Stepping into the Flow: Deciphering the Influence of Topographic Steps on the Dynamics and Hazards of Pyroclastic Density Currents

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1. Abstract

Concentrated Pyroclastic density currents (PDCs) achieve extensive runouts due to two main processes. First, fragmentation-induced fluidization (FIF) occurs, which is a fluidization process caused by the widening of the grain-size distribution. Second, these currents undergo further compaction when they encounter changes in elevation or 'steps' in the landscape (step-induced compaction (SIC)). These topographical steps, found on a broad range of slopes on volcanoes (>30° to <5°) result from the erosion of lava flows. The fluidization of the concentrated basal layer and subsequent elutriation of ash that feeds the upper ash-cloud surge, consequently amplifies the flow's runout distance and increases the associated hazards.

2. Introduction

Fatalities from volcanic eruptions in the past decades have been largely related to the propagation of concentrated PDCs, such as block-and-ash flows, which form by gravitational collapse of volcanic domes or perched tephras located on steep slopes (i.e. Volcán de Fuego,).

Topographic steps exist on Volcán de Fuego on both steep (Fig.2) and shallow slopes (Fig.3) and may have impacted the BAFs produced on June 3 2018 (Charbonnier et. al., 2023, Naismith et al., 2019).

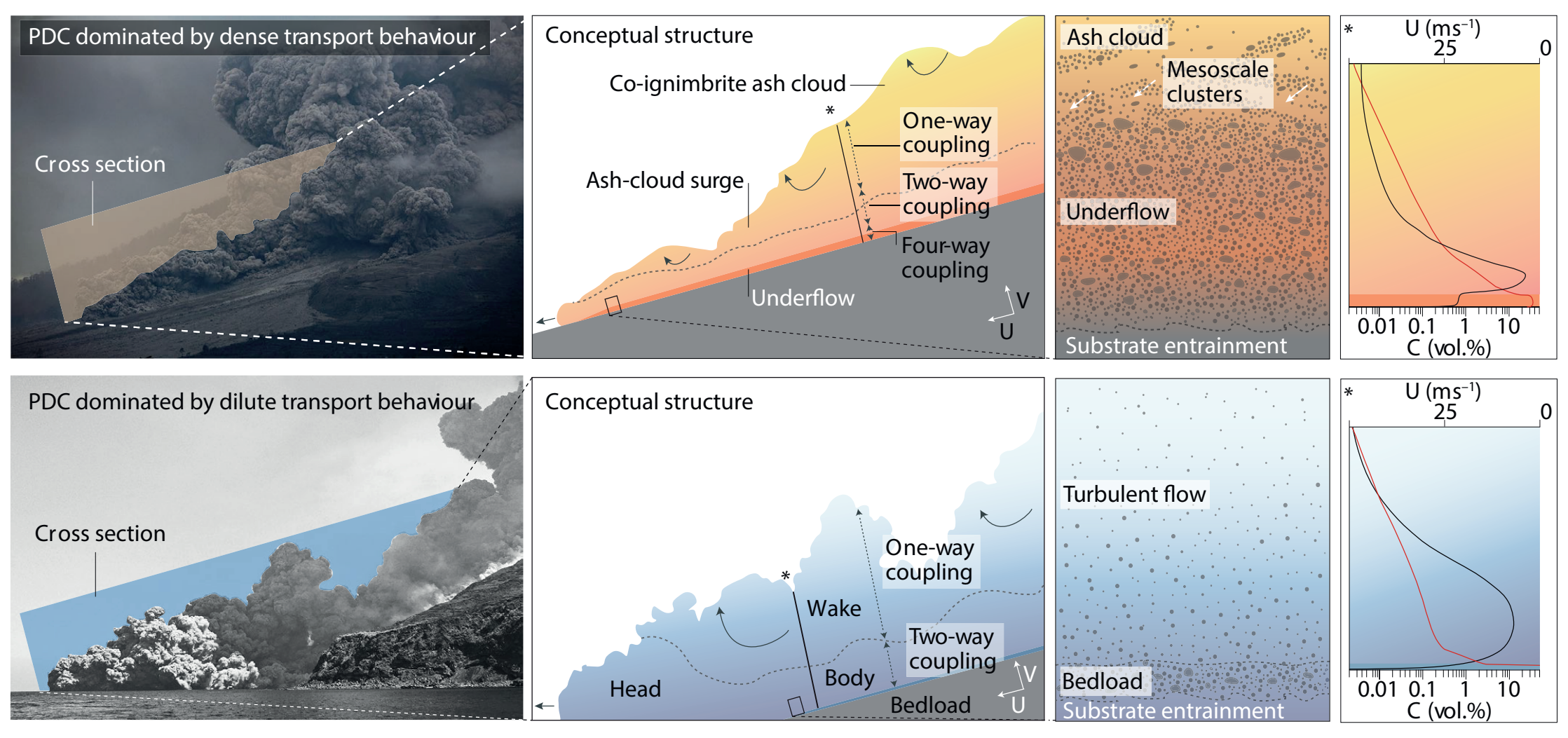

Fig.1: Concentrated and dilute pyroclastic density currents (Lube and Breard et al. 2020).

