ANNALS OF GEOPHYSICS, 62, 2, VO216, 2019; doi: 10.4401/ag-7859

“ADVANCES IN THE RHEOLOGY OF NATURAL MULTIPHASE SILICATE MELTS: IMPORTANCE FOR MAGMA TRANSPORT AND LAVA FLOW EMPLACEMENT”

Daniele Giordano*,1,2,3

(1) Università degli Studi di Torino, Dipartimento di Scienze della Terra, Torino, Italy
(2) Istituto Nazionale di Geofisica e Vulcanologia–Sezione di Pisa, Pisa, Italy
(3) Institute of Geoscience and Earth Resources (IGG–CNR), Italian National Research Council (CNR), Pisa, Italy

Article history
Receveid July 17, 2018; accepted March 18, 2019.
Subject classification:
Multicomponent and Multiphase silicate melts; Rheology.

ABSTRACT

A review of recent advances in the field of rheology of multicomponent silicate melts and multiphase silicate melt and multiphase silicate melt and analogue material suspensions is presented. is presented here. The advances include the development of new experimental de–vices and field and remote sensing methods for measuring the rheological properties of natural melts and magmas as well as new mod–elling strategies. These promising approaches combine laboratory experiments, theoretical models, numerical simulations and remote sens–ing data derived from ground, airborne and satellite–based tools. Each of these sub–disciplines has evolved rapidly in recent years and the growing range of complementary data appears now to provide an opportunity for the development of multi–disciplinary research. Ul–timately, these multidisciplinary initiatives seek to provide near–real–time forecasting of hazardous volcanic processes such as lava flow field evolution. The results and approaches described here focus on multiphase (i.e. melts, bubbles, crystals) rheology of natural systems and are pertinent to the effusive emplacement of lavas, dykes and sills, as well as, to the eruption dynamics attending explosive eruptions.

1. INTRODUCTION

The transport of magmas and volcanic materials is characterized by very dynamic, interdependent and com–plex, physical and chemical processes that all are affected by and affect the materials physical properties. Under–standing the dynamic processes operating during magma ascent and eruption and the timescales and mechanisms of emplacement, welding and remobilization of frag–mental or massive volcanic deposits, constitutes one of the main challenges in the Earth sciences [Dingwell, 1996; Papale, 1999; Sparks, 2004; Russell and Quane, 2005; Giordano et al., 2005]. Accurate description of these processes requires the characterization of a wide range of transport and thermodynamic properties for the melt or magma (e.g. viscosity, density, enthalpy, entropy, heat capacity, thermal conductivity, solubility of volatile phases). These properties play crucial roles at micro– to macroscopic scale and many are correlated, in a non–lin–ear manner [e.g. Richet et al., 1984; Giordano et al., 2008a; Russell and Giordano, 2017].

Lava flow dynamics are strongly governed by sub–surface buoyancy forces, resulting from the density con–trast with the host rock, which push the magma toward the surface [e.g. Wilson and Head, 2016a; Wieczorek et al., 2001] and by the evolving internal and external frictional forces (e.g. with dyke, conduit wall and topography) that oppose to the movement of magmas and lavas [e.g. Nemeth, 2010; Cañón–Tapia, 2016, Dragoni, 1993; Drag–oni et al., 2005; Giordano et al., 2007; Cashman et al., 2013; Kolzenburg et al., 2016a,b; 2018a,b; Hulme, 1974; Hiesinger et al., 2007; Chevrel et al., 2013, 2015; Cas–truccio et al., 2014].

The rheological properties of magmas undergo tremendous changes from transport in the subsurface to eruption or emplacement at the surface and to final de–

position and cooling. These changes are caused dominantly by the evolving of thermo–chemical and deformational conditions, imposing phase transitions and therewith heterogeneous textural and morphological variations of the magmatic and volcanic suspensions which evolve in space and time. The complex rheological evolution of lava flows can tentatively be constrained by carrying out laboratory measurements under controlled conditions, simulating natural systems, and by monitoring flow emplacement at the field–scale and via satellite–based platforms. In parallel with this, the sophistication of physical models of lava flows and domes have improved significantly and are capable of providing fast simulations [see, amongst the others, Costa and Macedonio, 2003, 2005; Del Negro et al., 2008, 2013, 2016; Melnik and Sparks, 1999, 2005; Melnik et al., 2009; Kilburn 2015 for reviews on this topic]. These models are increasingly informed by, or validated by, satellite–derived parameters such as lava flow discharge rate or periodic updates on flow advance/geometry. Together these capabilities represent an emergent strategy that may provide timely reliable projections of lava flow field evolution and derive information for hazard assessment and mitigation measures. Yet, to date they do not always provide coherent results reproduced in nature.

This highlights the necessity to estimate the rheological properties of magmas and volcanic materials at conditions pertinent to nature and to investigate the effect of each variable over the range of relevant environmental conditions (e.g. pressure, temperature, volatile contents) during varying thermodynamic (equilibrium and non–equilibrium) conditions, and deformation regimes.

Our understanding of the single– and multi–phase (liquid+crystals+bubbles) rheology of magmas and volcanic products has greatly improved in the last two decades. This can largely be attributed to the growing availability of empirical data from the following sources (each of which will be reviewed in detail below):

1) laboratory experimentation on natural and simplified silicate melts. These data support the creation of robust models for predicting the Newtonian viscosity of pure liquid natural melts as a function of temperature (T), pressure (P) composition (X), volatile content (Xv) and structural features (see Chapter 2).
2) the rheological experimentation and modelling of non–reactive multiphase suspensions (liquid+bubbles; liquid+crystal and liquids+bubbles+crystals) constituted by analogue materials or simplified or natural silicate melts mixtures (Chapter 4);
3) dynamic cooling rheological measurements on natural multiphase suspensions at non–isothermal and non–equilibrium conditions to explore the interdependent effects of composition, cooling–rate, shear–rate and oxygen fugacity acting during magma and lava transport in nature (Chapter 5);
4) rheological measurements of actively flowing lava. These represent snapshots of actual lava flow rheology at specific conditions and provide data that helps to constrain the conditions required to be reproduced in systematic laboratory studies (Chapter 6).
5) studies on the 3D and 4D evolution of lava flows at increasing spatial and temporal resolution and contemporary estimates of effusion rate and flow development from satellite data. These provide data for cross correlation and benchmarking of laboratory measurements (Appendix A1) and to re–visit long standing methods for deriving rheological parameters from morphologic data (Chapter 6).

These studies document that the effective viscosity of natural silicate melts and magmas can span more than 15 orders of magnitude (10^{1} – 10^{14} Pa s), primarily in response to variations in melt composition (X), dissolved volatile content (Xv), temperature (T), pressure (P), as well as the proportions, size, and shape distributions of suspended solid and/or exsolved fluid phases (i.e. crystals and bubbles). The deformation rate, which in nature would depend on the discharge rate will determine whether flow behavior will be Newtonian (i.e. one for which there is a linear relationship between stress and strain rate; or spatial variation of velocity) or non–Newtonian [e.g. Caricchi et al., 2007, 2008; Costa et al., 2007a, 2009; Vona et al., 2011; Hess et al., 2009]. Deformation rate also exerts an influence on the crystallization kinetics [Vona et al., 2013; Kouchi, 1986; Kolzenburg, 2018]. It may further determine whether the melt will deform viscously or elastically and, therewith, whether or not it will eventually fracture giving origin to effusive rather than explosive eruptive styles [Dingwell, 1996]. Combined the above experimental data and computational models form a basis from which to understand the flow behavior of natural magmatic and volcanic suspensions.

In the following I present a review of the research advances in the rheological characterization of pure silicate melts and multiphase silicate mixtures (i.e. lavas and magmas) achieved in the past decades. I follow the structure of points 1–5 outlined above to group the individual fields. In the Appendices (A1–A3) I summarize the

most commonly employed experimental devices and technological advances to measure the single and multiphase silicate melts also reporting the most common equations used to describe the viscosity variation as a function of P, T, X (Appendix A1) as well as suspended solids phase and/or porosity (Appendices A2 and A3). I conclude with a discussion on how new laboratory developments together with the growth in complementary datasets (e.g. remote–sensing; drone technology; high–speed calculation facility) is providing greater understanding of magma and lava transport on Earth.

2. PURE LIQUID MELT NEWTONIAN VISCOSITY EXPERIMENTS AND MODELS

2.1 T – DEPENDENT MODELS FOR PREDICTING MELT VISCOSITY

The first step toward characterizing multiphase rheology of natural silicate melts mixture is the knowledge of multicomponent viscosity of pure liquids as a function of their composition (including dissolved volatile species such as H_2O, C and S –species, F, Cl) temperature (T) and pressure (P). Early models for predicting the viscosity of silicate melts were developed using data that spanned relatively small ranges of temperature (T) and viscosity (η). These experimental data, restricted to superliquidus temperatures and a narrow compositional range, showed a nearly linear trend of viscosity in reciprocal temperature space. Thus, early models adopted an Arrhenian formulation of the temperature–viscosity relationship [Shaw, 1972; Bottinga and Weill, 1972]. Expansion of the melt viscometry database over a wider range of compositions and temperatures exposed the limitations of Arrhenian models. With the emergence of viscometry data closer to the glass transition temperature (T_g) (i.e. the temperature of transition between a liquid–like and a solid–like behavior) [e.g. Angell, 1991, Giordano et al., 2005], the Arrhenian models proved unsuitable to describe the temperature dependence of silicate melt viscosity. These measurements were enabled by experimental devices that allow very small displacements to be monitored (e.g. Linear Voltage Displacement Transducers) and, the production of quenched glasses, freezing in the crystal free melt structure. In these experiments, supercooled glasses are reheated above T_g, where the "relaxed melt" viscosity [e.g. Angell, 1991; Scherer, 1984] could then be measured. These experiments are performed at timescales shorter than phase transitions timescale, therewith allowing anhydrous and hydrous pure liquid viscosity measurements [Angell, 1991; Scherer, 1984; Giordano et al., 2008b].

Based on the large number of experimental studies [e.g. Richet et al., 1995, 1996; Hess and Dingwell, 1996; Whittington et al., 2000, 2001; Giordano et al., 2009 amongst the others], models of melt viscosity were developed [e.g. Avramov, 1998; Angell, 1991; Russell et al., 2003; Giordano and Dingwell, 2003a, b; Russell and Giordano, 2005; Giordano and Russell, 2007; Hui and Zhang, 2007; Giordano et al., 2006, 2008a,b; Ardia et al., 2008; Mauro et al., 2009], also accounting for the non–Arrhenian viscosity behaviour [e.g. Vogel, 1921, Fulcher,

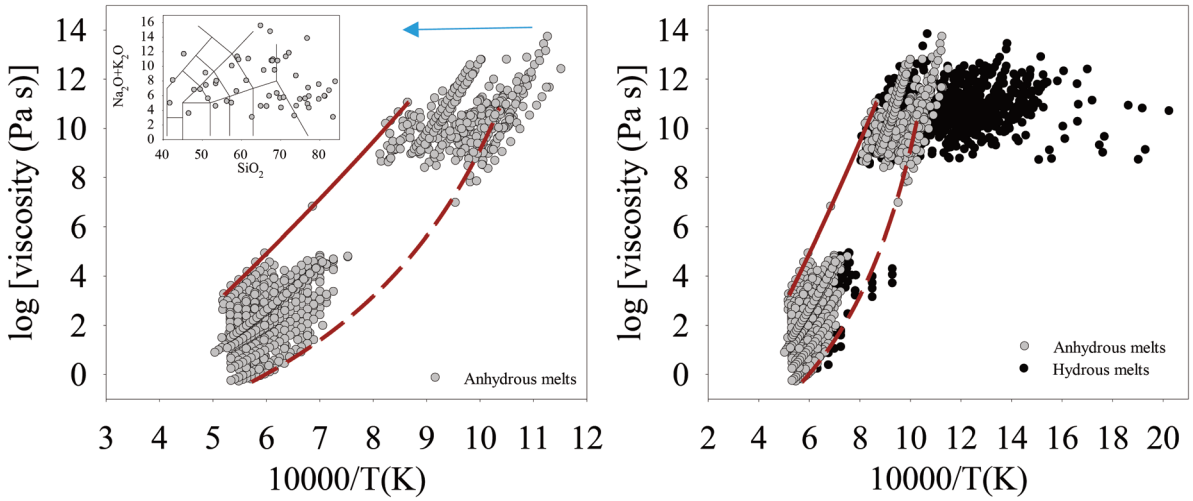

FIGURE 1. The figure shows the variation of viscosity as a function of the reverse of temperature for the anhydrous melts (a) and, per comparison, the anhydrous and hydrous melts (b) as reported by Giordano et al. (2008). The curves in a) represent the most Arrhenian (continuous line in a))(strong) and the least Arrhenian (dashed curve in a)) (fragile) melts amongst those reported in panel of Figure 1a. The effect of water is that of significantly reducing viscosity and the fragility (deviation from Arrhenian behavior) of the melts [details in Giordano et al., 2008].

1925; Tammann and Hess, 1926; Adam and Gibbs, 1965]. These models describe the P–T–X dependence of the viscosity of silicate melts. Some of the most relevant empirical and theoretical formulations describing the T–dependence of silicate melts and the relationships between constitutive parameters are reported in Appendix A2.

The growing database and the new models show that silicate melts display various degrees of non–Arrhenian behavior, from strong to fragile [Angell, 1991; Russell et al., 2002, 2003], which depend on composition and dissolved volatile content (Figure 1).

