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A review of analogue and numerical modelling in volcanology

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Abstract

Modelling has been used in the study of volcanic systems for more than one hundred years, building upon the approach first described by Sir James Hall in 1815. Informed by observations of volcanological phenomenon in nature, including eye-witness accounts of eruptions, geophysical or geodetic monitoring of active volcanoes and geological analysis of ancient deposits, analogue and numerical models have been used to describe and quantify volcanic and magmatic processes that span orders of magnitudes of time and space. We review the use of analogue and numerical modelling in volcanological research, focusing on sub-surface and eruptive processes including the accretion and evolution of magma chambers, the propagation of sheet intrusions, the development of volcanic flows (lava flows, pyroclastic density currents and lahars), volcanic plume formation and ash dispersal.

When first introduced into volcanology, analogue experiments and numerical simulations marked a transition in approach from broadly qualitative to increasingly quantitative research. These methods are now widely used in volcanology to describe the physical and chemical behaviours that govern volcanic and magmatic systems. Creating simplified depictions of highly dynamical systems enables volcanologists to simulate and potentially predict the nature and impact of future eruptions. These tools have provided significant insights into many aspects of the volcanic plumbing system and eruptive processes. The largest scientific advances in volcanology have come from a multidisciplinary approach, applying developments in diverse fields such as Engineering and Computer Science to study magmatic and volcanic phenomenon. A global effort in the integration of analogue and numerical volcano modelling is now required to tackle key problems in volcanology, and points towards the importance of benchmarking exercises and the need for protocols to be developed so that models are routinely tested against 'real world' data.

Keywords: volcano, model, analogue model, numerical simulation

1.0 Introduction

Volcanic activity is often unpredictable and occurs in an environment that is highly changeable and forbidding; however, there is a compelling need to improve our understanding of these complex systems. Approximately 800 million people around the world live close enough to a volcano to be directly affected by an eruption (Loughlin et al. 2015), and many more are at risk of social or economic impact as the consequences of volcanism extend from regional to potentially global areas (e.g. Svensen et al. 2004). The effects of an eruption can be felt long after an eruption has ceased, with the potential for both physical environments and societies to be impacted many decades after the event (e.g. the occurrence of lahars decades after the 1991 Mt. Pinatubo eruption, and the continuing impacts on communities following the Nevado del Ruiz eruption in 1985).

The challenges of working in volcanic terrains and gathering useful data mean that analogue and numerical models have gained significant importance in studying the dynamics of volcano growth and eruption. The occurrence of volcanic and magmatic activity is challenging and potentially impossible to forecast, and the factors that influence processes such as magma storage, ascent, eruption and deposition have several, often poorly constrained, variables. Technological limitations place boundaries on what we can record in nature; for example, direct observations are often problematic as the processes of interest are frequently hidden from view as they occur beneath the Earth's surface or within a pyroclastic flow or plume. The often remote and difficult to access location of volcanoes poses further logistical problems in studying processes.

Volcanic and magmatic processes occupy a vast range of scales from sub-millimetre to kilometres in size, and the timescales over which they take place range over fractions of a second up to millennia. The benefits of analogue and numerical modelling mean that it is possible to study these processes in a controlled environment, with the opportunity to repeat the phenomenon as required. Laboratory experiments and numerical simulations can link well-constrained starting conditions with measureable outcomes, and with careful scaling these findings can be extrapolated to better understand the natural processes. Quantitative, systematic and rigorous modelling in volcanology means "the contribution of experimental research to our understanding of volcanic processes is difficult to overstate" (Mader et al. 2004).

In this invited review we will summarise the development of analogue and numerical modelling in the broad field of volcanology by providing some historical context and giving an overview of models that have been developed to study different parts of the system. Our intention is not to consider all parts of the magmatic and volcanic system, or review each area in depth, but instead to provide an account of the foundations of the subject, and to celebrate some of the key papers which have shaped modelling in volcanology. We describe some of the cutting-edge techniques that are being deployed to model volcanic and magmatic processes, considering magma and lava rheology, magma chambers, magma intrusions, lava lakes and lava domes, lava flows, pyroclastic density currents, lahars, volcanic plumes and ash dispersal (see Figure 1). We conclude by highlighting common challenges in the future of volcanology in our efforts to model these intriguing, captivating and potentially devastating phenomena.

2.0 Historical context of modelling in volcanology

Many of us have a profound fascination with volcanoes; from the beautiful landscapes they produce and art they inspire (see Sigurdsson (2015b) for a summary), to the impact their eruptions have on individuals, societies and civilizations (e.g. Sheets 2015). However, this fascination is often met with fear as the destruction volcanoes can cause may have far-reaching effects. The huge range of style and intensity of volcanic activity means that societies living nearby do so with high risk; there are however many benefits too, as volcanoes produce habitable environments on a local scale by the production of fertile soil and magmatic activity is associated with economic deposits such as copper porphyry. On a planetary scale the gases volcanoes emit lead to the creation of our oceans and the atmosphere. Life on Earth and the physical processes that govern volcanic activity are thus intimately connected.

Volcanology as a science

Our fear and fascination with volcanoes is evident in some of the earliest historical accounts of volcanic eruptions, which show that we have long tried to understand how volcanoes form and what causes them to erupt. Greek natural philosophers from the fifth and fourth century BC, such as Anaxagoras (c. 510-428 BC), Democritus (c. 460-370 BC) and Plato (c. 428-348 BC), proposed that volcanic eruptions were caused by 'great winds inside the Earth', an idea that

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was supported by Aristotle (384-322 BC) (see Sigurdsson (2015a) for details). The study of volcanoes is founded on eye-witness accounts and field observations of activity, starting in Italy with the descriptions of Pliny the Younger of the eruption of Vesuvius in 79 AD. William Hamilton, a pioneer in volcanology, gained recognition for his descriptions of a much later eruption of Vesuvius in 1767 (Hamilton and Cadell, 1774). The interpretation of the origin of intrusive and extrusive igneous materials in the rock record came later with the seminal work of James Hutton (1726-1797), the so-called 'Father of Geology', whose field observations in 1785 in the Cairngorm mountains, Scottish Highlands, demonstrated that granite rock was formed by the solidification of an initially liquid body that had intruded a pre-existing host rock (Hutton 1788).

Experiments in volcanology and a quantitative approach

Experimentation has long been an important tool in geological investigations. The first analogue experiments to study geological processes was published 200 years ago by James Hall in 1815. Hall's experiments, carried out 'with such materials as were at hand', used several pieces of cloth, linen and wool each placed upon one another horizontally to represent a sequence of rock strata (see Figure 2). A rig then applied horizontal shortening to create a folded structure which Hall deemed reminiscent of convoluted rock layers at Fast Castle, Cockburnspath, Scotland. Hall's research was read at a meeting of the Royal Society of Edinburgh, and has since inspired a new field of study using analogue materials to study geological processes in the laboratory. More specifically, the first experiments in volcanology used natural samples to explore the melting, crystallisation and fragmentation of igneous rocks. For example, Francesco d'Arezzo melted samples of lava from Etna in 1670 (Sigurdsson 2015a), James Hall melted and then crystallised 'whinstone' (dolerite) and basaltic lavas in 1790 (Hall 1805), and Auguste Daubrée performed volcanic diatreme analogue experiments to study vent processes and the formation of structures associated with diamondiferous kimberlite deposits (Daubrée 1891).

It wasn't until the 1960's that quantitative science started to emerge more prominently in the volcanological literature, transitioning away from largely qualitative and descriptive work. A pioneer in quantitative approaches in volcanology was George Walker (1926-2005), who is considered by many in the field to be the "the father of modern quantitative volcanology" due to his demonstration of how to integrate disciplines across the sciences, using field-based

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measurements to develop and test conceptual models. The breadth of Walker's interests and expertise across volcanology were impressive, and his guidance and influence in the literature is evident across many parts of the volcanic system from plumbing systems, lava flows, tephra fall and flows (see Sparks (2009) for a review). Walker's quantitative approach, for example mapping the regional distribution of zeolites in Icelandic basalt lavas (Walker 1960) and being one of the first to publish calculations of lava flow viscosity based on field measurements of flow thickness, velocity and angle of slope (Walker 1967), led to the development of laboratory experiments in volcanology (and eventually numerical simulations) that could test hypotheses based on field data.

Analogue and numerical modelling in volcanology

The use of numerical and analogue modelling has come from the application of methodologies developed for alternative, sometimes quite disparate, purposes. From the 1950's the fields of volcanology, fluid dynamics and engineering came together (Figure 3). Hubbert and Willis (1957) used gelatine solids injected with Plaster of Paris to study hydraulic fractures formed within pressurised boreholes, however the experiments also apply to modelling magma-filled fractures such as dykes and sills (Figure 3a); Fiske and Jackson (1972) subsequently used free-standing gelatine models to study magma propagation in a volcanic rift such as Hawaii (Figure 3b). The research of Morton et al. (1956) modelling industrial plumes rising from chimney stacks is the basis of many of the numerical models of volcanic plumes implemented today (Figure 3c). There are numerous examples where analytical models, numerical simulations and laboratory experiments have helped to explain processes that are too large or too complex to be understood in nature. George Walker and Lionel Wilson published experiments that studied the physics of pyroclastic fallout from large and highly explosive volcanic eruptions. They timed the fall of carefully characterized natural samples of tephra and compared these with theoretical computed terminal velocities to aid the analysis and interpretation of field deposits (Walker et al. 1971). Steve Sparks and Lionel Wilson developed early theoretical models to explore the controls of volcanic column height (Wilson et al. 1978) and the role of vent geometry on the collapse of eruptive columns to form ignimbrite deposits (Sparks & Wilson 1976). These works underpin much of the numerical and analogue modelling work conducted in volcanological research today.

3.0 Parameterisation of models in volcanology

Recent advancements in computational power, analytical techniques and experiment imaging have revolutionised numerical and analogue modelling in volcanology, ensuring their continued use in studying volcanic and magmatic phenomena. We define a numerical model as a set of algorithms and equations that are used to capture the physical or chemical behaviour of the system being modelled. We define an analogue model as a simplified representation of physical processes that is scaled down so it can be studied in the laboratory. Both analogue and numerical models are based on theoretical frameworks that have been developed to account for observations and measurements made in nature. Some of these models are directly informed by case studies, others are more generalised or focus on a specific process, and where possible the models are tested by comparing the model outputs with expected outcomes based on observed or measured phenomena. In engineering, analogue models are sometimes used to test and inform the development of numerical models; a numerical model of the analogue experiment is first created, and the results compared with those of the analogue experiment. This approach has great potential in volcanology, with examples in the field of tephra sedimentation and plume rise and formation, however the combination of analogue and numerical modelling is yet to be fully explored. By assessing the 'mismatch' between analogue and numerical models and testing the model outputs against natural observations, model errors can be quantified, incorrect assumptions investigated, and any limitations in the analogue or numerical model parameterisation can be identified (see Figure 4 for a flow diagram depicting model development and testing procedures).

Volcanic and magmatic processes are controlled by a range of physical processes and regimes, and these vary depending on whether subsurface or eruptive processed are being considered. For example, subsurface processes such as magma intrusion and conduit processes are largely controlled by the rheology of magma and deformation of the host rock, while eruptive processes are dependent on the density of an eruptive mixture and the characteristics of erupted products. Modelling volcanic mixtures is non-trivial due to their multiphase nature; magmas comprise melt, crystals and gas, while eruptive plumes and flows commonly comprise many different particles sizes, in addition to a gas phase. Fundamental to the success of models in volcanology is their parameterisation, with the model outputs strongly

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dependent on the quality of the model inputs. However, there are different considerations that need to be made when developing a numerical model or analogue experiment.

3.1 Numerical modelling

Numerical modelling involves the selection and application of a number of mathematical, physical and/or chemical assumptions to represent a particular phenomenon. Modelling requires simplifications in the way a system is presented to be made. In deterministic modelling the model output is controlled by the model parameters and the initial conditions, whereas stochastic modelling involves an inherent randomness such that the same set of parameter values and initial conditions will produce a range of model outputs. In volcanology, the majority of numerical models are deterministic and the application of stochastic approaches is limited to hazard assessments.

Steady state models are used to estimate key parameters; however, they only give a first approximation of the physical behaviour and require assumptions to be made. For example, the thickness of a pyroclastic density current can be modelled at different distances from source, assuming eruption conditions such as source flux are constant through time. Transient models consider system changes over time, and are more complex and require the closure of more equations, but they are able to reproduce the unsteady behaviour observed in a range of volcanic phenomena.

Regardless of complexity, all numerical models require description of boundary conditions taking into account interaction with the surrounding environment. Examples of boundary conditions relevant to volcanic systems include atmospheric conditions when modelling eruption plumes, as humidity and wind strength exert a strong control over the height a volcanic plume may reach in the atmosphere, and stiffness of a host rock when modelling magma intrusions, as this will affect the propagation behaviour of a dyke or sill. Environmental conditions can be approximated in simplified numerical models, for example when modelling magma chamber growth the lithosphere may be modelled as a mechanically homogeneous material (e.g. Galgana et al. 2013) or by including mechanical heterogeneity and a stiffness contrast between crust and mantle (e.g. Le Corvec et al. 2015). Interactions between a phenomena and its surroundings are commonly accounted for in numerical models by simplified coefficients; for example the entrainment of ambient air into a rising plume is described by two entrainment parameters: one considers radial entrainment due to turbulent eddies at the plume edge, and the other accounts for entrainment due to the effects of wind on the plume. These coefficients have been parameterised using a combination of both observations of the phenomena in nature and analogue experiments.

While it is possible to account for the effect of the ambient conditions on the modelled phenomena, it is considerably more difficult to account for feedback between the modelled phenomena and its environment as this requires significantly more computational power. Ultimately the results of any numerical simulation are dependent on the quality of input parameters, and these are either directly inferred from observations in nature or are estimated using analogue modelling (see Figure 4).

3.2 Analogue modelling

Analogue experiments are often three-dimensional models, although quasi-two-dimensional experiments are sometimes used. Parameterisation of analogue models requires the development of appropriate scaling laws and then careful material characterisation at experimental conditions. The choice of analogue material will depend on the parameters that are being investigated and the conceptual model that is being tested; many simplifications are required in order to track the impact of variables on experiment outcomes, e.g. how changes in density contrast between fluid and surroundings effect geometry, velocity or pressure. Extracting and measuring parameters and variables in analogue experiments is crucial for understanding the modelled phenomena, and for checking model parameterisation is consistent with appropriate scaling laws.

3.2.1 Scaling experiments and choosing analogue materials

The principles and methods to scale laboratory experiments were laid down by M. King Hubbert (1937) in a seminal paper that sets out the foundation upon which all analogue modelling should be undertaken. He stated that the choice and characterisation of analogue materials need to be carefully considered in reference to geometric, kinematic and dynamic scaling laws between the laboratory and natural components in order for experimental results to be applied back to nature. In the study of subsurface processes in volcanology, such as magma intrusion, scaling laws mean that it is possible to create a scaled laboratory experiment where several of the scaling criteria, e.g. based on model ratios that take into

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account length, time and forces, can be met by using a selection of domestic fluids, powders and gels. An early advocate of Hubbert's approach was Ramberg (1967) who used these principles to develop centrifugal models using silicone putty to model diapirs. Scaled analogue experimentation has since been applied in a huge range of geological contexts, using model ratios for magma and rock or using the pi theorem (e.g. Merle, 2015). Although compromises are nearly always needed, there are particular challenges for using analogue experiments to study conduit and eruptive processes. Recent review papers on scaling laboratory experiments in volcanology include Galland et al. (2015) and Merle (2015).

Once scaling laws have been determined, appropriate analogue materials need to be selected. To assist with this, temperature-dependant Newtonian and non-Newtonian fluids and gels have been characterised in a viscometer or rheometer at a controlled temperature and using a range of measurement geometries; these include rotary, concentric cylinder, falling ball, tube and parallel plate methods. A known shear stress (σ) is applied to a small sample of the fluid or gel, and the strain (γ) or strain rate ($\dot{\gamma}$) required to meet this stress is measured. The material's viscosity (η) is thus characterised, and the material properties can often be tailored so that it meets the required physical behaviour which can be used to help relate the experiment results back to nature.

3.2.2 Experiment imaging techniques

There have been several recent developments in imaging and measuring experiment parameters and variables in the laboratory, drawing on technologies developed for industrial purposes to study volcanic processes. For a complete description, imaging and measurements need to focus on detailed external and internal monitoring of an analogue experiment.

