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Abstracts volume

Monitoring of volcanic emissions in northern Chile, part I: Applications of direct gas sampling

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A volcanic gas monitoring project is being actually carried out in two active volcanoes located in Northern Chile: a) Lascar, a composite stratovolcano considered the most active volcano of the Andean Central Volcanic Zone (ZVC), is characterized by permanent fumarolic emissions occasionally interrupted by vulcanian explosions and was affected by a dome growth-and-collapse cyclic period between 1986 and 1994. Its largest historically recorded eruption occurred on 19–20 April 1993 and produced a 25 km height sub-plinian column, whose collapse generated pyroclastic flows up to 8.5 km NW from its summit. b) Lastarria, a composite stratovolcano that pertaining to the Lastarria-Cordón del Azufre (Lazufre) volcanic complex, is characterized by permanent fumarolic activity. Since 1998, the Lazufre complex has been affected by severe ground deformation, phenomenon probably associated to the evolution of a pre-caldera system. While since 2003, significant ground deformation affect the Lastarria volcano area, being interpreted as the result of pressurization of the hydrothermal system. 3 different gas sampling techniques have been applied in both volcanoes during April and June 2009, with the objectives to i) establish the state of activity, ii) better constrain the eruptive dynamics, and iii) decipher some precursory events to better predict the behaviour of these volcanoes.

The direct sampling method consists in the collection of gas in pre-evacuated glass flasks (Giggenbach bottles) directly from fumarolic emissions, which is analysed for inorganic and organic chemistry by gas and ion chromatography. The wide spectra of gases analysed by this technique permit to determine i) origin and nature of gas, ii) physical-chemical parameters (redox conditions, deep temperatures, etc.), iii) degassing process, iv) gas-rock interaction at crustal levels and v) shallow process (gas-water interaction at aquifer level, atmospheric compound mixing). Consequently, can be used to establish the state of activity of a volcano, identify some geochemical precursors and use to monitor its changes along time periods.

Perspectives of a global network for studies of volcanic plumes

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The effort for understanding the multifaceted and complex behavior of volcanic plumes requires a multidisciplinary approach and it is rewarded, when the information that is (literally) transported by the plumes is appropriately worked out, by a profound insight of the volcanic-environment interactions on broad spatial and temporal scales.

One way to integrate the specificity gained by studying plumes in the close range (within a few km from the emission point) with the advantage of keeping a global perspective of this far-reaching phenomenon is by establishing a global network of permanently observing stations around some active and strongly degassing volcanoes. A detailed description of the fluid dynamics of generation, transport and fate, or of the physical and chemical composition and distribution of the volcanic plumes is (sometimes only) achievable by observations from single or spaced-distributed stations around the volcanoes. Larger-scale objectives like the validation of satellite-based observations or the refinement of existing geochemical cycle and climate models, for which a reliable quantification of the volcanic input is necessary, are also accessible in this manner. Furthermore, local volcanological observatories become involved in a community, contributing to scientific cooperation and support.

The Network for Observation of Volcanic and Atmospheric Change (NOVAC) is an EU project initiated in 2005, which has been aimed at providing observatories around the world, particularly from developing countries where most of the most active and potentially risky volcanoes are located, with a standard method for the measurement of some volcanic gases (SO_2, BrO): the ground-based Dual-Beam Mini-DOAS instrument. The network presently comprises 20 volcanoes from Africa, Europe and South- and Central America, where 44 stations have been installed and operate with variable success. Data is used by the local observatories and transferred to a central database accessible by the participants.
Besides providing real-time measurements of the gas fluxes, the method has been exploited to obtain important parameters for more general studies of volcanic plumes and their environments. The measured gas is used as a tracer for mapping the spatial and temporal distribution of the plume by tomographic methods and to study dispersal dynamics of single or split plumes; from the measurement of plume dimensions it is possible to inventory atmospheric diffusion coefficients; accurate plume velocities can be measured in real-time; aerosol content can be assessed by radiative transfer calculations.

In this contribution, we propose NOVAC as a platform that can be expanded by including further collaborators with expertise in complementary methods for the study of volcanic plumes. The experience with NOVAC as a proof-of-concept of a global network in the volcanological community is unique in this respect and it is fully compatible with the goals of WOVO of integrating the existing information gathered on volcanoes to improve knowledge and cooperation in Volcanology.

Simulating the tephra dispersal and deposition of Violent Strombolian events at Vesuvius (Italy)

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In its eruptive history Vesuvius experienced a wide variety of activity. However, according to recent studies, a Violent Strombolian event is the most probable scenario in case of a near future reawakening. With the term Violent Strombolian here we mean a moderate event, similar to those occurred in 1906 and 1944, characterized by a prolonged emission of tephra through the formation of a volcanic plume a few km high. Based on recently reconstructed past events of this kind, two distinct sequential eruptive phases, with specific intensity, duration and grain-size, appear to characterize the emission. In this work we study and reproduce by numerical simulation the main features of this eruptive scenario and its potential hazard on the Vesuvian area. In detail we adopted the VOL-CALPUFF code (Barsotti et al. JGR 2008) to model the rising column, the ash cloud dispersal and its deposition on the ground. This code, based on a hybrid Eulerian-Lagrangian formulation, couples the dynamics of plume rise with atmospheric ash transport both in proximal and distal areas. Most importantly, VOL-CALPUFF describes the event dynamics by using transient and 3D meteorological conditions at high spatial and temporal resolution. Simulation results show that the column height, as well as the area interested by tephra fallout, are strongly affected by the source conditions assumed and by atmospheric dynamics in the lower troposphere. By adopting a Monte Carlo approach and using a meteorological dataset of several years from the ECMWF Re-analysis Archive, we achieve a statistical representation of the phenomenon. The maps produced can be used for land-use and emergency planning as well as for mitigating the impact of this phenomenon.

Comparing the dynamics of dilute pyroclastic density currents on Earth and Mars

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While the products of explosive volcanism have long been identified on the surface of Mars, the dynamics of Martian pyroclastic density currents (PDCs) remain poorly understood. Recent numerical models show that PDCs formed by Martian eruptions are capable of producing pyroclastic flows that reach up to 600 km from source, consistent with observations of ash deposits around many highland Patera (*e.g., Greeley and Crown, 1990, J Geophys Res 95 7133-7149*). However, these models neglect processes such as entrainment, sedimentation and thermal evolution of the currents, which contribute to changes in bulk density. We've developed an axi-symmetric model for flow of and sedimentation from a steady-state, vertically uniform density current for application to PDCs on Earth and Mars (following *Bursik and Woods, 1996, Bull Volcan 58 175-193*). The conservation of mass, momentum, and energy are solved simultaneously, and the effects of atmospheric entrainment, particle sedimentation, basal friction, temperature changes, and variations in current thickness and density are explored. Employing the Mars conditions proposed in Crown and Greeley (*1993, J. Geophys Res, 98, 3431-3451*), and neglecting entrainment and sedimentation, we too obtain run out distances up to 600 km. However, introducing sedimentation of 0.1 mm particles slows the current more quickly, and adding the effects of entrainment further slows the current, resulting in much shorter run out distances (<100 km). For a given set of identical initial conditions, our models show that PDCs on Mars will out distance Earth PDCs by approximately 33%, reflecting slower sedimentation rates. Although this general conclusion is consistent with previous studies, the difference between the Earth and Mars cases is much less than previously published. Additionally, we incorporate the Rouse number and Brunt-Väisäla frequency to estimate the wavelength of internal gravity waves in a density stratified current, which are thought be the primary control on bedform characteristics (*Valentine, 1987, Bull Volc 49 616-630*). The model predicts realistic wavelengths on Earth (dunes from 20 - 200 m), whereas longer wavelengths are predicted on Mars (50 - 300 m). This difference probably reflects the fact that lower particle settling velocities on Mars result in density stratification over a greater vertical extent.

On the Permeability of Pyroclastic Material

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An initially expanded bed of polydisperse material will, under the influence of gravity, settle back to its maximum packing. From 40% expansion down, settling is strongly influenced by the speed at which the interstitial gas can escape from the bed. The capacity to retain gas is best measured by the bed permeability, which so far has been directly measured in fluidization rigs. Here, we apply a generalized Blake-Kozeny law of permeability to highly polydisperse pyroclastic material in order to link grain size distribution to bed permeability. In addition to sieve data, the only free variable is the bed expansion. The method is able to retrieve measured permeabilities with a median relative accuracy of 25%. It has recently been shown that if the fluidized bed is flowing while settling, its deposition takes place by progressive sediment aggradation at a rate that nearly identical to that of a quasi-static bed. Combining such observations with the tool presented herein may open possible links between some types of deposits of pyroclastic density currents and the dynamic variables controlling the currents when still in motion.

Pyroclastic Flow Overview

Marcus Bursik

Following Moore's Law, the power of digital computers has exploded to the point where complex calculations of the propagation of pyroclastic flows is almost routine. While we continue to struggle with a full understanding of the mechanics of pyroclastic flows, we are thus already embarking on the use of numerical pyroclastic flow models in hazards assessment. In so doing, we find that certain factors have a large impact on flow inundation area, including but not limited to state of the atmosphere, value of basal friction and description of the topography. Can we properly characterize inundation given large uncertainties in parameter values or a poorly described topography? Alternatively, how important is a detailed understanding of flow mechanics, given parameter uncertainty or poor digital topography? Should we even attempt to use numerics in hazards assessment given the low level of knowledge that we may always have about certain parameters or factors? A proper understanding and respect for model uncertainty arising from poor parameter estimation, topographic description or mechanical understanding is critical to determination of whether use of numerics is appropriate in hazards assessment.

