Fracture Systems and Fluid Flow in Geothermal Reservoirs

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ABSTRACT

In most geothermal reservoirs fluid flow is largely controlled by the permeability of the fracture system in the host rock. Both for the direct use of reservoirs, as well as for effective stimulation, the geometry of the existing fracture system and its likely future development need to be known as accurately as possible. Here I review manifold elements of multidisciplinary approaches, altogether aiming at reliable estimations of potential fluid flow in geothermal reservoirs. Focus is on parameters and methods useful for fluid-flow estimations in geothermal reservoirs, and their interdependencies. Examples include the following: 1) Field studies in fracture-controlled paleo-geothermal reservoirs in fault zones in Great Britain and in outcrop analogues of Mesozoic rocks that could be used to host geothermal reservoirs in Germany. 2) Numerical models of local stress fields that provide the basis for numerical models of fracture propagation and fluid flow in geothermal reservoirs. The presented studies increase our understanding of fluid flow in geothermal reservoirs. Considering all relevant parameters and processes for reliable estimations of the existing fracture system and potential fluid flow in geothermal reservoirs contributes to maximize the likelihood of success of geothermal wells.

1. INTRODUCTION

In most geothermal reservoirs, fluid flow is largely controlled by the permeability of its fracture system ('fractured reservoirs', Nelson 1985). To act as geothermal reservoirs with economically appropriate fluid flow, significant permeability is necessary. In some reservoirs – particularly in fault zones with favorable orientations in relation to the current stress field – the existing fracture system, together with the host rock matrix, provides sufficient fluid flow. In other reservoirs, however, interconnected fracture systems need to be formed either by creating hydraulic fractures or by massive hydraulic stimulation of the existing fracture system in the host rock. Both for the direct use of fractured geothermal reservoirs, as well as for effective stimulation, the geometry of the existing fracture system and its likely future development need to be known as accurately as possible.

Relevant parameters and processes for reliable estimations of the existing fracture system and potential fluid flow in geothermal reservoirs, as well as multidisciplinary approaches for their investigation are indicated in the diagram on the next page (Fig. 1). In the following text, I briefly review all aspects included in the diagram step by step, illustrating some aspects with examples from research projects I have been involved in. The presented examples include the following: 1) Field studies in fracture-controlled paleo-geothermal reservoirs in fault zones in Great Britain and in outcrop analogues of Mesozoic rocks that could be used to host geothermal reservoirs in Germany, 2) Numerical models of local stress fields that provide the basis for numerical models of fracture propagation and fluid flow in geothermal reservoirs. For easier orientation, all terms used in the diagram (Fig. 1) are formatted in **bold face** within the following text.

2. MECHANICAL FACIES AND FRACTURE PROPAGATION

Depending on the relative displacement across the fracture plane, all reservoir fractures are either extension fractures or shear fractures. For extension fractures, the relative displacement is perpendicular to the fracture plane, whereas for shear fractures the relative displacement is parallel to the fracture plane. Shear fractures with large displacements are commonly referred to as faults. Extension fractures include tension fractures, which form when the minimum principal compressive stress is negative, and hydrofractures, that are at least partly formed by fluid pressure. In the field, however, it is often difficult to distinguish clearly between the different fracture types. In the following text, I therefore use the general term 'fracture' if the distinction is impossible.

For fluid flow to occur from one site to another in a fractured geothermal reservoir, there must be at least one interconnected fracture system, that is, a cluster of fractures that links these sites. The condition that such a cluster exists is commonly referred to as a percolation threshold (Stauffer & Aharony 1994). Important parameters of individual fractures in terms of reservoir permeability include the fracture geometry, in particular the fracture aperture, that is, the maximum fracture dimension measured perpendicular to the fracture walls. Few open fractures with larger apertures may enhance the permeability, because the flow rate depends on the cube of the fracture aperture ('cubic law', de Marsily 1986) and fluid flow may be channeled along the widest parts of a fracture (Philipp et al. 2013 and references therein).