All these models provide viscosity predictions based on composition commonly expressed in terms of oxide abundances or combination of oxides and a range of adjustable parameters. Of the various models only the HZ model [Hui and Zhang, 2007] and the GRD model [Giordano et al., 2008a] accounts for the effects of dissolved volatile species (H_2O, F). The GRD model is based on the well–known VFT (Vogel–Fulcher–Tammann) equation, such that:

$$\log [\eta \text{ (Pa s)}] = A_{VFT}+B_{VFT}/(T-C_{VFT}) \qquad (1)$$

where A_{VFT} is the pre–exponential factor, B_{VFT} is the pseudo–activation energy and C_{VFT} is the VFT–temperature. In contrast the HZ model uses a purely empirical T–dependent viscosity formulation of non straightforward correlation with thermo–physical amounts. The GRD model has gained support due to its simplicity and direct correlation of constitutive parameters (i.e. Appendix A2) to others important physical and structural properties such as the glass transition (T_g), the fragility (m) (i.e. the rate at which viscosity varies with temperature, that is an indication of melts capacity to store energy), the calorimetric properties (configurational entropy, S^{conf} and the configurational heat capacity C_p^{conf}; see Equation A2.4) [e.g. Giordano and Dingwell, 2003a; Giordano et al., 2008b; Chevrel et al., 2013; Giordano and Russell, 2017; Russell and Giordano, 2017] and the structural properties (e.g. Qn–species and Raman Ratio) [i.e. Le Losq and Neuville, 2017; Giordano and Russell, 2018; Giordano et al., 2019]. These models show that, to a first approximation, the viscosity of silicate melts and the descriptive parameters of Equation 1) can be correlated at constant temperature to empirical, composition–based pseudo–structural parameter (i.e. the SM – structural modifiers – and the NBO/T – i.e. the Non Bridging Oxygen over Tetrahedra – parameters). The NBO/T and SM parameters are commonly assumed as proxies for the degree of polymerization of silicate melts and glasses [e.g Giordano and Dingwell, 2003a, b; Giordano and Russell, 2018; Giordano et al., 2019] (Figures 2,3). Compositions with low values of the SM–parameter (or low NBO/T values) are associated to strong (Arrhenian–like) rheological behavior, i.e. a linear behavior in the logη–1/T space, and more polymerized melts. On the other hand high values of SM (or high NBO/Ts) are related to more depolymerized melts which show fragile rheological behavior (i.e. the logη vs 1/T paths are significantly non–linear) [e.g. Angell, 1991; Giordano and Dingwell, 2003] (Figures 1,2). Russell et al. [2003], in agreement with early theoretical studies [e.g. Angell, 1991 amongst others], showed that the pre–exponential factor of the VFT and AG formulations, i.e. the viscosity at infinite temperature (Appendix A2), is a constant independent of compositions [Russell et al., 2003; Giordano et al., 2008a]. In addition, approximately 1 logunit distinguishes the A_{VFT} and the A_{AG} values. The current models are applicable within the compositional space that they are based upon, but some compositional regions (e.g. peralkaline compositions) still remain unmapped and the models struggle to reproduce measured viscosity values [Giordano et al., 2006, 2008a, Di Genova et al., 2017]. Those formulations also put in evidence that the role of water (H_2O) dissolved in the melt is counterintuitive being opposite to that of network modifier cations. In fact, although dissolved H_2O strongly decreases the viscosity of silicate melts (Figure 1b), the parameters describing the T–dependence of viscosity (e.g. B_{VFT} and C_{VFT} in Equation 1) are differently affected by H_2O and by the most common structure modifiers (Figure 2).

2.2 P – DEPENDENT MODELS FOR PREDICTING MELT VISCOSITY

Measuring the effect of pressure (P) on the viscosity of melts is a complex experimental task and, as a result, has not been investigated extensively. A short summary of applied techniques and technological advances is reported in Appendix A1, together with some of the main results. Largely, and oppositely to silica–rich melts, the viscosity of silica–poor melts increases as pressure increases [Liebske et al., 2005; Ardia et al., 2008 and references therein]. However, the available data suggest that the effect of P is negligible at near surface conditions pertinent to explosive and effusive volcanism. As a consequence this effect will not be discussed any further in this contribution. Figure A2.1 shows for the Ab–Di system what is the effect of P which changing composition in the binary system, by using fitting procedure as adopt–

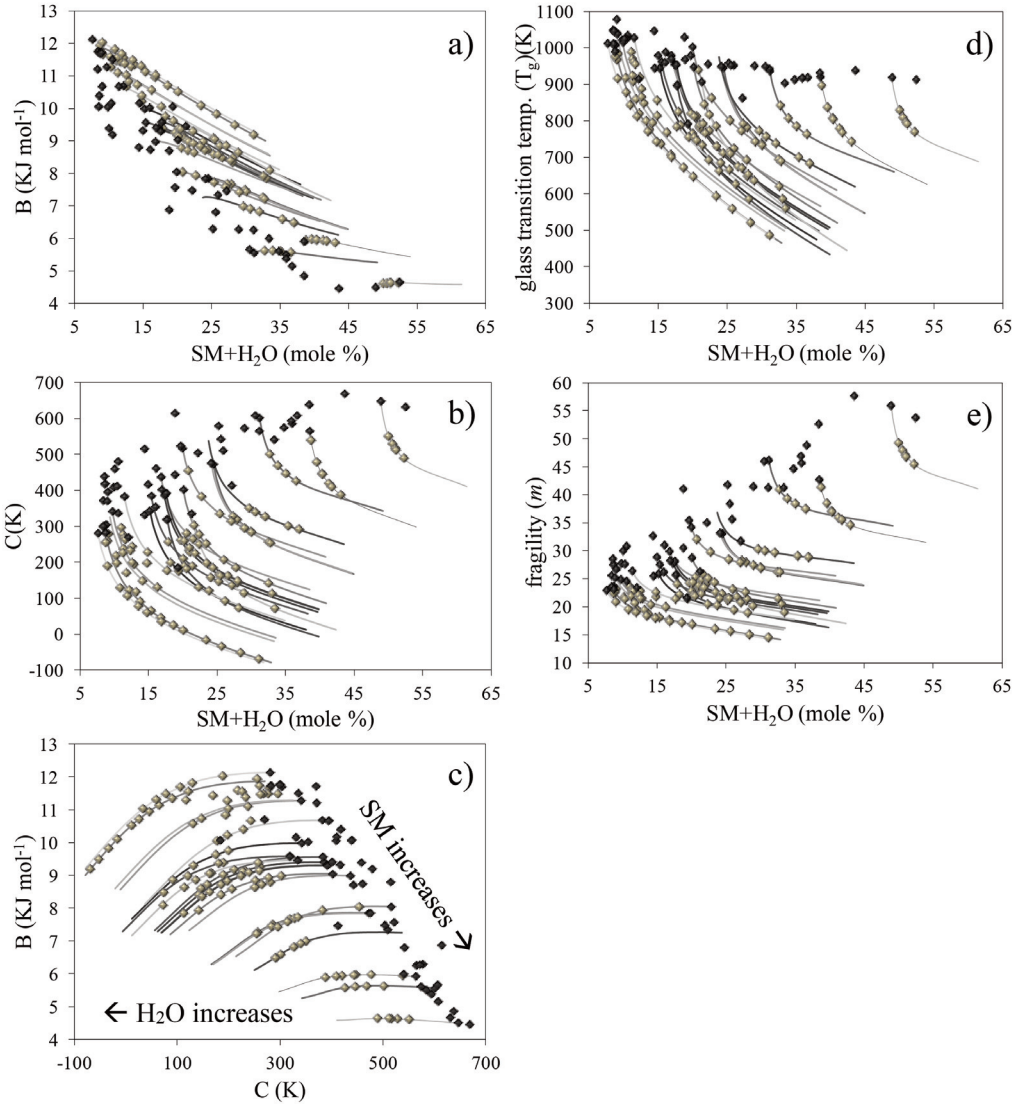

FIGURE 2. Relationships between constitutive parameters of the GRD model (Giordano et al., 2008), based on the VFT formulation (Equation 1), as a function of the modified SM (Structure Modifiers) parameter (Giordano and Dingwell, 2003). The role of increasing SM on the constitutive parameters of anhydrous melts (black symbols) is that of decreasing B_{VFT} and increasing C_{VFT} (Figure 2a, b) while increasing the fragility (m) (Figure 2e). On the other hand adding H_2O to the melt structure (gray symbols) results in decreasing B_{VFT} while decreasing C_{VFT}, the glass transition temperature T_g (as taken at a viscosity of 10^{12} Pas) (Figure 2d) and the fragility (m). This observation put in evidence that the structural role of H_2O is different from that of those cations which simply modify silicate melts structure (Giordano et al., 2008, 2009).

ed by Ardia et al. [2008]. This system is considered to show what is the effect of P on polymerized (Ab) to depolymerized (Di) synthetic compositions from low to high P. Similar behaviours is expected for natural compositions, but, as shown by previous authors [e.g. Giordano et al., 2008b; Chevrel et al., 2013; Whittington et al., 2009], simplified systems (e.g. An, Di, Ab) should not be considered as proxies for natural compositions.

2.3 TOWARD A STRUCTURAL MODEL FOR GEOLOGICAL MELTS

More recently, Le Losq and Neuville [2017], Giordano and Russell [2018] and Giordano et al. [2019], following different approaches, showed that the viscosity of simple and multicomponent anhydrous silicate melts over a temperature interval of ~ 700 to 1600°C, can be predicted from the Raman spectra obtained from the corresponding glasses (i.e. fast quenched melts). These methods prove to be very promising methods for in situ rheological investigations and may have great importance for planetary sciences studies [Angel et al., 2012; Giordano and Russell, 2018]. Le Losq and Neuville [2017] developed a 13 – parameters model for melt viscosity in the simple system SiO2–Na2O–K2O which connects the transport and thermodynamic properties of these simple melts explicitly to the structural state of the melt expressed via the

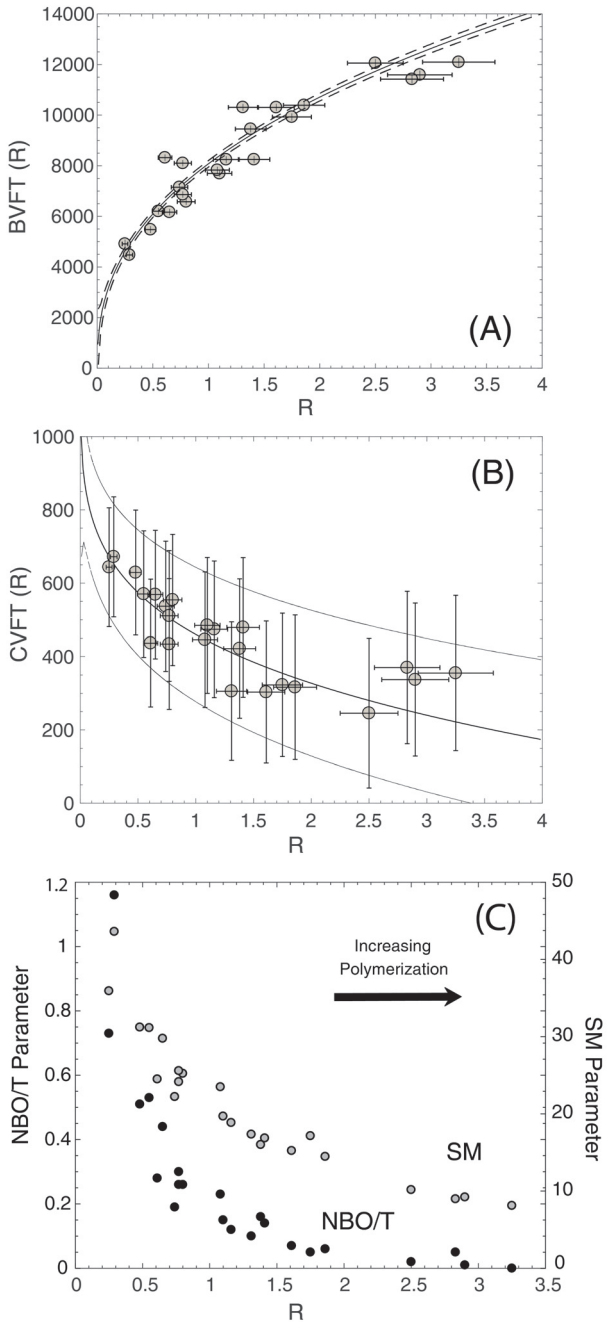

FIGURE3. Model VFT parameters B_{VFT} (R)(A) and C_{VFT} (R)(B) as defined by Giordano and Russell (2018) (panels A, B) and relationships between pseudo–structural parameters (SM, NBO/T)(C), as a function of the Raman ratio (R). According to the above mentioned authors: B_{VFT} (R) = b_1R^{b2} and C_{VFT} (R)=c_1R^{c2}+c3 where b_1, b_2, c_1, c_2, c_3 are adjustable parameters.

abundances of Qn –species recovered from Raman spectral analysis of the glasses. Giordano and Russell [2018] first and Giordano et al. [2019], later, the presented a first order model predicting the viscosity of multicomponent natural melts by the employment of the so–called Raman ratio (R) [Giordano and Russell, 2018] and normalized Raman ratio (Rn) [Giordano et al., 2019] derived by Raman spectra measured on the corresponding glasses as defined by Mercier et al. [2009, 2010]. As shown in Figure 3 a strong relationship exists between B_{VFT} and C_{VFT} parameters and R which allows the viscosity of anhydrous multicomponent natural melts to be predicted with a great accuracy. Although, the model requires expansion to use of the structural information of volatile–bearing melts, it allows accurate description of the viscosity of anhydrous melts by the employment of a simple equation with 6 adjustable parameters and the measured R. Also the SM and NBO/T parameters, calculated from compositions, are shown to be strongly correlated with R.

3. FROM PURE LIQUIDS TO MULTIPHASE ANALOGUES AND MAGMAS: ADVANTAGES AND DISADVANTAGES OF THE DIFFERENT EXPERIMENTAL APPROACHES

Being magmas and volcanic materials complex, texturally evolving (reactive) mixtures of crystals and vesicles suspended in a silicate melt phase which evolve as a function of the evolving P, T and compositional variations and dynamic regimes, the description of effect of suspended phases on the viscosity of these natural suspensions has followed different approaches. The early models devoted to describe the multiphase rheology were historically based on the investigation of analogue materials [e.g. Einstein, 1906; Einstein and Roscoe, 1952]. More recently, the basis for the description of natural multiphase suspensions has been largely developed using natural and simplified silicate melts mixtures at experimental conditions at around thermodynamic equilibrium [e.g. Campagnola et al., 2016; Chevrel et al., 2015; Robert et al., 2014; Sehlke et al., 2014; Soldati et al., 2016; Vona and Romano, 2013; Vona et al., 2011, 2013]. As such, their application to natural environments requires extrapolation into the thermal and deformational disequilibrium state at which magmatic and volcanic processes commonly operate. This is only possible to a limited extent, as natural magmatic and volcanic processes often operate quite far from equilibrium. Recent studies on the disequilibrium rheology of crystallizing natural silicate melts have documented that deformation–rate and cooling–rate may significantly affect the phase transitions of magmatic mixtures so to forcing the material toward a thermal and mechanical dise–

quilibrium state [e.g. Giordano et al., 2007; Kolzenburg et al., 2016, 2017a, b; 2018a,b; Arzilli and Carroll, 2013].

