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## An Experimental Study of Volcanic Tremor Driven by Magma Wagging

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Volcanic tremor is a feature of most explosive eruptions. Pre-eruptive tremors can be characterized by monotonic increases in the maximum frequency, frequency bandwidth and amplitude that are correlated with increases in gas flux from a volcanic vent. An enigmatic feature of this behavior is that is observed at volcanoes with widely ranging conduit geometries and structures. Accordingly, the "magma wagging" model introduced by [1] and extended by [2] hypothesizes an underlying mechanism that is only weakly-sensitive to volcano architecture: Within active volcanic conduits, the flow of gas through a permeable foamy annulus of gas bubbles excites and maintains an oscillation of a central magma column through a well-known Bernoulli effect. Furthermore, this oscillation has spectral properties that evolve depending on annulus thickness and permeability and the total flow of gas.

In this thesis, we carry out a critical experimental test of the underlying mechanism for excitation. We explore the response of columns with prescribed elastic and linear damping properties to forced air annular airflows. From high-speed video measurements of linear and orbital displacements and time series of accelerometer measurements we characterize and understand the excitation, evolution, and steady-state oscillating behaviors of analog magma columns over a broad range of conditions. Where the time scale for damping is much longer than the natural period of free oscillation, column oscillation is continuously excited by relatively short period Bernoulli modes through a reverse energy cascade. We also identify three distinct classes of wagging: i. rotational modes that confirm predictions for whirling modes by [3]; as well as ii. mixed-mode; and iii. chaotic modes that are extensions to previous studies[1,2]. Our results show that rotational modes are favored for symmetric, and high-intensity forcing. Mixed-mode responses are favored for a symmetric and intermediate intensity forcing. Chaotic modes occur in asymmetric or low intensity forcing. To confirm and better understand our laboratory results and also extend them to conditions beyond what is possible in the laboratory we carry out two-dimensional numerical simulations of our analog experiments.

Taken together, results from our experimental and numerical studies can be extended to a natural system to make qualitative predictions testable in future studies of pre- and syn-eruptive volcano seismicity. Far before an eruption, the total gas flux is low and magma wags in a chaotic mode no matter what is the spatial distribution of the gas flux. At a pre-eruptive state, as gas flux increases,

if the distribution of gas flux is approximately symmetric, we expect a transition to mixed and possibly rotational modes. During an eruption, fragmentation and explosions within the foamy annulus can cause spatial heterogeneity in permeability resulting in non-uniform gas flux that favors chaotic wagging behavior.

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