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Field observations and numerical models of fracture propagation and fluid transport in palaeogeothermal fields and man-made reservoirs

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Geothermal reservoirs are rock units from which the internal heat can be extracted using water as a transport material in an economically efficient manner. Geothermal energy produced from such reservoirs is a renewable resource that can be used to generate electrical power, particularly for base loads, as well as to produce hot water for heating purposes in large parts of the world. In most geothermal reservoirs, fluid flow is largely, and may be almost entirely, controlled by the permeability of a 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 (the percolation threshold must be reached). In order to generate permeability in man-made reservoirs, interconnected fracture systems are formed either by creating hydraulic fractures or by massive hydraulic stimulation of the existing fracture system in the host rock. For effective stimulation, the geometry of the fracture system and the mechanical properties of the host rock (particularly rock stiffnesses and strengths) must be known.

Here we present results of a study of fracture systems in, and mechanical properties of, rocks that could be used to host man-made geothermal reservoirs, such as Mesozoic sandstones and limestones in Germany. Studies of fracture systems in exposed palaeogeothermal fields can also help understand the permeability development in stimulated reservoirs. We therefore present data on the infrastructures of extinct fracture-controlled geothermal fields in fault zones in Iceland and Great Britain.

In fault zones there are normally two main mechanical and hydrogeological units.

The fault core, along which fault slip mostly occurs, consists mainly of breccia and other cataclastic rocks. The fault damage zone comprises numerous fractures of various sizes. During fault slip, the fault core may transport water (if its orientation is favourable to the hydraulic gradient in the area). In the damage zone, however, fluid transport through fracture networks depends particularly on the current local stress field. One reason for this is that fractures are sensitive to changes in the stress field and deform much more easily than circular pores. If the maximum horizontal compression is oriented perpendicular to the fault strike, its fractures (mainly in the damage zone) tend to be closed and lead less water than if the maximum horizontal compression is oriented parallel to the fault strike, in which case its fractures tend to open up and be favourable to fluid transport. In areas of potential geothermal reservoirs, fault zones must be studied, keeping in mind that the permeability structure of a fault zone depends partly on the mechanical units of the fault zone and partly on the local stress field.

To explore stress fields affecting fracture propagation we have run numerical models using the finite-element and the boundary-element methods. We focus on the influence of changes in mechanical properties (particularly Young's modulus) between host rock layers in and around fluid reservoirs. The numerical models 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 become rotated. Depending on the external loading conditions, certain layers may become stress barriers to fracture propagation. In a reservoir 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 not reach the percolation threshold needed for significant permeability.

The apertures of vertical hydrofractures are commonly greater in soft layers than in stiff layers. But in soft layers, hydrofractures are often inclined (shear) fractures and subject to higher normal stresses, and thus have smaller apertures, than vertical fractures. The permeability of an individual fracture is mainly controlled by its aperture. Aperture changes of fractures dissecting layers with different mechanical properties may thus lead to preferential flow (flow channelling) in certain layers in fractured fluid reservoirs.

Our results suggest that fluid transport along faults, and the propagation and aperture variation of hydrofractures, are important parameters in the permeability development of 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, natural analogues, laboratory measurements, and numerical models.

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