Fig.2: Visualisation of the Upper 4 km of Las Lajas barranca at Volcán de Fuego prior and post 3/6/2018 eruption.

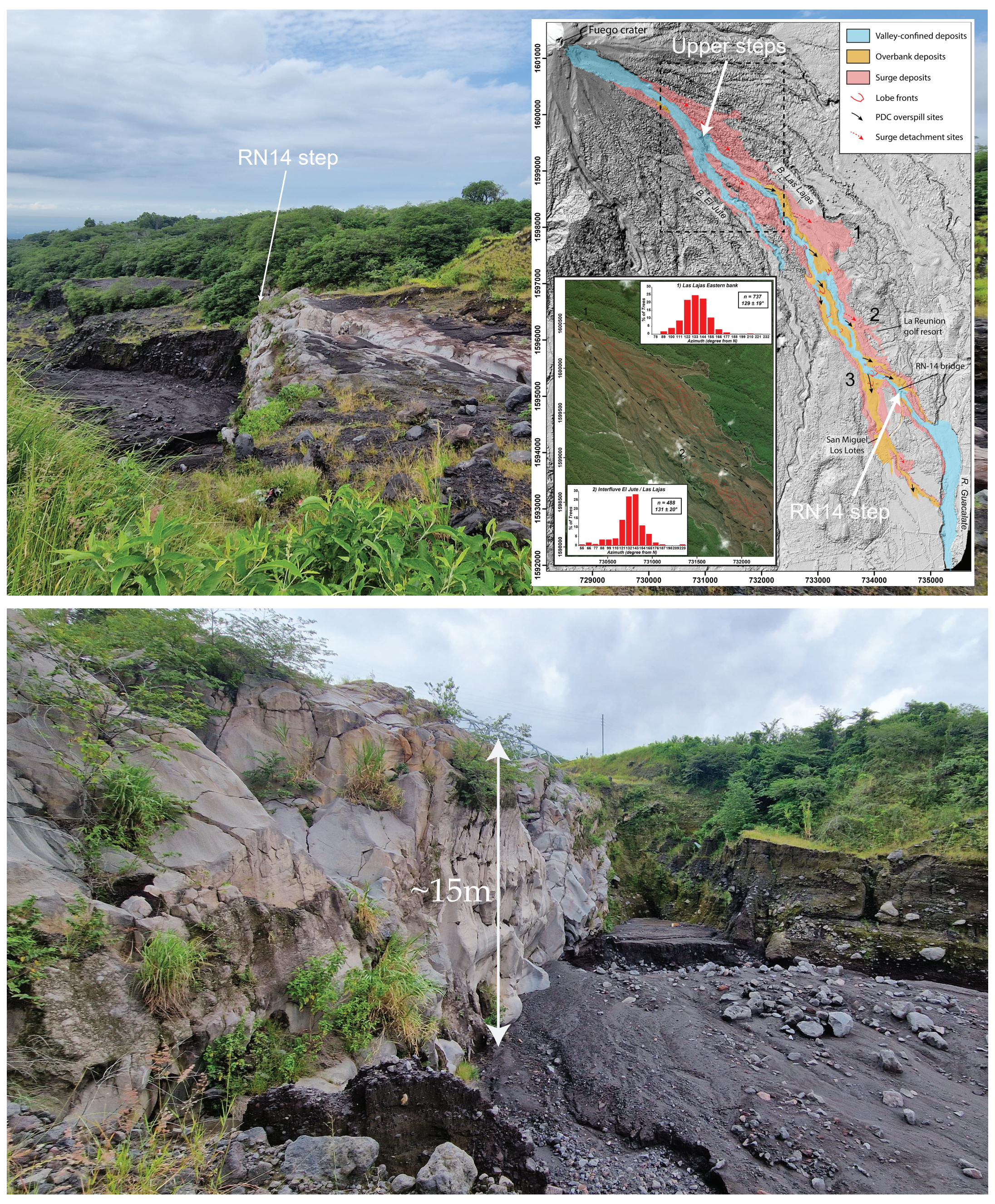

Fig.3: Pictures of the ~15m step in the Las Lajas valley of Volcan de Fuego. The insert map shows the June 3rd 2018 PDC deposits from Volcán de Fuego by Charbonnier et al. (2024) with the topographic steps.

How do topographic steps impact the behaviour of concentrated PDCs?

