Understanding and predicting coupled hydro-mechanical fracture propagation

Ernesto Meneses Rioseco[1], Dorothea Reyer[2], Rüdiger Schellschmidt[1].

[1] Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany

[2] Georg-August-University of Göttingen, Geoscience Centre, Goldschmidtstraße 3, 37077 Göttingen, Germany

Ernesto.MenesesRioseco@liag-hannover.de

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ABSTRACT

Hydro-mechanical processes involved in geothermal reservoir engineering are highly complex. Apart from additional thermal and chemical effects, their dynamic interaction has been the focus of attention of many geoscientists addressing hydraulic fracturing in natural and engineered geosystems. In particular, hydraulic fracturing represents a key component in enhanced geothermal systems (EGS). Especially the fracture path and geometry in a layered reservoir is influenced by a variety of factors such as different mechanical and hydraulic material properties, different stress regimes in the respective layers, material heterogeneities, interaction with pre-existing fractures, and others.

The North German Basin with its typical low-permeable sedimentary veneer has been the subject of recent intensive geothermal studies to evaluate the potentiality of cost-effective extraction of geothermal energy. Among the prominent projects currently in progress, the project “Hydro-mechanical response of geothermal reservoirs in the stress field generated by complex geological structures is a subproject of the interdisciplinary research association “Geothermal energy and high-performance drilling techniques” (Geothermie und Hochleistungsbohrtechnik “gebo”) in Lower Saxony, Germany. The goal of this subproject is to advance and refine the understanding of the hydro-mechanical behavior of geothermal reservoirs typical of the North German Basin.

Using FRACOD as two-dimensional boundary element code, a series of numerical models involving relevant scenarios were tested. Different numerical simulations with dissimilar layer sequences characteristic of the North German Basin at targeted depths were performed. By means of this a broad range of possible scenarios was examined. Loading conditions provided by previous modelling and data on the stress field in the region under investigation as well as material properties from laboratory data were varied over a wide parameter space. Specifically, the drilling demonstration project GeneSys-Borehole GT1 in Hanover Groß-Buchholz together with vast data obtained from laboratory measurements on specimens typical of the study area have provided valuable constraints on the hydraulic and mechanical properties of the modeled geothermal reservoirs. A multiple fracture scenario is also included to study fracture interaction, an applicable scenario in deeper targets such as vulcanite.

First, preliminary modelling results show that the difference in elastic properties such as Young’s modulus and Poisson’s ratio between the sedimentary layers has little influence on the fracture trajectory. The difference in these elastic properties does not lead to fracture containment or arrest at material interfaces, but rather has an influence on fracture aperture. This corroborates previous field observations but disagrees with recent numerical modelling. Difference in mechanical properties like fracture toughness in mode I and II and their ratio around sediment interfaces proofed to have a significant impact on the fracture path and mode of deformation. Model results demonstrate that with specific but in laboratory measured values of this parameter in both modes of deformation, fracture paths through interfaces may be clinked or splayed and switch to a mixed mode of deformation.

Model results of multiple fracture scenarios reveal the complex interaction of pre-existing fractures with a hydraulically induced fracture. Pre-existing cracks experience displacement and hydraulic changes before they are hit by the hydraulically induced fracture. Moreover, when this latter hits the natural cracks it does not continue its previous path but rather the pre-existing cracks propagate in the direction of maximum shear stress.

1. INTRODUCTION

Geothermal energy has gained significant importance worldwide in the last two decades since it represents an alternative green energy to conventional carbon-based energy. High-temperature fields have a great potential for the long-term extraction of clean energy since they constitute an unlimited and self-sustaining resource of non-pollutant, eco-friendly geothermal energy. Specially hotspots across the world where thermal, hydraulic and tectonic conditions make possible the extraction of huge quantities of energy from the underground has drawn special attention from public, academic and commercial institutions. Prominent examples of such attractive sites in the world are Iceland, New Zeeland and southern Italy where volcanic activity is intensive (Arias et al. 2010, Bignall 2010, Bignall et al. 2010, Harvey et al. 2010). Generally speaking, places where tectonic activity is taking place such as plate boundaries seem to be particularly suitable to recovering considerable amounts of geothermal energy.

