to erupt explosively (i.e, El Abrigo, Tambora and Pompeii phonolites). Another striking feature is that magmas that are stored at broadly similar depths with similar water contents, developed either effusive or explosive activities (ie Pompei and K1 phonolites). Thus, a first result obtained from our compilation is that the amount of water dissolved does not per se control the eruptive dynamic.

One possibility is to consider that the differences in the rheological properties of the magmas (ie magma viscosity) are controlling the eruptive style. However, the detailed comparison between calculated magma viscosities and associated eruptive dynamic shows that there does not exist a correlation between these two parameters: for instance, phonolite K1, which has a magma viscosity similar to that of the MLST explosive phonolite, erupted in an effusive way. Similarly, there appears to be no correlation between temperature and eruptive dynamic. Thus, neither the temperature nor the viscosity of the magma appears to exert a major control on the eruptive style of phonolitic eruptions. Therefore, it is not possible to anticipate the eruptive dynamic of phonolites based on the rheological properties of the magmas only.

Based on the foregoing discussion we can conclude that the main parameters controlling the eruptive dynamic of the magma at storage levels are the water content of the magma, the depth of magma ponding and how far the magma is from water-saturated conditions. Moreover, the divide line between explosive and effusive eruptions on figure 4 does not coincide with any specific threshold value of water content, or temperature or viscosity that would have prevented the magma to erupt explosively. It instead defines a depth value as a function of the water-content of the magma beyond which eruptions are explosive rather than effusive.

One anomalous point which deserves being discussed further is the ULST phonolite. This eruption started with a phreatomagmatic phase (Schmincke, 2000),

which gives it an explosive character, yet figure 4 predicts an effusive dynamic. The low water and crystal contents together with the high viscosity of the magma would inhibit vesiculation and bubble coalescence (Larsen and Gardner, 2004; Iacono-Marziano et al., 2007), thus promoting effusive rather than explosive behaviour. In this specific case, however, it appears that interaction of the magma with external water could readily explain the explosive origin of this eruption (as evidenced by the textural and structural criteria of the products which reveal a strong ground-water magma interaction during this phase of the eruption; Schmincke, 2000; Harms and Schmincke, 2000), which otherwise would have developed into an effusive regime.

Another case in point is the Erebus lava lake phonolite which is characterised by a steady state sporadically disrupted by small Strombolian eruptions. These have been explained as surface bursts related to large CO_2-rich gas bubbles rising from deeper levels of the plumbing system (Oppenheimer et al., 2011). Thus, despite of its permanent "effusive" activity, some explosive activity occurs in the Erebus Lava lake. In terms of classification, the Erebus phonolite lake could thus be considered either as effusive or an explosive system. However, phonolitic melt inclusions have H_2O contents lower than 1 wt% and record entrapment pressures exceeding 400 MPa (Oppenheimer et al., 2011), thus falling largely in the effusive field as drawn on figure 4. Hence, despite the sporadic explosive activity of Erebus lava lake, we conclude that, on average, the deep storage conditions and water contents impose a predominant effusive volcanic activity to this system.

The compilation of data presented in the current work also provides some insights on the origin of the various phonolitic magmas considered. Apart from an extreme value of 55 vol% of crystals for the ULST phonolite and two magmas containing about 30 vol% of crystals (Lavas Negras and Erebus lava lake), all studies reveal a low crystal content (< 1 to up to 15 vol%) for phonolitic magmas at the emplacement depths in the upper crust. They also conclude that phonolitic liquids are derived from a fractional crystallization process with minor amounts of mixing/assimilation of parental basalts (see Neumann et al., 1999; Ablay et al. 1998). However, the wide range of pre-eruptive water contents of phonolites suggests that the final water content cannot be solely controlled by the degree of crystal fractionation process occurring in the magmatic system. It must be also controlled by the characteristics of the source region, by the efficiency of the partial melting process that

produced the basaltic parental magma, the level of magma storage, and by the degassing events which may occur during magma evolution prior to eruption.

6. Concluding statements

The combination between the experimental phase equilibrium data available from the literature and the calculated magma viscosities has allowed us to illuminate the parameters that control the eruptive dynamic of phonolitic magmas.

Our results suggest that, in phonolitic suites, among the so called "pre-eruptive parameters", the depth of storage and amount of water dissolved are the main controlling factors of the explosive vs non-explosive character of a magma. Other factors such as rheology, the role of other volatiles (in particular CO_2), seems to have a second order influence. However, the non-explosive character of the magma may be changed by processes such as interaction with non-magmatic water, degassing behaviour or mixing within the conduit.