Following, the experimental efforts aimed at retrieving information of the multiphase rheology of natural silicate mixtures have been broadly summarized by subdividing it into, experiments on non reactive materials (Chapter 4) or reactive silicate melts mixtures undergoing variable thermal or deformational variation (Chapter 5). These kinds of experiments can be further subdivided into three main categories: a) experimentation on analogue materials; b) experiments on simplified silicate mixtures and c) experiments on natural volcanic products. Each of these experimental approaches has different advantages/disadvantages which are listed below.

3.1 ANALOGUE MATERIALS

Multiphase analogue materials are commonly constituted by non–reactive mixtures of mono– or poly–disperse particles and/or bubbles, with varying content and shape and size distributions, immersed in some Newtonian synthetic fluid (e.g. silicon oil, syrup, liquid paraffin), which can be investigated at room temperature. These multiphase mixtures can normally be investigated at room temperature conditions and therefore their rheological characterization is simplified as it does not involve the need for high temperature or pressure equipment and the sample texture can readily be controlled (e.g. the solid/bubble proportion or variation). These kinds of experiments are commonly performed on transparent multiphase mixtures and therefore allow observing and characterizing strain partitioning processes occurring amongst the phases during the deformation. The main disadvantage of this kind of experimentation is that it cannot reproduce neither the transient disequilibrium processes occurring in natural mixtures (e.g. crystallization or degassing stages) nor the natural dynamic physical properties of silicate melts (e.g. viscous and cohesive forces between the natural residual melt and suspended particles and bubbles). The largest part of these studies investigate two phase suspensions of either liquid and solid particles (simulating crystal bearing magma) or liquid and bubbles or vesicles (simulating the exsolution of volatile gases).

3.2 MULTIPHASE SILICATE MELT SUSPENSIONS

The experiments of categories b) and c), above mentioned, require significantly more complex experimental infrastructure and are substantially more complex to be characterized in terms of textural parameters (crystal and bubble content; crystals and bubbles size and shape distributions) but they offer the opportunity to perform measurements on materials with direct application to the Earth Sciences. The inherent inhomogeneity of geomaterials and the large variations of the size– and shape–distributions found in natural products can, to date, not be captured in a satisfactory manner by the available theoretical or empirical models. Experiments on natural materials at controlled conditions have the advantage of being representative of natural scenarios and, in most cases, they allow retrieving, at least, the final stage of textural evolution as a function of the imposed environmental conditions (i.e. isothermal; non–isothermal; isobaric; non–isobaric) as well as varying deformation regimes (i.e. constant or varying stress and/or strain rate). This allows the reconstruction of the rheological parameters in a tightly constrained parameter space, however it requires unique experimental characterization for each studied scenario. When volatile free samples are investigated, this kind of experiments can be performed, using a variety of experimental techniques (e.g. rotational concentric cylinder/Patterson deformation rig and uniaxial compression and/or micropenetration and parallel plates techniques; see Appendix A1 for details), over the entire temperature–viscosity interval from super– to sub–liquidus conditions that are characteristic of natural environments. For volatile–bearing natural melts and suspensions, this becomes more complex as limited experimental infrastructures exist to date to measure at the elevated pressures required to maintain volatiles in solution. There have been some recent advances which take advantage of the metastable liquid state close to T_g or by using devices which allow the sample to be pressurized [Paterson, 1978; Paterson and Olgaard, 2000; Caricchi et al., 2007; 2008; Ardia et al., 2008; Robert et al., 2008a, b; Piermarini et al., 1978]. A further advancement is the 4D characterization of the sub liquidus evolution of natural melts is represented by experiments within synchrotron facilities which allow real time monitoring of the textural evolution of samples of volcanological interest during crystallization and/or degassing [e.g. Ohtani et al., 2005; Pistone et al., 2015; Pleše et al., 2018; Polacci et al., 2018; Polacci et al., 2010; Song et al., 2001]. These techniques are starting to be coupled with devices for

rheometry, which may in the future allow for in situ estimates of both the crystallization kinetics and the rheological response of evolving natural systems [Coats et al., 2017; Dobson et al., 2015; Dobson et al., 2016; Raterron and Merkel, 2009]. The results of experimental campaigns and modelling of the multiphase rheology of natural magmatic suspensions performed on natural or analogue silicate melts at high temperatures will be presented in Section 4.2.

4. EXPERIMENTS AND MODELS OF NON-REACTIVE MULTIPHASE MIXTURES

Following the results obtained on isothermal bubble–bearing or particle–bearing suspensions rheology of analogue materials, simplified silicate melt mixtures and natural melts and magmas are here first introduced. Finally I summarize what is known on the effect of the presence of bubbles+crystals on suspension rheology measurements performed at constant temperature.

4.1 MODELS OF BUBBLE SUSPENSION RHEOLOGY

Early studies estimating the effect of void spaces within natural and simplified silicate melts [e.g. Bagdassarov and Dingwell, 1992, 1993; Lejeunne et al., 1999; Vona et al., 2016; Ryan et al., 2019] or synthetic analogues [e.g. Manga et al., 1998; Llewellin et al., 2002a, b; Llewellin and Manga, 2005] has been carried out by several authors. Those investigations showed, largely, that, two end member cases can be considered: 1) bubbles behave as rigid objects (capillary number Ca<1); 2) bubble are deformed (Ca>1) [Llewellin et al., 2002a,b]. For the different regimes various empirical equations were proposed [Bagdassarov and Dingwell, 1992; Lejeunne et al., 1999; Llewellin et al., 2002; Llewellin and Manga, 2005] (details in Appendix A3) which suggested that, during steady flow: a) an increase in relative viscosity in the case of the first end–member (Ca<1) and b) a decrease of the relative viscosity in the case of second end member condition (Ca>1) can be observed. Additional complexities are introduced, as discussed in Appendix A3, for non–steady flow for which the definition of a dynamic capillary number (Cd) is required. The same authors [e.g. Lejeune and Richet, 1996; Bagdassarov and Pinkerton, 2004, Llewellin et al., 2002, Llewellin and Manga, 2005] also provided important attainments concerning the understanding of the effect of closed and opened voids on liquid viscosity [e.g. Lejeune et al., 1999; Bagdassarov and Dingwell, 1992; Quane and Russell, 2004; Llewellin et al., 2002a, b; Llewellin and Manga, 2005; Mader et al., 2013; Vona et al., 2016; Ryan et al., 2019]. A summary of recent formulations and works related to both crystal bearing and bubble bearing rheological studies is reported in Appendix A3.

4.2 FROM SHEAR-RATE INDEPENDENT TO SHEAR-RATE DEPENDENT PARTICLE SUSPENSION RHEOLOGY MODELS OF ANALOGUE MATERIALS

Early studies on the rheological behavior of multiphase suspensions [e.g. Einstein, 1906; Roscoe, 1952; Krieger and Dougherty, 1959; Gay et al., 1969; Pinkerton and Stevenson, 1992] suggested a threshold in solid fraction, the so–called crystal maximum packing fraction (ϕ_c), that separates a liquid dominated rheology from a solid–dominated rheology. For dilute suspensions of solid mono–disperse spherical particles (ϕ < 3 vol%) Einstein [1906] proposed that the relative viscosity η_r (i.e. the ratio between the viscosity of the particle–bearing suspension and that of the particule–free melts) could be calculated as: $\eta r = (1+ B\phi)$, where B is a constant depending on object geometrical features (B=2.5 for spheres). Roscoe [1952] extended Einstein's expression to higher concentration of spheres, by first defining the maximum crystal packing fraction (ϕ_m) and providing for the relative viscosity the following expression: $\eta_r = (1 + \phi/\phi_m)^{-2.5}$. Different ϕ_m values were proposed by different authors depending on crystal geometry (see appendix A3 for more details). Later, Krieger and Daugherty [1959] generalized the previous expressions as it follows: $\eta_r = (1 + \phi/\phi_m)^{-}B_e\phi_m$ where B_e is a constant called the Einstein coefficient (KD model). Others similar expressions were formulated for which different value of the B_e coefficients were determined (see appendix A3). Although widely applied, a limitation of those empirical or semi–empirical laws is that they do not account for neither the strain–rate dependence nor the existence of, although still debated, yield strength [Moitra and Gonnermann, 2015] of multiphase mixtures typical of non–Newtonian fluid (see appendix A3 for more details). For a review on the two phase rheology of particle bearing analogue suspensions the reader can refer to Mader et al. [2013], who presented a comprehensive review on this topic

4.3 NON-NEWTONIAN MODELS FOR PARTICLE SUSPENSION RHEOLOGY OF SIMPLIFIED SILICATE MIXTURES

Concerning magma–equivalent suspensions, more recently, Caricchi et al. [2007], Costa et al. [2007a, 2009], based on the available experimental data obtained at constant temperature, presented models describing the non–Newtonian strain–rate–dependent rheological effects of crystals in the range of solid fractions from 0 to 0.8 and over. These models cover the transition from the regime where the deformation behavior is controlled by melt viscosity up to the beginning of the regime where the deformation behavior is controlled by a solid framework of interlocking particles. The most detailed and comprehensive model to date proposed by Costa et al. [2009] model (CM) (Eqs. A3.3–A3.4.), describes the relative viscosity η_r (i.e. the viscosity of a crystal melt mixture (ηmix) divided by the viscosity of the melt phase (η_r)). The CM model is the result of the combined mathematical and experimental efforts condensed in the works of Costa [2005], Costa et al. [2007a] that was used by Caricchi et al. [2007] to describe their experimental data. Compared to previous models [e.g., Einstein–Roscoe, 1952; Costa, 2005; Caricchi et al., 2007], the CM model accounts for the strain–rate dependent changes in the rheology of liquid+crystal mixtures. The model in particular shows that the strain rate dependence of the relative viscosity at varying crystal volume fractions follows a sigmoid curve with exponential increase above a critical solid fraction (ϕ_c ~ 0.3–0.4) which is also a function of strain rate and crystal shape. This model is consistent with the early Einstein–Roscoe equation [Einstein, 1906; Roscoe, 1952] for crystal fractions in the range of 0 to 0.1–0.3 depending on crystal shape and size [e.g. Cimarelli et al., 2011]. A summary of the main results obtained by the employment of the CM and a summary of its original formulation are reported in Appendix A3. Extension of CM devoted to characterize the effect of crystal size and shape distribution and suspended particle ratio and particle roughness are discussed in Appendix A3.

4.4 NON-NEWTONIAN STRAIN-RATE DEPENDENT MODELS FOR PARTICLE SUSPENSION RHEOLOGY OF NATURAL MIXTURES

The fermenting production of studies [Shaw et al., 1968; Lejeune and Richet, 1995; Giordano et al., 2007; Caricchi et al., 2007, 2008; Ishibashi, 2009; Vetere et al., 2010, 2017; Vona et al., 2011; Pistone et al., 2012, 2016; Chevrel et al., 2015, 2017; Campagnola et al., 2016] devoted to the characterization of the isothermal viscosity evolution of silicate melts at subliquidus temperature as a function of presence and size and shape distributions of crystals and bubbles and deformation regimes of the last twenty years has permitted extraordinary advances that are condensed in empirical and theoretical models of suspension rheology [Saar et al., 2001; Caricchi et al., 2007; Costa et al., 2009; Mueller et al., 2011; Vona et al., 2011; Moitra and Gonnermann, 2015]. According to the comprehensive model of Costa et al. [2009] (CM) (see Section 3.1), inspired by the previous work of Costa [2005], Costa et al. [2007a] and Caricchi et al. [2007], the relative viscosity of two–phase mixture increases following a sigmoid curve with exponential increase above a critical solid fraction (ϕ_c) corresponding to the first (phi~0.3–0.4) inflection point. A second inflection point (ϕ_m) at phi ~0.6–0.7 is determined by the beginning of crystal dominated rheology (Figure A3.3).

Since the seminal contributions of Caricchi et al. [2007] and Costa et al. [2009], numerous scientists provided new and more complete formulation of the critical crystal fraction (ϕ_c) for the natural variability in of crystal size and shape distribution which would also account for new variables (e.g. crystal surface roughness) [e.g. Mueller et al., 2011; Klein et al., 2018]. The employment of these critical contributions have allowed interpreting, based on model calculations, the effect of rheological constraints on eruptive behavior.

4.5 MODELS FOR PARTICLES AND BUBBLES SUSPENSION RHEOLOGY

Complex three–phase suspensions (i.e. liquid+bubbles+crystals) have been investigated in only a few studies [Cordonnier et al., 2009; Robert et al., 2008a, b; Lavalleé et al., 2007, 2008; Vona et al., 2013, 2017; Campagnola et al., 2016; Pistone et al., 2012, 2015, 2016]. Given their complexity only a fewer studies have provided preliminary models describing the complex rheology of three–phase mixtures [Pistone et al., 2012, 2013, 2015, 2016]. The viscosity data presented in those studies are the same as those presented in Pistone et al [2012], but the authors apply their results to different geological context by showing that size– and shape–distributions of crystals and bubbles may significantly vary while undergoing certain stress–strain regimes. The experiments by Pistone et al. [2012] were performed at pressurized and isothermal temperature con–

ditions in a Paterson device (Appendix A1) on samples for which the liquid+crystal rheology was characterized by Caricchi et al. [2007]. They show that bubbles strongly affect the rheological properties of crystal–rich mushes. By presenting a comprehensive review of existing literature and performing new measurements, they estimated that a decrease of up to 4 orders of magnitude is observed by the addition of only 9 vol% of bubbles to a liquid+crystals suspension containing 70 vol% of crystals. They also established that two non–Newtonian deformation regimes originate as a consequence of the bubble and crystal interaction: i) a shear thinning behavior result of the crystal size reduction and shear banding due to strain localization [also observed by Caricchi et al., 2008] which is typical of magmas which are transported and emplaced in Earth's crust and may feed eruptions; ii) a shear thickening behavior which is the consequence of crystal interlock and flow blockage which they argue locks plutonic rocks in the lower and upper crust, inhibiting eruptions. More details of the results obtained by the works of Pistone and coauthors are provided in Appendix A3.3.