Eulerian-Lagrangian particle tracking of tephra deposition

Marcus Bursik and Shannon Kobs

Operational ash deposition models have so far depended on the advection-diffusion-sedimentation equation. This approach provides a good, low-cost fit for fine grain sizes and medial to distal deposits for which ash transport is wind-dominated. The deposition-enhanced ATHAM model (ATHAM-dep) instead uses Lagrangian particle tracking of coarse ash in an unsteady, Eulerian, Navier-Stokes plume simulation to focus on plume-influenced ash transport and deposit grain size distribution. The use of this approach allows for the investigation of airborne pyroclast sorting and the development of isopleth maps. ATHAM-dep was used to simulate the deposition of the Pululagua BF and the Fogo A eruption deposits. Both of these eruptions produced deposits that are radially symmetric around their respective vents, indicating very low ambient wind. As such, the eruptions provide an excellent opportunity to test ATHAM-dep in a simple no-wind condition. Both eruptions were simulated using ranges of eruption conditions such as vent diameter, mass flux, and temperature drawn from published literature. The model was used to generate isopleth maps that were compared to published maps for both deposits. Model results fit well with the published data and indicate column heights slightly lower than previous estimates.

Quantitative measurements of explosive and passive degassing: volcanological and climatological implications

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Recent methodological advances in ground-based remote sensing of volcanic gases have allowed examination of volcanic degassing processes with unprecedented detail. In this paper I summarise observations of the persistently degassing Stromboli volcano, and discuss the implications for forecasting volcanic activity and the climatological impact of basaltic eruptions.

One of the most exciting recent advances in volcanic plume measurements is the SO_2 camera, an instrument that allows imaging of the amount of SO_2 over a wide field of view. This device was used on Stromboli volcano to record the amount of SO_2 released in individual explosions. Combining this

information with explosive gas compositions derived from OP-FTIR measurements allows us to calculate the total mass of gas released during each explosion. Comparisons with the total mass of gas released via passive degassing clearly demonstrates that at this volcano explosive activity, in terms of gas release, a secondary process compared with quiescent degassing.

Long-term combined measurements of CO_2/SO_2 ratios and SO_2 fluxes on Stromboli have allowed the first time series of CO_2 fluxes to be determined. These data were collected before, during and after an effusive eruption during which an anomalously large explosion occurred. The very high CO_2 gas fluxes recorded prior to the explosion, in the absence of explosive activity indicate the presence of an extended degassing regime which tapped a magma reservoir.

These data also allow a precise determination of the long-term average CO_2 release from this volcano. The high CO_2 fluxes observed strongly suggest that the original CO_2 content of magma feeding this volcano is larger than that recorded in the deepest melt inclusions, implying the presence of a gas phase at great pressures. The presence of this gas phase will strongly condition the behaviour of magma during its ascent to the surface.

If high original CO_2 content were a ubiquitous feature of basaltic magmas then CO_2 emissions from these sources may be much larger than has previously been thought, with implications for the climatological impact of the largest basaltic eruptions.

Towards a new approach for generating probabilistic hazard maps : a case example for pyroclastic flows during lava dome eruptions.

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It is increasingly being understood that development of mathematical models of a geophysical phenomena, while a fundamental step, is only part of the process of modeling and predicting inundation limits for natural hazards. In this work we combine data from hundreds of observed pyroclastic flows at the Soufriere Hills Volcano, Montserrat, a geophysical flow model, and statistical modeling to derive a new methodology for generating probabilistic hazard maps. The initial step consists of estimating probabilities of inundation at particular discrete points of interest (e.g. airport and Plymouth). The methodology starts with a computer model of the geophysical process, in this case the TITAN2D model that has been developed for modeling geophysical mass flows. A key input to the computer model is the probability distribution for the initial volume and direction of the flows based on observed data. An important limitation is that for modeling purposes, the observations represent relatively scarce datasets, while from a volcanological perspective datasets such as those from the prolonged and relatively well-monitored eruption of the Soufriere Hills Volcano, are as complete as can be realistically obtained.

By combining flow event data, probability modeling and statistical methods, a probability distribution of severity and frequency of flow events is derived. Understanding and predicting the effects of volcanic hazards involves understanding the extreme event tail (the largest flow events) but this is notoriously difficult, especially with the limited data and prohibitively expensive to compute. Instead a statistical emulator (or surrogate of the computer model) is used, a computationally cheap response surface approximating the output of the flow simulations, which is constructed based on carefully chosen computer model runs. The speed of the emulator then allows to 'solve the inverse problem': that is, to determine regions of inputs values (characteristics of the flow) which result in the events of interest (such as one that that reaches a given critical point). The flow frequency distribution is then used to determine the probability of this region, that is, the probability that an event of a given magnitude will occur at a particular site. Using quantitative measures like these to solve for the probabilities across an area, zoned maps could be generated from which civil protection authorities can make more informed decisions about hazard mitigation. This methodology has wide applicability and can be used for any flow modeling technique (plume dispersal/pyroclastic density currents and/or debris flows), at any location.

Enhanced proximal sedimentation during high intensity Plinian Plumes: Examples from Askja 1875, Novarupta 1912 and Quizapu 1932 eruptions.

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Studies of proximal volcanic deposits in near-vent regions (< 2 km) are the only means to constrain rates and processes of pyroclast transport and sedimentation in the jet and lower convective column regions of strong volcanic plumes. Leading examples of over-thickened proximal deposits exist, such as Askja 1875, Novarupta 1912 and Quizapu 1932, where complex proximal stratification and rapid lateral thinning relationships indicate unsteady conditions of the jet and lower convective column margins.

These widespread fall units has been modeled using the segmented exponential thinning model (*Bonadonna et al., 1998*), and three to five segments have been recognized on a semilog plot of thickness vs. area$^{1/2}$. On these plots, a newly defined Seg-1 can be observed with Bt values an order of magnitude less than that of Bonadonna et al's Seg0, but significantly greater than Bt's for cone-forming lower intensity basaltic eruptions.

Seg-1 must be related to one or more proximal sedimentation regimes not captured by existing models for high intensity eruptions and the geometry is suggestive of ephemeral and sectoral sedimentation from principally the jet, with some contribution from the lower plume. Current conceptual models for the examples described above propose that short-lived fluctuations of mass flux, coupled with the heterogeneity in the distribution of erupted particle sizes above the fragmentation surface and complex velocity profiles across the jet drive unsteadiness and short-lived local mass overloading.

New computational models are an important next step into understanding the forcing mechanisms that dominate particle transport from, and air entrainment into, the jet and lower plume regions. These studies are particularly important as sedimentation and entrainment are two factors which influence collapsing vs. buoyant column behavior, with obvious hazard implications.

Satellite remote sensing of volcanic clouds and plumes: state-of-the-art and future prospects

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Over the last decade, the use of satellite observations of atmospheric composition in analysis of volcanic clouds and plumes has proliferated. Low-resolution, synoptic imaging of major volcanic eruption clouds has been supplanted by vertically resolved measurements of volcanic plume constituents at altitudes from the planetary boundary layer (PBL) to the stratosphere on many spatiotemporal scales. We summarize recent developments in the field and look ahead to key future satellite missions. Satellite instruments now offer the ability to detect passive volcanic degassing of sulfur dioxide (SO_2) from space on daily basis, improving constraints on global volcanic emissions of this important aerosol precursor and making satellites an increasingly viable tool for volcano monitoring. NASA's A-Train fleet of six polar-orbiting satellites makes near-coincident, multi-spectral measurements of volcanic gases and particles from several sensors, permitting vicarious validation of retrieval algorithms. The advent of space-borne lidar observations is an important advance for studies of explosive volcanism. Lidar data provide vertical profiles through aerosol-laden volcanic clouds, revealing internal structure and providing direct measurements of plume-top altitude, a key parameter when assessing mass flux during explosive eruptions. Hyperspectral measurements at ultraviolet and infrared wavelengths permit direct retrieval of SO_2 cloud altitude and provide information on the composition of volcanic ash particles. Such measurements offer improved parameterization and validation for models of eruption dynamics and plume dispersion. These and other new techniques are illustrated using examples from recent explosive eruptions of Chaitén (Chile), Okmok (Aleutian Islands), Kasatochi (Aleutian Islands), Redoubt (Alaska), and Sarychev Peak (Kurile Islands). We also look ahead to new and planned satellite missions with potential applications in volcanology. These include space-based carbon dioxide measurements, and near real-time tracking of volcanic emissions from proposed geostationary air quality monitoring platforms.

Insights into pyroclastic flow behaviour from field characteristics of deposits: from hare to tortoise?

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It is commonly recognized that the deposits of pyroclastic flows do not represent the physical flow state of the parent flow system. However, deposit characteristics are fundamental in reflecting many important dynamic aspects of pyroclastic flows, especially during deposition. Flow front and trailing/enclosing ash cloud parts of flows produce distinctive deposit types (layers 1 and 3), reflecting turbulence during transport and deposition. Layer 2 deposits, however, remain enigmatic because the flow state of the “body” of the flow remains debatable because deposits do not provide a unique solution. Although much ash is elutriated from flows the abundance of fine ash matrix in layer 2 deposits indicates that a high particle concentration granular flow regime exists in the body of almost all pyroclastic flows, with likely suppressed turbulence, and particle concentration limiting the ability of hot buoyant gas to elutriate most fine ash. By analogy turbidites are usually well size graded, unless they result from high particle concentration flows, and highly turbulent, fully expanded Saharan dust storms do not produce thick massive deposits that fill topography. They produce thin, mantling, fallout-like, loess-like deposits. The frequent preservation of a sub-horizontal AMS fabric defined by minute magnetic minerals is remarkable, defining a sub-horizontal alignment of some of the smallest particles in a pyroclastic flow. A sub-horizontal clast alignment fabric is also commonly defined by larger lithic and pumice clasts, but remarkably, also, by visible mineral grains, such as biotite (e.g. pervasive fabric in the Cerro Galan Ignimbrite).