These results represent an important improvement in predicting the behaviour of magmas in phonolitic volcanic suites and thus, for improving the hazard assessment in such regions. To achieve such a goal, it is necessary to have an accurate knowledge concerning the plumbing system beneath the volcano as well as information concerning the range of water contents characteristic of each reservoir(s). In particular, knowing the range of water content displayed by the magmas and the depth of tremors occurring during a period volcanic unrest, may help to provide a first indication on the possible explosive vs effusive transition of an on-going eruption.

References

Ablay, G. J., Ernst, G. G. J., Martí, J., Sparks, R.S.J., 1995. The 2ka subplinian eruption of Montaña Blanca, Tenerife. Bulletin of Volcanology 57, 337-355.

Ablay, G. J., Carroll, M.R., Palmer, M.R., Martí, J., Sparks, R.S.J., 1998. Basanite-Phonolite Lineages of the Teide-Pico Viejo Volcanic Complex, Tenerife, Canary Islands. Journal of Petrology 39, 905-936.

Andújar, J., Costa, F., Martí, J., Wolff, J.A., Carroll, M.R., 2008. Experimental constraints on pre-eruptive conditions of phonolitic magma from the caldera-forming El Abrigo eruption, Tenerife (Canary islands). Chemical Geology 257, 173-191.

Andújar, J., Costa, F., Martí, J., 2010. Magma storage conditions of the last eruption of Teide volcano (Canary Islands, Spain). Bulletin of Volcanology 72, 381-395.

Andújar J., Scaillet, B, (in press). Experimental Constraints on Parameters Controlling the Difference in the Eruptive Dynamic of Phonolitic Magmas: the case from Tenerife (Canary Islands).

Ardia, P., Giordano, D., Schmidt, M.W., 2008. A model for the viscosity of rhyolite as a function of H_2O-content and pressure: a calibration based on centrifuge piston cylinder experiments. Geochimica et Cosmochimica Acta 72, 6103-6123.

Behrens, H., Zhang, Y., 2009. H_2O diffusion in peralkaline to peraluminous rhyolitic melts. Contributions to Mineralogy and Petrology 157, 765-780.

Berndt, J., Holtz, F., Koepke, J., 2001. Experimental constraints on storage conditions in the chemically zoned phonolitic magma chamber of the Laacher See volcano. Contributions to Mineralogy and Petrology 140,469-486.

Blundy, J., Cashman, K., Humphreys, M., 2006. Magma heating by decompression-driven crystallization beneath andesite volcanoes. Nature 443, 76-80.

Caricchi, L., Burlini, L., Ulmer, P., Gerya, T., Vassalli, M., Papale, P., 2007. Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics. Earth and Planetary Science Letters 264, 402-419.

Caricchi, L., Giordano, D., Burlini, L., Ulmer, P., Romano, C., 2008. Rheological properties of magma from the 1538 eruption of Monte Nuovo (Phlegrean Fields, Italy): An experimental study. Chemical Geology 256, 158-171.

Carroll, M. R., Blank, J.G., 1997. The solubility of H_2O in phonolitic melts. American Mineralogist 82, 549-556.

Champallier, R., Bystricky, M., Arbaret, L., 2008. Earth and Planetary Science Letters 267, 571-583.

Cioni, R., Marianelli, P., Santacroce, R., 1998. Thermal and compositional evolution of the shallow magma chambers of Vesuvius : Evidence from pyroxene phenocrysts and melt inclusions. Journal of Geophysical Research 103, 18,277-18,294.

Cioni, R., Santacroce, R., Sbrana, A., 1999. Pyroclastic deposits as a guide for reconstructing the multi-stage evolution of the Somma-Vesuvius Caldera. Bulletin of Volcanology 60, 207–222.

Cioni, R., 2000. Volatile content and degassing processes in the AD 79 magma chamber at Vesuvius (Italy). Contributions to Mineralogy and Petrology 140, 40-54.

Costa, A., Caricchi, L., Bagdassarov, N., 2009. A model for the rheology of particle-bearing suspensions and partially molten rocks. Geochemistry Geophysics Geosystems 10, doi:10.1029/2008GC002138.

Costa, F., Scaillet, B., Pichavant, M., 2004. Petrological and experimental constraints on the Pre-eruption conditions of Holocene dacite from Volcán San Pedro (36ºS, Chilean Andes) and the im portance of sulphur in silicic subduction-related magmas. Journal of Petrology 45, 855-881.

Cordonnier, B., Hess, K.-U., Lavalle, Y., Dingwell, D.B., 2009. Rheological properties of dome lavas: case study of Unzen volcano. Earth and Planetary Science Letters 279, 263-272.

Couch, S., Sparks, R.S.J., Carroll, M.R., 2003. The kinetics of degassing-induced crystallization at Soufrière Hills Volcano, Montserrat. Journal of Petrology 44, 1477-1502.

