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Conditions for detection of ground deformation induced by conduit flow

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On mature andesitic volcanoes, magma can reach the surface through the same path for several eruptions which forms an open volcanic conduit. During its ascent through the conduit, physical properties of the magma as well as flow dynamics evolve. Due to degassing, cooling and crystallization, the magma viscosity increases in the upper part of the conduit inducing the formation of a viscous plug. Here, we perform numerical simulations to quantify the deformation field caused by the emplacement and the evolution of a plug in the conduit. The volcanic conduit is a vertical cylinder embedded in an elastic medium. Magma is considered in first approximation as a Newtonian fluid. Stress continuity between magma flow and elastic crust is considered. The reference state is a Poiseuille flow with a constant viscosity initiated by a fixed pressure gradient between the bottom and the top. The increase of viscosity, due to the emplacement of the plug, is first modelled by a step function only dependent on depth. Plug emplacement causes a ground inflation correlated to a decrease of the magma discharge rate comparing to the reference case. A parametric study shows that surface displacements depend on three dimensionless numbers: (i) the conduit aspect ratio (radius/length), (ii) the length ratio between the plug and the conduit and (iii) the viscosity contrast between the plug and the magma column. Larger displacements and tilts are obtained for the most viscous plugs whatever the size of the conduits. Moreover, for a given viscosity contrast, larger displacements are associated with a critical plug thickness which is not always the thinnest plugs. We also demonstrate that even if most of the vertical displacement or tilt signal is due to shear traction induced by magma flow, a non-negligible amount (>20%) is due to pressurization occurring beneath the plug. By calculating the distance of detection of ground motion, we find that only tiltmeters or GPS located within a few hundred meters from the vent might record the plug emplacement. At the immediate proximity of the vent, plug emplacement might even dominate the deformation signal, in comparison with dome growth or magma chamber pressurization effects. These results can help to constrain the location of geodetic instrumentation on andesitic volcanoes. We then applied our model to two andesitic volcanoes, Soufrière Hills (Montserrat) and Mt. St. Helens (USA), where rapid tilt cycles (over few hours) were recorded during extrusive periods. Considering various plug thicknesses and viscosity contrasts, our flow model can explain part of the amplitude of measured tilt variations (from 1 to 25 microradians), such that the evolution of the plug size within the upper part of the conduit is a possible mechanism for the succession of ground inflation and subsidence observed within one cycle.