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Experimental access to volcanic eruptions

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Abstract

Well-chosen experiments provide access to a vast array of magmatic and volcanic processes, from magma transport within the lithosphere through volcanic eruptive phenomena to the fate of erupted materials in the earth system. This selected overview of contributions from our labs collates examples from early work on rheology and fragmentation to some recent experimental excursions into post-fragmentation modification and the thermal and chemical journey of lavas and pyroclasts leading up to their deposition and lithification.

Keywords: Experimental volcanology; Rheology; Fragmentation; Eruption; Cooling history; Relaxation

1. Introduction

Volcanology has the distinction of being one of the very few fields of the solid earth sciences where direct observation of the rock-forming processes, observable on the conveniently short time scales of deposit emplacement, can be used directly to augment our understanding of the deposits themselves. We can often literally watch these rock-forming processes happening in real time. The inspiration that derives from this has made volcanology one of the most vibrant, multidisciplinary and scientifically progressive subjects in the earth sciences.

At the same time, such spectacular observations are, in general, limited to the surface of the earth, such that we experience far more detail of the emplacement of volcanic deposits than we can currently experience of the petrogenetic and eruptive processes below the planetary surface that immediately precede eruption.

This richness of observation afforded by volcanic phenomena has transformed modern volcanology into a thoroughly holistic combination of theory, observation and experiment. It is the experiments that have been added to the mix in the last half century and which have diversified substantially in recent decades and is the contribution of experiments (from our research labs) with which we will concern ourselves below, for they truly provide direct and testable elements of the subsurface processes of volcanic eruptions. For the author these experiments have also been his personal scientific journey for 40 years. This paper is intended as a primer for the reader, to draw them into a deeper analysis of the copious literature cited here.

2. Newtonian Viscosity

Up to the 1990s the petrological community had been admirably served by models for the composition-dependence of melt viscosity that were Arrhenian in nature.

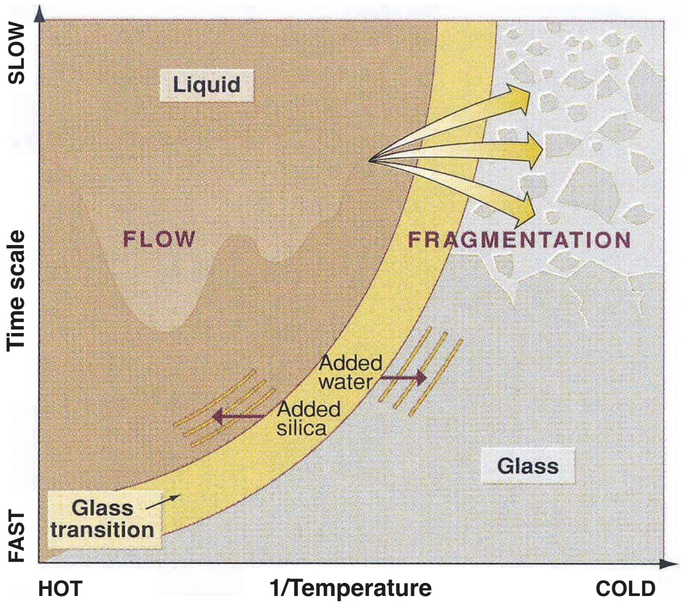


Figure 1. Simplified conceptualisation of the glass transition in molten silicate systems relevant to explosive volcanism on Earth (from Dingwell, 1996).

The inadequacy of this approximation is indeed not severe under the near liquidus conditions which dominated the petrological application of these models. As attention began however to turn to the viscosities associated with the generation of volcanic glasses, in lava flows, ash deposits, and volcanic welding, the need for models capable of predicting viscosities near the glass transition temperature (Fig. 1) became apparent (Dingwell and Webb, 1989; 1990; Dingwell, 1996). It was also becoming generally established that the subliquidus determination of metastable melt viscosities was a fully legitimate pursuit which could generate viscosity data to complement those of the classical superliquidus studies. At about the same time the concept of the general equivalence of glass transition determinations (Fig. 2) (Dingwell and Webb, 1989; Stevenson et al., 1995; Dingwell, 1998; Gottsmann et al., 2002) began to be generally applied in the Earth Sciences. As a result, several new sources of data began to be incorporated into the universal data archive of silicate melt viscosity. These included scanning dilatometric and calorimetric determinations of the glass transition, dilatometric determinations of viscosity, and the like. An example of a fully novel technique applied to the determination of the glass transition of hydrous melts is provided by the application of synthetic fluid inclusions in glass (Fig. 3). These new data sets demanded a non-Arrhenian approach to the parameterization of viscosity-temperature relationships and with that the older Arrhenian approximations were slowly driven into extinction.

The generation of a non-Arrhenian model for the prediction of hydrous melt viscosity in highly silicic melts was a milestone in the development of our modelling capability of highly viscous volcanic systems. The parameterization provided by Hess and Dingwell in 1996 is graphically portrayed in Fig. 4. On the left hand side the dependence of viscosity on the thermodynamically dissolved water content is portrayed as a series of isotherms. Taking the isotherm, for example at 1200 K, the clear and evident rise of viscosity with decreasing water content can be seen to impact viscosity in total, from 8 wt% to 0 wt% water, by five orders of magnitude. This impact is strongly non-linear, such that the effect of the dehydration of the silicic melt by magma degassing, bubble growth or diffusive loss during fragmentation becomes extreme at the lowest water contents. Although such effects could already be inferred qualitatively in earlier studies, the parameterization displayed in Fig. 4a placed modelling of such processes on a wholly new basis of calibration.

In Fig. 4b the parameterization of Hess and Dingwell (1986) is displayed in terms of the $\log_{10}$ of viscosity versus reciprocal temperature for lines of constant water content. It is here that we can clearly see the magnitude of the curvature of these isochemical viscosity-temperature relationships, i.e., the degree of non-Arrhenian nature of the Hess and Dingwell model. The dry haplogranitic/leucogranitic/calcalkaline melt viscosity-temperature relationship is virtually Arrhenian, whereas the addition of even moderate amounts of dissolved water leads to a very noticeable drop in the viscosity and increase in the degree of non-Arrhenian behavior in these viscosity temperature relationships. This plot demonstrates the need for the non-Arrhenian model of viscosity itself. Yet

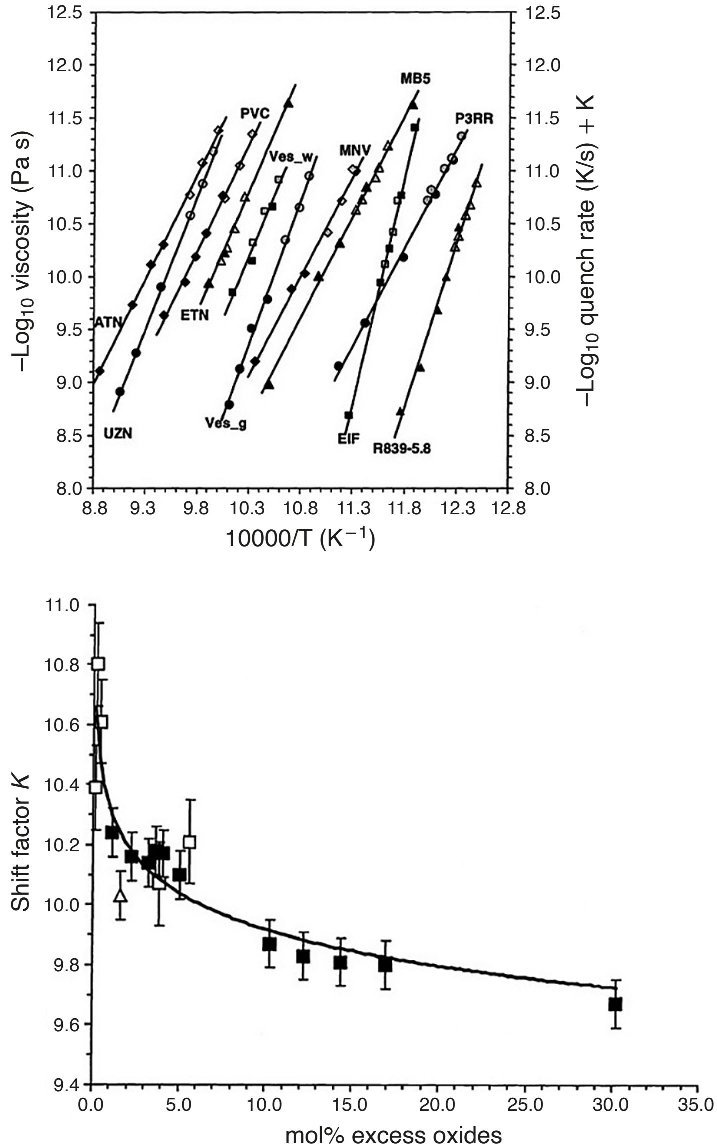


Figure 2. Confirmation of the equivalence of stress and enthalpy relaxation in geological melts and the determination of the “shift factor” for the calorimetric determination of viscosity for a wide range of natural compositions (from Gottsmann et al., 2002).

despite the noticeably non-Arrhenian temperature dependence of viscosity for high water content melts, their slopes at low temperatures and high viscosities do not curve around to generate such steep slopes as is the case for the equivalent addition of individual alkalis to make peralkaline rhyolitic melts. Clearly there is more to the temperature-dependence of water´s role in these melts (Dingwell and Webb, 1990; Stevenson et al., 1998) than we can, as yet, input into the parameterization of melt viscosity.