Field studies in outcrop analogues of rocks that could be used to host geothermal reservoirs give valuable information although we have to consider that measurements under surface conditions are not directly applicable for permeability calculations, for example due to uplift-induced expansion and erosion as well as weathering effects. The measurements rather provide indications for fracture geometry distributions, but no absolute values. Mineralized fractures are indicators for past fluid flow, while they can also act as barriers for recent fluid flow in potential geothermal reservoirs (e.g., de Marsily 1986). As mineralized fractures record the history of fluid flow through fracture systems, field studies in paleogeothermal reservoirs help understand the development of fracture porosity and permeability (Figs 2 and 3). In the exploration of geothermal reservoirs, core and well log analyses are important to gain information on the existing fracture system in the subsurface.
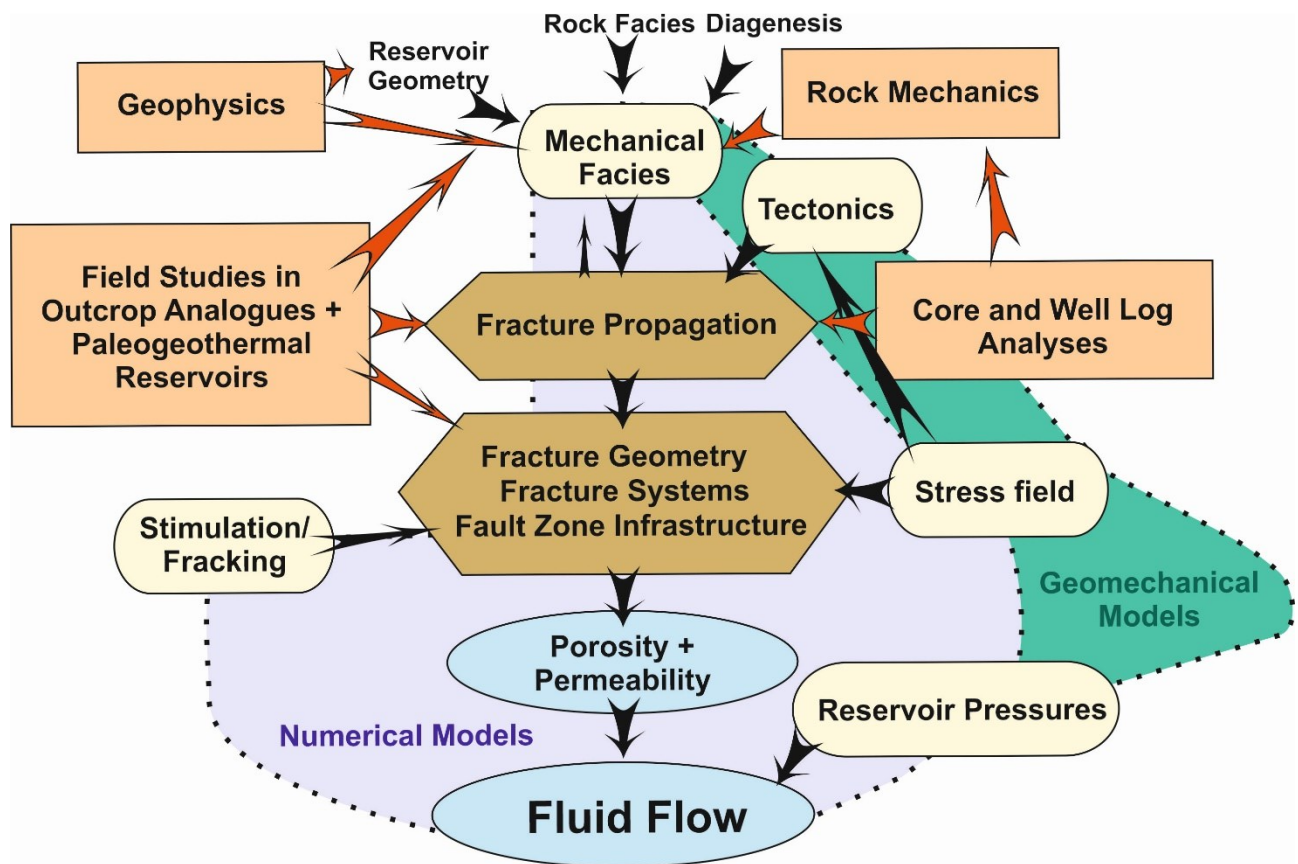
Figure 1: Relevant parameters and processes for reliable estimations of the existing fracture system and potential fluid flow in geothermal reservoirs, as well as multidisciplinary approaches for their investigation.