Dingwell D.B., Bagdassarov, N.S., Bussod, J., Webb, S.L., 1993. Magma rheology, in: Short Handbook on experiments at high pressure and applications to the Earth's mantle, vol 21, edited by R.W. Luth, pp. 131-196. Mineralogical Association of Canada, Ontario.

Edgar, C.J., Wolff, J.A , Olin, P.H., Nichols, H.J., Pittari, A., Cas, R.A.F., Reiners, P.W., Spell, T.L., Martí, J., 2007. The late Quaternary Diego Hernandez Formation, Tenerife: Volcanology of a complex cycle of voluminous explosive phonolitic eruptions. Journal of Volcanology and Geothermal Research 160, 59–85.

Fabbrizio, A., Carroll, M.R., 2008. Experimental constraints on the differentiation process and pre-eruptive conditions in the magmatic system of Phlegrean Fields (Naples, Italy). Journal of Volcanology and Geothermal Research 171, 88-102.

Foden, J., 1986. The petrology of Tambora volcano, Indonesia; a model for the 1815 eruption. Journal of Volcanology and Geothermal Research 27, 1-47.

Freise, M., Holtz, F., Koepke, J., Scoates, J., Leyrit, H., 2003. Experimental constraints on the storage conditions of phonolites from kerguelen Archipielago. Contributions to Mineralogy and Petrology 145, 659-672.

Gardner, J.E., Ketcham,R.A., 2011. Bubble nucleation in rhyolite and dacite melts: temperature dependence of surface tension. Contributions to Mineralogy and Petrology 162, 929-943.

Gertisser, R., Self, S., Thomas, L.E., Handley, H.K., Van Calsteren., P., Wolff, J.A., 2012. Processes and Timescales of Magma Genesis and Differentiation Leading to the Great Tambora Eruption in 1815. Journal of Petrology 53, 271-297.

Giordano D., Dingwelll D. B., Romano C., 2000. Viscosity of a Teide phonolite in the welding interval. Journal of Volcanology and Geothermal Research 103, 239–245.

Giordano D., Russell J. K., Dingwell, D.B., 2008. Viscosity of magmatic liquids: a model. Earth and Planetary Science Letters 271, 123–134.

Giordano D., Ardia, P., Romano C., Dingwell D.B., Di Muro A., Schmidt M.W., Mangiacapra A., Hess K.-U, 2009. The rheological evolution of alkaline Vesuvius magmas and comparison with alkaline series from the Phlegrean Fields, Etna, Stromboli and Teide. Geochimica et Cosmochimica Acta 73, 6613-6630.

Gualda, G. A. R., Anderson, A. T. Jr.,2007, Magnetite scavenging and the buoyancy of bubbles in magmas. Part 1: Discovery of a pre-eruptive bubble in Bishop rhyolite, Contributions to Mineralogy and Petrology 153, 733–742,

Harms, E., Schmincke, H.-U., 2000. Volatile composition of the phonolitic Laacher See magma (12,900 yr BP): implications for syn-eruptive degassing of S, F, Cl and H_2O. Constributions to Mineralogy and Petrology 138, 84-98.

Harms, E., Gardner., J.E., Schmincke, H.-U., 2004. Phase equilibria of the lower Laacher See Tephra (East Eifel, Germany): constrainsts on pre-eruptive storage conditions of a phonolitic magma reservoir. Journal of Volcanology and Geothermal Research 134, 135-148.

Holloway, J.R., 1976. Fluids in the evolution of granitic magmas:consequences of finite CO2 solubility. Geological Society of American Bulletin 87, 1513-1518.

Hui, H., Zhang, X., Xu., Z., Del Gaudio, P., Behrens, H., 2009. Pressure dependence of viscosity of rhyolitic melts. Geochimica et Cosmochimica Acta 73, 3680-3693.

Iacono-Marziano, G., Schmidt, B.C., Dolfi, D., 2007. Equilibrium and disequilibrium degassing of a phonolitic melt (Vesuvius AD 79 "white pumice") simulated by decompression experiments. Journal of Volcanology and Geothermal Research 161, 151-157.

Jaupart, C., Allègre, C.J., 1991. Gas content, eruption rate and instabilities of eruption regime in silicic volcanoes. Earth and Planetary Science Letters 102, 413-429.

Kelly, P.J., Dunbar, N.W., Kyle, P.R., McIntosh, W.C., 2008. Refinement of the late Quaternary geologic history of Erebus volcano, Antarctica using [40]Ar/39Ar and 36Cl age determinations. Journal of Volcanology and Geothermal Research 177, 569-577.

Kyle, P.R., Moore, J.A., Thirwall, M.F., 1992. Petrologic evolution of anorthoclase phonolite lavas at Mount Erebus, Ross Island, Antarctica. Journal of Petrology 33, 849-835.