Although this model is built solely for the single, iconic composition of a haplogranitic melt directly relevant to calc-alkaline rhyolitic eruptions, the effects of water, which play the central role in melt viscosity during explosive and effusive stages of silicic eruptions, it has been widely used in the modelling and interpretation of such systems to date.

The Hess and Dingwell model was merely one step along the path towards a general multicomponent model for the non-Arrhenian temperature dependence of silicate melts both wet and dry. Also clear was the magnitude of the experimental work that would be required to complete such a database for the construction of such a general model, and many of the steps along the way priorised the active volcanoes for which the INGV is responsible (Giordano and Dingwell, 2003a; Romano et al., 2003; Giordano et al. 2009; Misiti et al., 2009; Di Genova et al., 2013). It took several years until, in 2003, the “dry” version and in 2008 the “wet” (including water and fluorine) versions (requiring major experimental campaigns, Dingwell et al., 1996) of such a multicomponent model were generated (Giordano and Dingwell, 2003b; Giordano et al., 2008) Redox dependence of viscosity was mapped along the way (Dingwell and

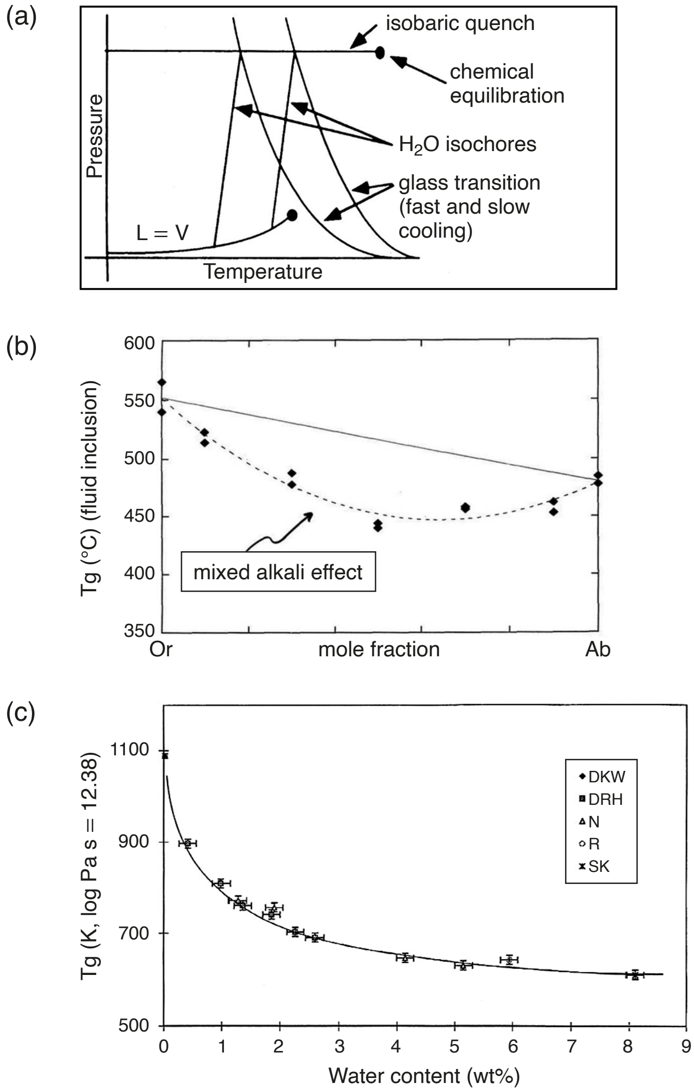


Figure 3. Method (a), results (b) and synthesis (c) of glass transition temperature determinations of hydrous melts at high temperature and pressure using synthetic fluid inclusions in glass and compared with dilatometric, calorimetric and spectroscopic Tg determinations (from Romano et al., 1994; Dingwell, 1998).

Virgo, 1987; Dingwell, 1991; Di Genova et al., 2017; Casas et al., 2023). Beyond the relatively broad compositional boundaries of Giordano´s approach to the empirical modelling of these non-Arrhenian parameterisations continues the work, both experimental and modelling, to obtain a truly universal model for multicomponent melts at all extremes of composition (Dingwell et al., 2004; Casas et al., 2023; Hess et al., 2023; Weidendorfer et al., 2023; Bissbort et al., 2024). Along the path to such models it was well-demonstrated that, for the purpose of modelling volcanic processes in pre-eruptive to eruptive states, the pressure-dependence of such models could be neglected. Stepping into the multicomponent models of such melt viscosities has also required the stewardship of a careful attention to the science of robust modelling and the limits of parameterization (Russell et al., 2001; 2003; 2022) even as we approach the eve of AI techniques in this area (Liu et al., 2025). For a recent in-depth review of models of melt viscosity see Russell et al. (2022).

3. Magmatic Suspensions

The physical influence of crystals and bubbles on lava rheology has also been the subject of decades of experimental investigation. From the simplest of considerations, such as the largely strain rate and cooling rate insensitive, highly reproducible, so-called “rheological cut-off” temperatures exhibited by relatively low viscosity crystallising systems

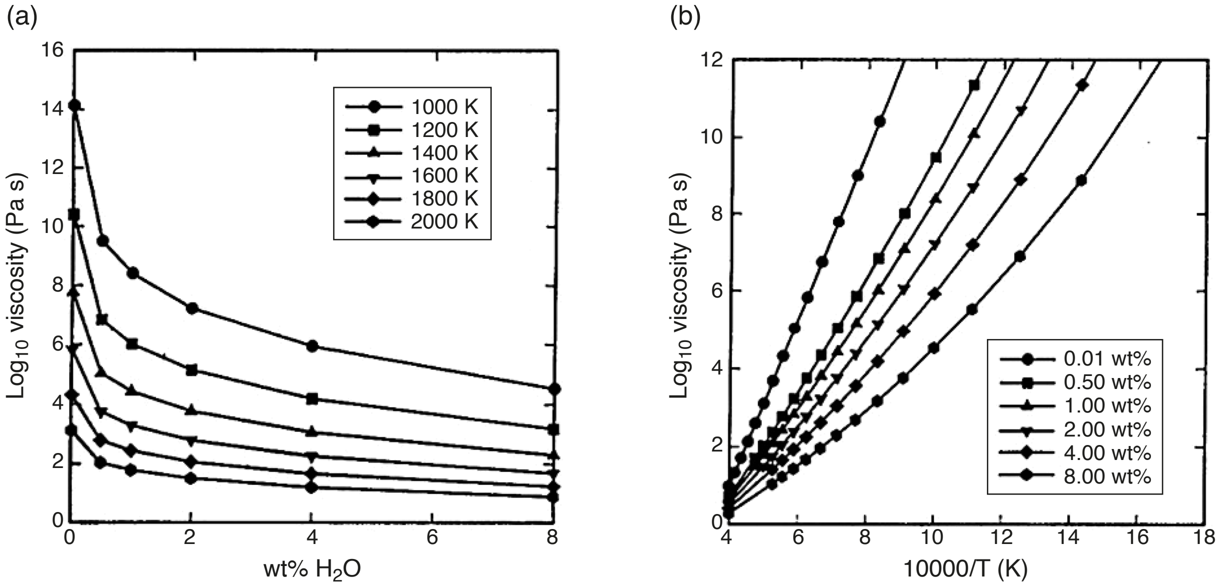


Figure 4. The predictions of the Hess and Dingwell non-Arrhenian model for the viscosity of hydrous leucogranitic melts as originally presented in Hess and Dingwell (1996).

with falling temperature (Giordano et al., 2007), to the enormous potential complexity of the slow crystallization and long coexistence of suspended crystals in liquid silicate, such as suspended in intermediate to silicic systems, this line of experimental investigation has consumed perhaps more time and effort that any other. Yet the work continues.

The fundamentals of the experimental approach began with operation under of one of two essential assumptions. Either the sample can be assumed to be in thermodynamic equilibrium or the sample is so sluggish in its crystallization and strain dynamics that the texture and crystal content can be assumed to remain constant under experimental conditions. In both cases the crystallinity of the sample can be estimated, if not its texture in the former case. Liberation from the constraints of these assumptions has come in two forms. Firstly carefully designed scenarios of successive and repeated experiments wherein the temperature and strain history is fully documented, together with intermediate sampling, has given us a further insight into the potential complexity of lava rheology and its parameterisation (Kolzenburg et al., 2017; 2018; 2020; Soldati et al., 2021). Secondly the onset of full 3D synchrotron-assisted tomographic real-time monitoring of the physical phase state of multiphase systems during deformation experiments is upon us (Dobson et al., 2020). Through the combination of both approaches it may be expected that the most rapid advances in the ultimate parameterization of lava rheology will be finally achieved. As noted below when talking about microlites and nanolites, the physical effects of crystallization must always be measured against the backdrop of the evolving chemistry of the residual liquid whose own chemical dependence of viscosity may outweigh any physical suspension effects.