3. Methods

- 2D multiphase flow simulations using the MFIX solver (Table 1, Fig.4) to simulate coupled two-phase flows in a continuum framework.
- Solving mass, momentum and energy equations for fluid & solid phases

Parameter	Value
Particle sizes	200×10⁻⁶ m (99 wt.%) and 16×10⁻⁶ m (1 wt.%) (added fine ash to visualize elutriation)
Solid density	2500 kg/m3
Input temperature of gas and solid	320°C
Specific heat of solid	1000 J/ Kg K
Input concentration	0.6
Maximum packing concentration	0.8
Inlet velocity	10 m/s (parallel to slope) for gas and solid phases
Friction coefficient	0.7
Fluid property	Air (compressible fluid)
Mesh resolution	Square cells of 0.5 m² (with cutcells on boundaries)
Flow thickness/step height (Hf/Hs)	2–0.2
Solid Shear stress	Kinetic Theory and Guo and Boyce (2021) friction model (using mu(I)-rheology)
Gas-particle drag law	Gidaspow

Table 1: Input parameters used in the MFIX multiphase flow solver. Input temperature was chosen following Risica et al . (2022)

4. Anatomy of a (Pyroclastic) Fall

Using multiphase flow simulations, we explore the granular and fluid dynamics of a concentrated hot granular mixture moving across a step in the topography (Fig.4). The chosen grain-size distribution makes the permeability equivalent to that of BAFs at Fuego.

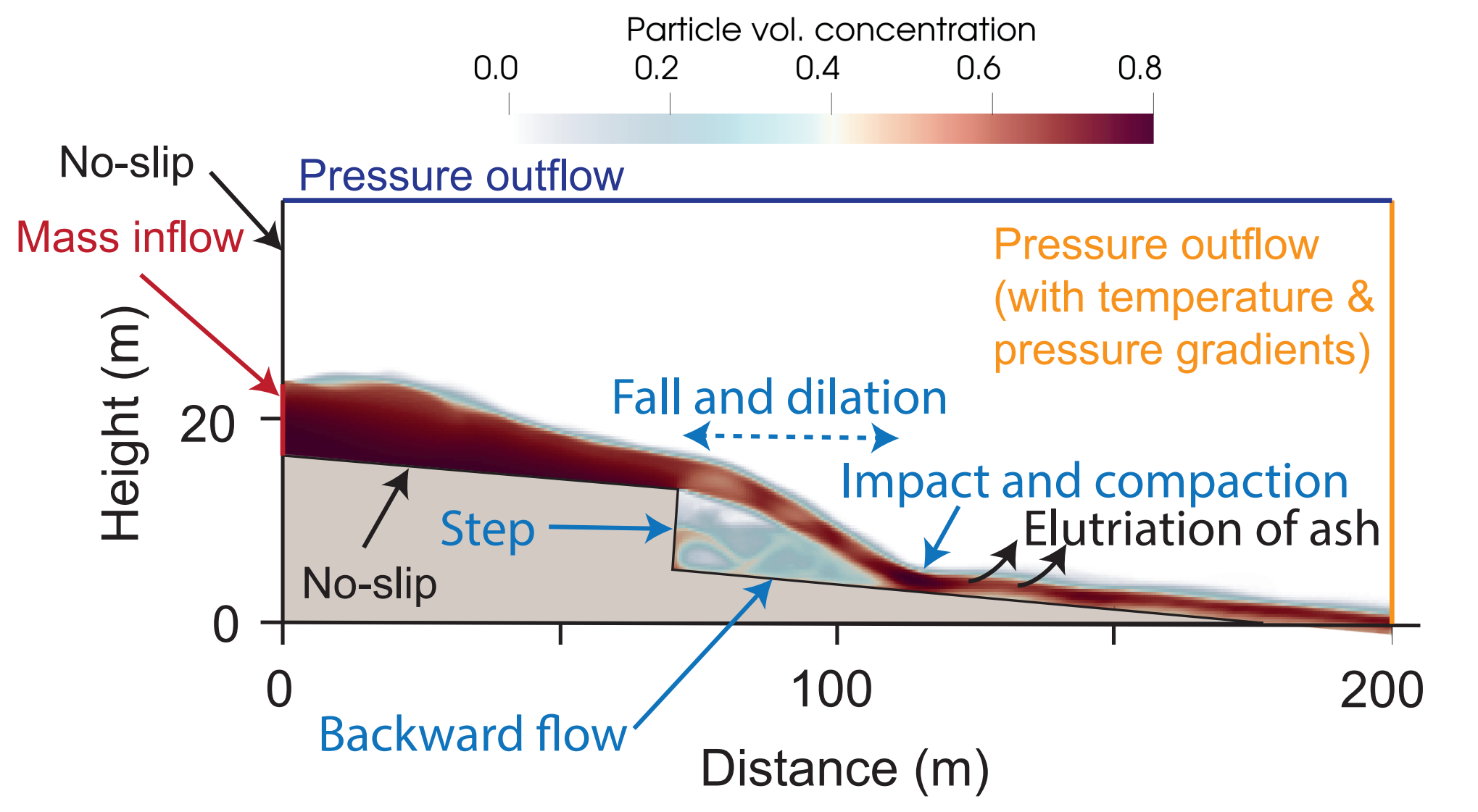

Fig.4: MFIX simulation of a concentrated PDC moving across a 15 m high step (Hf/Hs~0.5) and boundary conditions used in the multiphase model.

In the following section, we illustrate PDCs' behaviour on various slopes and with different ratios of flow thickness to flow height (Figs.5-9).