It is proposed that pyroclastic flows are highly ephemeral 4D density currents, capable of changing their flow state in 4D space. Every flow is different, and every flow changes its flow state in 4D space. Single pulse triggered pyroclastic flows may behave differently to continuously fed pyroclastic flows, at least at different time scales. During waxing flow, the flow front may be highly turbulent, but during waning flow the flow front may be less turbulent than the flow behind. Similar vertical and lateral variations are likely to exist. The sub-horizontal magnetic and textural fabric present in many pyroclastic flow deposits is interpreted to represent a laminar shear flow state during the final stages of flow and during deposition zt any point in the flow system. The depth of this laminar flow zone is unknown and could vary from a thin basal “boundary layer” in highly expanded, high velocity pyroclastic flows or the proximal, initial parts of flows, to a thick laminar flow zone, kept mobile by trapped gas, in waning “highly depositional” low velocity flows (e.g. at distal settings), in which such a flow regime is likely to back-step towards proximal settings, which during waning flow may transform from dynamic flow zones where currents are erosional or by-passing, to waning state laminar depositional flow systems. Similar vertical variations also occur everywhere. Some pyroclastic flows are hares, at least initially, but many become tortoises in distal settings (and/or everywhere during waning flow stages), explaining other features such as levees, and high relief terminal lobe geometries, which cannot be explained by high velocity, highly turbulent flow states. Depicting pyroclastic flows in terms of simple vertical profiles or gradients is accurate only at a single point along the flow path, but at different points along the flow path that profile varies. Flows also cannot be depicted by uniform flow conditions or flow state because they are such complex 4D systems.

Flow mobility is likely to be a function of both momentum and gas lubrication, with relative roles changing during flow and between flows, but in most cases momentum being important initially followed by gas lubrication later in a flow event. Lack of erosional interaction at the base of many deposits suggests some flows may even glide over the ground surface facilitated by pressurized gas exerting a downward pressure on the ground surface and/or that the flow front rolls over the ground surface and exerts a downward pressure on it, causing the substrate to stay in place because a lateral, erosional shear force is not exerted on the substrate by the laterally moving flow.

Modelling the dynamics of block-and-ash flows: a case study of the 2006 eruption of Merapi Volcano, Java, Indonesia

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The dynamics and depositional processes associated with block-and-ash flows (BAFs) are most commonly inferred to be a function of granular or inertial grain flow, similar to debris flows and cold rock avalanches. Existing geophysical mass flow models are either based on frictional (Mohr-Coulomb) behaviour (the Titan2D model developed at the University of Buffalo, USA) or another rheological law (i.e., a constant retarding stress), eventually adding some viscous and turbulent components (the VolcFlow model developed at the Laboratoire Magmas et Volcans, Clermont-Ferrand, France).

The 2006 BAFs of Merapi have been used to test the validity of these two well-established models. The May-June 2006 eruption of Merapi Volcano consisted of three eruption phases that produced two main types of BAFs (short- to medium-runout BAFs that show similar behaviour as granular-free surface flows on unconfined planes and long-runout BAFs interpreted as unsteady, modified grainflows) that have been recognized based on various parameters such as their generation mechanisms, flow volume, travel distance, deposit morphology, distribution, lithology and grain size distributions. The influence of various types of topographic settings on transport and deposition mechanisms of these two types of BAFs was examined through the development of two conceptual models. Based on these models, a new classification of the different types of BAFs observed at Merapi is proposed and can be directly integrated into numerical simulations.

Our modelling work has allowed the definition of key flow parameters that will lead to more reliable predictions of the areas and levels of hazards associated with such flows. We first show that with the incorporation of spatially varying bed friction angles, Titan2D is capable of reproducing the paths, runout distances, areas covered and deposited volumes of the 2006 Merapi flows over highly complex topography. However, some discrepancies with field data are noted and the velocity and travel time of the flows do not match entirely. Using a single free parameter (a constant retarding stress), simulations obtained with the VolcFlow model also reproduce the morphology and distribution of the natural deposits as well as the time of emplacement and velocities of the flows. The results suggest that the performance of these models in simulating actual events is critically dependent on (1) the calibration of the model by using extensive field-based data such as deposit distribution, processes of flow generation, transport and deposition, (2) the incorporation of a suitable empirical law into the model (spatially varying bed friction angles or constant retarding stress) and (3) the choice of input parameters, such as location and volume of the initial pile of material and source characteristics (single or multiple dome-collapse, dome-collapse duration and total volume of collapsed material). The model evaluations presented here provide an invaluable tool for guiding hazard assessement of BAFs during future eruptive crises at Merapi.

Visualizing the internal structure of short-lived, unsteady plumes to investigate the effect of time-varying source fluxes on eruption plume evolution

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Volcanic vent exit velocities, eruption column velocity profiles, and atmospheric entrainment are important parameters that control the evolution of explosive volcanic eruption clouds. In particular, these parameters control maximum flow height and width, collapse height, particle carrying capacity and corresponding particle dispersal and deposition. Additionally, temporal variations in source conditions affect the overall motion of eruption clouds, which is particularly relevant to short-lived, unsteady explosive eruptions which occur more frequently than long-lived quasi-steady eruptions. However, due to their complexity, relationships between time-varying source fluxes and evolution of unsteady turbulent flows is poorly understood. Here we document the velocity structure of unsteady, short-duration flows driven by both buoyancy and momentum using Particle Image Velocimetry (PIV) on scaled laboratory experiments. PIV is an effective technique for measuring instantaneous velocity structure in unsteady fluid flows, to determine the influence of spatial and temporal velocity variations on flow evolution. The experiments involve source fluids of various densities (960-1000 kg/m^3) injected with a range of initial momentum and buoyancy into a tank of fresh water through a range of vent diameters (3-15 mm). Time-resolved video images of the flows were obtained using a high-speed CCD camera and velocity vector fields were identified from the displacement of particles from one image to the next. Cross-sectional profiles of vertical velocity and entrainment of ambient fluid were characterized using the resulting velocity vector maps. A scaled analysis was used to determine the fundamental parameters governing the evolution of the laboratory plumes as a function of unsteady source conditions. The subsequent model can be applied to predict flow front propagation speeds and maximum flow height and width of transient volcanic eruption plumes which can not be adequately described by existing steady approximations.

Eruptive styles and modalities of pyroclastic density current formation and deposition at Vesuvius (Italy)

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The explosive activity of the last 20 ky at Somma-Vesuvius has been the object of many studies in the past decade. The range of compositional and physical parameters which drove past activity is now quite well known, giving us the chance to discuss the different eruptive styles in terms of the associated eruptive plumes, their deposits and expected effects. Pyroclastic density currents of different types were associated to the most intense eruptions (from sub-plinian to plinian), clearly graduating their transport and depositional features as a function of eruption intensity. An attempt of PDC classification is proposed mainly based on the sedimentological features of the related deposits, trying to assess, for each type of PDC, the main physical parameters which governed transport and deposition, the temperature at deposition, the location of first deposition, the maximum runout, and the expected time-dependent variation of dynamic pressure. A wide variability is observed in the deposits, covering a very large range of conditions and giving a detailed picture of the first order parameters to be carefully evaluated while trying to assess eruptive scenarios for future eruptions.

Quantifying the dynamics of explosive eruptions using ground-based Doppler radar

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For about a decade ground-based Doppler radars have been used to investigate various aspects of volcanic activity ranging from dome destabilization processes and rockfalls, to the dynamics of lava jets, ash plumes and ash clouds. Their all-weather, mobility and Doppler capabilities make the equipment particularly useful for monitoring active volcanoes as well as to investigate the dynamics of explosive activity for a wide range of eruption intensities.

Our Doppler radar (VOLDORAD 2) operates at the 23.5cm wavelength and provides data for several slices through the plume at high sampling (<<1s) rates. Data allow measurement of ejection velocities along with reflected energy, and provide information about the amount and size of ejecta. Given some field constraints, these measurements can be used to retrieve crucial plume dynamic parameters. The power backscattered by solid ejecta, in particular, can be inverted using an assumed particle size distribution, to estimate the mass of pyroclasts and other derived parameters, such as the mass flux rate, the ejecta volume, kinetic and thermal energies and particle concentration. Minimum estimates of gas velocities can also be retrieved. In turn, radar time series can be used as feedback to refine models and improve our understanding of the eruptive conditions controlling the ascent dynamics of volcanic plumes.

For volcano monitoring, ground-based radars can allow assessment of the evolution of eruption intensity in real-time and under all weather conditions, and give early information for the ash load of the plume, ejection velocities, and transport speed of the ash cloud as it drifts in the wind. Radar data at the emission source can also be input into models for tephra dispersion to improve the risk assessment, in particular regarding tephra fallout and impact on air traffic. A particularly promising direction if we are to improve our constraint of solid and gas fluxes during explosive eruptions is the coupling of Doppler radar data with complementary remote sensing instruments such as thermal and UV cameras, FT-IR spectroscopy and DOAS.

Emergent Flow Dynamics Generated by Pyroclastic Density Current-Bed Interaction

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Explosive volcanic eruptions produce turbulent, multiphase flows that encompass a vast range of scales from micron-scale ash to eruptive plumes that can extend 100s of kilometers. Abrupt flow transformation (e.g. from dense to dilute pyroclastic density currents) can arise due to the energy exchange across multiple length scales and phases. Much of the flow dynamics are determined through energy exchange at the flow-bed boundary. Deposit genesis is also critically dependent on flow-boundary coupling and our understanding of deposits as probes of flow dynamics is limited by our understanding of the basal flow interaction. In this talk we will examine the sensitivity of flow dynamics to interaction with its boundary from multiple perspectives: 1. As sites of bed-load formation and emergent particle-size segregation, 2. Mechanical and thermal energy exchange between the flow and bed, 3. Mass exchange between the flow and the bed including deposition and resuspension, and 4. Flow transformation (dense to dilute) controlled by topographic variability. Each process will be discussed in the context of eruptive examples including the Kos Plateau Tuff, Montserrat, the 1980 eruption of Mount St. Helens, and the 2006 eruption of Tungurahua.

