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Thermo-mechanical evolution of the magmatic plumbing system of Soufrière Hills volcano, Montserrat, and resultant ground deformation

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We exploit cyclic ground deformation timeseries from Soufrière Hills volcano expressed by ground uplift during reservoir priming and subsidence during extrusion. This study focuses on the period of eruptive repose between July 2003 and August 2005 marked by ground uplift prior to renewed dome growth thereafter. Using finite - element analysis we simulate the stress and pressure evolution in the magmatic plumbing system using a time-dependent, non-linear pressure-time history and inelastic thermo-mechanical properties of the upper crust. We compare two models of the plumbing system assembly: 1) two stacked spheroidal reservoirs and 2) a single prolate reservoir. In addition, two different crustal rheology models are tested for each of the plumbing models, with one order of magnitude difference in near-surface (<1 km) rock stiffness.

Assuming reasonable values for the tensile strength of encasing rocks as proxies for reservoir excess pressure (1 to 10 MPa), we use the deformation timeseries as a reservoir barometer. We compare the amplitude of pre-eruptive pressurisation capable of explaining the observed ground displacements from the four best-fit time-dependent model designs with pressure changes deduced for purely elastic mechanical conditions. We find that assuming an elastic rheology for the upper crust beneath Montserrat requires unrealistically low rock rigidities with values on the order of 100 MPa - similar to rubber or beeswax - to fit both near and far-field deformation data. Although one might invoke such low rigidities in the immediate (heated) vicinity of an active magmatic plumbing system, they are unreasonable to assume over a large subsurface volume.

Our results show that the thermal perturbation of the geotherm by the presence of a hot plumbing system is significant and fundamentally alters the portioning of subsurface stresses and strains. We further find that the thermal perturbation caused by best-fitting dual source and single source models are very similar, yielding practically identical relaxation times of encasing rocks if generalised Maxwell visco-elastic properties are invoked for the crust.

The reservoir excess pressures upon simulated periodic recharge over the 15 months of uplift reach 4 MPa for a single large pressurised volume of 100 km3 extending from 6 to 17 km depth before reservoir failure and the onset of depressurisation. The pressure increase in the stacked reservoir assembly is predicted at 6 MPa almost exclusively incurred by pressurisation of a deep reservoir at 12 km depth.

On the basis of the simulations and their fit to observations, we cannot distinguish between pressurisation of multiple vertically stacked reservoirs or a single vertically elongated reservoir, and the stiffness of near-surface rocks has no significant influence. This indistinctiveness predominantly results from the thermal effect of the plumbing system on encasing rocks and the resultant inelastic mechanical response to reservoir stressing. Our study provides important insight into the complexities of time-dependent reservoir evolution of andesitic systems which can only be poorly constrained by models invoking crustal elasticity.