5. Flow Fields and Kinematics

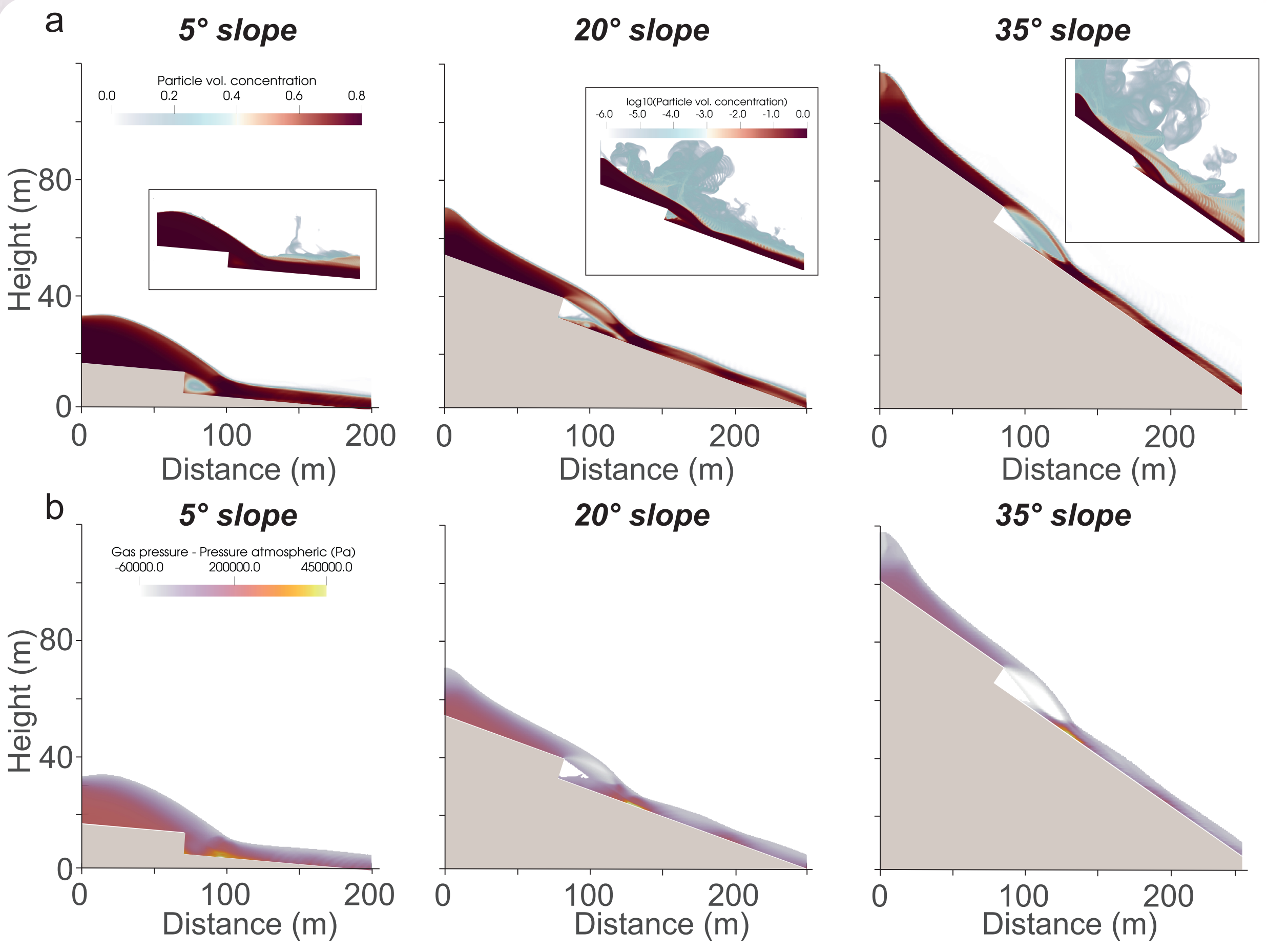

Fig.5: Time-averaged (over 10 s) particle volumetric concentration (a) and pore-fluid pressure (b). MFIX simulations were run on three slopes with and without a topographic step with size ratio Hf/Hs ~ 1.

