Inverting pyroclastic flow deposits from the characteristics of substrate-derived clasts: an experimental investigation

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Pyroclastic flows commonly propagate on granular substrates formed by earlier geological events and whose properties may influence the emplacement dynamics. We addressed this issue through scaled laboratory experiments on granular flows propagating on a granular substrate. The flows were generated from the release of columns of fine (80 microns) glass beads into a 3 m-long horizontal channel whose base consisted of an unconsolidated granular layer. The initial column was either non-fluidized or gas-fluidized in order to investigate flows having a range of properties. Pore pressure measurements revealed an upward pressure gradient at the flow-substrate interface because a dynamic underpressure (relative to that of atmosphere) proportional to the square of the front velocity was generated there while (atmospheric) pressure within the substrate was unchanged. A smooth substrate of fine (80 microns) particles was sheared by the sliding head of the flow, leading to the formation of small-height (1 mm) bedforms. These structures stretched horizontally as the flow propagated so that there was almost no evidence of entrainment in the deposit. In contrast, in the case of a rough substrate of coarse (1.6 mm) beads, most of the uppermost particles were first dragged horizontally individually. Then, many of these particles were uplifted to a height that increased up to 6-8 mm at flow velocities up to 2.5-3 m s-1. They were entrained over significant distances of several tens of cm, and then fell down so that the basal layer of the resulting deposit consisted of a mixture of fine and coarse particles. Assuming particle uplift was caused by the upward pressure gradient evidenced by our measurements, we did a theoretical analysis to determine the critical pressure gradient and the corresponding flow velocity at which uplift can occur, and found that this depended basically on the mass of individual particles entrained and on the flow bulk density. These contrasting modes of substrate entrainment are counterintuitive but nonetheless consistent with field observations. As shown by the Peach Springs tuff, an unconsolidated substrate of relatively fine (typically less than 1-2 mm) particles can be preserved at the base of a pyroclastic flow deposit whereas a substrate made of large particles (pebbles, boulders) is commonly reworked. The latter phenomenon is also observed at Mt St-Helens, where the 1980 pyroclastic flows emplaced on a debris avalanche deposit and entrained dense lava boulders of size up to several tens of cm on subhorizontal slopes. Using our model in order to invert the deposits, assuming a bulk flow density of 875-1400 kg m-3, we obtain flow velocities of 9-13 m s-1 in agreement with field observations.

Modeling dynamics and sedimentation of dilute pyroclastic density currents

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Dilute pyroclastic density currents (dilute PDCs, or surges) are lethal and destructive types of flows generated by volcanic eruptions. Such flows are typically unsteady, density-stratified and turbulent, producing a range of deposit characteristics. Here we discuss models aimed at improving our understanding of the first order dynamics that influence dilute PDC runout and damage potential. We also explore the mechanisms of sediment transport and deposition in order to link depositional characteristics with current dynamics. Model (1) comprises simulation of axi-symmetric flow and sedimentation from a steady-state, vertically uniform density current. Equations for conservation of mass, momentum, and energy are solved simultaneously, and effects of atmospheric entrainment, particle sedimentation, basal friction, temperature changes, and variations in current thickness and density are explored. The Rouse number and Brunt-Väisäla frequency are used to estimate the wavelength of internal gravity waves in a density-stratified current, in order to predict deposit bedform characteristics. The model predicts realistic runout distances and bedform wavelengths for several well-documented field cases, although results are heavily dependent on source conditions, grain-size characteristics, and entrainment and friction parameters. For instance, increasing particle settling velocity, by increasing particle size and/or decreasing total particle concentration, decreases both runout distance and bedform wavelength. Model (2) uses a one-dimensional hydraulic balance of sedimentation of clasts and entrainment of air for an idealized ash-cloud surge current moving away from the channeled PDC "avalanche" source. The idealized ash-cloud surge is assumed to flow normal or obliquely to an avalanche track along a series of 1D flow paths defined by digital topography and broken into segments of constant slope and arbitrary length. In its existing form a series of starting points for 1D surge calculations are selected along the PDC channel, or arbitrarily specified within the modeled pyroclastic flow inundation limits, while mass flux is provided as an input parameter.

In both models, the surges move laterally while entraining air and sedimenting particles until their bulk densities fall below that of ambient air, signifying lift-off and defining the surge deposit limit. Deposit limits are used to define the possible area that may be inundated by surges. For both models, preliminary runs for test cases are consistent with observations, but because our existing formulations are based on depth-averaged equations, assumptions about density stratification and corresponding Brunt-Väisäla frequencies are oversimplified. Future model development seeks to quantify controls on density profile, and make use of experimental observations of sedimentation mechanics in controlled laboratory experiments.

Pyroclastic Density Currents from the May 18th, 1980 Eruption of Mt St Helens (Washington, USA) - Uncovering the influence of surface roughness, substrate erosion and self-channelization

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Detailed measurements of recently exposed strata from the May 18, 1980 eruption of Mt St Helens, Washington, provide substantial insight into the influence of surface roughness, substrate erosion, self-channelization and varying mass flux on the dynamics of pyroclastic density currents (PDCs). The infamous eruption began with the debris avalanche and lateral blast that swept across the north side of the volcano, leaving behind a modified, deforested terrain of variable slopes and irregular topography. The afternoon PDC phase occurred several hours into the Plinian eruption and was dominated by column collapse and boil-over PDC behavior. Debris avalanche hummocks scattered across the pumice plain, north of the volcano, provided meters to 10s of meters of vertical relief for later PDCs to interact with. The first PDCs to traverse the hummocky topography left behind the fines-depleted, stratified to diffusely-stratified deposits of Units 1 and 2. Vertically in the sequence, or as the terrain filled in, the deposits become more massive and the degree of fines depletion diminishes. This observation suggests bed shear stress, transport mechanisms and elutriation are strongly controlled by the degree of surface roughness. The climactic phase of the eruption produced the most voluminous and wide-spread PDCs (Units 3 and 4) which are characteristically massive and rich in lithic blocks. Lithic levee deposits in Unit 3 transition downstream into a 10 m deep, 130 m wide channel scour, which cuts into the earlier PDC deposits. This occurs in an area where debris avalanche relief is limited, suggesting self-channelization was important during the transport and deposition of Unit 3. The channel scour is filled with two lithic breccias of Units 3 and 4. The average size and percent of lithic blocks within Units 3 and 4 increase with distance from source, suggesting that self-channelization increases the carrying capacity of the flows. This counterintuitive trend of increased lithic size in more distal locations is also observed downstream from debris avalanche hummocks. Componentry analysis of the blocks downstream from hummocks demonstrates that many were eroded from the debris avalanche deposits (see abstract by Nicholas Pollock). However, as the hummocks were progressively filled in the percent of blocks derived from the hummocks approaches zero. Thus, while many interesting findings are associated with this work, the most important include our ability to understand the influence of self-channelization on carrying capacity of the currents and the influence of surface roughness on elutriation and substrate erosion. These observations have critical consequences for understanding the flow dynamics and hazard potential of PDCs.

The control of source processes and topography on the dynamics of devastating pyroclastic density currents generated during the Merapi 2010 eruption

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The Merapi 2010 eruption, the most intense at Merapi since 1872, provided a unique detailed empirical dataset on the generation, emplacement, and devastating impact of a diversity of pyroclastic density currents (PDCs) during an escalating rapid-onset, multi-stage eruption that threatened a large population. An 11-minute sequence of laterally-directed explosions and retrogressive collapses on 5 November 2010 at Merapi destroyed a rapidly-growing dome and generated high-energy PDCs (stage 4) spreading over 22 km2 with a runout of 8.4 km, while co-genetic valley-confined PDCs reached 15.5 km. The deposits and the widespread devastating impact of associated high-energy PDCs on trees and buildings show striking similarities with those from historical volcanic blasts (Montagne Pelee, Bezymianny, Mount St. Helens, Soufriere Hills). We provide data from extensive stratigraphic and sedimentologic field studies of the first unequivocal blast-like deposits in the recent history of Merapi. We used high resolution satellite imagery to map eruptive units and flow direction from the pattern of extensive tree blowdown. The stratigraphy of Stage 4 PDCs consists of three depositional units (U0, U1, U2) that we correlate with the second, third and fourth explosions of the seismic record. Both U1 and U2 show a bi-partite layer stratigraphy each with a lower L1 layer and an upper L2 layer. The lower L1 layer is typically very coarse-grained, fines-poor, poorly-sorted and massive, and was deposited by the erosive waxing flow head. The overlying L2 layer is much finer grained, fines-rich, moderately to well-sorted, with laminar to wavy stratification. L2 was deposited from the waning upper part and wake of the PDC. Field observations indicate that PDC height reached 330 m with an internal velocity of 100 m.s-1 within 3 km from the source. The geometry of the summit and terrain morphology formed by a major transversal ridge and a funneling deep canyon significantly limited the loss of kinetic energy of the PDC hence focussing their mass into a major canyon constriction. The resulting elevated PDC velocities and high particle concentration promoted overspilling of high ridges into tributary valleys, while generating elevated dynamic pressures offset from the crater that caused major destruction of buildings and forest to 6 km from the summit. The Merapi 2010 eruption highlights that source and path effects can significantly control the dynamics of high-energy PDCs generated as a result of explosive and gravitational disintegration of a rapidly growing dome. This constitutes a challenge for current efforts in mathematical modelling of PDCs and quantitative risk assessment of potential impact areas at Merapi and at other volcanoes, particularly during multi-stage eruptions that can generate a diversity of PDCs in a short time-period during which the properties of the substratum over which succesive PDCs are emplaced can evolve significantly with time.

Merapi 2010 eruption: An interdisciplinary approach to constraining pyroclastic density current dynamics

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The large explosive eruption of Merapi volcano, Indonesia, in 2010 presented a key, and rare, opportunity to study the impacts of a major explosive eruption in a densely populated area. Pyroclastic density currents (PDCs) produced throughout the 2010 eruption were unusually destructive, causing near complete devastation across a 22 km2 swath of the densely populated and forested southern flanks and casualties to the end of their runout, 15.5 km from the volcano. Decline to eruption end within a further 18 days enabled us to collect perishable geological, damage and casualty data safely and within a pristine impact environment, before rains or human activity could destroy valuable data. By integrating the results of our interdisciplinary studies, we could reconstruct the spatial and temporal dynamics of the PDCs and their main hazard characteristics. In the areas damaged by PDCs, we used empirical damage data and calculations of material and structural resistance to lateral force to estimate approximate dynamic pressures. Estimates of dynamic pressures associated with the 5 November paroxysm exceed 15 kPa more than 6 km from source and rapidly attenuate over a distance of less than 1 km at the end of the PDC runouts. Findings clarify how the temporal and spatial distribution of devastation was influenced by summit and flank morphology and by the preceding sequence of activity. Analysis of thermal indicators, such as deformed plastic, and correlation with information on burns injuries and fires provided estimates of ambient temperatures associated with the PDCs. Even at the relatively low temperatures estimated for the PDCs (200-300 deg C) they were lethal to people inside as well as outside buildings, in part because of the building design that enabled the PDCs to rapidly infiltrate inside. Such detailed quantitative data can be used to support numerical PDC and impact modelling as well as risk assessment and mitigation at dome-forming volcanoes, providing an improved understanding of the complexity of PDCs and their associated impacts on exposed populations.

Ground Penetrating Radar and Terrestrial Laser Scanner survey on cross-stratified overbank deposits from the 2006 eruption of Tungurahua volcano, Ecuador.

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The deposits of the August 2006 pyroclastic density currents (PDCs) at Tungurahua, Ecuador exhibit two main depositional characteristics. Topography confined deposits show coarse, unsorted, massive, meter thick layers. Ash dominated, cross stratified deposits outcrop on the overbanks of valleys, organized as spatially isolated and limited bodies. Dune bedforms shape the surface of these deposits. We combined a terrestrial laser scanner (TLS) and a ground penetrating radar (GPR) survey on the overbank deposits.

TLS provides a dense data cloud (measurements at ca. 5cm steps) with cm precision. The GPR survey permits to look at the internal cross stratification patterns in a non destructive way. Three antennae with frequencies of 250, 500 and 800MHz, permitted to image the deposits down to 10, 7 and 3m depth, resp. The GPR data profits from the TLS results, which are integrated in the processing.

The TLS results permitted to compare previous eyewitness measurements with quantitative parameters derived from the numerical data. We picked the crests of the dune bedforms by defining them as local maxima. Their orientations, average slope angles, length and thickness are defined from two successive local extrema. We applied a Fourier and wavelet analysis in all directions to characterize wavelengths and pseudo amplitudes.

