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Mechanical rock properties, fracture propagation and permeability development in deep geothermal reservoirs

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Deep geothermal reservoirs are rock units at depths greater than 400 m from which the internal heat can be extracted using water as a transport means in an economically efficient manner. In many geothermal reservoirs, fluid flow is largely, and may be almost entirely, controlled by the permeability of the fracture network. No flow, however, takes place along a particular fracture network unless the fractures are interconnected. For fluid flow to occur from one site to another there must be at least one interconnected cluster of fractures that links these sites, that is, the percolation threshold must be reached. In "hydrothermal systems", only the natural fracture system (extension and shear fractures) creates the rock or reservoir permeability that commonly exceeds the matrix permeability by far; in "petrothermal systems", by contrast, interconnected fracture systems are formed by creating hydraulic fractures and massive hydraulic stimulation of the existing fracture system in the host rock. Propagation (or termination, that is, arrest) of both natural extension and shear fractures as well as man-made hydraulic fractures is mainly controlled by the mechanical rock properties, particularly rock toughness, stiffness and strengths, of the host rock. Most reservoir rocks are heterogeneous and anisotropic, in particular they are layered. For many layered rocks, the mechanical properties, particularly their Young's moduli (stiffnesses), 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 limestone or sandstone layers commonly alternate with soft shale layers. In geothermal reservoirs fracture termination is important because non-stratabound fractures, that is, fractures not affected by layering, are more likely to form an interconnected fracture network than stratabound fractures, confined to single rock layers. Thus, to minimise exploration risks and for effective stimulation, the geometry of the fracture system and the mechanical properties of the host rock must be known.

Here we present first results of structural geological field studies of fracture systems in outcrop analogues studies of rocks that could be used to host man-made geothermal reservoirs in sedimentary rocks in the North German Basin. As examples, we show data from different lithologies, including Buntsandstein (Lower Triassic), a sandstone-shale succession and Muschelkalk (Middle Triassic), a limestone-marl succession. We analyse natural fracture systems and the effects of rock heterogeneities, particularly stiffness variations between layers (mechanical layering) on the propagation of natural fractures. Important fracture parameters include attitude, aperture and interconnectivity to fracture systems. The field studies are supplemented by laboratory measurements of the above mentioned rock mechanical properties.

Our field studies indicate that many fractures become arrested at layer contacts, particularly at contacts between layers with contrasting mechanical properties. Measurements of thousands of fractures indicate that even very thin layers (mm to cm-scale thicknesses) of shale or marl may be responsible for the arrest of many fractures. Our results suggest that the propagation and aperture variation of fractures are important parameters in the permeability development of deep geothermal reservoirs. These studies provide a basis for models of fracture networks and fluid transport in future man-made reservoirs. We conclude that the likely permeability of a man-made geothermal reservoir can be inferred from field data from outcrop analogues, laboratory measurements, and numerical models.