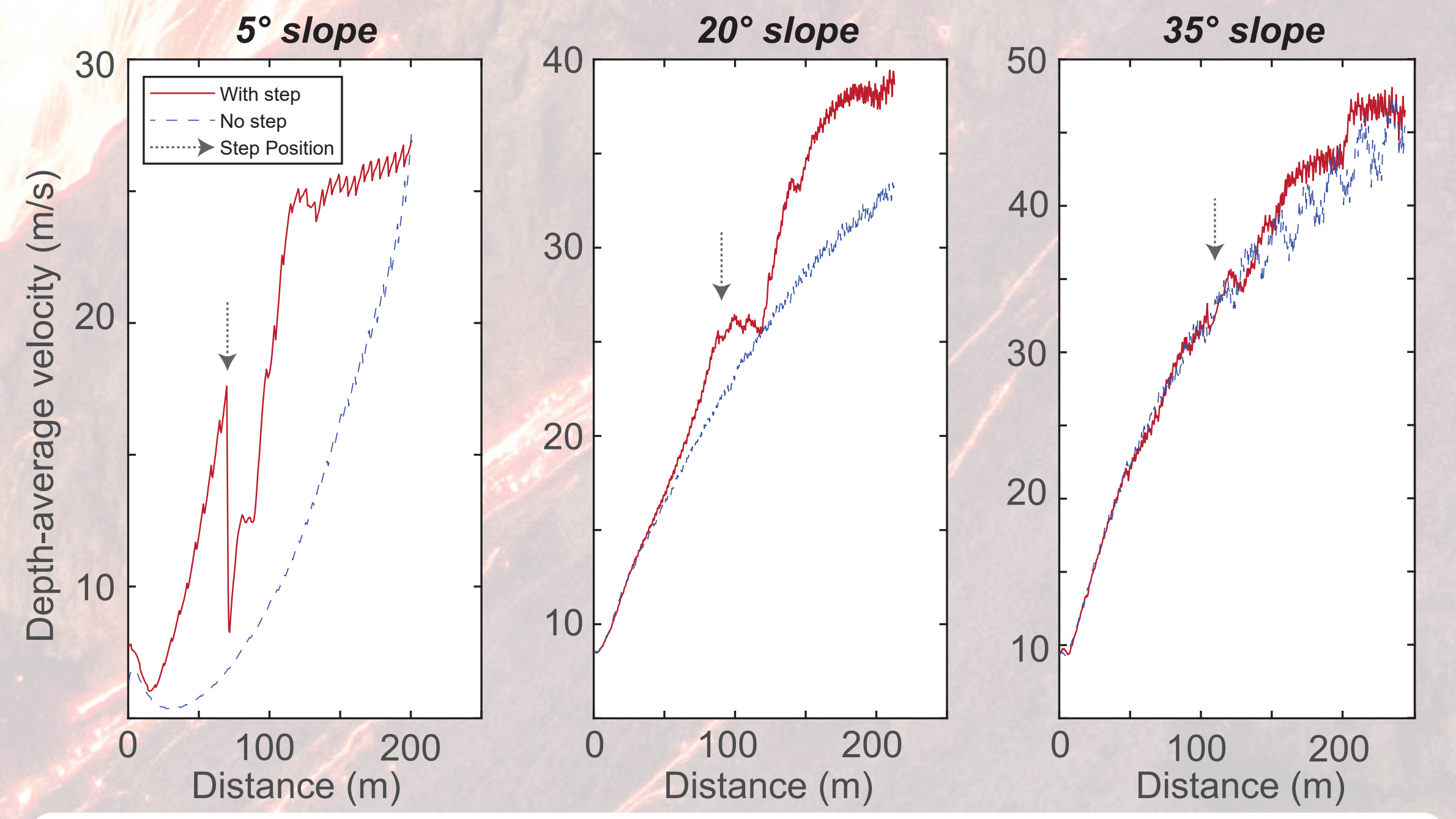

Fig.6: Depth- and time-averaged (over 10 s) flow velocity along the runout for MFIX simulations on three slopes with and without a topographic step with size ratio Hf/Hs ~ 1.