Favourable conditions for cost-effective and profitable extraction of geothermal energy include at least high underground temperatures and high hydraulic conductivity of the geothermal reservoir (e.g. Huenges 2010, and references therein). When the latter aspect is not fulfilled the geothermal reservoir has to be engineered to create paths within the rock mass to allow for sufficient heat exchange and fluid production at acceptable extraction rates. This falls under the category of the so-called enhanced geothermal systems (EGS). Basically, they involved hydraulic fracturing the geothermal reservoirs to either connect the hydraulically induced fracture with the natural pre-existing cracks or simply create a possibly large and highly conductive hydraulic fracturing penetrating in the geothermal reservoir as much as possible.

EGS has become very popular in the last decades as it has proofed to substantially improve the thermal output of geothermal reservoirs (e.g. Ziagos et al. 2013). Previously, it has been broadly implemented in the hydrocarbon industry to facilitate the extraction of hydrocarbon resources (e.g. Economides and Nolte 2000, Fisher 2010, Reinicke 2012). Vast and valuable experiences concerning hydraulic fracturing have also been accumulated in a particular form of EGS, the so-called Hot Dry Rock (HDR) systems in the last years (Tischner et al. 2007). A pioneering work intended to study different exploitation concepts of heat from low-permeable crystalline rock mass has been successfully carried out in the early seventies by a team of scientists in Los Alamos National Laboratory, New Mexico, USA (Brown 1012, Tester et al. 2006, and references therein). Since then a great deal of follow-up projects have been initiated across the world to perfect and further elaborate heat extraction concepts from tight sedimentary or crystalline rock. Another outstanding geothermal project launched in Europe to put to the test the workability and usefulness of such HDR heat exploitation concepts constitutes Soultz (e.g. Baumgärtner et al. 2004, Jung & Weidler 2000, and references therein).

Among numerous projects dealing with EGS across the World, the project "Hydro-mechanical response of geothermal reservoirs in the stress field generated by complex geological structures is a subproject of the interdisciplinary research association "Geothermal energy and high-performance drilling techniques" (Geothermie und Hochleistungsbohrtechnik "gebo") in Lower Saxony, Germany (Reinicke et al. 2010). This subproject is generally aimed at advancing and refining the knowledge and understanding of the hydro-mechanical behavior of geothermal reservoirs typical of the North German Basin (NGB). Particularly this part of Germany has been the recent target of extensive studies dealing with the feasibility and practicability at affordable costs of geothermal energy extraction.

The NGB is specifically characterized by relatively highly conductive units deep underground, but exhibits extremely low-permeability and low-porosity sedimentary rocks. Economical and profitable geothermal resource exploitation under the circumstances mentioned before requires the creation of relatively large and highly conductive artificial fractures to improve the heat exchange and production rate, i.e. the performance of the geothermal reservoir. Among the recent EGS research and demonstration sites situated in the NGB, Groß Schönebeck (north of Berlin) (e.g. Blöcher et al. 2010, Legarth et al. 2005, Moeck et al. 2009, Zimmermann et al. 2007), Horstberg Z1 (north of Celle) (e.g. Sulzbacher & Jung 2010, Wessling et al. 2008), and GeneSys GT1 (in Hannover) (e.g. Jung et al. 2005; Kehrer et al. 2007; Orzol et al. 2004, 2005; Tischner et al. 2010, 2013, and references therein) constitute classic examples of remarkable efforts made to put to the test different drilling and geothermal concepts intended to evaluate the potentiality and practicability of small-scale deep geothermal energy extraction under such harsh hydraulic conditions.

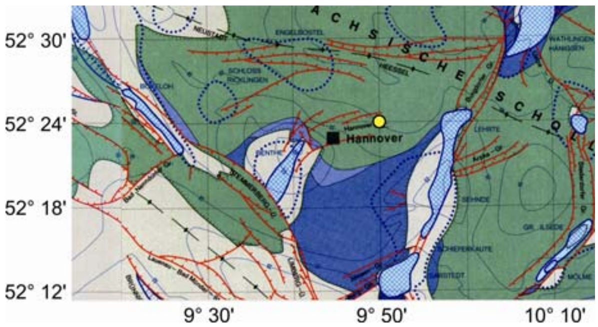

Figure 1: Map showing a representative part of the North German Basin (NGB) in the region of Lower Saxony, Germany. The location of the drilling demonstration site GeneSys Groß-Buchholz is depicted with a yellow circle. Light blue shaded areas display salt diapirs. This map has been drawn with the help of the geotectonic atlas of NW Germany (Baldschuhn et al. 2001).

