1- Why do pyroclastic density currents occur?
Post-doctoral project of Dr David Jessop (LMV-UBC)

Overview

Subduction zones, and hence arc volcanism, produce the most cataclysmic and devastating eruptions (e.g. Soufrierre Hills, 1997, Pinatubo, 1991, Mt. St. Helens, 1980). These explosive eruptions of silicic magma are surface expressions of the processes that occur during the life cycle of an arc volcano, often producing jet-like eruption columns that may undergo gravitational collapse to produce pyroclastic density currents (PDCs), or loft material several tens of kilometres and spread out as an ash cloud (**Figure 1**).

The key ingredient that determines which of these two phenomena will occur is the turbulent entrainment of atmospheric air into the jet which adds buoyancy to the jet. Classical models of eruption columns assume that the rate of entrainment is ~10% of the upflow rate of the jet [Morton et al., 1956; Woods 2010] and assumes that the inflow of air is unaffected by either the mixture properties of the pyroclastic material or the source conditions. In fact the addition of particles has generally been assumed to only contribute to the mean density of the jet [e.g. Carey et al., 1988; Woods, 2010]. However, recent studies have shown that the presence of particles of certain particle size distributions (PSDs) in the jet can have a significant effect on the entrainment rate owing to their buoyancy and inertia [Dufek and Bergantz, 2007; Jessop and Jellinek, 2014a,b]. As a consequence, the conditions for collapse as previously understood [e.g. Woods 2010] need to be reconsidered, particularly the possibility for an eruption to produce both a buoyant column and a collapsing fountain.

Recent work has shown how the shape of the vent works in combination with the momentum flux of particles to alter entrainment [Jessop and Jellinek, 2014a]. In a context such as the Cascades Arc, there are many complex forms of vent, which may be characterised into two end member forms: a caldera (annular or quasi-linear vent), e.g. Crater Lake (OR) or a cylindrical vent, e.g. Mt St Helens (WA). Thus implications for hazard assessment include: which type of vent will produce more often a lofting jet and which will more often produce PDCs? When will a volcanic jet collapse to produce PDCs? More powerfully, we ask: with which source geometry will PDCs form most frequently?

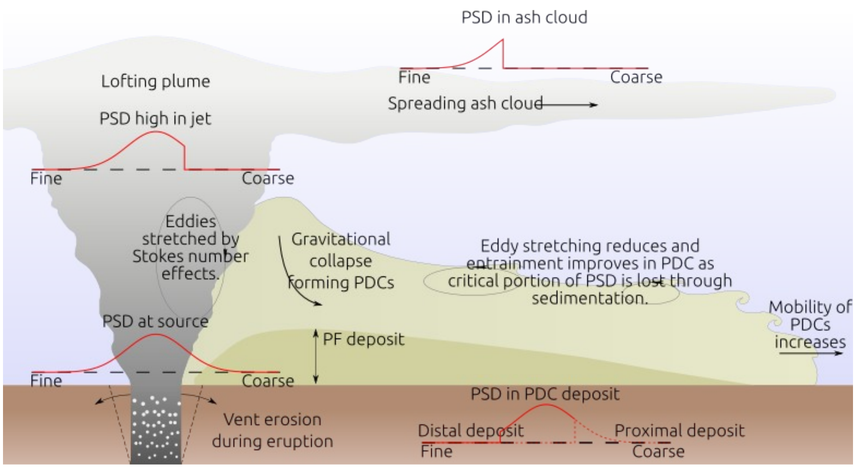


Figure 1: Schematic of a volcanic jet undergoing partial gravitational collapse and generating pyroclastic-density currents (PDCs), and also lofting to produce a spreading ash cloud. The particle-size distributions (PSDs) and their impact on entrainment dynamics are indicated for various locations in the flows.

Key aspects of the underlying physics crucial for hazard assessment that need to be addressed are:

- What are the critical PSDs, vent geometries and other source conditions that affect jet stability, leading to partial or complete column collapse?
- How do these source conditions determine the generation and characteristics (e.g. density, run-out distances and thickness) of PDCs?
- With which vent geometry (say, (i) simple central vent or (ii) annular/linear vent in case of a caldera) will PDCs form most, as opposed to a lofting plume?

In this project we aim to produce a global view of the dynamics of such volcanological processes by building understanding from the microphysics on up to the full scale phenomena. We will use experiments and theory to address the temporal and spatial distribution of particle sizes in jets and the mechanisms that determine the conditions for column collapse and PDC formation. Our results will be applied to understand time series observations from historical eruptions as well as to prehistoric deposits.