Photogrammetry enables measurements to be made from photographs with great precision and can be used to construct three-dimensional representations of real-world objects. The open-source photogrammetric software MicMac (e.g. Galland et al. 2016) uses Structure-from-Motion algorithms to process experiment images from synchronised cameras and for example create a time-series of digital elevation models (DEMs) representing the changes in the surface of an experiment. X-ray micro-tomography can produce high resolution three-dimensional reconstructions of a static model topography with cross-sections showing internal structures; though the imaging is limited to small experiments, variation in signal to noise ratio and the need to have stable models during the duration of the scan (e.g. Kervyn et al. 2010). Dynamic processes can be studied for example using gelatine as a host-rock material which enables stress to be imaged when it is deformed and then viewed with polarised light. An interference pattern and colour fringes are produced due to gelatine's photoelastic properties (Crisp 1952). This method allows differential stresses and their evolution to be mapped qualitatively during an experiment (see Section 6 for examples). Lasers can also be used to illuminate a thin vertical sheet within a gelatine experiment (e.g. Kavanagh et al. 2015, 2017) or particle suspension experiment (e.g. Andrews and Manga 2012), with images recorded at time-defined intervals. Techniques such as Digital Image Correlation (DIC) can then be used to map internal strain changes for example within gelatine with suspended fluoresced tracer particles. Particle Image Velocimetry (PIV), which is a comparative technique to DIC, can be used to map fluid flow and produces instantaneous velocity measurements using passive-tracer seeding particles within the fluid, e.g. water as an analogue for magma within a dyke (e.g. Kavanagh and Dennis 2014, 2015) and particulate suspension in a pyroclastic density current or volcanic plume (Andrews and Manga 2012). The ability to integrate measurements of the surface and subsurface development of, for example, magma intrusion in the laboratory greatly strengthens the ability of analogue experimentation to help inform numerical modelling that is used to interpret volcano-deformation data in nature.

In the following sections, we describe and discuss the range of analogue and numerical modelling methods and techniques that have been applied to different physical volcanic processes.

4.0 Magma and Lava Rheology

Magma is one of the principal components of a volcanic system and the modelling of magma encompasses the study of magma chambers, volcanic plumbing systems, conduit processes, the development of lava domes and flows, and magma fragmentation in explosive eruptions. It is for this reason that a review of modelling in volcanology must start with models of magma and lava rheology. Numerical models of magma have focused on the development of analytical solutions that can account for the range of conditions that magma is subjected to

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from source to surface. Analogue experiments have aided the development of these numerical models using scaled analogue materials which test and help to build a theoretical framework for modelling magma.

Magma can be modelled as a multi-phase fluid, comprising a melt phase with variable proportions of bubbles and crystals. Single-phase magmas (melt only) are very rare, and possibly only occur deep within the crust. Silicate melts are often modelled as a Newtonian fluid with constant viscosity (Lejeune & Richet 1995; Ishibashi 2009):

$$\eta = \frac{\sigma}{\dot{\gamma}} \qquad [1]$$

where viscosity (η) is the ratio of shear stress (σ) and strain rate ($\dot{\gamma}$). Several types of non-Newtonian rheology have been applied to model the behaviour of magmas and lavas based on field observations. A Bingham fluid has to overcome a yield stress before it can begin to flow (Hulme 1974):

$$\eta = \frac{\sigma - \sigma_0}{\dot{\gamma}} \qquad [2]$$

where σ_0 is the initial shear stress required to cause the onset of flow when $\dot{\gamma}$ = 0. Once the yield stress has been overcome, the fluid has a constant viscosity. More recently, the Herschel Bulkley model (Herschel & Bulkley 1926) has been applied to the behaviour of magmas (Llewellin, Mader & S. Wilson 2002b; Mueller et al. 2011) due to its versatility in allowing for the modelling of a spectrum of magma behaviours (Newtonian, shear thinning, shear thickening):

$$\sigma = \sigma_0 + K\dot{\gamma}^n \qquad [3]$$

where σ_0 is yield stress when there is no flow, K is the consistency (η when $\dot{\gamma}$ = 1), and n is the degree of non-Newtonian behaviour (where n = 1 is Newtonian, n < 1 is shear-thinning, and n > 1 is shear-thickening).

4.1 Two-phase suspensions: Particle suspensions

Modelling the behaviour of particulate suspensions is crucial for describing the physical behaviour of volcanic processes. Particulate suspensions are ubiquitous across a volcanic system, from crystals in magma to ash particles within an eruptive plume. Within magmas, variations in crystal content mostly originate from changes in temperature, but the particle size within a volcanic plume or pyroclastic density current is related to the type of eruption (phreatomagmatic eruptions have significantly smaller particle sizes than magmatic eruptions for example). For the purposes of numerical and analogue modelling, particle distributions are simplified with either a single well-defined particle size or a small number of particles sizes used to replicate natural systems (e.g. Figure 5a-c). However, both numerical and analogue studies have shown that particulate concentration has a first order control on eruptive behaviour. In volcanic plumes, higher particulate concentrations, relating to higher plume densities, lead to column collapse, as shown by the analogue experiments of Carey et al. (1988). In addition, numerical studies have shown that particle concentration has a first order control on initiation of coignimbrite plumes (Engwell et al. 2016).

4.2 Two-phase suspensions: Bubble suspensions

The effect that bubbles have on magma viscosity depends on bubble shape, size and ability to deform under stress. In steady flow regimes, where stress and shear are constant, the bubbles reach an equilibrium deformation defined by the capillary number *Ca* (Manga & Loewenberg 2001; Llewellin et al. 2002b):

$$Ca = \frac{\eta_0 r \dot{\gamma}}{\Gamma} \qquad [4]$$

where η_0 is the fluid viscosity without bubbles, r is the un-deformed bubble radius, $\dot{\gamma}$ is strain rate, and Γ is interface surface tension between the liquid and gas. Small capillary numbers are dominated by surface tension, meaning that bubbles reach their equilibrium deformation soon after there is a change in shear rate (Llewellin et al. 2002a; Llewellin et al. 2002b), and they produce spherical bubbles that act to increase the viscosity of the suspension by creating an obstacle to flow. Large capillary numbers give rise to easily deformable and often elongate bubbles, acting as sites where shear localization can occur due to a reduction in friction, and will reduce bulk viscosity (Manga et al. 1998; Mader et al. 2013).

In unsteady flow regimes, when there is a variable strain rate, the forces causing deformation and restoration of the bubble shape are not in equilibrium (Llewellin et al. 2002b). As such *Ca* number (equation 4) does not adequately describe the behaviour of the bubble, and so a dynamic capillary number *Cd* is defined:

$$Cd = \lambda \frac{\ddot{\gamma}}{\dot{\gamma}} \qquad [5]$$

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where $\ddot{\gamma}$ is the rate of change of the imposed deforming force. This relationship explains how bubbles behave under time-dependant shear conditions.

4.3 Three-phase suspensions

Three-phase suspensions are well suited to explaining the behaviour of magmas and bring us closer to understanding the volcanic systems, but they also present several challenges associated with the additional complexity modelled.

A three-phase suspension can be modelled assuming a bubble suspension base fluid with the particles suspended within (Truby et al. 2015; see Figure 5d):

$$\frac{\eta_*}{\eta_b} = (1 - \frac{\varphi_p}{\varphi_m}) \quad [6]$$

where $\eta*$ is relative viscosity, η_b is bubble suspension viscosity, φ_p is particle volume fraction and φ_m is the maximum packing fraction. This simplifies the calculation of the three-phase rheology, and assumes a low bubble capillarity (see Truby et al. 2015, eq. 3.2); however if this is not appropriate then the bubble viscosity η_b may need to be substituted by a high bubble capillarity viscosity equation. This new model can account for a crystal bearing magma that has no bubble content at depth but vesiculates during ascent. It therefore marks a significant advancement in our understanding of magma behaviour through time and space, and will be an important tool in future models to better constrain the impact of three-phase magma rheology on volcanic eruptions. Gas escape and the development of permeable pathways in particle-rich suspensions has applications to the study of degassing crystal-rich magmas, with analogue experiments showing that migration patterns (either by bubble formation or fracture-like) are controlled by particle fraction and the degree of particle-packing (see Figure 5e; Oppenheimer et al. 2015).

Depending on the application and level of complexity, a variety of analogue materials have been used to model magma (see Table 1 for a summary). Many models use a melt-only magma analogue for simplicity, or in more complex models two-phase suspensions (bubbles in liquid, or crystals in liquid) and rarely three-phase (bubbles and crystals in a liquid). As such, the spectrum of rheology that has been considered in magma analogue models is broad and includes the use of Newtonian fluids, Bingham fluids or Herschel-Bulkley.

5.0 Magma Chambers

Magma chambers are the deepest and therefore arguably the most obscure parts of the volcanic and magmatic system. The relationship between large, ancient magma bodies, such as laccoliths and plutons, and magma chambers that feed volcanic eruptions is enigmatic and currently under debate (e.g. Lundstrom & Glazner 2016). Plutons are large accumulations of coarse-grained igneous rock and they express a broad range of compositions, generally falling between granite and gabbro, with physical properties (such as viscosity) that can span several orders of magnitude and vary both in space and time. A growing body of literature challenges the traditional "big tank" conceptual model of magma chambers as dynamic, large and long-lived accumulation of magma that slowly cools, crystallises and differentiates (Glazner et al. 2004). Instead it is proposed that large igneous bodies and magma chambers are incrementally emplaced from the accumulation of sill-like bodies (horizontal planar magma-filled sheets), and that they are discrete and ephemeral regions of melt and mush (Figure 1; see Annen et al. 2015 for a review).

5.1 Analogue models of magma chambers

High viscosity magmas

Examples where large magma bodies have been studied experimentally in the laboratory are relatively rare. Pluton emplacement has been modelled as a large body of viscous fluid which plastically deforms its surroundings, focusing on pluton geometry and how space is accommodated in the lithosphere. Perhaps one of the earliest analogue experiments to study granitic pluton emplacement was by Ramberg (1970) who used a combination of clay, putties, wax-oil mixtures, plates of concrete and aqueous solutions to simulate diapiric ascent of fluid-like magmas through rock layers with differing competency (see Tables 1 and 2). In his experiments, Ramberg used a centrifuge model arrangement capable of reaching an acceleration of 4000 x g to assist with scaling. Roman-Berdiel et al. (1997) and Roman-Berdiel (1999) studied granite emplacement by injecting low-viscosity Newtonian silicone putty into a tank of sand. Processes such as granite intrusion under the influence of tectonic stresses (Mazzarini et al. 2010), interaction with coincident faults and fractures during transpression (Benn et al. 1998) and strike-slip (Corti et al. 2005) motion have also been considered.

Low viscosity magmas

Several papers were published in the 1980's exploring the cooling of a large predominatly-liquid magma reservoir using analogue models, studying the so-called 'double diffusive convection' model and its application to magma chamber evolution (Huppert & Turner 1981b). The double diffusive convection model accounts for convection of a fluid with composition and temperature gradients acting in opposing directions. It was originally derived from oceanographic applications, yet has proved helpful to explain geological features such as large-scale cyclic crystal layering within large igneous bodies and supports the proposed conceptual model that magma chambers are compositionally zoned (Huppert & Sparks 1980). Subsequent analogue models have investigated magma mixing and magma mingling, for example for the case of a rhyolite magma chamber injected by basalt from below (Huppert et al. 1983) or mafic magma chambers replenished by felsic injections (Weinberg and Leitch 1998). The impact of volatile exsolution and bubble formation on magma mixing was explored in the laboratory by Huppert et al. (1982) and Turner et al. (1983) by introducing reactive HNO_3 into liquid layers of K_2CO_3 (upper layer) and KNO_3 (lower layer) to cause the release of gas. Phillips and Woods (2001) then studied the accumulation of bubbles and movement of bubbles within a magma chamber, using a salt solution as the magma analogue and an electrolysis cell with gauze to produce the bubbles. All these studies demonstrated that a recharge event of bubble-rich and low density magma, such as basalt, into a magma chamber may generate a turbulent bubble plume within the chamber that can be described by plume theory. Such bubble plumes could impact magma mixing within the chamber, the stability of the magma chamber, have the potential to trigger and eruption and could affect the style of eruptive activity. Magma contamination from roof and wall melting has also been studied experimentally (Leitch 2004).

Magma chamber failure

Fracture and failure of a magma chamber to feed a volcanic eruption has also been studied in analogue experiments, studying the nucleation of magma-filled fractures (dykes). McLeod and Tait (1999) used gelatine models to study the pressurisation and failure of liquid-filled cavities, creating a crustal 'magma chamber' by inflating a balloon within the liquid gelatine and removing it when the gel had solidified. Fluid was then injected into the cavity using a head pressure. Under increasing stress and strain, the gelatine undergoes an initially elastic deformation and then brittle failure. They found that dyke nucleation occurred from a pre-existing flaw in the analogue chamber wall, and that the viscosity of the fluid influenced the tendency for dykes to propagate. Koyaguchi and Takada (1994) also used gelatine models and glycerine to explore how the evacuation of a low viscosity fluid may lubricate the path of a more viscous fluid into a pre-existing fracture. Earthquakes are also potentially an important external influence on magma chamber stability that may trigger dyking that leads to a volcanic eruption. Namiki et al. (2016) considered two different scenarios of foam stability over a liquid layer of diluted glucose syrup in a partially filled tank (open vent) or fully-filled tank with density-stratified fluids (sealed magma reservoir). The use of a shaking table enabled the authors to identify the conditions for 'sloshing' of the magma chamber to occur. They found that the foam layer completely collapsed when oscillations were near the resonance frequency of the fluid layer and when sloshing low viscosity fluids surrounding large bubbles. In nature the collapse of a foam would potentially release a gas slug and produce a magmatic eruption, or result in magma overturn and a delayed eruption.

5.2 Numerical models of magma chambers

Increasingly complex Finite Element Modelling (FEM) techniques are being developed to account for the evolving thermo-mechanical and chemical processes associated with magma chamber recharge events. Such techniques are applied to volcanic centres that are experiencing periods of unrest to infer characteristics of the magma chamber including depth, overpressure, volume change and shape (e.g. Hickey et al. 2016; see Figure 6a). However numerical modelling of magma accumulation in the crust is generally one-dimensional.

Annen et al. published a series of papers that accounts for the generation of intermediate and silicic magmas in Deep Hot Zones based on a heat-transfer numerical model that simulates magma injection in the crust or crust-mantle boundary and calculates the conditions required for the accumulation of melt to build a reservoir of eruptible magma (e.g. Annen et al. 2006a; Annen et al. 2006b; Annen 2009). The equilibrium thermodynamic model is based on a heat balance between injected magma and surrounding rock; parameters such as density, specific heat capacity, temperature, time, melt fraction, latent heat of fusion, thermal conductivity and depth are included. These models have calculated that a 10 km thick pluton requires a magma flux that exceeds 10^{-2} km^3/yr to permit the development of a magma chamber with a volume of eruptible magma sufficient to feed the largest silicic explosive eruptions (Annen 2009).

The occurrence of plutons that are layered mafic intrusions (LMI's) has been invoked as a record of dynamic processes that can occur within magma chambers. Bons et al. (2014) developed a simple finite difference one-dimensional model that simulates the vertical profile of evolving crystal fraction of an initially liquid magma chamber. Similarly to 'traffic jam' theory, their models suggest that self-organization of crystals will occur in a cooling magma reservoir due to gravitational sorting of floating or settling crystals. The distance the crystals travel depends on parameters such as melt viscosity and cooling rate; as the crystals interact barriers may form which instigate layers to develop, each of which then undergoes similar crystal sorting. This could explain rhythmic layering but also larger scale zonation observed in large igneous bodies.

5.3 Testing magma chamber models

The numerical simulations and analogue models of magma chamber dynamics can be tested against modern case studies with recent volcanic activity (e.g. the Soufriere Hills volcano, Montserrat (Annen et al. 2014; see Figure 6b)) but also against the rock record to help interpret whether an exposed pluton was once a magma chamber or several discrete and small magma bodies (e.g. the Torres del Paine Intrusive Complex, Chile (Leuthold et al. 2012), and the Tuolumne Intrusive Suite, Sierra Nevada, USA (Coleman et al. 2004)). One current limitation of numerical models of magma chambers is that they are static and for example do not consider magma injection mechanisms. There is therefore scope for more interaction between numerical and analogue modellers of magma chambers, with great potential to advance our understanding of this dynamic and yet highly enigmatic component of volcanic systems.

