18.Oct.2010 version

Title: Workshop on large-scale experiments for volcano processes and geohazards – research priorities and infrastructure concepts

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Some of the least understood and most hazardous geologic processes involve complex multiphase flows, particularly those related to explosive volcanic eruptions. These phenomena inherently involve a wide range of characteristic length and time scales, and processes that are coupled across those scales in a range of flow regimes. For example, a pyroclastic density current's (PDC; a.k.a. pyroclastic flows and surges) behavior is governed in a complex way by the interactions between individual particles ($\sim10^{-4}$-10^{-1} m, $\sim10^{-1}$-10^{1} s) as well as by turbulent mixing with surrounding air ($\sim10^{-2}$-10^{2} m, 1-10^{2} s). Material properties within individual flows can vary over huge ranges. A second example is the large-scale interaction between shearing magma and external water in a volcanic conduit, where the starting material is viscous melt and upon fragmentation the material properties range from brittle glass to steam. There are four ways in which we explore these processes: observations in real time, observations of deposits after an event, bench top and analog experiments that try and recreate conditions that occur at much larger scales, and numerical models. Data collection from active volcanic flows is greatly limited by the unpredictability of the events and the dangerous conditions they produce; and, even if measurements can be made, the initial and boundary conditions of the eruptive flows are poorly constrained and this limits the physical insight that can be gained. Data measured on deposits or other eruptive products, such as individual clasts, provide important, but indirect information on the parent processes. While analog experiments provide many insights into the flows, a fundamental difficulty with multiphase volcanic processes is that they cannot be strictly scaled to the bench top. Numerical modeling is of growing importance in predicting and interpreting volcanic flows. However, such modeling is limited by two important factors: (1) our inability to resolve all the scales and processes due to computer capacity and to a lack of appropriate "sub-models" (i.e., constitutive models) for processes such as multiphase turbulence coupled with granular flow, coupled solid-fluid mechanics, and extremely rapid processes that include phase changes; and (2) the difficulty of validating complex numerical models, which requires high-quality measurements on real flows that incorporate the dynamics represented in the governing conservation equations.

Addressing the above gaps, as well as learning about as-of-yet undiscovered emergent behaviors, requires the development of large-scale experiments that capture all the relevant regimes, length and time scales and material properties that occur in nature, but under controlled situations where careful measurements can be made with known initial and boundary conditions. Such a capability would be consistent with research needs identified at recent workshops on explosive volcanism (Prescott, Arizona, 2007, and Clermont-Ferrand, France, 2009), and would be a natural follow-on to the existing experience in volcanology. In the last two decades, laboratory scale experiments have been carried out in volcanology both on magma fragmentation (e.g., Alidibirov and

Dingwell, 1996; Büttner et al., 2002; Kueppers et al., 2006; Alatorre et al., 2010) and particulate flows (e.g., Girolami et al., 2010; Chojnicki et al., 2006), including the very recent 10 m scale multiphase experiments of Dellino et al (2007, 2010a,b) and the field magmatic fragmentation/ejection experiments of Kueppers et al. (2010). A new experimental facility will also build upon previous and ongoing experimental approaches of other Earth-science relevant processes which share common features with volcanic processes, such as debris avalanches and debris flows (Iverson, 2010) and sediment gravity currents in water (Garcia and Parker, 1993; Kneller at al., 1999). Because large-scale experiments are inherently complex and costly, and the geohazards and volcanology communities are relatively small with limited resources, it makes sense to pursue large-scale experimental capabilities with a "community use facility" approach. Such a shared facility would provide basic infrastructure, sensors, data acquisition and archiving, and engineering support, while promoting independent use by multidisciplinary teams.

