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Non-isothermal propagation and arrest of km-sized km-deep sills at calderas

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Caldera unrest is often attributed to magma intrusion into a sill. In several cases, like Fernandina and Sierra Negra, Kilauea south caldera, and Campi Flegrei, the sill is km-sized and km-deep. A few questions related to sill emplacement at calderas seem still unanswered: how do sills form and spread, why can magma propagate for kilometers without solidifying, and why do ground deformation data rarely, if ever, detect sill propagation.

When considering isoviscous incompressible magma intruding at a constant rate into a homogeneous half-space under non-isothermal conditions and forming a circular sill, mathematical modeling includes: a fluid-dynamic equation (relying on lubrication theory), a fracture propagation criterion, an elasticity equation (link between fluid overpressure and sill opening), and a heat-transfer magma-solidification equation. As already known, a small lag must exist between the fluid (magma) and fracture fronts, because of the large pressure gradients required to drive a viscous liquid into a narrow opening.

We show that the free-surface effects on the elasticity equation are negligible, provided that depth-to-radius is smaller than one, as at the above-mentioned calderas; thus, spreading occurs like in an infinite medium. Taking advantage of published studies on hydraulic fracture propagation, first we consider isothermal spreading, as governing equations admit approximate analytical solutions for sill radius, sill opening, fluid overpressure and lag size. Next we consider non-isothermal spreading of an isoviscous incompressible single-component magma, which is initially at its solidification temperature.

We show that if the sill is at least a couple of kilometers deep and the product of viscosity and injection rate is sufficiently small, then the lag between the magma and fracture fronts is much smaller than the sill radius during most of the propagation process; as a consequence, propagation velocity is practically unaffected by the lag, except for the initial phase. Because of the way solidified magma thickness and sill opening grow with distance from the tip in the near-tip region, zero-lag non-isothermal spreading would stop after travelling unrealistically short distances, unless magma intrudes rocks that are as hot as the solidification temperature or has unrealistic overpressures. Thus, we consider how the lag might affect the sill maximum size, by preventing solidification at the tip. We compute non-isothermal propagation velocity and the solidified magma thickness by adapting the approach originally developed by Dontsov (2016) for the zero-lag propagation of penny-shaped hydraulic fractures with leak-off; then we relate the lag size to the propagation velocity using the isothermal solutions.

We find that the lag plays a fundamental role in postponing the sill arrest by magma solidification,

because heat exchange between the magma and the hosting rock is effective only behind the lag, where the magma has some finite thickness and sill opening grows with distance from the tip faster than thickness of solidified magma.
As for ground deformation, we show that its pattern does not change appreciably over time if the final sill radius is smaller than 2 to 3 km: this explains why it is usually attributed to the inflation of a stationary source.