A large gridding with the 250MHz antenna permitted to recognize and follow the major flow units and the pre eruptive surface. Up to 6 units are recognized, the 3 basal ones interpreted as dense pyroclastic flows deposits and the top ones as dilute PDCs deposits, based on the GPR signal. This may indicate that the valleys were filled by the time of deposition of the dune bedforms, a result not inferred in previous studies. The deposited volume can also be derived.

From a dense array (profiles at 10cm spacing) over dune bedforms with the 800 and 500MHz antennae, we imaged the 3D internal patterns. This confirmed previous 2D, outcrop based observations and constrained the lateral evolution of stratigraphic features. Monotone lateral profiles rule out genesis from currents with different orientations. However, a single dune bedform can show both downstream and upstream migrating crests during the same stage of the flow. The root of the structures is located much deeper than previously expected and record the initial conditions for initiation of a bedform. The striking spatial stability during the whole deposition stage indicates that these bedforms are triggered by basal topographic disturbances. Several structures cannibalized by larger ones proof that the bed rapidly accommodates temporal changes in the dynamics of the currents.

This innovative combination of field methods brought unexpectedly good results. In particular, they permitted to image individual flow events and how deposits from successive pulses interacted with each other.

Assessing pyroclastic density currents hazard by means of complex multiphase flow models

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Pyroclastic density currents (PDC) hazard assessment at active volcanoes represents a complicated problem and a scientific challenge, since the fundamental mechanisms of PDC propagation and interaction with topography are not fully understood and initial conditions cannot be predicted on a deterministic basis. On the other hand, probabilistic approaches integrating different sources of uncertainty (including those associated to the target eruptive scenario) need rapid execution of numerical models with variable input parameter distributions and control on errors and uncertainty. Such conditions are seldom simultaneously fulfilled by multidimensional multiphase flow models, which are needed to describe the complex fluid dynamics of high-temperature particulate currents.

To provide a useful tool for probabilistic hazard assessment, while retaining parts of the information supplied by complex multiphase flow models, we have undertaken a systematic study on the propagation of gravity-driven PDCs aimed at deriving a parameterization of the radial trend of hazard variables (dynamic pressure and temperature) and their associated uncertainty. In particular, we here focus on the propagation of PDCs in the absence of a significant topographic mean slope (as significant for caldera settings). To evaluate PDC hazards in a caldera, we need to understand the mechanism and the controlling factors of current sedimentation and deposition during its propagation, since these control PDCs stratification and their capability of overcoming topographic obstacles and eventually inundate the region outside the caldera margins.

To this aim, we have analyzed the dynamics of finite-volume pyroclastic currents on a flat surface by means of two- and three-dimensional numerical simulations. Initial conditions have been simplified in order to reduce the input parameter space to a few variables (initial mass and buoyancy and mixture temperature), in respect to which scaling properties and uncertainty have been evaluated. By adopting a multiphase flow model for a polydisperse gas-pyroclast mixture and new constitutive equations based on kinetic theory of particulate flows and laboratory experiments, we have simulated the mechanism of flow stratification and the influence of the flow rheology on the large-scale dynamics. In particular, the front propagation velocity, the momentum dissipation rate and the kinetic energy decay have been quantified. A semi-empirical law expressing the decay of dynamic pressure and temperature defined on this basis will be tested in the framework of probabilistic PDC hazard mapping at the Campi Flegrei caldera.

Laboratory experiments on transport and deposition of granular flows over a variable break in slope: insights for depositional behaviour of pyroclastic and volcaniclastic density currents

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Gravity-driven flows in volcanic areas comprise some of the most complex and hazardous natural phenomena, and can occur either during explosive eruptions or during volcanic quiescence. Among volcanic gravity-driven flows the study of those characterised by high-particle concentration is exceedingly important, since they encompass some of the most destructive volcanic phenomena. In all these phenomena the same basic forces govern motion, but differing mixture compositions, initial and boundary conditions yield varied dynamics and deposits. Examples range from dry rock avalanches, in which pore fluid may play a negligible role, to liquid-saturated debris flows and gas-charged pyroclastic density currents, in which fluids may enhance bulk mobility. Field studies on real volcanic gravity-driven deposits remain an irreplaceable tool for obtaining crucial information about their behaviour. This is because a volcanic gravity-driven deposit records the physical processes that occurred at time of deposition, and particle morphology and deposit texture can yield precious information about transportation regime. However, the direct observation of physical processes acting on real flows is usually prevented by the hostile nature of these natural phenomena. For this, laboratory experiments can supply precious information for validating sedimentological models derived from field studies. New insights on behaviour of granular flows come from laboratory experiments carried out using a 5 m flume engineered at the Instituto de Geologia, University of San Luis Potosi (Mexico). The flume is equipped with different sets of sensors and the spreading area is bordered with glassy walls in order to observe the deposit aggradation. The experimental runs are carried out using real volcanic particles combined to form synthetic grain size distributions. A set of laboratory experiments were performed using the same Weibull grain size distribution and changing the slope ratio between flume and expansion box area. The results indicate how depositional behaviour is greatly influenced by the slope ratio, whit changing velocity and flow runout using different slope configurations. These first results highlight some fundamental processes in particle transportation and deposition over break in slope useful for the understanding of natural granular gravity currents.

Latest explosive eruptive episodes of Ulleung Island, Korea: eruption styles, transport mechanisms, and stratigraphy of an intra-caldera tephra sequence

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Ulleung Island is a Quaternary volcanic island located in the mid-western part of the East Sea (Sea of Japan), which has been active until the recent geological past. This study focuses on reconstructing the latest eruptive history of the island by delineating the sedimentological and stratigraphic characteristics of the most recent tephra sequence, named the Nari Tephra Formation. This entire formation is preserved as a succession of unwelded pyroclastic and epiclastic deposits within an embayed margin of the Nari Caldera. The embayment acted as a topographic trap for proximal pyroclastic deposits, and contains a complete record of the past 19,000 years of eruption history. Field measurements reveal that the Nari Tephra Formation comprises five pumiceous tephra units of trachytic/phonolithic composition (Members N-1 to N-5 in descending stratigraphic order), with intervening weathering horizons and/or soil horizons indicating hundreds to thousands of years of repose between each event. Eruption styles and depositional mechanisms were variable between the eruption episodes, as well as during the individual episodes, depending on the dynamics of the magma plumbing system and the role of external water. The eruption history can be reconstructed as follows: (1) the earliest eruption associated with cryptodome disintegration (N-5), (2) a plinian eruption that emitted voluminous pumiceous tephra (N-4), (3) a sustained fountaining eruption with precursory hydrovolcanic activity (N-3), (4) a subplinian eruption that gradually changed from wet to dry eruption (N-2), and (5) the final hydrovolcanic activity followed by effusive lava dome extrusion (N-1). Mapping medial extra-caldera sequences reveals that only a few of the recognized eruptive episodes generated sustained eruption columns or pyroclastic density currents (PDCs) with sufficient inertia or buoyancy to surmount the caldera wall and deposit substantive tephras beyond the caldera rim. The results imply that the tephra sequences outside the caldera are incomplete records of the eruptions of the volcano, and that the topographic effects of the caldera should be considered not only for the assessment of PDC-related hazards but also for the interpretation of terrestrial or marine tephra records.

Building collapse and density current in volcanology via engineering

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This paper explores the behavior of skyscrapers collapse that, on impact of the fragmented material with the ground, generates shear density currents. These currents resemble some volcanic flow, e.g. the one generated during the May 18, 1980 explosive eruption of Mount St. Helens (MSH), when, after a sector of the volcano collapsed, a highly mobile, multiphase turbulent current formed and interacted with the surrounding landscape. In order to investigate on the similarity between these two events, computational fluid dynamic is employed to simulate the propagation of the dusty currents that were generated by the World Trade Center (WTC) collapse over Manhattan, since the size and multiphase behavior were similar to those of MSH. Results reveal that the flow dynamic pressure strongly increases because of flow-building interaction, and the surrounding buildings make the urban setting an area of exponential decay of the deposits. These results can be of help for understanding the hazard of explosive eruptions over complex urban settings.

Friction properties controlling deposit shape of dense pyroclastic flows: insights from recent dome collapse events in Soufriere Hills Volcano, Montserrat

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Capturing the major characteristics of dense pyroclastic flows generated by the collapsing of lava domes is important to assess volcanic activities and hazards, but is a significant challenge because the mechanics of the grains and their interactions are incompletely understood. One approach has been to exploit the thinness of the flows relative to their length by employing a depth-averaged description. A key issue is the granular friction law that is introduced into the models. Recent laboratory studies on dense granular flows suggest that rheology can be described by a friction coefficient. Variation of this coefficient with shear rate and pressure is captured through a dimensionless inertial number. Under the shallow water assumption how well this friction model works remains unclear when applied to pyroclastic flows.

Recent dome collapse events in Soufriere Hills volcano, Montserrat, provide good examples to study the dynamics of dense pyroclastic flows and to examine granular flow models, because of abundant geological and geophysical data. In this study, the July 2003 and May 2006 dome collapse events and resultant pyroclastic flow deposits are investigated. The most intense phase of the 2003 event produced the deposit 170 M m^3 in 2.6 hours, and the shape of proximal submarine deposit offshore Montserrat is characterized by semicylindrical, steep-sided lobes. The 2006 event produced 97.8 M m^3 in 35 min and the deposit is characterized by a more elongated shape in flow direction than the 2003 deposit and by channel and levee-like facies (Trofimovs et al., 2012, BV). Geophysical observation such as seismic and strain records also constrain the variation of discharge rates of pyroclastic flows during the events.

To investigate the factors controlling the shape of pyroclastic flow deposit, we used a 2D shallow water model with two types of Coulomb-type friction models. One had a constant friction coefficient, and another had a friction coefficient that depends upon the dimensionless inertial number of the motion. The models are applied to a simple system or the terrain of Soufriere Hills volcano. When the latter friction model was examined, the variation of deposit shape such as channel and levee-like facies was reproduced, depending on initial mass, discharge rate or slope angle. Also our numerical results suggest that the inertial number dependent friction model works better after the flow passing a slope break point where slope angle is equal to the friction angle at zero shear rate. Coupling effects of discharge rates, slope and granular friction properties may explain the different shapes of the pyroclatic flow deposits produced by dome collapse events in Soufriere Hills volcano.

Comparing block and ash pyroclastic flow deposits and debris flow deposits from the 1990-1995 Mount Unzen Eruption (Heisei-Shinzan), Kyushu, Japan: implications for hazard assessment

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Mount Unzen is a polygenetic dacitic composite stratovolcano located on the Shimabara Peninsula, Nagasaki Prefecture, Kyushu, south western Japan. The most recent eruption from 1990 and 1995 produced 13 lava domes and approximately 9800 block and ash pyroclastic flows resulting from lava dome collapse events. 44 people were killed during the eruption. Five major deposit types were produced during and after the eruption: block and ash flow, debris flow, pyroclastic surge, hyperconcentrated flood flow and fallout deposits.

Distinguishing block and ash and debris flow deposits at Mount Unzen is very difficult in the field especially when close to the volcano (less than 2 km from summit). Currently the main criteria used to distinguish block and ash and debris flow deposits include: clast shape and angularity, carbonised versus non-carbonised vegetation material and ash matrix proportions. Grain size analysis revealed no differences between block and ash flow and debris flow deposits. The block and ash flow (BAF) deposits consist of block, lapilli and ash sized lava dome fragments of the same composition (monomictic). The deposits are very poorly sorted, massive, reverse and/or normal graded, and contain angular to subrounded clasts. Organic material is overwhelmingly carbonised. Ash particles are typically angular in form using photomicrographs and SEM imagery.

Debris flow deposits consist of remobilised block and ash flow deposit material and minor country rock material. The deposits are very poorly sorted, massive, normal and/or reverse graded, ash poor and contain angular to rounded clasts. Organic material varies from non-carbonised to variably carbonised. Photomicrographs and SEM images show ash sized clasts from debris flow and hyperconcentrated flood flow deposits are more rounded than block and ash flow and ash cloud surge deposit clasts.

Using the stratigraphic record of a volcano's style of behaviour as a tool to anticipate future hazards will not be easy given the difficulty in distinguishing primary eruption from secondary deposits. Detailed work is required in distinguishing block and ash flow from debris flow deposits. Similarly, there may be some difficulties in distinguishing some surge and hyperconcentrated flood flow deposits.