6.0 Magma Intrusions

Magma transport through the crust is facilitated by a series of interconnected magma-filled sheet intrusions called dykes and sills (see Figure 1). Together these comprise a volcanic plumbing system that stores magma at depth but also can directly feed eruptions at the surface. A key assumption in many models is that sills are fed by dykes. The modelling approach depend on the assumptions on the controls of magma intrusion: 1) magma intrusion is modelled as a hydraulic fracture using the principles of linear elastic fracture mechanics (LEFM) and propagation is driven by fracturing of the host rock, or 2) magma intrudes as a viscous indenter and the growth dynamics are governed by the plastic deformation of the host and fluid properties of the magma.

6.1 Analogue models of sheet intrusion

To study the intrusion of magma-filled fractures in the laboratory, scaling of both magma and host-rock materials and their interaction needs to be considered. Two types of host-rock analogues are commonly used depending on the model being explored: gels such as gelatine for modelling intrusions as hydraulic fractures, and granular materials such as compacted silica flour to model them as viscous indenters. Magma analogues include air, water or a solidifying fluid such as vegetable oil (most frequently Vegeteline). Tables 1 and 2 describe material properties of magma and host-rock analogue materials and the combinations they have been used to study sheet intrusions.

6.1.1 Gelatine models of hydraulic fractures

Gelatine has been used as an analogue host material for magmatic sheet intrusions since Hubbert and Willis (1957) injected a plaster-of-Paris slurry 'fracturing fluid' into a gelatine solid to study hydraulic fractures (Figure 3a). For decades since, this material has been used to investigate the dynamics of magma intrusions considering a large range of parameters such as density contrasts between magma and host rock, impact of a stress field and mechanical layering of host rocks.

Gelatine mixtures are slightly denser than water (see Table 1), and the magma analogue that is used (e.g. air or water) is often buoyant and injected into the gelatine slab using a pump which supplies the fluid at a controlled flux or pressure. The dyke which is created takes the form of a penny-shaped crack, as expected by theoretical models of a pressurised fluid-filled crack in an elastic medium, but can become isolated from its injector (Takada 1990); in doing so its geometry changes from elliptical to teardrop with a rounded head and pinched lower tip (e.g. Weertman 1971, see Figure 7a for an example). Menand and Tait (2001) showed how liquid and gas mixtures injected into gelatine become segregated, with gas moving into the dyke tip region and liquid into the tail region. The buoyant gas then had a dominant control on the propagation dynamics of the dyke.

Impact of mechanical layering of the crust on magma intrusion

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Mechanical heterogeneities such as layering and the presence of discontinuities has been shown to influence the propagation of a fluid-filled crack in an elastic gelatine host material. Le Corvec et al. (2013) studied magma ascent in fractured crustal rocks by injecting air into a gelatine slab that has been pre-cut in its upper part to mimic the presence of faults and fractures in the lithosphere. They found that dyke geometry and dynamics were affected by the presence of the fractures, and a dyke would decelerate as it began to propagate between two fractures. A layered crustal analogue can be created by varying gelatine concentration (e.g. Kavanagh et al. 2013), and the strength of the bonded interface between layers is controlled by the temperature contrast between layers during experiment preparation (Kavanagh et al. 2015; 2017). The conversion from a dyke to a sill in gelatine experiments (e.g. Rivalta et al. 2005; Kavanagh et al. 2006) depends on the rigidity contrast between the layers and the fracture toughness (ability to resist fracture) of their bonded interface, with a rigid upper layer and weak interface being most favourable for the dyke-to-sill transition and dyke-sill hybrid structures formed in intermediate regimes (Kavanagh et al. 2017). Layered gelatine experiments have also been used to study laccolith emplacement whereby viscous grease was injected into layered-gelatine with a lubricated interface (Pollard 1973; Pollard & Johnson 1973; Johnson & Pollard 1973).

Interaction of magma-filled fractures with a stress field

The orientation of dykes in nature suggests they can be strongly influenced by the stress field in which they propagate, and this process has been explored in gelatine analogue experiments. Fiske and Jackson (1972) used a gelatine solid to study the impact of gravitational forces on the trajectory of magma injections in the crust applied to volcanic rifts in Hawaii (Figure 3b). They used a variety of moulded shapes of gelatine such as linear, ridge-shaped and curved-tapered ridge-shaped which visibly deformed due to gravity when released from their mould and adhered to a surface. When injected with dyed water the dykes moved laterally following the ridge axis (straight or curved). The experimental dykes were vertical, oriented perpendicular to the least compressive stress direction and propagated in the direction of the ridge. Subsequent gelatine studies have investigated dyke injection into a conical edifice (e.g. McGuire & Pullen 1989) and have explored the impact of the formation of a collapse scarp on dyke orientation (e.g. Walter & Troll 2003).

Dyke injection into gelatine under extension was studied by Daniels and Menand (2015) as an analogue for magma propagation in the Afar rift zone; extension was created by applying a uniform load to the entire surface of the gelatine and therefore compressing it from above with the gelatine slab margins moved outwards to occupy a water-filled margin. They found that the orientation of an experimental dyke in this environment was perpendicular to the maximum extensional stress, and that the dyke arrested beneath a thin rigid layer. Subsequent dyke orientations were affected by the ratio of the overpressure of the unerupted initial injection and the remote tensile stress, causing a rotation to occur. Menand et al. (2010) investigated the impact of stress reorientation on the propagation path of buoyant magma-filled fractures using air injected into gelatine. To create a lateral deviatoric compressive stress field in the initially hydrostatic slab, they inserted vertical plates between the solidified gelatine and tank walls exerting uniform compression across the whole slab such that σ_1 was horizontal and σ_3 was vertical. Their results showed that a buoyant, initially vertical dyke rotated to propagate horizontally and form a sill in response to the imposed stress field and following the direction of the maximum compressive stress σ_1. The impact of the load from a volcanic edifice on dyke propagation, dyke trajectory and eruption has also been studied using gelatine experiments (e.g. Hyndman and Alt 1987; Muller et al. 2001; Kervyn et al. 2009; see Figure 7b). When dyke injection was offset from the centre of the edifice it acted as an attractor to the dyke, causing the initially vertical trajectory to be deflected towards the load. Dyke ascent from directly beneath the edifice was initially vertical and then either stalled or changed to propagate laterally and caused a 'flank' eruption at the cone base (see Figure 7b).

Due to the photoelastic properties of gelatine, stress in the host material associated with the formation and growth of fluid-filled dykes and sills is shown in polarised light (e.g. Kavanagh et al. 2017; see Figure 7a and 8a). The evolution of incremental and finite strain in the deforming gelatine due to dyke, sill and hybrid intrusions has been quantified using DIC using passive-tracer particles suspended within the gelatine layers illuminated by a thin, vertical laser sheet (Kavanagh et al. 2015; 2017; see Figure 8b). This analysis has shown there are significant (up to 60%) decreases in strain around a feeder dyke as a sill forms (Kavanagh et al. 2015; 2017; see Figure 8c). As gelatine deformed elastically at the experimental conditions (e.g. Kavanagh et al. 2013; Van Otterloo and Cruden 2016), the decrease in strain correlates with a decrease in stress. At the feeder dyke margin this stress change can be directly linked to a decrease in fluid pressure when the sill forms (Kavanagh et al. 2015; 2017).

6.1.2 Compacted granular materials and viscous indenters

Compacted fine-grained silica flour has been used as a host-rock analogue where magma intrusion is modelled as a viscous indenter. This material can fail both in tension and in shear due to its non-negligible cohesion. Other comparable granular materials that have been used to study sheet intrusions include ignimbrite, diatomite and dry plaster powder which, in general, are fine grained frictional, cohesive and variably permeable (see Table 1 for material properties and Table 2 for host-rock and magma analogue combinations). Factors such as the surface deformation associated with sheet intrusion and the impact of mechanical layering and ambient stress field have been considered using these materials. As they are opaque this requires solidifying fluids to be injected (often Vegeteline, see Table 2) and then either the resulting intrusion is excavated post-emplacement and its dimensions linked to surface deformation (see Figure 8d for an example experiment setup), or a thin quasi-two-dimensional tank is used to show a cross-section through the experiment as intrusions form. A variety of analogue intrusions have been created in compacted silica flour experiments, ranging from cone sheets to dykes and sills (Galland et al. 2014; see Figure 7c). Galland et al. (2016) used the photogrammetry software MicMac to reconstruct their three-dimensional excavated solidified intrusions and geo-referenced these to the surface deformation that was produced. For sill emplacement, Galland (2012) noted the symmetrical up-doming of the initially flat experiment surface in response to the sill emplacement, with the complexity of the sub-surface intrusion that was later excavated being comparable to the complexity of the surface deformation it caused. The formation and growth of visible fractures, lateral and vertical displacement, and calculation of shear strain based on surface changes with time was mapped using DIC.

6.1.3 Solidification and viscosity effects

Experimental work has shown that the viscosity of the fluid within sheet intrusions can impact the geometry of dykes and sills as they propagate in their host material. Solidifying magma analogues used in dyke experiments include vegetable oil (Vegetaline), and viscous liquids such as golden syrup and honey (see Table 1). Solidification within dykes has been studied in gelatine experiments (e.g. Taisne and Tait 2011, Figure 7d) and show a transition in propagation behaviour of the dyke tip from continuous to step-wise; with progressive stalling, inflation and then breakout due to breach of an insulated and relatively low viscosity fluid from the intrusion interior through a cooled margin. Chanceaux and Menand (2014; 2016) formed sills between gelatine layers by injecting solidifying Vegetaline directly into an interface (Figure 8e-f). They found that the sill tip region has the tendency to become segmented especially when the injected fluid is viscous or has become more viscous due to solidification.

6.2 Numerical modelling of sheet intrusions

Numerical models of sheet intrusions are often two-dimensional and adhere to physics-based principles which consider the coupled transport of a viscous fluid through a host rock that deforms and fractures. Additional complexities such as heat exchange with the surroundings, magma cooling and solidification, impact of mechanical layering of the host, local or regional stress perturbations and the presence of weak discontinuities such as faults or fractures are sometimes considered, though rarely simultaneously due to the increased complexity.

Dyke propagation

A comprehensive review by Rivalta et al. (2015) explores the state of knowledge regarding dyke propagation models that use: 1) Weertman theory (1971), where the dyke is modelled as a buoyant magma-filled fracture, 2) lubrication theory (Spence et al. 1987; Lister 1990), where the dyke propagation is controlled by the flow of magma, or 3) a combination of both. A commonly used numerical approach to study dyke propagation is the boundary element method (BEM) (e.g. Dahm 2000; Muller et al. 2001; Maccaferri et al. 2011) which considers the coupling between magma pressure and rock deformation, using analytical solutions for elementary dislocations to represent a pressurised, propagating crack. Dyke propagation in a stress field, controls on dyke trajectory and tendency to form sills have been well studied numerically (e.g. Maccaferri et al. 2011; Barnett and Gudmundsson 2014). Three-dimensional FEM models are rare as they require re-meshing of the entire domain and so are more computationally demanding than the two-dimensional BEM approach, where re-meshing requires only that new elements are added to the dyke tip (see Figure 9a). The future of numerical model approaches to study dyke propagation will need to move towards three-

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dimensional simulations to account for the complexities that are apparent in field geology studies and geophysical surveys.

Sills and laccoliths

Numerical models of sills and laccoliths are often static, two-dimensional and axisymmetric. They commonly consider the evolving intrusion geometry and surrounding deformation of the host material by idealising deformation of the rock overburden as bending a stack of thin elastic plates, following the approach outlined by Pollard and Johnson (1973). Bunger and Cruden (2011) expanded the thin elastic plate theory to include fracture propagation criteria, fluid flow and the weight of the magma to explain the progression if the intrusion geometry from a bell-shaped geometry to flat-top and steep sided laccolith to thin disc-like morphology of large mafic sills over time (Figure 9b). In comparison, Michaut (2011) models shallow magma intrusions using nondimensionalization of the flow equation to describe magma spreading beneath an elastic crust, finding that the characteristic intrusion length depends on the elastic properties of the overburden and the characteristic intrusion thickness depends on the magma properties and the injection rate. Galland and Scheibert's (2013) model accounts for axisymmetrical uplift both above and outside the intrusion, and it has recently been used to invert for laccolith dimensions and depth associated with surface deformation at Cordón Caulle volcano during a rhyolite eruption in 2011 (Castro et al. 2016). Additional complexities such as accounting for natural topography, tackling non-axisymmetric intrusion geometries, assessing the impact of inelastic deformation of the host (e.g. Scheibert et al. 2017; see Figure 9c) and considering pressure variations within the intrusion result in a non-unique set of best-fit simulations when applying models.

6.3 Testing magma intrusion models

There are several challenges that mean testing magma transport models is not straightforward. By their very nature, magma intrusions are sub-surface features and so cannot be directly observed during their formation or when they are active. Insight into active intrusion processes in nature is typically interpreted based on analysis of surface deformation thought to be related to magma movement, and in combination with seismic data that is inferred to result from intrusion-related rock fracturing. Due to these limitations, there is much discussion in the literature regarding how to model dykes, either as hydraulic fractures or viscous indenters as described above, and how horizontal sheet intrusions (sills) relate to the construction of larger igneous bodies such as laccoliths and magma chambers.

Numerical models of a penny-shaped hydrofracture propagating in an infinite elastic material (e.g. Savitski and Detourney 2002) have been used to interpret the results of hydraulic fractures in gelatine experiments. Using measurements from gelatine experiments (e.g. intrusion dimensions, injection flux, fluid viscosity, host material Young's modulus and Poisson's ratio) it has been shown that dyke propagation occurs in a toughness-dominated regime, where the fracture properties of the host-material control the dynamics (e.g. Menand and Tait 2002). Recently this method has been applied to water-filled sill intrusions and similarly their growth was found to be better approximated by growth in a toughness-dominated regime, where a sill forms along an interface between layers and is fed by a dyke (Kavanagh et al. 2017). However, in some cases sill growth in gelatine experiments has been better explained by viscosity-controlled dynamics (e.g. Kavanagh et al. 2006; Chanceaux and Menand, 2016).

There is great potential to use analogue models and numerical models of magma intrusion in combination to assist the development of inversion methods to characterise magma intrusion geometry and depth in nature. The numerical models that calculate intrusion geometry and depth using ground deformation measurements such as GPS and InSAR at active volcanoes (e.g. Fukushima et al. 2005) could be tested on analogue models of magma intrusion where the volume, depth and geometry of the experimental dyke or sill is known. This comparison will enable the validation and improvement of inversion models, with the identification of any experiment parameters that are modelled well and those which are not to help guide future research for hazard assessment at active volcanoes.

7.0 Lava lakes and lava domes

7.1 Lava lakes

Lava lakes are effusions of lava either at the top of an open conduit (e.g. Halema'uma'u lava lake, Kilauea), or a ponded area of an active lava flow (e.g. Kilauea Iki 1959-1960, Kilauea, Hawaii (Richter et al. 1970)). There are several active lava lakes in the world, each with a range of hazards; from gas plumes and outpourings of lava, to explosions which could occur without warning.

Surface morphology

Techniques such as time-lapse photography have shown that lava lake surfaces in nature are highly dynamic parts of a volcanic system (Orr & Rea 2012), and spreading of the gradually cooling lava lake surface has been linked to convection in the underlying lake and conduit. Karlstrom & Manga (2006) used molten paraffin wax to study lava lake dynamics, monitoring the surface of the wax with infrared cameras. The wax surface was cooled before a partially submerged bar pulled the crust apart at a constant velocity along an incision in the wax surface. This formed zig-zag rifting morphologies reminiscent of structures described at natural lava lakes, and enabled the calculation of the spreading rate, crustal thickness and yield stress of the crust and thus the strength of the convective forces acting upon the underlying magma. Harris (2008) used numerical modelling to study convection of a molten lava lake fed by a conduit. In his models, an upwelling injection of hot, degassing, buoyant and less viscous magma rises through the conduit to the lava lake. Radiative heat loss and surface spreading then induces cooling and an increase in fluid density that causes down-welling of the magma, with the highest viscosity magma flowing back down the conduit. This model is supported by syrup analogue models of Beckett et al. (2011) where it was shown that different density fluids may flow past one another during exchange flow in the conduit.