4. Frequency domain rheology

Due to the complexity of phase growth and rearrangement during rheological experiments with low viscosity hosting liquid phases an alternative has been sought that can obtain “snapshots” of the viscosity coefficients of multiphase samples without crystallization or other phase changes and without significant strain, yet at a wide range of strain rates. The geoscientific application of so-called “torsional” rheology provides such a solution. Samples investigated at a range of torsional oscillation frequencies near 1 Hz under and at temperature conditions near the glass transition have provided a rich data set for the influence of crystals and bubbles on the rheology of magma (Bagdassarov and Dingwell, 1993; Bagdassarov et al., 1994). Such frequency domain experiments are also possible in container-based systems such as high temperature crucibles whereby strain rate and strain can be independently controlled and evaluated. In this manner the strain rate dependence of the deformability of bubbles can also be investigated and the issue of whether vesicularity will increase or decrease suspension viscosity can also be addressed. Estimates of the kinematics of tube pumices, where a bubble size dependence of their deformation is observed, together with estimates of magmatic dissolved water contents and so-derived viscosity-temperature relationships, as well as Xray tomographic statistical analysis of vesicles in tube pumices have yielded a tensorial description of the geometry of extreme deformation in elongational flow (Marti et al., 1999; Dingwell et al., 2016). For a recent in-depth review of suspension rheology see Kolzenburg et al. (2022).

5. Nanolites

Despite the observation of "nanolites" in volcanic glasses in the late 1990s (Sharp et al., 1996) their characteristion and significance was largely neglected for some time. In the past 5 years the impact of the presence of nanolites on the rheology of magmatic melts has been the focus of considerable attention. Caceres et al. (2020 and 2022) have evaluated the effects of microlites and nanolites on degassing and explosivity. Following along from a comparative technique presented for determining the effect of microlites on viscosity (Stevenson et al., 1996), Caceres et al. (2024) have distinguished the viscosity consequences of FeO nanolites separating from an iron-rich rhyolite (Fig. 5a). The basis for the comparison lies in the ability to obtain matrix glass viscosities in a nanolite-bearing sample using scanning calorimetry. By comparison of bulk viscometry of nanolite-bearing samples with the calorimetry-derived melt viscosities the relative effects of the nanolite suspension on viscosity can be separated from that of the shift in melt chemical composition resulting from the subtraction of the iron oxide into the nanolites. Figure 5b illustrates the magnitude of this latter effect resulting in a viscosity jump to be expected during nanolitisation

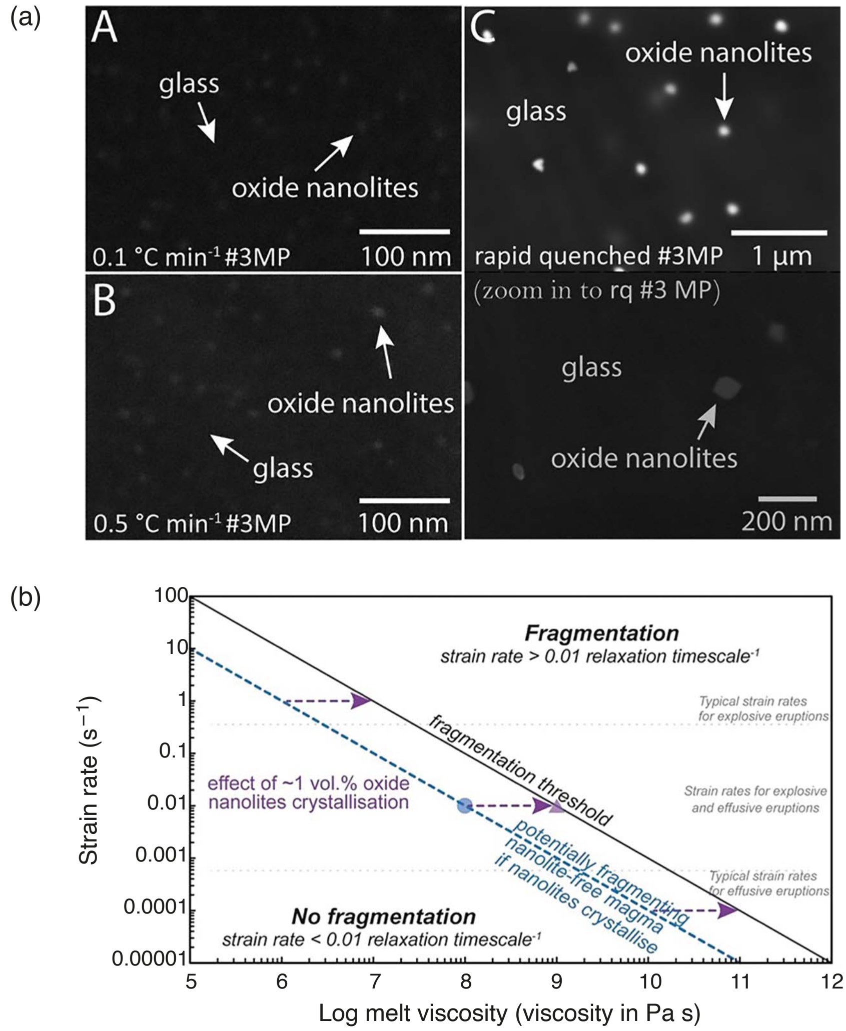


Figure 5. Oxide nanolites in silicic glasses initially containing a few wt% iron oxide (a). Their crystallisation generates a viscosity increase as illustrated in (b), potentially acting as a trigger for magma fragmentation (from Caceres et al., 2024).

of this phase. Further potential effects of the generation of nanolites in magma have been recently explored by Thivet et al., (2023) for the case of liquid-liquid unmixing, by Hornby et al. (2024) for the surface modification ash and for the interparticle forces and Brownian motion by Pereira et al. (2024).

6. Non-Newtonian viscosity and shear thinning

Exploring the limits to the regime of the Newtonian response of silicate melts under increasing shear and volume stresses also became the subject of considerable debate in the earth sciences in the late 1980s. Experiments to systematically drive silicate melt response from the Newtonian to the non-Newtonian were conducted in the early 1990s where fibers hand-drawn from rhyolitic, andesitic, basaltic and nephelinitic melts and fused to dumbbell shapes were subjected to extension in high temperature fiber elongation experiments. The results strikingly demonstrated the limits of the Newtonian approximation and the consequences of overriding those limits in the form of shear thinning and ultimate fiber breakage in the brittle state (Webb and Dingwell, 1990a; 1990b). Normalised to the Newtonian viscosity those experimental results illustrate (Fig. 6) that the physics of relaxation, when corrected to the relaxation time of the chemical composition of the melt of interest, yield a very nearly monotonous character of behavior which can be modelled using very simple equations. This understanding unleashed the mechanistic modelling of the fragmentation of degassing, decompressing magma columns in volcanic conduits.

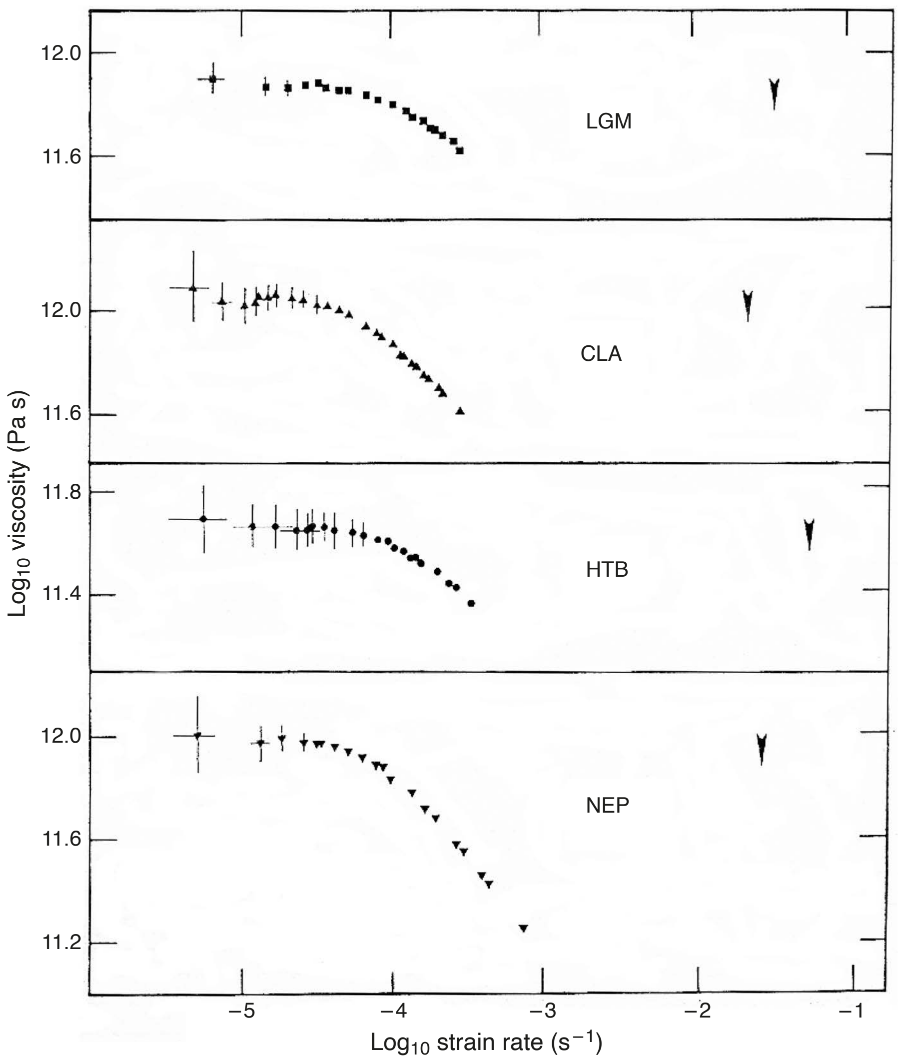


Figure 6. The onset of non-Newtonian rheology (shear thinning) confirmed for calc-alkaline rhyolite, andesite, tholeiitic basalt and nephelinite Experimentally synthesized “dumbbells” of these glasses, drawn as thick fibers from high temperature crucibles, were dilatometrically investigated (from Webb and Dingwell, 1990b).