Analytical and numerical models show that – in homogeneous host rocks – any significant overpressure in a hydrofracture theoretically generates very high crack tip tensile stresses. Consequently, overpressured hydrofractures should propagate and help to form interconnected fracture systems that would then contribute to the permeability of fluid reservoirs. Also, field observations in relatively homogeneous rocks show that the formation of well-interconnected fracture systems leading to temporarily very high permeability is possible (Fig. 2). Field observations, however, also show that in heterogeneous and anisotropic, e.g., layered, rocks many fractures become arrested or offset at layer contacts and do not form vertically interconnected fracture systems (Fig. 3). This is very common for mineral veins, joints and igneous dykes (e.g., Philipp et al. 2013). This phenomenon has also been observed for hydraulic fractures (e.g., Economides and Nolte 2000). This indicates, that fracture arrest in heterogeneous rocks is very common.

In geothermal reservoirs, heterogeneities and anisotropies range in sizes from crystals and grains and pores over layer contacts and fractures to entire basins. However, for the formation of fracture systems and related fluid flow, the most important heterogeneity in reservoirs is their mechanical heterogeneity. Independent from the rock facies depending on the rock's formation, for example its sedimentary facies, it is the rock's mechanical facies (also referred to as geomechanical facies) what matters for fracture propagation (e.g., Shanmugam 1990, McDermott et al. 2007). Since fracture development is mostly controlled by the state of stress in the host rock, which in turn correlates with rock mechanical properties (Hudson and Harrison 1997, Gudmundsson 2011), fracture development is largely controlled by the mechanical properties of the layers. From Hooke's law (strain varies linearly with stress) it follows that, for a given strain, the stress concentration in a stiff material will be greater than in a soft material. Whereas the existing fractures are related to the tectonic history of the reservoirs, the current remote stress field in a reservoir depends on today's tectonics of the area. The local stress fields in a rock consisting of stiff and soft parts, however, will be very different from the ones in homogenous, isotropic media (e.g., Gudmundsson 2011, Philipp et al. 2013).

Figure 2: In relatively homogeneous rocks, such as this Triassic mudstone at Watchet (England, UK), interconnected networks of mineral veins (here gypsum) and other fractures may form. Permeability must have been temporarily very high (from Philipp 2008).

Figure 3: In mechanically layered rocks, such as this Jurassic limestone-marl alternation at Nash Point (Wales, UK) many fractures as these calcite veins, are restricted to individual layers (here limestone). Thus, interconnected fracture systems, necessary for permeability in fractured reservoirs, are less likely to occur (Philipp et al. 2013).

The most common mechanical heterogeneity in a reservoir rock is that the rock masses are mechanically layered, that is, the rock mechanical properties change between layers. Mechanical layering may coincide with changes in grain size, mineral content, or facies. For example, in layered sedimentary reservoirs, such are common in carbonates (limestone interlayered with marl) or siliciclastics (sandstone interlayered with shale or clay), some rock types forming individual layers (such as limestone or sandstone) may be considerably stiffer (higher Young's modulus) than other layers (such as marl or clay) Also, volcanic rocks are commonly mechanically layered, since they often consist of rather stiff lava flows (and sills) and softer volcanic tuffs or other pyroclastic rocks. Metamorphic rocks such as gneiss may show mechanical layering where leucosome and melanosome may have different mechanical properties. (cf., Philipp et al. 2013).

In mechanically layered rocks and reservoirs, fracture propagation is very complex. Discontinuities (including contacts), rock stiffness and toughness changes between layers, and stress barriers, where the local stress field is unfavorable to fracture propagation may lead to fracture arrest (Philipp et al. 2013). If a layered rock mass, however, has essentially the same rock mechanical properties throughout, and if the layers are welded together so that there are no weak or open contacts, the layers may function mechanically as a single unit (Gudmundsson 2011). Mechanical layering and the resulting heterogeneous stress field largely control whether evolving fractures become confined to single layers (stratabound) or not (non-stratabound; Odling et al. 1999) and, therefore, if a vertically interconnected fracture system is formed. Non-stratabound fractures may propagate through many layers and generate interconnected fracture systems. Such systems commonly reach the percolation threshold and largely control the overall permeability of the fluid reservoirs within which they develop (Stauffer and Aharony 1994). Generally, ignoring the variation in permeability between layers of a layered reservoir can lead to an overestimate of the overall permeability of the reservoir (Aguilera 2000).