Topographic effects on pyroclastic density current dynamics: examples from Merapi, Lascar and Soufriere Hills volcanoes

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The scale, duration, periodicity and spatial distribution of pyroclastic density currents (PDCs) are remarkably difficult to predict. This is partly due to the characteristics of the source itself (for example, size, volume, orientation and material rheology), but also to the nature and complexity of the topographic profile of the volcanoes both near the source (proximal areas) and down the flanks (medial to distal areas). Traditionally, qualitative techniques for studying PDCs have been crucial to improve knowledge of the topographic effects on flow dynamics. Detailed work on the small-volume PDCs at Merapi, Lascar and Montserrat support delineation of significant flow features: (1) a main transport and deposition model for valley-confined flows that involves unsteady flow conditions generated by pulses of collapse at the source and/or by the development of kinetic waves during flow movement; (2) the development of syn-eruption deposit accretion in areas where the original channel morphology/topography provides accommodation space and/or creates distinct flow barriers; (3) the breakout of valley-confined PDCs into overbank flows and/or ash cloud surges, where the topography of the infilling valley deposits reaches a critical distance relative to the retaining capacity of the topography. For any given flow, and location in the valley, this distance is a dynamic function relating to the depth of the previous in-filling material, the height and detailed morphology of the valley, the cross-sectional area of the valley, the velocity and thickness/volume of the flow and, possibly, the presence/influence of kinetic waves in the main flows. Moreover, PDC hazards related to overbanking processes are often associated with the dynamic pressure associated with large block impacts, stressing the importance to better resolve the relationship between block velocity, block deposition, and topography.

The 2006 and 2010 events at Merapi Volcano, as well as some case studies from volcanoes in Central and South Americas, offer great opportunities to test the ability of some conceptual flow models to reproduce the studied actual events. It can also be shown that the use of high-resolution satellite datasets and digital elevation models (DEMs) allow us to better understand the influence of varying topographic parameters on the dynamics of PDCs by quantifying the relationships between deposit sedimentological features, retaining capacity of landscape features and scale-dependent tendencies for flows to overbank.

The integration of results and constraints from field-derived data, satellite imagery and numerical modeling is one of the main challenges for future research into the dynamics of PDCs. A combination of these different techniques is vital for an accurate characterization of areas prone to such currents and their associated hazard levels, thereby reducing their future risk and impact.

The dynamics of pyroclastic density currents: experimental insights

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We model dilute pyroclastic density currents (PDCs) using scaled, warm, particle-laden density currents in a large air-filled tank (described in Andrews and Manga, JVGR 2012). The currents comprise heated particles turbulently suspended in air. As the currents are initially denser and warmer than the ambient fluid, buoyancy reversals can occur when the currents have sedimented enough particles or entrained and heated enough air to become less dense than the atmosphere. Our experiments demonstrate the effects of thermal energy, atmospheric stratification, topography, and substrate roughness on current runout, liftoff, coignimbrite mass fraction, and sedimentation processes. In general:

1) cold currents travel farther and fractionate less mass into coignimbrite plumes;

2) topographic barriers must be >1.5 times as tall as current thickness to reduce runout distance, but barriers do focus plume liftoff;

3) substrate roughness increases runout until the roughness is comparable to the thickness of the turbulent lower layer of the current;

4) portions of currents can reverse direction during coignimbrite plume liftoff;

5) sedimentation rate is not steady but is instead coupled to and tracks large eddies moving along the bases of the currents.

Comparison of relevant bulk properties (Reynolds number, densimetric and thermal Richardson numbers, excess buoyant thermal energy density) and turbulent properties (Stokes and settling numbers) between our experiments and natural dilute PDCs indicates that we are accurately modeling at least the large scale behaviors and dynamics of dilute PDCs.

Experimental investigation of pyroclastic flows generated by continuous supply of material

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Understanding the dynamics of pyroclastic flows is an important step in developing better models for the internal physical processes within these flows and in providing better hazard assessment to local populations. Fluidization and related reduced internal friction is a key contributor to this for fines-rich flows, with particle settling and exsolution of gas from juvenile tephra being the primary contributors.

Scaled analogue experiments have been conducted in order to investigate the degree to which high pore pressure controls the mechanism of flows generated from sustained supply of material at source. Sub-80 micron diameter silica beads are released into a flume capable of providing a pre-determined basal gas flux along the length of the channel. The gas flux can be set from zero through to the minimum fluidization velocity of the particles at which the material is fully supported by internal pore pressure. Vertical release from a large hopper provides a relatively sustained sediment supply, enabling the vertical migration of the flow boundary layer and aggrading deposit to be observed and the flow runout distance to be investigated.

By varying mass flux and the initial condition of the flow as it enters the flume, we are able to observe how flow dynamics, runout and deposition vary as a function of the input, which can provide insight into the interpretation of deposits in the field. This in turn has implications for the understanding of pyroclastic flow behavior at active volcanic centers, and the hazards posed by these types of eruptive behavior.

Transformation of blast-like hydrothermal jets into highly mobile pyroclastic surges. New insights from the August 2012 Te Maari eruption

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Cold (Bandai-type) pyroclastic surges are a particularly hazardous type of pyroclastic density current. They can comprise spectacular mobility in terms of their runout, their ability to surmount topographic barriers and their extremely destructive and lethal potential. In comparison to magmatic and phreatomagmatic/phreatic surges, our knowledge on the generation mechanisms and on the flow behaviour of cold surges remains largely fragmentary. The August 6 2012 eruption of Te Maari volcano, Tongariro (New Zealand), caused by the sudden decompression of the hydrothermal system below the crater, produced highly mobile cold surges that travelled and spread for 2.1 and 2.3 km along wide sectorial arcs to the E and W, respectively. In the W, surges reached and caused damage beyond the popular Tongariro Crossing Track, largely affecting Tourist businesses in the Central North Island of NZ until today.

Direct observations of the eruption, geophysical and geochemical monitoring data, and detailed mapping of the pyroclastic successions over the entire 6.3 square km surge inundation area allows: (a) a quantitative reconstruction of the eruption sequence comprising an initial debris avalanche, two surge units and associated ballistics strew fields related to two discrete and directed blast-like explosions that also formed the new fissure-type crater, and final fall deposits from a third, plume-forming explosion through the main Upper Te Maari vent; (b) a reconstruction of the surge generation mechanism through a longitudinal transformation of two high-velocity, discrete, blast-like hydrothermal jets expelled at 30 to 60 degrees to the horizontal; and (c) describing and interpreting associated transitional sedimentary facies changes along the main blast or surge sectors from massive breccias, a three-partite surge bed succession over a narrow, medial region with anti-dune formations and a wider distal region of normal dunes and planar surge forms.

Here we will give a brief description of the eruption sequence. We will show and discuss detailed quantitative datasets of the laterally and longitudinally evolving surge bed forms including dune and bed geometry data, deposit distribution, grain-size, particle density and componentry data and relate these to the explosion mechanisms at source, to the space- and time-variant formation of a highly density stratified surge, and to local interaction with 5 successive ridges and valleys in the surge runout path.

Through integrating surge thickness and grain-size data we will also present computations of the bulk/initial grain-size distribution of the two hydrothermal blasts/surges. This rarely obtainable piece of information will be used to model the absolute, vertically and longitudinally variable mass partition of the stratified surge flow. The model allows us to finally discuss general aspects of surge transport and deposition as well as surge destruction behaviour that is characteristic for mobile cold surges.

Transportation and deposition processes in pyroclastic flow and co-ignimbrite ash deposits from Mashu caldera volcano, eastern Hokkaido, Japan, inferred from grain size distribution

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Mashu volcano is a Holocene active volcano, East Hokkaido, Japan. The largest caldela-forming eruption Ma-f (20km3)occurred 7.5 ka. Ma-f can be divided into three layers, which correspond to the typical section to explain different regions within a pyroclastic density current: Layer 1-3, bottom to top. The Layer 1 is coarse-grained, lithic rich, dark gray layer. The Layer 2 is matrix-supported, pumice rich, light gray layer. The Layer 3 is well-sorted, tan ash layer. To investigate the transportation and deposition processes of Ma-f, we performed field surveys and grain size analysis. The survey region consists of three areas: East of Mashu (along Shibetsu River: E1-6, near to far from the source), Southeast of Mashu (along Nishibetsu River: SE1-4) and West of Mashu (W1-4).

Boundaries between the Layer 2 and 3 are gradual, and lahar deposits are found between them at SE1-3. Layer 2 shows larger thickness change (9-800cm) than Layer 3. In the West area, Ma-f can be recognized within Akan caldera (W4), relative elevation of whose topographic barrier (caldera rim) is 580m.

Based on field occurrences and grain size data, we firstly discuss whether the Layer 3 is co-ignimbrite ash or pyroclastic fall from a eruption column. Comparing the data of windward side (W4) and the leeward side (E5), both of which are on the same distance (38km) from the source, the thickness and grain-size of the Layer 3 is larger in W4. However, Ma-j to -g (preceding plinian falls of the same eruption) are distributed only in the east side of the source by westerlies. These suggest that the Layer 3 can be concluded as co-ignimbrite ash.

Secondly, we discuss the transportation and deposition processes of Ma-f in the West area. The thickness of Layer 2 at W2 is 30cm, whereas that of W3 (on the starting point for climbing of the Akan caldera wall) is 600cm. The Layer 2 at W4 (in the Akan caldera) is 20cm thick, and finer-grained and better-sorted than those of W2 and 3. These suggest that when the Ma-f run up the Akan caldera wall, coarser particles were left at W3. Compared with the Layer 2, lateral facies change is very small in Layer 3 . However, Layer 3 at W4 is finer and better sorted than those of W2 and W3. This infer that the transportation process of Layer 3 is also influenced by significant land forms. This is consistent with the previous conclusion that the Layer 3 is co-ignimbrite ash.

Finally, we discuss the relationship between the Layer 3 and lahar. Lahar had occurred during the Ma-f eruption in Southeast area. Layer 3 of SE1-3 are thinner, finer and more sorted than that of E3-5 at a given distance (20-30km) from the source. The grain size distributions of the upper, middle and lower parts of Layer 3 at East area show that it becomes finer and more sorted toward the top. It seems that coarser particles of Layer 3, which could be deposited in the earlier, were swept away by accompanying lahar at SE1-3.

Flow deposit and erosion processes in granular collapse over sloping beds

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Experimental granular column collapses were conducted over an inclined channel covered or not by an erodible bed of granular material in order to reproduce at laboratory scale granular flows and erosion processes of natural flows propagating over deposits formed by earlier events. The studied control parameters were the slope angle, the aspect ratio (i.e. height over length), volume and shape of the granular column released, and the thickness and compaction of the erodible bed.

For flows on a rigid (non erodible) bed, there is a critical slope angle θ_c between 10° and 16° that separates two different dynamics for granular flows. For slope angles below θ_c, the flow runout distance increases as a linear function of the column initial height. On slopes over θ_c, however, the runout distance is also dependent of the column volume, contrary to what was reported on the horizontal in former studies and extrapolated for higher slopes. Three regimes are observed during a granular collapse: an acceleration followed by a deceleration and a last slow propagation phase that appear for slope angles over θ_c and which duration increases for decreasing aspect ratio and increasing volume.

For flows on an erodible bed, erosion processes significantly boost the flow front propagation over the critical angle θ_c, mainly during the deceleration and the slow propagation phase. The granular avalanche excavates the erodible layer immediately at the flow front, behind which waves traveling downstream help entraining grains from the erodible bed. Erosion efficiency (i.e. depth and duration of excavation, waves amplitude and duration) is shown to increase as the slope angle and the column volume increase. It is also dependent on the thickness gradient in the initial column, and on the nature of the erodible bed: the maximum excavation depth and the duration of excavation are smaller as the degree of compaction of the erodible granular bed increases.

Erosion processes notably increase granular flows runout distance at inclinations close to the repose angle of the grains in particular for columns of small aspect ratio and great volume. The runout distance increase compared to the case on the rigid bed is shown to increase as the duration of bed mobilization increases. We demonstrate, moreover, that the flow runout distance on an erodible bed cannot be reproduced on a rigid rough bed by simply adding the entrained volume of erodible bed to the initial column volume. This suggests that a regular supply of mass by entrainment during the propagation is necessary to increase the flow runout distance.

Un-channelized dam-break flows : effect of the lateral spreading on the flow dynamics.