We will discuss the use of multiphase models in addressing these different scales of fluid motion as well as how they can provide a platform to integrate microphysical, analogue experiments and observational constraints. Microphysical experiments can provide the necessary closure for statistical mechanics based models, and provide a way to examine grain-scale processes in a probabilistic manner. One example we will explore is the thermal energy transfer of flows to their substrate in the context of determining a critical condition for steam explosions. Steam explosions, or littoral blasts, generated when pyroclastic density currents interact with seawater may be a common, although rarely documented, phenomena. The development of steam explosions rather than passive steam production is related to the rate of thermal energy transfer from hot pyroclasts to water. We conduct a series of laboratory experiments to quantify the heat transfer and steam production rates when hot pyroclasts encounter water. Hot pumice (> 200 °C) rapidly ingests water while remaining at the surface, producing measurable amounts of steam during the process. Approximately 10 % of the thermal energy of the pumice particles is partitioned into the production of steam, and smaller particles have greater steam production rates.

The laboratory experiments are used to develop a subgrid model for steam production that can be incorporated into a multiphase numerical framework. We use this model to study the critical steam production rates required to initiate explosive events. For conditions typical of many pyroclastic flows, particles smaller than ~ 1 - 5 mm are required to initiate a littoral blast. A second set of 2-D numerical simulations is conducted to simulate the July 12-13 Soufriére Hills dome collapse event that reached the sea. The simulations predict that the focus of the blast is likely generated several hundred meters off-shore and although the landward directed base surge is primarily dry (< 15% water vapor), the area immediately above the blast is steam-rich and may be a likely site for the production of accretionary lapilli. Analogous subgrid experiments will be explored to discuss mechanical energy coupling with the bed necessary for the formation of bed load, deposition and resuspension mechanics.

Cone-forming vs sheet-forming tephra fall deposits: Insights into violent strombolian eruptions from recent field data analyses and novel analogue modelling experiments on fallout from particle-laden jets

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Explosive eruptions can generate eruption jets (lava fountains), turbulent buoyant plumes and asssociated wind-advected gravity currents. This leads to distinctive deposits with specific thickness or maximum class size decay rates with distance and corresponds to cone-forming and sheet-forming deposit facies. End-members include plinian eruptions which are dominated by sheet-forming deposits but also produce cone-forming deposits (so far little documented) ultra-proximally and monogenetic cones which typically produce mainly cone-forming deposits and little volume in the sheet deposit part, as a result of gas content and intensity and coarse initial grainsize distribution. In the last year of his life George Walker, who pioneered the modern CEV research approaches, wanted his last contribution to be about revisiting violent strombolian eruptions, now one of the most intensily researched topic in CEV research. These are interesting in that they lead both to a cone-forming and sheet-forming facies. Several of his coworkers/friends helped him achieve this last legacy to his volcanological family in the form of a recent publication (Rowland et al 2009) showing that some monogenetic cones are indeed quite different from most such cones. The cones are larger and higher, with wider and deeper craters, the eruptions producing them longer-lasting and more intense and resulting in extreme fine grain size compared to typical monogenetic cones. In volume terms, the ash blanket is as voluminous as the cone itself. These latest analyses based on George’s field work at Paricutin and El Jorullo, accomplished with George, are reviewed briefly and then novel ongoing analogue modelling experiments on particle-laden gas momentum jets carried out at UGhent are presented. In a typical experiment, both a cone and an ash blanket are formed and the crater rim size can be directly related to eruption intensity as predicted by Riedel et al (2003) via numerical experiments. Of special interest, there are several distinct regimes: initially both the cone and the ash blanket grow until the cone and crater assembly reach the angle of repose; in a second stage, inner-crater instability and material recycling into the vent modulate eruption jet mass loading, leads to secondary fragmentation in the vent and favours a higher eruption plume and ash blanket development; higher mass loading leads to rapid crater rim overthickening and instability and enhances non-linear feedbacks and eruption intensity modulation; in a third stage, the vent gets blocked and violent vent clearing events (vulcanian-style events) can lead to much higher plumes and wider dispersal. Implications for our understanding of violent strombolian eruptions and hazards will be briefly discussed.

Dynamics of lateral blasts by using numerical simulation

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The dynamics of lateral blasts has been investigated numerically by adopting a transient, multidimensional, and multiphase flow code to simulate the rapid decompression of a pressurized porous dome, the expansion of the eruptive mixture and the subsequent propagation of the blast cloud. Initial source conditions, e.g. gas content, mass of juvenile and entrained rocks, temperature, grain size distribution and pre-eruption pressure distribution in the dome or cryptodome have been parameterized according to geological constraints. Specifically, the 1997 Boxing Day event at Montserrat (UK) and the May 18, 1980 blast at Mount St. Helens (USA) have been adopted as test cases. Model results suggest that, independently from the eruption scale analyzed, the main blast can be schematized by an expansion phase (burst), lasting on the order of tens of seconds, followed by collapse and pyroclastic density current phases. In the burst phase the pressure forces dominate, the flow can reach supersonic velocities and generate pressure waves. Conversely, in the PDC phase, the flow is gravity-driven and its dynamics are strongly controlled by its vertical stratification and the 3D topography. Although the source models investigated thus far represent a simplification of the actual geometry and complex sequence of initial events, we show that the explosion mechanisms are significantly robust over a wide range of initial conditions and are consistent with first-order observations of the phenomena.

Dynamics of the 1997 Vulcanian explosions of Soufrière Hills, Montserrat

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Soufrière Hills Volcano had two periods of Vulcanian activity in 1997, during which 88 explosions occurred. Each of these explosions discharged the upper 0.5-2 km of the conduit; two thirds as pyroclastic flows and the rest as fallout from 3-15 km high buoyant plumes. During the first 10 s of each explosion, the plumes consisted of multiple finger jets, exit velocities of which increased with time from 40 to 140 m s^{-1}. Exsolved water contents required to achieve these velocities have been estimated to be 0.1 to 1.8 wt%.

In order to better understand the dynamics of these explosions, we studied the eruption products texturally and petrologically. Products include frothy pumices from a deep, gas-rich zone in the conduit, lava and breadcrust bombs from a thin degassed surface plug, and dense pumices from an intervening transition zone. Bulk porosity is 1-66 vol% in breadcrust bombs and 24-79% in pumices, all vesicles larger than a few tens of µm being interconnected. Small vesicles (< few tens of µm) in all pyroclasts are interpreted to be syn-explosive, as shown by their presence in breadcrust bombs formed from originally non-vesicular magma. Most large vesicles (> few hundreds of µm) in pumices are interpreted as pre-dating explosion. However,

~15% of the large voids in pumices and all those in breadcrust bombs, formed by syn-explosive fracturing of amphibole phenocrysts. An intermediate-sized population formed by coalescence of the syn-explosive bubbles. This interpretation of the vesicle populations implies pre-explosive conduit porosities up to ~55% for the deepest-derived samples. Syn-explosive boudinage of amphiboles provides independent estimates of pre-explosive porosity that are consistent with this value.

Development of vesicle textures was controlled by the time interval between decompression and the onset of clast-surface cooling in contact with air. Plug fragments entered the air quickly after fragmentation (~10 s), so interiors continued to vesiculate once the rinds had quenched. A larger time interval for deep-derived pumices (~50 s) allowed complete vesiculation prior to surface quench, accounting for the lack of surface breadcrusting or radial vesicularity gradients, as well as the textural similarity between flow and fall pumices, despite different thermal histories after leaving the vent. Vesiculation in pumices is inferred to have been largely confined to the conduit. Bubble nucleation occurred heterogeneously on magnetite microlites during each explosion, and growth was essentially decompression-driven, with only minor diffusion. Syn-explosive decompression rates estimated from vesicle number densities (> 0.3-6.5 MPa s^{-1}) are consistent with those predicted by numerical models.

Water contents in residual glasses range from <0.4 wt% in dense samples to >2.3 wt% in pumices, implying pre-explosive confining pressures up to at least 40 MPa. Estimates of exsolved water contents in the deep conduit prior to an explosion (0.1 to 2.1 wt%), are consistent with those required to drive the eruption jets, if negligible diffusion is assumed.

Unusual ignmbrites: some problems and developments of the current understanding of pyroclastic current mobility

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Current views on pyroclastic current dynamics are largely based on the interpretation of pyroclastic density current deposits, and analogue and numerical simulations. Most case studies are derived from explosive eruptions of gas rich, viscous magmas producing small to large volume ignimbrites, underlain by plinian fall deposits. Here we review three case studies of unusual, low aspect ratio (10^{-4}) ignimbrites, some aspects of which raise more questions than give answers.

The 0.87 km^3, phreatomagmatic, K-foiditic, Peperino Albano ignimbrite (Colli Albani, Italy), was erupted from the Albano maar at < 23 ka. The ignimbrite displays both thick valley pond and veneer facies. The juvenile component is 30-40% of the total volume and is highly fragmented to ash, with only a very minor proportion of small, vesicular lapilli. The unit reaches 10 km from vent, where it is confined in major valleys. Emplacement temperatures retrieved from paleomagnetic data and field data are at 350°-100°C.

