# The role of depth-dependent background crustal viscosity in volcano deformation

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Geodetic (GPS and/or InSAR) observations have provided precise constraints on the mechanism that drives volcanic crustal deformation. Viscoelastic relaxation may play an important role in a long-term component of the deformation because in volcanic region the crustal viscosity is likely weakened by high geothermal gradient. A model with spatially uniform viscosity may be reasonably simple to examine the response of viscoelastic crust in a first-order approximation. But, in more detail, the crustal viscosity spatially varies in rich variety of ways, but the variation with depth is probably the most essential on which further variation would be superimposed, because the crust constitutes a part of the thermal boundary layer in which temperature increases with depth. This study investigates the role of depth-dependent viscosity (DDV) structure in viscoelastic crustal deformation by magmatic intrusion.

The linear Maxwell viscoelastic response of the crust and mantle to the inflation of a magmatic sill is solved, using a parallelized 3-D finite element code, OREGANO_VE [e.g., Yamasaki and Houseman, 2015, J. Geodyn., 88, 80-89]. The viscoelastic crust has depth-dependent viscosity (DDV) structure; the viscosity hc exponentially decreases with depth: hc = h0 exp[c(Zc - z)/L0)], where h0 is the viscosity at the bottom of the crust, c is a constant; c > 0 for DDV model but c = 0 for uniform viscosity (UNV) model, Zc is the thickness of the crust, z is the depth and L0 is a reference length-scale. The viscoelastic mantle has spatially uniform viscosity hm. For UNV model, so high viscosity is given to the uppermost layer with a thickness of H that it deforms in elastic fashion. DDV model however avoids having such an artificial elastic layer. The sill inflation is introduced by using the split node method developed by Melosh and Raefsky [1981, Bull. Seism. Soc. Am., 71, 1391-1400]. The geometry of the sill is approximated as an oblate spheroid whose depth is D, equatorial radius is W and thickness at the centre is dc. The inflation occurs instantaneously at time t = 0.

UNV model (c = 0) behaviour shows that an inflation-induced surface uplift abates with time by means of viscoelastic relaxation, whose subsidence rate is higher and slower if the sill is inflated at deeper in elastic and viscoelastic layer, respectively, and accordingly maximised by the inflation at the boundary between elastic and viscoelastic layers. The rate also depends on the artificially assumed elastic layer thickness H. DDV model (c > 0), on the other hand, shows that for a given c the subsidence rate is greater for greater D, which reflects the viscosity variation with depth. The available magnitude of the subsidence is greater for greater c, which is consistent with the UNV model behaviour that the subsidence is smaller for smaller H. Even if the viscosity gradient is very small, however, the model, having W and D being relatively small to a length-scale over which the viscosity decreases with depth, enhances the rate and available magnitude of subsidence as if the elastic layer is effectively thickened.

The DDV model behaviour requires an effective elastic thickness (EET) to be constrained for a given viscosity gradient in order to properly evaluate the deviation from UNV model behaviour. We thus in this study constrain EET by applying a UNV model behaviour that the post-inflation subsidence rate is slower for a deeper inflation if the inflation occurs in the viscoelastic layer. The DDV model is compared with a UNV model with H = EET, showing that at each surface point the UNV model approximates DDV model behaviour to some extent, but the apparent UNV which best fits the DDV model displacement history is smaller at greater distance from the centre of the uplift and that DDV model displacement is characterised by higher viscosity later in post-inflation period.