Clearly, the mechanical facies of a rock is related to its rock facies. It also depends, however, on diagenetic processes such as cementation and compaction. When determining mechanical facies, it is also important to take into account the internal geometry of the reservoir. Architectural elements (cf., Miall 1985) such as river channels, or fault zones, considerably affect the reservoir geometry. Of particular importance are discontinuities and heterogeneities that affect the local stress field and therefore fracture propagation and permeability. Geophysical methods, such as seismics, build the basis for a detailed structural model of the subsurface, which commonly is part of geothermal exploration concepts (e.g., Huenges 2010).
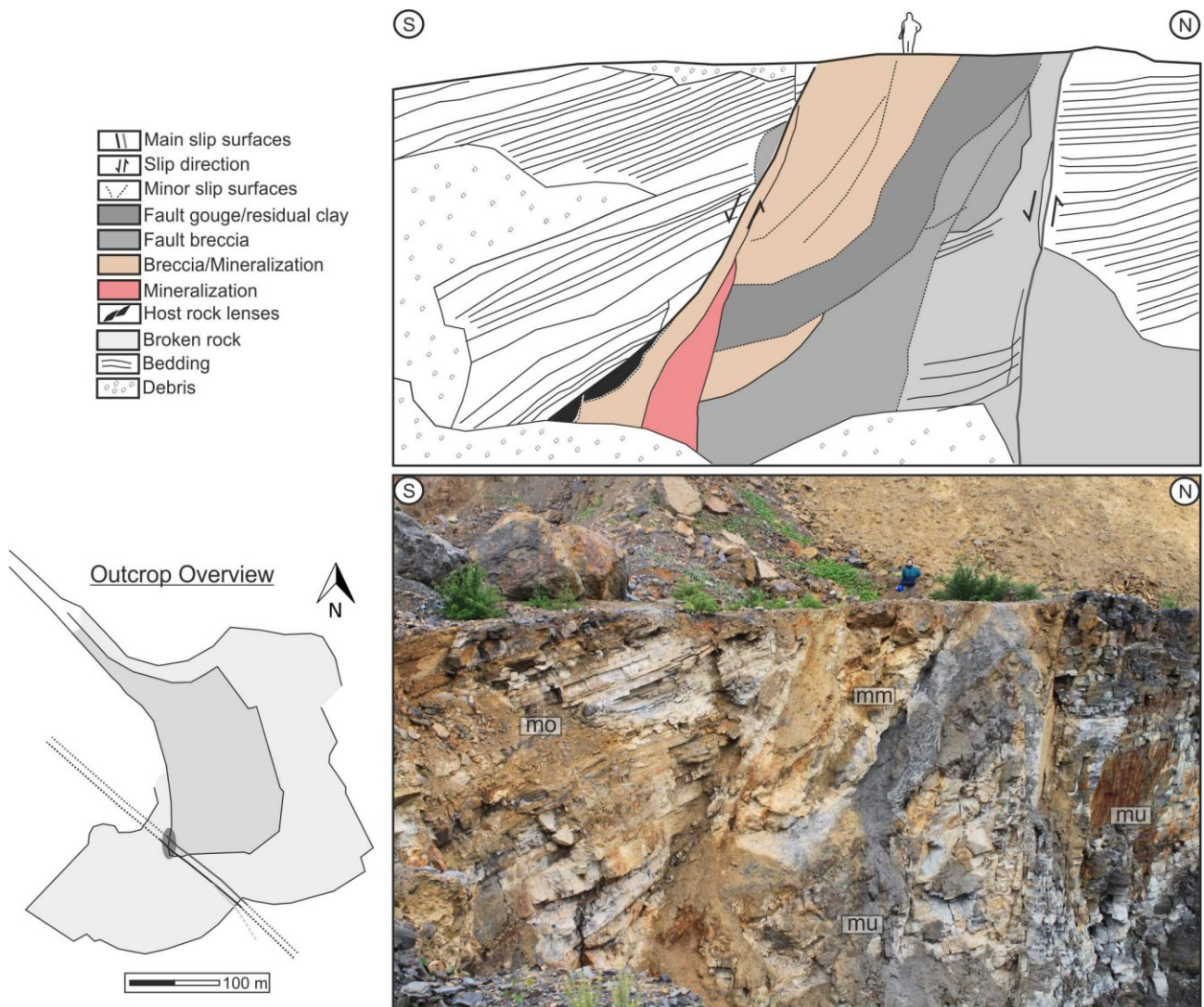

Figure 4: Sketch and field photograph of a normal fault in the Muschelkalk, Kraichgau, Germany (Meier et al. 2015). See person for scale. mo – Upper Muschelkalk, mm – Middle Muschelkalk, mu – Lower Muschelkalk.