As just noted, predicting the location in time and temperature of the transition from liquid to glassy behavior of volcanic melts was the first step to opening up the quantitative modelling of such processes. But knowing where and when the brittle fragmentation of volcanic melts should occur was still a long way obtaining the ability to predict the products of volcanic eruptions entirely in physical modelling. It is a goal we are still chasing today. The substantial evidence for post-fragmentational deformation of pyroclastic particles from the minor deformation exhibited by breadcrust bombs (Colombier et al., 2023a) to the wholesale welding a rheomorphic transformation of glassy lava (Lavallée et al., 2015) both in the conduit (Tuffen et al., 2003; Tuffen and Dingwell, 2005), and on the Earth´s surface, together with the additional complexity of transport-driven shape relaxation of particles, and post-fragmentation ash-gas reactions (Ayris et al., 2014; 2015; Casas et al., 2019) and winnowing have added to the challenge. Obtaining the full picture of the journey from pre-eruptive, bubbly volcanic magma to dispersed volcanic products from the Earth´s surface to its stratosphere employs a great deal of research capacity to this day. Nevertheless, the first parametric steps of the fragmentation had to be taken. The first observations of a general nature in the decompression fragmentation of magma were delivered by a new experimental approach involving a so-called fragmentation tank (Alidibirov and Dingwell, 1996a; 1996b). By systematically varying the overpressure in a high temperature autoclave and then subsequently decompressing the pressurized magma, followed by inspection of the experimental products, one could infer the conditions of this decompression required to obtain magma fragmentation and the experimental generation of pyroclasts from lapilli to ash. Initial determinations of the fragmentation threshold to within an order of magnitude (Romano et al., 1994; 1995; 1996; Martel et al., 2000; 2001) in the pursuit of which exquisite synthesis abilities of complex pyroclastic geometries were developed (Fig. 7), were first parameterised systematically by Spieler et al. (2004) using the results of the so-called "fragmentation bomb" of Alidibirov where ejecting freshly fragmented pyroclasts were seen for the first time in high speed photography (Fig. 8). In Fig. 9 a clear broad trend of a new parameter, called the "fragmentation threshold", as a function of sample void space is evident. The effective dynamic tensile strength of vesicular magma became visible for the first time, ranging from 30 MPa for low vesicularity magma to 3 MPa for vesicularities around the

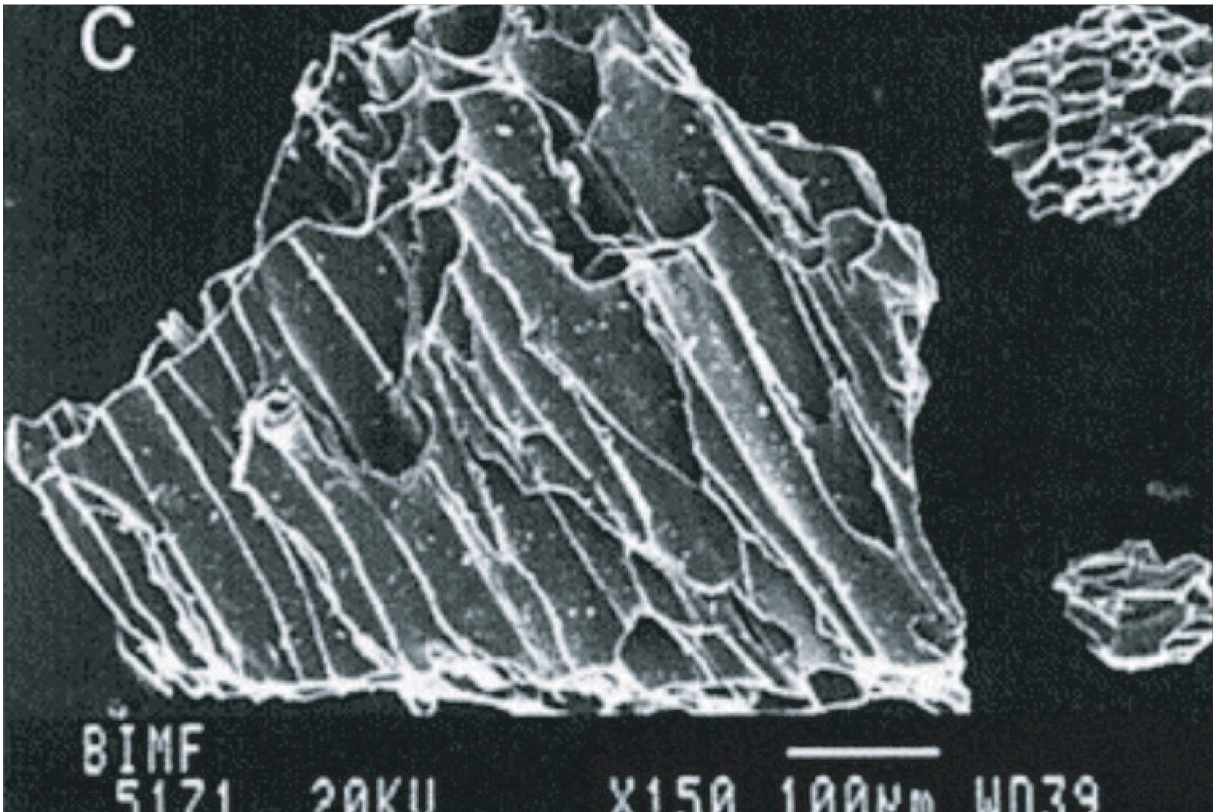


Figure 7. A tube pumice pyroclast composed of calk-alkaline rhyolite synthesized from reagent grade chemicals, fusion, homogenisation, hydration, decompression, foaming and fragmentation (from Martel et al., 2000a).

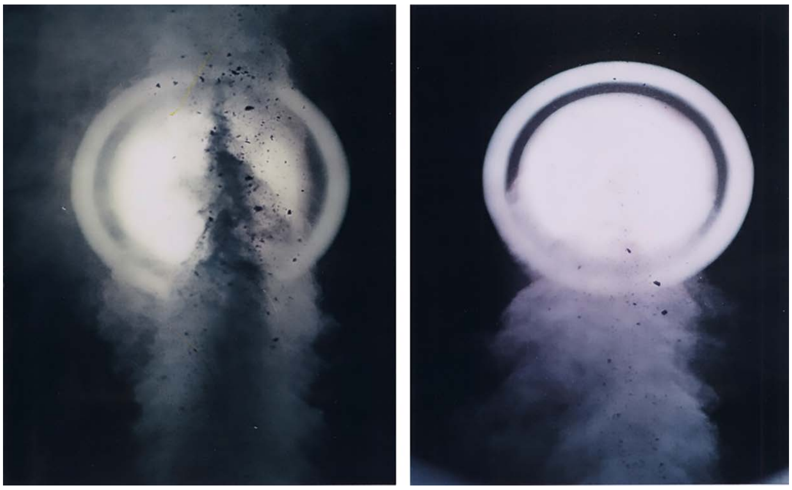


Figure 8. The first high speed photographs of the experimental ejection of pyroclasts produced experimentally by rapid decompression (from Alidibirov and Dingwell, 1996a).

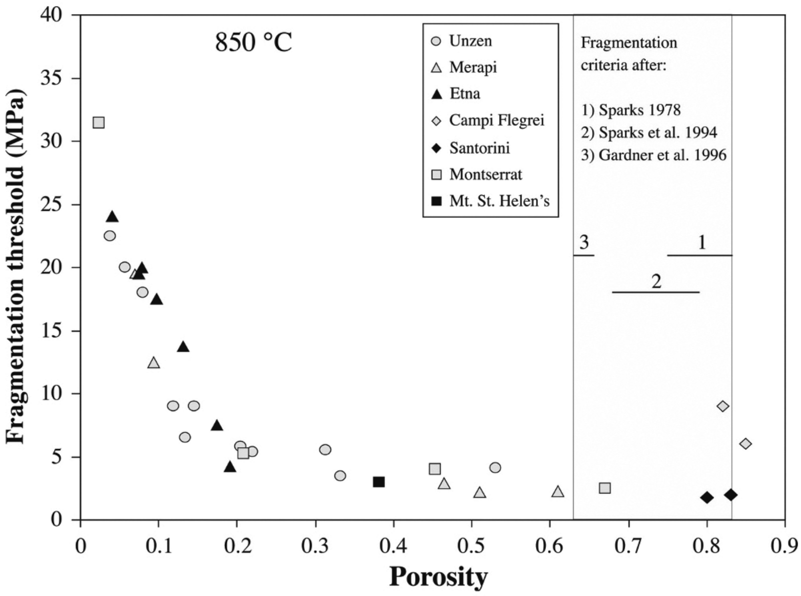


Figure 9. The fragmentation threshold of pyroclastic rocks as originally presented in Spieler et al. (2004).

maximum commonly found in silicic pyroclasts. Several consequences of this parameterization become apparent. Firstly, for a homogeneous decompressive event in a volcanic conduit filled with homogeneously distributed equally vesiculated magma we might anticipate that it is the degassing history which determines where, in terms of stress and decompression rate, the trigger of fragmentation will be placed. Secondly, for the possibly more realistic scenario of a volcanic edifice filled with variably degassed and vesiculated magma undergoing a moderate decompression event we might expect that the low strength of highly vesiculated magmas versus the high strength of poorly vesiculated magma will lead to a bias in the generation of pyroclasts towards a domination by the highly vesiculated sort.