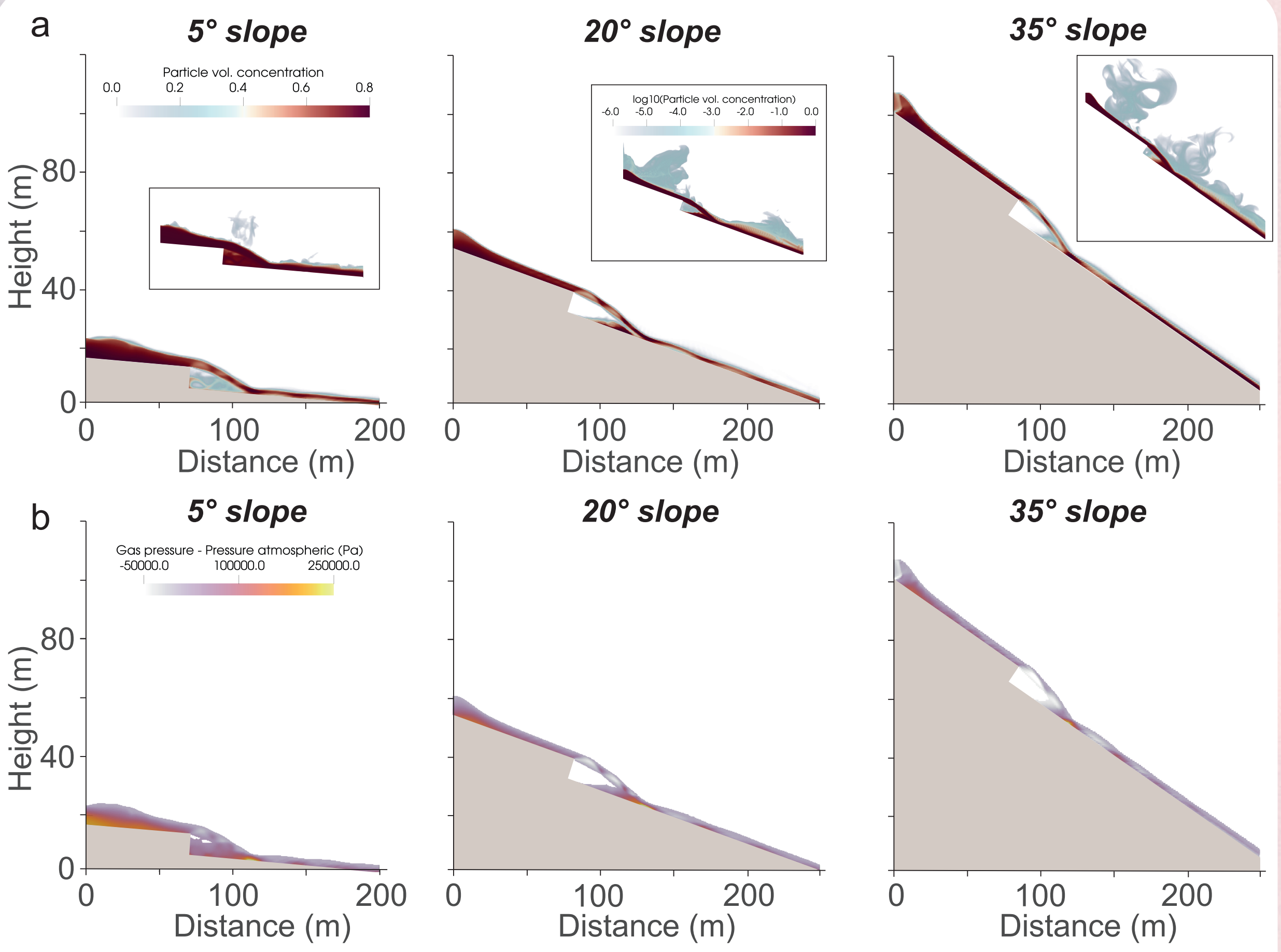

Fig.7: Particle volumetric concentration (a) and pore-fluid pressure (b). MFIX simulations were run on three slopes with and without a topographic step with size ratio Hf/Hs ~ 0.2-0.4.

