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Modelling pre-eruptive damage at Grimsvötn volcano, Iceland: consequences for the pre-eruptive process

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On active basaltic volcanoes, continuous monitoring of seismicity and surface displacement reveals important features of the eruptive cycle. At Piton de la Fournaise volcano, based on averages performed over 22 eruptions, Schmid et al. (2012) showed that seismicity rate and displacement rate were increasing in the days and weeks preceding the eruption. At Grimsvötn volcano, high-quality earthquake and continuous GPS data were recorded and exhibited remarkable patterns : acceleration of the cumulated earthquake number, and a 2-year exponential decrease in displacement rate followed by a 3-year constant inflation rate. The 2-year exponential decrease in displacement rate may be explained by the pressurization of a superficial reservoir feeded by magma through a cylindrical vertical conduit and may be modelled using a linear elastic model. This model however can not explain the constant inflation rate that follows, which corresponds to a constant volume increase rate, that is, a constant input magma flow. Imposing a constant magma flow condition in the reservoir in a linear elastic medium leads to the magma pressure linearly – and infinitely – increasing with time. However real rock strength is limited and rupture occurs. Rock mechanics experiments show that rupture is preceded by a damage phase, during which anelastic deformation increases, micro-rupture number accelerates, and Young's modulus decreases with strain. We show that Kachanov's elastic brittle damage law may be used, in the pre-eruptive case, to express the decrease of the effective shear modulus with time. Using this law and a simple pressurization model, we found analytical solutions for the state variables : magma reservoir overpressure, surface displacement, magma flow and strain power in the case where magma is incompressible. Critical time may be estimated from the fit of the seismicity model to the data, and model parameters are estimated from the fit of the displacement model to the data. Results show how the shear modulus decreases with time; they also show that overpressure and magma flow respectively decreases and increases before the rupture and eruption. Overpressure decrease is controlled by damage and shear modulus decrease. Displacement increases, although overpressure is decreasing, because shear modulus decreases more than overpressure. Normalized strain power reaches a maximum 0.25 value. State variable extrema provide four reference times that may be used to assess the mechanical state and dynamics of the volcanic edifice. When magma is incompressible, the final stage of the pre-euptive process is controlled by damage.

We also performed the spatial modelling of the progressive damage and strain localization around a pressurized magma reservoir. We used Kachanov's damage law and finite element modelling of an initially elastic volcanic edifice pressurized by a spherical magma reservoir, with a constant pressure in the reservoir and various external boundary conditions. At each node of the model, Young's modulus is decreased if deviatoric stress locally reaches the Mohr-Coulomb plastic threshold. For a compressive horizontal stress, the result shows a complex strain localization pattern, showing reverse and normal faulting very similar to what is obtained from analog modelling and observed at volcanic resurgent domes.