What are the critical PSDs and source conditions that affect jet stability?

Volcanic jets are a mixture of pyroclastic ash, rock fragments and volatiles. Even though the solids concentration is low (<1-10%) [Woods, 2001] they are denser than the atmosphere and so will collapse as a fountain, producing potentially devastating PDCs, unless they can entrain and heat enough atmospheric air to produce a buoyancy reversal. Explosive eruptions produce a wide range of particle sizes from fine ash to metre-scale blocks. A portion of the PSD will have critical properties of buoyancy and inertia and so will be coupled to the fluid phase in complex ways, through so called “Stokes number effects” [Dufek and Bergantz, 2007]. The specific size range of particles which couple to the fluid in this way is also dependent on how vigorous the flow is so that, at various stages in the rise and collapse of the column and the generation of PDCs, different portions of the PSD maybe critically coupled to the flow (**Figure 1**).

Recent work has shown how particles work in tandem with the shape of the vent to either reduce (if the vent is narrow and straight sided) or enhance (if the vent is broad and/or outwardly flared) entrainment in the jet [Jessop and Jellinek, 2014a]. In this case, even jets that do not conform to the collapse criteria as we understand them [cf. Woods 2010] could still collapse as entrainment is effectively choked off by certain critical PSDs.

How do source conditions determine the generation and characteristics of PDCs?

PDCs generated from the collapse of a jet have as initial conditions: mass, momentum and buoyancy fluxes of the collapsed jet and PSD at the point of collapse. PDCs generated from jet collapse can form two end members with differing retarding physics:

- dilute, turbulent suspensions of fine particles (surges) where momentum transfer is through particle-fluid interactions and the entrainment of ambient fluid. Particle-particle interactions are rare.
- dense flows of both fine and coarse particles (e.g. pyroclastic flows, pumice flows) where particle-particle interactions are numerous and sustained and the main mechanism for momentum transfer is friction. Particle-fluid interactions act largely to reduce frictional forces through fluidisation [Jessop et al., 2013].

Complexity arises as PDCs may consist of a basal pyroclastic flow overridden by dilute surge, which may provide particles to the flow through sedimentation. Both classes of PDCs are highly mobile (Roche, 2012) and can be devastating to infrastructures. A thorough understanding of the PSD at the point of PDC generation will allow us to better understand whether a collapsing jet will form a surge or a flow. This knowledge has profound consequences for our ability to predict areas that will be affected by volcanic flows (i.e. mobility and run out) and the degree to which structures will be impacted (i.e. flow thickness, velocity and density).

Appropriateness of research methodology and approach

The project will entail laboratory-based and theoretical studies, building on recent work in the literature and will be used to predict the time-dependent structures of jets and PDCs.

Analogue experiments

The planned experiments are scaled with natural flows and will map out the regimes encountered within this parameter space. They are isothermal and will be conducted in density-stratified tanks by injecting a well-stirred mixture of water and well-sorted particles at a fixed rate. Two forms of apparatus will be used: i) a cubic tank with a central nozzle through which the particle/water mixture can be injected - the resulting particle-laden jets and clouds are axisymmetric in form, and offer excellent information on the large-scale dynamics; ii) a tank with width much narrower than its length, allowing for the internal cloud dynamics and layering to be viewed and to make more precise measurements of the entrainment dynamics and small-scale (i.e. particle-scale) processes in the jet. Both set-ups enable us to vary the source and environmental conditions that govern flow dynamics: i) the particle concentration and PSD, ii) the volumetric flow rate, iii) the nozzle size and geometry, and iv) the stratification in the tank.

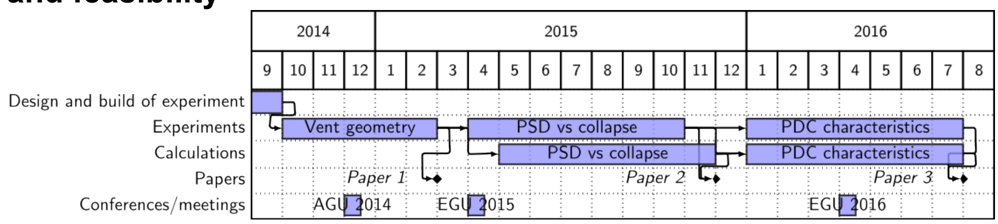
Modelling

We will look to further understanding of our experimental results using theoretical descriptions of turbulent jets explosive volcanic eruptions using two methods:

- Numerical modelling in either 3D and axisymmetric geometries [e.g. Neri et al., 2003; di Muro et al., 2004].
- Simple conservation models for momentum-driven jets with buoyancy [e.g. Morton et al., 1956; Woods, 2010; Jessop and Jellinek, 2014a] which, despite their simplicity, remain a powerful tool for testing entrainment theories.

