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Combining numerical and experimental modelling to constrain the surge formation mechanism

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Introduction

The commonly accepted model for **pyroclastic density currents** (PDC) predicted a flow in **two parts**: the basal flow, rich in particles and blocks, overridden by the ash-cloud surge, a turbulent suspension of ashes. The **mechanisms of formation** for each part are not fully understood. For small volume PDC, the ash-cloud surge seems to be generated from the basal flow. A **better constrain** of these mechanisms could greatly improve the mitigation of the **hazard** they pose.

- In this study, we investigate the **formation and evolution** of the pyroclastic surge by **coupling** a numerical and an experimental
- The **empirical mass flux** proposed in the numerical model is **tested** in the experimental model to build a **conceptual model** for surge genesis in the natural system

1. Numerical modeling

- Our model **simultaneously simulates** the two parts of the PDCs: the pyroclastic flow, and the overriding ash-cloud surge. Both parts are based on the resolution of mass and momentum balance equations (Kelfoun, 2017 ; Kelfoun et al., 2017):

For the pyroclastic flow

$$\frac{\partial h_d}{\partial t} + \frac{\partial}{\partial x}(h_d u_x) + \frac{\partial}{\partial y}(h_d u_y) = \frac{\phi_s - \phi_m}{\rho_d}$$

$$\frac{\partial}{\partial t}(h_d u_x) + \frac{\partial}{\partial x}(h_d u_x^2) + \frac{\partial}{\partial y}(h_d u_x u_y) = gh_d \sin \alpha_x - \frac{1}{2} \frac{\partial}{\partial x}(gh_d^2 \cos \alpha_x) + \frac{T_x}{\rho_d} + \frac{\phi_s v_x}{\rho_d} - \frac{\phi_m u_x}{\rho_d}$$

$$\frac{\partial}{\partial t}(h_d u_y) + \frac{\partial}{\partial x}(h_d u_x u_y) + \frac{\partial}{\partial y}(h_d u_y^2) = gh_d \sin \alpha_y - \frac{1}{2} \frac{\partial}{\partial y}(gh_d^2 \cos \alpha_y) + \frac{T_y}{\rho_d} + \frac{\phi_s v_y}{\rho_d} - \frac{\phi_m u_y}{\rho_d}$$

For the ash-cloud surge

$$\frac{\partial h_s}{\partial t} + \frac{\partial}{\partial x}(h_s v_x) + \frac{\partial}{\partial y}(h_s v_y) = \frac{\phi_m}{\rho_m}$$

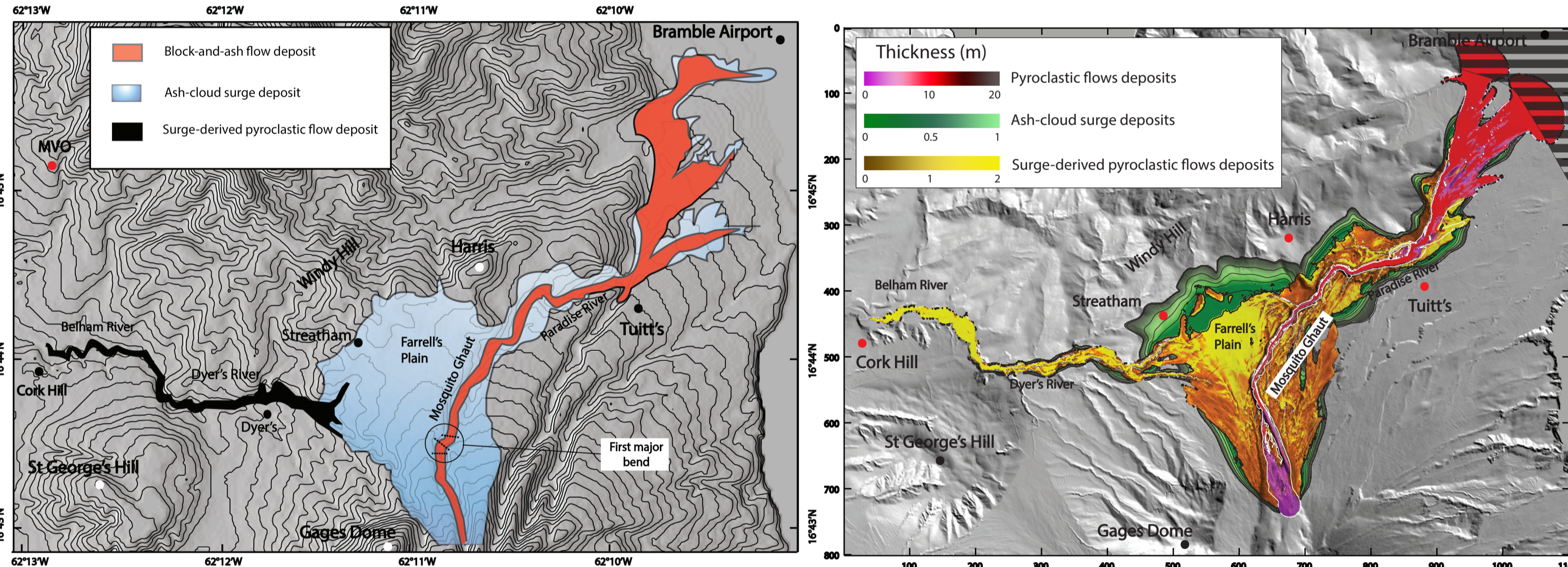
$$\frac{\partial}{\partial t}(\rho_s h_s v_x) + \frac{\partial}{\partial x}(\rho_s h_s v_x^2) + \frac{\partial}{\partial y}(\rho_s h_s v_x v_y) = (\rho_s - \rho_a) g h_s \sin \beta_x - \frac{1}{2} \frac{\partial}{\partial x}((\rho_s - \rho_a) g h_s^2 \cos \beta_x) + R_x + \phi_m u_x - \phi_s v_x$$

