Factsheet Faults

It is generally acknowledged that the groundwater yield in carbonate rock reservoirs only to a negligible extent depends on the primary rock porosity (matrix permeability) but principally is controlled by faults, fractures, and karst conduits. The groundwater flow in carbonate reservoirs thus is governed by the fracture and fault network. Accordingly, as opposed to porous rocks systems, carbonate plays are highly anisotropic and heterogeneous, and mapping the fault network is the prime goal at the forefront of any hydro-geothermal exploration. This is also because the structural inventory is the only subsurface feature that can be reliably assessed by geophysical surveys, before drillings are carried out, however, on a larger scale only (cf. Diepolder & GeoMol Team 2015).

The vast majority of basinal faults in HotLime's Case Study Areas are blind faults, 3D modelled based on evidence of seismic surveys and rare deep drillings. Tectonic boundaries featuring throws of less than approximately 10 m, likewise soft links between faults, e.g. relay ramps and fault terminations (Figure 1), commonly are subseismic in legacy surveys and detectable only in novel high-resolution 3D-seismic projects that have been carried out in few focus areas only. The fault inventory depicted in HotLime's maps, thus, represents the seismically resolvable portions of the principal faults only. Actually, the hydraulically effective area can be much larger, in length as well as laterally (cf. Figures 1 and 2), than indicated by the slip surface trace in the maps.

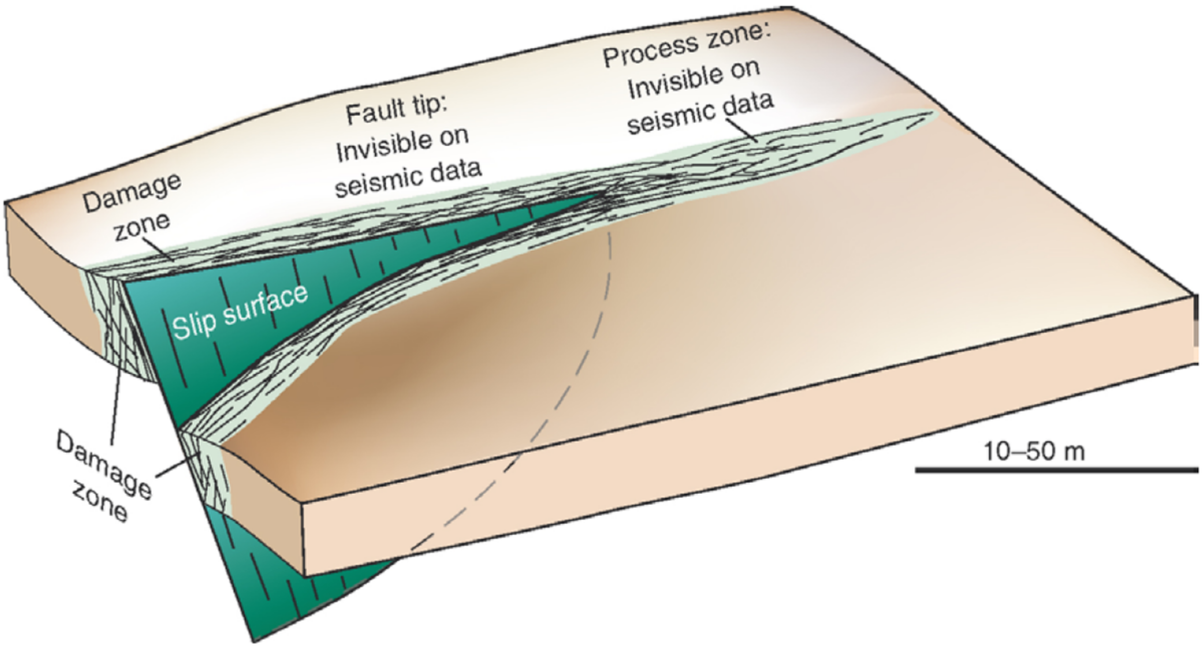

Figure 1: Conceptual sketch of a fault termination (from Fossen 2016). In usual seismic surveys information as available to HotLime's partners, only the slip surface could be modelled. The wide damage zone (cf. Figure 3), the fault tip, and its progress (propagation) zone could not be detected.

Unlike faults in rocks tending to a ductile behavior, which tend to dye out into a zone of ductile deformation, in carbonate rocks, due to their brittle characteristics, the displacement is partitioned into several branching pinnate structures. These small faults, curved away from the strike of the main fault, form an open, imbricate fan called a horsetail splay. However, the formation kinematics of horsetail splays requires at least a subordinate strike-slip deformation trajectory.

Figure 2: Horsetail splay structure at the southeastern end of [Velden Fault](), the smoothed fault traces (red) refer to the top of Upper Jurassic reservoir. Such branching out at the termination of faults could be fairly common, but is detectable in high-resolution up-to-date 3D seismic surveys only. The blue line represents the "pre-HotLime" trace of Velden Fault, as modelled based on legacy seismic surveys.

Generally, faults comprise two major architectural elements: the core zone and the damage zone (Figure 1 and 3). The fault core and damage zone are distinct structural and hydraulic units that reflect the material properties and deformation conditions within a fault zone. Whether a fault zone will act as a conduit, barrier, or combined conduit-barrier system is controlled by the relative percentage of fault core and damage zone structures and the inherent variability in grain scale and fracture permeability (Caine et al. 1996).