7. Speed, energetics and seismicity of fragmentation

In the early 2000s the investigation of the timing of the fragmentation process, or the speed by which the fragmentation front progresses through the magma because the subject of intensified investigation (Spieler and Dingwell, 2000; Spieler et al., 2004; Richard et al., 2013). Working out the energetics, and the run of the fragmentation through magmas has been the subject of several studies whose applications run from a fundamental understanding of the fragmentation mechanism to the consequences for risk deriving from ballistic products of explosive fragmentation events (Alatorre-Ibargüengoitia et al. 2010; 2011). One clear observation which has remained throughout these investigations is that the speed of fragmentation is low. Experiments using dynamic pressure transducers indicate that the fragmentation typically exhibits speeds of 100 s to 10 s of meters/second, whereas the seismic velocities of these materials are on the order of km/sec. Clearly, we are not simply observing the acoustic pressure release of these samples but rather more likely a materials-specific fragmentation process involving critical crack propagation through multiphase, vesicular materials. The acoustic source characteristics arising from these fragmentation experiments are the subject of ongoing experimental investigation (Lavallée et al., 2008; Arciniega-Ceballos et al., 2015; Alatorre-Ibargüengoitia et al., 2018; 2022; Arciniega et al., 2025 (in prep)).

8. Magma permeability

Initial indications of serious deviations from the simple fragmentation threshold curve of Fig. 9 led to the search for an explanation for the relatively high deviations of fragmentation threshold pressure for some samples from the baseline curve. The answer was sought in the nature of degassing of decompressing samples during fragmentation experiments. This led to a vast campaign of permeability determinations using an unsteady permeability apparatus constructed for the purpose (Mueller et al., 2008). Analysis of the fragmentation energy versus the specific potential energy of the experimental samples demonstrates that there is a permeability threshold beyond which the sample degassing is effectively outrunning the fragmentation front with its slow speed. Thus, the nature of volcanic degassing slips into the center of the consideration of fragmentation in response to rapid decompression, as must surely be the case in nature.

9. Fragmentation efficiency

One major advantage of the fragmentation tank approach has been the opportunity it affords to obtain the products of the fragmentation. Through a sophisticated combination of specific area (pre- and post-fragmentation), and grain size distribution (sieving and laser particle analysis) determinations, one is able to correlate the state of the magma and the energetics of the fragmentation to the generation of new surface in the fragmentation event (Kueppers et al., 2006). By evaluating the energy invested in fragmentation one can begin to develop an energy budget for the fragmentation process, including the energy available for ballistic ejection velocities. For a recent in-depth review of the physics of fragmentation see Scheu and Dingwell (2022).

10. Hydrothermal explosions

Fragmentation and explosions in volcanic structures are not, of course, restricted to magmatic materials. In fact, a vast array of the plethora of structures, lithologies and deposits resting astride magmatic sources may also be subjected to the rapid decompression associated with steam explosions in these structures. These, together with magmatic events lead to the phenomenon of phreatomagmatic and purely phreatic explosions. In one sense these are the most enigmatic of volcanic hazards, occurring as they often do, with little or no precursors, and generating risk even in the absence of magma in motion. A major experimental campaign to understand the energetics of these events was launched and has over the past decade or more generated a series of advances in our understanding of the energy associated with these events. Due to the prodigious complexity of the materials involved, together with the very high hazard potential, this line of research has become a very intensive one also involving extensive field work (Heap et al., 2015; 2017; Mayer et al., 2015; 2016; 2017; Montanaro et al., 2015; 2016a; 2016b; 2016c; 2017; 2021; Rott et al., 2019; Gallagher et al., 2020).

11. Volcanic near-vent lightning

The direct optical observation of electrical discharges during the ballistic expulsion of pyroclasts in the fragmentation bomb (Fig. 10) must surely be classified as the greatest serendipitous discovery of the experimental volcanology research group (Cimarelli et al., 2014; Stern et al., 2019; Springsklee et al., 2022; Springsklee et al., 2023; Wadsworth et al., 2017c). The recognition of experimental "near-vent" lightning discharges has opened up a whole new field of experimental enquiry including the development of electrical discharge monitoring at active volcanoes (Aizawa et al., 2017; Cimarelli et al., 2016; Vossen et al., 2021).

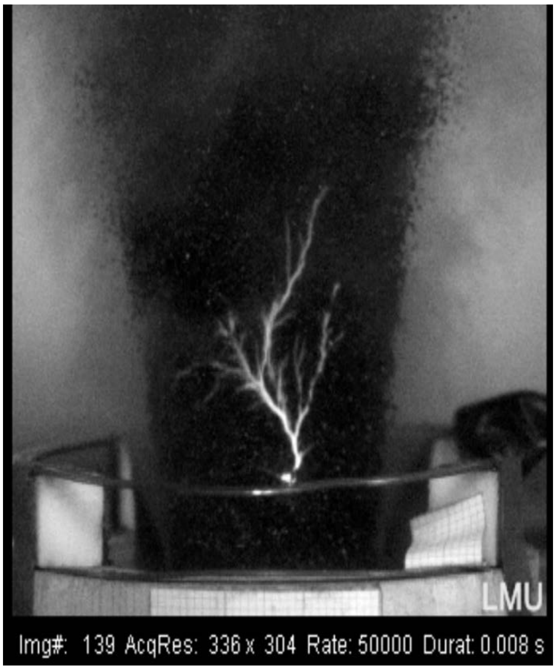


Figure 10. Still frame from a high speed video of spontaneous "near vent" lightning generation during ejection of an experimntally-generated pyroclastic jet.

12. Diffusivities

The chemical diffusivities of mobile, volatile components in ascending, degassing, vesiculating magmatic/volcanic systems control the kinetics of a host of interactions between phases (crystals, liquids, fluids) in igneous petrogenesis and volcanic dynamics In particular, the degassing of ascending and erupting silicic magma by bubble nucleation and growth is a process wherein the diffusivity of water, and CO_2 can play a rate-limiting role. Once formed, the fluid-filled vesicular phase becomes a sink for the solubility of all components to varying degrees defined by their partitioning between the silicate- and volatile-hosted phases of melt and bubbles. Due to their highly mobile nature and to the wide range of partition coefficients as well as diffusivities, the halogens have long been recognized as potential clocks for understanding the degassing dynamics of vesiculating systems. In, principle a budget between erupted halogen concentrations potential of F, Cl, Br and I in the gas and the glassy phases, combined with a quantification of the diffusivities and partition coefficients of these halogens might give insight into the absolute timing of the degassing event associated with pre-eruptive ascent. Towards this goal the diffusivities of F, Cl, Br and I have recently been determined using diffusion couple experiments doped at magmatic concentration levels and employing sorption profiles obtained from microanalytical analysis (Fig. 11a). The results (Fig. 11b) display the range of halogen diffusivities to be expected and illustrate the substantial variation in magnitudes of the diffusivities. With such data one can now envisage tests for the potential of diffusive relative fractionation of the halogens during eruption and possible insights into the absolute time frame of the degassing event in a given volcanic system.

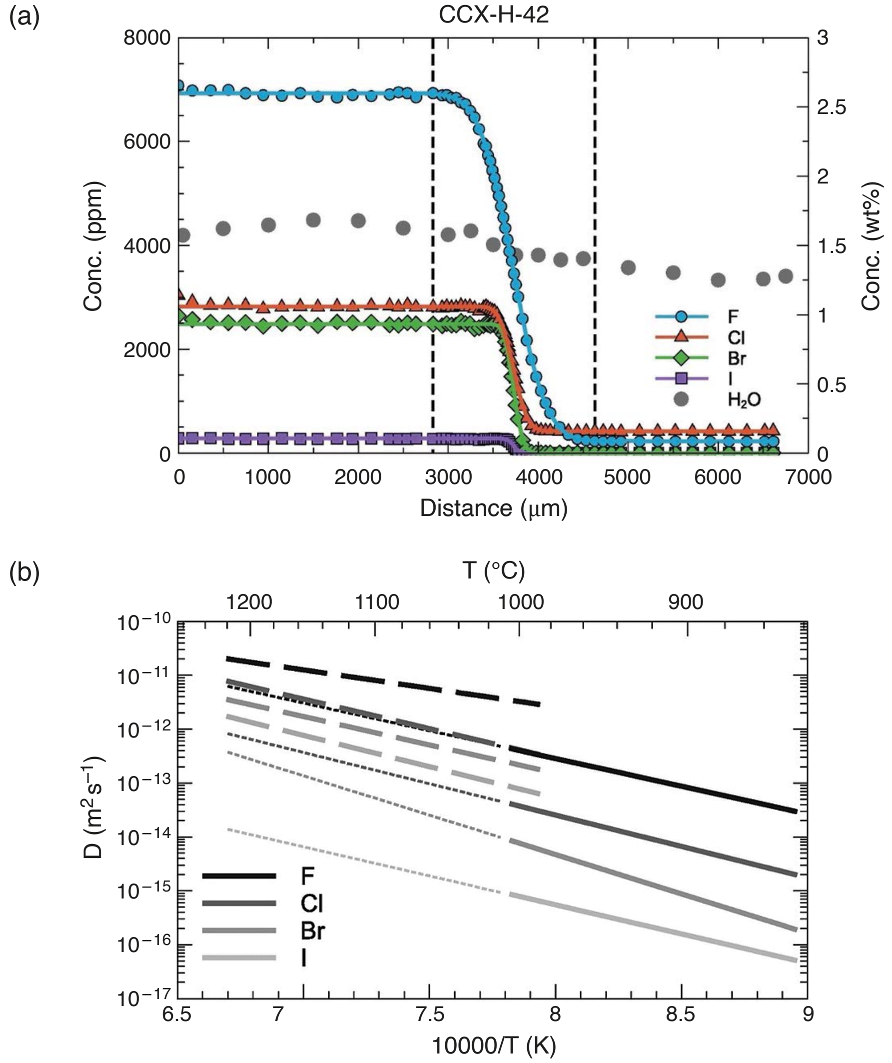


Figure 11. (a) Concentration profiles of multiple halogens from a single experiment using microanalysis of natural concentrations of halogens. (b) Halogen diffusivities in anhydrous (left) and hydrous (right) trachytic melts (from Feisel et al., 2023).