Lange, R.A., 1994. The effect of H_2O, CO_2 and F on the density and viscosity of silicate melts. Reviews in Mineralogy and Geochemistry 30, 331-369.

Larsen, J.F., Gardner, J.E., 2004. Experimental study of water degassing from phonolite melts: implications for volatile overaturation during magmatic ascent. Journal of Volcanology and Geothermal Research 134, 109-124.

Le Bas, M.J., Streckeisen, A.L., 1991. The The IUGS systematics of igneous rocks. Journal of the Geological Society of London 148, 825-833.

Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., La Meyre Le Bas, M.J., Sabine, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Wooley, A.R., Zanettin, B., 1989. A classification of igneous rocks and glossary of terms. Blackwell Scientific Publications, 193 pp. Oxford.

Liebske, C., Behrens, H., Holtz, F., Lange, R.A., 2003. The influence of pressure and composition on the viscosity of andesitic melts. Geochimica et Cosmochimica Acta 67, 473-485.

Liebske, C., Schmickler, B., terasaki, H., Poe, B.T., Suzuki, A., Funakoshi, K-I., Ando, R., Rubie, D.C., 2005. Viscosity of peridotie liquid up to 13 GPa: Implications for magma ocean viscosities. Earth and Planetary Science Letters 240, 589-604.

Manga, M., Loewenberg, M., 2001. Viscosity of magmas containing highly deformable bubbles. Journal of Volcanology and Geothermal Research 105, 19-24.

Marianelli, P., Sbrana, A., Proto, M., 2006. Magma chamber of the Campi Flegrei supervolcano at the time of eruption of the Campanian Ignimbrite. Geology 34, 937-940.

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 and Planetary Science Letters 156, 89-99.

Martel, C., Pichavant, M., Holtz, F. and Scaillet, B., 1999. Effects of fO$_2$ and H$_2$O on andesite phase relations between 2 and 4 kbar. Journal of Geophysical Research **104**, 29,453-29,470

Martel, C. and Schmidt, B.C., 2003. Decompression experiments as an insight into ascent rates of silicio magmas. Contributions to Mineralogy and Petrology 144, 397-415.

Martel, C., Poussineau, S., 2007. Diversity of eruptive styles inferred from microlites of Mt Pelée andesite (Martinique, Lesser Antilles). Journal of Volcanology and Geothermal Research 166, 233-254.

Morizet, Y., Brooker, R.A., Kohn, S.C. , 2002. CO$_2$ in haplo-phonolite melt: solubility, speciation and carbonate complexation. Geochimicia et Cosmochimica Acta 66, 1809–1820.

Mueller, S., Llewellin, E.W., Mader, H.M., 2010. The rheology of suspensions of solid particles. Philosophical Transaction of the RoyalSociety A. 466, 1201-1228.

Neumann, E.-R., Wulff-Pedersen, E., Simonsen, S.L., Pearson, N.J., Martí, J., Mitjavila, J., 1999. Evidence for fractional crystallization of periodically refilled magma chambers in Tenerife, Canary Islands. Journal of Petrology 40, 1089-1123.

Oppenheimer, C., Moretti, R., Kyle, P.R., Eschenbacher, Al., Lowenstern, J.B., Hervig, R.L., Dunbar, N.W., 2011. Mantle to surface degassing of alkali magmas at Erebus volcano, Antarctica. Earth and Planetary Science Letters 306, 261-271.

Papale, P., Polacci, M., 1999. Role of carbon dioxide in the dynamics of magma ascent in explosive eruptions. Bulletin of Volcanology, 60, 583-594.

Papale, P., Moretti, R., Barbato, D., 2006. The compositional dependence of the saturation surface of H$_2$O+CO$_2$ fluids in silicate melts. Chemical Geology 229, 78–95

Petford, N., 2009. Which effective viscosity?. Mineralogical Magazine 73, 167-191.

Pichavant, M., Costa, F., Burgisser, A., Scaillet, B., Martel, C, Poussineau, S., 2007. Equilibration scales in silicic to intermediate magmas - Implications for phase equilibrium studies. Journal of Petrology 48, 1955-1972

Putirka, K., Johnson, M., Kinzler, R., Longhi, J., Walker, D., 1996. Thermobarometry of mafic igneous rocks based on clinopyroxene-liquid equilibria, 0-30 kbar. Contributions to Mineralogy and Petrology 123, 92-108.

Santacroce, R. (Ed) 1987. Somma-Vesuvius. Quaderni de "La Ricerca Scientifica" CNR, Roma 114, 230 pp.

Scaillet, B., Holtz, F., Pichavant, M. (1998). Phase equilibrium constraints on the viscosity of silicic magmas 1. Volcanic-plutonic comparison. Journal of Geophysical Research 103, 27,257-27,266.