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In this study, we used a three-dimensional discrete-grain model (Grains3D) to explore the flow and deposit characteristics of un-channelized dam-break collapses. A series of numerical experiments was performed to predict the behaviour of different granular columns (characterized by different initial aspect ratio a, varying from 0.5 to 18). As observed previously in similar channelized dam-break flows and axisymmetric slumps, the phenomenology of the collapse depends strongly on a, revealing different flow regimes. Small collapsing heaps develop shallow cascades that form deposits characterized by a tail extended by a rounded frontal region. Instead, tall avalanching columns generate dense, fast-moving currents that form a circular final deposit that resembles to those obtained from axisymmetric columns. The conversion from vertical to horizontal momentum was observed to be more efficient in these flows. The aggrading inner tapering region of static grains developed during the flow increases the number of final cascades necessary to adjust the slope of the final deposit, extending the total flow duration from 3tc in dam-break flows to 7tc in un-channelized ones. Surprisingly, mean aggradation velocities measured at different locations were observed to be independent of the lateral position, depending primarily on the longitudinal distance from reservoir and the initial aspect ratio. Scaled deposit widths and runouts revealed different power-law dependences on a exposing a non-isotropic behaviour which tends to form a smooth transition from channelized dam-break flows to axisymmetric slumps.

Hurricane–triggered lahars at Volcán de Colima: evidences of flow dynamic from monitoring and field survey.

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Rain–triggered lahars represent a very common and dangerous phenomenon at Volcán de Colima, with between 15 and 20 events occurring per year including some that generate major damage to infrastructure. These flows initiate on the upper slope of the cone above 2500 m a.s.l. and usually erode and entrain material to transform into debris flows that deposit 1–2 m of sediment along ravines up distances of 12–15 km from source. The October 12th, 2011, Jova hurricane was an anomalously large rainfall event over Volcán de Colima area, with important effects on the morphology of the area and on the dynamic properties of lahars along the main ravines. This hurricane produced more than 200 mm of rainfall in 24 hours, triggering several lahars that lasted for more than 2 hours. Based on data recorded at the monitoring station located 4 km from the crater along the Montegrande ravine (equipped with a rain gauge station, a soil moisture sensor, a video–camera, a geophone, and a broadband seismometer of the COLIMA–RESCO network) we were able to record the event and to obtain physical parameters of some of these flows. Three main lahars were detected from the spectrograms, being the last one characterized by a train of seismic peaks that lasted for more than an hour. No images were available since the event occurred at night. However, comparing the topography before and after the event at the monitoring site, these flows were able to deeply erode older terraces. Field surveys performed three days after the Jova event, let us to better understand the downflow behaviours. Three main depositional units were recognized: the two lower units are massive, mostly composed of sand and gravel, with maximum thickness up to 50 cm. The upper unit is up to 1.5 m thick, massive or normally–graded with clasts up to 30 cm imbedded in a sandy matrix. The granulometric analyses show a very low percentage of the silt fraction (<5 wt%), with predominance of sand for the two lower units, and of gravel for the upper unit. Based on the extraordinary erosive power observed along the ravine and on the textural characteristic of the deposits we interpret that lahars were dilute, supercritical flows, within the hyperconcentrated flow regime. These flows are prone to entrain sediment through turbulence and tractive shear stress. The last lahar was probably the most erosive pulse, which subsequently transformed into a debris flow depositing a coarse, normally–graded unit farther downstream. Immediately after the event, a box–shaped canyon was formed, leading to tens of landslides occurring along the ravine, some of them damming the river and thus exacerbating the risk of highly sediment charged and damaging lahars in the near future.

The Possibility Hazards Mapping of Future Lahar on Merapi Volcano

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Post Merapi volcano eruption 2010 were issued 130 million m3 of material pyroclastic flow destroyed 9 hamlet in Sleman district, the secondary affect was lahar occured, threatened lives, destroy settlements and infrastructure damage. In the rainy season period November 2010 - July 2011 was 88 times lahar occured, 13 of them destroyed the settlements, damaging farmland and infrastructure. Residents of 18 villages have to evacuate, 381 household must live in shelter, 742 houses damage, 2500 hectares of farmland and 200 hectares of rice fields buried in material of lahar, 13 schools, 22 bridges and 77 Sabo Dam badly damaged (BNPB, 2011). Base on survey, potentially of lahar is still high. That material deposit is about 100 million m3 in 2010-2011 and in the last 2012 it left about 77 million m3 and spreading out 12 rivers of Merapi volcano. The most of potential lahar material in Gendol river in Sleman district, but the most of lahar event occurred in Putih river and Pabelan river in Magelang District.

Based on lahar event on 2010-2011, Geological Agency have done mitigation effort to reduce the risk impact of future lahar both casualties and property loss. One of effort is lahar modeling which supported by the software LAHARZ and Lidar DEM data with accuracy about 30 cm and also the volume of lahar deposit that obtained from survey. These parameters used as a basis to create potential of lahar hazard and innundation zones. Based on the result of model lahar in Putih river - Blongkeng river have the most overbank areas (12,121,754 km2) than 12 other rivers. The number of potentially area affected by lahar model have 8 villages consist of 42 hamlets, while the potentially area affected by lahar model around Gendol river have (7,121,638 km2) threat of 6 villages 12 hamlets. Actually in the lahar events in 2010 - 2011, Putih river have 19 times event and threated 8 villages consist of 42 hamlets, while the lahar event around Gendol river occured 7 times and threated 5 villages consists of 19 hamlets. The result of lahar model showed that range of distance the lahar flow modeling in Putih river about 19.2 km and Gendol river about 22,3 km. While the number of overbank areas in Putih river 16 location more than Gendol river which have 12 location.

Lahar monitoring in the Belham Valley, Montserrat, West Indies: flood bores and flow behaviour

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In March 2012, a camera was permanently installed overlooking a relatively straight section the Belham Valley, on the Soufrière Hills volcano, Montserrat. The remote site provides a new vantage point on lahar activity and overcomes challenges of monitoring an aggrading channel in an inaccessible mid-reach location. High quality (1296 × 960 pixel) images were captured continuously at >1 frame s^{-1} and stored in-situ on a field computer. This allows objects, 10 cm and greater, travelling up to 9 m s^{-1}, to be tracked between sequential images.

On 13-14th October 2012, tropical storm Raphael deposited 2×10^6 m^3 of rain on the 15.35 km^2 catchment, generating seven lahars in the Belham Valley that were identified on the MVO seismic record. Rainfall measurements were derived from Meteo France radar images and one local rain gauge. Five lahars that occurred during daylight were captured by the remote camera and simultaneously observed in person. These were strongly unsteady, turbulent, sediment-laden, shallow (<1 m) flows. Suspended sediment concentrations changed dramatically (4.9 to 106.5 g l^{-1}), and support visual observations that flows rapidly transformed from dilute to hyperconcentrated streamflow.

Three hundred and forty-nine bores were recorded within lahars observed by the camera. These bores are mechanically similar to breaking front tidal bores and arid flood bores. The bores created a depth increase of a few centimetres to 0.3 m, and had an average velocity of 5 m s^{-1}; the average flow velocity before and after these bores was 3.5 m s^{-1}. Their occurrence was not periodic; the interval between successive bores varied from 6 to 6×10^3 s. Flood bores were not observed by eye-witnesses in the lower reach indicating that they attenuated as they travelled downstream.

Multiple peaks and fluctuations in discharge are thought to result from the complex catchment response to rainfall patterns. Imagery suggests that the bores transfer significant amounts of sediment downstream, as well as rapidly changing channel boundaries. Critically, the passage of each flood bore results in a sudden increase in flow depth and velocity, highlighting the importance of better understanding the rapidly varying, unsteady nature of lahars to inform hazard assessment beyond forecasting location and timing.

Numerical modeling of the Mount steller rock-ice avalanche flow history and it's associated seismic signal.

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Gravitational instabilities, such as landslides, avalanches or debris flows play a key role in erosion processes and represent one of the major natural hazards in mountainous, coastal or volcanic regions. Despite the great amount of field, experimental and numerical work devoted to this problem, the understanding of the physical processes at work in gravitational flow is still an open issue, in particular due to the lack of observations relevant to their dynamics.

In this context, the seismic signal generated by gravitational flows is a unique opportunity to get information on their dynamics. Indeed, as shown recently by *Favreau et al., (2010)* and *Moretti et al.(2012)*, simulation of the seismic signal generated by landslides makes it possible to discriminate different flow scenarios and estimate the rheological parameters during the flow. Because global and regional seismic networks continuously record gravitational instabilities, this new method will help gathering new data on landslide behavior.

The purpose of our research is to establish new relationships making it possible to extract landslide characteristics such as volume, mass, geometry and location, from seismic observations (amplitude,duration,energy...).

The Mount Steller rock-ice avalanche, that occurred the 14th Septmeber 2005 in the south of Alaska, and the associated seismic waves have been simulated. We shown that the stress field applied on the ground surface by the landslide is highly sensitive to the flow history, that is to say, sensitive to the rheological properties and the physical processes, as erosion, involved in the flow.

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Long runout debris avalanche emplacement and subsequent landscape response surrounding Mt Ruapehu, New Zealand

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Major catastrophic edifice failures from long-lived stratovolcanoes produce debris avalanche deposits that almost instantaneously transform the surrounding landscape, by filling valleys or creating new ridge and fan systems. Mt Ruapehu, in the Central North Island, is one of the most active volcanoes of New Zealand. Volcaniclastic diamictons exposed on its surrounding ring plain show evidence for at least five major cone collapse events over the last c. 180 ka. The instability of Ruapehu's flanks is enhanced by active rifting, hydrothermal alteration, and possibly gradual volcano-spreading due to the loading of substrate Tertiary sediments. The surrounding landscape is characterised by uplifted poorly consolidated Tertiary marine sediments and is heavily dissected by numerous river systems. Debris avalanche deposits preserved within these, up to 50 km from source, are used to demonstrate the transforming sedimentological characteristics of long runout volcanic debris avalanche deposits. They typically consist of a clay rich matrix with poorly sorted subangular to subrounded jig-saw fractured andesitic clasts less than 4 m, and in places ripped-up Tertiary mudstone megaclasts larger than 5 m in diameter. The subrounded boulders suggest a general transformation of a debris avalanche into a debris flow with emplacement mechanisms changing from dominantly mechanical fluidization plus fragmentation into a more frictional flow regime. These catastrophic events changed the landscape by cutting off drainage pathways with massive volcaniclastics, forcing river capture into neighbouring streams and exacerbated incision into soft Tertiary sediments. The harder volcaniclastic deposits act as armour, allowing parts of the landscape to resist erosion cycles brought about by climatic and sea-level fluctuation, and the ongoing uplift of the areas surrounding Ruapehu. The result is an inverted stratigraphy, which not only outlines the previous river courses but also provides insights into localised rates of uplift and erosion. This study shows how volcanic debris avalanches induce effectively permanent changes to the surrounding landscape, which may have ongoing consequences for populated areas.

What happens when a pyroclastic flow enters the water - numerical modelling of an offshore pyroclastic turbidite

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When pyroclastic flows encounter water they are understood to deposit a proximal course unit, as well as generate a highly mobile turbidity current comprising an unknown fraction of the particulate fines. There is little information regarding how this secondary current forms, where it forms, how it flows, or what fraction of the original material is included within it. This work attempts to address these shortfalls through applying the Move sediment tool (a depth averaged turbidity current numerical model) to high resolution bathymetry and vibrocore data from a single pyroclastic-derived turbidite unit from the 2003 dome collapse event from Soufrière Hills Volcano, Montserrat.

We model tens of thousands of individual flows, each with initial conditions selected randomly from within a parameter space defined by known physical and measured constraints. Each flow is compared to the measured core data, and a root mean square error (RMSE) is calculated as a measure of quality of fit. It is subsequently possible to observe where the lowest RMSE (best fitting) flows exist within the parameter space, such that the initial conditions can be refined and further runs in this smaller parameter space are performed in an iterative process until an appropriate range of parameter values has been isolated. These analyses reveal the grainsize parameters for the load which is transported, as well as a wealth of information on flow concentration, thickness, velocity and form. Forward modeling of these input parameters assists in understand the behavior of the flow after its initiation, and help to interpret grading patterns and structures seen in the sediment cores obtained from the sea floor.