The 37 km^3, tephritic-phonolitic, Villa Senni ignimbrites were erupted during the last caldera collapse of Colli Albani at 355 ka. The succession starts with subplinian fallout of poorly vesicular scoria lapilli. The overlying two major ignimbrites cover more than 1600 km^2 and relate to pyroclastic flows with significant mobility, able to surmount hills at more than 20 km from vent. The facies is almost ubiquitously massive and chaotic. Juvenile pyroclasts are made of variably porphyritic, poorly to moderately vesicular scoria and spatter lapilli, and coarse ash. The texture of juvenile clasts indicates that the presence of little fine ash is not due to elutriation but to weak fragmentation of poorly vesicular and poorly viscous magma.

The > 500 km^3, rhyodacitic Galan ignimbrite (Altiplano Puna, Argentina) was erupted at 2.1 Ma. There is no basal fallout deposit. The ignimbrite is lithic poor, very crystal rich, massive and chaotic throughout, emplaced above Curie temperature, and develops valley confined facies, but no veneer facies, from proximal to distal (> 80 km) locations.

The three cases show that:

- the mobility of pyroclastic flows does not necessarily relate to the conversion of potential energy into kinetic energy during the collapse of an initially buoyant column;
- extreme fragmentation and entrapment of fine ash seem not to be a pre-requisite for mobility;
- temperature also seems not to be a pre-requisite.

Laboratory ash flows

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We studied the transport and sedimentation behavior of rapid shear flows of gas-fluidized volcanic ash in a laboratory flume in order to better understand the kinematics of pyroclastic flows. The work was based on a previous study in which we explored the fluidization and settling behaviour of ash under quasi-static conditions in a 1-D high-temperature fluidization rig. Provided that temperature is high enough (>150 °C) to significantly reduce cohesion, ash fractions of pyroclastic flow deposits fluidize in the manner of Geldart group-A powders, with large expansions in the non-bubbling regime. When the flux of fluidizing gas is removed, the ash re-sediments by hindered settling at rates which, for a given material, are independent of temperature up to 550 °C.

Armed with this knowledge, we built a 3-m-long lock-exchange flume in which we generated horizontal flows of fluidized ash. The ash was first placed in the flume reservoir, heated to 180 °C and expanded by gas flow up to 45 % above loose packing. It was then released down the flume and allowed to defluidize freely. The resulting flows were filmed at high speed, and the films were then analyzed visually and using a particle-tracking algorithm. The flows were typically several cm thick, had frontal speeds of up to ~2 m s^{-1}, and were non-turbulent on scales larger than the constituent particles. Since the settling behavior of quasi-static ash is temperature independent, we expect the same to be true for flowing ash.

Deposition took place progressively during transport until the flow was entirely consumed and motion ceased. It commenced 5-20 cm rearward of the leading edge and (for a given expansion) proceeded at a rate independent of distance from the lock gate. Deposit aggradation velocities were equal to those inferred beneath quasi-static bed collapse tests of the same ash at the same initial expansions, showing that shear rates of up to ~300 s^{-1} have no measurable effect on aggradation rate. Initially non-expanded (but just fluidized) ash deposited progressively at a rate indicative of an expansion of a few percent, perhaps due to Reynolds dilation during initial slumping. These behaviors have subsequently been confirmed by similar experiments using industrial group-A cracking catalyst powders instead of ash, and the combined results collapse to reveal a very simple scaling for the runout durations of the flows. Velocity profiles in the ash flows reveal that the frontal regions slid across the flume floor on very thin basal shear layers, implying high basal stresses, but that once sedimentation commenced, a no-slip condition was established at the depositional interface.

The experiments show that even cm-thin, non-turbulent and poorly expanded flows of ash deposit progressively, as inferred for many pyroclastic flows. This raises the possibility that deposit aggradation rates in mathematical models of dense pyroclastic flows could be parameterized using values measured using 1D rigs. High frontal stresses are consistent with the occurrence of scour surfaces at the bases of some pyroclastic flow deposits.

Retrieval of volcanic SO_2 emissions from thermal infrared remote sensing using satellite-based sensors

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Every year, volcanoes emit billions of tons of ash and gas in the earth atmosphere, and this activity has a real impact on our environment, although difficult to assess. These issues are especially important today, in a context of climate changes. The study presented here deals with the detection and estimation of sulphur dioxide inside volcanic plumes. Sulphur dioxide is one of the main components, in amount, of the gas emitted by volcanoes, and especially critical for the radiative balance forcing. In contrast with volcanic ash, SO_2 has a very large spatial scale impact, due to its longer lifetime in the atmosphere. Moreover, sulphur dioxide may transform into sulphate (H_2SO_4) relatively quickly, having even longer atmospheric lifetime. Besides, note that sulphate may also aggregate on ash particles, hence changing their scattering properties, making estimates of SO_2 emissions even more complex. In this work we present two models based on band ratios, allowing a fast first order estimation of SO_2 concentrations emitted by basaltic volcanoes (Piton de la Fournaise – La Réunion and Karthala – Comores), from spaceborne infrared sensors (SEVIRI – MSG2 and MODIS – Terra/Aqua),using on-line high resolution spectral calculator (http://www.spectralcalc.com), and compared to OMI (Aura) results. This approach permits SO_2 concentration estimates with high temporal (SEVIRI ~ 1 img/15min) and spatial (MODIS ~ 1×1 km) resolution in near real time. For both eruption studied the results obtained from the band ratio model at $\lambda_{8.6}/\lambda_{11}$ are in good agreement with OMI measurements, giving maximum SO_2 concentrations values ranging from about 50 to 70 DU, showing that this method can be advantageously used for large basaltic eruptions.

Source and emission conditions for explosive events at Stromboli and Santiaguito

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Integrated geophysical combining infrasound, seismic and thermal data, supported by high speed (30 Hz) thermal imaging, allows the geometry of the shallow system as well as the ascent dynamics of the erupted plume to be measured. When coupled with textural (vesicle and crystal size distribution) analysis of the erupted clasts, these information allow us to build a well-constrained model for the magma conditions, fragmentation style and system geometry/dynamics.

The persistent explosive events that characterize Strombolian activity at Stromboli (Italy) typically send plumes to heights of between 150 m and 300 m around nine times an hour. On the basis of plume ascent dynamics apparent in thermal video, emissions can be split into two types: Type I (ballistic-dominated) and Type II (mixed ash and ballistic). Type II emissions themselves can be split into two sub-types: those with a gas-thrust phase and those lacking a gas thrust phase. Thermal data give emission velocities for the ejected fragments of up to 100 m/s. During paroxysmal eruptions emission velocities may be as high as 320 m/s. The explosion source has been modelled in terms of the coalescence of gas within the magma to form large gas slugs that ascend the remaining portion of the conduit to burst at the free surface. While our seismic (VLP) data indicate that gas coalescence occurs at a depth of around 260 m, infrasonic and thermal data show the explosion source to be located 20 m to 220 m below the vent (i.e., 40 m to 240 m above the VLP source). Sampling shows the shallow system magma to be of a mixed population, with zones of fresh (crystal poor) and degassed (crystal-rich) magma apparent within single bombs. The slug must thus ascend through, and sweep up, dense, degassed magma residing in the uppermost portion of the conduit.

At Santiaguito, explosions persist at a rate of 1 to 2 events per hour sending plumes 1 km to 4 km above the vent. Plumes have a minor gas thrust region within which ascent velocities are 15–50 m s^{-1}. A transition to buoyant ascent occurs 20 m to 50 m above the vent, where ascent velocities decline to 4–15 m s^{-1}. The transition between the gas thrust and buoyant regions is also marked by changes in the spreading and cooling rates measured for the plumes. Thermal imaging of the vent reveal emission from an annular structure, consistent with the explosion source being shear-induced fragmentation at the conduit walls due to stick–slip movement of a degassed magma plug in the upper portion of the conduit. The geophysical array data indicate a zone of stick–slip movement located 100 m to 620 m below the vent.

Comparison of the thermal and infrasonic energies released during explosive events at Stromboli and Santiaguito, as well as Villarrica and Fuego, show that two types of event can be separated on the basis of the relative dominance of the gas thrust and buoyant ascent regions. As a result, Stromboli's and Santiaguito's differing explosive styles can actually be separated and identified using geophysical data alone.

Field aspects of the deposits of volcanic plumes: Constraints on computational models.

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Computational simulations of tephra dispersal and sedimentation depend on field measurements of deposit thickness or mass/area and bulk and maximum particle size. Such measurements have been made for more than 120 years but there is no consensus on best field practices. For example maximum particle size has been constrained on the basis of the basis of the 3 or the 5 largest clasts and on the basis of either the maximum diameter of each clast or some average of 3 orthogonal axes per clast.

We use an unusually tightly constrained set of data from the 19 March 2008 explosion of Halema`uma`u, Kīlauea to address several of the key issues. The eruption had an estimated total masses of 10E+6 kg; using an inferred durations of 50 s, respectively, this equates to eruption rates of 2 x 10E+4 kg/s. Despite this low intensity there was a clear partitioning of ejecta between a ballistic block apron and a wind-advected lobe sedimented from the convective plume.

We use data collected on the day of the eruption and for several subsequent days to constrain: (1) contrasting values for column height and mass discharge rate using different measurements of maximum particle size. (2) the significance of 'out-sized' clasts. (3) lateral margins to coarse grained falls. (4) the partitioning of mass between convective fall and ballistic transport.

Lascar pumice flows and the levée-channel-lobe morphology

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Pumice flows are very dense and often destructive volcanic events which may derive from eruption column fallout or lava-dome collapse. Their dynamics are poorly understood: direct measurements are constrained by technical limitations and the flows are rare and hazardous. Generally only the flow deposits are able to be studied. The flows principally consist of coarse granular material. The local topography, which can strongly affect the behaviour of the flows, is highly variable in nature. A high level of polydispersivity in conjuction with possible scaling issues means that material properties on the laboratory scale (angle of repose/internal friction) seldom correspond to those seen on in natural flows. We expect, however, the same qualitative behaviour to occur in both cases.