Scaillet, B., Luhr, J.F., Carroll, M.R., 2003. Petrological and volcanological constraints on volcanic sulfur emissions to the atmosphere. Geophysical Monograph 139, 11-40.

Scaillet, B., Pichavant, M., Cioni, R., 2008. Upward migration of Vesuvius magma chamber over the past 20,000 years. Nature 455, 216-219.

Schmidt, B.C., Behrens, H., 2008. Water solubility in phonolite melts: Influence of melt composition and temperature. Chemical Geology 256, 259-268.

Schmincke, H-U., 2000. Volcanism, Springer-Verlag, Heidelberg. 324 pp.

Self. S., Gertisser, R., Thordarson, T., Rampino. M.R., Wolff, J.A., 2004.Magma volume, volatile emissions, and stratospheric aerosols from the 1815 eruption of Tambora. Geophysical research Letters 31, L20608.

Sigmundsson, F., Hreinsdóttir, S., Hooper, A., Árnadóttir, T., Pedersen, R., Roberts, M.J., Óskarsson,N., Auriac, A., Decriem, J., Einarsson, P., Geirsson, H., Hensch, M., Benedikt G. Ófeigsson, B.G., Erik Sturkell, E., Hjörleifur Sveinbjörnsson, H., Feigl, K.L., 2010. Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. Nature 468, 426–430.

Signorelli, S., Rosi, M., Vaggelli, G., Francalanci, L., 1999. Origin of magmas feeding the Plinian phase of the Campanian Ignimbrite eruption, Phlegrean Fields (Italy): Constraints based on matrix-glass and glass-inclusion compositions. Journal of Volcanology and Geothermal Research 91, 199-220.

Sparks, R.S.J., Bursik, M.I., Carey, S.N., Gilbert, J.S., Glaze, L.S., Sigurdsson, H., Woods, A.W., 1997. Volcanic plumes. Wiley, Chichester.

Stein, D. J., Spera, F. J., 1992. Rheology and microstructure of magmatic emulsions Theory and experiments. Journal of Volcanology and Geothermal Research 49, 157-174.

Stein, D. J., Spera, F. J., 2002. Shear viscosity of rhyolite–vapor emulsions at magmatic temperature by concentric cylinder rheometry. Journal of Volcanology and Geothermal Research 113, 243–258.

Suzuki, A., Ohtani, E., Terasaki, H., Funakoshi, K-I., 2005. Viscosity of silicate melts in $CaMgSi_2O_6$-NaAlSi2O6 system at high pressure. Physics and Chemistry of Minerals 32, 140-145.

Suzuki, A., Ohtani, E., Terasaki, H.,Nishida, K., Hayashi, H., Sakamaki, T., Shibazaki, Y., Kikegawa, T., 2011. Pressure and temperature dependence of the viscosity of a $NaAlSi_2O_6$ melt. Physics and Chemistry of Minerals 38, 59-64.

Takeuchi, S., 2011. Pre-eruptive magma viscosity: An important measure of magma eruptibility. Journal of Geophysical Research 116, B10201, 19 pp.

Vona, A. Romano, Dingwell, D.B., and Giordano, D.,2011. The rheology of crystal-bearing basaltic magmas from Stromboli and Etna. Geochimica and Cosmochimica Acta 75, 3214-3236.

Wallace, P. J., Anderson, A. T., Davis, A. M., 1995. Quantification of pre-eruptive exsolved gas contents in silicic magmas. Nature 377, 612–616

Weis D., Frey, F.A., Leyrit, H., Gautier, I., 1993. Kerguelen Archipelago revisited: geochemical and isotopic study of the Southeast Province lavas. Earth and Planetary Science Letters 118,101–119.

Whittington A., Richet P., Linard, Y, Holtz, F., 2001. The viscosity of hydrous phonolites and trachytes. Chemical Geology 174, 209-223.

Whittington A., Richet P., Linard, Y, Holtz, F., 2004. Erratum to "The viscosity of hydrous phonolites and trachytes. Chemical Geology 174, 209-223.". Chemical Geology 211, 391.

Woods, A.W., Koyaguchi, T., 1994. Transitions between explosive and effusive eruptions of silicic magmas. Nature 370, 641-644.