The AD 536 Phreatoplinian eruption of Volcán Ilopango, El Salvador: physical character of ash-rich pyroclastic-density-current deposits and coeval ash aggregates

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In AD 536 Volcán Ilopango erupted violently through a substantial caldera lake and changed Central American prehistory through the destruction of the Miraflores culture. About 2.5 million people now inhabit El Salvador's capital, San Salvador, less than 12 km from the caldera. The complex eruption sequence (informally named Tierra Blanca Joven) includes (1) a vent-clearing fall, (2) a short-lived Plinian fall, (3) a complex sequence of phreatomagmatic pyroclastic density currents and coeval ash fall, (4) an alternating sequence of ash falls (commonly wet) and pumice lapilli falls, and (5) a climactic ignimbrite. Total bulk-deposit volume exceeds 50 km3. Pyroclastic density currents generated by the eruption travelled more than 20 km from the caldera and left ash-rich ignimbrites that cumulatively reach 50 m thick within some valleys but thin over ridges to thicknesses of a few meters. Flow deposits include ash-rich, lithic-poor, massive to planar-bedded and cross-stratified ignimbrites. Within 5 to 10 km of the caldera, ignimbrite units are composed of fine- to coarse-grained ash and contain abundant matrix-supported accretionary lapilli and accretionary-lapilli fragments separated by planar to wavy erosive scours. At distances of 10 to 15 km, clast-supported ash pellet layers, interpreted as fall deposits, either from the co-ignimbrite plume or from a spreading umbrella cloud, separate fine-ash-rich ignimbrite units. Confinement of the accretionary lapilli to pyroclastic flow units is evidence in support of their formation within pyroclastic density currents. Fallout of millimetre- and centimetre-sized ash aggregates formed metre-thick massive ash deposits in medial to distal areas during the latter stages of the eruption.

Motion and remanent magnetization of particles in eruption-fed density currents: Late Eocene scoria deposits, Oga Peninsula, NE Japan

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Exposed on a large marine terrace of Oga Peninsula, an eruption-fed low-density current deposit occurs in-between Late Eocene wave-dominated offshore to foreshore succession. The deposit commonly contains basaltic andesite scoria blocks and lapilli, which partly retain fluidal externals with millimeters-thick skins and intermingle mainly with their finer fragments. Dense rock fragments locally concentrate at lower levels, and the basal part casts its load into the underlying sandstone-mudstone bed and locally contains rip-ups of mudstone and sandstone. Inversely-to-normally graded coarse beds (<4 m thick) and thinner and finer or fines-poor beds (<0.3 m thick) constitute large-scale cross-bedding developed over the total thickness of 40 m. Scoriae concentrate upwards where beds are thicker than 2 or 3 m, and sparse accretionary and/or armored lapilli occur in the associated finer beds. Internal channels and long axes of scoriae extend from NNW to SSE and cross beds dip to the SSE, indicating a current to the SSE.

Examined the ash matrix of scoria deposit and associated 43 block-to-lapillus size scoriae by stepwise thermal demagnetization, the magnetization direction of the ash matrix fluctuates significantly, whereas the magnetization directions of scoriae remain stable at temperatures above 200 to 300 degrees C and are almost completely demagnetized at above 500 to 600 degrees C. The stable magnetization directions are, however, different by individual scoria fragments, and all the directional data projected onto a sphere appear distributed along a small circle with the along-circle standard deviation of 26.2 degrees and the across-circle standard deviation of 15.0 degrees, smaller than 29.5 degrees of the standard deviation from the mean direction. The unstable magnetization direction of the ash matrix implies that the constituent ash grains were cooled and magnetized much earlier than scoriae and were carried by the current while being supported by turbulence with rotation in various directions. The large along-circle standard deviation relative to the across-circle standard deviation likely indicates that after magnetized, scoriae were carried by traction along the substrate with a limited range of rotation, mainly back and forth about the axis of a small circle on which magnetization directions concentrate. Conformably with this interpretation, the rotation axis lies in a direction, normal or slightly oblique to the inferred current direction. Where it entered shallow water, this hot and dilute current presumably decelerated and was transformed into a water-logged current, so scoriae were rapidly cooled and magnetized in direct contact with the water, and were soon saturated with water and came to rest on the substrate from the decelerating water-logged current. This case study shows potential application of remanent magnetization directions of individual fragments to infer the mechanisms and directions of eruption-fed density currents.

Forming mechanism of Taiheizan pyroclastic flow: Block and ash flow generated from eruption column collapse

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Taiheizan pyroclastic flow erupted from Sambe volcano, southwestern Japan, 3600years ago. The pyroclastic flow was regarded as a block and ash flow because of non-vesiculated essential fragments and its monolithologic facies. However Taiheizan pyroclastic-flow deposit is composed of fine ash and smaller blocks compare with 1991-1995 block-and-ash-flows of Unzen volcano originated. In this work, we examine that the Taiheizan pyroclastic flow was not formed by block and ash flow from lava dome collapse, but by the eruption column collapse based on (1) the distribution and emplacement temperature of the deposit, (2) component analysis of the essential fragments of the deposit, and (3) fractal analysis.

(1) Taiheizan pyroclastic flow distributes around the Sambe Volcano composed of four peaks, mainly filling the valley in south, east, north and west. More than three flow units are observed. The deposit consists of non-vesiculated essential fragment and matrix. The emplacement temperature of Taiheizan pyroclastic flow was estimated to be higher than 590 degree C by the thermal magnetization. The high temperature emplaced Taiheizan pyroclastic-flow deposit was also recognized on the ridge near the summit of the Sambe volcano, suggesting that the settlement near the summit should be by not lava dome collapse but eruption column collapse.

(2) Although Taiheizan pyroclastic-flow deposit mainly consists of essential non-vesiculated dacite fragments, breadcrust bomb and weakly vesiculated essential fragments are included slightly. Major element compositions of 60 essential fragments were determined by an XRF method from two exposures located at south and east from the vent area. Two sample shows low K2O content, which is correspond to southern peak of Mt. Sambe, but the rest shows the same chemical component as the other peaks of Mt.Sambe, suggesting that the essential fragment did not come from nearest peak but from all peaks.

(3) Fractal dimension of the relationship between the grain size and cumulative number for Taiheizan pyroclastic-flow deposit or cumulative weight for Unzen were obtained. Fractal dimension of Taiheizan pyroclastic-flow deposit is larger than that of the Unzen. This suggests that the degree of fracutuation of Taiheizan pyroclastic flow is more advanced than Unzen. Since the essential fragments of the both area are porphyritic dacite, we assume that the degree of the homogeneity are equal each other. In this case, the difference in a fractal dimension dependent on the fracture energy. Therefore, it can be considered that fracture energy is larger on Taiheizan pyroclastic-flow eruption, so that a fractal dimension is high. Generally block and ash flow deposit is considered to be formed by lava dome collapse, but highly fragmentated Taiheizan block and ash flow should be generated by the eruption column collapse.

Emplacement processes and provenance of submarine volcaniclastic deposits (IODP Site C0011, Nankai Trough)

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During IODP NanTroSEIZE Expedition 322, four packages of tuffaceous sandstones (TST 1, 2, 3a, 3b) were recovered within a moderately lithified and bioturbated silty claystone succession in the Late Miocene (>7.6 to 9.1 Ma) upper part of the middle Shikoku Basin deposits. To assess the emplacement processes of the tuffaceous sandstones we investigate modal and geochemical compositions of 24 thin sections that reveal systematic vertical changes within each bed.

The volcanic glass particles (pumice and shards) are the dominant modal constituents of each sandstone bed. They either have homogeneous compositions (major and trace element glass-shard compositions) or define a well-constrained compositional variation trend. This implies that each package derived from a single pyroclastic or a single eruptive event as opposed to gravity currents resulting from collapse of large, heterogeneous slope sections. TST 1, 2 and 3b are single beds whereas TST 3a is composed of at least three beds suggesting several rapidly succeeding sedimentation events. The beds are density-graded such that low-density pyroclasts including pumice lapilli are enriched at the top whereas dense lithic components and minerals are enriched at the bottom.

All tuffaceous sandstones support emplacement by volumetrically large, high-energy, turbidity currents directly derived from major explosive volcanic eruptions, probably involving the entrance of massive pyroclastic flows into the ocean (TST 1 to 3a) or generated by a submarine eruptions (TST 3b) with sufficient momentum to pass over into turbidity currents and travel over hundreds of kilometers at the seafloor.

Moreover, major and trace element glass compositions as well as isotopes show that the tuffaceous sandstones came all from a similar source region at the Japanese mainland despite the vicinity to the Izu Bonin arc or backarc. Trace element ratios like Nb/Zr versus La/Sm, Th/Yb versus Ta/Yb or Ba/Zr versus B/Zr assist this and additionally element ratios of Th/La versus Sm/La, Rb/Hf versus Th/Nb or U/Th versus Th/Nb suggest a mantle source region lying below continental crust, which is inexistent below the Izu-Bonin arc. Regional geological settings, and convergence of some chemical and isotopic indicators toward an early-stage Izu-Bonin influence culminate in the result that the collision zone between Izu-Bonin and Honshu Palaeo-arc on Izu-Peninsula, Japan, has been the most likely potential source area for the ignimbrites of Unit IIa.

Occurrence of the Take tephra distributed in the northern flank of Kitadake, Sakurajima Volcano, Japan

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Sakurajima Volcano, which is located in the southern part of Aira caldra, is one of the most active volcanoes in Japan. This volcano consists of two main edifices: Kitadake and Minamidake, which are composed of pyroclastic rocks and lava flows of pyroxene andesite and dacite. Four historic explosive eruptions in AD 764, 1471, 1779 and 1914 produced pumice fall deposits and lave flows, and damaged extensively its surrounding area.

The Take tephra distributed on the northern flank of Kitadake. The deposit is producted by the last summit eruption of Kitadake at 4900 ^{14}C years BP. Two lithofacies were identified in the Take tephra: massive facies and stratified facies. The massive facies are composed of relatively large pyroclastic flow deposits, while the stratified facies are alternating beds of small pyroclastic flow deposits and pumice fall deposits. Some small pyroclastic flow deposits contain accretionary lapilli. The large pyroclastic flow deposits are divided into pumice flow deposits and block-and-ash deposits. Most pumice flow deposits are welded within 2.2 km from the summit crater of Kitadake.

Based on the components, the Take tephra is divided into three types. Type 1 contains abundant pumice grains. Type 2 consists mostly of lithic fragments. Type 3 includes a large amount of crystal particles. Large pumice flow deposits are characterized by Type 1. Small pyroclastic flow deposits and pumice fall deposits are classified into Type 2 and 3.

These facts suggest that the pyroclastic flow is intra-plinian flows generated by successive partial collapses of the sustained plinian eruption column. Since some pumice flow deposits are fine grained and poorly sorted, and contain accretionary lapilli, they are interpreted to be formed as a consequence of an interaction of magma and water. It is suggested that a part of pumice flow deposits in the late stage are welded, and that a partial collapse of the welded pyroclastic rocks occurred.

A benchmarking exercise to promote inter-comparison for numerical models of pyroclastic density currents

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Prediction of the impacts of pyroclastic density currents (PDCs) is required for hazard and risk assessment, and for design of risk mitigation measures. The goal of such predictions is to estimate the area that may be affected by the movement of a potential PDC, and to map hazard intensity parameters, such as temperature, dynamic pressure, velocity, depth of flow and thickness of deposits. The technology for making such predictions has advanced substantially in recent years. Numerical computer-based models now exist, capable of approximating the motion of a given volume of pyroclastic material from its source to the deposition area. As the technology begins to mature, it is useful to compare the various models each other.

A benchmark is a comparison of models aimed at simulating the same physical process upon common initial and boundary conditions and outputs, but using different physical formulations, mathematical approaches and numerical techniques. Recently, an effort has been done on PDC numerical modeling in the direction of constraining the models themselves with data coming from different approaches, such as field study and experiments. In particular, one fluid depth-averaged and multiphase models have been constrained with field and observation data from some representative eruptions of Merapi, Montserrat, Mount St. Helens, and Vulcano. Results of these numerical simulations mainly apply to stratovolcanoes, and show interesting points. When PDCs interact with topography, the basal part of the flow is strongly affected by interaction. Then, this interaction is responsible for supplying sediment to the basal flow through a sedimentation rate. Finally, the sedimentation rate is redistributed laterally on the substrate from the basal flow itself. This is a general geological context in which to locate the benchmarking exercise as a starting point of models comparison.