$$\frac{\partial}{\partial t}(\rho_s h_s v_y) + \frac{\partial}{\partial x}(\rho_s h_s v_x v_y) + \frac{\partial}{\partial y}(\rho_s h_s v_y^2) = (\rho_s - \rho_a) g h_s \sin \beta_y - \frac{1}{2} \frac{\partial}{\partial y}((\rho_s - \rho_a) g h_s^2 \cos \beta_y) + R_y + \phi_m u_y - \phi_s v_y$$

- The two flows are coupled through two empirical mass flux laws, obtained from wind tunnel experiments and by comparing numerical model with real deposits:

- From the flow to the surge: $\phi_m = c u^3$ **empirical**
- From the surge to the flow: $\phi_s = (\rho_s - \rho_a) \cdot w_{sed}$ **theoretical**

- We then investigate the conditions that favor the generation of surge-derived pyroclastic flows during dome-collapse events, by simulating the eruption of the 25 June 1997 at Soufrière Hills, Montserrat :



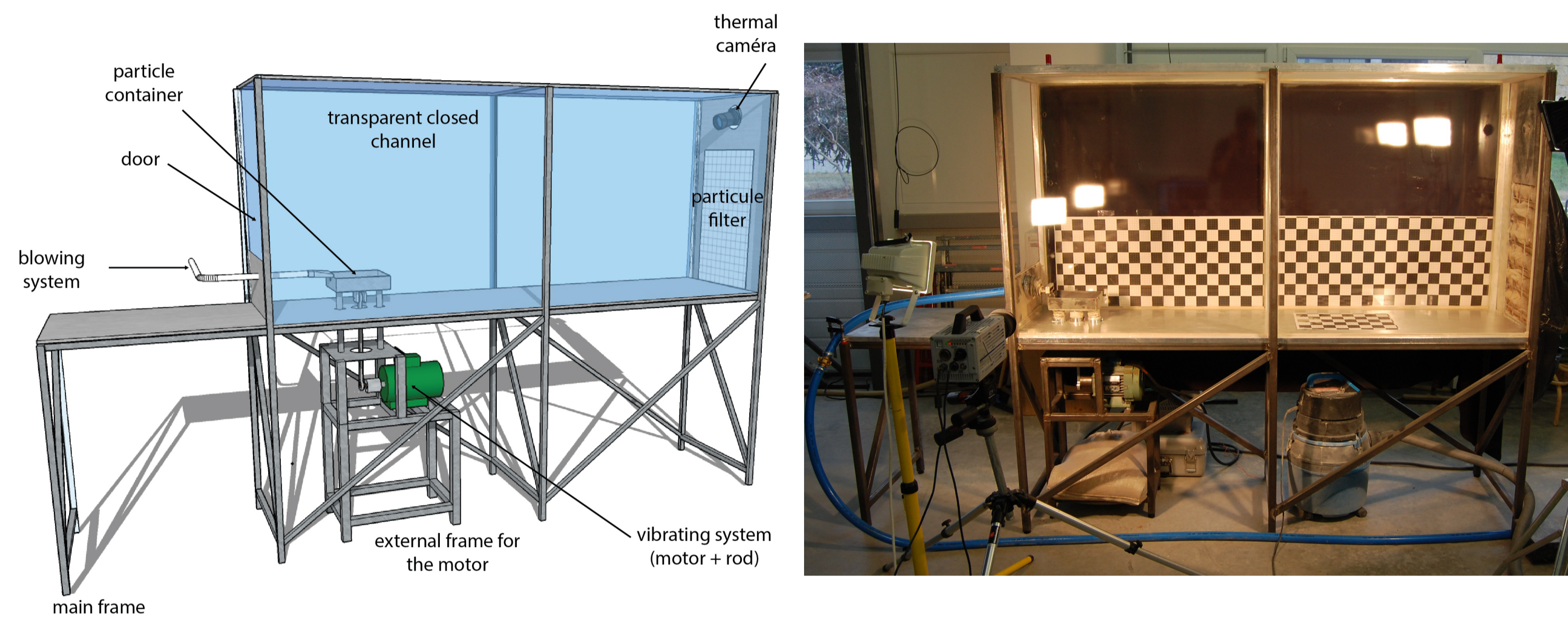
The best result is obtained with the **plastic rheology**