A workshop on the topic of a potential shared use facility, sponsored by the National Science Foundation and the University at Buffalo, was held at the Beaver Hollow Conference Center, near Buffalo, New York, on 17-19 September 2010. The workshop brought together 55 researchers from around the world including eleven US universities and the U.S. Geological Survey, as well as from research organizations in Canada, Japan, United Kingdom, Italy, Germany, France, Switzerland, New Zealand, Ecuador, Mexico, and Colombia. This group encompassed scientists who use a range of approaches to understand volcanic processes, and ranged from experienced and early career workers, as well as graduate students and postdocs. The fundamental objective of this workshop was to define the science priorities and functional design for the facility. The event was part of a larger effort to coordinate development of multiple test facilities on large-scale experiments of "extreme events;" this large effort focuses on research, development, testing and evaluation to reduce vulnerability of US infrastructure. The 700-acre facility is referred to as the Experimental Campus for Large Infrastructure Protection, Sustainability, and Enhancement (a.k.a. ECLIPSE Campus, located near Buffalo), and is already being used for studies such as seismic design of full-scale highway bridges and structural resilience of construction components. ECLIPSE is being developed jointly by the University at Buffalo's MCEER (formerly the Multidisciplinary Center for Earthquake Engineering Research) and Calspan Corporation. This report summarizes the results of the workshop. Because of the expertise of the participants, much of the discussion centered on explosive volcanic processes. The Geohazards Field Station at ECLIPSE will address a range of natural hazards but with an initial focus on volcanoes, which encompass a full suite of phenomena ranging from magma ascent in the subsurface, to eruption columns, pyroclastic fallout and density currents, debris avalanches and lahars.

Subsurface volcanic processes. One class of problems discussed at the workshop included those associated with the shallow feeding systems of volcanoes, through which magma ascends, fragments, and accelerates. Important processes include bubble dynamics, magma fragmentation (driven by magmatic volatiles and by explosive interaction with external water, and by shear deformation), and the interaction of those processes with surrounding rocks and the resulting geologic structures (e.g., diatremes).

Many experimental studies have been conducted with both analog materials and with real magmas to elucidate these processes, but these have been mainly limited to scales of centimeters to decimeters. There are several drivers for moving to larger scales (meters), including: the need to reduce wall effects, to replicate natural velocity gradients and profiles, to allow full evolution of processes (such as bubble coalescence), to develop steady-state fragmentation flows from significant revervoir volumes, and to mimic natural geometries under dynamic conditions. For example, much experimental research on explosive magma-water interaction has involved injection of water into small volumes of static magma in crucibles, whereas in Nature flowing magma in a dike geometry might interact with water held in an adjacent aquifer. In addition to length scale issues, some of the processes have potential to be highly energetic, requiring larger facilities or outdoors experiments. Key issues that require large-scale experiments to resolve include: (1) influence of natural rheologies, geometries, and fluxes (magma and water) on explosive magma fragmentation; (2) development of "feeding" structures such as diatremes and vents in materials with properties reflecting natural host rocks; (3) overall energy budget of the above processes and energy partitioning (e.g., seismic, acoustic, kinetic, and surface energy); (4) development of natural eruptive particle size distributions; and (5) dynamics of long-lived, low magma-flux bubble-driven systems such as those that drive Strombolian activity.

Eruption columns and tephra dispersal. Eruption columns consist of both inertia- and buoyancy-driven, high-speed flows of volcanic gas and particles in the atmosphere. The dynamics of volcanic plumes are strongly controlled by exit velocities and vent geometry, and by the interaction with the atmosphere (e.g., entrainment and wind shear). These parameters control plume height, gravitational collapse, and associated particle dispersal and deposition. Additionally, temporal variations in source conditions affect the overall motion of eruption columns, which is particularly relevant to short-lived, unsteady and long-lived, pulsatory explosive eruptions. Key hazards associated with explosive eruption columns are column collapse PDCs and tephra dispersal. Both processes can transport volcanic material for long periods and over large distances, causing respiratory problems to humans and animals, serious damage to buildings. In addition these processes can directly affect several sectors such as aviation, agriculture and tourism.

Participants of the workshop identified a series of critical questions regarding eruption column dynamics that could be answered by a large-scale experimental facility were divided into three main categories. These include: (1) differential velocity between particles (tephra) and gas, which ultimately may be critical in terms of understanding turbulent energy and scales in multiphase plumes, and particle sedimentation and resulting deposit characteristics; (2) better characterization of turbulence in multiphase flows, which strongly affects atmospheric entrainment and plume stability (for impulsive, pulsing, and sustained behaviors); (3) effects of jet overpressure, which controls large-scale plume morphology and dynamics and can be closely related to vent geometry. A flexible conduit/vent system will be designed according to a suite of 'model' eruptions, keeping in mind the necessary scaling of dimensionless numbers. The design will allow for critical measurements of important parameters (e.g., velocity, particle concentration) with respect to time and space, as well as subsequent deposit sampling.