Wörner. G., Schmincke, H-U., 1984. Petrogenesis of the zoned Laacher See Tephra. Journal of Petrology 25, 836-851.
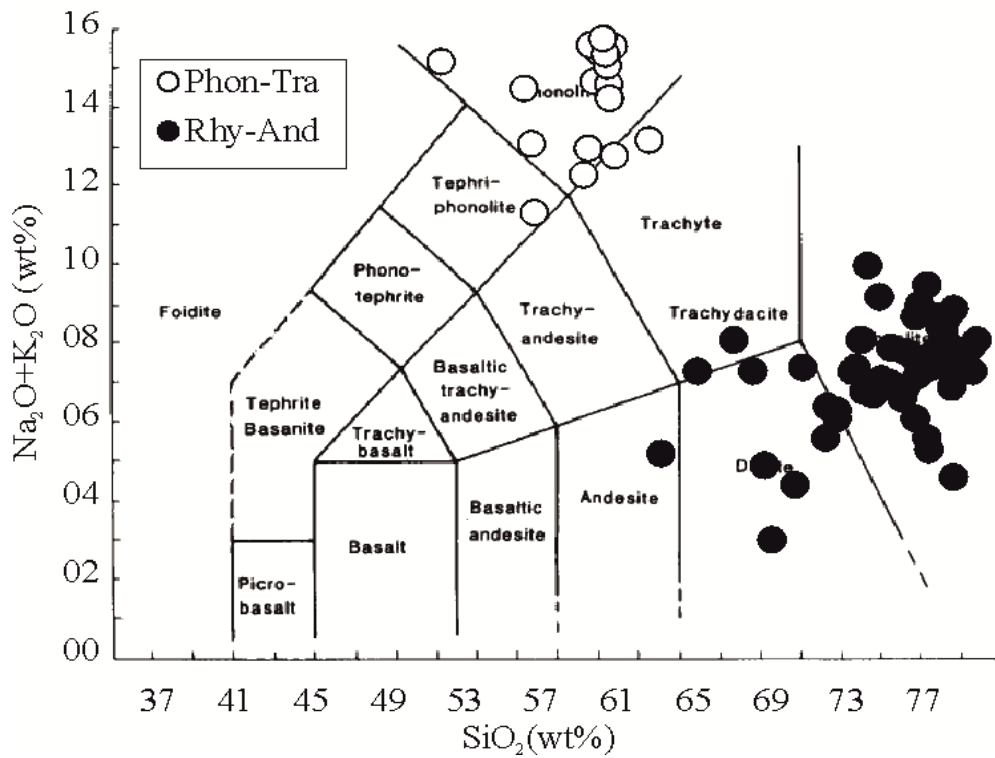
Figure Captions

Fig.1

Figure 1. Total alkali ($Na_2O + K_2O$) versus SiO_2 diagram (after Le Bas and Streckeisen, 1991) showing the bulk and melt composition of phonolite-trachyte (Phon-Tra, open circles) and rhyolite-andesite (Rhy-And, black circles) volcanic rocks from Tables 1 and 3, used for the calculations in this study.
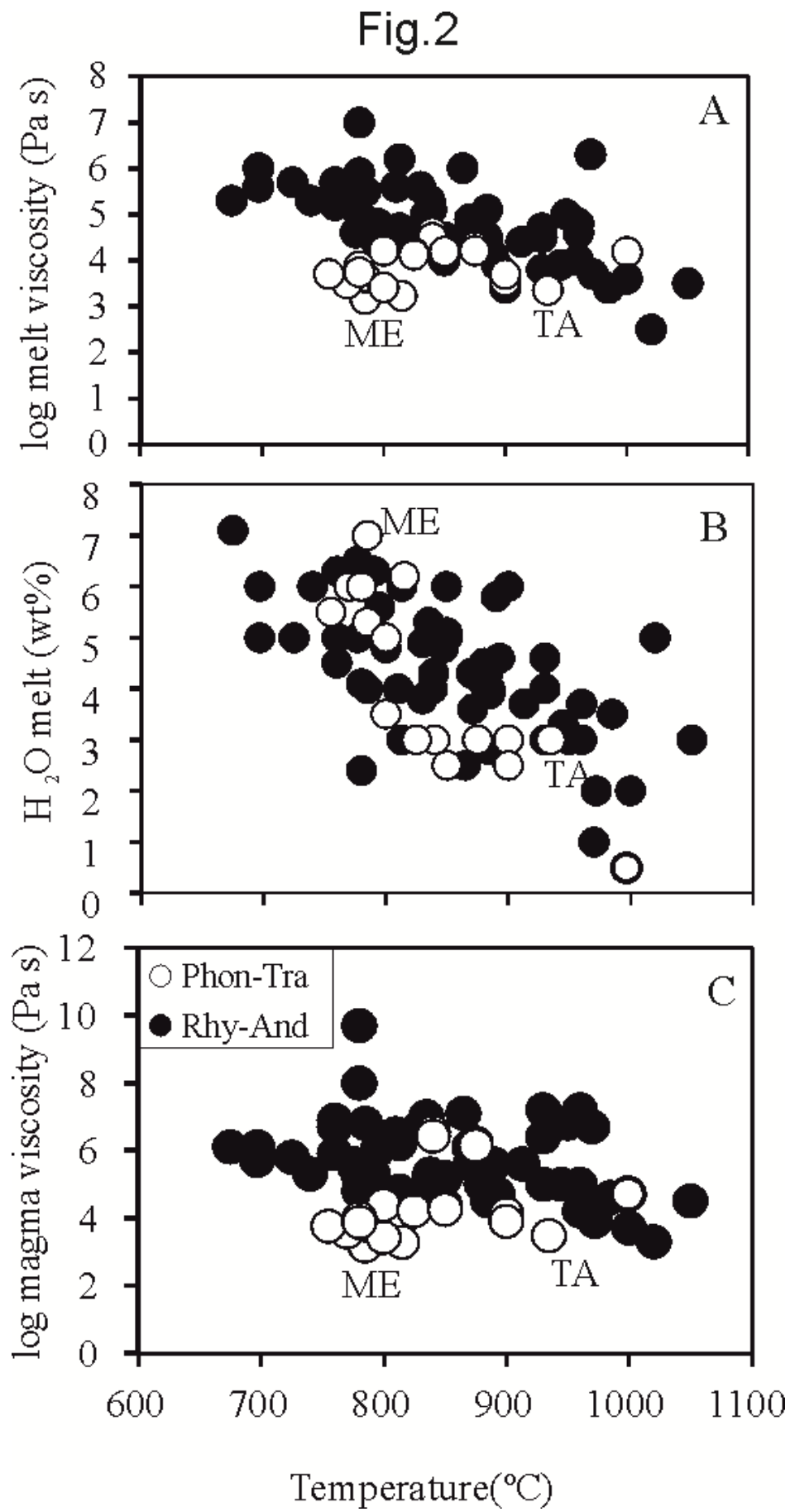
Fig.2