Surface level variations

Fluctuations in lava lake level have been associated with gas exsolution. Witham et al. (2006) carried out a series of experiments that released air from a deep ‘chamber’ into a cuboidal conduit (1 x 1 x 18 cm) of water attached to an approximately cubic (14.1 x 14.1 x 15 cm) ‘lava lake’. Gas was released into the base of the conduit using a compressor; this decreased the water-air density, causing the bubbly mixture to rise into the surface reservoir due to buoyancy, resulting in an increased lava lake level. Gas was then released from the water at the surface of the higher reservoir, progressively increasing the hydrostatic pressure. Eventually the hydrostatic pressure of degassed-water in the lake exceeded the pressure from below, preventing further rise of gas-rich water and resulting in collapse of the conduit, fluid flow back down into chamber and lowering of the lake level. These analogue experiment results show that rising lava lake levels in nature could be explained by periods of increased gas emission from the chamber through the conduit, and that decreases in lake level could

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occur when the magma-static pressure in the overlying magma column exceeds the pressure of the rising magma.

7.2 Lava Domes

Lava domes are effusions of degassed, highly viscous, silica-rich magma that accumulate at volcanic vents. Their emplacement can cause the build-up of gas and pressure in the conduit, increasing the potential for explosive eruptions or the formation of pyroclastic density currents. Modelling lava dome emplacement and stability is key for identifying thresholds for collapse and therefore for assessing the potential risk of such events. Aspects of lava dome emplacement that have been studied in analogue experiments include morphological variations due to topography, magma rheology and the preservation of flow fabrics using magnetic fabrics.

Dome morphology

Analogue models of lava domes have largely focussed on the influence of lava rheology on dome morphology. Griffiths & Fink (1993) investigated the progressive spreading of lava domes by effusing liquid PEG 600 wax into a tank of cold sugar solution with a horizontal base. The temperature gradient between the wax and solution caused the onset of solidification, and the lava viscosity had a large influence on the morphology of the dome that was formed. Fink & Bridges (1995) found that pulsating the wax effusion and decreasing its temperature resulted in predominantly vertical growth of the dome rather than flow away from the vent, and so the length of lava domes could be explained primarily by variations in effusion rate.

Several lines of evidence suggest that lava dome rheology in nature is more complex than a simple temperature-dependent Newtonian fluid. Balmforth et al. (2000) carried out numerical simulations of lava dome growth and evolution using a Herschel-Buckley rheology. They found that the yield stress acting in the dome is important in determining dome morphology, however the combined effects of shear-thinning and yield stresses were difficult to distinguish. Experimentally, Griffiths and Fink (1997) used a PEG-kaolin mixture to study lava dome morphology with the kaolin powder converting the fluid from a temperature-dependent Newtonian fluid to a Bingham fluid. These analogue lava domes produced spines and irregular breakouts of wax (Figure 10a) due to the yield strength of the magma analogue. Lyman et al. (2004) used a similar mixture to investigate the impact of slope and effusion rate on dome morphology. They found that contrasting dome morphologies (e.g., platy, spines, lobes) were associated with extrusion onto a surface at different slope angle, but that the effusion rate had the greatest impact on dome morphology. These results can be compared to lava dome morphologies in nature, such as Wilson Butte in California (Lyman et al., 2004), to calculate the effusion rate of prehistoric domes.

Internal deformation

Internal flow patterns within lava domes in nature has been inferred from crystalline and bubble fabrics within the crystalline lava, thus providing insight into the processes occurring within a dome during formation. Závada et al. (2009) studied magnetic fabric development within lava domes by effusing plaster of Paris seeded with magnetite particles from a point source, injecting with increasing pressure onto a deformable surface of sand (Figure 10b). The plaster of Paris and magnetite mixture behaves as a shear thinning fluid and was allowed to solidify once extruded. The solidified dome was then cut into slices and oriented samples drilled for analysis by applying Anisotropy of Magnetic Susceptibility (AMS) to quantify the direction and intensity of any fabric that was developed by the magnetite particles during the extrusion of the lava dome. They found more concentrated suspensions with higher viscosity created complex dome structures that had relatively steep sides, akin to lava domes commonly observed in nature.

8.0 Volcanic flows

Analogue and numerical modelling has been extensively applied to investigate the processes involved in the eruption, emplacement and deposition of hazardous flows such as lava flows, pyroclastic flows, lahars, debris flows and jökulhlaups (see Figure 1). The application of analogue modelling to volcanic flows has largely focused on understanding small-scale dynamic processes, such as granular interaction or controls on sedimentation, and the role of these processes on the large scale phenomena are commonly simulated in numerical models. Numerical models are driven by field observations and theoretical frameworks but also provide a stimulus for interpreting observations and recognizing new phenomena. Two types of modelling are used in the numerical simulation of volcanic flows; those applied to investigate the physical process behind flow emplacement, and those used in hazard assessment. Numerical models developed to reproduce volcanic phenomena are typically deterministic and as such are more complex, have a large range of input parameters, and can have long run times. In comparison, models used for hazard assessment tend to simplify the physical problem by making several assumptions and characterising complex phenomena in terms of coefficients. As such, hazard assessment models are much more computationally efficient and can be used in real time.

8.1 Lava flows

8.1.1 Analogue models of lava flow dynamics

The emplacement dynamics and morphology of lava flows has been investigated experimentally using a range of fluids (see Tables 1 and 2) and considering a spectrum of rheologies, from Newtonian fluids (e.g. glucose syrup; Stasiuk et al. 1993) to more complex fluids that account for cooling, crystallisation and develop a solidified crust during flow (e.g. PEG wax (e.g. Hallworth et al. 1987; Fink & Griffiths 1990; Gregg & Fink 1995). These experiments model variations in heat flux, thermal gradients and cooling on the temporal and spatial variation of lava flow viscosity, extrapolating on the impact these factors have on e.g. runout length and flow morphology.

Lavas have been modelled in the laboratory as a particle suspension, with experiments showing that increasing particle volume fraction (Soule & Cashman 2005; Castruccio et al. 2014) and particle size (Del Gaudio et al. 2013) increases lava viscosity and can affect lava flow morphology. High concentration particle suspensions produce low flow velocities, shear localisation and subsequent break-up of the flow surface, causing transition from pahoehoe-like to ‘a’a-like morphologies that are reminiscent of natural flows in nature (Soule & Cashman 2005).

Lava levees, crust formation and breakout

Critical in the evolution of lava fields is the development of lava levees, crust formation and progressive breakout. This has been investigated in the laboratory using paraffin wax where the progressive cooling of the hot, liquid wax causes levees to form and channelization of the flow (Blake & Bruno 2000; Miyamoto et al. 2001; Nolan 2014). Crust formation over the cooling flow surface insulates the molten wax and creates tube-fed flows, and blockages or restrictions in the tube-fed flow of wax to the flow lead to flow inflation and eventually breakout from the crust. Blake & Bruno (2000) used PEG wax experiments to demonstrate the link between lava effusion rate, lava viscosity and strength of the chilled crust which impacts how and where breakouts from lobate structures occur. Karlstrom & Manga (2006) used spreading paraffin wax experiments to study the morphological transition from pahoehoe to ‘a’a flows due to breakouts from the cooled, spreading crust (also see section 7.1 on lava lakes).

Substrate erosion

Field observations of erosion channels within lava tubes suggest that assimilation of the lava substrate can occur when lava flows are emplaced with high heat flux or flow over substrate with a low melting temperature. Huppert and Sparks (1985) investigated the development of thermal erosion channels in komatiite lava flows by pouring hot water onto a slab of PEG 1000 wax; Komatiite lavas are thought to have had unusually high heat flux, and so thermal erosion of their substrate is expected to have been an important process in the development of these ancient flows. Kerr (2001) used theoretical models alongside molten PEG 600 effused onto an inclined sheet of solid PEG 600 (Figure 11a) to investigate how the thermal profile of lava flows evolves both spatially and temporally. His experimental results agreed with the theoretical models which showed that there is a critical thickness range at which chilled margin formation at the base of the flow ceases and erosion begins, depending on the initial temperature of the lava; for basaltic lavas on Hawai’i, this range is 7.3 to 34 cm after a period of 0.21 to 4.6 days.

Flow indicators

When studying ancient solidified flows in nature, crystal distribution and stretched bubbles have been used to infer flow direction. The preservation of flow indicators in solidified lavas was investigated in analogue experiments using layered viscous silicone to model internal strain within extruding and spreading fluids (Gilbert & Merle 1987). The experiments showed that in channelized flows, or at the base of a lobe, the lava flow trajectory indicators could be both parallel and perpendicular to each other in the upper portion of lobes. When applied to lava flows in nature, such observations can explain emplacement mechanisms and possibly account for variations in deformed bubble and crystal shape-preferred orientations compared to AMS fabrics in different parts of the flow (e.g. Caballero-Miranda et al. 2016). Solidification and development of columnar jointing in lava flows has been modelled using corn starch slurries that are placed under heat lamps to allow the water to evaporate away (Goehring & Morris 2005; Müller 1998). The loss of water was used as an analogue for heat loss within lavas; as the starch dries out it shrinks, resulting in cracks forming and propagating through the material (Figure 11b). The morphology of the vertical columns formed within the analogue lava correlates well with the morphology of columns in natural lava lakes and ponded lava flows such as in Hawaii (Goehring et al. 2006; Müller 1998) or the Giant's Causeway in Northern Ireland (Goehring & Morris 2005). However, further rheological studies to understand better the material properties are needed to improve scaling these experiments to nature.

8.1.2 Numerical modelling

Numerical models of lava flows have been applied to investigate the dynamics of lava flow emplacement, for example the controls on flow length. Lava flow emplacement models have been used to simulate edifice growth from the accumulation of multiple lava flows (Annen et al. 2001), the insulating properties of lava tubes (Keszthelyi 1995), cooling of pahoehoe lavas (Keszthelyi & Denlinger 1996) and formation of lava levées (Quareni et al. 2004). Lava flows have been modelled using a range of numerical techniques, from the simulation of physical process of emplacement using Navier Stokes equations with simplified equations of state, to probabilistic assessment of lava flow inundation. Particular emphasis has been on investigating the effects of rheology on flow behaviour. Robertson and Kerr (2012) analysed the effects of viscoplastic lava rheology on lava flow dynamics by modelling the flow as a Bingham fluid within a rectangular flow. Their results show that the formation of plug regions have a large impact on modelled flow velocities. Castruccio et al. (2014) apply the Herschel-Bulkley model to investigate the rheology and infer eruption source conditions, for example flow rate, of lava flows using observed lava flow dimensions and petrological and validate model results with analogue model results.

Numerical models are the main tool for hazard and risk assessment of lava flows, in particular inundation. For these purposes, simulated lava flows are emplaced over a DEM to predict the inundation pathways of flows. Cellular automata models are commonly used for hazard assessment (e.g. Miyamoto & Sasaki 1997; Crisci et al. 2004; Vicari et al. 2007; Connor et al. 2012; Rongo et al. 2016) (Figure 11c). In these models, the area of interest is discretised into a regular grid of cells, with each cell having a finite number of states. In the case of lava flow

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modelling, these states generally reflect the whether a cell has been inundated or not. In Connor et al. (2012), the probability of a cell being inundated is dependent on the relation between the elevation of the empty cell and the thickness of the lava in neighbouring cells. Such models assume a given volume is erupted, with this volume being distributed amongst the inundated cells. While these models do not provide insight into the physical process of lava flow emplacement, their simplicity and computational efficiency means that they can be run many times using, for example using Monte Carlo simulations, to produce probability assessments of inundated areas.

8.2 Particle-laden flows

Particulate-laden flows are one of the most hazardous phenomena associated with explosive volcanic eruptions. Pyroclastic density currents and lahars can impact areas hundreds of kilometres from source. Our understanding of pyroclastic density current and lahar processes is particularly reliant on numerical and analogue modelling, due to the hazardous nature of the phenomenon.

8.2.1 Pyroclastic density currents

The term pyroclastic density current (PDC) encompasses a wide range of flows from dilute surges, to dense flows, block-and-ash flows and pumice flows; they represent a wide-ranging spectrum of flow behaviour from dense to dilute (Branney & Kokelaar 2002; Sulpizio & Dellino 2008). Such flows occur as a mixture of particles and gas is emplaced as a gravity current which propagates down the slopes of a volcano and are related to, for example, collapse of a volcanic column or lava dome.

For the purposes of this overview, it is sufficient to consider a pyroclastic flow as divided into two main parts: a dense basal portion where movement is controlled by particle-particle interaction, and an overlying turbulent dilute region that is composed of ash and gas. It is not well understood how these distinct portions of the pyroclastic density current interact; this complexity and additional numerical challenges, have resulted in analogue and numerical modelling techniques typically representing either the lower dense portion of the flow (e.g. the flow simulation software TITAN2D) or the dilute portion of the flow (e.g. Bursik & Woods 1996; Andrews & Manga 2011).

Analogue models of PDCs

Some of the first analogue experiments to investigate controls on pyroclastic density current propagation involved the injection of dense, sometimes particle laden, fluid into less dense fluid (Carey et al. 1988; Huppert et al. 1986; Sparks et al. 1993; Woods & Bursik 1994; Woods & Caulfield 1992). In the example of Carey et al. (1988), buoyant plumes were produced by injection of particle laden freshwater into saline water. Flows formed when the particle concentration of the injected fluid was large such that the density difference with the ambient was negligible, leading to collapse of the plume. Woods and Bursik (1994), specifically focused on the movement of flows on slopes and their interaction with topographic barriers (Figure 12a). In this example, dense fluid was made of a mixture of methanol and ethylene glycol (MEG) which was injected or released into water. Such experiments provided information on the control of entrainment on flow density, and controls of topography on both entrainment and sedimentation from a flow. More recently analogue experiments have considered the effect of interstitial pore pressure on flow motion (Figure 12b) (Roche 2012; Rowley et al. 2014) and the controls on co-ignimbrite plume formation from dilute flows using talc to represent fine grained ash particles (Andrews & Manga 2011; 2012). As for all analogue experiments, scaling is a key issue when designing experiments to simulate explosive eruptive phenomena. However, over the past 5 – 10 years, significant effort has focused on the development of so-called 'large-scale' experimental setups to overcome this (Figure 12c) (Dellino et al. 2007; Lube et al. 2015; Valentine et al. 2015) and try to more accurately reproduce observed phenomena. Such modelling also allows the use of natural eruptive pyroclastic materials to more accurately reproduce the physical dynamics, states and relations that occur within real flows.

PDC Numerical models

Numerical models that describe either the dilute- or dense- end member flow are typically depth averaged, and solve equations for conservation of mass, momentum and thermal energy (e.g. Bursik and Woods 1996). Such models are also steady state, and therefore do not account for changes in flow behaviour with time. An example of a numerical model that has been developed to account for both the turbulent upper layer and the dense layer is the transient model of Doyle et al. (2008). In this model, the dilute current is described by depth averaged, isothermal, continuum conservation equations, while the basal flow is modelled as a granular avalanche of constant density.

In addition to the production of separate models to account for different physical processes, numerical models of varying complexity also exist. Numerical models have been developed that consider dilute particle-laden gravity currents (e.g. Bursik & Woods 1996; Dade & Huppert 1996) to calculate properties such as velocity, temperature and density of the flows. These calculations have a small number of parameters and as such involve a number of simplifications, allowing parametric studies to be conducted to understand the control of inputs on the modelled outputs. The advancement of computational efficiency has enabled the development of supercomputer calculations, solving full Navier-Stokes equations for flows and fountains (Valentine et al. 1992; Neri & Dobran 1994; Esposti Ongaro et al. 2012). These are elaborate computer codes, incorporating a large number of input parameters, and solving for a number of different phases, for example fluid (magmatic and atmospheric gases) and particles of different sizes and density simultaneously (Figure 12d). While numerical studies of pyroclastic density currents still largely follow these two strands, open source computational fluid dynamics programs (e.g MFix and OpenFOAM) are being increasingly used to capture the multiphase behaviour that occurs within these volcanic flows. A comprehensive overview of the numerical models describing pyroclastic density currents is provided in Dufek (2016).

8.2.2 Lahars

Primary lahars form when an eruption causes melting of ice overlying the volcano, and eruptive products mix with melt water to produce high-density mixtures of water and debris. Secondary lahars form as debris emitted by an eruption is mobilized after deposition, usually in relation to heavy rainfall between eruptive events.