Following the approach of inter-comparison projects for volcanic ash dispersal and atmospheric models, and the 2007 Hong Kong Landslide Runout Analysis Benchmarking Exercise, a one-day workshop will be held at the 2013 IAVCEI Scientific Assembly that will set up the basis for a future general benchmarking exercise on volcanic mass flow models. The workshop program will include an introductory lecture, an open discussion to establish the set of benchmarks able to cope with the challenges of modeling volcanic mass flows and, if possible, selected presentations of preliminary results from the future participants of the benchmarking exercise.

Taisho lahar as a cohesive lahar in 1926 eruption of Tokachidake Volcano, Central Hokkaido, Japan: Implications for generating mechanism of cohesive lahars

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Understanding generation mechanism of hazardous lahars is important for hazard assessment. The Taisho lahar (TL) (>0.69-1.9 *10^7 m^3) that occurred in the 1926 AD eruption of Tokachidake volcano, Central Hokkaido, killed 144 people in towns more than 25 km away from the volcano. The lahar has been considered as a typical snow-melt lahar caused by the runout of hot debris on a snow-covered slope, the mechanism similar to that caused the huge mud flow during 1985 eruption of Nevado del Ruiz. However, the origin of the water in the lahar remains a controversial topic because the calculated water mass based on the assumption that all of the snow on the runout area of the TL was melted is much less than the estimated water volume in the TL. In addition, the lahar deposit had not been adequately reinvestigated. Thus, we reexamined proximal deposits of the TL, along with their paleomagnetic characteristics, to investigate the sequence of the eruption and the formation process of the TL.

The proximal deposits of the TL are divided into three units: A, B and C in ascending order. Unit A and C are composed of hydrothermally altered rocks with a muddy matrix showing features of debris avalanche deposits, indicating a relatively low emplacement temperature (<100 ℃). In contrast, unit B consists of hydrothermally altered gravel and sand without clay-size fine and sometimes shows cross-laminas, indicating that the deposits can be considered as surge-like deposit, showing a relatively high emplacement temperature (approx. 350 ℃). At the downward gully, unit B changes to a debris flow deposit. Moreover, this can be also recognized to be one of cohesive lahar induced by collapse of hydrothermally altered pyroclastic cone because the deposits contain more than 3-5 wt. % clay in fragments smaller than 2 mm.

The presence of unit B indicate that the TL was caused not by a simple collapse of a cinder cone but by a phreatic explosion resulting in a sector collapse, suggesting that the hydrothermal water system was related to the eruption. This inference is consistent with the geophysical monitoring of the present state of the volcano, suggesting that a considerable portion of the hydrothermal water system has already been in existence beneath the active crater. In conclusion, the TL can be not only recognized the snow-melt lahar but also the cohesive lahar with hydrothermal water system explosion. This case study implies three points for the generation mechanism of cohesive lahar as follows: 1) Hydrothermal system explosion triggers a cohesive lahar, 2) hydrothermal water and snow melt water are important water sources in a cohesive lahar, 3) water sources plays a role to make a cohesive lahar fluid. The case also suggests that it is important for forecast of catastrophic lahar to monitor hydrothermal systems and to estimate hydrothermal water beneath volcanoes.

Change in components of lahar deposits from Chokai volcano

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Chokai volcano, located in the northern Honshu arc, is an andesitic stratovolcano that collapsed the edifice partly at ca.2500 years ago. The post-collapse lahar deposits (Shirayukigawa lahar deposit) are distributed in the northern foot of Chokai volcano. These deposits form a volcanic fan and consist of 16 units of debris flow and hyperconcentrated flow deposits. The Shirayukigawa lahar deposits 30 m thick, overly the 2.5 ka Kisakata debris avalanche deposit.

On the basis of sedimentary facies and structures, units of the Shirayukigawa lahar deposits are classified into three types: clast-supported debris flow deposit (Cc), matrix-supported debris flow deposit (Cm1), and hyperconcentrated flow deposit (Cm2). Each type has the following lithological characteristics.

Debris flow deposit (Cc) is massive, very poorly sorted, partly graded, and clast-supported with polymictic clasts dominated by subrounded to rounded volcanic clasts. Matrix is sandy to muddy. Preferred clast orientation are present.

Debris flow deposit (Cm1) is massive, very poorly sorted, and matrix-supported with polymictic clasts dominated by subrounded to rounded volcanic clasts. Matrix is sandy to muddy. Some layers exhibit coarse-tail normal/inverse grading. Most clasts are oriented.

Hyperconcentrated flow deposit (Cm2) is massive to diffusely laminated, very poorly sorted and matrix-supported with polymictic clasts dominated by subrounded to rounded volcanic rocks. Matrix is sandy. The clasts are randomly distributed in the sandy matrix except for some clast-concentrated lenticular layers. Clasts smaller than 1cm account for about 10 percent of the deposits. Maximum clast size is about 30 cm.

The clasts of these deposits consist of altered andesite, fresh andesite, mudstone and sandstone. The sedimentary clasts were derived from the substrate. The proportion of altered andesite clasts decreases upwards.

Matrix components in the lower 8 units (C-LHR) are different from those of the upper 8 units (S-LHR). In C-LHR units, grayish blue clay is dominant in matrix, whereas in S-LHR units, brownish yellow volcanic sand is dominant in matrix. The change in matrix component reflects the source material and is consistent with the change in clay mineral assemblage determined by X-ray diffractometry. Clay minerals such as smectite, chlorite, pyrophyllite and kaoline group mineral, are rich in C-LHR units whereas they are poor in S-LHR units. Presence of these clay minerals in the C-LHR units indicates that hydrothermal activity was dominant near the summit of Chokai volcano when the early lahars occurred. These deposits imply repetitive lahar events after sector collapse of Chokai volcano.

Lahar characteristics and erosion measurements using multiparameter recording stations and DEMs in the Gendol catchment after the 2010 Merapi eruption

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Lahars, including debris flows and hyperconcentrated streamflows, represent the most frequent natural hazard around the Merapi volcano because they can be triggered during and after, or even without eruptions. Each year lahars with a discharge range between 200 and 2000 m^3/s are triggered during the rainy season in several rivers which drain the west, SW and south flanks. We carry out an experimental method to measure hydraulic and physical characteristics of lahars in the Gendol River channel on the south flank of Merapi. This valley was heavily impacted by Pyroclastic Density Currents (pyroclastic flows and surges) during the October-November 2010 eruption and flooded by lahars, which have started to remobilize the PDC deposits a few months later. Six months after the 2010 large (VEI 4) eruption, small areas in Gendol down-valley 20 km from summit have been affected by subsequent over-bank and avulsed lahars. The over-bank process can be attributed to low-gradient (0.04 m/meter), meandering rivers (sinuosity index of 1.25) across the low-angle (<2°) ring plain and the limited capacity (200-300 m^2) of river channels.

The method encompasses: (1) hydraulic and geophysical in situ measurements of flows with sensors located at the valley bottom and on the edges, (2) high-resolution (decimetric) Digital Elevation Models (DEM) of the valley channel before and after a lahar, aiming at measuring the processes of aggradation and degradation in the catchment, (3) remote sensing analysis of erosion processes such as lahars and fluvial transport remobilizing the 2010 thick aprons of pyroclastic deposits (~30 million m^3). We use two experimental stations located on two check-dams ~250 m apart for in situ measurements along the middle course of the Gendol River at about 700 m elevation. The stations include 2 seismometers, 2 geophones, 2 load cells, 2 pore pressure sensors, 1 radar gauge, 2 rain gauges, a barometer and cameras. We measure discharge, sediment concentration, arrival and surface velocities, and dynamics features at the flow surface. The sediment concentration is measured simultaneously using buckets in the lower station every five minutes during the flow. We then compute the volumes of transported sediment allowing us to understand the flow dynamics, the processes of entrainment, and the parameters for describing the rheology of the lahar material. We finally evaluate the processes of erosion and sedimentation of two channel segments using multi-temporal DEM (before and after lahars) derived from low altitude stereoscopic images acquired by UAV (Unmanned Autonomous Vehicle). The final goal is to track the time-related propagation of the flows down valley and calibrate the input parameters of two numerical models (Titan2D, VolcFlow), which will be used to outline lahar-prone areas in the heavily populated ring plain of Merapi.

Prediction of Lahar Inundation Area for Volcanic Eruption of Baegdusan using LAHARZ

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Recent monitoring reports pointed out various unrest activities in Baegdusan (Chanbaishan in Chinese) volcano located in the border region of China and North Korea. The eruption of Baegdusan volcano introduces substantial damages to adjacent countries. The generation of lahar in the study area is strongly associated with the mixing process of magma within Cheonji (Tianchi in Chinese) caldera and results into the overflow of density current due to the rising of mixed fluid level. Both gravity and density difference are controls for fluid behavior and the topography primary determines the spatial distribution of lahar inundation. Digital terrain analysis had been performed using the digital elevation model with spatial resolution in 50 m obtained from United State Geological Survey (USGS). LAHARZ (USGS) was used for a tool for flow path delineation based on D8 algorithm. Assuming the flow direction toward Erdaobaihe in Jilin, China, the overflows over Cheonji caldera were assumed to be varied between 1 and 10 m for modeling conditions. Based on delineated proximal hazardous zone, the conventional relationships between lahar volume and cross sectional or planimetric areas were used to predict the lahar inundation area. Depending on various overflow scenarios, different lahar inundation hazard zones were obtained. However, spatial distributions of flow pattern also indicated the implementation of D8 algorithm may require further improvement for the simulation of flow divergence in conjunction with allowance of flow direction in multiple without restriction of 8 angles.

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Development of Multiparameter Telemetry System for Monitoring and Early Warning Lahar at Merapi Volcano, Java, Indonesia

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Merapi Eruption 2010 (VEI 4) considered as the biggest eruption in the last 100 years. Volcanic material deposition approximately 100 million m^3 and mainly concentrated in the southern and western slopes. Very high rainfall during the rainy season eroded the sediment easily and triggers lahar. More than 300 lahars events occurred in 12 rivers during 2010 to 2012. About 10% of the lahars event caused huge damage and losses along Putih, Boyong and Gendol rivers.

During 2010-2012, 24 stations have been established for monitoring and early warning lahar located near the rivers on the southern and western slopes. Five stations were built in November 2010 and supported technically by VDAP (USGS). Furthermore, 15 stations built in January 2011 and 4 stations in January-March 2012 in collaboration between the Geological Agency with National Agency for Disaster Management Indonesia.

Five of 24 stations are rainfall monitoring located at the upper flank as the initial information of lahar possibility. Five stations have one seismic sensor (geophone) of each. One station only equipped with a visual camera, nine stations of each have a combined of rainfall sensor, geophone and visual camera and four stations of each have a camera and geophone.

IP camera has specification of motion resolution JPEG 4CIF with 12X optical zoom, geophone of 10 Hz natural frequency and tipping bucket rain gauge. Data transmission from field stations to the central processing unit use a combination of broadband digital radio and analog VHF radio.

Data processed separately for each signal, such as rainfall, visual camera and seismic data. Rainfall warning is given if the cumulative rain intensity exceeds the threshold i.e. greater than 40 mm in 15 minutes. Threshold value for RSAM varying between 3000 - 7000 depends on background noise at each station. Information of rainfall intensity and RSAM (seismic) distributed via SMS and emails to the list of recipients automatically. Visual information can be accessed continuously via www.merapi.bgl.esdm.go.id. Local governments were given access to all information directly from the data center over internet protocol.

Data obtained from this monitoring system is a qualitative and early warning not yet delivered specifically. However, as a ringing bell to a potential lahar event this system plays an important role of the overall Merapi lahar mitigation.

Depositional processes of the Kuner ignimbrite from the Cubukludag graben, western Turkey: implications for generation of the phretomagmatic eruptions triggered by dome emplacement

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The subaerial silicic volcanism (the Cumaovasi volcanic succession) Neogene in age, occurs within the Cubukludag graben, which is delimited by the NE-SW -orientated faults that reflect a crustal fissure-fracture zone between Izmir and Kusadasi in west-central Turkey. The volcanic products are represented by cluster of rhyolite domes and lava flows together with pyroclastic deposits in the graben basin that form the upper part of the graben infill. The pyroclastic deposits dominate of this volcanic association which is an excellent example of dome triggered phreatomagmatic eruptions and related volcanic products.

The early phase is fine-grained pumice and ash-rich deposits, which are partly deposited in a lacustrine environment. The main part of the volcanic succession, Kuner ignimbrite, was derived from pyroclastic density currents. They represent various structural features in different layers of the succession. They are fine-grained and laminated at the base and pass laterally and vertically to the deposits which show well-developed traction structures. Alternation of diffuse stratified and massive lapilli, ash deposits are the common products of the later explosive stage which formed from abundant pumices, cognate and accidental lithic fragments displaying typically chaotic flow structures. Massive lithic breccias forming the top of the sequences are the proximal facieses of the pyroclastic density current.