The objectives of the large-scale experiments with respect to eruption column dynamics will be to explore deposits produced by using a full-range of realistic particle sizes, a full range of potentially important length-scales, well-constrained initial (eruptive) conditions, and an accurate characterization of external effects (e.g., local wind field). Observations from small-scale natural examples (e.g., Kilauea 2008, Hawaii, and Santiaguito ongoing eruptions, Guatemala) will be used to help guide the design of experiments.

Pyroclastic density currents. PDCs can be generated by a range of phenomenon including collapse of eruption columns, lateral blasts, and gravitation failure of lava domes. PDCs are density-stratified currents that encompass a wide range of multiphase flow conditions that vary in space and time. Due to their high velocities and destructive nature, PDCs are among the most unpredictable and dangerous of natural hazards. The workshop highlighted five key issues that motivate large-scale experiments: (1) the interaction between the two main zones of PDCs, the basal avalanche and overlying dilute portion, is not understood or quantified experimentally, but is critical in terms of predicting inundation and damage areas; (2) near-bed effects, such as shear stress, development of pore overpressure and interaction with and erosion of topography are also critical; (3) sources of unsteadiness within PDCs are important, but poorly constrained and documented; (4) particle-particle and particle-gas interactions over a range of particle and flow length scales must be understood as they play a key role in generating and modulating internal friction; (5) the control of source parameters (e.g., mass eruption rate, grain size distribution and conduit geometry) on pdc mobility.

The main reasons for prescribing large-scale experiments to pursue these issues are related to the need for longer length and time scales. For example, small-scale experiments (meter-scale) typically only have the capability of using a single grain size. However, density stratification with respect to time and space in a current is difficult to model without the use of multiple grain sizes with varying densities. Thus while small-scale experiments lend insight into dynamic processes, they severely limit our ability to recreate natural flow conditions and thus reconstruct and interpret depositional features. Moreover, precise measurements of internal friction, sedimentation velocities, basal shear rates, and non-dimensional characteristic numbers (as Froude, Darcy, Bagnold, Savage, pore-pressure numbers for the basal underflow/ Reynolds and Richardson numbers for the dilute end-member), and unsteadiness behaviors should be of great interest for the improvement of theoretical models and complementary to small-scale experiments.

The volcanology community relies heavily on the characteristics of PDC deposits to develop hazard and risk assessments. However, much of our interpretation of features such as bed forms is borrowed from the classical sediment transport literature that focuses on shallow, clear water flows. Thus one goal of large-scale experiments is to enable researchers to constrain the dynamic conditions under which various bed forms are developed in density-stratified flows. This better understanding of emplacement mechanisms will result in a more accurate assessment and interpretation of depositional features associated with PDCs, and thus a better understanding of the hazards associated with these currents.

Debris avalanches, debris flows, and lahars. Debris avalanches, debris flows and lahars are highly concentrated mass flows consisting of a heterogeneous sediment mixture with a broad particle size range, which may include a fine-grained matrix. These flows can be initiated on the flanks of a volcano or other steep terrain, and can move downslope for many tens of kilometers. As such, at volcanoes, they occur both during eruptive and non-eruptive periods, and represent a major hazard. Although these flows constitute a continuum in many classifications of gravity-driven mass flows, it is necessary to distinguish avalanches and flows because of their different transport mechanisms and emplacement regimes which are mainly laminar-turbulent for debris flows and laminar for debris avalanches. However, it is still both possible and desirable to use the same experimental set-up to study both phenomena (i.e. a flume with variable cross section ending with an unconstrained accumulation zone of variable slope). The single set-up would permit an easy and useful comparison between debris flows/lahars and debris avalanches, and importantly would make possible the validation of the systems used for monitoring both. In addition, the experimental facility would be designed to allow study of dilution processes and deposits as the mass flows travel on or enter a standing ice, snow or water body and as they transform within a subaqueous environment; this will also enable a comparison with PDC's entering water bodies. A flexible and mobile flow initiation unit would also be used to study different processes of flow initiation (e.g. slip planes, internal deformation, liquefaction/fluidization). Mobile detectors for pressure can be included within the models.

