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# Field studies and numerical models of hydrofracture propagation in mechanically layered rocks

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Hydrofractures are formed, at least partly, as a results of internal fluid overpressure. They may be formed by magma (dykes, sheets, sills), geothermal water (mineral veins), or oil, gas and water (many joints) and also include the man-made hydraulic fractures used to increase the permeability of reservoirs. Theoretical models show that any hydrofracture with a significant fluid overpressure (fluid pressure in excess of the fracture-normal stress) develops such high tensile stresses at the fracture tips that it should continue its propagation upwards and eventually reach the earth surface provided the crust was homogeneous and isotropic. Rocks, however, are normally heterogeneous and anisotropic, in particular they are layered. For many layered rocks, the mechanical properties, particularly their Young's moduli, change between layers, that is, the rocks are mechanically layered. Mechanical layering may coincide with changes in grain size, mineral content, fracture frequencies, or facies. For example, in sedimentary rocks, stiff (high Young's modulus) limestone or sandstone layers commonly alternate with soft (low Young's modulus) shale layers. Also, in volcanic rocks, lava flows commonly have much higher Young's moduli than pyroclastic rocks such as tuff.

Here we present results of studies of fracture systems in mechanically layered rocks. These include joints in the Lower Triassic Buntsandstein in Northern Germany (sandstone interlayered with shale), joints and veins in the Lower Jurassic Blue Lias Formation in South Wales (limestone interlayered with calcareous shale) and dykes and sheets in the Upper Tertiary Lava Pile in Iceland (basaltic lava flows interlayered with pyroclastic rocks). These field studies show that most hydrofractures become arrested at layer contacts, particularly at contacts between layers with contrasting mechanical properties.

To understand the mechanics of hydrofracture propagation we explore the stress fields affecting fracture propagation using numerical models (finite-element and boundary-element methods). The models focus on the effects of mechanical layering and show that stresses commonly concentrate in stiff layers. Also, at the contacts between soft and stiff layers, the stress trajectories (directions of the principal stresses) may rotate. Depending on the external loading conditions, certain layers may become stress barriers to fracture propagation. 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 hydrofracture propagation.

Our results suggest that changes in mechanical properties (particularly Young's modulus) are important parameters for the propagation of hydrofractures. In mechanically layered volcanoes (stratovolcanoes), for example, dyke propagation to the surface, that is, volcanic eruptions, can only occur if the stress field along the entire pathway of the dyke is favourable and homogenous. 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. The results also have significant implications for fluid transport in reservoirs (for petroleum, natural gas, geothermal and ground water). In reservoirs where most hydrofractures become stratabound (confined to individual layers), interconnected fracture systems are less likely to develop than in one with non-stratabound hydrofractures. Reservoirs with stratabound fractures may thus not reach the percolation threshold needed for significant permeability. We analyse these processes through quantitative structural geological field studies of hydrofractures in all kinds of rocks and comparison of the results with numerical models.

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