Of particular interest are the flow deposits and the morphology between the levée-channel form towards the rear and the lobe formed at the head. These are features that occur in both laboratory and natural-scale flows. Pumice flow deposits resulting from the 1993 eruption of Lascar (South East Sector) has been mapped in detail using a LiDAR device. This data set has been analysed in order to investigate how the geometry of the flows varies as a function of distance from the lobe tip and of the slope angle.

The challenge in studying these flows is the lack of dynamical information and the difference in some of the material properties between laboratory and natural scale flows. We present our analysis of several of the Lascar flow deposits having identified dimensionless groups of the available parameters. These will be compared against results from an experimental investigation in which both the dynamic and static behaviour of flows of granular materials will be measured. We intend that the results of this comparison will improve our knowledge of the physical processes that control granular flows of all scales.

On flows of fluidised particles down slopes

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We study flows of fluidised particles on horizontal and inclined surfaces which are common in industry as a method of transporting powders and also in geophysical flows such as pyroclastic flows.

The physical mechanisms that control the flows are poorly understood. A range of possible theoretical models are proposed which are based on the ideas present in the current literature on fluidisation and granular flows. It is argued that fluctuations in the gas flow allow viscous-like stresses in the solid phase to be dominant in the force balance of the flows. The resulting governing equations are therefore similar in form to those proposed for flows of viscous fluids.

In an extensive experimental programme measurements are made of the front position, height profiles and velocity profiles of fluidised granular currents. The experiments are carried out in a planar, narrow-channeled apparatus. Granular material is introduced at a constant rate and the gas flow is constant for each experiment. Inclining the apparatus allowed us to investigate flows down slopes of various angles. Flows along the horizontal produced scaling laws for the motion of the front position as a function of time and the material flux, whereas flows down sufficiently steep slopes were steady.

The results of these experiments were compared to solutions of the governing equations. Although for some of the models it was possible to predict the scaling of the front as a function of time for horizontal surfaces and down slopes, the scaling as a function of the material flux could not be simultaneously captured. Our results indicate that there is an insufficient understanding of the rheology of fluidised granular materials to be able to model them accurately.

VolcFlow : simulation of dense volcanic granular flows

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Long runout avalanches and dense pyroclastic flows are composed of broken rocks, present a very long runout compared to their drop height, and are thin relative to their area. Numerical simulations of volcanic granular flows are increasingly being used for hazard assessment on volcanoes and appear to be essential for future hazard mitigation. A potential problem of such an approach, however, is that the rheological behaviour of such flows is very complex and currently impossible to fully describe from a physical point of view. As we cannot at present simulate all the complexity of the interactions at a microscopic level, we have to use simplified rheological laws.

However, before using any model in hazard assessment, we should ensure that it correctly captures the first order features of the natural phenomenon. Thus, the following key questions need to be addressed: is it realistic to consider volcanic granular flows as mainly frictional as often assumed? Is this behaviour compatible with field observations?

To answer these questions, numerical simulations are compared to well constrained field examples: pyroclastics flows at Tungurahua, Merapi, Lascar, etc. and debris avalanches at Socompa, Llullaillaico, etc. Simulations are done with the code *VolcFlow* (http://wwwobs.univ-bpclermont.fr/lmv/pperm/kelfoun_k/VolcFlow/VolcFlow.html).

Results show that the frictional law is not appropriate for the simulation of pyroclastic flows and long runout avalanches, even to the first order. Instead, a simple empirical law, a constant retarding stress, involving only one free parameter appears to be much more adapted for modelling of volcanic granular flows. The constant retarding stress represents a much better alternative for hazard assessment.

The diversity of flow pattern during the eruption column collapse

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During explosive volcanic eruptions, a mixture of pyroclasts and volcanic gas forms a buoyant eruption column or a pyroclastic flow, according as its density becomes less than that of the ambient atmosphere before it loses its upward momentum or not. We systematically investigated how the flow pattern at the column collapse condition depends on crater shape and magma chamber conditions as well as magmatic properties by integrating the theoretical models for conduit flow, flow inside craters and eruption column dynamics.

When a crater is present, magma issues from the crater as a free decompression flow, an underexpanded flow, an overexpanded flow, or a subsonic flow during explosive eruptions. For a given crater shape, the column collapse occurs in two distinct situations: those are the collapse of the free decompression flow or the underexpanded flow during the waxing stage of eruption and that of the subsonic flow or the overexpanded flow during the waning stage of eruption. The collapse during the waxing stage is associated with increase in conduit radius, whereas that during the waning stage is induced by decrease in magma chamber pressure. The magma discharge rate at both types of the column collapse strongly depends on water content of magma and crater shape; for a fixed water content, it tends to have a small value for a shallow crater with a small opening angle and vice versa.

Three dimensional simulations suggest the flow pattern at the column collapse condition depends on the Richardson number at the vent as well as on the above features of the compressible fluid dynamics inside the crater. We discuss how the crater shape, magma chamber conditions, and magmatic properties affect the Richardson number, and hence the flow pattern at the column collapse condition.

Inferring eruption magnitude and style from volcanic ash deposits: recent examples from El Reventador and Tungurahua volcanoes, Ecuador

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Volcanic ash particles deposited at some distance from erupting vents are valuable tools to estimate eruptive parameters (volume and mass of téphras, magnitude, and intensity of associated eruptive phases) and investigate processes such as degassing behavior and eruptive style. Two recent eruptions in Ecuador show how tephras studies can help to analyze eruption size and style.

El Reventador volcano erupted suddenly on Nov. 3, 2002, venting a ~13 km-high tephra column and numerous pyroclastic flows. A thin tephra layer accumulated downwind in the interandean valley and its rain-compacted volume is estimated at ~70 x 10^6 m^3. The bulk tephra volume of ~120 x 10^6 m^3 ranks the eruption at VEI 4, making it the most explosive one since 1886 in Ecuador. At sampling distances between 50 and 110 km from source, the deposit displays a uni-segmented pattern and a fines-dominated grain size distribution, with strong density-driven fractionation of the components. Scanning Electron Microscopy images show dissimilar juvenile grain morphologies. Dense juvenile grains and xenoclastic particles suggest magma-water interactions and intense conduit erosion, while strongly vesiculated and tubular juvenile particles argue for a fragmentation process dominated by magmatic disruption.

The activity of Tungurahua volcano started in 1999. The August 2001 phase left an andesitic tephra layer whose volume is estimated at 6 x 10^6 m^3. The layer is composed of many dense juvenile particles (20-

40%) and a few xenoclastic grains (~4%). Instead of phreatomagmatic interactions, we infer an intense recycling of a stagnant and largely degassed andesitic magma in the conduit or near the vent. The paroxysmal eruption of August 2006 produced a 16 km-high tephra column that drifted westward. The deposit is multi-segmented, with exponential thinning rates in proximal areas and a power law decay rate in distal areas. The bulk volume exceeds 35 x 10^6 m^3, making it the first VEI 3 phase since the onset of the activity at Tungurahua. Grain size analyses reveal that the ash fall deposits are well to poorly sorted with multimodal grain size distributions. Rain flushing and incorporation of ash elutriated from nearby pyroclastic flows may explain these mixed grain size populations.

These Ecuadorian examples show that the study of volcanic ash is relevant to elucidate the dynamics of explosive eruptions, and offers a valuable monitoring tool in the context of eruptive crises.

Geomorphic and kinematic control of pyroclastic flow avulsion from channels

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Small- to medium-volume pyroclastic density currents (PDC) constitute one of most hazardous phenomena associated with explosive volcanism. Of particular concern for the hazard mitigation around PDC-forming volcanoes is the avulsion of a normally valley-confined current onto interfluvial surfaces and its subsequent impact on densely populated areas. A short time-window existed in 2007, when the deposits of the June 2006 eruption from Mount Merapi were ideally exposed, to undertake a detailed sedimentological and geodetic survey of their deposits. This revealed data for a first quantification of the critical geomorphic and fluid dynamical conditions controlling pyroclastic flow avulsion.

On June 14 2006 multiple partial dome-collapses fed four block-and-ash flows with volumes of 1.13, 3.12, 1.93 and 0.56x10^6 m^3 to travel along the Gendol valley for 4.17, 7.78, 6.63 and 4.13 km, respectively. While the first flow was kept confined within the valley, each of the three successive events largely escaped onto the interfluves where the rootless currents propagated for up to 2 km, destroying large parts of the village of Kali Adem and burying it under up to 7 m of deposit. We present detailed sedimentological evidence that the largest volume of valley-escaped material originated from the basal avalanche of the current.

High-precision RTK-GPS data were combined with 1-m-resolution Ikonos images to compute the pre- and post-eruption surfaces for each of the four events. This data-set allowed us to determine the main geomorphic parameters controlling flow avulsion: channel capacity, rate of downstream capacity change and channel sinuosity; and to quantify their critical values. These values in turn were integrated into a fluid dynamic model to constrain the kinematic conditions of the basal avalanche prior to avulsion and the kinematic properties of the veneering flows. The analysis reveals that the basal avalanche of the climactic flow event propagated as a slightly supercritical flow of 8-10 m thickness in medial reaches. The valley-escaped flows, however, propagated as highly supercritical flows with average volume fluxes of 400-500 m^3/s along the interfluves. We demonstrate how this model can be used to guide hazard mitigation from flow avulsion in future eruptions.