13. Magma Mixing

Mixing of magma reservoirs has long been recognized as a petrogenetic process. The process of "mixing" as a chemical contributor to the diversity of igneous rocks had been modelled as a simple chemical mass balance between putative chemical reservoirs. The observation of mingled systems, especially in erupted products of volcanism, brought home the understanding that magma mingling (physical intercalation of liquids before the completion of chemical homogenization by advection and chemical diffusion) was a petrogenetic process and, quite possibly, a volcanic eruptive trigger (De Campos, 2004; 2008; 2011; Perugini et al., 2008; 2010).

This led to the launching of an experimental program based on a high temperature gas-mixing tube furnace together with a so-called "journal-bearing" drive-head (Fig. 12). The system permits the chaotic mixing of two liquids at magmatic temperatures. The geometry of the starting juxtaposition of the two end-member liquids and the rotor providing the strain is precisely defined and the strain (a combination of crucible rotation and rotor rotation, is also precisely defined). The products of such experiments are available for sectioning both vertically and horizontally and can then be prepared for microanalysis. The microanalytical results of variable chemistry of the mingled systems (Fig. 13) were then analysed in terms of the concept of relaxation of the variance of the data sets and the timescales characteristic of this relaxation were then used to scale the heterogeneity of natural mingled, erupted systems and to infer the time between a triggering mixing event and its subsequent eruption

(Morgavi et al., 2013a; 2013b; 2013c; 2016; 2019; Perugini et al., 2012; 2013, 2015a; 2015b; Vicentini et al., 2023; 2024). These studies have been systematically extended to magmatic rather than volcanic scenarios and bubble- and crystal-bearing systems rather than pure liquids (Wiesmaier et al., 2015; Renggli et al., 2016; Morgavi et al., 2016; 2019). For a recent in-depth review of magma mixing physics see Morgavi et al. (2022).

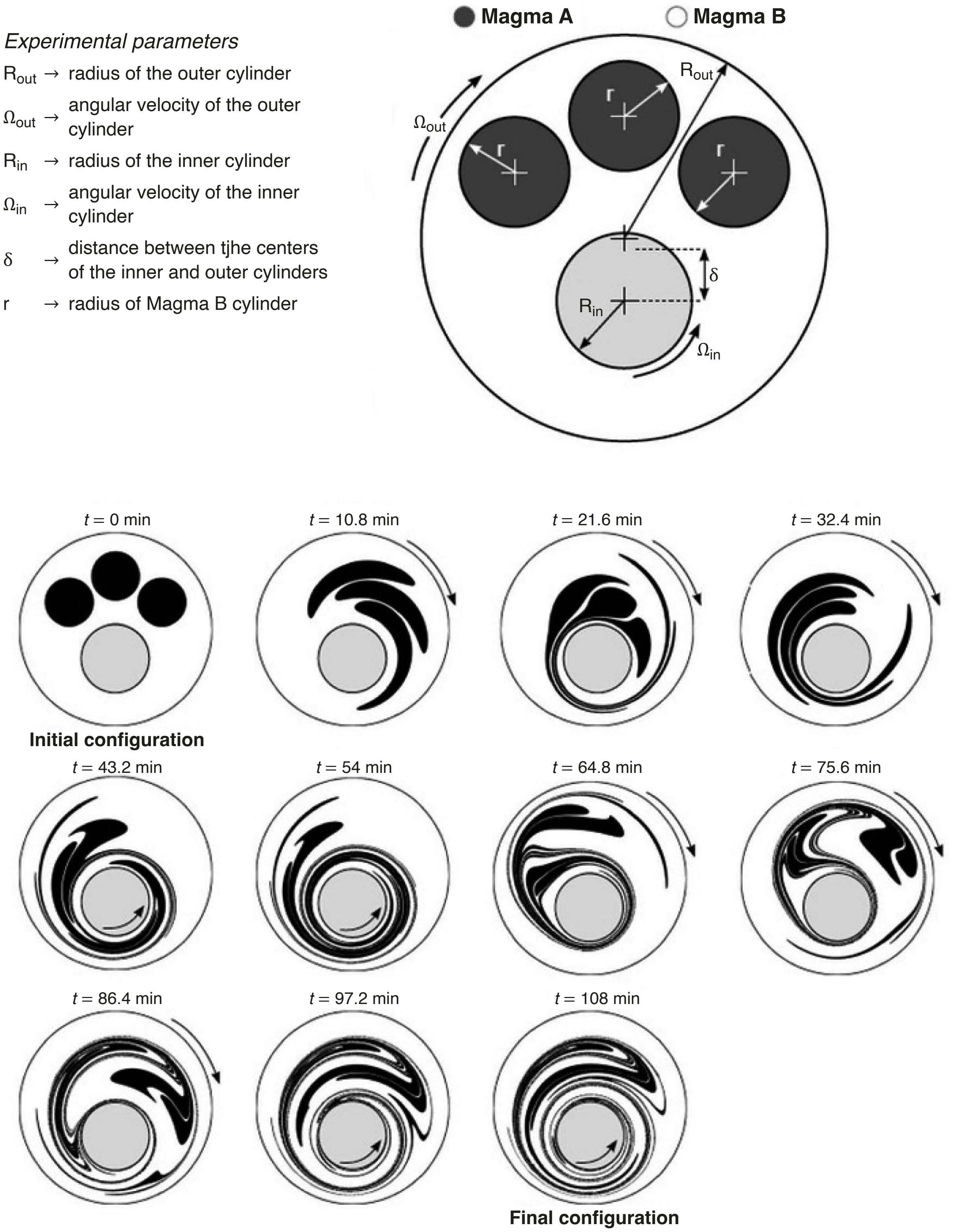
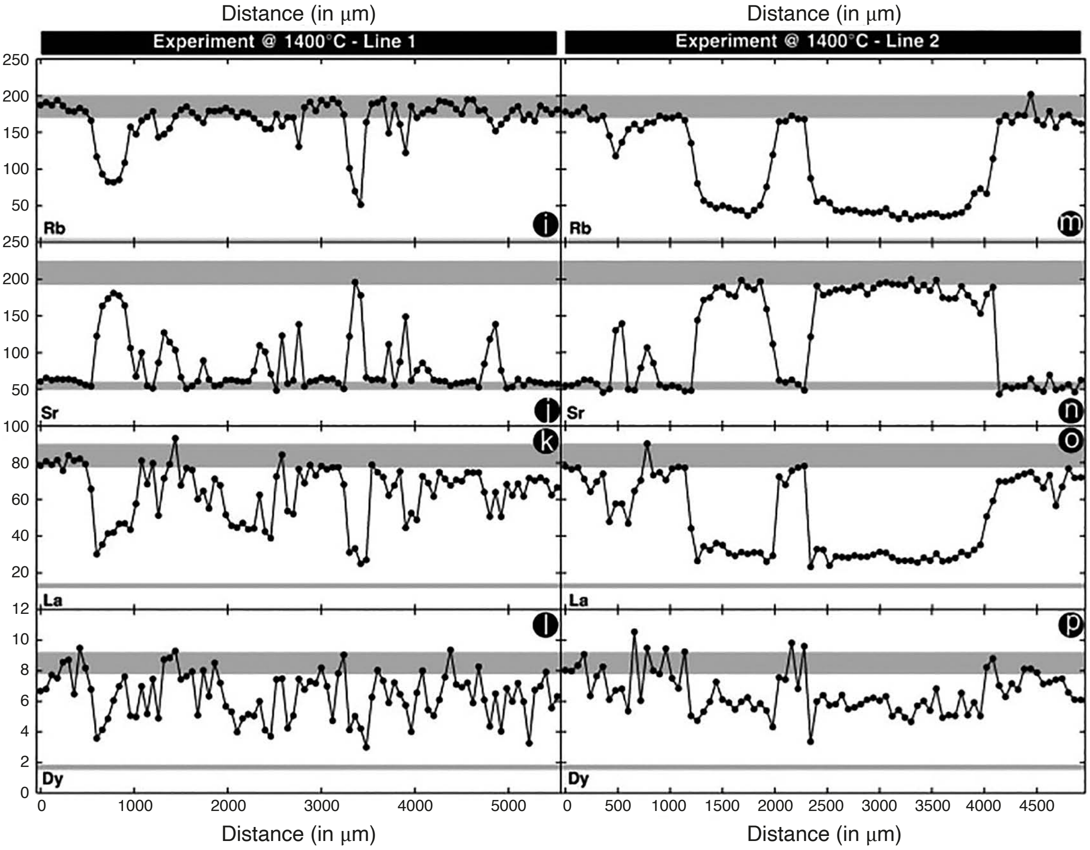


Figure 12. Experimental starting conditions and time evolution of mingling in the journal bearing device for chaotic mixing experiments (Morgavi et al., 2022).