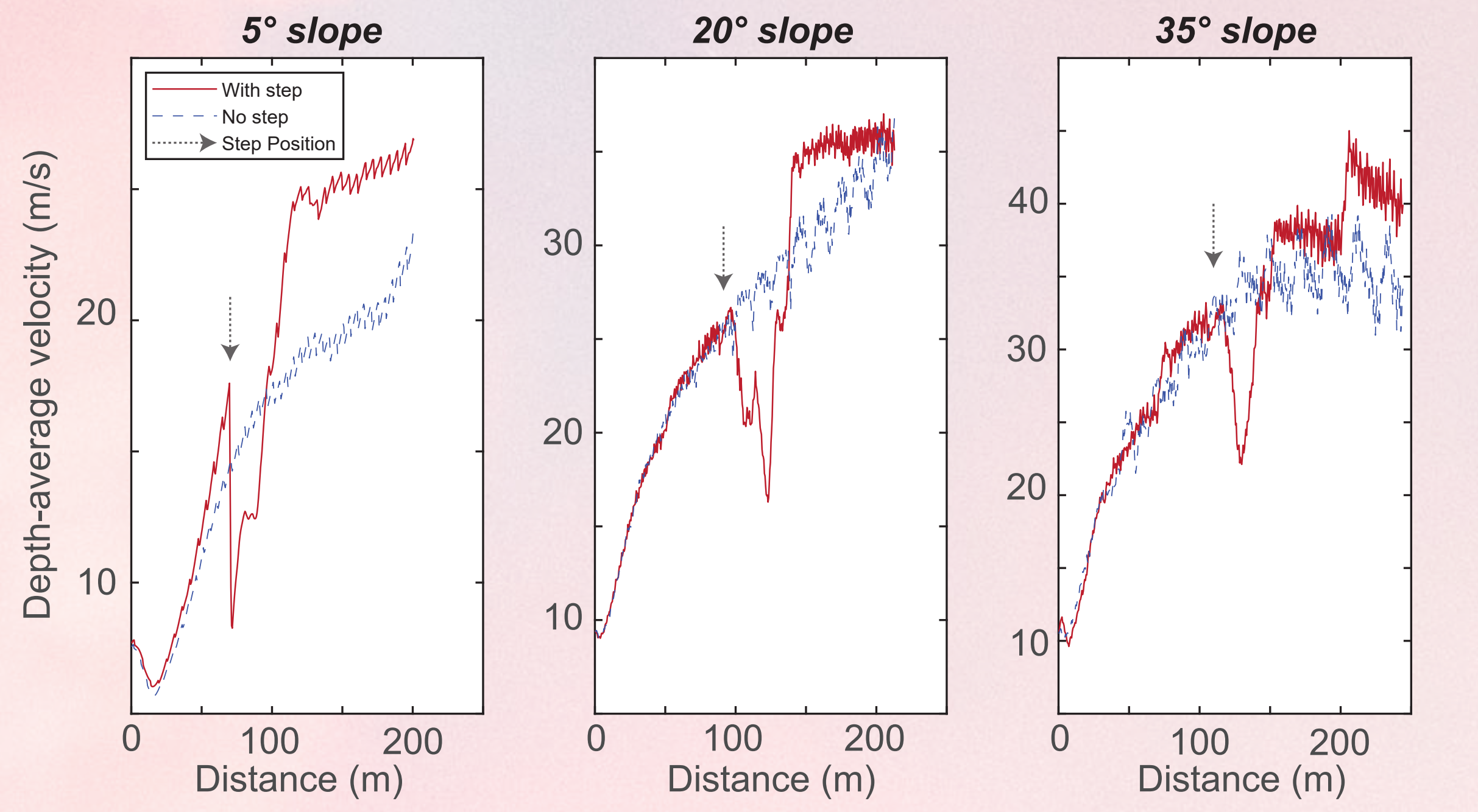

Fig.8: Depth- and time-averaged (over 10 s) flow velocity along the runout for MFIX simulations on three slopes with and without a topographic step with size ratio Hf/Hs ~ 0.2-0.4.

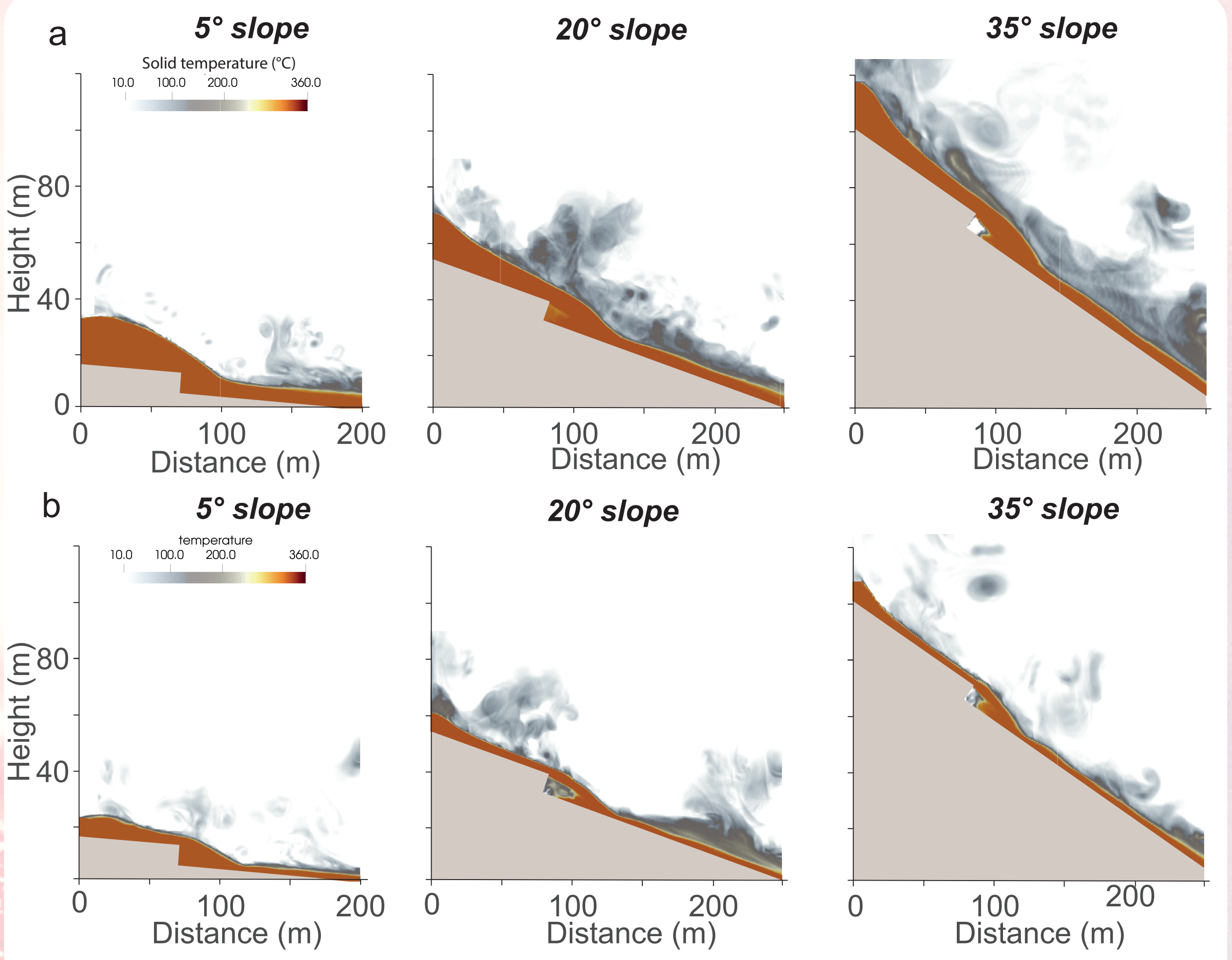

Fig.9: Time-average (during 10 s) temperature of the solid phase for simulations with a flow at inlet of 33 m (a, Hf/Hs ~ 1) and 13 m (b, Hf/Hs ~ 0.2-0.4) of thickness. The grey color represents the colder ash elutriated. Note the temperature of the concentrated basal layer does not change with distaance due to negligible air entrainment.