- SDPFs form by a cycle of accumulation-remobilisation of surge deposits on a steep slope, channelised into one valley. Highly dependent on the topography.
- The plastic rheology for the pyroclastic flow seems to be the most accurate.

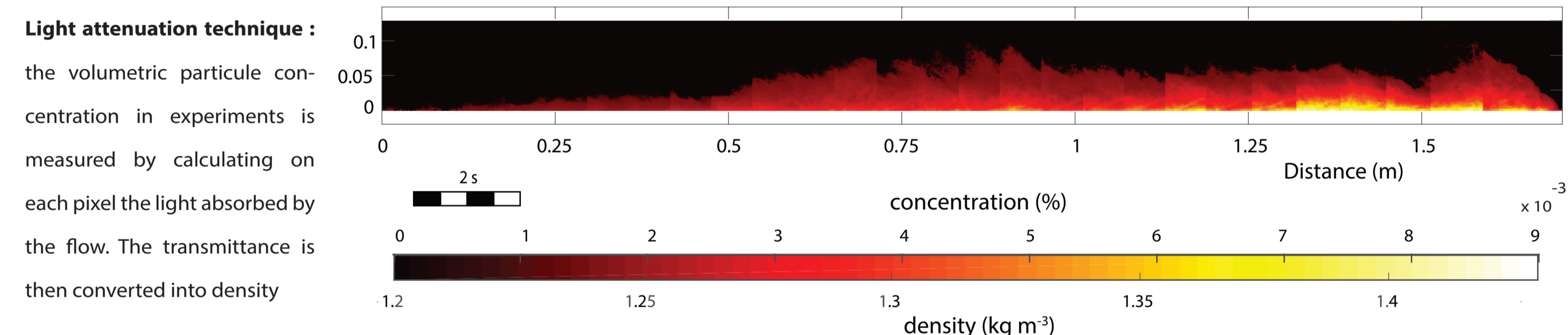
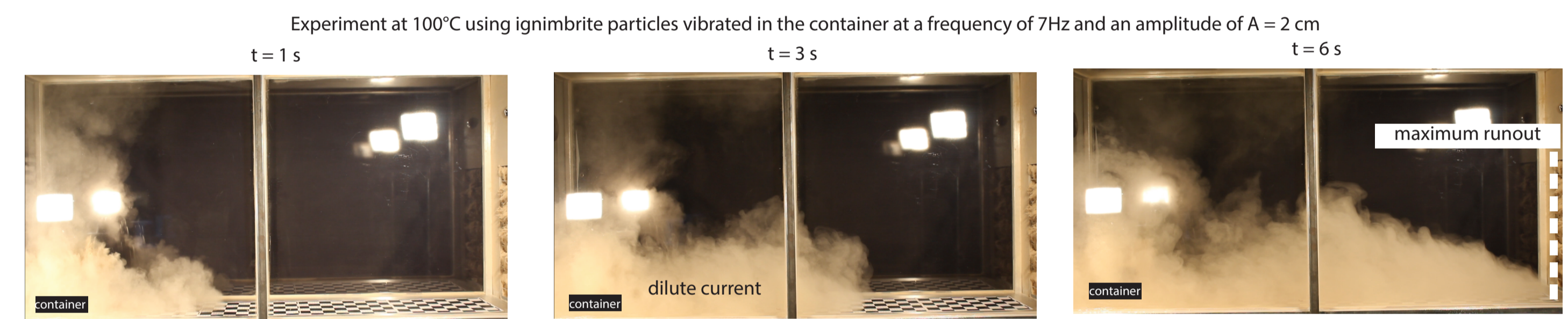
Gueugneau V., Kelfoun K., Druitt T. (2018) Investigation of surge-derived pyroclastic flow formation by numerical modelling of the 25 June 1997 dome collapse at Soufrière Hills Volcano, Montserrat, Bulletin of Volcanology, Under review.

