Time-dependent stressing and failure of an andesitic magma reservoir

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Andesitic magmas account for two-thirds of subaerially erupted magmas world-wide and an understanding of the processes behind magma accumulation at depth prior to eruptions is critical for volcanic risk assessment. Of particular interest is the interpretation of geodetic time series prior to eruptions as they provide information on the spatial and temporal evolution of magmatic systems. Here, we exploit GPS timeseries data from Soufrière Hills volcano on Montserrat that records cyclic deformation vs. time history expressed by ground uplift during a period of repose between July 2003 and August 2005 and subsidence accompanying renewed dome growth over the subsequent 12 months. The data are consistent with a pre-eruptive pressurisation of a deep prolate magma reservoir at depths of around 12 km followed by depressurisation as a result of reservoir failure and eruption initiation. Using finite - element analysis we simulate the stress evolution in the magma reservoir using a time-dependent non-linear pressure history. Assuming reasonable values for the tensile strength of encasing rocks (1 to 10 MPa) we can use the deformation timeseries as a reservoir barometer. 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.

Invoking depth-dependent rock rigidity values deduced from published seismic data, the simulations require inelastic stress relaxation upon reservoir pressurisation in order to match observed deformation amplitudes while also satisfying tensile stress conditions consistent with reservoir stability upon recharge. We achieve a fit to the uplift data by invoking a visco-elastic response of the surrounding medium over a volume of seven times the pressurised volume. Time-dependent stress relaxation is applied using a generalised Maxwell model with a short-term relaxation time of four months. The reservoir excess pressures remain below a few MPa upon simulated periodic recharge over the 15 months of uplift reaching a maximum value of 8 MPa for a pressurised volume of 32 km3̂ before reservoir failure and the onset of depressurisation. The failure excess pressure is consistent with published values for mode 1 extension failure of rocks and hence permits dyke injection. The simulated pressure-time history fits the observations well, although the data precision of the deformation time series do not allow constraint of a unique recharge history. These simulations provide important insights on the complexities of time-dependent reservoir dynamics in andesitic systems, which can only be poorly constrained by simplistic models invoking crustal elasticity in volcanic terrains.