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Deformation of mechanically layered volcanic zone induced by an arrested dike

Mohsen Bazargan and Agust Gudmundsson
Royal Holloway University of London, Department of Earth Sciences, Egham, United Kingdom
(rock.fractures@googlemail.com)

Almost all eruptions, whether in volcanic zones/fields or central volcanoes (composite volcanoes/stratovolcanoes, collapse calderas, basaltic edifices), are supplied with magma through dikes or inclined sheets (cone sheets). The dikes/sheets, in turn, derive their magmas from a source, normally a shallow magma chamber or a deep-seated reservoir. During a volcanic unrest period with dike injection, one of the main tasks is thus to assess the geometry and the propagation path of the dike path and, in particular, the likelihood of the dike reaching the surface to erupt. The dike path and geometry (including depth and opening/aperture) are both partly determined from geodetic surface data, in particular InSAR and GPS data, using mostly dislocation models that assume the volcanic zone to be elastic half spaces of uniform mechanical properties. By contrast, field observations of volcanoes (active and extinct) show that they are composed of a variety of layers whose mechanical properties vary widely. In particular, Young's modulus of layers and contacts in a typical active volcanic zone may vary by 2-3 orders of a magnitude.
Here we provide field observations and new numerical models on the effects of a typical variation in Young's modulus on internal and surface stresses and displacements induced by a dike whose tip is arrested at 0.5 km depth below the surface of an active volcanic zone. In particular we vary the stiffness of one layer from 10 GPa to 0.01 GPa. The results show as the layer becomes more compliant (0.1-0.01 GPa) stresses and displacements (lateral and vertical) above the layer, including the surface, become suppressed but the stresses and displacement of the layer hosting the dike increase and their peaks to not coincide in location with those of the other layers.
Thus, the internal deformation of the volcanic zone increases as the layer becomes softer. For a stiffer layer (1-10 GPa), the surface tensile and shear stresses peak at lateral distances of 0.5-0.7 km from the projection of the dike to the surface. By contrast the maximum surface displacements (uplift) peak at lateral distances of 2.8-3.3 km from the dike projection to the surface. If tension fractures and faults – in particular the boundary faults of grabens – are induced by the dike, they should form at the tensile/shear stress peaks and not, as is commonly suggested, at the location of the surface displacement peaks.
The results suggest that reasonable mechanical layering needs to be taken into account in models that aim at reliable estimates of dike dimensions and propagation paths during unrest periods. In particular, numerical models show, for the first time, how the internal dike-induced stresses and deformation in a volcano vary as a function of mechanical layering from the tip of the dike to the surface.

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