Similarly to pyroclastic density currents, lahars can be described by two end members: stream flows and debris flows, but with an intermediate flow type called hyper-concentrated flows. Flow type can vary within an individual event both spatially and temporally, in association with changes in channel and underlying topography (e.g. Manville et al. 2013). Definition of lahar flow type is dependent on the concentration of particles, with stream flows representing those with low particle concentrations and debris flows with high particle

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concentration. The flow end members have very different rheology, and as a result the application of both analogue and numerical modelling techniques are affected by similar challenges to those for pyroclastic density current.

Lahar analogue experiments have largely considered debris flows, i.e. those with high particle concentration. As for pyroclastic density currents, both small (metre) and large (tens of meters) scale analogue experiments have been conducted. Iverson (2015) showed that experiments of debris flows are particularly susceptible to scaling issues. The USGS has developed a 95 metre long flume that allows the release and flow of 10 m^3 of water-saturated sediment onto a bed with variable roughness to closely mimic conditions in natural debris flows (Iverson et al. 2010; 2011).

In comparison to the number of models available to simulate the emplacement of pyroclastic density currents, there are relatively few models that simulate lahars. Numerical modelling of lahar dynamics is non-trivial due to spatial and temporal variation in flow behaviour, for example rheology (see Manville et al. 2013). Perhaps the most commonly used numerical model to simulate lahar emplacement is LAHARZ (Schilling 2014), a computational model that uses empirical relations of past inundation events to forecast inundation for a given future event. More complex numerical models applied to lahars include a version of TITAN2D that accounts for both particles and fluids (Pitman et al. 2003; Williams et al. 2008), the commercial hydraulic model Delft3D (Carrivick et al. 2008), GIS-based models (Darnell et al. 2012), and application of models more typically applied to water floods, e.g. LISFLOOD. No single model can account for the all the different phenomena described above, due to the complex interactions between the solid and liquid phases. As such, research into the rheology of lahars is required to provide a description of the underlying physics to be utilized in numerical models.

9.0 Volcanic plumes

Much of our current understanding of plume dynamics can be traced back to the 1950's and the work of Morton et al. (1956) (see Figure 3c). While not focusing specifically on volcanic plumes, their study has been the basis for much of the subsequent research into volcanic plumes using analogue modelling and numerical models to reproduce behaviour observed in nature.

9.1 Analogue models of volcanic plumes

Traditional analogue modelling of volcanic plumes has involved the injection of a less dense fluid (e.g. fresh water or methanol) into a tank of denser fluid (e.g. saline fluid or ethylene-glycol respectively). The difference in densities between the two fluids allows the less dense fluid to rise through the dense fluid, reproducing those characteristics associated with buoyancy plume rise (see Figure 13a Carey et al. 1988). Injection into a stratified fluid enables not only modelling of plume rise, but also the dynamics of plume spreading once the injected mixture reaches neutral density (e.g. Carey et al. 1988). Variation in the injection rate provides first order information on plume dynamics, and in particular on the controls on column collapse (Woods & Caulfield 2007; Kaminski et al. 2005). In some examples, the injected fluid is particle laden to investigate the additional effect of particle sedimentation and re-entrainment on buoyant columns (Ernst et al. 1994 and Carey et al. 1988), such that experimental observations can be related to those seen in ash fallout deposits in the field. In particular, Ernst et al. (1994) looked at the effect of wind on volcanic plumes, reproducing the bifurcation of the plume. These experiments are based around buoyant theory, and therefore ignore the processes occurring in the jet region of the plume, where dynamics are controlled by the upward velocity of material as it is ejected from vent. Such laboratory experiments underlie the one-dimensional numerical models currently used to investigate volcanic plume behaviour and inform inputs for ash dispersal models widely used today.

A key issue with analogue modelling of volcanic plume dynamics is scaling, particularly when considering that plumes in nature are injected into a stratified and turbulent atmosphere and are affected by local weather patterns. To account for such scaling issues, macro scale experiments are increasingly applied to investigate eruption processes (e.g. Dellino et al. 2014; Figure 13b). These experiments, which often use natural materials, have enabled analysis of the effect of vent conditions and processes on subsequent eruption behaviour, and in particular have been used to estimate the rate at which air is entrained into the rising plume, a key input parameter for numerical modelling of plume rise (Costa et al. 2016).

9.2 Numerical models of volcanic plumes

Numerical models of volcanic plumes serve two main purposes: 1) to provide input information (for example plume height and mass flux of ash into the atmosphere) for ash-

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dispersal models, and 2) to investigate the controls on these parameters. Two types of numerical model are available; one-dimensional (integral) models and multicomponent multiphase three-dimensional models.

9.2.1 One-dimensional numerical models of volcanic plumes

One-dimensional models (Figure 13c) are commonly used for defining source parameters for ash dispersal models, largely because they are computationally inexpensive, and results can be acquired quickly. These models account for conservation of mass, momentum and energy, and are largely based around the model developed by Morton et al. (1956), with the constituent equations modified for application to the volcanic example by Wilson and Walker (1987), Sparks (1986) and Woods (1988). Since the 2010 eruption of Eyjafjallajokull, there has been increased emphasis on development of models that are able to account for the effects of wind on a rising plume (e.g. Woodhouse et al. 2013; Degruyter & Bonadonna 2013). The models assume that the emitted gas and particles are in dynamic and thermal equilibrium; an approximation that is reasonable for dilute, fine grained plumes but is less appropriate in the jet part of the plume. To address this, Kaminski et al. (2005) and Carazzo et al. (2008) developed a modified Reynolds number dependent entrainment law to account for the negative buoyancy in the jet portion of the plume.

Entrainment coefficients are key inputs for plume models, and these parameters have been the focus of much research in recent years. Entrainment in one-dimensional models is captured using two additive entrainment parameters, one accounting for radial entrainment associated with the incorporation of ambient air by turbulent eddies at the plume edge, and the second accounting for the effect of wind on air entrainment. The first coefficient has been well defined using observations from analogue experiments of turbulent jets (Kaminski et al. 2005). In comparison, the second coefficient is still relatively poorly constrained, and requires more targeted experiments, both analogue and using three-dimensional numerical models.

9.2.2 Three-dimensional numerical models of volcanic plumes

While modifications to one-dimensional axisymmetric models have been relatively minor over the past 60 years, there have been great advancements in the application of more complex three-dimensional models. Great improvements in computational efficiency have enabled the development of increasingly sophisticated models (e.g. Figure 13d; Cerminara et

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al. 2016). These models are able to account for a larger range of particle sizes, over much greater scales than possible previously (e.g. Woods 1988), and are increasingly used to investigate the assumptions utilized in one-dimensional models (Suzuki & Koyaguchi 2015). Three-dimensional models are increasingly able to account for small-scale processes, for example turbulence and microphysics (Cerminara et al. 2016; Herzog & Graf 2010; Suzuki & Koyaguchi 2012), on plume behaviour. Within such three-dimensional models, gas and ash phases are treated as intermingled continua, accounting for mass and momentum transfer between the phases. Such models are utilized in an experimental way, and provide detailed insights into plume processes. Despite these great advances in three-dimensional numerical modelling capabilities, there is still a large amount to learn about the relative motion of particles and gas. In addition, further detailed laboratory analysis is required to understand variation of entrainment under real atmospheric conditions, particularly when under the influence of wind. From a practical point of view, while results are likely more accurate than those from one-dimensional models, the application of three-dimensional numerical models is still limited by computational efficiency, and their results may take many weeks to process and interpret.

10.0 Ash dispersal models

Perhaps the most disruptive aspect of an explosive eruption in terms of geographical scale is the injection of volcanic ash into the atmosphere. Ash can be transported hundreds to thousands of kilometres downwind from the source, impacting aviation and downwind communities and infrastructure. Ash dispersal is controlled by a complex relationship between volcanic source and atmospheric conditions; proximal to source dispersion is almost completely controlled by the characteristics of the eruption, while distally, atmospheric physics take over. Given the potential for significant disruption over long timescales, large amounts of research has focused on the mechanisms controlling both ash dispersal and deposition.

10.1 Analogue models of ash dispersal

Analogue modelling of ash transport in the atmosphere predominantly relates to near source processes and to investigating controls on sedimentation. A number of studies have focused on the intrusion of the volcanic plume as a buoyancy driven gravity current (e.g. Didden &

Maxworthy 1982; Ivey & Blake 1985; Bursik et al. 1992; Kotsovinos 2000) into the atmosphere. In these examples, a dense fluid is injected into a stratified fluid and the less dense fluid rises through the dense fluid until it reaches its level of neutral buoyancy and begins to spread laterally.

A considerable number of experiments have focused on the physical controls on sedimentation, and constraining parameters such as particle terminal settling velocity. Koyaguchi et al. (2009) specifically focused on the effects of turbulence on particle dispersion in the atmosphere by mixing spherical glass-bead particles in water with various intensities of turbulence and measuring the spatial distribution and temporal evolution of the particle concentration. These experiments provide insight into the settling behaviour of particles within a turbulent regime, with results providing information on how particles are dispersed during an eruption. Particle terminal settling velocity is estimated by dropping particles with well-constrained characteristics through a fluid of a known density and viscosity (E.g. Dioguardi et al. 2016). Analogue experiments have been used to quantify the effect of the interactions between particles, but also particle-fluid interaction, on sedimentation (Del Bello et al. 2017), by releasing different volume fractions of ash at variable discharge rates through a chamber. Particle settling behaviour was captured using high-speed cameras, which showed a large increase in settling rate with increase in particle volume fraction. The results were validated by numerical simulation of particle behaviour. Manzella et al. (2015) also looked at the effect of volume fraction of ash on settling behaviour, reproducing the gravitational instabilities noted in field observations by mixing high concentrations of ash into water. Finally, significant research has focused on how different particles interact with each, in particular in relation to the formation of particle aggregates (Mueller et al. 2016). In such example, as particles are released into a tank, and their sticking efficiency is measured using high-speed camera imaging.

10.2 Numerical models of ash dispersal

Dispersal models are used to simulate the dispersal of particulate matter and gases during a volcanic eruption, and in comparison to analogue models, generally focus on more distal dispersal. In the case of particulate matter, the dispersion models have two main roles; to forecast the dispersion of ash during a volcanic eruption, and to reproduce ancient eruptions by fitting model results to observed deposit distributions. Numerical modelling of volcanic ash in the atmosphere requires the definition of three components (Folch 2012): 1) the source describing the emission of particles and gas in the atmosphere, 2) an atmospheric model (typically offline, providing information at fixed locations at regular time intervals) describing the physical characteristics of the environment into which the plume is injected, and 3) the transport model which describes how the particles are transported.

Two main types of numerical models exist: a) buoyancy models that consider near source plume characteristics, assume intrusion of the ash as a buoyant current and simulate the deposition of coarse ash, and b) advection-diffusion ash transport models (Folch 2012). Buoyant plume models describe the horizontal intrusion of volcanic plumes into the atmosphere as a gravity current (Bursik et al. 1992; Baines et al. 2008; Suzuki & Koyaguchi 2009; Johnson et al. 2015). They are capable of reproducing both upwind dispersal (e.g. Baines et al. 2008) and plume thickness variation (Johnson et al. 2015, which are key considerations when assessing hazard to aviation. However, the majority of ash models utilized to predict ash transport in the atmosphere are based on the advection of particles by atmospheric winds, and the diffusion of ash by atmospheric turbulence (Folch 2012). A number of different types of such tephra transport and dispersal models exist, and a comprehensive review is provided in Bonadonna et al. (2011) and Folch (2012); they are favoured as they are computationally efficient, allowing results in the order of 10's of minutes. Transport models are typically Eulerian, solving for variable particles at fixed locations, or Lagrangian, calculating the trajectories of a parcel of 'particles' and computing mass concentration by averaging over the background. Advection-diffusion models predict ash dispersion through the action of vertical wind shear, which can disperse ash in different directions at different altitudes. Their results are therefore highly dependent on the wind field that is used.

Characterization of depositional processes is crucial for interpreting volcanic deposits, however these are only accounted for in numerical models to a limited extent. Recent advances in numerical modelling have aimed to incorporate the effects of aggregation (Folch et al. 2016) and buoyancy forces (Costa et al. 2013) on plume dispersal. Attempts to include aggregation in simulations are somewhat simplistic and are generally conducted by fixing a priori input grainsize distributions rather than accounting for the physics of the process (e.g. Cornell et al. 1983).

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11.0 Perspectives and Conclusions

This review provides an overview of the development of modelling in volcanology, describing some of the first experiments carried out using analogue materials and the development of numerical models to describe volcanic phenomenon. It has not been possible to consider all aspects of the volcanic system in detail meaning that some important research will undoubtedly not be included here. By focusing on sub-surface processes such as magma flow, magma chamber development and magma intrusion, and extrusive processes such as the development of hazardous flows, volcanic plumes and ash dispersal we have identified emerging lines of thought and make four suggestions listed below that point towards the future of modelling in volcanology.

1. <u>Increased interaction between analogue and numerical modelling communities</u>

There is great potential to improve the interaction between analogue and numerical modelling communities, and to develop iterative processes using both techniques to test against data derived from nature. Scaled laboratory experiments allow us to observe and understand physical processes and test basic assumptions; and in parallel with this, numerical simulations model and enable the quantification of processes that are too complex, too large or last too long to be reproduced in the lab. The approaches are therefore highly complementary. Adopting an engineering approach of systematically testing a numerical simulation against the expected outcomes from a scaled analogue experiment would be a positive step towards integrating these techniques.

A number of studies of volcanic processes using numerical modelling (e.g. Scollo et al. (2008) and Costa et al. (2016), and references therein) have shown how statistical techniques such as uncertainty quantification and sensitivity analysis can be used to systematically evaluate numerical models. The effect model input uncertainties have on the model outputs, and the interaction of inputs within the model, is evaluated highlighting important interdependencies. A key advancement in the application of numerical techniques is the way in which they are applied with the use of ensemble modelling, where several different models are applied to investigate the most likely outcomes. Such techniques are well used in other sciences, for example in climate studies, but have yet to be systematically utilized in volcanology.

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2. Implement benchmarking exercises and systematic review

Analogue and numerical models in volcanology study processes that span the crust-mantle interface into the stratosphere and cross orders of magnitude in time and space. The objectives of any model are carefully defined, and different approaches need to be considered depending the application. Models that are developed in the laboratory or numerically are ultimately limited by the conceptual models they simulate, and these will be based upon diverse data sources such as geochemistry, petrology, geophysics, real-time observations and field geology. Referring the model outputs back to known outcomes based on observations from nature is a fundamental step that ensures the model boundary conditions are well informed.

Benchmarking has been employed for modelling tectonic processes (e.g. Schreurs et al. 2006) and similar exercises would be of benefit in volcanology. A recent benchmarking operation of numerical modelling of volcanic behaviour was undertaken by Costa et al (2016) and demonstrated the benefits of this but was limited as the models tested against each other all have the same underlying assumptions. Further testing against observed eruptions would allow continued examination of the validity of these assumptions. However, similar exercises are needed for analogue modelling in volcanology.

3. Periodic review of conceptual modelling framework

In many cases the conceptual models of physical processes in volcanology are constantly evolving, and new insights and developments that come from advancements in formative fields have the potential to revolutionise the framework upon which the analogue and numerical models are based. For example, in the case of magma chambers there is current discussion regarding their formation (see Sparks and Cashman 2017 for a review) and relationship with plutonic bodies (see Lundstrom and Galzner (2016) and papers in the same Volume for discussions). Advancement in geochronology has meant that high resolution dating of ancient magma bodies is now possible, and has since demonstrated that in at least certain case studies the magma was emplaced over a timescale that is longer than the thermal lifetime such large magma masses (Galzner et al. 2004). Consequently, plutons are now thought to have been accreted by the in-situ amalgamation of many small increments and

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the relationship between magma chambers and plutons and the numerical and analogue models that are used to study them are being revisited.

4. Utilise a multidisciplinary approach

Volcanology as a discipline has significantly benefitted from the understanding and technological advancements across diverse fields, from engineering to material science. Fluid dynamics theory has been applied to study all parts of the volcanic system, for example plume theory that was initially developed to study factory emissions has been applied to the development of ash plumes but also the injection of hot, buoyant magma into the base of a magma chamber. The combination of field observations with geophysical analysis and monitoring techniques has enabled construction of informed conceptual models and hypotheses; these have then been tested in the laboratory using analogue experiments or computationally using numerical modelling. It is clear that the most significant advancements have come from utilising a multidisciplinary approach, and this needs to be developed further in order to push the frontiers of volcanology.

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Tables and Captions

Table 1. Properties of analogue materials used to model magmas and lavas for rheology and processes. *Material not currently used in analogue modeling of volcanic processes however displays properties that may lead to its future use.

