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Structural geological field analysis in outcrop analogues as a tool to understand permeability development in geothermal reservoirs

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A necessary condition for deep geothermal reservoirs to be of economic use is a high flow rate of hot water through the rock. In most geothermal reservoirs, particularly in man-made reservoirs, fluid transport is largely controlled by the permeability of the fracture network (“fractured reservoirs”). In fractured reservoirs only interconnected fracture systems reach the percolation threshold necessary for fluid transport. Therefore, information on the geometry of existing fracture systems is necessary to be able to estimate the potential permeability of man-made geothermal reservoirs. In addition, active faults commonly have great effects on the transport of crustal fluids and create high permeability in reservoirs. That is why in both natural and man-made geothermal reservoirs, the orientation of fault zones in relation to the current stress field and their internal architecture needs to be known as accurately as possible.

To obtain this information, we analyse outcrop analogues, that is, outcrops of the same rock types (stratigraphy, lithology, facies) as those supposed to host the man-made reservoir at geothermal depths. We focus on rock heterogeneity and anisotropy, mainly mechanical layering, that is, changes in the mechanical properties, particularly rock stiffness (Young’s modulus), and how these heterogeneities influence fracture propagation and the infrastructures of fault zones. As examples, we present results of two case studies on the prognosis of fracture systems and permeability in potential geother-

mal reservoir rocks of different lithologies in Germany. The first study was performed in the Buntsandstein (Lower Triassic) in the North German Basin, a sandstone-shale succession. The second study is in the Muschelkalk (Middle Triassic) in the Kraichgau area next to the Rhine Graben in southern Germany in a limestone-marl succession. Important fracture parameters include attitude, aperture, and interconnectivity to fracture systems.

Our field results indicate that in both areas, two orthogonal sets of joints as well as several faults occur. 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 joints. These results are in agreement with the results of numerical models (finite-element and boundary-element methods) that 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. The field results also indicate that the mechanical layering affects fracture propagation differently. For some joints the lithological layering coincides with the mechanical layering (e.g., the E-W striking joints in the Buntsandstein and most of the joints in the Muschelkalk, are restricted to individual sedimentary layers), so that the fractures become stratabound. Other joints, and most of the faults, however, propagate through many sedimentary layers (are non-stratabound), meaning that the mechanical layer thickness is much greater than the lithological layer thickness. Non-stratabound fractures may still be affected by the layering; in particular, they often change their attitudes (strike and dip; observed for many joints) and apertures from one layer to the next.

These results have significant implications for permeability and fluid transport in geothermal reservoirs. In reservoirs where most fractures become stratabound, interconnected fracture systems are less likely to develop than in reservoirs with non-stratabound fractures. Reservoirs with stratabound fractures may thus not reach the percolation threshold needed for significant permeability. The contacts between individual layers may, however, be weak or open as well, in such a way as to form interconnected systems of fluid pathways in geothermal reservoirs. In addition, fault zones may interconnect fluid pathways in individual layers in a reservoir.

Structural geological field studies in outcrop analogues of the same rock types as the potential geothermal reservoir rocks help to understand the fluid transport in future man-made geothermal reservoirs and thus contribute to maximise the likelihood of success in deep geothermal projects