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Cyclicity in slug-driven basaltic eruptions: insights from large-scale analogue experiments

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Basaltic eruptions commonly exhibit cyclical or pulsatory behaviour. Strombolian eruptions are typically discrete and rhythmic, with return interval of minutes-to-hours; lava fountains may fluctuate over similar, or shorter, timescales. In both cases the cyclicity results from the separation of gas from the magma, and its localization into discrete gas slugs or gas-rich packets. We report analogue experiments which model the fluid dynamics of slug-driven basaltic eruptions. Experiments were conducted in liquid-filled vertical pipes at a range of scales, from 0.02 to 0.2 m in diameter, and 2 to 13 m in height, allowing us to investigate Reynolds numbers $10^{-3} < Re < 10^{5}$, encompassing the natural range for volcanoes. The dynamics of both discrete gas slugs (Taylor bubbles) and continuous sluggy flow were quantified. A significant novelty of this study is that we explore the role played by the boundary conditions at the top and bottom of the conduit, which may be either closed (zero flux) or held at constant pressure. This setup allows us to mimic plugged or open vent, and the influence of a magma chamber. Our study combines the direct observation of in-conduit fluid dynamic processes with measured pressure variations inside the conduit.

Our results demonstrate that, when discrete gas slugs are injected, plugging the vent has a strong influence on the development of overpressure in the system, and on the potential for the system to manifest cyclic behaviour. When gas is injected continuously, with constant pressure boundaries at the top and bottom of the conduit, the system spontaneously self-organizes into rhythmic sluggy flow when the injection rate exceeds a critical value. In both cases we find that the capacity of the system to sustain well-formed, discrete slugs depends strongly on the Reynolds number of the flow. Well-formed Taylor bubbles – which have a smooth hemispherical cap, occupy the width of the conduit, and ascend relatively slowly – only form when the liquid column is stagnant, or is flowing in the laminar regime. Slugs that rise through turbulent liquid are poorly-formed and, at the extreme, ascend as highly-turbulent gas-rich packets; these occupy less of the conduit width and therefore ascend more rapidly than true Taylor bubbles. A major factor influencing the turbulence in the liquid is the separation between slugs; when slugs are closely spaced, the wake of one slug tends to disrupt the next. At the onset of eruption, therefore, the tendency is for poorly-formed, fast-moving slugs to catch up with the well-formed, slow-moving lead slug, increasing the potential for an impulsive, explosive onset. During sustained eruption, lower gas fluxes lead to lower-frequency, higher amplitude fluctuations in eruption rates, whilst higher gas fluxes lead to higher-frequency, lower amplitude fluctuations. The spectrum of natural activity, from discrete Strombolian eruptions to sustained, pulsatory lava fountaining can, therefore, be characterized as a change in the behaviour of the separated gas phase in the conduit.