5. NON-ISOTHERMAL COOLING-RATE AND STRAIN-RATE DEPENDENT RHEOLOGY OF VOLCANIC MATERIALS

Efforts to systematically describe and predict magma migration and lava flow behavior rely heavily on these experimental measurements to derive empirical models. However, during migration and transport of silicate melts in the Earth's crust and at its surface magma/lava can experience varying cooling and deformation conditions which may drastically influence its thermorheological evolution; see for example Rhéty et al. [2017] and Robert et al. [2014]. As a consequence, data intended for application to the natural environment will have to account for the disequilibrium behavior of natural magmatic suspensions. Cooling rates of basaltic lavas, measured at the surface and within active lava channels during emplacement range from ~0.01 to 15 C/min [Cashman et al., 1999; Flynn and Mouginis–Mark, 1992; Hon et al., 1994; Witter and Harris, 2007; Kolzenburg et al., 2017]. These values are largely representative for the exterior part of lava flows or for the initial cooling of newly emplaced dikes. They can, therefore, be taken as maximum cooling rates that are expected to be lower in the interior of the lava flow or a cooling dike. The importance of varying thermal conditions on the crystallization kinetics and textural development of silicate melts has been recognized for decades and inspired disequilibrium experimentation in petrology and volcanology [e.g. Walker et al., 1976; Arzilli and Carroll, 2013; Coish and Taylor, 1979; Gamble and Taylor, 1980; Hammer, 2006; Lofgren, 1980; Long and Wood, 1986; Pinkerton and Sparks, 1978; Giordano et al., 2007; Vetere et al., 2013]. These studies highlight that significant differences in textures and paragenesis emerge when moving from equilibrium to disequilibrium conditions that can, in turn, affect the flow behavior. Albeit a growing experimental disequilibrium database is becoming available no models for the disequilibrium phase dynamics of natural silicate melts have been developed to date.

Understanding the rheological evolution of crystallizing melts, magmas and volcanic products requires direct measurement of the flow properties of investigated materials at such disequilibrium conditions in the field or in the laboratory. In such environments, the studied materials are degassed and undergoes transient increases in viscosity as it is increasingly undercooling until a "rheological cut–off temperature" [Giordano et al., 2007; Kolzenburg et al., 2016, 2017, 2018a, b, c; 2019] is reached and the lava rheologically solidifies. This transient rheological gradient, which occurs in all natural, non–isothermal environments, governs the lavas emplacement style. In recent years, the first sets of measurements were presented that constrain the rheological evolution of natural silicate melts under temperature– and deformation–conditions pertinent to the transport of silicate melts on the earth's surface and in shallow magma plumbing systems. The recovered data show a strong dependence of composition [Kolzenburg et al., 2017, 2018a], cooling–rate [Giordano et al., 2007; Kolzenburg et al., 2016, 2017], oxygen fugacity [Kolzenburg et al., 2018a] and shear–rate [Kolzenburg et al., 2018] on the thermorheological evolution of natural silicate melts. They represent the first contributions to a growing database of lava rheology under natural conditions. However, significant experimental effort in this field is required to expand the range of available data to cover the most relevant compositions and to experimentally map the range of parameters pertinent to flow of natural silicate melts under disequilibrium. Such a database would then allow deducing the underlying processess and expanding these into a theoretical description of the flow behavior of magma and lava. So far, the main limitation of this kind of studies is the difficulty to monitor, and therefore extend, the results to

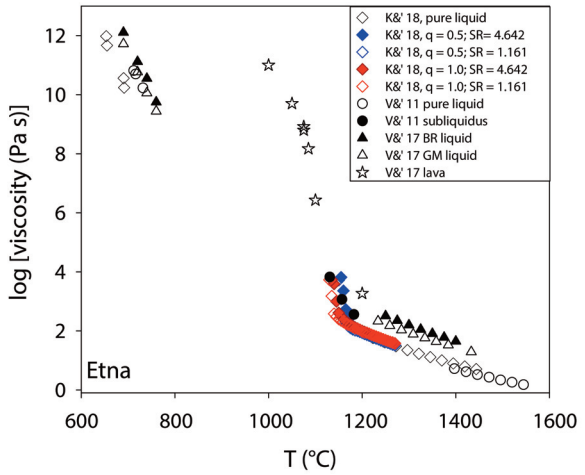

FIGURE 4. Summary of available melt and crystal–suspension viscosity data on remelted Etnean lava as a function of temperature. Melt viscosity measurements (open black diamonds, black circles and black triangles) were performed via concentric cylinder viscometry, micro penetration and differential scanning calorimetry; Sub liquidus viscosity measurements were preformed using 1) concentric cylinder viscometry at constant temperature (black circles), 2) concentric cylinder viscometry at varying cooling– and shear–rates (open and filled red squared and blue diamonds) and 3) parallel plate viscometry via unconfined uniaxial deformation (open black stars). K&' 18; V&' '11 and V&' '17 refer to work published by Kolzenburg et al (2018), Vona et al. (2011) and Vona et al (2017).

non–degassed materials and therefore the application to intra–crustal magmatic or explosive volcanic processes. According to previous authors [e.g. Melnik and Sparks, 1999, 2005; Costa and Macedonio, 2003, 2005; Costa et al., 2007b; Hess et al., 2008; Cordonnier et al., 2012] an additional complexity could be due to the effects of non–linear thermal effects, potentially generated by viscous dissipation and loss by conduction at the contact between the molten material and the hosting rock, in conduits, and channels or tunnels after eruption to the surface. The nonlinear behaviour of thermal effect are mainly governed by specific non–dimensional numbers (Graetz; Nahme; Prandtl; Reynolds regimes), which according to Costa et al. [2007b], amongst the others above mentioned, may determine the necessity to distinguish between three main regimes – a conductive–heat–loss–dominated regime, an intermediate regime and a viscous–heating–dominated – may have significant effects for the definition of the rheological behaviour and emplacement dynamics of lava flows and lava domes.

Figure 4 shows a summary of rheological data recovered using a variety of experimental methods on Etna melts. The melt compositions, albeit stemming from different eruptions, are similar for most major oxides with the exception of the sample from Vona et al. [2017], that is more rich in silica and poor in iron and, as a result, more viscous than the samples in Vona et al. [2011] and Kolzenburg [2018].

For the investigated degassed materials these data summary highlights a number of effects acting during the transport of magma and lava at sub liquidus conditions. Comparison of the pure liquid viscosity of the remelted bulk rock and the separated groundmass [Vona et al., 2017]; triangles documents that, for basaltic melts, crystallization induced changes in melt composition result in relatively small changes in the viscosity of the liquid phase of the evolving suspension.

Therefore, the variations of the flow behavior of crystallizing basalts are controlled by variations in the volumetric fractions of crystals and bubbles. These data also reflect the measurement limits of the respective methods that are described in more detail in Kolzenburg et al. [2016a]. Concentric cylinder suspension viscometry for these Etnean lavas is confined to $<10^4$ Pa s and shows that the measured viscosities at constant temperature (i.e. at or near thermodynamic and textural equilibrium) are commonly higher than non–isothermal measurements at the same temperature. This is due to the fact that under dynamic thermal conditions, the crystal nucleation and growth kinetics lag behind the equilibrium state and commonly produce lower crystal contents. The non–isothermal viscosity data from Kolzenburg et al. [2018c] document that both cooling–rate (blue circles vs. red squares) and shear rate (open vs. filled symbols) exert a modulating effect on the disequilibrium rheology of the Etna melt. Measurements beyond the mechanical limit of concentric cylinder (CC) viscometry were presented in Vona et al. [2017] who employed parallel plate (PP) viscometry via unconfined uniaxial deformation (open black stars) to measure the viscosity of three phase magmatic suspensions. The data form an apparent continuing trend with respect to the concentric cylinder viscometry measurements but document lower lava viscosities than extrapolation from the two phase measurements would suggest. This is likely a result of the differences in sample texture, where all CC data are restricted to bubble free two phase suspensions of crystals and melt, whereas the PP data are measured on three phase (i.e. crystal and bubble bearing) suspensions.

In summary, the rheological evolution of lava at sub–liquidus conditions can be reconstructed neatly by combination of datasets from differing sources. This is also

shown in Figure 3 in Kolzenburg et al., [2019, this issue], where laboratory and field estimates of lava rheology at emplacement conditions are compared and the respective data fall within a range of similar values. This highlights the potential of cross correlation of data from different experimental and field sources and the need to expand the available experimental database in order to generate a holistic view of the dynamics of magma and lava transport.

6. ALTERNATIVE WAYS OF RETRIEVING RHEOLOGICAL INFORMATION FROM REMOTE SENSING GROUND- OR SATELLITE-BASED TECHNIQUES

Besides laboratory viscometry (i.e. the direct measurement of melt / suspension viscosity under controlled conditions) there are several other sources of rheological information that are useful to place the laboratory measurements in context of the natural environment. This kind of information is important as it allows accounting for the multiphase nature of lava bodies and can serve to place the laboratory measurements within the framework of conditions relevant in natural scenarios. However, to date such data only represents a very limited source of information of the rheological evolution of lava flows, in space and time. This is largely due to large logistical and financial efforts required for some of these measurements and to the uncertainties associated. Broadly these approaches can be separated into:

1. Direct measurement of viscosity on active lava flows via penetration– or rotational–viscometry [Einarsson, 1949; Gauthier, 1973; Panov et al., 1988; Pinkerton and Sparks, 1978; Belousov et al., 2015; Belousov and Belousova, 2018; Shaw et al., 1968; Pinkerton and Norton, 1995; Pinkerton and Wilson, 1994; Chevrel et al., 2018]. These represent snapshots of actual lava flow rheology at specific conditions and provide data that help to constrain the conditions required to be reproduced in systematic laboratory studies. However, such measurements are quite difficult and require significant logistical effort and manpower. Further, the available devices [e.g. Belousov and Belousova, 2018; Chevrel et al., 2018] for such measurements are only slowly advancing to be able to measure all relevant parameters sufficiently well to recover high quality viscosity data (Appendix, A1.5).
2. Calculation of the apparent viscosity based on Jeffreys' equations [e.g. Jeffrey, 1925; Hulme, 1974] (Appendix 4, SMO) using flow rate measurements of active lavas in channelized flows [Naboko, 1938; Nichols, 1939; Minakami, 1951; Einarsson, 1966; Walker, 1967; Gautier, 1973; Moore, 1978; Andreev, 1978; Fink and Zimbelman, 1986; Vande–Kirkov, 1987; Panov, 1988; Soldati, 2016; Belusov and Belousova, 2018]. Such data are still few due to the difficulty of accessing active lava flows. However, the development of affordable unmanned aerial vehicles (UAV's) in recent years appears to be promising making this method widely applicable with the opportune considerations. In fact, the above mentioned approach has strong limitations as it is based on the assumption of parabolic velocity profile that is not generally valid because of thermal effects [e.g. Costa and Macedonio, 2003, 2005; Costa et al., 2007b; Filippucci et al., 2013 and Filippucci et al., 2019, this issue] (details at Section 3.1.2). Such aspect is still never considered to describe the nonlinear dynamic of lava flows and lava domes rheology [Melnik and Sparks, 1999, 2005; Melnik et al., 2009]. To an adequate analysis of this contribution for specific cases, it is recommended to refer, for instance, to the above mentioned works and e.g. Filippucci et al. [2019, this issue].
3. Ties between lava flow geometry and viscosity. Morphological–derived rheological parameters (i.e. viscosity and yield strength) are commonly obtained in planetary sciences [Heisinger et al., 2007; Castruccio et al., 2010 and Chevrel et al., 2015] provide excellent reviews of the employed equations and results). Rheological information is obtained by retrieving, in the field or remotely also from satellites, length, width, thickness and slope of emplacement of lava flows. This methodology has also been applied based remote sensing data collected during active flow emplacement [James et al., 2015; Farquarson et al., 2015; Kolzenburg et al., 2018a]. Also in this case, the emplacement of lava flows is commonly modelled using a single rheological parameter (apparent viscosity or apparent yield strength) calculated from morphological dimensions using Jeffreys' and Hulme's [Jeffrey and Acrivos, 1976; Hulme, 1974] equations. The rheological parameters are then typically further interpreted in terms of the nature and chemical composition of the lava (e.g., mafic or felsic). Chevrel et al. [2013, 2015] employing this

methodology has shown that providing an unique factor to describe rheology of lava flows is definitely far from being representative of the real emplacement dynamics of lava flows. As above mentioned (Point 2), given the nonlinear dynamics of lava flows and domes, which may determine significant thermal effects, significant limitations may be observed and should be carefully considered before applying to any natural context [e.g. Costa and Macedonio, 2003, 2005; Costa et al., 2007b; Filippucci et al., 2013 and Filippucci et al., 2019, this issue].

4. Ties between the intensity of thermal anomalies generated by actively flowing lava and its silica content and therewith discharge rate of lavas [e.g. Coppola et al., 2013, 2017]. This approach takes advantage of the fact that low viscosity lavas are readily able to spread into thin sheets during flow, whereas high viscosity lavas usually retain lower aspect ratios. Since the heat loss of a lava is largely governed by its surface to volume ratio, its spreading ability (i.e. viscosity) can, empirically, be correlated to the measured heat loss. Over the last decades such satellite–based remote sensing and data processing techniques have proved well suited to complement field observations and to allow timely eruption detection, as well as for flow tracking.

7. CONCLUDING REMARKS AND OUTLOOK

The present review shows the extraordinary improved knowledge of rheological properties of multicomponent and multiphase silicate melts occurring in the last twenty years. Such knowledge advancement has been due to the necessity of constraining natural processes and parallel the development of new technological advances, frequently obtained to face specific problems. It has been observed that the continuously evolving rheology of magmas and eruptive products during their ascent, eruption and emplacement can be described with increasing accuracy and specifically applied to geological issues with improved confidence. The observed transition between Newtonian to strongly non–Newtonian rheological behaviour is typical of both simple liquids and/or multiphase natural mixtures. These transitions govern the observed eruption dynamics and the eruption dynamic transitions, potentially determining also whether an eruption will be effusive or explosive.