Specifically the GeneSys project (GeneSys: Generated geothermal energy systems), situated in Hannover Groß-Buchholz (Fig. 1), is aimed at supplying geothermal heat to the GEOZENTRUM Hanover with a thermal output of 2 MW. To achieve this, the planning and designing of adequate utilization concepts has been pivotal for the encountered tight (low-permeable) sediments of low porosity. The GeneSys project of the Federal Institute for Geosciences and Natural Resources (BGR) essentially involves the arrangement of single-well concepts as well as the employment of water-frac techniques to sedimentary rocks, see Fig. 2. An extensive and in-depth description of target, goals as well as milestones reports of this demonstration site can be found in www.genesys-hannover.de. The data collected in this project has provided valuable constraints. Therefore, similar geological scenarios to the encountered sediment layers at the targeted depth were assumed in the present study to possibly answer key questions raised within the framework of the GeneSys project.

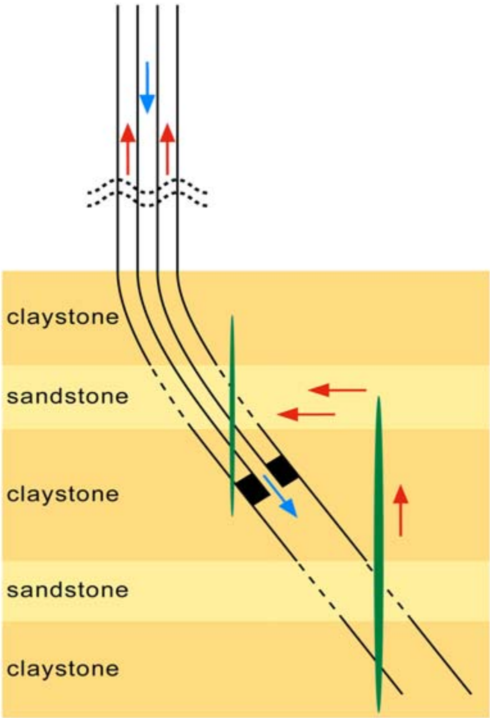

Figure 2: Schematic representation of the drilling, injection as well as extraction concept drawn and implemented in the framework of the GeneSys Groß-Buchholz GT1 geothermal drilling project. Note the large vertical hydrofractures (vertical green elliptical features) planned as part of the production concept.

Studying fluid-driven fracture path and geometry is at the heart of every geothermal project dealing with EGS in low-permeable rock formations. Key questions also raised within the GeneSys project concern the fracture trajectory, the fracture dimensions, and factors controlling them. Apart from the complex hydro-mechanical dynamic interaction that extensively dominates fracture initiation and further propagation, a variety of factors directly affects the fracture passage and geometry (e.g. Naceur et al. 1990, and references therein). Among these factors counts the elastic properties of the involved sedimentary veneers, the mechanical intrinsic properties (e.g. fracture toughness), the hydraulic properties of the rock matrix, the mechanical and hydraulic properties of the interfaces between different materials involved, the in-situ stress distribution, and pre-existing fracture network, fracture density, fracture percolation etc (e.g. Gudmundsson 2011, McClure 2012, McClure & Horn 2013, Rossmanith 1998, and references therein).

Although remarkable progress in understanding fracture formation and growth has been achieved in the last decades, the science and engineering of fluid-driven fracturing, and in particular the hydro-mechanical processes involved, are not completely understood and are therefore the subject of a great deal of recent and current investigations. Especially, understanding the hydro-mechanical coupling and feedback have been the focus of numerous scientific and engineering works (e.g. Adachi et al. 2007, Economides and Nolte 2000). Theoretical (e.g. Detournay 2004, Anderson 2005, Gudmundsson 2011, and references therein) and numerical efforts (e.g. Adachi et al. 2007, McClure 2012, McClure & Horn 2013, Mutlu and Pollard 2008, and references therein) have been devoted to refining and improving the knowledge of the mechanisms involved.

