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Preface

The role of laboratory experiments in volcanology

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Experiment is central to scientific methodology. Within science in general, experiments are used for four primary purposes, i.e. as a tool to explore novel phenomena and to provide systematic observations of processes, to determine the values of key parameters, to test hypotheses and theoretical models, and to validate computational models, which themselves can be considered as numerical experiments. The study of volcanic eruptions and magmatic processes is becoming increasingly systematic, quantitative and rigorous. The drive is towards providing detailed quantitative descriptions and models of the flow phenomena in terms of fundamental physico–chemical processes. This is motivated in no small way by an increasing need for reliable and quantitative predictions of volcanic eruptions on which to base rational hazard and risk management decisions during volcanic crises. A natural consequence of this development of the scientific study of volcanic flow phenomena is that rigorous laboratory experimentation is becoming an increasingly important feature within volcanic research.

The contribution of experimental research to our understanding of volcanic processes is difficult to overstate. The determination of the values of key parameters has traditionally taken place in the laboratory. However, more recently experiments have become much more widely applied to the problem of understanding complex dynamical processes and their underlying mechanisms. Without models (experimental, theoretical, numerical) we are limited to qualitative interpretations of field observations and remote sensing. Field data are of course essential and provide the measure against which ultimately the applicability of observations from other sources must be assessed. However, there are several reasons why the scientific study of volcanic phenomena cannot rely solely on field data. Direct observations of eruption processes in the field are limited to those parts of an eruption that are accessible. This restricts detailed observations to a limited range of above-surface processes. Moreover, logistical constraints mean that the systematic collection of data will usually only be possible for volcanic eruptions near an established observatory and for activity for which there has been some forewarning. As a result of these constraints, direct field-based observations of natural volcanic eruption processes are generally incomplete and uncertain. Another source of natural data derives from observations made on volcanic deposits. In principle, processes can be inferred from the features

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of those deposits. However, such inferences have the character of hypotheses, which remain to be validated against direct observation of the process.

In a laboratory experiment, the problems of accessibility are much reduced and the logistical field constraints are circumvented. The process can be run repeatedly and the known starting conditions correlated with measurable outcomes. In considering the strengths and limitations of the experimental approach it is helpful to distinguish between experiments using natural materials and those that use non-magmatic materials, so-called magma 'analogues'. Experiments on natural materials include those that are directed towards determining the basic physico–chemical parameters of the system. By contrast, both natural and analogue materials have been useful in experiments directed at understanding dynamical processes. Which is to be preferred depends on the nature of the process under consideration. As a rule of thumb, natural materials are preferable for very small-scale processes whereas analogue materials are to be preferred for the study of large-scale dynamics. For example, decompression experiments on natural melts are widely used to study the dynamic process of bubble nucleation and growth (Hurwitz and Navon, 1994; Gardner et al., 1999; Mourtada-Bonnefoi and Laporte, 2000; Mangan and Sisson, 2000) and two additional studies are included in this volume (Lensky et al., 2004-this issue; Mangan et al., 2004-this issue). Using natural melts in this case is advantageous because it means that the complete system is automatically considered. Moreover, the length and timescales of the natural process are such that there is no need for scaling. The process under consideration is not expected to be strongly affected by large-scale interactions and so the small sample size in the experiments does not present a problem.

Dynamic experiments on natural materials are complicated (compared to those performed on analogue materials) by several factors primarily associated with the requirement for high temperatures and sometimes also high pressures. The equipment is expensive. The sample size is heavily restricted. Direct observations are more difficult usually because the furnaces are in the way. Setting-up an experiment can be time consuming (for example, obtaining a homogeneously hydrated melt sample in situ can take several days). This latter problem typically means that fewer runs are performed and the parameter base is as a result sometimes not fully mapped. The materials themselves are also sufficiently complex that it can be difficult to reproduce the starting conditions. Many of these problems are overcome by the use of analogue materials. For example, waxes are often used to study lava flow mechanics and morphology because they reproduce the transition from liquid to solid at easily accessible temperatures (e.g. Fink and Griffiths, 1990; Lyman et al., 2004-this issue). Other studies have used analogue materials to understand the interaction of a pressure wave impinging on the viscoelastic medium of a bubble suspension (Ichihara et al., 2004-this issue) and to investigate the nature of the seismic signals generated by the formation and ascent of gas slugs (James et al., 2004-this issue). However, analogue materials rarely capture the full range of the physico–chemical behaviour of the natural system; it is always possible that some crucial feature of the system is different in some way that has a major effect on the observed dynamics. This remains the primary objection to the use of magma analogues. Consequently, it is important to thoroughly characterise analogue materials and consider their relevance to the volcanic process of interest (e.g. Soule and Cashman, 2004-this issue).