The lava phase, mainly rhyolitic lavas, extruded from domes and fissures which are aligned along NE-SW trending faults and the extensional cracks nearly perpendicular to the main faults within the graben and form spacely-developed hills. Main lithologies of the domes are foliated stony rhyolite, rhyodacite, dacite, obsidian, perlite and autobrecciated flows. The Cumaovasi volcanic succession is co-eval with the sedimentation of the NE-SW trending cross-grabens which were developed under the extensional tectonic regime of the western Turkey.

Ground Penetrating Radar (GPR) survey on volcanogenic outburst flood deposits, northeast Japan

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Volcanogenic outburst floods from volcanic lakes such as intra-caldera lakes or volcanically dammed river-valleys tend to be voluminous with discharges that are usually several orders of magnitude greater than normal river flow condition. Such a large flood can travel long distance, and cause enormous transport of unconsolidated sediments and eventually burials of downstream areas. Therefore, sedimentary architectures, depositional patterns, and bedforms are important to understand properties, processes and mechanisms of large-scale hazardous flows. In contrast to the extensiveness of sediments and bedforms/landforms left after the volcanogenic outburst floods, outcrop information obtained by classical geological and geomorphological field surveys is limited to the dissected/terraced parts, road cuts and/or large quarries. This study therefore uses Ground Penetrating Radar (GPR), using the properties of electromagnetic wave propagation, to obtain extensive images of subsurface sedimentary structures of volcanogenic outburst flood deposits.

The GPR survey was carried out over two volcanogenic flood fan/apron sediments in northeast Japan, at surrounding the Numazawa and Towada volcanoes. The 5 ka Numazawa flood deposits in the Tadami river catchment has been emplaced by a breakout flood from ignimbrite-dammed valley leaving pumiceous gravelly sediments with meter-sized boulders in the flow path (Kataoka et al., 2008). At Towada volcano, a comparable flood event originating from a breach in the caldera rim emplaced the 13-15 ka Sanbongi fan deposits in the Oirase river valley, which is characterized by a bouldery fan deposits (Kataoka, 2011).

The GPR data was collected following 200 to 500 m long lateral and longitudinal transects, using a GPR Pulse-Ekko-Pro mounted with 50 MHz and 100 MHz antennas. We obtained radargrams up to 13 m depth, where the dielectric properties of the material were allowing a good penetration of electromagnetic waves. GPR profiles show large internal cross structures with 2-5 m amplitude and 10s m wavelength indicating lateral/downstream accretion in flood fan deposits. Some of them are slightly inclined towards upstream (backsets) which may suggest upstream migration of bedforms. These cross stratifications revealed by the GPR profiles correspond with very low-angle cross-stratifications or parallel stratifications in outcrops. The GPR images also containing hyperbolic reflectors suggest 1-3 m diameter boulders scattered in the fan deposits. Both the 5 ka Numazawa flood deposits and 13-15 ka Sanbongi fan deposits have underlying ignimbrites emplaced by the eruptions. Boundaries between fan deposits and ignimbrites/buried terrace deposits can be detected as clear reflectors. Thus, GPR survey on volcaniclastic material is useful to understand not only sedimentary architectures of the flood deposit but also paleotopographies, volumes of buried ignimbrite and overlying breakout flood or lahar sediments.

Alternating subaerial pyroclastic and marine reworking processes during eruption of a coastal tuff ring, Jeju Island, Korea: A high-resolution record of Holocene sea-level

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Explosive volcanic eruptions commonly result in rapid aggradation of pyroclastic materials in a very short period of time, allowing for the preservation of the details of the deposition history. The Songaksan mount, located near the southwestern coast of Jeju Island, Korea, is a typical tuff ring formed by phreatomagmatic activity in the middle Holocene when the sea level was almost identical to that at present. The purpose of this study is to unravel the depositional processes of the 120 cm-thick basal portion of the medial-distal rim beds of the tuff ring, which comprises seventeen units of alternating primary and reworked volcaniclastic deposits. Primary volcaniclastic units show pinching-and-swelling but laterally continuous bed geometry and a variety of deposit features such as migrating megaripple bedforms, accretionary lapilli, impact sags, and various grading patterns, suggesting deposition from pyroclastic surges and falls in a subaerial condition. On the other hand, reworked volcaniclastic units are ripple cross-laminated and better sorted (fines depleted) with intercalating mud drapes, indicative of reworking of volcanic debris and winnowing of fines by marine waves and currents. These two groups of facies alternate seven times and then pass upward into the wholly subaerial pyroclastic surge deposit with raindrop marks and footprints of birds on the bedding planes in between. This facies transition suggests repetitive marine reworking of pyroclastic material during the deposition of the lowermost rim beds of the tuff ring in an intertidal zone. Considering the short duration of monogenetic volcanic activity, it is inferred that the alternating deposition of the primary (subaerial) and reworked (submarine) units occurred within "several days", and that the daily fluctuations of the sea level due to tides were responsible for the alternation of the facies. This study implies that coastal tuff rings and tuff cones can provide high-resolution information of paleo-sea levels, which cannot be obtained by the study of nonvolcanic deposits.

The thermal state of pyroclastic flow deposits, 4.6 ka Fogo A plinian sequence, São Miguel, Azores, using TRM analysis and charcoal reflectance data: implications for eruption and flow processes

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The Fogo A plinian eruptive sequence is characterised by a complex stratigraphy, constituted by an initial Plinian fallout deposit of white trachytic pumices, followed by two intraplinian ignimbrites and one last main ignimbrite, which is dominated by more basic dark pumices, interstratified within the plinian fallout sequence. The aim of this research is to reconstruct the emplacement temperatures of the three ignimbrites and assess the factors that have influenced these. Emplacement temperatures of the three ignimbrites of the Fogo A plinian sequence, have been investigated using thermal remanent magnetization (TRM) of lithic clasts and a relatively new method of using charcoal reflectance of charcoal fragments embedded within the deposits. A total of 132 oriented lithic clasts from the three ignimbrite deposits, were collected from 15 localities distributed around Fogo volcano. The clast population is dominated by lava trachytic clasts and subordinate syenite clasts. The TRM analyses show the emplacement temperatures of the two intraplinian ignimbrites were respectively greater than 400 and 580textdegree; while the temperature reached by the final ignimbrite was 300 to 350textdegree. These thermal estimations are supported by the results of the analysis of inertinite-like maceral reflectance within the charcoal fragments entombed in the ignimbrites. The reflectance of 17 samples of charred fragments that the temperature reached by the wood fragments in the first intraplinian ignimbrite correspond to a temperature of 400 to 450textdegree, whereas the R% = 0.85 of the last ignimbrite indicate temperatures of 300 to 350textdegree. The different temperatures for the ignimbrites can be explained by a combination of componentry, especially lithic clast content, collapse level in the eruption column, turbulence level of the pyroclastic flows, degree of incorporation of water vapour from volatilised vegetation, and degree of topography confinement by the pyroclastic flows. The results also show that TRM and charcoal reflectance methods give comparable results, indicating that either method can be used depending on the characteristics of ignimbrites and availability of facilities.

The 3640-3510 BC eruption of Chachimbiro volcanic complex, Ecuador: a violent directed blast produced by a satellite dome

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Located in northern Ecuador, the Chachimbiro volcanic complex developed since about 500,000 years. The recent activity of this complex is marked by recurrent explosive eruptions, the most powerful of which occurred between 3640 and 3510 BC. This eruption produced a complex pyroclastic density current (PDC) deposit that covers an area of about 50 km2. In this area, the PDC overpassed four valleys and adjacent hills, transverse to the flow direction. The thickness of the deposits varies from few decimeters on the hills to several meters in the valleys, highlighting an important topographical control of the sedimentation process. Isopach and isopleth mapping show that this PDC was not issued from Chachimbiro's main and central vent, but from a satellite dome, located 6 km to the east. This eccentered origin is confirmed by the fact that no rock of composition similar to that of the PDC components (SiO2 = 69 wt.percent) has been encountered in the central edifice. The absence of a well-defined edifice in the area of maximum thickness of the deposit suggests that most of the dome was destroyed by the eruption. Due to the location of the source on an abrupt slope, recent landslides might have also buried possible remnants. The shape of the deposit and the fact that the PDC crossed four valleys indicate a high-energy event. The deposit shows different valley and interfluve facies. The valley facies comprises at least two massive units characterized by a very poorly sorted and coarse grain size distribution. No significant evolution of the valley facies is observed between the proximal and the distal area. The interfluve facies is more complicated. In the proximal area, its characteristics are similar to those of the valley facies while in the distal area it is much more stratified with a better sorting and a finer grain-size. Density measurements made on juvenile clasts show a very wide range of vesicularity with two peaks of vesicularity at 30-35 percent and 45-50 percent, that probably corresponds to two vesiculation stages during the eruption. These characteristics of the PDC deposit suggest that the 3640-3510 BC eruption produced a powerful multi-stage lateral blast. This blast destroyed a large rhyodacitic dome formed near Cerro la Viuda and traveled more than 10 km southeastward. The event was apparently not associated with a large volcanic landslide, differing in that manner from examples like that of Mt St Helens 1980 eruption. Additionally, the grain-size and density analysis show some discrepancies from typical directed blast deposits that can be attributed to the high-silica composition of the lava. Due to its amazing destructive power, this eruptive style must be integrated in the hazard assessment in volcanic arcs with high-silica satellite domes like the active Frontal Volcanic Arc in Ecuador and Colombia.

Valley-filling ignimbrites and the incursion of a pyroclastic density current into a lake: the Stallachan Dubha Ignimbrite Member, Ardnamurchan, NW Scotland

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The Palaeogene Ben Hiant Member of Ardnamurchan, NW Scotland, comprises a thick sequence of breccias and conglomerates interpreted as debris flow deposits. These rocks are unconformably overlain by a recently identified sequence of pyroclastic rocks, which we interpret as ignimbrites. We propose the name the Stallachan Dubha Ignimbrite Member for these rocks. Silicic explosive eruptions generated pyroclastic density currents that deposited a range of ignimbrite lithofacies. Lateral thickness variations in the ignimbrites record the localised filling of the palaeotopography. Periodically, the pyroclastic density currents entered a small lake and the ash was subject to aqueous reworking.

Four phases of eruption have been recognised in the sequence. Phase 1 was marked by the emplacement of valley-filling massive lapilli-tuffs and breccias. The presence of clasts of Phase 1 material in upper parts of this unit indicate that the current was eroding its own deposit during emplacement. Phase 2 was marked by the emplacement of rheomorphic tuffs and breccias. The rheomorphic tuffs display a strong flow-fabric/parataxitic texture and folds are locally present. The tuffs coarsen up in to a massive lithic breccia, which contains clasts of the rheomorphic tuff, before fining to rheomorphic tuff. The massive lithic breccia records a significant increase in mass flux, perhaps related to a high-energy vent clearing event, and/or vent collapse. Phase 3 is marked by the emplacement of a sequence of stratified tuffs, lapilli-tuffs and breccias. The tuffs and lapilli-tuffs are planar- to cross-stratified and alternate with massive lapilli-tuffs and breccias. In the finer units, convolute laminae and ripples are present. These rocks record the entry of a dilute pyroclastic density current into a small lake and the aqueous reworking of finer pyroclasts. Phase 4 is marked by the emplacement of a valley-filling crystal-rich massive lapilli-tuff. This unit unconformably overlies both Phase 2 and 3 rocks, including siltstones interpreted as lacustrine deposits associated with Phase 3. Locally, breccia lenses, dominated by clasts of Phase 2 rheomorphic ignimbrite, are present.