In-situ production of ash and clast breakup in conduits and pyroclastic density currents

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Abrasion and comminution of clasts within conduits and during the propagation of pyroclastic density currents (PDCs) have long been recognized as a potential sources for the enhanced production of volcanic ash, however their relative importance has eluded quantification. The amount of ash produced in-situ can potentially affect runout distance, deposit sorting, the volume of ash introduced in the upper atmosphere, and internal pore pressure. We conduct a series of laboratory experiments on 1) clast breakup and 2) the collisional and frictional production of ash that may occur during different regimes of pyroclast transport. We find that collisional ash production rates are proportional to the square of impact velocity. Frictional ash production rates are a linear function of the velocity of the basal, particle-enriched bed load of these flows. We also determine the collisional velocity needed for clast breakup and the fraction of clasts that breakup upon collision. Ash produced in these experiments is predominately 10-100 microns in size and has similar morphology to tephra fall ash from Plinian events.

Using these laboratory experiments we develop a subgrid model for ash production that can be included in analytical and multiphase numerical procedures to estimate the total volume of ash produced during transport. We find that for typical pyroclastic density currents, 10-20% of the initial clasts comminute into ash with the percentage increasing as a function of initial flow energy. Most of the ash is produced in the high-energy regions near the flow inlet, although flow acceleration on steep slopes can produce ash far from the vent. On level terrain, collisionally and frictionally produced ash generates gravity currents that detach from the main flow and can more than double the effective runout distance of these flows. Ash produced at the frictional base of the flow and in the collisional upper regions of the flow can be redistributed through the entirety of the flow, although frictionally produced ash accumulates preferentially near its source in the bed load. Flows that descend steep slopes produce the majority of their ash in the collisionally dominant flow head, and flow snouts likely develop sub-angular to rounded pumice during this process. We determined experimentally a relationship between the amount of ash produced and the change in roundness of pumice clasts.

Erosion and mobility of granular flows over sloping beds

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The research field dealing with dynamic analysis of gravitational mass flows is rapidly expanding. One of its ultimate goals is to produce tools for prediction of velocity and runout extent of rapid avalanches or pyroclastic flows. Of special interest are experimental, theoretical and modeling developments that can help explain the occurrence of rapid motion over long distances. Despite the great amount of work devoted to the study of debris avalanches and pyroclastic flows, there is no consensus to explain their high mobility or the occurrence of surges that can propagate along the slope without decelerating.

We show here that erosion of granular material already present on the bed can significantly increase the mobility of the flow and possibly generate surges. Laboratory experiments and numerical simulation of granular material flowing over an inclined plane covered by an erodible bed are presented, designed to mimic erosion processes of natural flows traveling over deposits built up by earlier events. Two controlling parameters are the inclination of the plane and the thickness of the erodible layer. We show that erosion processes increases by up to 40 % the flow mobility (i. e. runout) over slopes with inclination close to the repose angle of the grains even for very thin erodible beds. Erosion efficiency is shown to strongly depend on the slope of the topography. Entrainment begins to affect the flow at inclination angles exceeding a critical angle, almost equal to half of the repose angle. Runout distance increases almost linearly as a function of the thickness of the erodible bed suggesting that erosion is mainly supply-dependent. Two regimes are observed during granular collapse: a first spreading phase with high velocity followed by a slow thin flow, if either the slope or the thickness of the erodible bed is high enough. Surprisingly, erosion affects the flow mostly during this slow regime. The avalanche excavates the erodible layer immediately at the flow front. Waves that help removing grains from the erodible bed are observed behind the front. Triangular shaped frontal surges are seen at high inclination angles over rigid or erodible bed. Finally, simple scaling laws are proposed making it possible to obtain a first estimate of the deposit extent and flow dynamics of a granular collapse over rigid or erodible inclined bedrock.

Monitoring of volcanic emissions in northern Chile, part II: DOAS measurements and aerosol sampling

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A volcanic gas monitoring project is being actually carried out in two active volcanoes located in Northern Chile: Lascar and Lastarria volcanoes. 3 different gas sampling techniques have been applied in both volcanoes during April and June 2009. These results will enable us to establish the state of activity, to better constrain the eruptive dynamics, but also will help us to decipher some precursory events to better predict the behaviour of these volcanoes. In this abstract, we will focus on the two following sampling methods:

- SO_2 is a common gas species in volcanic plumes and is absent in normal atmosphere, so it is accurately detected by remote techniques. SO_2 fluxes are often correlated with magmatic dynamic parameters, so they can be used to monitor geochemical precursors of regime changes. The SO_2 fluxes will be measured by remote-sensing techniques UV absorption spectroscopy names DOAS.
- Furthermore, volcanoes represent one of the most important natural sources of pollutants in the atmosphere, both during and between eruptions. Indeed, volcanic emissions contribute to the natural atmospheric cycles of many species as H_2O, CO_2, SO_2, H_2S, HCl, HF principally, but also trace elements (as As, Hg, Pb, Cu..). A good understanding of volcanic volatile emissions in space and time and their atmospheric chemistry is essential to better constrain the eruptive dynamics, as well as the impact of gases on the local environment and global climate. The concentrations of these species will be determined by filtration of the diluted plume, chemistry and ionic chromatography or ICP-MS analysis.

Lagrangian simulation of large volcanic particles

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A new 2D/3D Lagrangian particle model (LPAC) for analysing the dynamics of clasts and lapilli ejected during explosive eruptions is presented. The novelty of the model lies in the one-way coupling of the carrier flow field, given by a Eulerian multiphase flow code, and the particles. The model is based on a simplification of the Basset-Boussinesq-Oseen (BBO) equation, expressing the Lagrangian equation of a particle as the sum of the forces exerted on the particle along its trajectory. It is assumed that particles are non-interacting, do not affect the background carrier flow and that the drag coefficient is constant.

The model was applied to the description of particle dynamics produced by Vulcanian explosions, in particular those occurring in 1997 at Soufrière Hills Volcano, Montserrat. Simulation results allowed parametric studies as well as semi-quantitative comparisons between modelling results and field evidence. Major results include: 1) the carrier flow was found to play a fundamental role even for meter-sized particles (a 1 m block is predicted to reach a distance that is 70% greater than that predicted without the effect of the carrier flow), 2) assumption of the initial velocity of the particle were dropped thanks to the description of both the acceleration and deceleration phases of the particle trajectory, 3) by adopting experimentally-based drag coefficients that are consistent with field observations, large particles were able to reach greater distances with respect to smaller particles and 4) the main influence of the particle initial depth on the ejection velocity and of the radial position with respect to the conduit axis on the distance reached by the particle.

Throbbing lava lakes: magma supply and effusive/explosive degassing at Erebus

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Erebus is well-known for its sustained lava lake, alkaline, intraplate character, and, of course, its southerly latitude. I have been associated with the Mount Erebus Volcano Observatory and collaborating with its leader, Phil Kyle, since 2003. In the time I have worked there, Erebus has shown two kinds of behaviour: (i) lava lake, and (ii) lava lake plus intermittent strombolian eruptions (e.g., 3 per day, lasting for several months). A key research question is: what processes switch on/off the explosive phases? Another remarkable aspect of Erebus' behaviour, notwithstanding the strombolian episodes, is its stability – the heat and gas output, as well as the geochemical character of erupted bombs, display only minor fluctuations on decadal timescales. Thanks to a combination of melt inclusion modelling (with Roberto Moretti) and high time resolution gas measurements and thermal imaging at the crater, we are building a new conceptual model for the plumbing system of Erebus – from the deep basanite supply, through intermediate magmas, to the evolved phonolite lake. On one level, the behaviour is simple, stable, sustained but the magma differentiation, mantle-to-surface degassing, conduit geometry, and the moderate viscosity of the phonolitic magma superimpose fascinating complexity on the long-lived lava lake. I will highlight what we have been doing on Erebus (principally using remote sensing techniques) over the past 5 years or so, and summarise where we have reached in our understanding of the volcano's behaviour. Arguably, the principal volcanic risks posed by Erebus are to the field scientists who work there, but we believe the findings will have broader implications for understanding the onset of explosive activity at other volcanoes, and we note also that Erebus may provide some analogies to Vesuvio in respect of its magmatic evolution and eruptive style.

Propagation, deposition, and mobility of pyroclastic flows: what do we learn from laboratory experiments?

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The processes of propagation and deposition of ash-rich pyroclastic flows have been investigated through laboratory experiments on transient air-particle flows. We first studied the kinematics of flows of fine (80 µm) particles generated from the release of fluidized granular columns of various height-to-length ratios $a=h_0/x_0$, and we made comparison with flows of water in the same apparatus. The air-particle flows behaved as their inertial water counterparts for most their emplacement, as both propagated at constant front velocity U~$(2gh_0)^{1/2}$, before they entered a granular-frictional regime at late stages. The fluid-inertial behavior of the dense air-particle flows suggested that the pore-fluid pressure was high during propagation, and this issue was investigated in subsequent experiments. We made non-invasive measurements of the pore-fluid pressure in the air-particle flows, and analyses of high speed videos allowed correlation of the pressure signal with the flow structure. The latter consisted of a sliding head that caused underpressure relative to the ambient, followed by a body that generated overpressure and at the base of which a deposit aggraded. The combination of pressure advection from the source, relatively slow pressure diffusion and auto-fluidization during propagation resulted in long-lived high pore-fluid pressure in the body of the flows during most their emplacement, which is consistent with their inertial behavior. These experimental studies suggest that dense pyroclastic flows on subhorizontal slopes can propagate as inertial fluidized gas-particle mixtures consisting of a sliding head, that possibly samples accidental lithic clasts, and of a gradually depositing body. Complementary 3-D experiments revealed that the normalized distance x/x_0 travelled by the flows scales with $Ca^{1/2}$, where the constant C increases when the internal friction is reduced as in the case of initially fluidized flows of fine granular material. Initially non-fluidized flows of fine particles can experience auto-fluidization at a>~4, as their mobility is similar to that of their initially fluidized counterparts.

Cyclic patterns of SO_2 emissions at Santiaguito volcano,Guatemala, revealed by UV camera measurements

Smekens, J-F. and Watson, I.M.

