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Forecasting volcanic eruptions: the control of elastic-brittle deformation

Christopher Kilburn, Robert Robertson, Richard Wall, and Alexander Steele
University College London, UCL Hazard Centre, Earth Sciences, London, UK (c.kilburn@ucl.ac.uk)

At volcanoes reawakening after long repose, patterns of unrest normally reflect the elastic-brittle deformation of crust above a magma reservoir. Local fault movements, detected as volcano-tectonic (VT) earthquakes, increase in number with surface deformation, at first approximately exponentially and then linearly. The trends describe how crustal behaviour evolves from quasi-elastic deformation under an increasing stress to inelastic deformation under a constant stress. They have been quantified and verified against experiments for deformation in compression [1]. We have extended the analysis to extensional deformation. The results agree well with field data for crust being stretched by a pressurizing magmatic system [2]. They also provide new criteria for enhancing the definitions of alert levels and preferred times to eruption.

The VT-deformation sequence is a field proxy for changes in deformation with applied stress. The transition from quasi-elastic to inelastic behaviour is characterised in extension by the ratio of differential failure stress S_F to tensile strength σ_T. Unrest data from at least basaltic to andesitic stratovolcanoes, as well as large calderas, yield preferred values for $S_F/\sigma_T \leq 4$, coinciding with the range for tensile failure expected from established theoretical constraints (from Mohr-Coulomb-Griffiths failure). We thus associate the transition with the approach to tensile rupture at the wall of a pressurized magma reservoir. In particular, values of about 2 are consistent with the rupture of a cylindrical reservoir, such as a closed conduit within a volcanic edifice, whereas values of about 3 suggest an approximately spherical reservoir, such as may exist at deeper levels.

The onset of inelastic behaviour reflects the emergence of self-accelerating crack growth under a constant stress. Applied to forecasting eruptions, it provides a new and objective criterion for raising alert levels during an emergency; it yields the classic linear decrease in inverse-rate with time for VT seismicity, which can be extrapolated to an expected eruption time shortly after the inverse rate becomes zero [3]; and, for extension, it identifies preferred inverse-rate gradients of 0.001-0.01, which can be used to distinguish between physically-meaningful and spurious inverse-rate trends.

[1] Kilburn CRJ (2012) J Geophys Res, doi: 10.1029/2011JB008703; [2] Robertson R, Kilburn CRJ (2016) Earth Planet Sci Lett, doi: 10.1016/j.epsl.2016.01.003; [3] Voight B (1988) Nature. 332: 125-130.