Whereas field observations (Cooke et al. 2000, De Joussineau et al. 2007, Granier 1985, Leroy and Sassy 2000, Segall and Pollard 1983, Willemse et al. 1996, and references therein), *in-situ* and laboratory experiments (e.g. Fisher and Warpinski 2012, Teufel and Clark 1984, Warpinski et al. 1982), as well as theoretical considerations derived from the preceding studies have substantially helped shape a more complete picture of the behaviour of fluid-driven cracks; their complex dynamic hydro-mechanical behaviour, their geometry and interaction with the rock matrix and natural pre-existing cracks can only be study at large spatial- and time-scale on computers. Fully coupled hydro-mechanical numerical models that consider fracture initiation and fracture propagation in at least two modes of deformation as well as fracture interaction are extremely rare. FRACOD is a promising code still in progress that includes these model capabilities (Shen et al. 2013).

Using FRACOD, as two-dimensional boundary element code, the present study addresses the hydro-mechanical behaviour of fluid-driven fractures in layered reservoirs with similar loading conditions and material properties to the ones encountered at targeted depths in GeneSys Groß-Buchholz GT1 and in general typical of the NGB region. In addition, fracture interaction between hydraulically induced and natural fractures is included to come closer to more realistic conditions at deeper targets such as vulcanite. This work focuses on fracture path and fracture geometry controlling factors such as differently stratigraphically layered reservoirs with differing elastic properties and fracture toughness, as well as the influence of the interaction between pre-existing cracks with the newly generated hydraulic fracture on the fracture trajectory and dimensions.

2. MODEL SETUP AND PHYSICS BEHIND

Because of the data wealth collected within the framework of the GeneSys project, similar reservoir layering and material properties to the ones encountered at targeted depths were adopted. This makes possible to answer crucial questions raised within the GeneSys project related to fracture path and fracture geometry under similar loading and hydraulic conditions. Additional important data on the mechanical properties of rocks typical of this region has been provided by Reyer and Phillip (2013) and Backers and Stephansson (2012). The considered layered reservoir scenarios are displayed in Fig. 3, 4, and 5.

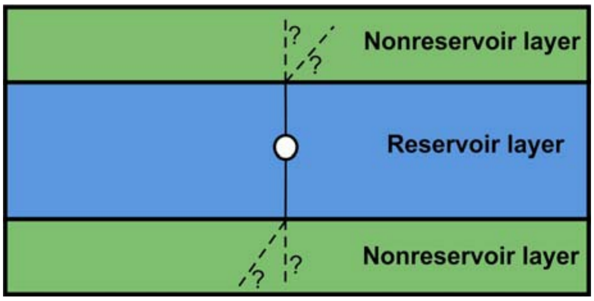

Figure 3: 2-D model setup of layered reservoir with vertically symmetric layering. A specific case typical of the NGB represents a sandstone layer (reservoir layer) with overlying and underlying claystone layers. The write circle in the middle depicts the injection hole from which the hydraulically induced fracture (black lines) propagates. Black dashed lines denote possible paths of the through-going fractures.

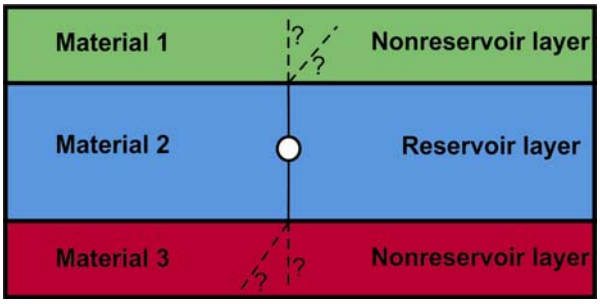

Figure 4: Analogous to Fig. 3, this case concerns a three-layered scenario of vertically asymmetric distribution of sediments. A combination of three possible sedimentary layers encountered at targeted depths in the NGB may be halite, sandstone and claystone or siltstone alternated with two of the other preceding sedimentary rocks. White circle and white solid as well as dashed lines are described in Fig. 3 caption.