Figure 2: a: Melt viscosities, b: water content in the melt (w%) and c: magma viscosities plotted versus pre-eruptive temperatures of rhyolites-andesites (Rhy-and, black circles) and phonolitic-trachytic (Phon-Tra, open circles) volcanic rocks from Tables 1 and 3. ME: Mercato eruption; TA: Tambora eruption
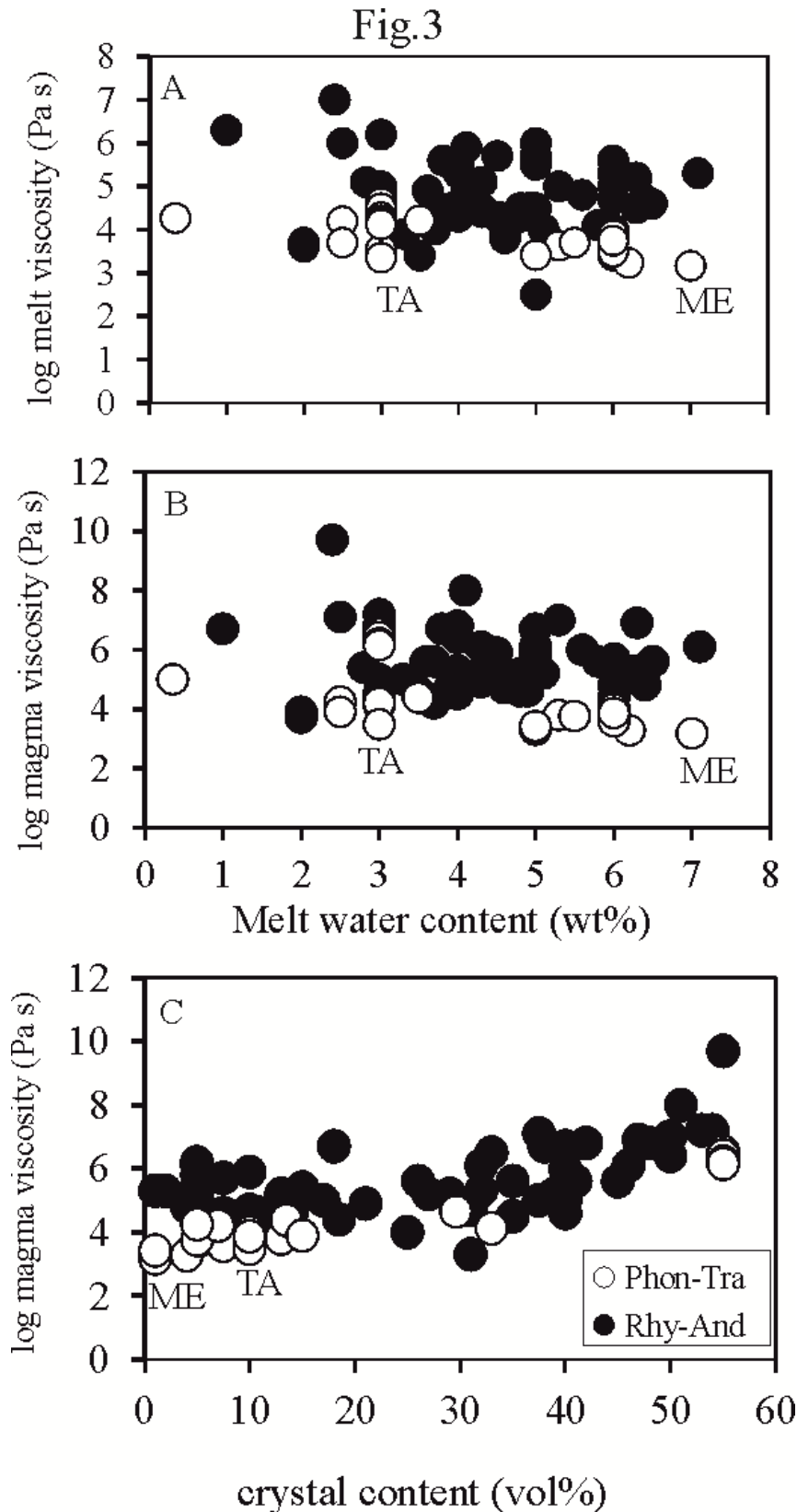
Figure 3: a: Melt viscosities and b: magma viscosities plotted versus water in the melt (wt%); c: magma viscosities plotted versus pre-eruptive crystal content of the melt (see text for more details concerning the phenocryst crystal content of the phonolite magmas). Legend as in Figure 2. ME: Mercato eruption; TA: Tambora