(a)



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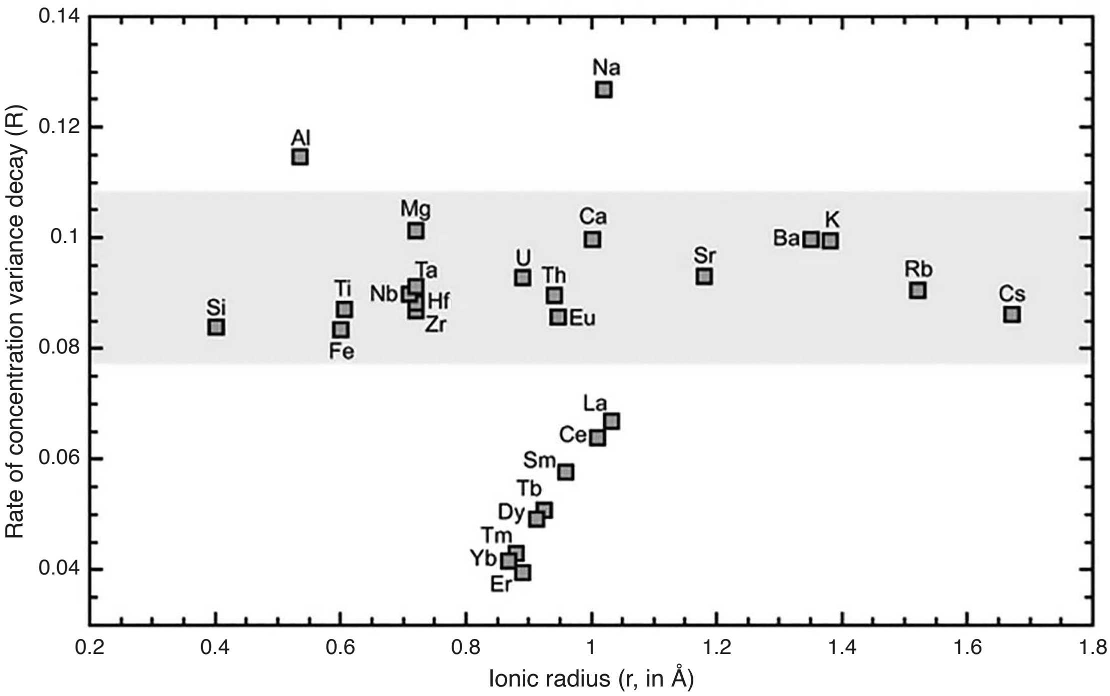

Figure 13. (a) Compositional mapping of mingled melt pairs (Morgavi et al., 2022). (b) Compositional Variance Decay as a tool to evaluate timescales of magma mingling with application to eruption triggering as a volcanic chronometer (Perugini et al., 2015).

14. Ash-gas reactions

Upon fragmentation, the "dusty gas" phase assemblage consists largely of broken glassy shards and a cocktail of gas-forming species (Dingwell et al., 2012) that co-exist for a finite time at high temperature within the conduit-enclosed ascent column of the fragmented material. Due to the irony that the silicate and fluid phases which existed in near equilibrium in the bubbly liquid system, are suddenly thrown out of equilibrium by the fragmentation event and subsequent thermal and pressure perturbation during ascent, some chemical interaction between ash and gas will be inevitable. Given the potential climatic consequences of the flux of the co-erupted gas components, the nature of this high-temperature ash-gas interaction was deemed worthy of investigation. A new design of an ash-gas reactor (AGAR), based on a tumbler design, was constructed and experimental campaigns were initiated with, e.g., SO_2 and HCl, as major gas phases (Ayris et al., 2014; 2015; Casas et al., 2019; Wadsworth et al., 2020).

These AGAR experiments between ash and gas have led to several major observational conclusions. The ability of glass to incorporate gas-forming components onto its surface has been clearly demonstrated. The magnitude of this mechanism permits the postulate that major fractions of co-erupted gas-forming components might be "sequestered" back onto the surfaces of glassy ash particles in eruptions where a significant high temperature residence time of ash-gas coexistence can be surmised. This in turn may relate to the depth of fragmentation in the conduit. Glass chemistry plays a role in the efficacy of sequestration and the dynamics of redox reactions at high temperature is also involved. Diffusional modelling of the results has led to a very consistent picture and interpretation of the results. The somewhat lower temperature issue of salt aggregation onto pyroclastic materials has received increasing attention due to the recent submarine eruptions of Hunga Tonga. A combination of experimental work and careful characterization of salts on natural ash is adding substantially to our understanding of ash in the earth system (Mueller et al., 2017; Casas et al., 2022; Colombier et al., 2019; 2023b).

15. Geospeedometry

Having grasped the significance of the glass transition for structural and derivative property behavior it was immediately apparent that the evaluation of hysteresis upon transiting the glass transition might offer a window into the cooling history of natural volcanic glasses. This in turn might resolve controversies concerning the thermal

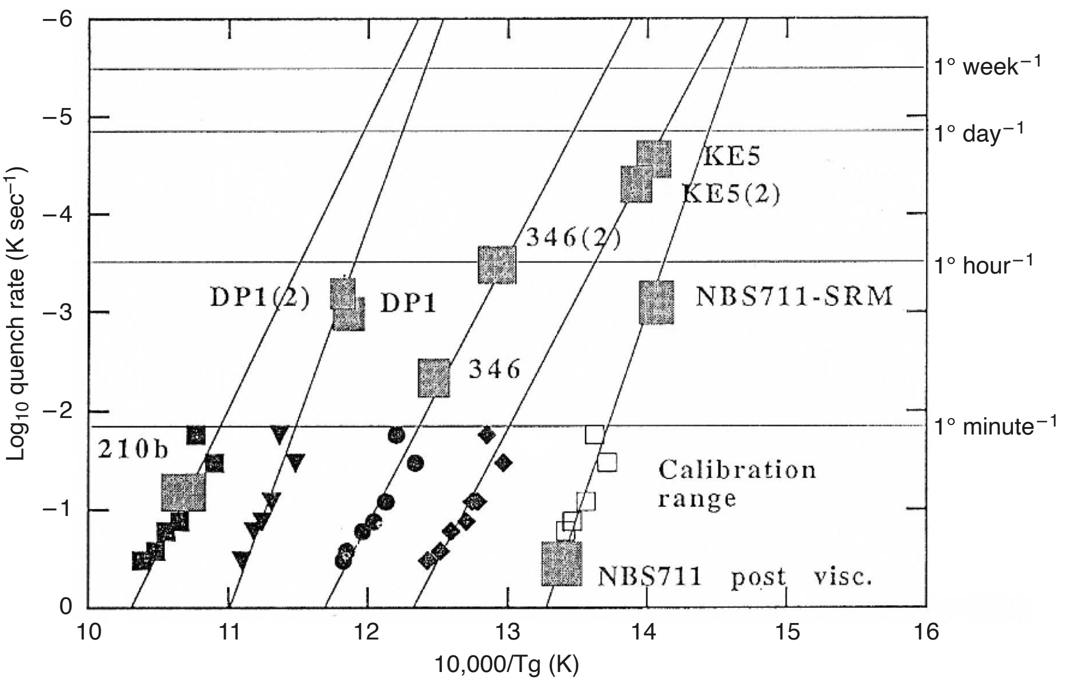

Figure 14. The first direct estimates of the cooling rates of pristine volcanic glasses demonstrating the validity of the method employing scanning calorimetry and enthalpic relaxation geospeedometry (from Wilding et al., 1995).

origins of obsidian deposits, such as the debate on lava flows versus air fall welded deposits and many other examples. Several measures were employed before embarking on this experimental line of investigation. The compositions chosen for the first investigations were peralkaline silicic obsidians, systems with large Tg signals, with low Tg temperatures and with a good glass-forming ability. The samples chosen were unaltered and unhydrated, or so-called "pristine" glasses. The scanning method chosen was calorimetry using sufficiently high scanning rates to obtain good Tg signals but not too high to avoid encountering severe thermal gradients across samples. The first results were a complete success and indicated that a very large range of cooling rates are involved in the formation of obsidian. The 5 log units of cooling rate observed in this first study (Fig. 14) vastly exceeded the precision of the method demonstrating that the method would be useful for natural investigations (Wilding et al., 1995). Subsequent studies evaluated submarine hyaloclastites, rhyolitic lava flows, phonolitic airfall, welded deposits and lavas, and the glasses from the drill core of the Hawaii drilling project (Wilding et al., 1996; 2000; Gottsmann and Dingwell, 2001a; 2001b; 2002 , Nichols et al., 2009). To date the fastest and the slowest cooling rates determined for natural glasses are for limu o pele glass shards from (Potuzak et al., 2008; Gottsmann and Dingwell, 2002) Loihi seamount and Mayor Island pantellerite, respectively (Fig. 15). Gradients in sections of glassy flow units yield the expected cooling rate variations and the Tg values encountered fix nicely the solidification temperatures of glassy flows, and welded units.