System Component	Material	Key Properties: Rheology or Mechanical Behaviour	Key Properties: e.g. Viscosity, density, strength	Example reference
Magma or Lava analogues				
Syrups	Corn syrup	Newtonian	180 Pa s at 22 °C	Rust and Manga (2002b)
	Glucose syrup	T-dependant Newtonian	454.7 Pa s at 20 °C	Schellart (2011)
	Golden Syrup	Newtonian	50-78 Pa s at 20 °C	Castruccio et al. (2010)
	Honey	Newtonian	200 Pa s at 22 °C	Mathieu et al. (2008)
Oils	Glycerine	Newtonian	Density of 1.26 g cm^{3} viscosity of 7.7 cm s^{-1}	Huppert and Hallworth (2007)
	Silicon oil	Newtonian	41.32 Pa s at 25 °C	Mueller et al. (2009)
	Vegetable oil (Vegetaline)	Newtonian	2 x 10^{-2} Pa s at 50 °C	Galland et al. (2006)
Waxes	Paraffin	T-dependant Newtonian	10 Pa s at 52 °C	Rossetti et al. (1999)
	Polyethylene glycol (PEG)	T-dependant Newtonian	0.18 Pa s at 21 °C	Griffiths and Fink (1997)
Other	Air	Gas		
	Water	Newtonian	Density of 0.9982 g cm^{3} and viscosity of 0.01 cm s^{-1} at 20 °C	Huppert and Hallworth (2007)
	RTV silicone	Newtonian	When freshly exposed to air 25 Pa s solidifying after c. 5 hours	Gressier et al. (2010)
	Silicone putty	Viscoelastic/ Newtonian	Density of 1.12-1.14 g/cm^{3}. Viscosities of 2-2.57 x 10^{4} Pa s at 24 °C	Ramberg (1970)
	Gum rosin with 21.8% acetone	Newtonian	1.07 Pa s at room temperature	Lane et al. (2001)
	Hair gel	Shear thinning	27 Pa s at room temperature	Castruccio et al. (2014)
	Shaving foam	Viscoelastic	172 Pa s at room temperature	Bagdassarov and Pinkerton (2004)

	Collophony and ethyl phthalate mixtures	Viscoelastic	5.73×10^6 Pa s at 22 °C. Collophony mixtures are almost Newtonian at low stress	Ramberg (1970)
	Plaster of Paris and water suspensions (2.2 to 2.6 ratio)	Shear thinning	Viscosity of 0.8 - 6.2 Pa s shear rate dependant	Závada et al. (2009)
Host rock analogues				
Gels	Gelatine (pig-skin type)	Viscoelastic	For 2.5 wt% at 10 °C: viscoelastic at strain rates <0.147 s^{-1}; however highly variable with different concentrations and temperatures. At strain rate of 10^{-2} s^{-1} viscosity is ~50 Pa s.	Di Guiseppe et al. (2009)
	Laponite powder (synthetic clay)*	Viscoelastic	Commonly used as a rheology-modifier with variable behaviour depending on concentration.	Ruzicka and Zaccarelli (2011)
	Carbopol*	Visco-elasto-plastic	Highly variable depending on concentration, shear stress and strain rate	Di Guiseppe et al. (2015)
Granular	Silica flour (spheres and crystals)	Brittle	When compacted: *crystals* have density of 1.33 g cm^{-3} ± 0.2%, cohesion of 288 Pa ± 26 with angle of internal friction 40°. spheres have density of 1.56 g cm^{-3} ± 0.18%, cohesion of 288 Pa ± 26 with angle of internal friction ~24°.	Galland et al. (2006)
	Diatomite powder	Frictional	When compacted: density of 400 kg m^{-3}, cohesion of 300 Pa at normal stresses 50-300 Pa.	Gressier et al. (2010)
	Sand	Shear	Cohesion of 0 - 10 Pa, angle of internal friction of 30°	Mathieu et al. (2008)
	Ignimbrite powder (Grande Nape Ignimbrite, Mont Dore volcano, France)	Shear	Cohesion of 100 - 230 Pa, angle of internal friction of 38°	Mathieu et al. (2008)
Other	Modelling clay	Plastic	At density of 1.71 g cm^{-3}, yield strength 4×10^5 Pa s. Above yield strength viscosities range from 0.5-7.4 x 10^7 Pa s	Ramberg (1970)

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	Painter's putty	Plastic	Densities of 1.8 to 1.9 g cm^{-3}, yield strength of 3 x 10^3 Pa s. Above yield stress viscosities from 1 x 10^4 to 10^7 Pa s	Ramberg (1970)
Particle analogues				
	Sand and gravel		Without mud – bulk density of 1710 ± 119 kg m^{-3} and internal angle of friction 39° With mud – bulk density of 1650 ± 107 kg m^{-3} and internal angle of friction 39°	Iverson et al. (2010)
	Spherical glass beads		Density of 2500 kg m^{-3}	Mueller et al. (2016)

Table 2. Examples of different analogue materials and their combinations used to model different parts of the volcanic and magmatic system.

Processes considered	Analogue Material Combinations			Example studies
	Magma or Lava	**Host**	**Particulates**	
Magma				
Two phase: melt + bubbles	Golden syrup with nitrogen	-	-	Llewellin et al. (2002b)
	Aerated golden syrup	-	-	Bagdassarov and Pinkerton (2004)
	Corn syrup with air	-	-	Rust and Manga (2002a, 2002b)
Two phase: melt + crystals	Silicone oil with silica-glass beads	-	-	Mueller et al. (2009), Cimarelli et al. (2011)
	Silicone oil with art glitter	-	-	Mueller et al. (2009)
	Silicone oil with silicon carbide grit	-	-	Mueller et al. (2009), Cimarelli et al. (2011)
	Silicone oil with wollastonite particles	-	-	Mueller et al. (2009), Cimarelli et al. (2011)
	Golden syrup with glass beads	-	-	Mueller et al. (2011)
	Golden syrup with art glitter	-	-	Mueller et al. (2011)
	Golden syrup with glass fibres	-	-	Mueller et al. (2011)
	Shell Motor oil with paraplex plastic	-	-	Bhattacharji and Smith (1964)
	Epoxy resin with glass beads/carbon fibres	-	-	Cimarelli et al. (2011)
Three phase: melt + bubbles + crystals	Golden syrup, with air and glass beads	-	-	Truby et al. (2015)
Intrusions				

Dykes	Air	Gelatine	-	Muller et al. (2001), Rivalta et al. (2005), Le Corvec et al. (2013)
	Water	Gelatine	-	Fiske and Jackson (1972), McLeod and Tait (1999), Taisne et al. (2011)
	Air and water	Gelatine	-	Menand and Tait (2001)
	Hydroxyethyl cellulose	Gelatine	-	McLeod and Tait (1999)
	Silicone oil	Gelatine	-	McLeod and Tait (1999), Watanabe et al. (2002)
	Golden syrup	Sand and plaster powder mix	-	Kervyn et al. (2009)
	Golden syrup	Gelatine with a sand and plaster mix load	-	Kervyn et al. (2009)
	Golden syrup	Silica flour	-	Abdelmalak et al. (2012)
	Honey	Sand	-	Mathieu et al. (2008)
	Golden syrup	Ignimbrite powder	-	Mathieu et al. (2008)
Sills	Water	Gelatine	-	Kavanagh et al. (2006), Kavanagh et al. (2015)
	Vegetable oil (Vegetaline)	Silica flour	-	Galland et al. (2006; 2012)
	Vegetable oil (Vegetaline)	Gelatine	-	Daniels and Menand (2015), Chanceaux and Menand (2014, 2016)
	RTV silicone	Diatomite powder	-	Gressier et al. (2010)
Larger igneous bodies	Hot salty water injected into cold fresh water	-	-	Huppert et al. (1986)
	KNO_3, $NaNO_3$ and K_2CO_3	-	-	Huppert and Turner (1981a), Turner et al. (1983)
	Glycerine-ethanol mix injected into molten PEG 600 wax	-	-	Weinberg and Leitch (1998)
	Hydroxethylcelluloase polymer and silicone oil	-	-	De Bremond d-Ars et al. (2001)
	Diluted glucose syrup and bubbles	-	-	Namiki et al. (2016)
	Water or hydroxyethyl cellulose or silicone oil	Gelatine	-	McLeod and Tait (1999)

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	Sunflower oil/silicone oil and natrosol solution/glucose solution/ Na polytungstate	-	-	Saumur et al. (2016)
	Glycerine	Gelatine	-	Koyaguchi and Takada (1994)
	Grease	Gelatine	-	Pollard and Johnson (1973)
	Silicone putty	Sand layers	-	Roman-Berdiel et al. (1995)
	Silicone putty/$KMnO_4$ solutions	Modelling clay/painter's putty/Concrete	-	Ramberg (1970)
Lavas				
Lava lakes and hot conduit	Golden syrup mixed with water	-	-	Beckett et al. (2011)
	Water and air	-	-	Witham et al. (2006)
	Paraffin wax	-	-	Karlstrom and Manga (2006)
Lava domes	PEG wax into sucrose solution	-	-	Griffiths and Fink (1993), Fink and Bridges (1995)
	PEG wax with kaolin powder	-	-	Griffiths and Fink (1997), Lyman et al. (2004)
	Plaster of Paris seeded with magnetite particles	Sand	-	Závada et al. (2009)
Lava flows	PEG wax into sucrose solution	-	-	Hallworth et al. (1987), Fink and Griffiths (1990)
	Glucose syrup into sucrose solution	-	-	Stasiuk et al. (1993)
	PEG 600 wax	Peg 600 wax surface	-	Kerr (2001)
	Paraffin wax	-	-	Miyamoto et al. (2001), Nolan (2014)
	Golden syrup and sugar crystals	-	-	Castruccio et al. (2010)
	Hot water	PEG 1000 wax surface	-	Huppert and Sparks (1985)
	KNO_3, $NaNO_3$ and K_2CO_3	-	-	Turner et al. (1983)
	Viscous silicone	-	-	Gilbert and Merle (1987)
	Corn starch and water slurry	-	-	Goehring and Morris (2005),

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				Goehring et al. (2006)
Granular flows				
Pyroclastic density currents	-	-	Particle bearing freshwater injected into saline water	Carey et al. (1988)
	-	-	Methanol-ethylene glycol injected into water	Woods and Bursik (1994)
Lahars	-	-	Sand and gravel with and without mud	Iverson et al. (2010)
Plumes				
Plumes	-	-	Particle bearing freshwater into saline water	Carey et al. (1988)
	-	-	Cold or warm water into cold flowing water	Ernst et al. 1994)
	-	-	Methanol-ethylene glycol injected into fresh water	Woods and Caulfield (1992)
Ash dispersal	-	-	Spherical glass beads in water with various additives	Koyaguchi et al. (2009)
Air fall	-	-	Spherical glass beads in water with various additives	Koyaguchi et al. (2009)
	-	-	Soda-lime glass beads suspended in hot air	Mueller et al. (2016)

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Figures and captions

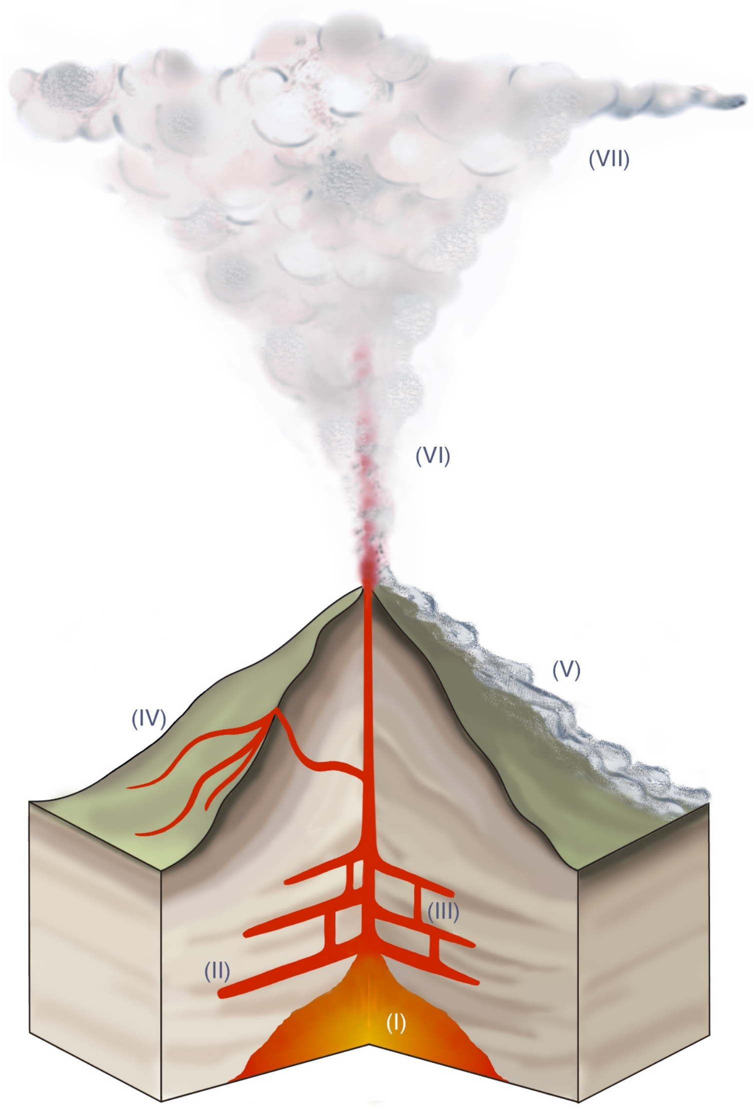

Figure 1: Schematic illustration of the magmatic and volcanic phenomena that have been modelled in the laboratory and in numerical simulations. In this review we focus on: magma chambers (I; see section 5), magma sheet intrusions such as sills and dykes (II, III; see section 6), lava lakes and lava domes (see section 7), volcanic flows such as lava flows, pyroclastic density currents and lahars (IV, V; see section 8), volcanic plumes (VI; see section 9) and volcanic ash dispersal (VII; see section 10).

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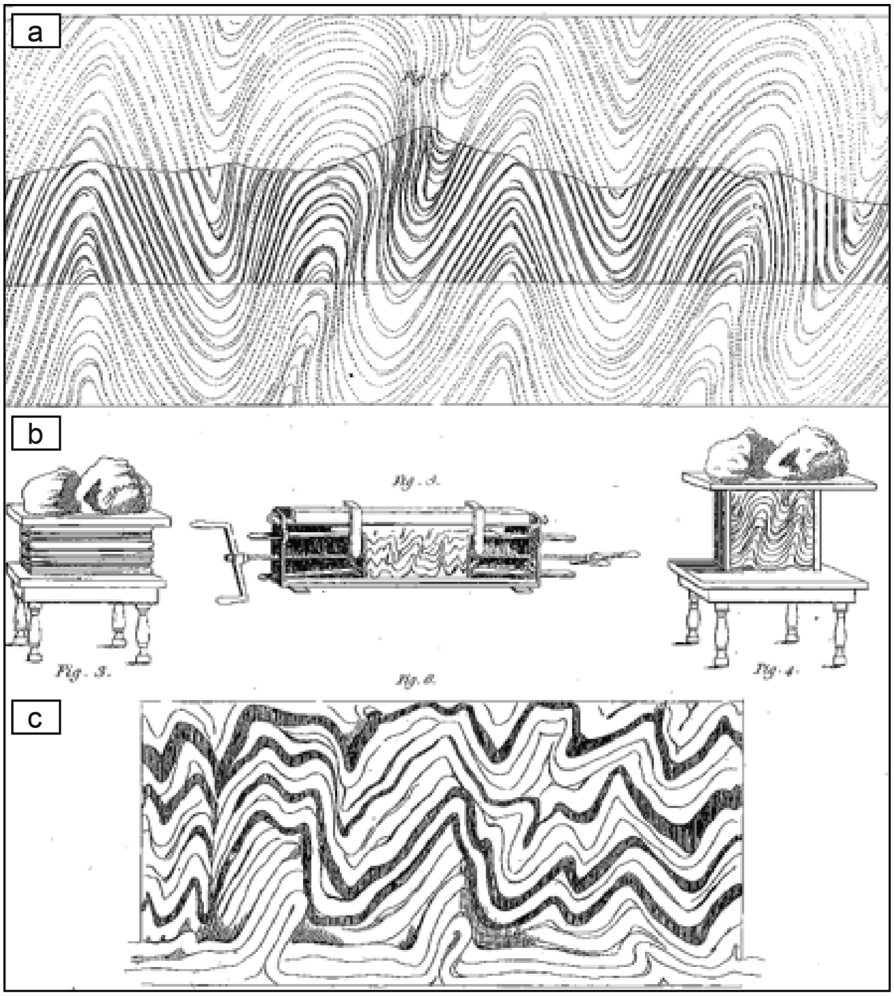

Figure 2: Reproduction of Plate IV from Hall (1815). A series of images depict a set of experiments which have since inspired the use of analogue materials to provide a physical explanation for geological observations made in the field. Hall produced an ‘ideal’ coastal section (a) to demonstrate the continuous nature of the folded rock layers observed in the field. Sketches depict a set of experiments that were performed (b) by compressing clay layers to produce convolutions (c) that are reminiscent of the structures observed in the field.