The employment of the rheological flow laws for multicomponent and multiphase silicate melts find a very promising application to constraining the advancement and halting of lava flows. For these superficial phenomena, the opportunity of monitoring important variables such as the discharge rate and the topography of emplacement provide fundamental advantage for the employment of numerical simulations tools. These have allowed showing that more accurate estimates of the effects of crystals and bubbles during lava flow emplacement can be obtained only by real–time monitoring of lava flows through field and remote sensing methods paralleled by a proper experimental campaign, which in particular would account and would be related to the non–equilibrium, non–isothermal rheology of multiphase mixtures.

This progress in understanding the mechanisms of advancement and emplacement of lava flows and domes has also been made possible recently thanks to the recent emplacement of large long–lasting silicic to basaltic effusive eruptions. Prior to 2008, for instance, no rhyolite lava flow–forming eruptive event was observed or documented. Hence, the real–time observations of active rhyolitic flow and dome emplacement at the Chilean volcanoes of Chaitén [Carn et al., 2009; Lara 2009; Bernstein et al., 2013; Pallister et al., 2013] and Puyehue–Cordón Caulle significantly developed our knowledge of rhyolitic lava emplacement [Castro et al., 2013; Schipper et al., 2013; Tuffen et al., 2013; Bertin et al., 2015; Farquharson et al., 2015; Magnall et al., 2017]. Analogously the long lasting 2014–2015 basaltic eruption at Holuhraun, Bardarbunga system, Iceland [e.g. Pedersen et al., 2017], offered the opportunity to establish/calibrate, through the contemporaneous employment of field work, remote sensing techniques [Kolzenburg et al., 2018a] and laboratory experimentation [Kolzenburg et al., 2017], which allow retrieving thermal properties, estimates of effusion rate [Coppola et al., 2013, 2017] and evaluate the effect of bubbles by comparison with experimental campaign on liquid+ crystals material as collected during eruption [Kolzenburg et al., 2017, 2018 a,b]. Worth mentioning is also the integrated field, remote sensing, physical properties and physical modelling and numerical simulations studies performed in the recent years for intermediate compositions producing effusive activities [Chevrel et al., 2013 a,b; 2015]. For andesitic domes huge progresses in understanding the non–linear thermal effects which determine non–linear eruption dynamics has been made by previous authors [e.g. Costa et al., 2007b; Melnik and Sparks, 1999, 2005; Melnik et al., 2009]. Although the

purposes of this paper is to mostly describe the development of rheological properties in relationship to the emplacement of lavas, most of the general results obtained here, and in particular those related to the effect of crystals and vesicle on multiphase rheology, can be extended to eruption dynamics of explosive phases.

Some of the main results deduced by application of the existing rheological models and experimental studies, supported by petrological analysis and field work, allowed to unequivocally show that lava flow emplacement may be a long lasting process also for silicic magmas and that flow may continued also unrooted from the vent for long times [e.g. Farquarson et al., 2015] and that extremely voluminous silicic lava flows may be emplaced in relatively short time without giving origin to significant explosive stages [Tuffen et al., 2013; Farquarson et al., 2015; Giordano et al., 2017; Polo et al., 2018a, b]. In addition, Kolzenburg et al [2016, 2017, 2018] showed that disequilibrium, cooling– and shear–rate controlled rheological properties may have fundamental influence in determining the effective length of basaltic lava flows.

Although the results evidenced by performing non–equilibrium, non–isothermal, transient rheology of basaltic lava flows, are promising and provided a first understanding of lava flow rheology under natural conditions, it is possible to anticipate that future studies will require performing this kind of experiments also to a wider range of effusive products.

Acknowledgements. I would like to thank Stephan Kolzenburg and Kelly Russell for sharing ideas and help in the reorganization of the manuscript. Fabio Arzilli and an anonymous reviewer are also acknowledged for the careful revision of the manuscript. Daniele Giordano acknowledges the University of Turin for support provided by the local research funds (2017/2020).

REFERENCES

Adam G., Gibbs J.H. (1965). On temperature dependence of cooperative relaxation properties in glass–forming liquids. J. Chem. Phys. 43, 139–146.

Andreev, V.I., Gusev, N.A., Kovalev, G.N., Slezin, Y.B. (1978). Dynamics of lava flows of southern breakthrough of great Tolbachik fissure eruption, 1975–76. Bull Volcanol Stations 55:18–26 (in Russian).

Angel, S.M., Gomer, N.R., Sharma, S.K. & McKay, C. (2012). Remote Raman Spectroscopy for Planetary Exploration: A Review. Applied Spectroscopy 66.

Angell, C.A., Relaxations in Complex Systems, (1995). U.S. Department of Commerce National Technical Information Service, ed. K. L. Ngai and G. B. Wright, 1985. pp. 3–11.

Angell, C.A. (1991). Relaxation in liquids, polymers and plastic crystals – strong fragile patterns and problems. J. Non–Cryst. Solids 131, 13–31.

Ardia, P., Giordano, D., Schmidt, M.W. (2008). A model for the viscosity of rhyolite as a function of H2O–content and pressure: a calibration based on centrifuge piston cylinder experiments. Geochim. Cosmochim. Acta 72, 6103–6123.

Arzilli, F., Carroll, M.R. (2013). Crystallization kinetics of alkali feldspars in cooling and decompression–induced crystallization experiments in trachytic melt. Contrib. Miner. Petrol. 166, 1011–1027.

Audetat, A., Keppler, H. (2004). Viscosity of Fluids in Subduction Zones. Science 303, 513 – 516.

Avard, G., and Whittington, A. G. (2011). Rheology of arc dacite lavas: experimental determination at low strain rates. Bull. Volcanol. 74, 1039–1056.

Avramov I. (1998). Viscosity of glassforming melts. J. Non–Cryst. Solids 238, 6–10.

Bachmann, O. and Bergantz, G. (2006) Gas percolation in upper–crustal silicic crystaal crystal mushes as a mechanism for upward heat advection and rejuvination of near–solidus magma bodies. J. Volcanol. Geoth. Res. 149, 85 – 102.

Bagdassarov, N.S., Dingwell, D.B. (1992). A rheological investigation of vesicular rhyolite. J. Volcanol. Geoth. Res. 50, 307–322.

Bagdassarov, N.S., Dingwell, D.B. (1993). Deformation of foamed rhyolites under internal and external stresses: an experimental investigation. Bull. Volcanol. 55, 147–154.

Bagdassarov, N., and H. Pinkerton (2004). Transient phenomena in vesicular lava flows based on laboratory experiments with analogue materials. J. Volcanol. Geoth. Res. 132, 115 – 136.

Bagdassarov, N. and Dorfman, A. (1998). Granite rheology: magma flow and melt migration. J. Geol. Soc. 155, 863–872.

Baker, D.R., Vaillancourt, J. (1995). The Low Viscosities of F+ H_2O–Bearing Granitic Melts and Implications for Melt Extraction and Transport. Earth Planet. Sci. Lett. 132, 199–211.

Behrens, H. and Schulze, F. (2003). Pressure dependance of melt viscosity in the system $NaAlSi_3O_8$–$CaMgSi_2O_6$. Am. Min. 88, 1351–1363.

Belousov, A., and M. Belousova. (2018). Dynamics and Viscosity of 'A 'ā and Pāhoehoe Lava Flows of the 2012–2013 Eruption of Tolbachik Volcano, Kamchatka (Russia). Bull. Volcanol. 80.

Belousov A, Belousova M, Edwards B, Volynets A, Melnikov D (2015). Overview of the precursors and dynamics of the 2012–13 basaltic fissure eruption of Tolbachik Volcano, Kamchatka, Russia. J. Volcanol. Geotherm. Res. 307, 22–37.

Bernstein, M., Pavez, A., Varley, N,, Whelley, P., Calder, E. (2013). Rhyolite lava dome growth styles at Chaitén volcano, Chile (2008–2009): interpretation of thermal imagery. Andean Geol 40, 295–309.

Bertin, D., Lara, L.E, Basualto, D., Amigo, Á., Cardona, C., Franco, L., Gil, F., Lazo, J. (2015) High effusion rates of the Cordón Caulle 2011–2012 eruption (southern Andes) and their relation with the quasi–harmonic tremor. Geophys. Res. Lett. 42, 7054–7063.

Bottinga, Y., Weill, D. (1972). The viscosity of magmatic silicate liquids: a model for calculation. Am. J. Sci. 272, 438–475.

Brearley, M., Dickinson, J. E., Scarfe, C. M. (1986). Pressure–Dependence of Melt Viscosities on the Join Diopside–Albite. Geochim. Cosmochim. Acta 50, 2563–2570.

Brearley, M. and Montana, A. (1989). The Effect of Co2 on the Viscosity of Silicate Liquids at High–Pressure. Geochim. Cosmochim. Acta 53, 2609–2616.

Burnham, C.W. (1963). Viscosity of a water rich pegmatite. Spec. Pap. Geol. Soc. Am. 76, 26.

Campagnola, S., Vona, A., Romano, C., Giordano, G. (2016). Crystallization kinetics and rheology of leucite–bearing tephriphonolite magmas from the Colli Albani volcano (Italy). Chem. Geol. 424, 12–29.

Cañón–Tapia, E., Walker G. (2004). Global aspects of volcanism: the perspectives of ''plate tectonics'' and ''volcanic systems''. Earth Sci. Rev. 66, 163–182.

Cañón–Tapia, E. (2016). Reappraisal of the significance of volcanic fields. J. Volcanol. Geotherm. Res. 310, 26–38.

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 Planet. Sci. Lett. 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. Chem. Geol. 256, 158–171.

Carn SA, Pallister JS, Lara L, Ewert JW, Watt S, Prata AJ, Thomas RJ, Villarosa G (2009). The unexpected awakening of Chaitén volcano, Chile. EOS Trans Am Geophys Union 90, 205–206.

Cashman, K.V., Thornber, C., Kauahikaua, J.P. (1999). Cooling and crystallization of lava in open channels, and the transition of P¯ahoehoe Lava to'A'¯a. Bull. Volcanol. 61, 306–323.

Cashman KV, Soule S, Mackey B, Deligne N, Deardorff N, Dietterich H (2013). How lava flows: New insights from applications of lidar technologies to lava flow studies. Geosphere 9, 1664–1680.

Castro, J. Schipper, C.I. Mueller, S.P. Militzer, A.S., Amigo, A. et al. (2013). Storage and eruption of near–liquidus rhyolite magma at Cordón Caulle, Chile. Bull. Volcanol. 75, 1–17.

Castruccio, A., Rust, A.C., Sparks R.S.J. (2010). Rheology and flow of crystal–bearing lavas: Insights from analogue gravity currents. Earth Planet. Sci. Lett. 297, 471–480.

Castruccio, A, Rust, AC Sparks, RSJ (2014). Assessing lava flow evolution from post–eruption field data using Herschel–Bulkley rheology. J. Volcanol. Geoth. Res. 275, 71–84.

Champallier, R., Bystricky, M., Arbaret, L. (2008). Experimental investigation of magma rheology at 300 MPa: From pure hydrous melt to 75 vol. % of crystals, Earth Planet. Sci. Lett. 267, 571–583.

Chang, C., Powell, R.L. (1994). Effect of particle size distributions on the rheology of concentrated bimodal suspensions. J. Rheol. 38, 85–98.

Chevrel, M.O., Platz, T., Hauber, E., Baratoux, D., Lavallée, Y., Dingwell, D.B. (2013a). Lava flow rheology: a comparison of morphological and petrological methods. Earth Planet. Sci. Lett. 384, 109–120.

Chevrel, M.O., Giordano, D., Potuzak, M., Courtial, P., Dingwell, D.B. (2013b). Physical properties of CaAl2Si2O8–CaMgSi2O6–FeO–Fe2O3melts: analogues for extra–terrestrial basalt. Chem. Geol.346, 93–105.

Chevrel, M.O., Cimarelli, C., deBiasi, L., Hanson, J.B., Lavallée, Y., Arzilli, F., Dingwell, D.B., (2015). Viscosity measurements of crystallizing andesite from

Tungurahua volcano (Ecuador). Geochem. Geophys. Geosyst. 16, 870–889.

Chevrel, M.O., Harris, A., James, M., Gurioli, L., Patrick, M. (2017). Measuring the viscosity of lava using a field rheometer. MemoVolc Meeting Abstract. 21 – 23 February, 2017, Catania, Italy.

Chevrel, M.O., Harris, A.J.L., James, M.R., Calabrò, L., Gurioli, L., Pinkerton, H. (2018). The viscosity of pāhoehoe lava: In situ syn–eruptive measurements from Kilauea, Hawaii. Earth and Planetary Science Letters, 493, 161–171.

Chong, J.S., Christiansen E.B., Baer, A.D. (1971). Rheology of concentrated suspensions. J. Appl. Polym. Sci.15, 2007–2021.

Cimarelli, C., Costa, A., Mueller, S., Mader, H.M. (2011). Rheology of magmas with bimodal crystal size and shape distributions: Insights from analog experiments. Geochemistry Geophysics Geosystems 12, 1–14.

Coats, R., Cai, B., Kendrick, J., Wallace, P., Hornby, A., Miwa, T., von Aulock, F., Ashworth, J., Godinho, J., Atwood, R. (2017). Understanding the rheology of two and three–phase magmas. In: AGU Fall Meeting Abstracts.

Coish, R., and Taylor, L.A. (1979) The effects of cooling rate on texture and pyroxene chemistry in DSDP Leg 34 basalt: a microprobe study. Earth and planetary science letters, 42(3), 389–398.

Coppola, D., Piscopo, M.L.D., Cigolini, C. (2013). Rheological Control on the Radiant Density of Active Lava Flows and Domes. 239, 39 – 48.

Coppola, D., Laiolo, M., Franchi, A., Massimetti, F., Cigolini, C., Lara, L.E. (2017). Measuring effusion rates of obsidian lava flows by means of satellite thermal data. J. Volcanol. Geoth. Res. 347, 82 – 90.

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

Cordonnier, B., Schmalholz, S. M., Hess, K.–U., Dingwell, D. B. (2012). Viscous heating in silicate melts: An experimental and numerical comparison. J. Geophys. Res. 117, B02203.