Proximal pyroclastic density current deposits at a glaciated composite volcano: Mount Ruapehu, New Zealand

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Young (<13.6 ka BP cal.) proximal pyroclastic density current (PDC) deposits at Ruapehu Volcano, New Zealand are described for the first time. The deposits result from some of the largest known eruptions at Ruapehu and its subsequent transition to vulcanian and phreatomagmatic activity. They provide insight into the emplacement and preservation of small to medium volume PDCs at glaciated composite volcanoes, reflecting complex interactions with palaeomorphology and possibly also changing ice cover at the volcano. Five distinct PDC episodes have been observed. 1.) The oldest units are massive pumiceous deposits including a full spectrum of dense to highly expanded pumices that represent collapsing plinian columns sourced from Ruapehu's Northern Crater. These are correlated with a sequence of plinian fall deposits preserved on the ring plain. Directly overlying these is unit 2.), an unusual <30m thick variably welded grey-black PDC deposit that comprises rounded monolithologic scoriaceous clasts supported by a vesicular ash matrix. Unit 2 is interpreted to represent a collapsing near-vent spatter pile deposited on the steep upper flanks. Transport over ice may have been significant in producing the unusual rounding of the clasts and vesicular matrix, but the incipient welding and presence of well developed cooling fractures suggest that extensive cooling did not occur during transport. The role of ice in the emplacement of this flow may be important for understanding the pyroclastic flow hazard at similar glaciated composite volcanoes worldwide. 3.) A younger locally exposed pumiceous PDC deposit containing fibrous and colour banded pumices is thought to correlate to the last known plinian episode at Ruapehu, associated with the opening of the presently active South Crater. 4.) Overlying this is a sequence of small PDC deposits with dense juvenile clasts that may represent flows generated from vulcanian eruptions sourced from smaller degassed magma pockets remaining after the plinian events. This sequence is capped by 5.) a thin (<1m) black PDC deposit containing distinctive large (<1m) cauliform and breadcrust bombs. The complete PDC sequence reveals systematic temporal changes in magma composition, density, and the role of magma mingling during a period of significant change at Ruapehu. Complex interactions with palaeomorphology and possibly surface ice appear to have been important factors in the generation, emplacement and preservation of the PDCs, and these effects are important for understanding the until now overlooked PDC hazard at Ruapehu and other glaciated composite volcanoes worldwide.

Emplacement time interval and temperature estimation for the Agatsuma pyroclasitic flow, Asama-Maekake volcano, central Japan.

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In order to estimate emplacement time interval between each flow units of Agatsuma pyroclastic flow deposits and emplacement temperature of them, rock magnetic and heating experiments for the pyroclastic flow deposits were carried out. Paleomagnetic experiment implies the pyroclastic flow were emplaced at least 580℃. Magnetic susceptibility of natural oxidized reddish matrix of the pyroclastic flow deposit is lower than non-oxidized blackish one. The a* value indicating reddish color of the oxidized one is higher than non-oxidized one. Based on magnetic susceptibility and color index, heating experiment for the non-oxidized material indicate that time interval between prior flow unit and subsequent flow unite of the pyroclastic flow at the site we investigated was within 30 minute and that emplacement temperature was about 600 − 700℃.

Field evidence for substrate entrainment by pyroclastic density currents and its effect on downstream dynamics at Mount St Helens, Washington (USA)

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Despite recent advances in the study of pyroclastic density current (PDC) dynamics, several fundamental aspects of the behavior of these hazardous currents remain poorly understood. Perhaps two of the more significant gaps in our knowledge are the primary control(s) on substrate erosion and the effect that substrate entrainment, i.e. bulking, has on current dynamics. Perhaps the largest limitation to a comprehensive investigation into this topic previously was the lack of sufficient exposures to confidently identify depositional evidence for substrate entrainment, the source of entrained blocks, and the effect on downstream flow dynamics. However, more than thirty years of erosion into the May 18, 1980 PDC and debris avalanche hummock deposits at Mount St Helens has revealed kilometers of new outcrops containing substantial evidence for erosion and entrainment. Here we present evidence for the entrainment of lithic blocks (>1 m in diameter in some locations) from the debris avalanche hummocks, as determined through detailed componentry and granulometry studies on the PDC deposits and debris avalanche hummocks where the lithics were derived. We find that in some locations up to 50 percent of the lithics found in lithic-rich PDC facies appear to have been locally derived from the debris avalanche deposits. We also observe numerous scours filled with block-rich lithic facies downstream from hummocks where lithic plucking has been determined. This suggests that erosion is a self-perpetuating process; when substrate entrainment occurs the increased bulk density and concentration gradient that result in the current enables further erosion and entrainment downstream from the location where bulking initially occurred. In addition, the presence of large, locally entrained lithics at various heights within a single flow unit suggests both a progressive entrainment of the substrate as well as a progressive aggradation of the deposit, depending on localized flow conditions. However, as the hummocks were progressively filled in during the eruption, the amount of entrained substrate material decreased to zero, suggesting that surface roughness is important for promoting erosion by PDCs. Taken together, these results suggest that the incorporation of substrate material by PDCs has a significant impact on PDC dynamics and deserves to be investigated further. It is possible that with the combination of field investigations, laboratory experiments, and numerical modeling a more complete understanding of how erosion and entrainment affect PDC dynamics can lead to a more accurate hazard assessment for these dangerous currents.

Rock-magnetic evidence for the low-temperature emplacement of the Habushiura pyroclastic density current, Niijima Island, Japan

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The emplacement temperatures of juvenile and accidental fragments in the Habushiura PDC deposit were estimated by rock magnetic analysis to understand its eruption process. The Habushiura PDC was generated in a shallow-sea area during the early stage of the A.D. 886 eruption in Niijima Island, Japan. The Habushiura PDC deposit is exposed about 5 km and composed of about 20 beds. The beds show various characteristics and are divided into three lithofacies. Facies A is a massive lapilli tuff, Facies B shows grading and/or diffuse stratification, and Facies C is abundant in large pumice.

We collected 160 specimens from 11 beds divided into each of the lithofacies. Juvenile specimens have the high-temperature magnetic component whose directions are changed irregularly. In Facies A and C, some low-temperature components whose blocking temperatures are less than 300 ℃ show linearly stable magnetic components and are parallel to the Earth' s field. In this study, the magnetic components whose blocking temperatures are lower than 150 ℃ are not used for the estimation of the emplacement temperature due to the possibility of the replacement by viscous remanent magnetization. IRM acquisition test and thermal demagnetization of the composite IRMs confirm that the low-temperature components whose blocking temperatures are between 150 and 300 ℃ are partial thermal remanent magnetization acquired during cooling after deposition. Thus, juvenile specimens from Facies A and C are estimated to be emplaced at less than 300 ℃. Meanwhile, the beds of Facies B contain the juvenile specimens less than 150 ℃. Accidental specimens from all lithofacies show stable one- or two-component magnetization. The low-temperature components of two-component magnetization have blocking temperatures at less than 350 ℃ and are parallel to the Earth' s field. Two-component accidental specimens are estimated to be emplaced at less than 350 ℃ in any bed.

Morphological characters of ash components in the Habushiura PDC deposit indicate quench fragmentation of hot particles in direct contact with external water. Thus, juvenile specimens estimated to be emplaced at lower temperature than rhyolitic magma temperature indicate that effective cooling was occurred by interaction between high-temperature juvenile material and external water and ingestion of ambient atmosphere during transport. High-temperature emplacement up to 300 ℃ of juvenile specimen comprised in Facies A and C are thought to be due to small ratio of external water, relatively large size or short transport time. The emplacement temperatures of accidental fragments were up to 350 ℃, which is higher than juvenile fragments within the same bed, are considered to have been heated by magma around the conduit prior to explosions and cooled more slowly than juvenile fragments due to high thermal content.

Size-segregation, self-channelization and enhanced runout of bidisperse granular avalanches

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In geophysical mass flows, such as pyroclastic currents and debris flows, the runout distance is of crucial importance in hazards assessment. The polydisperse character of these natural flows can have a strong influence on the flow dynamics. In particular, particle size-segregation can have a significant feedback on the bulk motion of granular avalanches when the larger grains experience greater resistance to motion than the fine grains. When such segregation-mobility feedback effects occur the flow may form digitate lobate fingers or spontaneously self-channelize to form lateral levees that enhance run-out distance. Such leveed flows have been observed in deposits from small volume pyroclastic flows.

Through small-scale laboratory experiments using bidisperse mixtures of dry grains released onto an inclined chute, we investigate the formation of elongated fingers bounded by lateral confining levees. The formation of fingers is due to particle size-segregation which leads to the transport of large material to the flow front. If the large material experiences greater frictional resistance than the fine grains, the front in unstable (Pouliquen et al. 1997; Pouliquen & Vallance 1999; Woodhouse et al. 2012) and degenerates into a series of elongated fingers bounded by large-rich static lateral levees.

By varying the composition of the mixture we assess the influence of the grain assemblage on the flow dynamics. We show that the number of fingers and the distance to which material is carried are strongly dependent on the proportion of large grains in the mixture. By utilizing a front tracking algorithm, we determine the velocity of the propagating granular avalanche and show that enhanced runout occurs due to reduced frictional resistance experienced by material flowing in leveed channels.

Pyroclastic gas escape structures

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Pyroclastic flows and vent deposits consist of mixtures of particles of different sizes and densities, which can separate from each other resulting in grading or vertical pipe structures from which the finer particles have been removed. Sometimes these elutriation pipes are associated with logs or large clasts, and it is hypothesised that the release of volatiles induces an overlying pipe. The origins and conditions of formation of these structures have been explored through laboratory experiments with mixtures of solid particles placed in a planar container through which dry air is passed. The particle beds were well defined mixtures of spherical particles or material from natural deposits.

A variety of structures formed in the experiments: pipes of various lengths can grow either upwards or downwards; horizontal layers of fine or coarse particles can lie at the bottom or the top of a bed; there are areas where particles are mixed well. Several mechanisms enable this segregation and mixing of particles of different sizes and densities. First, fine particles are able to move, or percolate, through the pores between larger particles. In a binary bed, this process requires that the size ratio between the finer and coarser particles is less than a critical value called the percolation limit. The upper bound of the percolation limit, calculated for regularly packed coarse particles, is 0.41, which is consistent with experimental results.

A second mechanism for mixing and segregation of particles is fluidisation. The vertical gas velocity at which the drag matches the particles weight is the minimum fluidisation velocity u_{mf}. At this point particles are able to move freely and rearrange themselves. u_{mf} is dependent on the size distribution of particles and how they are packed; so, heterogeneities in the bed lead to heterogeneities in u_{mf}. This can lead to complex behaviour as the segregation of particles and the value of u_{mf} are closely coupled. The experiments demonstrate that specific configurations of vertical or horizontal sorting depend on precise conditions for formation such as gas velocity, proportion of fine particles, and size and density ratios, suggesting that pipes and other structures seen in natural deposits may be linked to the particular processes that led to them.

A third process by which segregation can take place is through the presence of an embedded object substantially larger than the particles that make up the bulk of a deposit. The effect of the embedded object depends on the composition of the bed. For bed clast size ratios less than the percolation limit, the presence of a larger object does not significantly affect pipe formation; however, above the limit then a large, single pipe forms above the obstacle. These results indicate large clasts and logs may initiate pipe above them due to their effect on gas flow, and are not necessarily significant gas sources.

Supra-Ignimblite Channel-Fill Sedimentation of the Towada-Hachinohe (15Ka) Tephra Produced from the Towada Caldera, NE Japan

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After three large-scale eruptions occurred of the Towada Volcano, located in the northern part of the Northeast Honshu Arc, a gigantic crater lake was formed. Voluminous ash-fall and pyroclastic flow deposits are thought to be caused by caldera forming large-scale eruptions; and low-relief landforms around calderas, called pyroclastic flow plateaus, are thought to be formed by large volumes of pyroclastic flow deposits. A tephra, which formed during the third eruption of the Towada Volcano, is composed of ash-fall and pyroclastic flow deposits, and is called Towada-Hachinohe Tephra (To-H). This tephra is distributed thickly and widely. We can decode a complete eruption episode during the 15Ka in this tephra as a lahar process from supra-ignimbrite deposits. I was able to observe and decode deep gully-like structures filled by debris flow and stream flow deposits with slump block and wide channel structures filled by debris flow and stream flow deposits above the ignimbrite. It was revealed that these deposits are covered by hyper-concentrated flow deposits and fluvial deposits, and they are characterized by a braided river system. This study has also clarified that these rithostratigraphic changes of the supra-ignimbrite deposits indicate that the channel-fill sedimentary system occurred as an initial event during a lahar process that occurred just after emplacement of pyroclastic flow deposits. Furthermore, this study revealed that in an initial stage of the lahar process, conspicuous erosion and slope failure have dominantly taken place and that resedimentation of pyroclastic flow deposits commonly occurred on the ignimbrite plateau. In conclusion, I could clarify that deep and broad-based shaped channel structures indicated that the erosional processes act downward and later changed to lateral and that these directional changes of the erosion caused slump blocks to derive from existing deposits or ignimbrite as channel wall deposits.