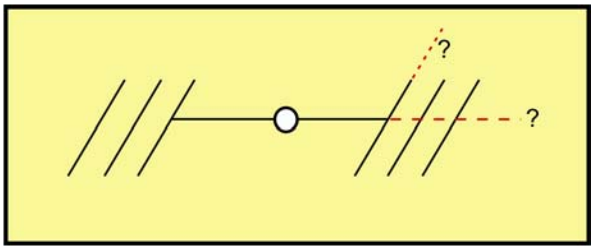

Figure 5: Model setup considering a multiple fracture scenario relevant to deeper geothermal reservoirs in the NGB such as vulcanite. Black inclined solid lines represent pre-existing cracks. Red dashed lines denote possible fracture propagations after the hydraulically induced fracture hits the pre-existing cracks. See also Fig. 3 and 4 captions for further picture details.

The in-situ or far-field stresses in the reservoir region have been assumed according to previous geo-mechanical modelling (Meneses Rioseco et al. 2013) and the results of a minifrac test performed in the context of the GeneSys project. In addition, data on the regional/local stress field recently published by Röckel and Lempp (2003) was also taken into account. Finally, the loading conditions as well as the material properties were varied over a wide range. Fluid pressure was held constant during the whole simulation time for all the models considered in the present study.

2.1 Modelling technique and underlying physics

To address the hydro-mechanical coupling mechanism in the geothermal reservoir, the code FRACOD was selected (Shen et al. 2013). This fracture initiation and propagation code is a two-dimensional boundary-element numerical tool especially designed to capture the fundamental features of the fully coupled hydro-mechanical behaviour of a rock matrix exposed to mechanical and hydraulic loading (see Fig. 6 and 7). It employs more specifically the Displacement Discontinuity Method (DDM). FRACOD is particularly appropriate for modelling fracture initiation and fracture growth in elastic and isotropic media (e.g. Shen and Stephansson 1992, 1993a,b, Shen 1994, 1995, Shen et al. 1995, 2002, 2004, 2013).

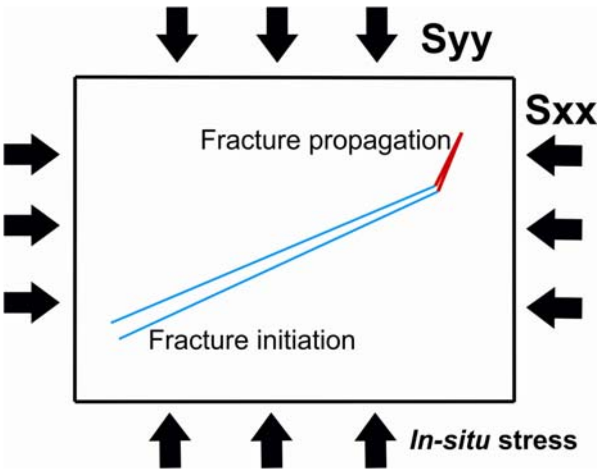

Figure 6: Cartoon representing fracture initiation and further propagation within far-field or *in-situ* stresses as considered in FRACOD.

Fracture initiation is modelled utilizing the well-known Mohr Coulomb failure criterion. Fracture propagation or the possible crack growth behaviour is simulated using a modified G-criterion (G: strain energy release rate) suggested by Shen and Stephansson (1993a,b). A more detailed description can be found in the user manual of FRACOD.

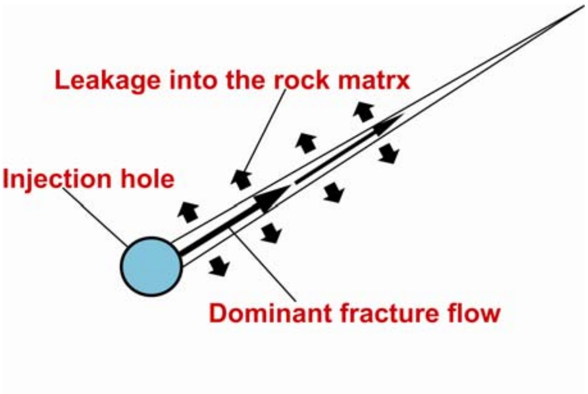

Figure 7: Schematic representation of the fluid flow mechanism considered in FRACOD. Note the predominant fracture fluid flow and minor drainage into the rock mass.