2. Experiments

- We have developed an experimental model that reproduces a dilute current in air from a dense granular bed. The experimental apparatus is 2D horizontal channel in which a container filled of granular particles is vibrated vertically. Experiments are then recorded by a regular, a thermal, and an high speed camera.



- The experiment exhibits a mechanism of dilute flow formation by forced incorporation of air into the dense part by vibrations. The air is aspirated into the granular bed during dilatations, and expelled during the contraction phases. A part of the particles are then sustained by the turbulent expelled air and forms a mixture of gas and particle that transforms into a dilute current :

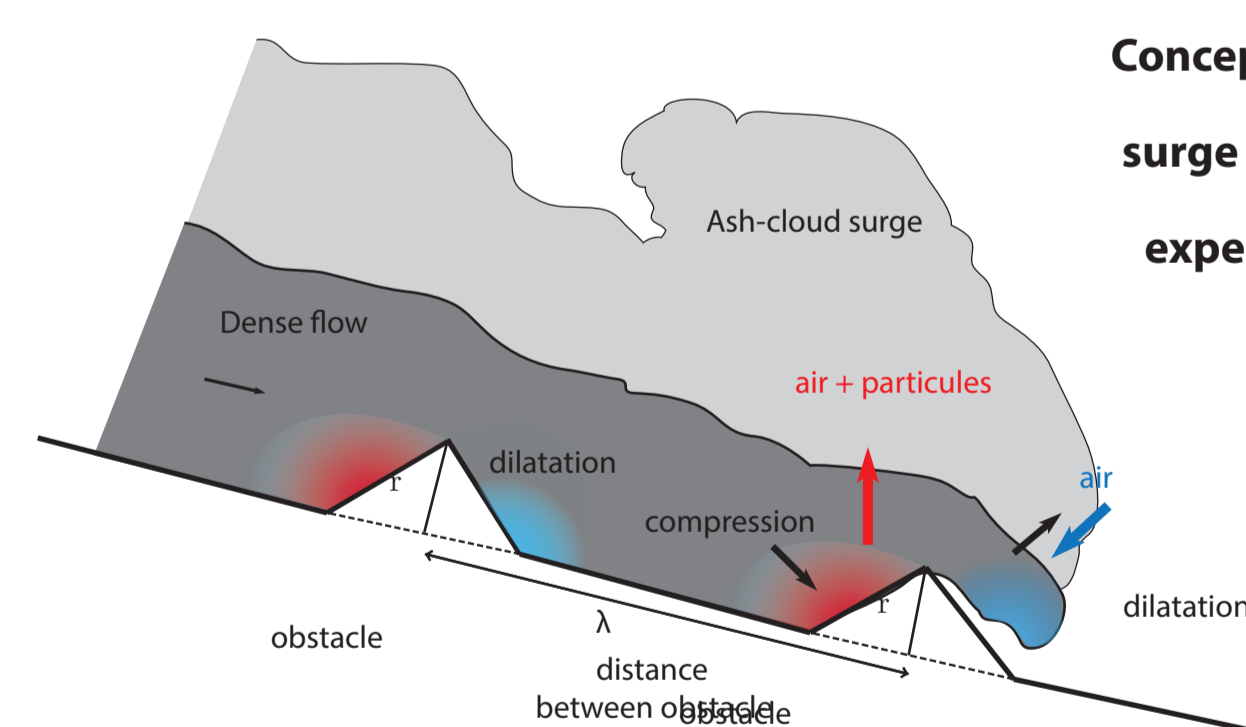


- By measuring the properties of the experimental currents we are able to establish the mass flux generated by the vibration mechanism, and correlate it with the properties of the dense flow :