A significant difficulty in all laboratory experiments aimed at investigating the large-scale processes and interactions of volcanic systems lies in the problem of scale. Volcanic systems, in common with many natural systems, involve processes that operate over a much wider range of length and timescales than is possible to capture in the laboratory. The range of scales present can be crucial to the dynamics because they can be dominated by the interaction of processes on different scales. This means that for any laboratory experiment of the eruption process to simulate the natural dynamics careful consideration must be given to how to scale the process to laboratory length and timescales. For a wide range of problems, this can be done rigorously, for example, in the lava flow studies using waxes (review by Griffiths, 2000; Lyman et al., 2004-this issue; Soule and Cashman, 2004-this issue) and caldera formation experiments (e.g. Roche et al., 2000; Acocella et al., 2004-this issue; Lavallee et al., 2004-this issue). But in many cases, the appropriate scaling relationships are not known. It is worth noting, however, that rigorous scaling almost invariably involves changing the physical parameters of the materials used as well as the dimensions of the system. This means that fully-scaled dynamical simulations will usually require the use of suitably-chosen analogue materials.

If analogue experiments cannot be fully scaled, what then is their value? Such experiments are not true ‘simulations’ of the natural flow processes and are unlikely to reproduce the full range of behaviour. The role of experiments, in this case, is primarily as a tool to identify and investigate the fundamental processes and interactions operating within the flows. Consider, for example, the problem of quantifying the thermal and petrologic changes that occur during the evolution of magma chambers, a problem that motivates two studies in this special volume (Kaneko and Koyaguchi, 2004-this issue; Leitch, 2004-this issue). Beginning in the 1980s, experimental models of differentiation (e.g. McBirney, 1980; Turner, 1981), double-diffusive convection (e.g. Huppert and Sparks, 1984), mixing (e.g. Turner and Campbell, 1986), crystal settling (e.g. Martin and Nokes, 1989), solidification (e.g. Kerr et al., 1989), and melting and assimilation (e.g. Woods, 1991; Kerr, 1994) have clearly illustrated fundamental processes that can occur as basaltic magmas interact with their surroundings (see Jaupart and Tait (1995) and Campbell (1996) for recent reviews). However, laboratory experiments that employ analogue fluids and solutions do not always capture the potentially important effects of the more complex phase equilibria and kinetics of actual magmas (e.g. Hort et al., 1999), nor do they necessarily account for the full rheological complexity of multiphase magmas (e.g. Bergantz, 1995). Nevertheless, even the earliest laboratory studies have provided insights into magma-crust interactions and magma chamber evolution that in turn have provided new directions for field-based studies (e.g. McBirney and Noyes, 1979). Laboratory studies continue to lead to new and increasingly precise questions that are being integrated and evaluated with field- and geochemically-based measurements (e.g. Jellinek and Kerr, 2001).

In principle, magmatic processes and interactions ought to be deducible from the laws of physics and indeed this is the essential precept that underlies much theory and numerical simulations. However, the natural system is so complex that usually simplifications are necessary to render the mathematics tractable. Dynamic experiments provide a means of at least partial validation for such theoretical and computational modelling. Full validation can only be provided by comparison with field observations of the dynamics, which may not be possible. The study of magmatic fragmentation provides a good example of the way dynamical experiments using both analogue (Hill and Sturtevant, 1990; Mader et al., 1994; Phillips et al., 1995; Mourtada-Bonnefoi and Mader, 2004-this issue) and natural (Alidibirov and Dingwell, 1996; Raue, 2004-this issue; Spieler et al., 2004-this issue) materials can interface with hypotheses (Sparks, 1978; Papale, 1999; Zhang, 1999) and numerical models (Dobran, 1992; Melnik, 2000) to lead to a greater understanding of a highly complex process that is inaccessible to direct observation in the field.

This issue is dedicated to experimental research with applications to volcanology. With this issue we do not aim to provide a comprehensive overview of the field of experimental volcanology – that would be more properly accomplished in a textbook. The issue, however, does provide a snapshot of some current research philosophies and covers a wide range of techniques and topics.

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