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Numerical modelling of dike-induced surface stresses and fractures

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Most volcanic eruptions occur when a magma-filled fracture propagates from its source to the surface. In rift zones outside central volcanoes the minimum principal compressive stress is normally horizontal so that most of the magma paths are vertical dikes. Many injected dikes, however, do not reach the surface to erupt but rather become arrested at various depths in the crust. Correct interpretation of dike-induced surface stresses and deformation during volcanotectonic episodes is of fundamental importance for hazard assessment and dike-path forecasting.
Here we present new general numerical models on the local stresses induced by arrested vertical dikes in rift zones. In the models, the crustal segments hosting the dike vary greatly in mechanical properties, from uniform or non-layered (elastic half-spaces) to highly anisotropic (layers with strong contrast in Young's modulus). The shallow parts of active volcanoes and volcanic rift zones are normally highly anisotropic.
The numerical results indicate that non-layered (half-space) models underestimate the dike overpressure/thickness and overestimate the likely depth to the tip of a dike that is supposed to induce a given surface deformation. Also, as the mechanical contrast between the layers increases, so does the stress dissipation and associated reduction in surface stresses (and related fracturing). In the absence of open contacts at shallow depths in the rift zone, the distance between the two dike-induced tensile stress and shear stress peaks at the surface is roughly twice the depth to the tip of the dike. The width of any dike-induced graben or zone of tension fractures should therefore be roughly twice the depth to the tip of the associated arrested dike. Numerical results also show that the surface-uplift peaks occur at locations which differ widely from those of the tensile/shear stress peaks and do not, in contrast with common interpretations, coincide with the location of the boundary faults of a dike-induce graben.
When applied to the 2009 volcanic unrest episode at Harrat Lunayyir, western Saudi Arabia, the main results are as follows. The 3-7 km wide fracture zone/graben that formed during the episode is far too wide to have been generated by induced stresses of a single, arrested dike. The eastern part of the zone/graben may have been generated by the inferred, arrested dike, but the western zone then primarily by regional extensional loading. The dike tip was arrested at only a few hundred metres below the surface, the thickness of the uppermost part of the dike being between 6 and 12 m. For the inferred dike length (strike dimension) of about 14 km, this yields a dike length/thickness ratio between 2400 and 1200, similar to commonly measured ratios of regional dikes in the field.

Gudmundsson, A., 2003. Surface stresses associated with arrested dykes in rift zones. Bull. Volcanol., 65, 606-619.
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