Costa, A., Macedonio, G. (2003). Viscous heating in fluids with temperature–dependent viscosity: implications for magma flows. Nonlinear Processes in Geophysics 10, 545–555.

Costa, A. (2005). Viscosity of high crystal content melts: dependence on solid fraction. Geophysical Research Letters 32, 5.

Costa A., Macedonio G. (2005). Computational modeling of lava flows: A review. Geological Society of America Special Papers 396, 209–218.

Costa, A., Macedonio, G. (2005). Numerical simulation of lava flows based on depth–averaged equations. Geophysical Res. Lett. 32, L05304.

Costa, A, Melnik O.,Vedeneeva E. (2007a). Thermal effects during magma ascent in conduits. J. Gepophys. Res. 112, B12205.

Costa, A, Melnik O., R.S.J. Sparks (2007b). Controls of conduit geometry and wallrock elasticity on lava dome eruptions. Earth Planet. Sci. Lett 260, 137 – 151.

Costa, A., Caricchi, L., Bagdassarov, N.S., (2009). A model for the rheology of particle bearing suspensions and partially molten rocks. Geochem. Geophys. Geosyst. 10, 1–13.

Del Gaudio, P., Behrens, H., Deubener, J. (2007). Viscosity and glass transition temperature of hydrous float glass. Journal of Non–Crystalline Solids 353, 223–236.

Del Negro, C., Fortuna, L., Herault, A., Vicari, A. (2008). Simulations of the 2004 lava flow at Etna volcano by the MAGFLOW Cellular Automata model. Bull Volc. 70, 805 – 812.

Del Negro, C., Cappello, A., Neri, M., Bilotta, G., Herault, A., Gnci, G. (2013). Lava flow hazards at Mount Etna: constraints imposed by eruptive history and numerical simulations. Sci. Rep. 13, 3493.

Del Negro, C., Cappello, A., Ganci, G. (2016). Quantifying lava flow hazards in response to effusive eruption. GSA Bull. 128, 752–763.

Di Genova, D., Kolzenburg, S., Wiesmaier, S., Dallanave, E., Neuville, D., Hess, K–U, Dingwell, D.B. (2017). A chemical tipping point governing mobilization and eruption style of rhyolitic magma. Nature 552, 235 – 238.

Dingwell DB (1986). Viscosity–temperature relationships in the system Na2Si2O5–Na4Al2O5. Geochim. Cosmochim. Acta 50,1261–1265.

Dingwell DB (1989). Shear viscosities of ferrosilicate liquids. American Mineralogist (9–10):1038–1044.

Dingwell, D.B., Virgo, D., (1987). The effect of oxidation state on the viscosity of melts in the system Na_2O–FeO–Fe_2O_3–SiO_2. Geochimica et Cosmochimica Acta 51, 195–205.

Dingwell, D.B., Virgo, D., (1988). Viscosities of melts in the Na_2O–FeO–Fe_2O_3–SiO_2 system and factors controlling relative viscosities of fully polymerized

silicate melts. Geochim. Cosmochim. Acta 52, 395–403.

Dingwell, D.B., Bagdassarov, N.S., Bussod, G.Y, Webb, S.L. (1993). Magma Rheology. Am. Min. Ass. Can., Short Course Handbook 21, 131 – 196.

Dingwell, D.B. (1996). Volcanic dilemma: flow or blow? Science, 273, 1054–1055.

Dobson K, Pistone M, Fife J, Cordonnier B, Blundy J, Dingwell D, Lee P (2015). Quantifying dynamic rheology, phase interactions and strain localisation in deforming three phase magmas using high–speed x–ray tomography. In: EGU General As–sembly Conference Abstracts.

Dobson K, Wadsworth F, Di Genova D, Kolzenburg S, Vasseur J, Marone F, Dingwell D (2016). Magmas on the Move: in situ 4D Experimental Investiga–tion into the Rheology and Mobility of Three–Phase Magmas Using Ultra Fast X–ray Tomogra–phy. In: AGU Fall Meeting Abstracts.

Dorfman, A., Hess, K.–U., Dingwell, D. B. (1996). Cen–trifuge–assisted falling–sphere viscometry. Eur. J. Mineral. 8, 507–514.

Dorfman, A., Dingwell, D. B., Bagdassarov, N. S. (1997). A rotating autoclave for centrifuge studies: falling sphere viscometry. Eur. J. Mineral. 9, 345–350.

Dragoni, M. (1993). Modelling the rheology and cool–ing of lava flows, in Active Lavas: Monitoring and Modelling, edited by C. R. J. Kilburn and G. Luongo, pp. 235– 261, Univ. Coll. of London Press, London.

Dragoni, M., Borsari, I., Tallarico, A. (2005). A model for the shape of lava flow fronts. J. Geophys. Res., 110, B09203, doi:10.1029/2004JB003523.

Einstein, A. (1906). A new determination of molecular dimensions. Ann. Phys. 19, 289 – 306.

Einarsson T (1966) Studies of temperature, viscosity, density and some types of materials produced in the Surtsey eruption. Surtsey Res Progr Rep 1, 163–179.

Farquharson, J., James, M., Tuffen, H. (2015). Examin–ing rhyolite lava flow dynamics through photo–based 3D reconstructions of the 2011–2012 lava flowfield at Cordón–Caulle, Chile. J. Volcanol. Geotherm. Res. 304, 336–348.

Faxèn, H. (1922). The resistance against the movement of a rigour sphere in viscous fluids, which is em–bedded between two parallel layered barriers. An–nalen Der Physik 68, 89–119.

Filippucci, M., Tallarico, A., Dragoni, M. (2013). Role of heat advection in a channeled lava flow with power law, temperature–dependent rheology. J. Geophys. Res. 118, 2764 – 2776.

Filippucci, M., Tallarico, A., Dragoni, M. (2019). Far–field boundary conditions in channeled lava flow with viscous dissipation. An. Geophys. 61, ag–7782, this issue.

Fink, J. H., J. R. Zimbelman (1986). Rheology of the 1983 Royal Gardens basalt flows, Kilauea vol–cano, Hawaii. Bulletin of Volcanology 48, 87–96.

Flynn, L.P., and Mouginis–Mark, P.J. (1992). Cooling rate of an active Hawaiian lava flow from nighttime spectroradiometer measurements. Geophysical Re–search Letters, 19(17), 1783–1786.

Frankel, N.A., Acrivos A. (1970). A versatile parallel–plate viscometr for glass viscosity measurement to 1000°C. J. Fluid Mech. 44, 65 – 78.

Fulcher G.S. (1925). Analysis of recent measurements of the viscosity of glasses, J. Am. Ceramic Soc. 8(6), 339–355.

Gamble, R.P., and Taylor, L.A. (1980). Crystal/liquid partitioning in augite: effects of cooling rate. Earth Planet. Sci. Lett. 47, 21–33.

Gay, E.C., Nelson, P.A., Armstrong, W.P. (1969). Flow properties of suspensions with high solids con–centration. Aiche Journal 15, 815–822.

Gauthier, F. 1973. “Field and Laboratory Studies of the Rheology of Mount Etna Lava. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 274, 83–98.

Gent, A.N. (1960). Theory of parallel plate viscometer. Brit. J. Appl. Phys. 11, 85 – 88.

Giordano, D. and Dingwell, D. B. (2003a). Non–Arrhe–nian multicomponent melt viscosity: a model. Earth Planet. Sci. Lett. 208, 337–349.

Giordano, D., Dingwell, D.B. (2003b). The kinetic fragility of natural silicate melts. J. Phys.: Condens. Matter 15, S945–S954.

Giordano, D., Nichols, A.R.L., Dingwell, D.B. (2005) Glass transition temperatures of natural hydrous melts: a relationship with shear viscosity and im–plications for the welding process. J. Volcanol. Geoth. Res. 142, 105–118.

Giordano, D., Polacci, M., Longo, A., Papale, P., Ding–well, D., Boschi, E., Kasereka, M. (2007). Thermo–rheological magma control on the impact of highly fluid lava flows at Mt. Nyiragongo. Geophys. Res. Lett. 34. L06301.

Giordano, D., Mangicapra, A., Potuzak, M., Russell, J.K., Romano, C., Dingwell, D.B., Di Muro, A. (2006). An expanded non–Arrhenian model for silicate melt viscosity: A treatment for metaluminous, peraluminous and peralkaline melts. Chem. Geol. 229, 42–56.

Giordano, D., Russell, J.K., (2007). A rheological model for glassforming silicate melts in the systems CAS, MAS, MCAS. J. Phys. Condens. Matter 19, 205148.

Giordano, D., Russell, J.K., Dingwell, D.B. (2008a). Viscosity of magmatic liquids: a model. Earth Planet. Sci. Lett.271, 123–134.

Giordano, Potuzak M, Romano C, Dingwell DB, Nowak M (2008b). Viscosity and glass transition temperature of hydrous melts in the system $CaAl_2Si_2O_{28}$–$CaMgSi_2O_6$. Chemical Geology 256, 203–215.

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. Geochim. Cosmochim. Acta 73, 6613– 6630.

Giordano D., La Felice S., Arzilli F., De Cristofaro S.P., Masotta M., Polo L. (2017). Il vulcanismo effusivo acido del Monte Amiata: stima delle condizioni pre–eruttive ed implicazioni vulcanologiche. Effusive acidic volcanism of Monte Amiata: estimates of pre– and syn–eruptive conditions and volcanological implications. Capitolo monografia Amiata. ISBN 978–88–99742–32–4.

Giordano, D., Russell, J.K. (2018). Toward a Structural Model for the Viscosity of Geological Melts. Earth Planet. Sci. Lett. 501, 202–212.

Giordano, D., González–García, D., Russell, J.K, Raneri, S., Bersani, D., Fornasini, L., Di Genova, D., Ferrando, S., Kaliwoda, M, Lottici, P.P., Smit ., and Dingwell, D.B. (2019). A calibrated database of Raman spectra for natural silicate glasses: implications for modelling melt physical properties. J Raman Spectrosc. 2019;1–17. https://doi.org/10.1002/jrs.5675

Glasstone, S., Laidler, K.J., Eyring, H. (1941). The Theory of Rate Processes. McGraw–Hill, New–York.

Hammer, J.E. (2006). Influence of fO_2 and cooling rate on the kinetics and energetics of Fe–rich basalt crystallization. Earth and Planetary Science Letters, 248(3), 618–637.

Harris, A.J., Allen, J.S. III (2008). One–, two– and three–phase viscosity treatments for basaltic lava flows. J Geophys Res. 1;113. B09212.

Herschel, W.H., Bulkle, R. (1926). Konsistenzmessungen von Gummi–Benzollösungen. Kolloid Z. 39:291–300.

Hess, K.–U., and Dingwell, D.B. (1996). Viscosities of hydrous leucogranitic melts: A non–Arrhenian model. Am. Min. 81, 1297–1300.

Hess, K.–U., Cordonnier, B., Lavallée, Y., and Dingwell, D.B. (2008) Viscous heating in rhyolite: An in situ experimental determination. Earth Planet. Sci. Lett. 275, 121–126.

Hiesinger, H., Head III, J.W., Neukum, G. (2007). Young lava flows on the eastern flank of Ascreus Mons: Rheological properties derived from High Resolution Stereo Capera (HRSC) images and Mars Orbiter Laser Altimeter (MOLA) data. J. Geophy. Res. 112, E05011, doi:10.1029/2006JE002717.

Hinch, E. J. & Acrivos, A. 1980 Long slender drops in a simple shear flow. J. Fluid Mech. 98, 305.

Hon, K, J Kauahikaua, R Denlinger, and K Mackay. 1994. "Emplacement and Inflation of Pahoehoe Sheet Flows: Observations and Measurements of Active Lava Flows on Kilauea Volcano, Hawaii." Geol. Soc. Am. Bull. 106: 351–70.

Hui, H.J., Zhang, Y. (2007). Toward a general viscosity equation for natural anhydrous and hydrous silicate melts. Geochim. Cosmochim. Acta 71, 403–416.

Hui, H., Zhang, Y., Xu, Z., Del Gaudio, P., Behrens, H. (2009). Pressure dependence of viscosity of rhyolitic melts. Geochim. Cosmochim. Acta 73, 3680 – 3693.

Hulme, G. (1974). The interpretation of lava flow morphology, Geophys. J. R. Astron. Soc., 39, 361– 383.

Hsueh. C.H., Becher, P.F. (2005). Effective Viscosity of Suspensions of Spheres. J. Am. Ceram. Soc. 88, 1046 – 1049.

Ishibashi, H. and Sato, H. (2007). Viscosity measurements of subliquidus magmas: Alkali olivine basalt from the Higashi–Matsuura district, Southwest Japan. J. Volcanol. Geoth. Res. 160, 223 – 238

Ishibashi, H. (2009). "Non–Newtonian Behavior of Plagioclase– Bearing Basaltic Magma: Subliquidus Viscosity Measurement of the 1707 Basalt of Fuji Volcano, Japan." J. Volcanol. Geoth. Res. 181: 78–88.

James, M. R., Pinkerton, H., Robson., R. (2007). Image–Based Measurement of Flux Variation in Distal Regions of Active Lava Flows." Geochemistry, Geophysics, Geosystems 8 (3). doi:10.1029/2006GC001448.

Jeffrey, H. (1925). The flow of water in an inclined channel of rectangular section. Philos. Mag. J. Sci. 49, 793 – 807.

Jeffrey, D.J., Acrivos, A. (1976). The rheological properties of suspensions of rigid particles. – AIChE Journal, 1976 – Wiley Online Library

Kanzaki, M., Kurita, K., Fujii, T., Kato, T., Shimomura, O., Akimoto, S. (1987). A new technique to measure the viscosity and density of silicate melts at high pressure. In: Manghnani, M. H. a. S., S. (Ed.), High–Pressure research in Mineral Physics, Washington.

Kahle, A., Winkler, B., Hennion, B. (2003). Is Faxe↔n's correction function applicable to viscosity measurements of silicate melts with the falling sphere method?. J. Non–Newtonian Fluid Mech. 112 203–215.

Kilburn, C.R.J. (2015). Chapter 55 – Lava Flow Hazards and Modeling A2 – Sigurdsson, Haraldur. In: The Encyclopedia of Volcanoes (Second Edition). Academic Press, Amsterdam, pp 957–969.

