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Effects of mechanical layering on local stress fields and the emplacement of dykes

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Rock masses where the mechanical properties change between layers are commonly referred to as mechanically layered. Mechanical layering may coincide with changes in grain size, mineral content, fracture frequencies, or facies. Volcanic rocks are commonly mechanically layered, since they often consist of rather stiff lava flows and softer volcanic tuffs or other pyroclastic rocks. Analytical and numerical models show that, in a homogeneous host rock, any significant overpressure in a dyke (its fluid pressure in excess of normal stress on the dyke) generates very high dyke-tip tensile stresses. Consequently, an overpressured and buoyant dyke should normally propagate to the surface and feed a volcanic eruption. Field observations, however, show that in heterogeneous, particularly layered, rocks many dykes become arrested or offset at layer contacts.

We discuss three related mechanisms by which dykes become arrested or offset: discontinuities, stress barriers, and changes in rock stiffness (Young's modulus). Dykes often end at layer contacts which show no evidence of slip. Many dykes, for example in Tenerife (Canary Islands) and Iceland, are arrested at contacts between lava flows and pyroclastic layers, or at bedding contacts in sedimentary rocks. Some dykes thin gradually towards the discontinuity; others end bluntly. When there are stress barriers, dykes may end vertically by tapering away in relatively homogeneous and isotropic rock layers. Offset of dykes is also commonly observed in mechanically layered rocks, particularly when the rock contains weak contacts. Weak contacts are non-welded, and the tensile strength across the contact is often negligible. Lateral dyke offsets across contacts between layers of contrasting mechanical properties, such as lava flows and pyroclastic rocks, are very common. In some cases, the individual arrested segments of a dyke are connected by thin, igneous veins across the contacts, or the dyke may even follow the contact as a sill before it continues propagating upwards. However, particularly in lateral sections, many dyke segments have no visible connections.

Growth of a dyke depends on its fluid pressure as well as the mechanical properties of the host rock. Dykes propagate by advancing their tips when the associated tensile stresses exceed the tensile strength of the host rock (this criterion can also be formulated using fracture toughness rather than tensile strength). Propagating dykes form their pathways by gradually linking up discontinuities in the host rock ahead of their tips into which the magma subsequently flows. A discontinuity is any significant mechanical break or fracture of low or zero tensile strength in the rock. Thus, the local stress fields, in combination with the discontinuities ahead of a dyke tip, largely determine the dyke-propagation pathway and influence the emplacement of dykes. Many models on dyke propagation assume the mechanical properties of the host rock to be homogeneous and isotropic. Assumptions such as these make the problem mathematically tractable, and the resulting analytical models highlight the basic physics involved in dyke development. These models are, however, of limited applicability to heterogeneous and anisotropic, particularly mechanically layered, rocks.

To explore how stress fields affect dyke propagation, we have run many numerical models using the finite-element program ANSYS (www.ansys.com) and the boundary-element program BEASY (www.beasy.com). These models indicate that, for dyke overpressure as the only loading, stiff layers concentrate tensile stresses and tend to favour dyke propagation, whereas soft layers suppress tensile stresses and tend to arrest propagating dykes. When the host rock is subject to remote compression or tension, however, the results may be very different. When a layered rock is subject to horizontal tension, tensile stresses concentrate in the stiff layers, which may become highly stressed, whereas soft layers tend to be stress barriers. When such a layered rock is subject to horizontal compression, however, the stiff layers are likely to take up most of the compressive stress and act as barriers to vertical dyke propagation. It follows that for a dyke to propagate to the surface, a necessary condition is that the stress field along its potential pathway is favourable and homogeneous so that the probability of dyke arrest is minimised. Stress-field homogenisation may be reached through host-rock alteration, faulting, and injection of dykes. By these processes, a layered rock mass may gradually develop essentially the same stiffness (Young's modulus) throughout, and if the layers are welded together so that there are no weak or open contacts, the layered rock mass will function mechanically as a single layer.

Analytical and numerical models of dykes show that the tensile stress concentration at the surface, or at weak interfaces, induced by a propagating dyke normally has two peaks. At the surface, the greatest deformation normally occurs at these peaks. At weak interfaces, the peaks are the most likely locations for induced offset fractures. In homogeneous, isotropic rocks, there is a clear correlation between the distance between the two peaks and the depth to the dyke tip below the surface. However, in heterogeneous, anisotropic rocks, this correlation may not hold. Numerical models of dyke propagation in mechanically layered rocks with welded contacts indicate that the peak stresses occur at distances slightly different from those for homogeneous, isotropic rocks. The alternation of stiff and soft layers is thus able to shift the peak stresses and change the location of possible offset fractures. This shift is much greater for models where there are weak contacts (modelled as horizontal discontinuities). These results indicate that mechanical layering, particularly horizontal discontinuities, may transfer the stress peaks at the surface, so that straightforward inversion of surface geodetic data may lead to unreliable inferred depths of dyke tips.

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