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On the plumbing system of volcanic complexes: field constraints from the Isle of Skye (UK) and FEM elasto-plastic modelling including gravity and tectonics.

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The plumbing system that connects a sub-volcanic magma reservoir to the surface has been the object of field characterization and mechanical modelling efforts since the pioneering work by Anderson (1936), who produced a detailed account of the spectacular Cullin Cone-sheet Complex (Isle of Skye, UK) and a geometrical and mechanical model aimed at defining the depth to the magma chamber. Since this work, the definition of the stress state in the half space comprised between the magma reservoir and the surface (modelled either as a flat surface or a surface comprising a volcanic edifice) was considered the key point in reconstructing dike propagation paths from the magma chamber. In fact, this process is generally seen as the propagation in an elastic media of purely tensional joints (mode I or opening mode propagation), which follow trajectories perpendicular to the least compressive principal stress axis. Later works generally used different continuum mechanics methodologies (analytic, BEM, FEM) to solve the problem of a pressure source (the magma chamber, either a point source or a finite volume) in an elastic (in some cases heterogeneous) half space (bounded by a flat topography or topped by a "volcano"). All these models (with a few limited exceptions) disregard the effect of the regional stress field, which is caused by tectonic boundary forces and gravitational body load, and consider only the pressure source represented by the magma chamber (review in Gudmundsson, 2006). However, this is only a (sometimes subordinate) component of the total stress field. Grosfils (2007) first introduced the gravitational load (but not tectonic stresses) in an elastic model solved with FEM in a 2D axisymmetric half-space, showing that "failure to incorporate gravitational loading correctly" affect the calculated stress pattern and many of the predictions that can be drawn from the models.
In this contribution we report on modelling results that include: 2D axisymmetric or true 3D geometry; gravitational body load; anisotropic tectonic stresses; different shapes and depths of the magma chamber; different overpressure levels in the magma chamber; different shapes of the topographic surface (e.g. flat, volcano, caldera); linear-elastic or elasto-plastic Drucker-Prager rheology. The latter point, which in our opinion constitutes a fundamental improvement in the model, has proven necessary because in a purely elastic model the stress state would rise at levels that cannot be sustained by geologic materials. Particularly around and above the magma chamber, yielding is expected, influencing the stress field in the remaining modelling domain. The non-linear problem has been solved with the commercial finite element package Comsol Multiphysics, using a parametric solver.
At the same time, a field structural analysis of the classical Cuillin Cone-sheet Complex has been performed. This analysis has shown that four distinct families of cone sheets of different age do exist. Among these, the sheets with the higher dip angle range (80-65°) are confirmed as purely tensional joints, but those with a lower dip angle range (60-40°) are quite often (when suitable markers are available) associated with a measurable shear component.
Combining these new field observations with mechanical modelling results, we propose a new interpretation for the Cuillin Cone Sheet Complex. The plumbing system was composed by both purely tensional joints and mesoscopic faults with a shear component, produced in response to the regional stress field perturbed by the magma chamber, and later passively re-used as magma emplacement conduits. Under this assumption, the observed geometry of the Cuillin Cone-sheet Complex is consistent with a relatively shallow magma chamber with a flattened laccolite shape. The shape of the palaeotopography, now completely eroded, has also been considered, but is more weakly constrained by modelling results.

References:

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