3. FAULT ZONE INFRASTRUCTURE AND MODELLING

Because matrix permeability in geothermal reservoir rocks is negligible in most cases and high flow rates are needed for successful geothermal projects, the characterization of fault zones and associated fracture systems is of particular importance (Paschen et al. 2003, Reyer et al. 2012). Fault zones can either act as conduits or barriers, depending on their infrastructure and the local stress field (e.g., Caine et al. 1996).

Widely accepted is a simple fault zone structure with a high-strain fault core consisting of gouge, breccia, and precipitated minerals enclosed by damage zones comprising high fracture density and minor faults reflecting the fault growth (Chester and Logan 1986, Caine et al. 1996, Faulkner et al. 2010). The damage-zone/fault-core model, however, is not applicable to all fault zones due to their formation in different rock types with heterogeneous mechanical properties (e.g., porous sedimentary rocks). Particularly in layered rocks, the fault-zone internal structure can be very complex due to the formation of a very heterogeneous fault core and an asymmetric damage zone, affecting the rock mechanical properties, the local stress field and permeability (cf., Reyer et al. 2012 and references therein; Fig. 4).

As mentioned in section 2, geothermal exploration concepts commonly include detailed structural models (e.g., Huenges 2010) containing information on the reservoir geometry, the structural inventory (fault zones, main fracture orientations, etc.). Ideally, they also enclose available information on the remote stress field. Geomechanical models are useful to plan well paths and adapt mud weights avoiding wellbore instabilities (Péška and Zoback 2007). They can be built based on data of rock mechanical properties, the stress field and reservoir pressures. Numerical models divide ('discretise') the idealized reservoir, or some specific details of it, into an equivalent system of small units ('elements') and solve simultaneous algebraic equations (resulting in numerical approximations) for each element that are then combined into solutions for the entire reservoir. Numerical solutions can be found for complex geometries, heterogeneous and anisotropic rock properties (e.g., mechanical, hydraulic, thermal properties). Therefore, numerical models are used to simulate physical problems when analytical solutions become too complex. Using numerical models, we can, for example, simulate local stress fields, fracture propagation and fluid flow in geothermal reservoirs (e.g., Philipp et al. 2013).

4. FROM FIELD STUDIES TO NUMERICAL MODELS

In this section I focus on some parts of diagram (Fig. 1) by presenting a field-study based workflow to develop 3D-numerical models on local stress fields within fault zones hosted in layered rocks at reservoir depths (cf., Meier et al. 2017). The workflow includes three main steps to receive input data and boundary conditions: (A) characterization of fault-zone units and mechanical layering, (B) estimations of rock mechanical properties and (C) assumptions on the in-situ stress regime. The fault-zone displacements and infrastructure characteristics are based on examples of fault zones in the Middle Triassic Muschelkalk in the Upper Rhine Graben, Germany, described in Meier et al. (2015; see also Fig. 4). The numerical models use the finite element software COMSOL Multiphysics®.

The first step in the workflow are detailed field studies in outcrop analogues. Outcrop analogues are outcrops of the same rock types and same facies (and preferably same stratigraphy) as those supposed to host the man-made reservoir at geothermal depth. Such studies in outcrop analogues are also commonly performed in petroleum exploration to understand the reservoir rocks at depth (Gluyas and Swarbrick 2003). In this example, we worked in Muschelkalk outcrop analogues located in the Kraichgau-Syncline on the eastern graben shoulder of the Upper Rhine Graben (cf., Meier et al. 2015), obtaining data on fracture geometry, fracture systems, fault zone infrastructure, and mechanical layering, of the limestone and marl rocks. The model geometries, however, were simplified due to modelling limitations.

In the numerical models we assume isotropic and linear elastic material as is commonly suitable for upper-crustal rocks (cf., Gudmundsson 2011). Therefore, only two elastic constants, here Young's Modulus E [GPa] and Poisson's ratio ν [-] of the reservoir rocks at geothermally relevant depths need to be defined. In the models, ν is constant at 0.25, and E follows estimations based on laboratory tests of field samples, measured fracture frequencies, analytical models using rock hardness measurements, and general assumptions on Young's moduli variations with increasing depths (cf., Philipp et al. 2013).