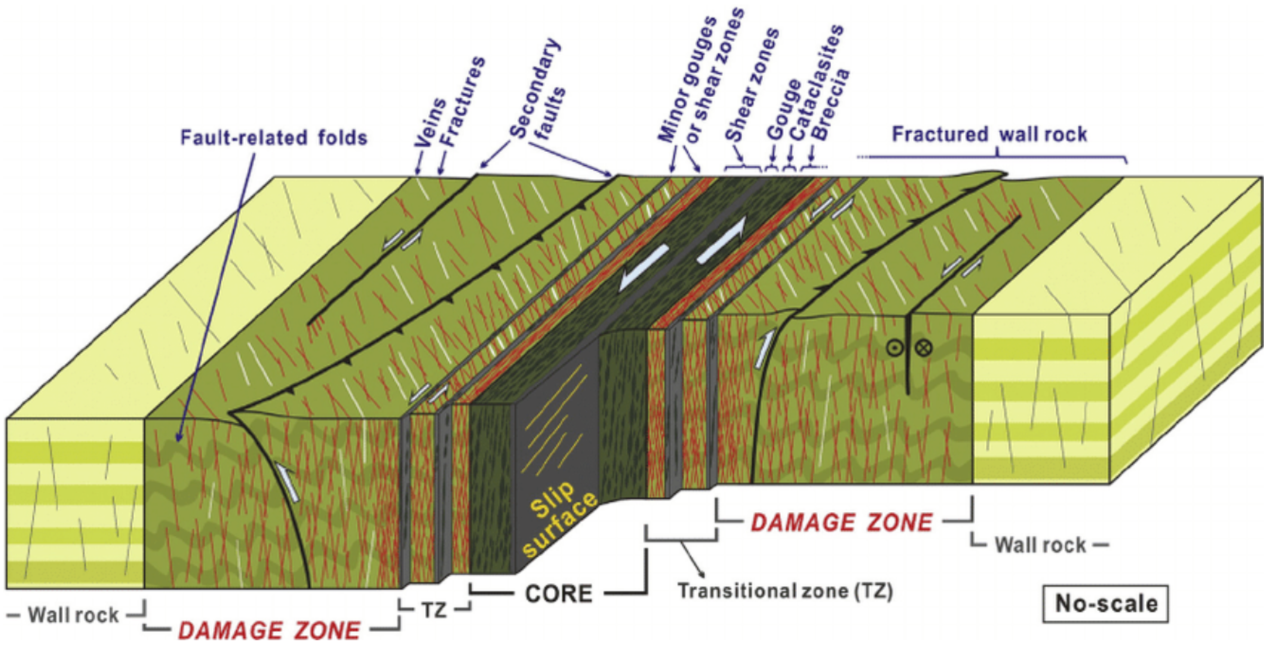

Figure 3: Conceptual fault zone model portraying the symmetrical, banded zonal distribution of the fault-zone architectural components (modified from Choi et al. 2016). The block's relative movement may be horizontal (strike-slip fault, e.g. sinistral as depicted), vertical (normal or reverse fault), or oblique (oblique-slip fault). Width and characteristics of the fault core and damage zones can largely vary, even on small scale, and certain parts of the damage zone may be absent (Caine et al. 1996, Wibberley et al. 2008).

The fault core, i.e. the portion of the fault where the majority of slip is accommodated, mostly shows a reduction in grainsize and associated permeability and porosity; this leaves the core with a lower permeability than the surrounding protolith (Caine et al. 1996). In contrast, the core encasing damage zone often has orders of magnitude greater permeability than the protolith and may enhance fluid flow on the fault (Caine et al. 1996, Bauer et al. 2016).

Specific lithologies can deform differently when subjected to stress, resulting in different permeability structures: fault damage zones in carbonate rocks tend to fracture, creating breccia or joints, making it hydraulically more important than the core (Bauer et al. 2016, Loveless et al. 2016). Likewise, the damage zone around the fault core in carbonate rocks, due to their brittle characteristics, often by far exceeds the core zone: Dussel et al. (2016), e.g., determined mechanically altered zones along main faults in deep-seated carbonate rocks with a width up to 150 m, Bauer et al. (2016) describe damage zones of up to "hundreds of meters" in exposed carbonate rocks of the Alps.

The importance of faults with respect to geothermal prospectivity, making them the prime targets for hydro-geothermal explorations, can be summarized in four bullet points:

- Fault zones, due to their higher permeability, feature a higher fraction of pore fluid (water) with a specific heat capacity 4.5-fold greater than that of the rock matrix, thus a higher quantity of stored heat (cf. HotLime Factsheet Heat-in-Place).
- Fault zones in brittle environments, such as carbonate rocks, act as conduits, making likely a sufficient flow rate for a viable geothermal installation.
- Due to fluid circulation from greater depth, fault zones may form small-scaled positive temperature anomalies allowing for lesser drilling depths than off-fault (cf. Read et al. 2013).
- As hydro-geothermal installations commonly are implemented as open-loop doublets or triplets, fault zones can act as an efficient re-injection target. However, to avoid induced or triggered seismicity, re-injecting into fault zones has to be well-considered and soundly balanced (cf. HotLime Deliverable 4.1).

Furthermore and beyond the purely geothermal point of view, in times of an increasing demand of subsurface space for various competing utilizations or synergies, detailed knowledge of the fault inventory is a sine qua non. For all present and future subsurface utilizations, mature, proved as well as prospective ones, like hydrocarbon E&P, geothermal E&P, underground storage of fluids, gas, and radwaste, and for groundwater abstraction in fractured aquifers, the fault network defines the compartmentalization of the reservoir and the seal integrity, the main conduits of (thermal) water flow, and the structural traps for the formation and integrity of hydrocarbon deposits (and its storage potential in after-use). In brief: faults, fractures, and other conduits are the connections, wished-for or unwanted, for material flow (fluid) in the subsurface, beyond the physico-chemical impact aureoles of subsurface utilizations might bring about.

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