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Fault zones in layered rocks: fault displacement, damage zone thickness, and hydrofracture injection

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In fault zones there are normally two main mechanical units. The fault core, along which fault slip mostly occurs, consists mainly of breccia and gouge. The fault damage zone comprises numerous fractures of various sizes. Commonly there is a correlation between the trace length of a fault, its damage zone thickness, and the fault displacement. In mechanically layered host rocks, however, where the stiffnesses of the rocks (their Young's moduli) change between layers, this correlation is less clear. This is mainly because the fault displacement may depend on the Young's moduli of the host rocks of the fault zone, but also because the fractures in the damage zone lower the stiffnesses of the rocks. Other things being equal, the lower the Young's modulus in the damage zone, the larger the fault displacement may become.

Here we present field examples of faults, and associated joints and mineral veins, in layered sedimentary rocks. The different lithologies studied include: (1) sandstone and shale layers of the Buntsandstein Formation (Lower Triassic) in Bad Karlshafen, Northern Germany; and (2) limestone and shale layers (Lower Jurassic) near Kilve, Somerset Coast (Southwest England), and at Nash Point, Glamorgan Coast (South Wales), that is, at both coasts of the Bristol Channel, UK. The field studies in the Buntsandstein show that the fault displacements correlate with the heights (dip dimensions) of strike-slip faults in vertical outcrops. The normal displacement along these faults, however, not only increases towards the centres of the faults, but also depends on the mechanical properties of the host rocks. In soft (low Young's modulus) shale layers, the normal displacement is always larger than in stiffer (higher Young's modulus) sandstone layers.

To understand the development of fault zones in layered rocks we have run numerical models using the finite element method. The models focus on the displacements of normal and strike-slip faults depending on the mechanical properties (Young's moduli) of layered host rocks and the damage zone. The models show that the displacements of the faults vary positively with the thicknesses of the damage zones. The models also show that in soft host rock layers, the fault displacement is larger than in stiff layers.

Active faults commonly have great effects on the transport of crustal fluids. During fault slip all the pores and small fractures that meet with the slip plane become interconnected so that the fault may suddenly develop a very high hydraulic conductivity. The best evidence of palaeo-fluid transport, for example in deeply eroded, inactive fault zones, are networks of mineral veins. In the study areas of the Bristol Channel, all the mineral veins are clearly related to the faults, indicating that geothermal water was transported along the then-active faults into the host rocks. At Kilve, calcite veins occur almost exclusively in the cores and damage zones of (mostly) normal faults. Similarly, at Nash Point, calcite veins are clearly related to strike-slip faults. In both areas there is evidence that the veins were injected as hydrofractures (fractures generated by internal fluid overpressure) from the fault planes into the limestone layers. Inactive faults may have low permeabilities and even act as seals, particularly if they develop clay smear along their planes. Fault planes in sedimentary basins, however, tend to be weak in extension so that fluids that flow into such planes would be likely to follow the fault planes to higher stratigraphic levels as hydrofractures. These hydrofractures may then be injected into the host rocks in the damage zone of the fault zone and build interconnected fracture networks that increase the permeability.