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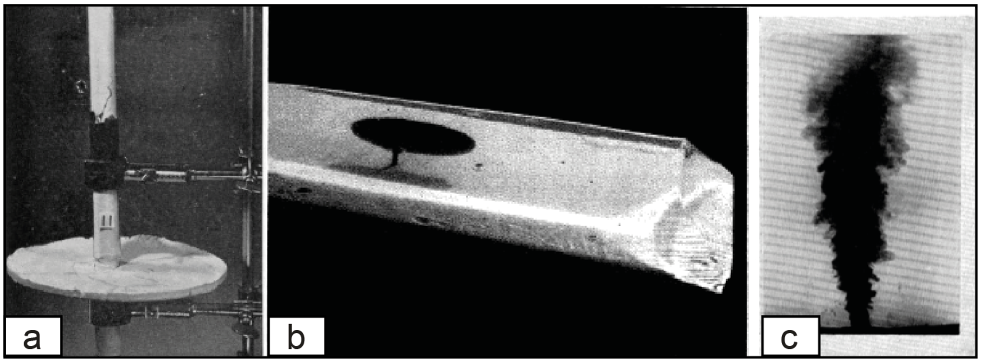

1853

1854 **Figure 3:** Photographs of early analogue experiments that have inspired and informed
1855 decades of laboratory studies of volcanic and magmatic processes: a) Excavated plaster of
1856 Paris mixture that was injected into a layered tank of gelatine to model dyke and sill
1857 emplacement (Hubbert and Willis, 1957), b) water injected into a free-standing triangular
1858 prism of gelatine to simulate magma intrusion in a volcanic rift (Fiske and Jackson, 1972), and
1859 c) injection of low density fluid into a uniform ambient fluid (Morton et al. 1956).

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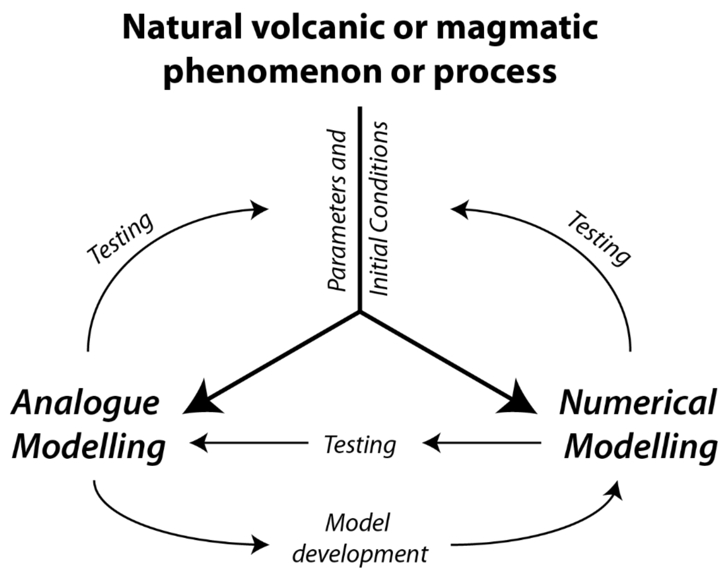

Figure 4: A flow diagram to represent the optimal approach to use analogue and numerical modelling in volcanology. Observations and measurements from natural volcanic and magmatic phenomenon provide the parameters and initial conditions for analogue and numerical models; these models are then tested against nature, with analogue models also aiding the development of numerical models.

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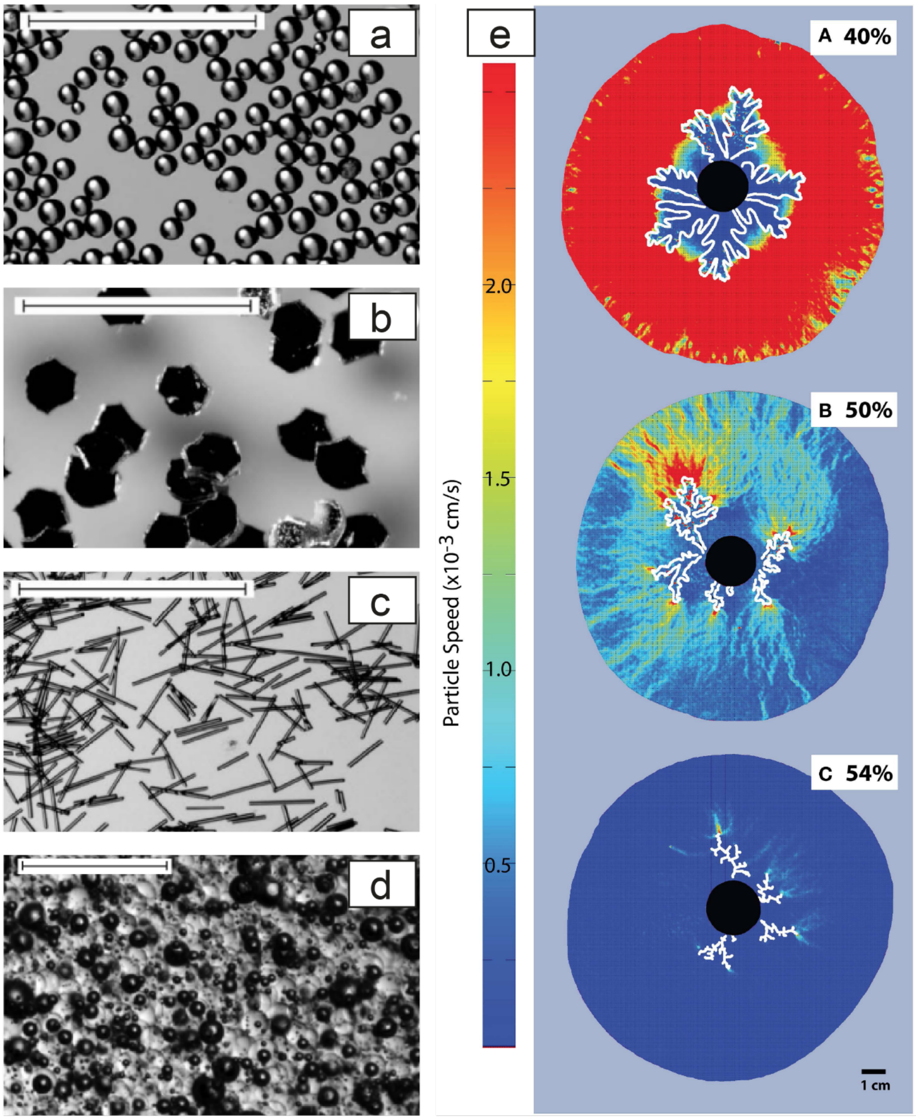

Figure 5: Magma rheology studied using analogue materials in laboratory experiments. (a-c) spherical glass beads, oblate art glitter, and prolate glass fibres in silicone oil (scale bars 1 mm; Mueller et al. 2011); (d) three-phase fluid where bubbles (black spheres) and spherical glass beads (light translucent particles) are suspended in golden syrup (scale bar 500 µm; Truby et al. 2015). (e) Bubble injection experiments using a small-gap parallel plate geometry to study the development of permeable pathways in a particle-rich suspension. Particle image velocimetry has been used to measure particle speed in three experiments with different crystal fraction (Oppenheimer et al. 2015).

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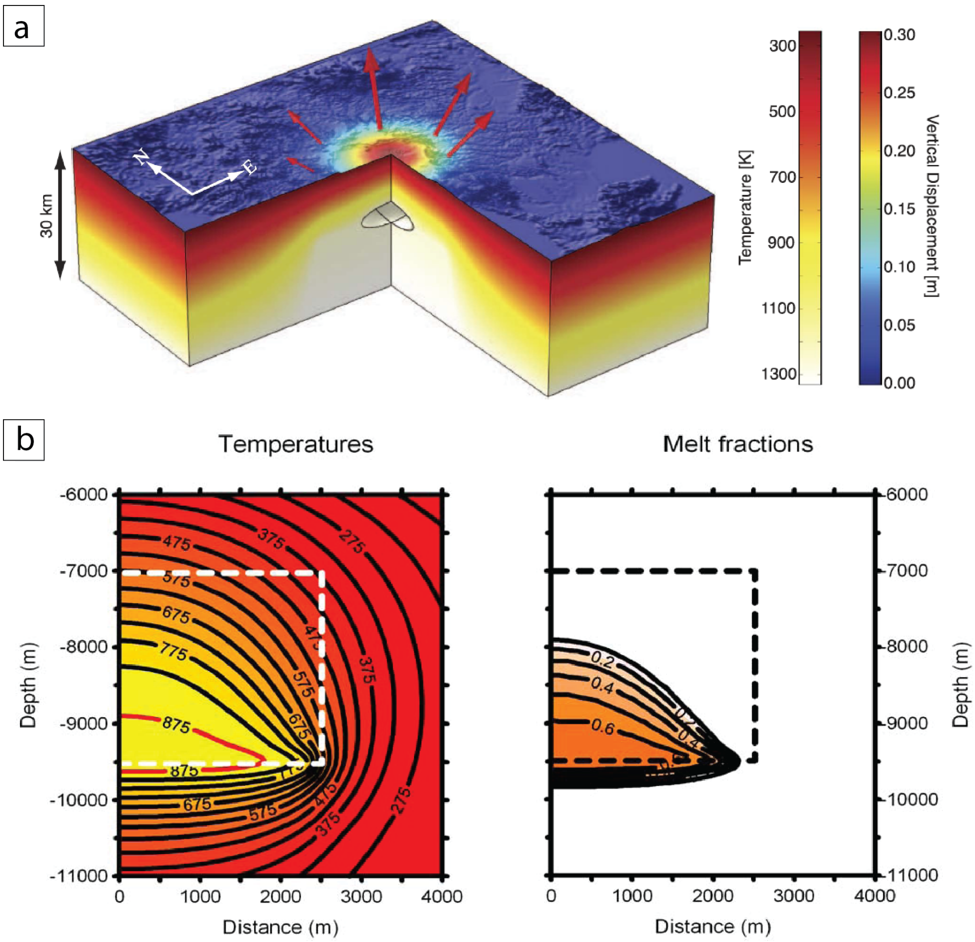

1877

1878 **Figure 6:** Numerical models to simulate magma chamber accretion and associated
1879 deformation of the crust: a) Thermomechanical model of the magma reservoir at Aira caldera,
1880 Japan, using a Finite Element model (Comsol Multiphysics) that incorporates the
1881 temperature-dependent viscoelastic rheology of the crust (Hickey et al. 2016). b) Numerical
1882 simulation of the magma chamber at Mt Pelee, Martinique, with accumulation of 5 km
1883 diameter sills at 15 x 10^{-4} km^3/yr over 62,500 years and solved for the temperature of the
1884 crust with depth and melt fraction (Annen et al. 2008).

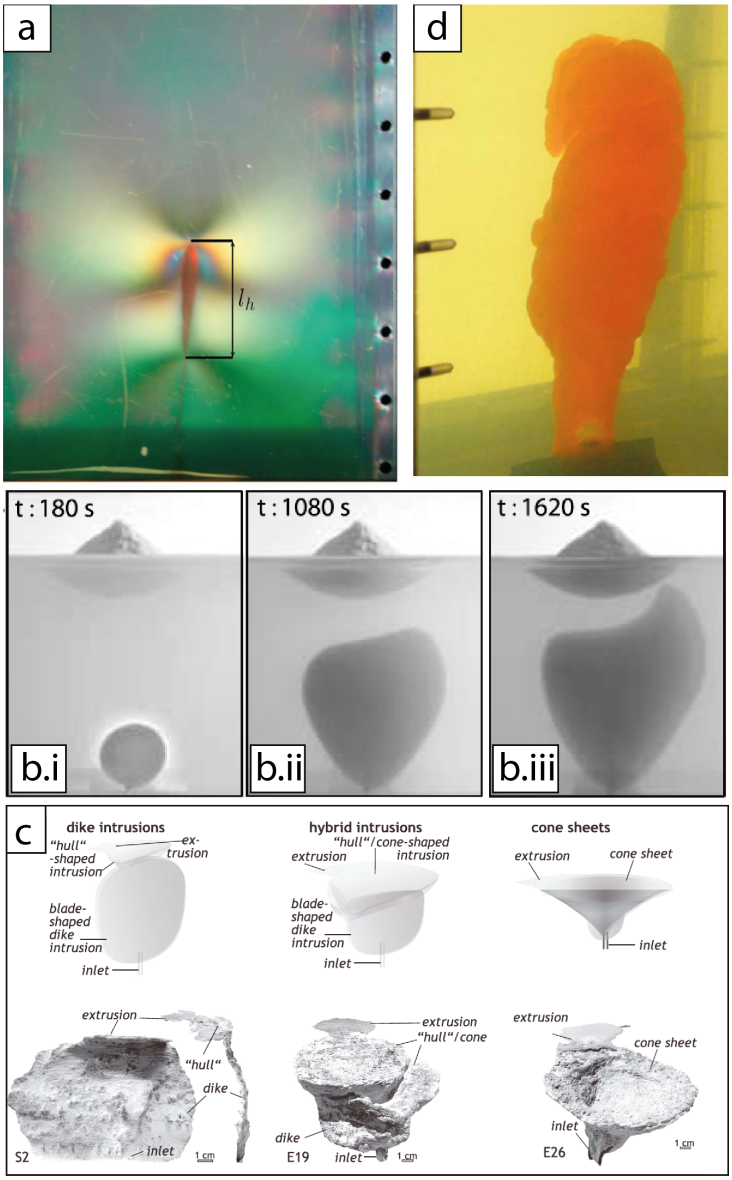

Figure 7: A series of photographs demonstrating a range of analogue experiments used to study dyke propagation dynamics. a) Injection of red-dyed isothermal heptane into a gelatine solid, with l_h indicating the length of the dyke's buoyant head (Taisne and Tait 2011). (b) Series of photographs showing the impact of a volcanic edifice on dyke propagation: injection of dyed water into gelatine with a conical surface load of sand and plaster (Kervyn et al. 2009). c) Schematic sketch and detailed photographs of excavated vegeteline intrusions such as dykes, hybrids and cone sheets formed within compacted silica flour experiments (Galland et al. 2014). d) Injection of a solidifying liquid (wax) causing the formation of an irregular and lobed dyke morphology (Taisne and Tait 2011).

