Geophysical Research Abstracts
Vol. 15, EGU2013-11826, 2013
EGU General Assembly 2013

Morphology and dynamics of piercement structures: an integrated laboratory and numerical study

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Piercement structures are numerous in many geological settings, including pockmarks, mud volcanoes, hydrothermal vents, maar-diatreme volcanoes, volcanic conduits in stratovolcanoes, and kimberlite volcanoes. These piercement structures exhibit various shapes, from sub-vertical pipes piercing through the country rock to open and wide conduits, such as volcanic craters resulting from volcanic explosions (e.g., Mount Pinatubo). In this contribution, we present an integrated laboratory/numerical study to constrain the dynamics of piercement structures and unravel the processes that control their morphology.

The laboratory experiments consist of a Hele-Shaw cell filled with a pack of cohesive fine-grained granular material, at the bottom of which a volume V_t of pressurized air is injected at high velocity. As a result of air injection, a piercement structure develops through the medium, and its morphology and evolution is monitored with an ultrafast camera. We varied systematically the thickness of the model h and the injection pressure P, and show that two morphologies of piercement structures develop: vertical and V-shaped conduits. In a phase diagram with h and P as horizontal and vertical axes, respectively, the two morphologies group into two distinct domains separated by a transition line of critical slope P/h. This phase diagram shows that vertical conduits form for high P/low h, whereas V-shaped conduits form for low P/high h.

2D numerical simulations are performed using Sage, a finite volume hydrocode developed at the Los Alamos National Laboratory. We ran simulations and varied systematically the input pressure P and the strength of the country rock T. Our simulations produced three types of piercement structures: vertical, sub-horizontal and V-shaped conduits. In a phase diagram with T and P as horizontal and vertical axes, respectively, the three morphologies group into distinct domains separated by transition lines of critical slopes P/T. Vertical conduits form for high P/low T, whereas V-shaped conduits form for low P/high T. Sub-horizontal conduits form at intermediate values of P and T.

Stress maps computed from the simulations show that the V-shaped/sub-horizontal and vertical conduits do not correspond to the same dynamics. Vertical conduits form when the country rock behaves in a plastic manner, i.e. like unconsolidated rock. In contrast, V-shaped and horizontal conduits form when the country rock behaves mostly in an elastic manner, and the conduit corresponds to a fracture-like feature.

The close similarities between our laboratory and numerical results allow us to define a new dimensionless parameter, the energy density $I_e = V_t P/h^3 T$, which corresponds to the ratio between the input energy and the potential energy for fracturing of the country rock. Our results show that I_e is a primary controlling factor for the dynamics of piercement structures: when I_e is small, the country rock remains competent, and the piercement proceeds like fracturing, leading to V-shaped or horizontal conduits. In contrast, when I_e is large, the country rock looses its competence and behaves like unconsolidated rock, and the piercement structure develops vertically.