Debris flows and lahars. For studies of pure debris flows, it is possible to use the experience derived from existing large experiments as summarized by Iverson et al. (2010). However, many issues remain unresolved for these flows and their more dilute transformations. New experiments are required to better constrain how the boundary conditions, flow and sediment bulking, and the substrate topography influence the mobility and total run out of debris flows, and how these may transform both process and character downflow. Heterogeneous material, with clasts up to decimeters in size, will be considered in order to study the effects of topography on such complex material, the behavior of the large fragments compared to the liquefied matrix and test/validate the Coulomb mixed theory model of Iverson (2003). An additional important issue to be considered is flow dilution, as an initiation process, as the flow enters a large standing water body and eventually along the course of the flow, only if, at large scale, it will be possible to achieve a time scale of the overall motion from source region to depositional region large enough compared to the timescale for entrained water to be distributed through the flow.

Debris avalanches. Although several theories have been proposed to explain the long run-out distances of debris avalanches, such as dynamic or acoustic fluidization, elastic release of energy and pore fluid mobilization, no general consensus has been yet achieved on which may be most important and under what conditions (see Hungr, 2002 and Legros, 2002 for a critical review). Laboratory experiments, which are essentially "inertia-less", have provided vital information on the frictional, brittle, kinematics of the body, but no modeling has yet examined either processes at the base, or fragmentation within the mass where inertial forces will play an important role. The objective of these large-scale experiments would be, in a controlled environment, to observe basal processes that could be related to low friction and characterize the textures and structures produced by each possible process. Since, at a large scale, it may not be feasible to achieve strain rates able to induce fragmentation of natural material, a synthetic analogue material will be researched and used, such as for instance the ETHAR, a material used for centrifuge modeling by Imre et al. (2010), together with a pneumatic acceleration mechanism at the inlet (see Mohammed and Fritz, 2010).

Testing new remote sensing technologies. Workshop participants anticipate an exciting feedback between large experiments and remote sensing technology. New ground-based remote sensing techniques are obtaining detailed information on particle velocities and concentrations in eruptive fountains, as well as gas concentrations and velocities. This combination of information is critical in our understanding of these fundamentally multiphase flows, and in developing accurate models of eruptive processes. However, it is extremely difficult to test emerging technologies on real eruptions, with their hostile environments and uncertain timing and initial/boundary conditions. Large-scale experiments provide opportunities to test new technologies in a controlled and scheduled environment, with multiple sensors for cross checking, and without necessarily having to engineer the technique for field portability. The experiments are crucial to the advances in remote observation systems, e.g. thermal camera, satellite imagery, UV camera, acoustic monitoring. In fact, potential experiments discussed at the workshop can be used to link and validate satellite and ground based observations at various wavelengths. At the same time, these new techniques will be extremely useful in gathering data about the experimental flow fields and increasing the diversity of data that can be used in analyzing flow physics.

Infrastructure to support the experiments. After discussing research needs and priorities for a large-scale experimental facility, workshop participants focused on ideas for the facility's infrastructure and instrumentation that allow the individual research priorities to be addressed while allowing maximum flexibility. General key infrastructure components include:

- Adequate power and water
- Well-maintained road access
- Machine shop
- Site meteorological instruments
- Computers and network for data acquisition

The first three items are already in place at the Geohazards Field Station. A high-speed computer network is being implemented for other experiments at the ECLIPSE Campus, and can be extended to accommodate the Geohazards Field Station.