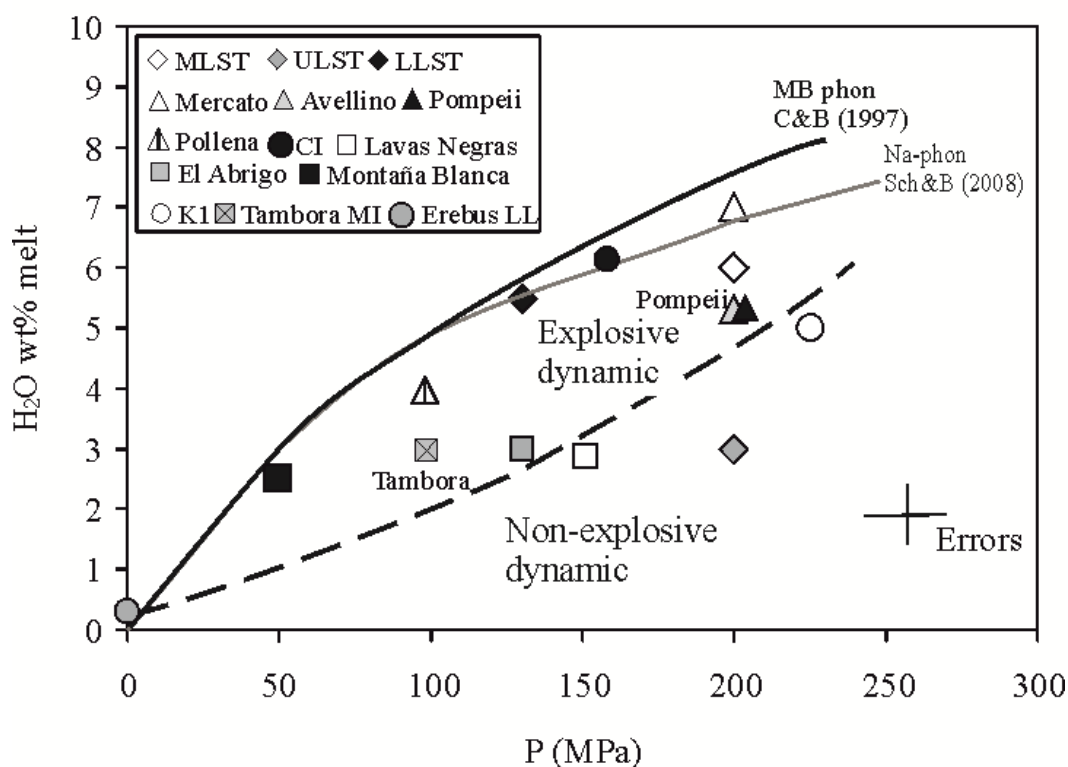
Figure 4

Figure 4: Pre-eruptive total pressure versus water content in the melt of the phonolitic eruptions of Table 1. The solid line correspond to the water-saturation curve for phonolitic melts determined for Carroll and Blank (1997). Whole grey line corresponds to the water-saturation curve determined by Schmidt and Behrens (2008) for Na-phonolites (see text for more details concerning the different position of the curve in each model). The dashed black line divides such phonolitic eruptions that erupted explosively (points above the line) from those that erupted effusively (points below the line). CI in legend: Campanian ignimbrite. See text for more details.