Klein, J., Mueller, S.P., Castro, J.M. (2017). The influence of crystal size distribution on the rheology of magmas: new insights from analogues experiments. Geochem. Geophys. Geosyst, 18.

Klein, J., Mueller, S.P., Helo, C., Schweitzer, S., Gurioli, L., Castro, J.M. (2018). An expanded model and application of the combined effect of crystal–size distribution and crystal shape on the relative viscosity of magmas. J. Volcanol. Geoth. Res. 357, 127 – 133.

Kohlstedt, D.L., & Zimmerman, M. E. (1996). Rheology of partially molten mantle rocks. Annual Review of Earth and Planetary Sciences, 24, 41–62.

Kolzenburg, S., Favalli, M., Fornaciai, A., Isola, I., Harris, A.J.L., Nannipieri, L., Giordano, D. (2016a). Rapid Updating and Improvement of Airborne LIDAR DEMs Through Ground–Based SfM 3–D Modeling of Volcanic Features. IEEE Transactions on Geoscience and Remote Sensing 99, 1–13.

Kolzenburg, S., Giordano, D., Cimarelli, C., Dingwell, D.B. (2016b) In Situ thermal characterization of cooling/crystallizing lavas during rheology measurements and implications for lava flow emplacement. Geochim. Cosmochim. Acta 195, 244–258.

Kolzenburg, S., Giordano, D., Thordarson, T., Höskuldsson, A., Dingwell, D.B. (2017). The rheological evolution of the 2014/2015 eruption at Holuhraun, central Iceland. Bull. Volcanol. 79, 45.

Kolzenburg, S., Jaenicke, J., Münzer, U., Dingwell, D.B. (2018a). The effect of inflation on the morphology–derived rheological parameters of lava flows and its implications for interpreting remote sensing data – A case study on the 2014/2015 eruption at Holuhraun, Iceland. J. Volc. Geoth. Res. 357, 200–212.

Kolzenburg S., Di Genova D., Giordano D., Hess K.U., Dingwell D.B. (2018b). The effect of oxygen fugacity on the rheological evolution of crystallizing basaltic melts. Earth Planet. Sci. Lett. 487, 21 – 32.

Kolzenburg, S.; Giordano, D., Di Muro, A., Dingwell, D.B. (2019). Equilibrium Viscosity and Disequilibrium Rheology of a high Magnesium Basalt from the 2007 eruption of Piton De La Fournaise volcano, La Reunion, Indian Ocean, France. AG, this issue.

Kolzenburg, S.; Giordano, D., Hess, K.U., Dingwell, D.B. (2018d). Shear Rate–Dependent Disequilibrium Rheology and Dynamics of Basalt Solidification. 10.1029/2018GL077799

Kouchi, A., Tsuchiyama, A., Sunagawa, I. (1986). Effect of stirring on crystalization kinetics of basalt: Texture and element partitioning. Contrib. Mineral. Petrol. 93, 429 – 438.

Krieger, I. and Dougherty, T. (1959). A mechanism for non–Newtonian flow in suspension of rigid sphere. Trans. Soc. Rheol., 3, 137 – 152.

Kushiro, I. (1976). Changes in Viscosity and Structure of Melt of NaAlSi2O8 Composition at High Pressures. Journal of Geophysical Research 81, 6347–6350.

Kushiro, I., Yoder, J., H.S., Mysen, B. O. (1976). Viscosities of Basalt and Andesite Melts at High Pressures. Journal of Geophysical Research 81, 6351–6356.

Kushiro, I. (1977). Phase Transformation in silicate melts under upper–mantle conditions. In: Akimoto, M. H. M. a. S. (Ed.), High Pressure Research Applications in Geophysics.

Kushiro, I. (1978). Viscosity and structural changes af Albite (NaAlSi3O8) melt at high pressures. Earth Planet. Sci. Lett. 41, 87–90.

Lara L.E. (2009). The 2008 eruption of the Chaitén volcano, Chile—a preliminary report. Andean Geol., 36, 125–129.

La Spina, G., Burton, M., Vitturi, M.D.M. (2015). Temperature evolution during magma ascent in basaltic effusive eruptions: a numerical application to Stromboli volcano. Earth Planet. Sci. Lett.426, 89–100.

La Spina, G., Burton, M., Vitturi, M.D.M., Arzilli, F. (2016).

Role of syn–eruptive plagioclase disequilibrium crystallization in basaltic magma ascent dynamics. Nature Communications 7, 13402.

Lavallée, Y., Hess, K.–U., Cordonnier, B., Dingwell, D.B. (2007). Non–Newtonian rheological law for highly crystalline dome lavas. Geology 35, 843.

Lavalleé, Y., Meredith, P.G., Dingwell, D.B., Hess, K. U., Wassermann, J., Cordonnier, B., Gerik, A. and Kruhl, J.H. (2008). Seismogenic lavas and explosive eruption forecasting. Nature 453, 507–510.

Lejeune, A.M., and P. Richet (1995). Rheology of crystal–bearing silicate melts: An experimental study at high viscosities, J. Geophys. Res., 100, 4215–4229.

Lejeune, A.M., Bottinga, Y., Trull, T.W., Richet, P. (1999). Rheology of bubble–bearing magmas, Earth Planet. Sci. Lett. 166, 71–84.

LeLosq, C., Neuville, D. (2017). Molecular structure, configurational entropy and viscosity of silicate melts: Link through the Adam and Gibbs theory of viscous flow. J. Non–Cryst. Solids 463, 175–188.

Liebske, C., Behrens, H., Holtz, F. Lange, R. (2003). The influence of pressure and composition on the viscosity of andesitic melts. Geochim. Cosmochim. Acta 67, 473 – 485.

Liebske, C, Schmickler, B., Terasaki, H., Poe, B., Suzuki, A., Funakoshi, K.I, Ando, R., Rubie, D.C. (2005). Viscosity of peridotite liquid up to 13 GPa: Implications for magma ocean viscosities. Earth Planet. Sci. Lett. 240, 589 – 604.

Llewellin, E.W., Mader, H.M., Wilson, S.D.R., (2002a). The rheology of a bubbly liquid. Proc. R. Soc. London, Ser. A 458, 987–1016.

Llewellin, E.W., Mader, H.M., Wilson, S.D.R. (2002b). The constitutive equation and flow dynamics of bubbly magmas. Geophys. Res. Lett. 29:23.1–23.4, (doi:10.1029/2002GL015697).

Llewellin, E.W., Manga, M., 2005. Bubble suspension rheology and implications for conduit flow. J. Volcanol. Geotherm. Res. 143, 205–217.

Lofgren, G. (1980.) Experimental studies on the dynamic crystallization of silicate melts. Physics of magmatic processes, 487.

Long, P.E., and Wood, B.J. (1986). Structures, textures, and cooling histories of Columbia River basalt flows. Geological Society of America Bulletin, 97, 1144–1155.

Mader, H.M., Llewellin, E.W., Mueller, S.P. (2013). The rheology of two–phase magmas: A review and analysis. J. Volcanol. Geoth. Res. 257, 135–15

Manga, M., J. Castro, K. Cashman, and M. Loewenberg (1998). Rheology of bubble–bearing magmas, J. Volcanol. Geoth. Res., 87, 15–28.

Magnall N, James MR, Tuffen H, Vye–Brown C (2016) Similarities in basalt and rhyolite lava flow emplacement processes. Geophys Res Abstr 18:9199

Magnall N, James MR, Tuffen H, Vye–Brown C (2017) Emplacing a cooling limited rhyolite flow. Volcanic and Magmatic Studies Group Annual Meeting, Liverpool, Abstr, p 141.

Maron, S.H. and Pierce, P.E. (1956). Application of ree–eyring generalized flow theory to suspensions of spherical particles. J. Colloid Sci. 11, 80–95.

Marsh B.D. (1981). On the crystallinity, probability of occurrence, and rheology of lava and magma. Contrib. Mineral. Petrol. 78, 85–98.

Mauro, J.C. , Yue, Y. , Ellison,, A.J. , Gupta P.K. , Allan D.C. (2009). Proc. Natl. Acad. Sci. USA., 106, 19780

McBirney, A.R., Murase, T. (1984). Rheological properties of magmas. Ann. Rev. Sci. 12, 337 – 357.;

Melnik, O., and Sparks, R.S.J. (1999). Nonlinear dynamics of lava dome extrusion. Nature 402, 37 – 41.

Melnik, O. and Sparks, R.S.J. (2005). Controls of conduit magma flow dynamics during lava dome building eruptions. J. Geophys. Res. 110, B02209.

Melnik, O., Sparks, R.S.J., Costa, A., Barmin, A.A. (2009). Volcanic Eruptions: Cyclicity during Lava Dome Growth. Encyclopedia of Complexity and Systems Science 9763 –9784.

Minakami, T., Ishikawa, T., Yagi, K. (1951). The 1944 eruption of Volcano Usu in Hokkaido, Japan. Bull. Volcanol. 11, 45 – 157.

Moitra, P. and Gonnermann, H.M. (2015). Effects of crystal shape– and size–modality on magma rheology. Geochemistry, Geophysics, Geosystems, 16, 1–26.

Moore, H., Arthur, D., Schaber, G. (1978). Yield Strengths of Flows on the Earth, Mars, and Moon, Lunar and Planetary Science Conference Proceedings. pp. 3351–3378.

Morgavi, D., Petrelli, M., Vetere, F., González–García, D., Perugini, D. (2015). High–temperature apparatus for chaotic mixing of natural silicate melts. Review of Scientific Instruments 86(10):105108.

Mueller, S., Llewellin, E.W., Mader, H.M. (2011). The rheology of suspensions of solid particles. Proc. R. Soc. London, Ser. A 466, 1201–1228.

Naboko, S.I. (1947). Bilyukai Eruption in 1938. Tr Lab Vulkanol 5:122– 134.

Németh, K. (2010). Monogenetic volcanic fields: origin, sedimentary record, and relationship with polygenetic volcanism. Geological Society of America Special Papers, 470, 43–66.

Nicolas, A. and Ildefonse, B. (1996). Flow mechanism and viscosity in basaltic magma chambers. Geophys. Res. Lett. 23, 2013–2016.

Nichols, R L. (1939). Viscosity of Lava. The Journal of Geology 47, 290–302.

Ohtani, E., Suzuki, A., Ando, R., Urakawa, S., Funakoshi, K., Katayama, Y. (2005). Viscosity and density measurements of melts and glasses at high pressure and temperature by using the multi–anvil apparatus and synchrotron X–ray radiation. In: Advances in High–Pressure Technology for Geophysical Applications. Elsevier, pp 195–209.

Pal, R. (2003). Rheological behavior of bubble–bearing magmas. Earth Planet. Sci. Lett. 207, 165–179. doi: 10.1016/S0012–821X(02)01104–4.

Pallister, J.S., Diefenbach, A.K., Burton, W.C., Muñoz, J., Griswold, J.P., Lara, L.E., Lowenstern, J.B., Valenzuela, C.E. (2013). The Chaitén rhyolite lava dome: eruption sequence, lava dome volumes, rapid effusion rates and source of the rhyolite magma. Andean Geol 40(2):277–294.

Panov VK, Slezin YB, Storcheus AV (1988) Mechanical properties of lava extruded in the 1983 Predskazanny eruption (Klyuchevskoi volcano). J Volcanol Seismol 7:25–37.

Papale, P., (1999). Strain–induced magma fragmentation in explosive eruptions. Nature (London) 397, 425–428.

Paterson, M.S., (1970). Experimental Rock Deformation—The Brittle Field, 13. Springer–Verlag, Berlin–Heidelberg–New York.

Paterson, M.S. (1978). Experimental Rock Deformation—The Brittle Field, 13. Springer–Verlag, Berlin–Heidelberg–New York.

Paterson, M.S., Olgaard, D.L. (2000). Rock deformation tests to large shear strains in torsion. Journal of Structural Geology 22, 1341–1358.

Pedersen, G.B.M., et al. (2017). Lava field evolution and emplacement dynamics of the 2014–2015 basaltic fissure eruption at Holuhraun, Iceland. J. Volcanol. Geotherm. Res 340, 155–169.

Persikov, E.S., Zharikov, V.A., Bukhitiyarov, P.G., Polskoy, S.F. (1990). The effect of volatiles on the properties of mgmatic melts. Eur. J. Mineral. 2, 621 – 642.

Petford, N. (2009) Which effective viscosity? Mineral. Magazine 73, 167 – 171

Phan–Thien, N., and Pham, D.C. (19979. Differential multiphase models for polydispersed suspensions and particulate solids. Journal of Non–Newtonian Fluid Mechanics, 72, 305–318.

Piermarini GJ, Forman RA, Block S. (1978). Viscosity measurements in the diamond anvil pressure cell. Rev. Sci. Instrum. 49, 1061

Pinkerton, H, and R S J Sparks. (1978). "Field Measurements of the Rheology of Lava." Nature 276: 383–85.

Pinkerton, H, and R J Stevenson. (1992). "Methods of Determining the Rheological Properties of Magmas at Sub–Liquidus Temperatures." Journal of Volcanology and Geothermal Research 53: 47–66.

Pinkerton, H, Wilson, L. (1994). Factors controlling the lengths of channel–fed lava flows. Bull.Volcanol. 56, 108 – 120.

Pinkerton, H, Norton, GE (1995). 'Rheological properties of basaltic lavas at sub–liquidus temperatures: laboratory and field–measurements on lavas from Mount Etna. J. Volcanol. Geoth. Res. 68, 307–323

Pistone, M., Caricchi, L., Ulmer, P., Burlini, L., Ardia, P., Reusser, E., Marone, F., Arbaret, L. (2012). Deformation experiments of bubble– and crystal–bearing magmas: rheological and microstructural analysis. J. Geophys. Res. 117. http://dx.doi.org/10.1029/2011JB008986.

Pistone, M., Caricchi, L., Ulmer, P., Burlini, L., Reusser, E., and Ardia, P. (2013). Rheology of volatile–bearing crystal mushes: mobilization vs. viscous death. Chem. Geol., 345, 16–39.

Pistone M, Arzilli F, Dobson KJ, Cordonnier B, Reusser E, Ulmer P, Marone F, Whittington AG, Mancini L, Fife JL (2015). Gas–driven filter pressing in magmas: Insights into in–situ melt segregation from crystal mushes. Geology 43(8):699–702.