Most experiments will require a large amount (several tons) of sediment and/or artificial particulate materials. To act as multifunctional facility, these materials should be available for a range of experiments including eruption column, PDC, debris avalanche/flow, and more. As such the facility should have the necessary sediment preparation equipment, as well as the ability to move and store the materials. This would include (but is not restricted to):

- Rock and sample preparation equipment such as saws and grinders
- Basic material separation and characterization equipment, such as industrial-sized sieves
- Space for storage of large volumes of experimental materials
- Dump truck or front-end loader for moving large volumes of material
- Equipment such as a large hopper for feeding particulate flows

A range of apparatuses would be necessary for the experiments themselves. An emphasis should be placed in designing these potentially costly systems to be capable of use by more than just one type of experiment. Workshop participants came up with the following ideas:

- Building with large open room for large experimental apparatuses
- A high tower and walls for controlling atmospheric and release conditions for tephra dispersion experiments
- Ability to modify landscape at the test facility

For vent and eruption column dynamics:

- A design including a flexible nozzle or “vent” with variable geometry for vent and eruption column dynamics studies

For PDC, debris avalanche or lahar experiments:

- A large flow channel with flexible geometry, “bed” characteristics, and slope

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For conduit and fragmentation experiments:

- The ability to melt, handle, and move necessary volumes of magma (possibly on the order of 4 m^3)
- Experimental bunker capable of containing explosive processes (such as magma-water interaction and fragmentation of viscous magmas) of being fitted with appropriate instrumentation, including line-of-site equipment
- Large column with variable geometry for liquid-bubble dynamics experiments

The above list focuses on relatively large-scale items that can be used across the wide spectrum of experimental research discussed at the workshop. Establishing this infrastructure would represent a major, long-lasting, and flexible investment in geological hazards research.

Importance of team approach. There was consensus that large-scale experiments should be done by large, multi-institutional and multi-disciplinary teams. Each team member could bring her/his expertise and instrumentation to participate in the design, execution, and analysis of a set of experiments. Examples of equipment that individual team members might bring to bear for a specific experiment might include ground-based lidar, Doppler radar, high-speed video, infrared cameras, various instruments for tracking particle motion in flows (such as RFID "marker particles"), pressure and temperature sensors, mini-DOAS (differential optical absorption spectrometer), and others. In a sense, the experiments can be viewed as scheduled and controlled eruptions; and, as with real (but unscheduled and uncontrolled!) eruptions, a broad group of experts and tools are used to collect and interpret data.

Path forward. Participants in the workshop expressed a high level of interest and enthusiasm for the concept of a user facility that would enable large-scale experiments. It was broadly recognized that such a facility would not only advance our fundamental understanding, and ability to forecast hazardous volcanic processes, but that it would also help to usher in a new, highly-collaborative and interdisciplinary way of conducting research for the volcanology community.

A key aspect of this shared user facility is "institutional neutrality," in that researchers should be able to access the facility independently, without feeling obliged to work through its host institution. The ECLIPSE Campus is being set up in a manner to promote such neutrality. A new not-for-profit company, ECLIPSE, LLC, will coordinate the logistics, administration, and engineering aspects of all field stations at the ECLIPSE Campus, including the Geohazards Field Station. Researchers will be able to work directly with ECLIPSE, LLC, to schedule time at the facility and to obtain engineering and proposal development support for specific experiments.

In order to build upon the momentum developed during the workshop, an Executive Committee for the Geohazards Field Station is being set up. This committee will consist of six to eight researchers from across the community who are committed to the development of the facility from a scientific perspective, as well as a representative from ECLIPSE, LLC. The role of the Executive Committee will be to manage community input, develop and articulate science priorities, facilitate communication to the community, and to help with coordination of proposals for basic infrastructure and for specific experiments.

Finally, a virtual site is being established on vhub.org, a new online collaboration hub for volcanology research and risk mitigation. At vhub.org, registered users will be able to see workshop presentations, summary reports, and to participate in an online discussion that will broaden input from the community beyond that of the workshop participants. To participate in the online discussion and to see the workshop materials it is necessary to register and set up a free account on vhub.org.

Acknowledgements. The workshop was sponsored by the US National Science Foundation, and by three organizations within the University at Buffalo: (1) Multidisciplinary Center for Earthquake Engineering Research; (2) Center for Geohazards Studies; (3) Extreme Events Faculty Advisory Committee. Many workshop participants provided useful comments and reviews of earlier drafts of this report, but we especially thank Brittany Brand and Laurence Girolami for in depth suggestions.

