Are geodetic models physically relevant for understanding magma transport processes?

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Abstract

This contribution intends to trigger discussion regarding the validity of physical assumptions inherent in the models most commonly used to fit geodetic data monitored at active volcanoes. For example, there is a general consensus that the Mogi point source model has no physical basis, yet it is still widely used to fit geodetic data. Another model often used to fit the ground movements associated with dyke and sill emplacement is Okada's model, which calculates surface displacement induced by a rectangular tensile dislocation. This model assumes a linear elastic rheology of the host rock and no far-field stress boundary conditions. For a vertical dislocation, Okada's model exhibits surface deformation consisting of a subsiding trough above the apex of the dislocation, bounded by uplifting bulges. This solution often successfully fits ground deformation patterns monitored in active volcanic rifts. Several facts, however, question the physical relevance of Okada's model, and therefore its systematic applicability to understand subsurface volcanic processes. Firstly, the far-field boundary conditions at active rifts involve anisotropic extensional stresses, thus the boundary conditions used to obtain a model fit are clearly incorrect. Secondly, the feeder of the 2011 Puyehue-Cordón Caulle eruption was a dyke, which triggered only surface uplift (and no subsiding trough or lateral bulges), inconsistent with Okada's model altogether. This mismatch questions whether the ground deformation measured in active rifts results solely from the emplacement of dykes or is partly induced by regional tectonic extension. Thirdly, the Okada model has been used to fit uplift data associated with volcanic sills (e.g. Eyjafjellajökull, Iceland; and Puyehue-Cordón Caulle, Chile), but the calculated sill opening are often unrealistically small (a few centimetres to 1 m spreading over kilometres of length). Finally, focal mechanisms monitored during dyke emplacement in the Iceland rift provide strong evidence that significant shear damage and failure accommodates the propagation of dykes. These disparities highlight the need for better understanding of the mechanics of intrusion-induced surface deformation.

To achieve this, we performed laboratory modelling of dyke emplacement, during which we monitored surface deformation using a high-resolution and high-precision photogrammetric setup. The model magma, a low-viscosity vegetable oil, was injected at constant flow rate into compacted fine-grained dry silica flour (host rock), a cohesive Coulomb material that undergoes both tensile and shear fracturing. In these experiments, the dykes propagated as viscous indenters, i.e. the dykes pushed the host rock ahead of themselves, causing the host rock to fail along reverse shear faults, in good agreement with focal mechanisms monitored in the Iceland rift. The resulting surface deformation exhibited only uplift, i.e. similar to

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surface uplift observed at the Puyehue-Cordón Caulle volcano, but incompatible with ground deformation generally measured in active rifts. Moreover, our laboratory dyke-induced uplift is compatible with monitored uplift in nature commonly fitted with the Mogi point source model despite its much more complex source. The good match between our laboratory results and geophysical and geodetic measurements supports the physical applicability of our laboratory models.

In contrast, the strong divergence between ground deformation patterns calculated using the Okada model and those measured both at the Puyehue-Cordón Caulle volcano and in our laboratory experiments suggests that the physical assumptions of the Okada model are not geologically realistic. Conversely, this implies that the measured ground deformation in active rifts results from an interference between surface deformation induced by dyke emplacement and surface deformation induced by extensional tectonics, and not, as the Okada model would advocate, from the tensile opening of a sheet within linearly elastic host rock. From this we must conclude that successful data fitting is not physically conclusive if the physical assumptions of the fitting models are incorrect.