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Analytical model of surface uplift above axisymmetric flat-lying magma intrusions: Implications for sill emplacement and geodesy

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Surface deformation in active volcanic systems reflects the dynamics of magma intrusion and transport at depth. Several analytical models have been designed to calculate the deformation field associated with flat-lying intrusions, such as sills and laccoliths, based on thin elastic plate theory. Nevertheless, the formulations in these models assume that the bending plate is clamped to a rigid foundation at the tips of the intrusions. In other words, the bending of the overburden is restricted upon the intrusion only, which is not realistic in geological systems.

In this contribution, we present a new axisymmetric analytic model of surface uplift upon sills and laccoliths, based on the formulation of a thin bending plate lying on an elastic foundation. In contrast to most former models also based on thin bending plate formulation, our model accounts for (i) axi-symmetrical uplift, (ii) both upon and outside the intrusion. The model accounts for shallow intrusions, *i.e.* the ratio $a/h > 5$ where a and h are the radius and depth of the intrusion, respectively. The main parameter of the model is the elastic length l, which is a function of the elastic properties of the bending plate and of the elastic foundation. The model exhibits two regimes depending on the ratio a/l. When $a/l < 5$, the uplift spreads over a substantial domain compared to that of the intrusion. In contrast, when $a/l > 5$, the uplift is mostly restricted upon the intrusion. When the elastic foundation is very stiff, our model converges towards that of a clamped plate.

We discuss three possible applications of our model: (i) The model can be used to describe sill propagation by introducing a propagation criterion. For realistic values, our model reproduces well the behavior of horizontal intrusions simulated in experiments; (ii) The model can also be used to compute the critical size of saucer-shaped sills. It shows, for instance, that a soft elastic foundation favors the horizontal spreading of sills before they form inclined sheets; (iii) We show that the classical Mogi point source model cannot be used to constrain sill properties from the surface uplift. We thus propose that our model can be used as a valuable alternative to both simple analytical models like Mogi's and more complex numerical models used to analyze ground deformation resulting from sill intrusions in active volcanoes. All in all, our theoretical model appears to be very relevant for understanding key aspects of the mechanics of sill and laccolith emplacement that were not captured in classical models.