The boundary conditions in the numerical models consider all likely in-situ stress regimes in Upper Rhine Graben Muschelkalk reservoirs. The magnitude of the vertical stress (S_V) is easily estimated based on average rock densities down to reservoir depths of 2,900 m. For horizontal stresses S_h (minimum horizontal stress) and S_H (maximum horizontal stress), possible magnitudes are limited by the frictional strength of favorably-oriented faults, obtained using a stress polygon (cf. Zoback, 2007). The stress polygon in this example assumes an average overburden density of 2,300 kg/m³ for the overlying Cenozoic sediments (Rousset et al. 1993, Rotstein et al. 2006), μ of 0.85, and a hydrostatic pore pressure ($P_P = 0.43 S_V$). The stress polygon (Fig. 6) shows that the allowable horizontal stress magnitudes are between $0.55 S_V \leq S_h$ and $S_H \leq 3.10 S_V$. The green dots on the periphery of the polygon indicate stress states in which the crust is at its frictional limit (Zoback 2007) used as boundary conditions in the numerical model series. We applied stress magnitudes of S_H and S_h for a normal faulting regime, a transitional regime from normal faulting to strike-slip faulting (here referred to as transitional regime), and a strike-slip faulting regime (Plenefisch and Bonjer 1997; Homuth et al. 2014). The stress orientations were estimated based on available stress measurements in the Upper Rhine Graben available in the world stress map (Heidbach et al. 2016).

Finally, we discretized the models into tetrahedron-shaped finite elements and run them with a combined iterative linear solver that computed the displacements at all element nodes and stresses within the elements. Figure 6 presents an overview of surface plots of the resulting shear stresses (equivalent stresses) for a series of 12 numerical models of the same geometry. The series consists of four fault-zone orientations (i.e., angle between fault zone strike and maximum horizontal stress S_H: 0°, 30°, 60°, 90°) displayed as downwards increasing angles, and the three possible stress regimes (i.e., normal faulting, transitional, and strike-slip faulting regime) discussed above, displayed as rightwards increasing magnitudes of the applied horizontal stresses S_H and S_h. Other parameters presented in a similar way and discussed in Meier et al. (2017) include principal stresses and displacements.

The results of the local stress fields in fault zones hosted in the layered Muschelkalk carbonate succession show pronounced heterogeneities. The stress orientations and magnitudes depend on the stiffness contrasts in the carbonate succession, stiffness contrasts between softer fault damage zones and host rocks, the fault-zone orientation and the applied stress regime. The decrease of stress magnitudes in soft rocks diminishes towards fault zones oriented at high angles to S_H. Changes in stress magnitudes become more gradual across fault-zone units in fault zones oriented at higher angles to S_H (60°, 90°), particularly in horizontal compression (strike-slip regime). Effects of mechanical layering increase from normal to strike-slip regime resulting in a vertically heterogeneous local stress field. The fault damage-zone and fault core form a transition zone between differing stress magnitudes in footwall and hanging wall if rocks with differing stiffness are displaced against each other, particularly in fault zones oriented at a high angle to S_H. Effects of mechanical layering may, for example, result in the formation of barriers to fracture propagation and thus lower probability of forming interconnected fracture networks necessary for fluid flow in reservoirs.
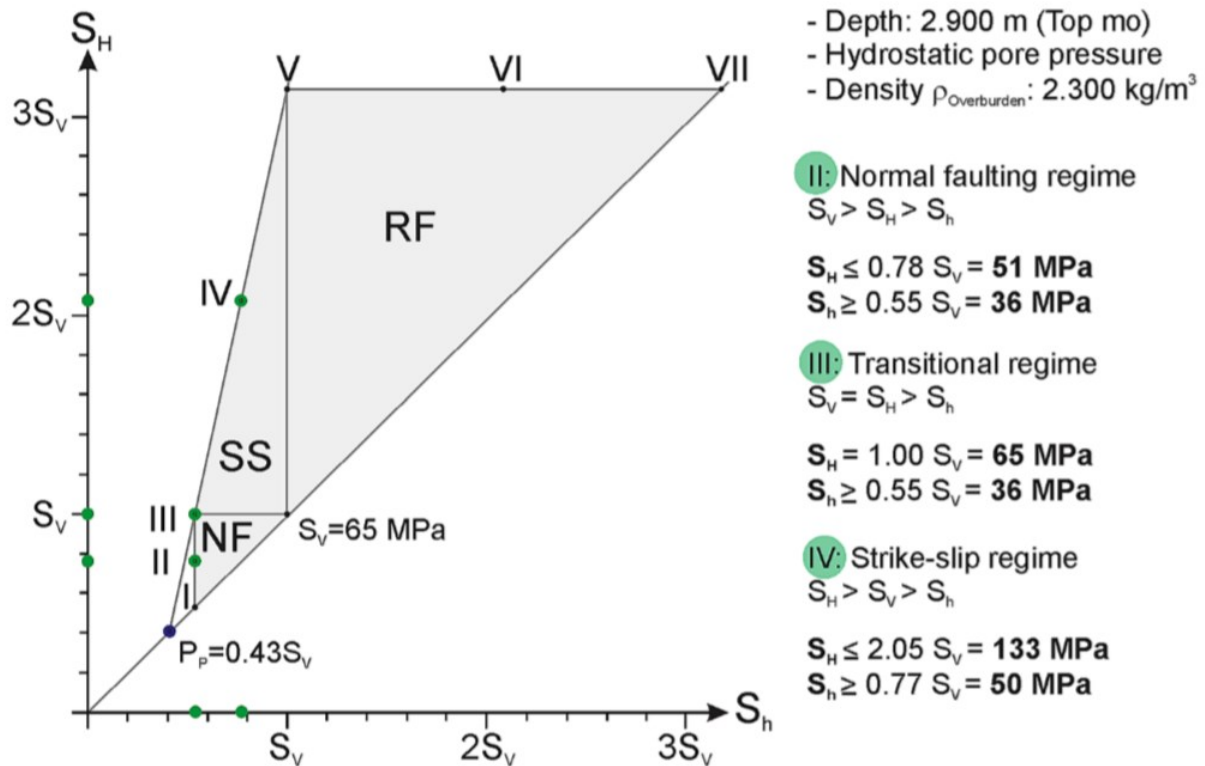