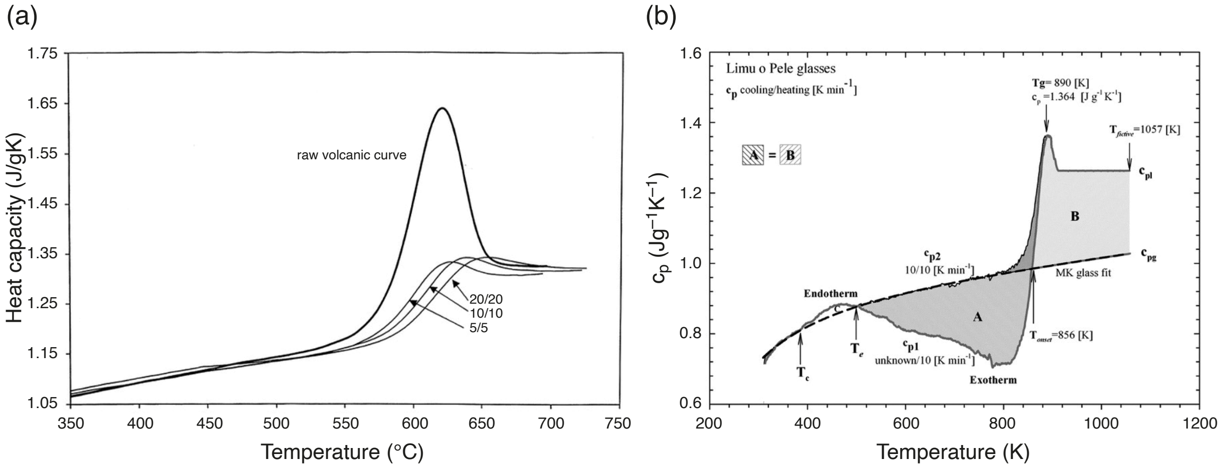

Figure 15. Examples of the calorimetric glass transition hysteresis of extremely slowly (Major Island pantellerite, (a)) and extremely quickly (Loihi seamount, limu o pele tholeiitic basalt, (b)) naturally cooled volcanic glasses (from Gottsmann and Dingwell (2002) and Potuzak et al. (2008), respectively).

16. Sintering of volcanic glass and permeability evolution

This has led directly into the enhanced significance of developing a fully quantifiable model of the sintering of glassy particles. Based in part on an experimental campaign involving synchrotron-based 3D imaging of the time evolution of porosity (and image analysis-based calculation of permeability) a general model of the sintering of volcanic ash and its implications for degassing is now assembled (Ashwell et al., 2015; Vasseur et al., 2013; 2016; 2017; Wadsworth et al., 2014; 2016a; 2016b; 2017a; 2017b; 2017c; 2018; 2019; 2020; 2021; 2024). As a result, the long campaign of adopting additional complexities to the sintering systems such as crystalline phases is beginning in a manner which rests very solidly on the fully exploited case of the dominantly glassy systems investigated to date. For a recent in-depth review of hot-sintering in melt-dominated systems see Wadsworth et al. (2022).

17. Viscosity monitoring

Much of what has been described above has had the character of delivering novel observables from sophisticated newly designed experiments which generate generalizable results and engender models of magmatic and volcanic behavior. But we may ask the question as to whether the routine determination of the physical properties of erupted products of volcanic eruptions has its place, alongside the geochemical and petrological description of these products, in an effort to infer a mechanistic basis for changes in style of eruptive activity as well as in the search for inferences regarding the causes of volcanic triggering and cessation and reservoir size. A first step in this direction has been taken now with the systematic determination of the Newtonian shear viscosities of erupted lavas sampled on a frequency of days to weeks during long-ongoing effusive eruptions of Hawaii, Iceland and La Palma (Fig. 16) (Roman et al., 2021; Soldati et al., 2021a; 2021b; 2024a; 2024b; 2024c). These data have been analysed in terms of volcanic eruptive style, seismic subsurface signatures of ascent and further monitoring variables. Answers to simple yet valuable questions regarding the start and stop of a particular volcanic eruptive phase, the relationships between successive phases, and interpretations involving the size of magma "chambers" and their evacuation efficiency can be informed by these measurements.

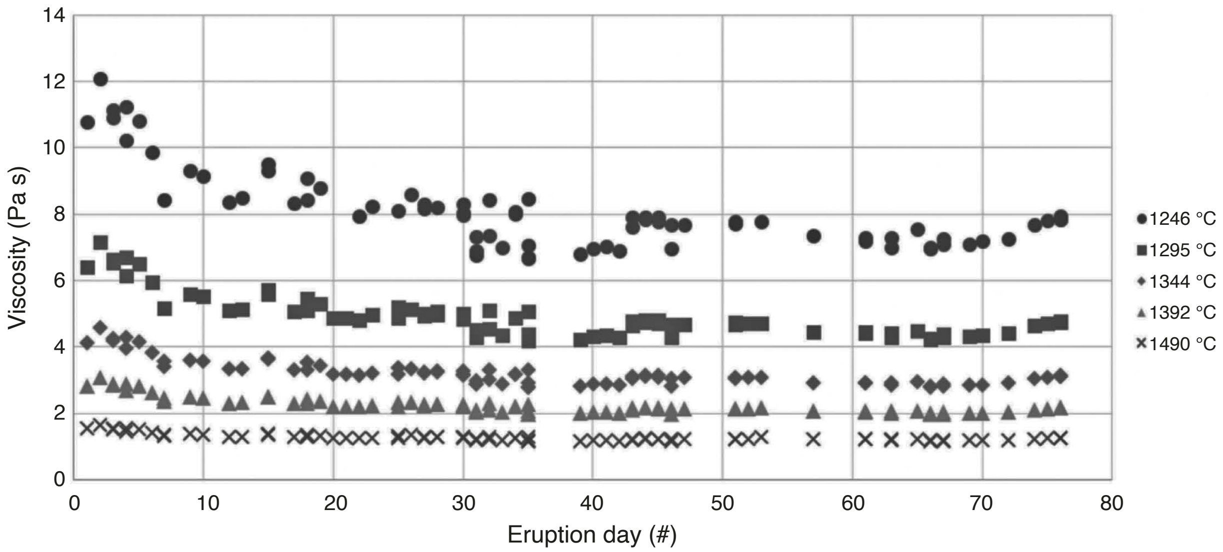

Figure 16. Viscosity monitoring of the 2021 Tajogaite eruption of La Palma (Canary Islands) (from Soldati et al., 2024c).

18. Ash-turbine interactions

The topic of aviation safety in the presence of atmospheric suspended ash has been the subject of intense scrutiny since the closure of European airspace due to the eruption of the Eyjafjallajökull system in 2010. A wide-ranging experimental program on topics from ash-turbine interaction to new candidate materials for the ceramic thermal barrier coatings of turbine blades has ensued. The problem of ash interaction is a multi-hazard one in that ash can not only affect the chemical stability of the so-called thermal barrier coating (TBC) generating loss of TBC and thermal cracking of affected materials, but also because the ash can abrade parts, and disrupt the fuel combustion process. In a series of experimental studies the study of TBC degradation via interaction with volcanic ash has been investigated in terms of the kinetics and reactivity of volcanic ash and TBCs and the physical analysis of the likelihood of ingestion and adhesion of ash to turbine parts (Kueppers et al., 2014; Song et al., 2014; 2016; 2017; 2019; 2022; 2023; Lockachari et al., 2020; Müller et al., 2019; Yang et al., 2020; Wu et al., 2022; Ma et al., 2022; Guo et al., 2023a; 2023b). The hazard potential of volcanic ash to air travel increases with operating temperature and thus technological innovations to increase efficiency by raising the temperature of fuel combustion can aggravate this hazard.

19. Ice Nucleation on Ash

The field of atmospheric ice nucleation has a long history of investigation and differing experimental devices have been employed to systematize the experimental investigation of ice nucleation on aerosol particles. The work on Ice Nucleation on volcanic ash has employed two different set-ups to date and the results of the influence of volcanic ash have demonstrated an active role for certain ash particles in the nucleation process but the results in total have not delivered a clear understanding of the variables that would lead to a simple parameterization (Maters et al., 2019; 2020; Umo et al., 2021).

20. Horizons

The horizons of our experimental work involving volcanic materials and systems today beggar the imagination; prebiotic chemistry on volcanic rock (Morasch et al., 2019, Matreux et al., 2021), drones for the investigation of volcanic fields (Schmid et al., 2023), mapping the CO_2 in the Cenozoic (Guo et al., 2021; Cheng et al., 2020; Li et al., 2024), paleomagnetics of volcanic deposits and palaeointensities (Ferk et al., 2010; 2011a; 2011b; 2014; Ferk, 2012; Leonhardt et al., 2014) and developing lunar regolith technologies (Stapperfend et al., 2023; 2024) are but a few examples. Fields of molten earth materials beyond volcanology also continue to stride forward apace; fulgurites (Çalışkanoğlu et al., 2023a; 2023b; 2024), and pseudotachylites (Lavallée et al., 2012; Kendrick et al., 2014a; 2014b, Wallace et al., 2019) and glass transition of further systems such as peridotite (Casas et al., 2023; Dingwell et al., 2004), carbonates (Di Genova et al., 2016; Dingwell et al., 2022; Hess et al., 2023; Weidendorfer et al., 2023; Bissbort et al., 2024; Veksler et al., 1998; 2011) and rare earth silicates (Courtial and Dingwell, 2005; Veksler et al., 2005; Müller et al., 2022, 2023; Müller and Dingwell, 2024) continue to surprise and inspire us. Volcanology must embrace these neighbouring research areas in order to flourish optimally.

Perhaps the greatest experimental ambition of them all still lies in the future It is the goal of drilling to active magma and setting up a so-called magma test bed (Lavallée et al., 2020; 2024; Wadsworth et al., in press) where the seemingly countless models and hypotheses of magmatic response can be tested in situ. We may live to see this bold initiative in the realm of high enthalpy geothermal exploration become a reality.

The future looks bright and innovative experiments will undoubtedly continue to contribute to major advances in volcanology, as well as its hazards, risks and applications.

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