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Structure and dynamics of surface uplift induced by sill emplacement

Craig Magee (1), Ian Bastow (1), Christopher Jackson (1), Benjamin van Wyk de Vries (2), Rachel Hetherington (3), Miruts Hagos (4), Murray Hoggett (5), Giacomo Corti (6), and Domenico Montanari (6)

(1) Imperial College, Earth Science and Engineering, London, United Kingdom (c.magee@imperial.ac.uk), (2) Laboratoire Magmas et Volcans, Université Clermont Auvergne, Clermont-Ferrand, France, (3) Geological and Mining Engineering and Sciences, Michigan Technological University, Houghton, USA, (4) Department of Earth Sciences, Mekelle University, Tigray, Ethiopia, (5) School of Geography, Earth and Environmental Science, University of Birmingham, Birmingham, UK, (6) Dipartimento di Scienze della Terra, Università degli Studi di Firenze, Florence, Italy

Ground deformation commonly heralds eruptions at active volcanoes, providing insight into the location and geometry of subsurface intrusions that are critical to volcanic hazard assessment. It is, however, difficult to test predictive models of intrusion morphologies derived from geodetic analyses of ground deformation induced by magma movement. To inform modelling and interpretation of geodetic data, it is thus crucial to consider insights from field observations, seismic reflection data, and analogue modelling pertaining to how emplacement and growth of different intrusion geometries deforms the host rock in three-dimensions. Here, we demonstrate how a range of techniques and comparisons can be used to unravel subsurface intrusion geometries and dynamics from ground deformation patterns. We particularly examine the structural and extrusive history of the 3.5 km long, 346 m high, Alu dome, which is located in the Danakil Depression, Ethiopia. Surface uplift and subsidence in 2008, recorded by Interferomertic Synthetic Aperture Radar (InSAR) during a nearby basaltic eruption, demonstrates that Alu is actively deforming; ground deformation patterns have originally been attributed to deformation of a shield volcano (or 'volcanic horst') above a tabular sill. We contend that Alu is a forced fold developed above an incrementally emplaced saucer-shaped sill because: (1) there is no central vent or evidence of significant construction from lava flow build-up; (2) surrounding lava flows deflect around Alu, indicating it had a topographic expression prior to extrusion; (3) the boundary of Alu directly overlies the lateral tips of a sill modelled from InSAR data; (4) normal faults across Alu are compatible with outer-arc extension during doming; (5) the disposition of lava flows radiating from Alu and emanating from vents and/or spatter cones distributed around the periphery of the dome is consistent with their being fed by a saucer-shaped sill; and (6) the scale and timespan of ground deformation during the 2008 eruption suggests that Alu formed through the incremental injection of distinct magma pulses. Although the size and shape of Alu resembles that of a laccolith, we show that forced folds above sills and laccoliths are commonly indistinguishable. We also present preliminary results from analogue models simulating sill emplacement and host rock deformation, which further demonstrate that surface deformation does not easily compare to intrusion morphology. Overall, our work shows that intrusion geometries interpreted from the topographic expression of long-lived magma bodies, like those modelled from geodetic data, are non-unique. However, by deriving deformation histories of active volcanoes, through examination of the surrounding structural geology, and comparison to similar features imaged in seismic reflection data or recreated in analogue models, we show that more realistic inferences on subsurface magma movement and accumulation can be made.