6. Pore Pressure Feedback in BAFs

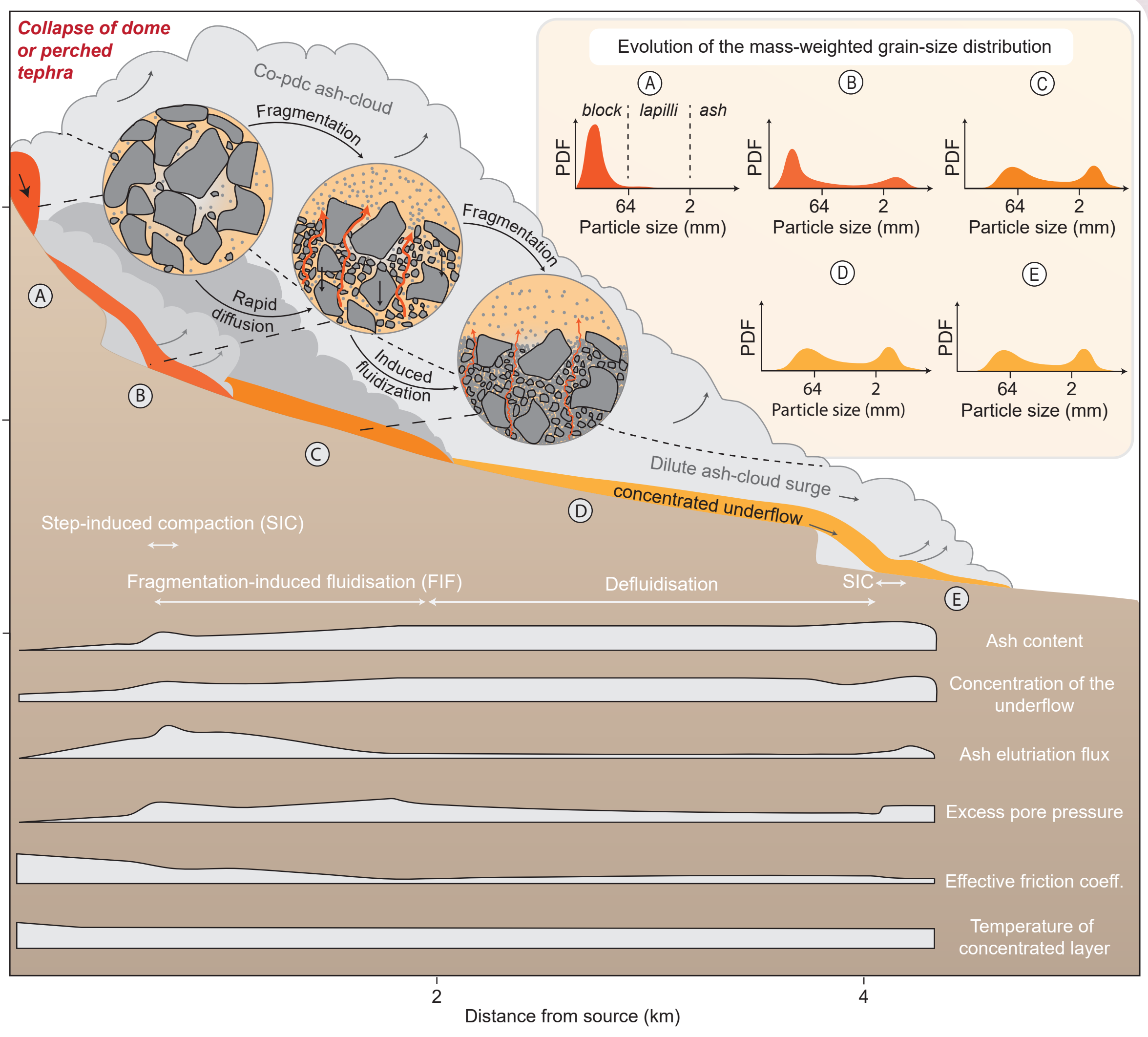

Fig.10: Pore pressure feedback operating in BAFs, which is driven by the step-induced compaction (SIC, Kelfoun and Gueugneau, 2021 and this study) and the fragmentation-induced fluidization (FIF, Breard et al. 2023).

7. Conclusions

- Topographic steps on steep to shallow slopes, as gentle as 5 degrees, can enhance the mobility of the concentrated layer in BAFs due to (re)fluidization and do not contribute to noticeable cooling of the concentrated mixture.
- The processes of fragmentation-induced fluidization (FIF) and step-induced compaction (SIC) create a pore-pressure feedback mechanism (Fig.10) that extends the runout and increase the hazard of concentrated PDCs.
- Ash elutriation, from the basal layer to the overriding ash-cloud surge, is particularly significant on steep slopes and just after the PDCs move over a step, intensifying the density of the ash-cloud and consequently its potential hazard.

Step simulation videos are there!

Check my other work!

8. References

Keen to work together? Contact me at eric.breard@ed.ac.uk

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