Pistone, M., Cordonnier, B., Ulmer, P., Caricchi, L. (2016). Rheological flow laws for multiphase magmas: an empirical approach. J. Volcanol. Geotherm. Res. 321, 158–170.

Pleše P, Higgins M, Mancini L, Lanzafame G, Brun F, Fife J, Casselman J, Baker D (2018). Dynamic observations of vesiculation reveal the role of silicate crystals in bubble nucleation and growth in andesitic magmas. Lithos 296:532–546.

Pocklington, H.C. (1940). Rough measurement of high viscosities. Proceedings of the Cambridge Philosophical Society 36, 507–508.

Polacci M., Papale P., Del Seppia D., Giordano D. and Romano C. (2004) Dynamics of magma ascent and fragmentation in trachytic versus rhyolitic eruptions. J. Volcanol. Geoth. Res. 131, 93–108.

Polacci, M, Arzilli, F, La Spina, G, Le Gall, N, Caiet, B, Hartley, M.E., Di Genova, D., Vo, N.T., Nonni, S., Atwood, R.C., Llewellin, E.W., Lee, P.D. and Burton, M.R. (2018). Crystallisation in basaltic magmas revealed via in situ 4D synchrotron X–ray microtomography. Nature.

Polacci M, Mancini L, Baker DR (2010). The contribution of synchrotron X–ray computed microtomography to understanding volcanic processes. Journal of synchrotron radiation 17, 215–221.

Polo L.A., Giordano D., Janasi V., Freitas–Guiaraes L. (2018). Effusive silicic volcanism in in the Paraná Magmatic Province, South Brazil: Physico–chemical conditions of storage and eruption and considerations on the rheological behaviour during emplacement. J. Volcanol. Geoth. Res. 355, 115 – 135.

Polo L.A., Janasi V., Giordano D., E. Canon Tapia, E. Lima, M. Roverato. (2018). Effusive silicic volcanism in the Paraná Magmatic Province, South Brazil: evidence for local fed lava flows and domes from detailed field work. J. Volcanol. Geoth. Res. 355, 204 – 218.

Quane SL, Russell JK (2005) Welding: insights from high–temperature analogue experiments. J Volcanol Geotherm Res 142, 67–87.

Ratteron P, Merkel S (2009). In situ rheological measurements at extreme pressure and temperature using synchrotron X–ray diffraction and radiography. Journal of synchrotron radiation 16, 748–756.

Rhéty M, Harris A, Villeneuve N, Gurioli L, Médard E, Chevrel O, Bachélery P (2017). A comparison of cooling and volume limited flow systems: Examples from channels in the Piton de la Fournaise April 2007 lava flow field. Geochemistry, Geophysics, Geosystems

Richet, P. (1984). Viscosity and configurational entropy of silicate melts. Geochim. Cosmochim. Acta 48, 471–483.

Richet, P., Bottinga, Y. (1995). In Structure, Dynamics and Properties of Silicate Melts, eds. J.F. Stebbins, P.F. McMillan and Dingwell DB, Rev. Mineral. 32, 67–94.

Richet, P., Lejeune, A.–M., Holtz, F., Roux, J. (1996). Water and the viscosity of andesite melts. Chem. Geol. 128, 185–197.

Robert; G., Russell, J.K., Giordano, D. (2008a). Rheology of porous volcanic materials: High–temperature experimentation under controlled water pressure. Chem. Geol., 256, 215–229.

Robert; G., Russell, J.K., Giordano, D., Romano, C. (2008b). High–T deformation of volcanic materials in the presence of water. American Mineralogist 93, 74–80.

Robert B, Harris A, Gurioli L, Médard E, Sehlke A, Whittington A (2014) .Textural and rheological evolution of basalt flowing down a lava channel. Bulletin of Volcanology 76, 1–21.

Roscoe, R. (1952). The viscosity of suspensions of rigid spheres. British Journal of Applied Physics 3, 306.

Russell, J.K., Giordano, D., Dingwell, D.B., Hess, K.U., 2002. Modelling the non–Arrhenian rheology of silicate melts: Numerical considerations. Eur. J. Mineral. 14, 417–427.

Russell, J. K., Giordano, D., Dingwell, D. B. (2003). High–temperature limits on viscosity of non–Arrhenian silicate melts. Am. Min. 88, 1390–1394.

Russell, J.K., Giordano, D. (2005). A model for silicate melt viscosity in the System CaMgSi2O6–CaAl2Si2O8–NaAlSi3O8. Geochim. Cosmochim. Acta 69, 5333–5349.

Russell J.K. and Quane S.L. (2005). Rheology of welding: inversion of field constraints. J. Volcanol. Geoth. Res. 142,173 – 191.

Russell, J.K., Giordano, D. (2017). Modelling configurational entropy of silicate melts. Chemical Geology 461, 140–151.

Ryan M.P. and James. Y. Blevins, (1987). The viscosity of synthetic and natural silicate melts and glasses at high temperatures and 1 bar (105 pascals) pressure and at higher pressures, Bulletin 1764, doi: https://doi.org/10.3133/b1764.

Ryerson, F.J., Weed, H.C., Piwinskii, A.J. (1988). Rheology of subliquidus magmas: 1. Picritic compositions. J. Geophys. Res.: Solid Earth, 93 (B4), 3421–3436.

Ryan, A., Kolzenburg, S., Vona, A., Heap, M., Russell, JJ.K. (2019). A proxy for magmatic foams: FOAMGLAS®, a closed–cell glass insulation. J. non–Cryst. Solids: X, 1.

Rust, A.C., Manga, M. (2002). Bubble Shapes and Orientations in Low Re Simple Shear Flow. J. Coll. Inter. Sci. 249, 476 – 480.

Saar, M. O., M. Manga, K. V. Cashman, and S. Fremouw

(2001). Numerical models of the onset of yield strength in crystal–melt suspensions, Earth Planet. Sci. Lett., 187, 367–379.

Sato, H. (2005), Viscosity measurement of subliquidus magmas: 1707 basalt of Fuji Volcano, J. Mineral. Petrol. Sci., 100, 133–142.

Scarfe, C.M., Mysen, B.O., Virgo, D. (1987). Pressure dependence of the viscosity of silicate melts. In: Magmatic processes: Physicochemical Principles. Geochem. Soc. Spec. Pub. 1, 59 –67.

Scherer, G.W. (1984). Use of the Adam–Gibbs equation in the analysis of structural relaxation, J. Am. Ceram. Soc. 67, 504 – 511.

Schipper CI, Castro JM, Tuffen H, James MR, How P (2013) Shallow vent architecture during hybrid explosive–effusive activity at Cordón Caulle (Chile, 2011–12): evidence from direct observations and pyroclast textures. J Volcanol Geotherm Res 262:25–37.

Schmidt M. W., Connolly J. A. D., Gu¨nther D. and Bogaerts M. (2006) Element partitioning: the role of melt structure and composition. Science 312, 1646–1650.

Sehlke A, Whittington A, Robert B, Harris A, Gurioli L, Médard E (2014) Pahoehoe to `a`a transition of Hawaiian lavas: an experimental study. Bull. Volcanol., 76(11):1–20.

Shaw, H R, T L Wright, D L Peck, and R Okamura. 1968. "The Viscosity of Basaltic Magma: An Analysis of Field Measurements in Makaopuhi Lava Lake, Hawaii." American Journal of Science 266: 225–64.

Shaw, H R. (1969). Rheology of Basalt in the Melting Range. J. Petrol. 10, 510–535.

Shaw H. R. (1972) Viscosities of magmatic silicate liquids: An empirical model of prediction. Am. J. Sci. 272, 438–475.

Soldati A, Sehlke A, Chigna G, Whittington A (2016). Field and experimental constraints on the rheology of arc basaltic lavas: the January 2014 Eruption of Pacaya (Guatemala). Bulletin of Volcanology 78(6):1–19

Soldati, A., Beem J., Gomez F., Huntley J.W., Robertson T., Whittington A. (2017). Emplacement dynamics and timescale of a Holocene flow from the Cima Volcanic Field (CA): Insights from rheology and morphology. J. Volc. Geoth. Res. 347, 91 –111.

Song S–R, Jones KW, Lindquist BW, Dowd BA, Sahagian DL (2001). Synchrotron X–ray computed microtomography: studies on vesiculated basaltic rocks. Bulletin of Volcanology 63(4):252–263.

Sparks, R.S.J. (2004). Dynamics of magma degassing. Volcanic degassing. Geol. Soc. Lond.Spec. Pub. 213, 5–22.

Stein, D.J., Spera, F.J (2002). Shear viscosity of rhyolite–vapor emulsions at magmatic temperatures by concentric cylinder rheometry J. Volcanol. Geoth. Res. 113, 243 – 258.

Suzuki A., Ohtani E., Terasaki H. and Funakoshi K. (2005). Viscosity of silicate melts in CaMgSi2O6–NaAlSi2O6 system at high pressure. Phys. Chem. Minerals 32, 140–145.

Tammann, G. and Hesse, W. (1926). Die Abhängigkeit der Viskosität von der Temperatur bei unterkühlten Flüssigkeiten. Zeitschrift für anorganische und allgemeine Chemie 156, 245–257.

Taniguchi H. (1995). Universal viscosity–equation for silicate melts over wide temperature and pressure ranges. J. Vol. Geoth. Res. 66, 1–8.

Tobolsky, A.V. and Taylor, R.B. (1963). Viscoelastic properties of a simple organic glass. J. Phys. Chemistry 67, 2439–2442.

Torquato, S., (2013). Random Heterogeneous Materials: Microstructure and Macroscopic Properties. Vol. 16. Springer Science & Business Media.

Truby, J.M., Mueller, S.P., Llewellin, E.W., Mader, H.M. (2015). The rheology of three–phase suspensions at low bubble capillary number. Proc. R. Soc. A 471 (2173):20140557. https://doi.org/10.1098/rspa.2014.0557.

Tuffen H, James M.R., Castro J.M. Schipper C.I. (2013). Exceptional mobility of an advancing rhyolitic obsidian flow at Cordo↔n Caulle volcano in Chile. Nature Communication. doi: 10.1038/ncomms3709

Vande–Kirkov YV (1978). Viscosity of the lavas of the Northern Breakthrough (Tolbachik), 1975. Bull Volcanol Stations 55, 13–17.

Vetere F., Behrens H., Holtz F. and Neuville D. R. (2006). Viscosity of andesitic melts–new experimental data and a revised calculation model. Chem. Geol. 228, 233–245.

Vetere F., Behrens H., Holtz F., Vilardo G., Ventura G. (2010). Viscosity of crystal–bearing hydrous andesites and its implication for magma ascent. Journal of Mineralogical and Petrological Sciences 105, 151–163.

Vetere, F., Sato H., Ishibashi H., De Rosa R., Donato P. (2013). Viscosity Changes during Crystallization of a Shoshonitic Magma: New Insights on Lava Flow

Emplacement. J. Mineralogical and Petrological Sciences 108, 144–160.

Vetere, F., Rossi, S., Namur, O., Morgavi, D., Misiti, V., Mancinelli, P., Petrelli, M., Pauselli, C., Perugini, D. (2017). Experimental constraints on the rheology, eruption and emplacement dynamics of analog lavas comparable to Mercury's northern volcanic plains. Journal of Geophysical Research: Planets.

Vogel, D.H. (1921). Temperaturabhängigkeitsgesetz der Viskosität von Flüssigkeiten. Physikalische Zeitschrift 22, 645–646.

Vona, A., Romano, C., Dingwell, D.B., Giordano, D. (2011). The rheology of crystal–bearing basaltic magmas from Stromboli and Etna. Geochim. Cosmochim. Acta 75, 3214–3236.

Vona, A., Romano, C., Giordano, D., Russell, J.K. (2013a). The multiphase rheology of magmas from Monte Nuovo (Campi Flegrei, Italy). Chem. Geol. 346, 213 – 227.

Vona A. and Romano C. (2013). The effects of under–cooling and deformation rates on the crystallization kinetics of Stromboli and Etna basalts. Contrib. Mineral. Petrol. 166, 491–509.

Vona, A., Ryan, A., Russell, J.K., Romano, C. (2016). Models for viscosity and shear localization in bubble–rich magmas. Earth Planet. Sci. Lett. 449, 26 –38.

Vona, A., Di Piazza, A., Nicotra, E., Romano, C., Viccaro, M., Giordano G. (2017). The complex rheology of megacryst–rich magmas: The case of the mugearitic "cicirara" lavas of Mt. Etna volcano. Chem. Geol. 458, 48–67.

Wadsworth, F.B., Vasseur, J., Llewellin, E.W., Dingwell, D.B. (2017). Sintering of polydisperse viscous droplets. Phys. Rev. E 95, 033114–1, 033114–7.

Walker, D., Kirkpatrick, R., Longhi, J., Hays, J. (1976). Crystallization history of lunar picritic basalt sample 12002: phase–equilibria and cooling–rate studies. Geol. Soc. Am. Bull. 87, 646–656

Wieczorek, M.A., Zuber, M.T, Phillips, R.J. (2001). The role of magma buoyancy on the eruption of lunar basalts. Earth Planet. Sci. Lett. 185, 71–83

Whittington, A., Richet, P., Holtz, F. (2000). Water and the viscosity of depolymerized aluminosilicate melts. Geochim. Cosmochim. Acta 64, 3725–3736.

Whittington, A., Richet, P., Linard, Y., Holtz, F., (2001) The viscosity of hydrous phonolites and trachytes. Chem. Geol. 174, 209–223.

Whittington, A., Bouhifd, M.A., Richet, P. (2009). The viscosity of hydrous NaAlSi3O8 and granitic melts: Configurational entropy. Am. Min. 94, 1–16.

Wilson, L., Head J.W (2016). Generation, ascent and eruption of magma on the Moon: New insights into source depths, magma supply, intrusions and effusive/explosive eruptions (Part 1: Theory). Icarus 283, 146–175.

Witter, J.B., Harris A.J. (2007). Field measurements of heat loss from skylights and lava tube systems. J. Geophys. Res.: Solid Earth 112, 1978–2012.

*CORRESPONDING AUTHOR: Daniele GIORDANO,
Università degli Studi di Torino, Dipartimento di Scienze della Terra
Torino, Italy

email: daniele.giordano@unito.it