Figure 5: Stress polygon constructed to define the boundary conditions for the numerical models in the presented case study (cf., Meier et al. 2017). The green dots represent selected stress regimes all possibly occurring in Muschelkalk geothermal reservoirs in the Upper Rhine Graben. See text for details.
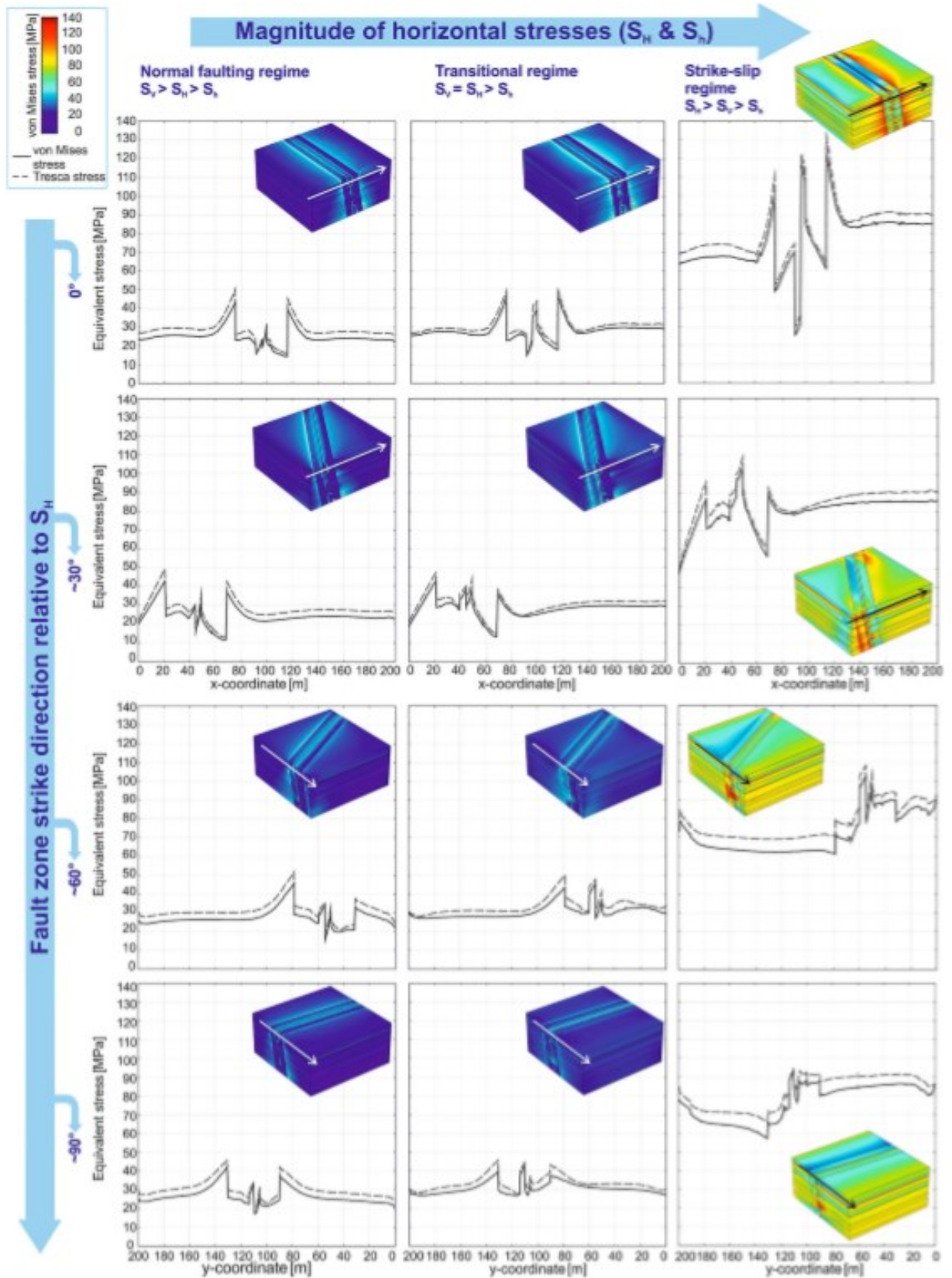
Figure 6: Shear stress magnitudes computed as equivalent stresses (von Mises stress and Tresca stress) [MPa] within a total of 12 3D-numerical simulations of a larger-scale fault zone crosscutting the entire Upper Muschelkalk (3 stress regimes: normal faulting (left), transitional (center) and strike-slip faulting (right) and 4 fault-zone orientations relative to S_H (0°, 30°, 60°, and 90°). The 1D-plots show magnitudes of von Mises stress and Tresca stress versus coordinates. The 3D-surface plots show the magnitude of von Mises stress in the entire 3D-numerical model surface (see color scale; modified from Meier et al. 2017).

