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Internal structure of fault zones in geothermal reservoirs: Examples from palaeogeothermal fields and potential host rocks

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Fault zones commonly have great effects on fluid transport in geothermal reservoirs. During fault slip all the pores and small fractures that meet with the slip plane become interconnected so that the inner part of the fault, the fault core, consisting of breccia or gouge, may suddenly develop a very high permeability. This is evidenced, for example by networks of mineral veins in deeply eroded fault zones in palaeogeothermal fields. Inactive faults, however, may have low permeabilities and even act as flow barriers. In natural and man-made geothermal reservoirs, the orientation of fault zones in relation to the current stress field and their internal structure needs be known as accurately as possible. One reason is that the activity of the fault zone depends on its angle to the principal stress directions. Another reason is that the outer part of a fault zone, the damage zone, comprises numerous fractures of various sizes.

Here we present field examples of faults, and associated joints and mineral veins, in palaeogeothermal fields, and potential host rocks for man-made geothermal reservoirs, respectively. We studied several localities of different stratigraphies, lithologies and tectonic settings: (1) 58 fault zones in 22 outcrops from Upper Carboniferous to Upper Cretaceous in the Northwest German Basin (siliciclastic, carbonate and volcanic rocks); (2) 16 fault zones in 9 outcrops in Lower Permian to Middle Triassic (mainly sandstone, limestone and granite) in the Upper Rhine Graben; and (3) 74 fault zones in two coastal sections of Upper Triassic and Lower Jurassic age (mudstones and limestone-marl alternations) in the Bristol Channel Basin, UK. (1) and (2) are outcrop analogues of geothermal reservoir horizons, (3) represent palaeogeothermal fields with mineral veins.

The field studies in the Northwest German Basin (1) show pronounced differences between normal-fault zones in carbonate and clastic rocks. In carbonate rocks clear damage zones occur that are characterized by increased fracture densities and higher percentages of fractures with large apertures. In the Upper Rhine Graben (2) damage zones in Muschelkalk limestones (Middle Triassic) are well developed even in fault zones with dm-scale displacements. Their fault cores, however, are narrow compared with that of fault zones with larger displacements and comprise brecciated material, clay smear, host rock lenses or zones of mineralization. Fracture apertures are larger parallel or subparallel to fault zone strike. A large fault zone footwall in Triassic Bunter sandstone shows a clearly developed fault core with fault gouge, slip zones, deformation bands and host rock lenses, a distal fault core with disturbed layering and high fracture density and a damage zone with increased fracture density compared with the host rock. In the study areas of palaeogeothermal fields in the Bristol Channel (3), all the mineral veins are clearly related to the faults and occur almost exclusively in the damage zones, indicating that geothermal water was transported along the then-active faults into the host rocks. Field measurements indicate that in all the localities, a large majority of the fractures in the fault damage zones are extension fractures, fewer are shear fractures. In the Jurassic Blue Lias there is evidence that the veins were injected as hydrofractures from fault planes into the limestone layers. In the Triassic Mercia Mudstone most veins were arrested during their propagation by layers with contrasting mechanical properties (stress barriers). Some veins, however, propagated through the barriers along faults to shallower levels.

Our studies contribute to understanding and modelling of hydromechanical behaviour of fault zones and fluid transport in geothermal reservoirs. For successful exploration and exploitation, fault zones must be studied in detail regarding their likely internal structure, fracture parameters and orientation in relation to the current stress field. We show that outcrop analogue studies and studies of palaeogeothermal fields improve predictions based on geophysical measurements because of their higher resolution and detailed information on the three-dimensional internal structure of fault zones.

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