References

Alatorre-Ibargüengoitia MA, Scheu B, Dingwell DB, Delgado-Granados H, Taddeucci J (2010) Energy consumption by magmatic fragmentation and pyroclast exit velocity: experiments and application to Vulcanian eruptions. *Earth and Planetary Science Letters* 291: 60-69.

Alidibirov, M. and Dingwell, D.B. (1996) High temperature fragmentation of magma by rapid decompression. *Nature* 380: 146-149.

Büttner R, Dellino P, La Volpe L, Lorenz V, Zimanowski B (2002) Thermohydraulic explosions in phreatomagmatic eruptions as evidenced by the comparison between pyroclasts and products from Molten Fuel Coolant Interaction experiments. *Journal of Geophysical Research* 107: B02277

Chojnicki K, Clarke AB , Phillips JC (2006) A shock-tube investigation of the dynamics of gas-particle mixtures: Implications for explosive volcanic eruptions. *Geophysical Research Letters* 33: L15309.

Dellino P, Zimanowski B, Büttner R, La Volpe L, Mele D, Sulpizio R (2007) Large-scale experiments on the mechanics of pyroclastic flows: Design, engineering, and first results. *Journal of Geophysical Research* 112: B04202.

Dellino P, Büttner R, Dioguardi F, Doronzo DM, La Volpe L, Mele D, Sonder I, Sulpizio R, Zimanowski B (2010b) Experimental evidence links volcanic particle characteristics to pyroclastic flow hazard. *Earth and Planetary Science Letters* 295: 314-320.

Dellino P, Dioguardi F, Zimanowski B, Büttner R, Mele D, La Volpe L, Sulpizio R, Doronzo DM, Sonder I, Bonasia R, Calvari S, Marotta E (2010a) Conduit flow experiments help constraining the regime of explosive eruptions. *Journal of Geophysical Research* 115: B04204.

Garcia M, Parker G (1993) Experiments on the entrainment of sediment into suspension by a dense bottom current. *Journal of Geophysical Research* 98: 4793-4807.

Girolami L, Roche O, Druitt TH, Corpetti T (2010) Particle velocity fields and depositional processes in laboratory ash flows, with implications for the sedimentation of dense pyroclastic flows. *Bulletin of Volcanology* 72: 747-759.

Hungr O, (2002) Rock avalanche motion: Process and modeling, *Proceedings of NATO Advanced Research Workshop, Massive Rock Slope Failure: New Models for Hazard Assessment*, p. 66-69.

Imre B, Laue J, and Springman SM, (2010) Fractal fragmentation of rocks within sturzstroms: insight derived from physical experiments within the ETH geotechnical drum centrifuge: *Granular Matter*, v. 12, p. 267-285.

Iverson RM, Logan M, LaHusen RG, and Berti M, (2010) The perfect debris flow? Aggregated results from 28 large-scale experiments: *Journal of Geophysical Research-Earth Surface*, v. 115, p. 29.

Kneller BC, Bennet SJ, McCaffrey, WD (1999). Velocity structure, turbulence and fluid stresses in experimental gravity currents. *Journal of Geophysical Research* 104: 5281-5291.

Kueppers U, Scheu B, Spieler O, Dingwell DB (2006) Fragmentation efficiency of explosive volcanic eruptions: A study of experimentally generated pyroclasts. *Journal of Volcanology and Geothermal Research* **153**: 125-135

Kueppers U, Alatorre-Ibargüengoitia MA, Hort, MK, Kremers S, Meier K, Scharff L, Scheu B, Taddeucci J, Dingwell DB (2010) Volcanic monitoring techniques applied to controlled fragmentation experiments. *Abstracts, American Geophysical Union Fall Meeting, 2010*: V21E-2366.

Legros F, (2002) The mobility of long-runout landslides.: *Engineering Geolology*, v. 63, p. 301-331.

Mohammed F, and Fritz HM (2008) Experiments on Tsunamis Generated by 3D Granular Landslides, in Mosher, D.C., Shipp, R.C., Moscardelli, L., Chaytor, J.D., Baxter, C.D.P., Lee, H.J., and Urgeles, R., eds., *Submarine Mass Movements and Their Consequences*, Volume 28: Advances in Natural and Technological Hazards Research: Dordrecht, Springer, p. 705-718.