We will build on existing experimental work [e.g. Jessop and Jellinek, 2014a,b], using simple models first to address the questions highlighted above and to provide a tool that can later be used to verify the numerical models. The new state-of-the-art models are essential for the precise quantification of hazards posed by these phenomena.

Time line and feasibility



The Gantt chart above indicates the time line of the proposed work. We anticipate being able to publish three papers around three themes during the project itself. Calculations and experiments for the second and third stages of the project will continue hand in hand. We also envisage attending 3 major scientific meetings during the course of the project.

Outcomes and improvements to the state-of-the-art

- Better understanding of volcanic jet stability in terms of the local concentration and distribution of particles.
- Better assessment and estimation of their stability and likelihood for collapse.
- Redefinition of the state-of-the-art in physical models for jet and PDC dynamics.
- Improvements in our ability to anticipate and estimate the risks PDCs pose to nearby populations and put action plans into place to reduce their impact.

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2- Presentation of institutions

Department of Earth, Ocean and Atmospheric Sciences (EOAS), UBC

EOAS is a an internationally-renowned and well-equipped centre of excellence in the domain of Earth Sciences. EOAS comprises researchers who are investigating pure science studies from the Earth's deep interior, through near-surface geological studies and environmental earth science, to the oceans and atmosphere. EOAS has a strong track record in attracting international visitors and of supporting early-career researchers holding fellowships on the path to independent research careers. Prof. Jellinek's group is renowned for its research in geophysical phenomena and has a very strong track record in many aspects of geological fluid mechanics, particularly applied to problems in physical volcanology. The candidate will have access to two state-of the art experimental spaces equipped with high-speed video cameras, imaging equipment and software, optical and thermocouple sensors, 2 Acoustic Doppler Velocimetry units, and a laser bed surface scanner. Access to high-powered computing facilities, including the WESTGRID network for parallel computing is also available. The candidate will also interact with world-class researchers such as Neil Balmforth, Christian Schoof (theoretical modelling) and Kelly Russell (field volcanology).

Volcanology Group at the Laboratoire Magmas et Volcans (LMV)

The main goal of the Volcanology Group at LMV is to provide a better understanding of volcanological processes, and draws on a combination of different approaches: field studies (including geophysical monitoring), numerical modelling, and laboratory experiments. Studies conducted by the Volcanology group have focused on various objectives, but of relevance here are the mechanisms of propagation and deposition of pyroclastic flows. To study the fundamental processes of these highly hazardous flows, the group has pioneered the development of a range of experimental devices, including flumes for fluidised granular flows, hence becoming the world-leading team in this research area. The experimental volcanology laboratory benefits from high-tech facilities, including a system of pore pressure and stress sensors, a high-speed video camera, laser sheet projector, image capture hardware and software allowing for surface deformations to be measured. For numerical modelling, there is access to high-performance computer equipment, parallel-computing servers and local grids (Auvergrid and EGEE). Group members with whom the candidate will interact to discuss and develop his work include Karim Kelfoun (numerical modelling), Philippe Labazuy, Franck Donnadieu and Andrew Harris (remote sensing/field data).

Principal post-doctoral supervisors for the candidate:

Mark Jellinek, Professor, UBC has an established record in many aspects of geological fluid mechanics applied to physical volcanology. The proposed project extends existing and well-developed research areas that have focussed on the dynamics of multiphase magma chambers, volcanic jets and volcanic umbrella clouds. Prof. Jellinek has worked with and supported 8 post-doctoral fellows, each of whom is now at the top of their respective fields.

Olivier Roche, Senior Researcher, IRD-LMV is Deputy Director of LMV and is in charge of the experimental volcanic multiphase flows laboratory. His research activities include the development and use of a series of experimental devices for the study of caldera collapse and pyroclastic flows. He was PI of a French National Research Agency "Young Researcher" program on pyroclastic flows (150 000€, 4 years, including 1 PDF) and of two international (France-Chile) research programs. He is currently the leader of a research program on volcanic gravitational flows (ClerVolc) and has supervised 5 PhD students and 2 PDFs.