Santiaguito volcano in Guatemala is the site of persistent explosive activity, producing explosions and weak ash plumes approximately every hour. Plumes generally appear to be buoyancy driven and reach altitudes of 1-2 km above the dome. Cyclic gas production has been observed at Santiaguito, using a UV imaging system. Data from a field campaign in 2007 suggests similarities in the production of SO_2 across an explosive cycle. There is an initial increase in output right after the explosion (more than 2 kgs^{-1} SO_2) which quickly returns to background levels (around 0.5 kgs^{-1} SO_2). These background levels vary systematically between explosions and have a sinusoidal pattern. Normalization of the gas flux to a constant rise rate indicates the maximum passive output occurs at approximately 0.4-0.7 cycles which is followed by a significant drop in emission rate before the next explosion. These observations are consistent with recent results obtained with DOAS and from thermal imaging. Three possible mechanisms may control the length of time the system requires to reset and produce another explosion: (i) pistoning associated with unsteady flow, (ii) resealing of cracks and subsequent pressurization and (iii) defluidization of the porous cap after perturbation. Each has its own merits and issues when explaining the observed gas cycles. This type of monitoring is only possible due to the instruments' rapid data acquisition of no more than a few seconds per measurement and the high frequency of measurements, producing near real-time data sequences. The method has the potential to provide real predictive capability at Santiaguito and provide insight into shallow processes governing gas production and release in quasi-open systems. Moreover, the same instrument has been used successfully to map ash mass distribution in explosive plumes at Santiaguito and could provide insight into plume rise dynamics at Santiaguito and at other volcanic centers.

Generation of pyroclastic density currents from pyroclastic fountaining or transient explosions: insights from large scale experiments

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Pyroclastic density currents (PDCs) encompass a wide spectrum of eruption, transport and depositional processes and accordingly produce a variety of deposit types. Despite the abundance of studies concerning their behaviour, because of the complexity, the physics of PDCs are still poorly understood, making it difficult to define their transport and deposition processes. In currents that initiate explosively, the behaviour of the PDCs critically relates to mechanisms of pyroclastic fountaining or of expansion of an overpressurised jet. Both triggering mechanisms were investigated through an experimental facility for the generation of large-scale, multiphase, gravity-driven currents available at LSV-Dipartimento Geomineralogico (Un. of Bari). Experimental runs were performed using fixed inflow pressure (175 bars) and pyroclastic load (200 kg), and changing the length of the conduit (from 55 to 320 cm). The first run (conduit of 320 cm) can be considered as a proxy of a pressure-adjusted pyroclastic jet. Video-footage and image analyses, coupled with near field geophones and pressure sensors data allowed to shed light on behaviour of PDC-generating collapses. The collapsing process can be divided in 3 main stages. The first stage starts with plug injection and encompasses the vertical motion of the pyroclastic mixture until the first sign of collapse. Gravitational forces and friction between the plug and the atmosphere govern the partition of kinetic energy transformation into potential energy and turbulence. In particular, turbulence partially disassemble the top and more concentrated part of the plug, but the almost constant section of the jet after injection testifies for the poor efficiency of this mechanism. The formation of small collapses from the basal part of the jet indicates the onset of stage 2. Small collapses of pyroclastic material that rapidly transform into finger-jets characterise the whole stage 2. At the time that some of the small finger-jets start to hit the ground, the main part of the pyroclastic material entrapped in the top part of the jet starts to collapse, marking the onset of stage 3. The small finger-jets collapse in an area close to the conduit base, and originate small and diluted PDCs when reaching the ground. The main collapse generates a larger PDC, which rapidly expands radially phagocytizing the previous small PDCs. The deposits are thick and massive close to the impact point and show a hummocky surface.

The second run of experiments was performed using a conduit of 55 cm filled by pyroclastic material. This configuration is a proxy for a transient explosion that generates an overpressurised jet, since the ejecting material doesn’t have the time for equalising with the atmospheric pressure. The experiment can be described in two stages. The first stage comprises the jet formation and expansion, while the second stage describes the collapse behaviour of the pyroclastic material. It is noteworthy that in this case the plug expands just after the ejection into the atmosphere, and rapidly triplicates the conduit radius. The more diluted basal part of the jet escape laterally to the dense top part to form upward-directed finger jets. In about 1s the inner overpressure and turbulence completely disassembles the initial plug and expands up to ten time the conduit radius. The formation of collapsing finger-jets marks the onset of stage 2. They develop at any level within the expanded cloud, and collapse almost simultaneously over a larger area than in the case of pressure-adjusted jet. This collapsing behaviour produces a mass partition among many different, small-volume fingerjets, which results in generation of a number of small, diluted PDCs. The deposits are thin and widely distributed, even in the impact area, in agreement with the observed behaviour of PDC generation. In summary, PDC generation from collapse of pressure-adjusted or overpressurised pyroclastic jets critically depends on behaviour of injection into the atmosphere, which controls the collapsing mechanisms and then the physical parameters of the initiating current. Preliminary analyses of velocity and pressure data seem to confirm the quantitative data here presented, and will allow a complete and qualitative analyses of pyroclastic collapses in the near future.

Cross-correlations of Doppler radar and seismic records: insights into the explosive source mechanisms at Arenal volcano, Costa Rica

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In order to better understand the physical processes associated with the complex eruptive behaviour of Arenal volcano (Costa Rica), we have deployed a network of 10 broadband seismic stations, a ground-based Doppler radar (VOLDORAD 2) and acoustic sensors during a 12-day period in February 2005. The Doppler radar enables the remote sounding of ash plumes, providing ejecta velocities and backscattered power, while seismic and acoustic records provide information on mechanical processes in the magmatic conduit and at the magma-air interface. We focus here on the relationships between radar and seismic observations in the hope of providing a more complete picture of the eruption dynamics from depth to the surface.

Extensive study of both records shows complex relationships among them, with no clear pattern on radar signals that can be associated to specific seismic processes. Unexpectedly, ash emissions as detected by the radar are not always associated to distinct seismic events. While some radar signals occur immediately after an explosion-type event, others are found during episodes of tremor, or even aseismic intervals when only background noise is recorded by seismic stations. Out of the 132 referenced radar events, only a third (39 events) show a distinct associated seismic event, and out of the 18 strongest radar signals 10 have no clear seismic counterpart. This result has important implications for volcano observatories, and questions the explosion processes involved in the eruption dynamics from depth to the surface.

Several of our observations are in agreement with the tremor source model proposed by Lesage et al. (2006). In particular, the occurrence of radar echoes in different range gates indicates that several vents are active, which is consistent with the idea that multiple conduits at Arenal can explain the apparent independence of tremor and explosions. A comparative analysis of several parameters, such as the radar backscattered power and kinetic energy, the seismic energy, amplitude and low-frequency content reveals a lack of correlation. A variable coupling efficiency of elastic energy radiated into the earth and atmosphere could explain this lack, possibly due to varying source conditions (depth, dimension), conduit conditions (obstruction, geometry), magma properties (rheology, impedence), and ejecta properties (plume density).

Fragmentation processes also remain unclear. Waveform analysis of the most impulsive seismic signals has shown no similarities among them, suggesting that either the explosion process is not repeatable, or that explosion source location changes over time. The low-frequency content of seismic events could give promising insights into the source mechanism as they capture information on the pressurization-depressurization of the system. Recent results have revealed that the low-frequency energy [0.2-0.5 Hz] of several seismic events is distributed into two clusters, separated by two orders of magnitude. This result might reflect distinct pressurization states of the conduit-plug system. But further investigations are needed to better understand the mechanical processes involved.

Forecasting changes of explosive activity in open-vent volcanoes: the July 14th and August 16th 2006 eruptions of Tungurahua volcano (Ecuador)

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Forecasting changes of explosive activity is a crucial step for any strategy of volcanic hazard mitigation. The Tungurahua 2006 eruptions are an ideal case study for understanding these changes and its implications for hazard assessment. Tungurahua volcano (5023 m asl), located in central Ecuador, is one of the most active volcanoes of the Northern Andes. Detailed eruptive chronology reveals a recurrence rate of at least one pyroclastic-flow forming eruption during the last centuries. During historical times, Tungurahua experienced important (VEI $\geq$ 3) pyroclastic flow-forming eruptions in 1640-41, 1773, 1886 and 1916-1918. At the end of 1999, Tungurahua started a new eruptive period, whose main feature was the recurrence of low-to-moderate explosive eruptive phases, the most important being those of the November-December 1999, August 2001, September 2002, September-October 2003, Juin 2004. These phases were characterized by strombolian fountaining, vulcanian (canon-like) explosions, and light regional ash fallout.

At the beginning of April 2006, IG scientists detected several deep LP seismic events (5-15 km depth) that preceded a change in the degassing pattern of the volcano (beginning of May), which was followed by an important deformation in the upper part of the cone (end of May). Since the beginning of July, seismic activity ramped up dramatically and culminated with the 14th July (VEI 2) and 16th August 2006 (VEI 3) eruptions. For the first time since the beginning of this eruptive period, Tungurahua volcano experienced highly explosive eruptive phases, which formed 16+ km height eruption columns, and produced pyroclastic flow-forming events, which swept the western half of the cones. The estimated juvenile material deposited during the two eruptions were around 2 millions and 20-30 millions cubic meter respectively. This important volume of erupted magma is consistent with a high magma ascent rate during these eruptions. This parameter could be considered as the key factor controlling the transition from low (1999-2005) to high (May-August 2006) explosive activity, by allowing or avoiding, respectively, the onset of an efficient gas segregation mechanism. To explain, in turn, such a change in the magma ascent rate, data suggest the occurrence of a deep magmatic intrusion as the driving force of the 2006 Tungurahua eruptions.