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Volcanic tremor caused by flow-induced oscillation of a magma-filled dike

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Volcanic tremor (VT) is known to be long-period and long-duration ground motion generally observed during or before eruptions. Majority of VTs show an emergent onset and, when accompanied with eruptions, an exponentially growing phase in amplitude is typically observed (Konstantinou and Schlindwein 2002; McNutt and Nishimura 2008). This characteristic suggests that VT is manifestation of self-oscillation, in which a persistent steady forcing excites an eigen oscillation of a system and the amplitude exponentially grows until a nonlinear process leads to a limit cycle. In volcanic settings, a steady magma flow through an underground conduit may cause flow-induced self-oscillation of bedrocks, and this is the idea first presented by Julian (1994). In the case of the collapse of Tacoma Narrows bridge, which is known to be caused by flow-induced oscillation, the vibrating bridge can be modeled by an elastic plate placed parallel to an infinite flow. Here we consider a reversed setting: a fluid-flowing thin layer in an infinite elastic body. This system is also unstable if the flow speed is high enough, and may be a generation mechanism of some VTs.

We consider a fluid-flowing plane layer sandwiched between two semi-infinite elastic bodies, expanding Julian's idea to a more general elastodynamic model (for details, see Sakuraba and Yamauchi 2014 to appear in *Earth, Planets and Space*). The eigen oscillation that should be excited in this self-oscillation model is an elastic surface wave. Therefore, we solve the Navier-Stokes equation linearized about a laminar flow with the boundary condition that can maintain a surface wave traveling along the layer. We succeeded in obtaining a complex phase speed of the surface wave as a function of wavenumber (and some parameters) using a shooting method, and found that a relatively slow magma flow could lead to instability in which the imaginary part of the phase speed is positive. Remarkably, the most unstable mode exhibits an antisymmetric (flexural) deformation, which has not been discussed in previous similar studies (Balmforth, Craster and Rust 2005; Dunham and Ogden 2012). The unstable mode is identical to two parallel Rayleigh waves traveling against the basic magma flow. The instability can be understood as acceleration of nearly circular particle motion of the Rayleigh wave due to viscous drag of the main laminar flow. As the critical flow speed giving a neutrally stable state decreases in inversely proportional to wavelength, instability will occur with the largest possible wavelength, which could be several kilometers and produce an oscillation period of around 1 second. In that case, the critical flow speed can be reduced to less than 1 m/s when the magma is basaltic. As the magma flow speed in a dike will not exceed several meters per second, there would be a lower bound in the critical wavelength, producing a period of 0.1 second. Thus our model naturally explains typical periods of 0.1-1 seconds observed on volcanoes. Our model also explains typical timescales of the linearly growing phase in some VTs.