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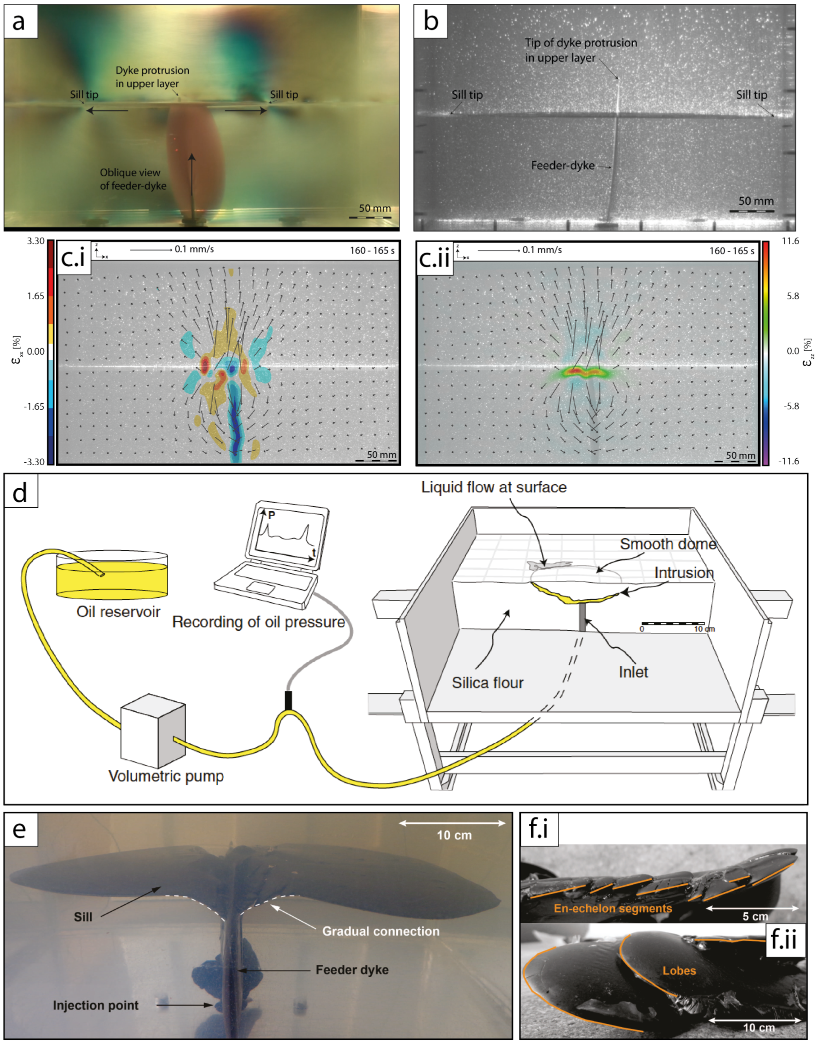

Figure 8: Analogue experiments studying sill formation. a-b) Dyke-sill hybrid formation from a feeder dyke in layered gelatine along a weak interface (Kavanagh et al. 2017): a) Polarised light enables stress to be visualised through coloured fringes, and b) a laser-illuminated vertical section through the experiment, showing the sharp boundary between intrusion and host. c) Digital image correlation of sill formation from a feeder dyke in layered gelatine (Kavanagh et al. 2015). Colours indicate incremental strain in the gelatine, and arrows are displacement vectors at the moment of sill formation: i) horizontal incremental strain, and ii) vertical incremental strain. d) Experimental setup where Vegetaline is injected into compacted silica flour to model sheet intrusions (Galland et al. 2014). e-f) Experimental sill formed from a feeder dyke in layered gelatine where solidification effects are considered (Chanceaux 2013): e) Typical sill-forming experiment and f) excavated 3D morphology of Vegetaline sill showing lobed and segmented propagation front (see also Chanceaux and Menand 2014 and 2016).

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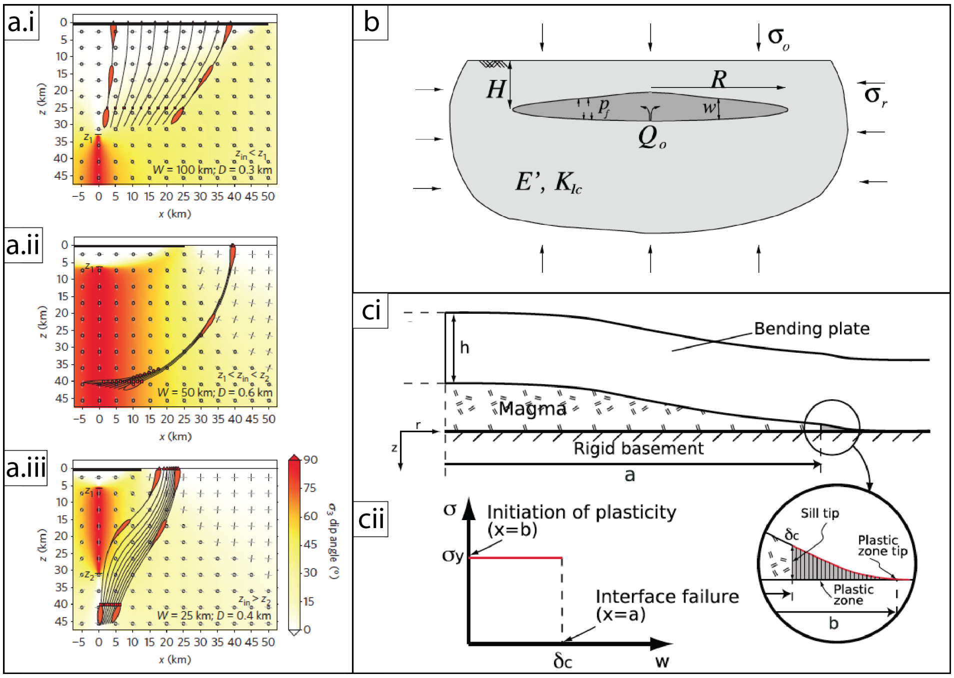

1909

1910 **Figure 9:** Example numerical models of sheet intrusions: a) dyke trajectories in the presence
1911 of a stress barrier (Maccaferri et al. 2014), b) the growth of a laccolith (Bunger and Cruden
1912 2011), and c) growth of a laccolith or sill with inelastic deformation (Scheibert et al. 2017).

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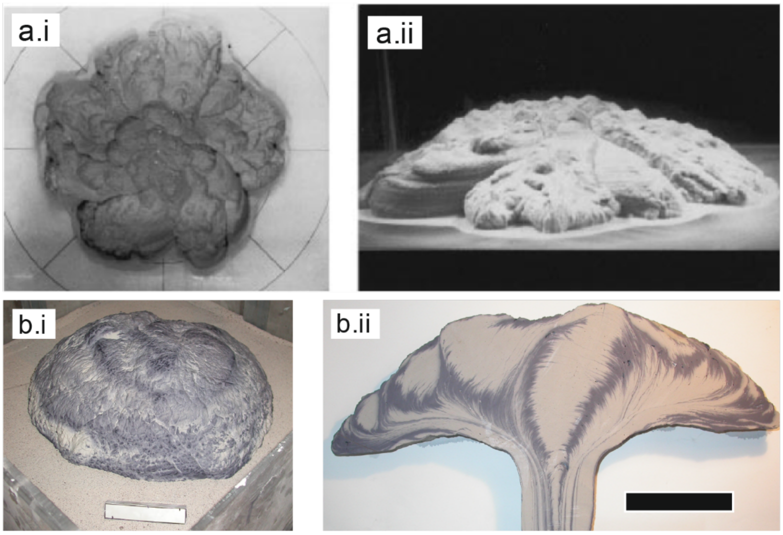

Figure 10: Studies of lava dome morphology: (a) Analogue experiment by Griffiths and Fink (1997) of polyethylene glycol extruded from a point source imaged in (i) plan view and (ii) side view. (b) Photograph showing i) external morphology and ii) cross section through plaster of Paris analogue model of lava dome emplacement seeded with magnetic particles for AMS (scale bars are 10 cm long, photos courtesy of Prokop Zavada. See also Zavada et al. 2009).

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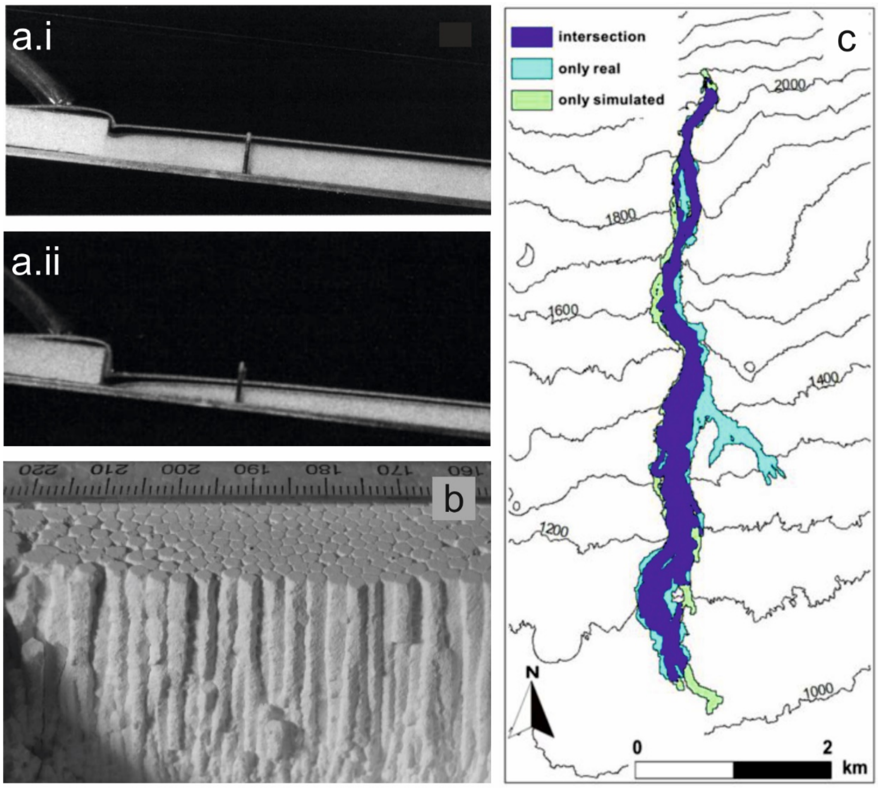

Figure 11: Analogue models and numerical simulations of lava flows. a) Effusion of molten wax onto bed of solid wax to study thermal erosion of lava flow into underlying material after (i) 4 and (ii) 14 minutes (modified from Kerr (2001)). (b) dehydration of corn starch-water slurry to study the formation of columnar jointing structures in lava flows (modified from Goehring et al. (2006)). c) cellular automata model of lava flow inundation (green and dark blue) compared with the flow path of the natural lava flow (light blue and dark blue) effused at Mt. Etna, Italy (modified from Rongo et al. (2016)).

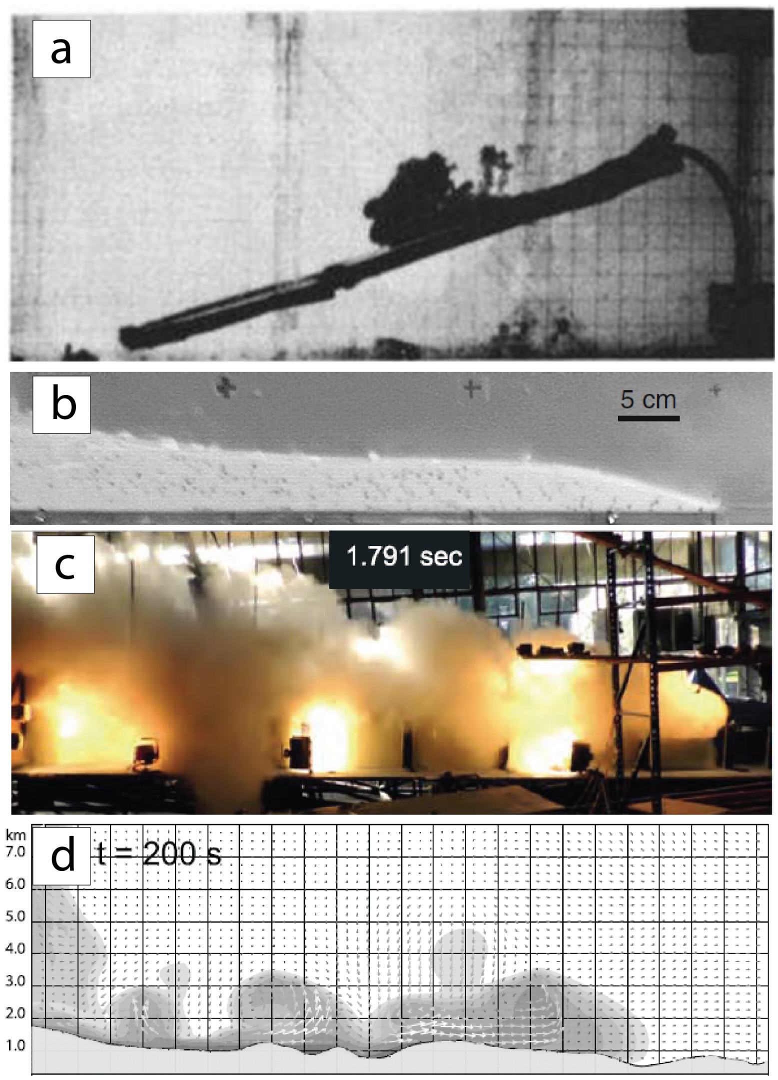

Figure 12: a) Example of early analogue experiments of particulate flows whereby a mixture of methanol, ethylene glycol and water was released on a slope into a tank of fresh water. The higher density of the mixture in comparison to the ambient fluid means it flows down slope as a gravity current, forming turbulent eddies at the top of the flow (Woods and Bursik 1994). b) Small-scale experimental model setup designed to investigate particle interactions in detail (Roche, 2012). c) Large scale analogue experiments using the PELE setup, allowing large scale processes within pyroclastic density currents to be investigated. The figure shows emplacement of a dilute mixture of particles and air (Lube et al. 2015). d) Results from application of the multiphase numerical model PDAC to the blast phase of the Mount St. Helens blast of May 18th 1980 (Esposti Ongaro et al. 2012). The models results reproduce numerous features of the flows that originated from the blast, including the formation of turbulent eddies.

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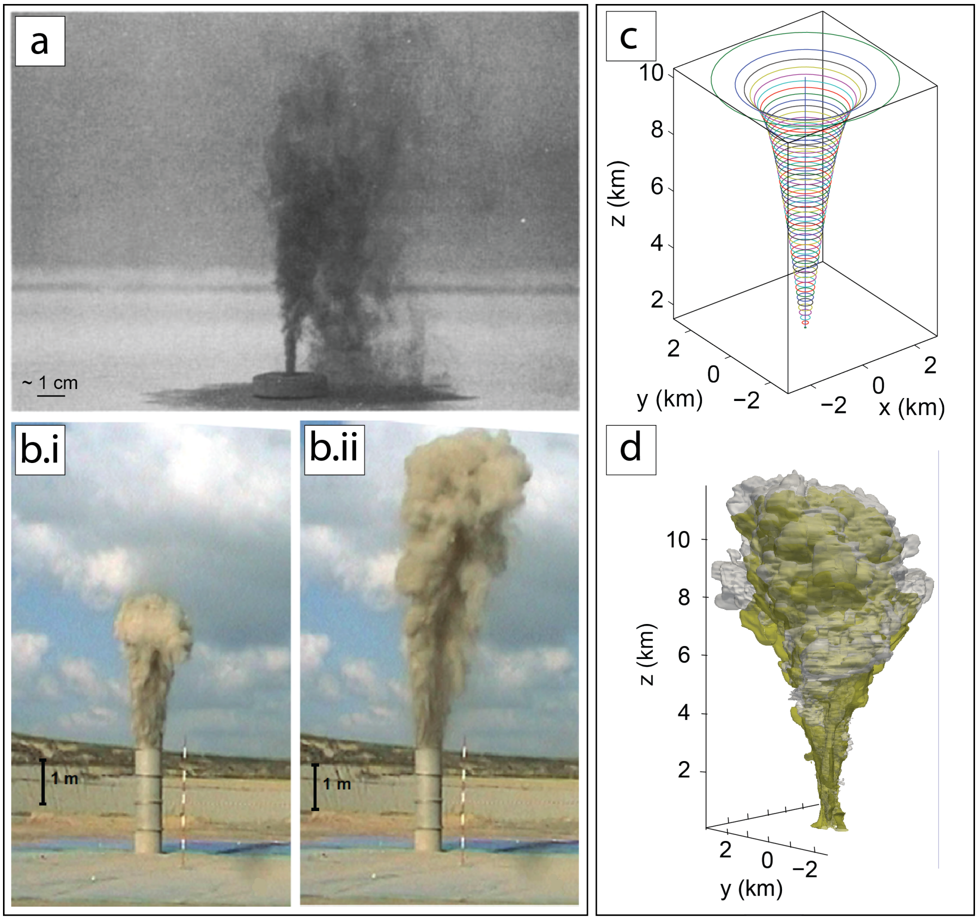

Figure 13: Examples of numerical simulations and analogue models of volcanic plumes. a) Flume tank analogue experiments of Carey et al (1988) where a particle laden fluid is injected into another fluid to investigate plume rise and particle sedimentation dynamics. b) Large scale experiments to investigate effects of entrainment coefficient on plume rise (Dellino et al. 2014). c) Modelled representation of a vertical plume using the one-dimensional model PlumeMoM (Vitturi et al. 2016). d) Three-dimensional model results from the multiphase model ASHEE for the same input conditions as c) (Cerminara et al. 2016).