- $\phi_m = c_2 (u - u_0)^{1.5}$ **theoretical** where u is the dense flow velocity and u_0 is a velocity threshold

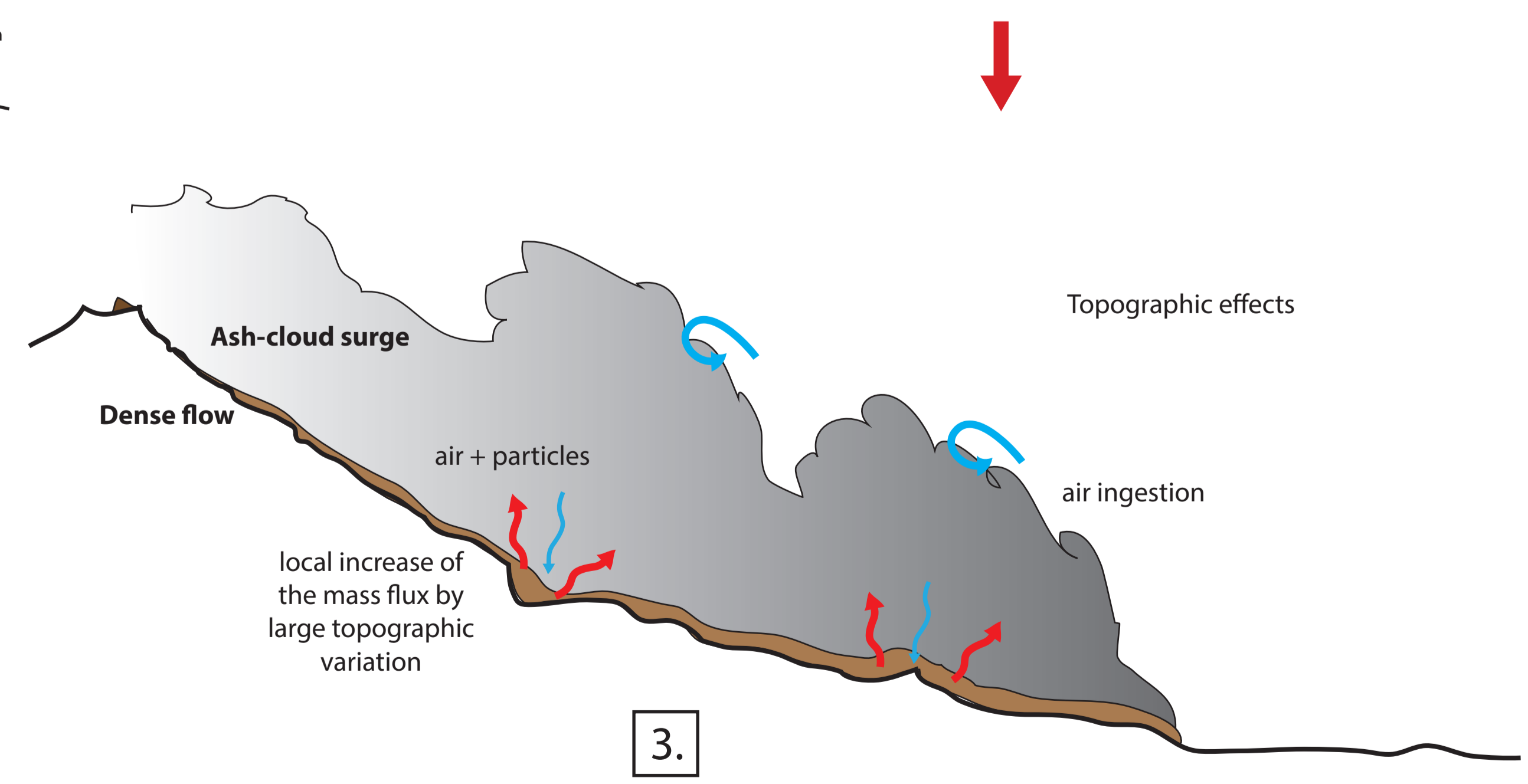
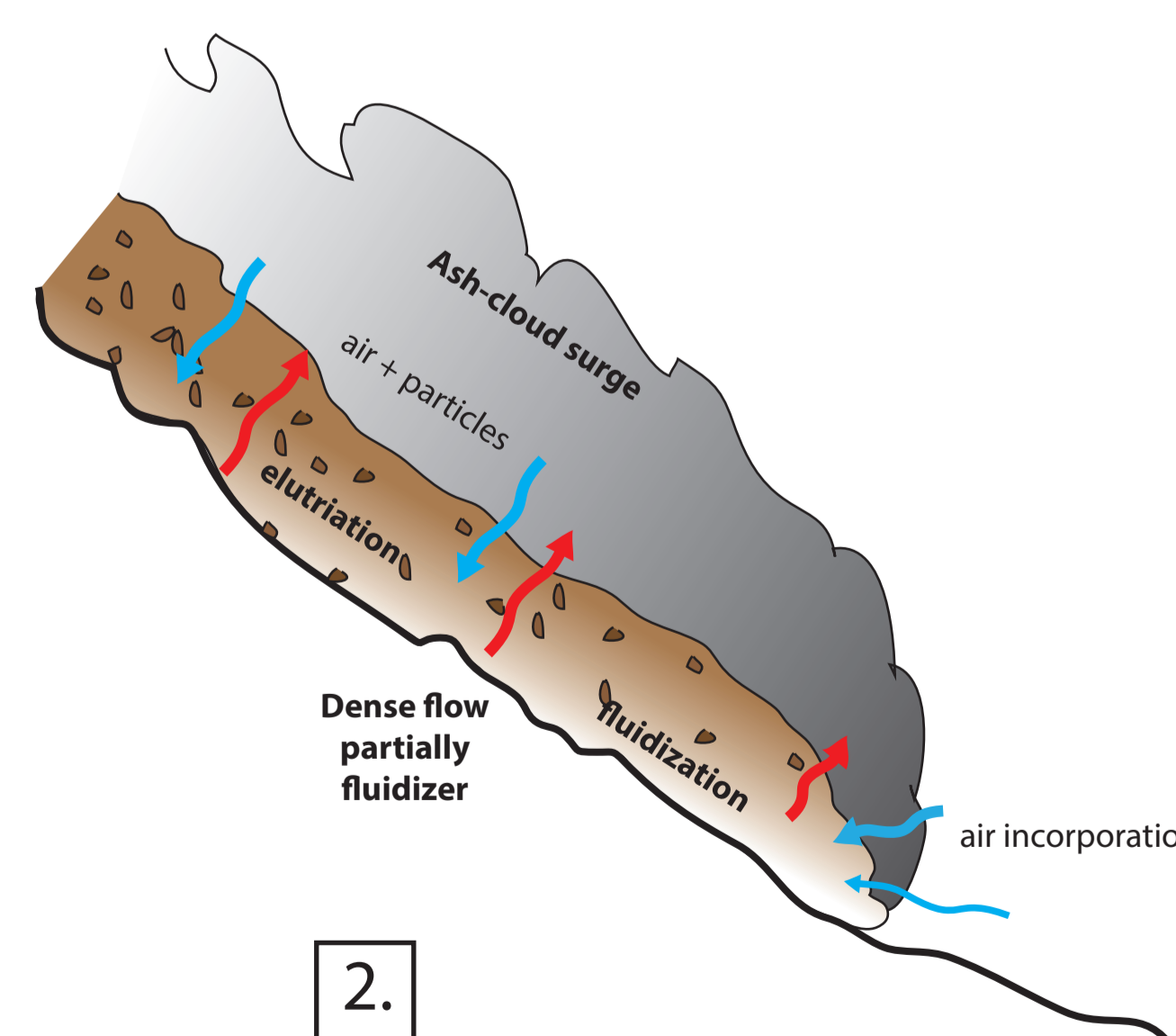
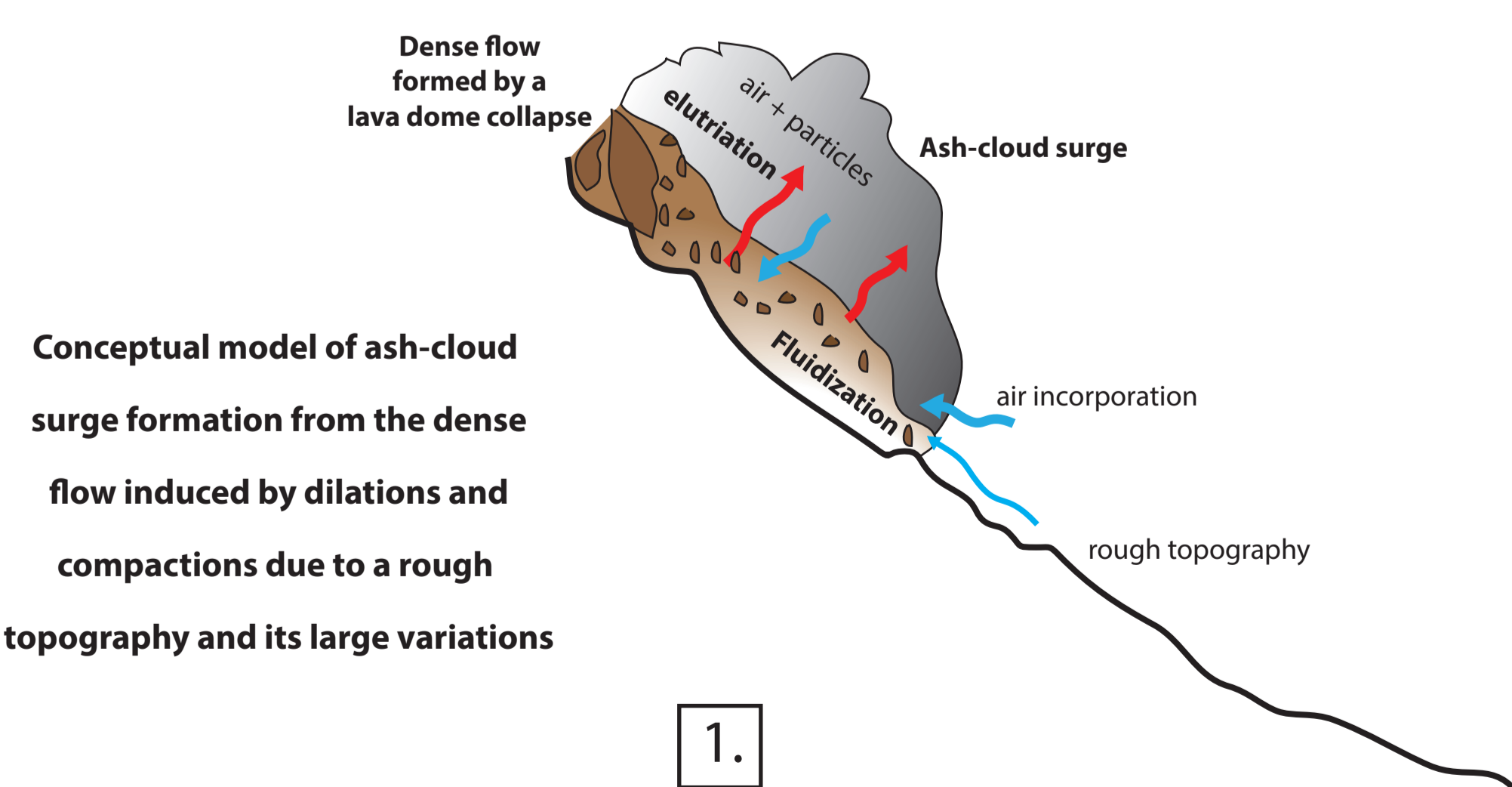
3. Conceptual model

- The mass flux obtained with the experimental model is similar to the empirical law of the numerical model and could be explained. In both cases, the mass flux is a function of the dense flow velocity and very sensitive to the topography.
- The vibration concept is extrapolated to the natural system by correlating the vibration of the container to the roughness of the topography: succession of topographic obstacles is comparable to the succession of vibration



Conceptual model of ash-cloud surge formation, coming from experimental and numerical models

- During dilatation phases, air is ingested into the dense flow and subsequently fluidized it partially. During compaction phases, the gas is released from the dense flow and carries fine particles with it to form a turbulent dilute upper level. Repetition of obstacles and large topographic variations constitute the ash-cloud surge.



Conclusion

The proposed physical model of formation of a dilute pyroclastic surge from a pyroclastic flow has been tested numerically and experimentally. Results show that this physical model seems accurate to reproduce block-and-ash flows and their overriding ash-cloud surge.

- Our numerical model using empirical law is realistic and can reproduce typical flows like SDPFs
- Results of the experimental model exhibit a mechanism that can explain this physical model
- Extrapolation of this mechanism to the pyroclastic density currents gives an explanation of the ash-cloud surge formation that could significantly improve the accuracy of the model

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