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Crustal viscosity and its control on volcanic ground deformation patterns

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Episodes of ground deformation, relating to the unrest of a volcanic system, are often readily identifiable within geodetic timeseries (e.g. GPS, InSAR). However, the underlying processes facilitating this deformation are more enigmatic. By modelling the observed deformation signals, the ultimate aim is to infer characteristics of the deforming reservoir; namely the size and time-dependent evolution of the system and, potentially, the fluxes of magma involved. These parameters can be estimated using simple elastic models, but the presence of shallow or long-lived magmatic systems can significantly perturb the local geothermal gradient and invalidate the elastic approximation. Inelastic rheological effects are increasingly utilised to account for these elevated thermal regimes, where a component of viscous (time-dependent) behaviour is expected to characterise the observed deformation field.

Here, our investigations are concentrated on Taupō volcano, New Zealand, the site of several catastrophic caldera-forming eruptions. We use 3D thermomechanical models of the Lake Taupō region, featuring thermal constraints and heterogeneous crustal properties, to compare the commonly-used Maxwell and Standard Linear Solid (SLS) viscoelastic configurations under contrasting deformation mechanisms; a pressure condition (stress-based) and a volume-change (strain-based). By referring to models allocated a single viscosity value, we investigate the influence of a temperature-dependent viscosity distribution on the predicted spatiotemporal deformation patterns. Comparisons of the overpressure models highlights the influence of the crustal viscosity structure on deformation timescales, by enabling the SLS rheology to account for both abrupt and long-term deformation signals. For the Maxwell rheology, we show that the viscosity distribution results in unexpected deformation patterns, both spatially and temporally, and so query the suitability of this rheology in other model setups. Further to this, the deformation patterns in volume-change models are governed by the resulting stress response, and the effect of the viscosity structure on its propagation. Ultimately, we demonstrate that variations in crustal viscosity greatly influence spatiotemporal deformation patterns, more so than heterogeneous mechanical parameters alone, and consequently have a large impact on the inferences of the underlying processes and their time-dependent evolution. The inclusion of a crustal viscosity structure is therefore an important consideration when modelling volcanic deformation signals.