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5. CONCLUSIONS

Both for the direct use of fractured geothermal reservoirs, as well as for effective stimulation, the geometry of the existing fracture system and its likely future development need to be known as accurately as possible. The main focus of this contribution is to discuss manifold elements of multidisciplinary approaches, altogether aiming at reliable estimations of potential fluid flow in geothermal reservoirs.

Relevant parameters and processes for reliable estimations include rock facies, diagenesis and tectonic history, which result in heterogeneities in the rock mechanical properties, in particular mechanical layering, complex geometry of individual fractures and fracture systems and fault-zone infrastructure and local stress fields. Multidisciplinary approaches for the investigation of the existing fracture system and potential fluid flow in geothermal reservoirs include field studies in outcrop analogues of rocks, field studies in paleogeothermal reservoirs, as well as core and well log analyses. Geophysical methods are needed to build structural reservoir models. Geomechanical models are useful to plan well paths and adapt mud weights. Numerical models are used to simulate physical problems in reservoirs with complex geometries and heterogeneous and anisotropic rock properties.

The second topic of this contribution is a field-study based workflow to develop 3D-numerical models on local stress fields within fault zones hosted in layered rocks at reservoir depths, including three main steps to obtain input data and boundary conditions: (A) characterization of fault-zone units and mechanical layering, (B) estimations of rock mechanical properties and (C) assumptions on the in-situ stress regime. The fault-zone displacements and infrastructure characteristics are based on examples of fault zones in the Middle Triassic Muschelkalk in the Upper Rhine Graben, Germany. The results show pronounced heterogeneities in the local stress fields. The stress orientations and magnitudes depend on the stiffness contrasts in the carbonate succession, stiffness contrasts between softer fault damage zones and host rock, the fault-zone orientation and the applied stress regime.

The presented studies increase our understanding of fluid flow in geothermal reservoirs. Thus, they contribute to maximize the likelihood of success of geothermal wells and help to improve the planning of well paths.

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