In tight sedimentary rocks or cracked hard rock, e.g. granite, fluid flow takes places fundamentally through fractures. Porous flow, though negligible under such exceedingly low-permeable conditions, is modelled using Darcy's law. Especially fluid withdrawal from fracture regions to the rock mass or vice versa is incorporated in FRACOD by Darcy's law. The fluid flow in fractured domains is implemented in FRACOD using the channel flow, more explicitly given by the cubic law, whereby the fluid flow is proportional to the fracture aperture to the power of three.

Finally, fluid pressure contained in fractures may lead to fracture walls displacement, further opening fracture width, or eventually fracture growth. These effects basically summarized in fracture mechanical deformation and propagation directly influence in turn the fracture hydraulic conductivity and possibly generate new fluid conduits. This dynamic interaction between fracture mechanical reactions to fluid flow alterations and feedbacks is a crucial component in coupled hydro-mechanically processes and it is appropriately handled in FRACOD.

2. MODEL RESULTS

A variety of models was tested with different vertical lithological stratification typical of the targeted depths envisaged in GeneSys project or in general of the NGB reservoir-relevant encountered layering. On the basis of laboratory values as well as core and log measurements of elastic parameters and mechanical (e.g. fracture toughness in mode of deformation I and II) and hydraulic parameters (e.g. hydraulic conductivity of the rock matrix and porosity) the possible fracture path and geometry were examined. Factors controlling fracture trajectory through interfaces between different sedimentary sequences were study. A special case of multiple fracture interaction is included to simulate the case of deeper reservoirs such as vulcanite, where multiple pre-existing cracks are expected. Because of the extent of this manuscript, only the most striking resulting cases are presented here.

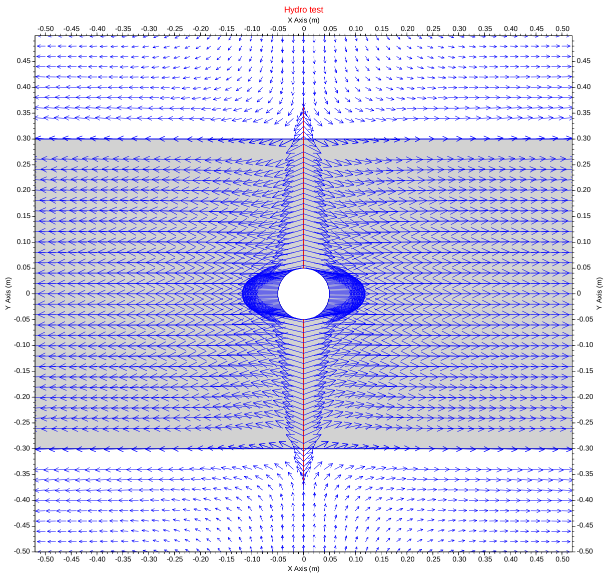

Figure 8: Schematic representation of the fluid flow mechanism considered in FRACOD. Note the predominant fracture fluid flow and minor drainage into the rock mass. Different background colours (white and gray) refer to different material properties. Red solid line depicts the hydrofracture. White circle displays the injection hole. Blue arrows exhibit the displacement field.

Several scenarios of sandstone layers sandwiched with claystone layers as well as different combinations of three-layered reservoirs with halite, sandstone, claystone and siltstone were considered. The elastic parameters of these materials were additionally varied over a wide range to assess the impact of the variation of such parameters on fracture arrest and fracture deformation in general.

Model results show that varying the Young's modulus and the Poisson's ratio over a wide range of values do not lead to fracture arrest but rather fracture containment, whereby fractures going through material interfaces experience damping. This has already been observed in experimental and *in-situ* experiments (e.g. Fisher and Warpinski 2012, Teufel and Clark 1984, Warpinski et al. 1982). These model results, however, contradict previous numerical modelling concerning hydraulic fractures intersecting geological formations of similar type (Jung and Sperber 2009). Moreover, these results strengthen the point that the concepts envisaged in the GeneSys project of generating hydraulically-induced fractures crossing material interfaces and connecting hydraulically different sediment layers are feasible. At least the contrast in elastic properties of the different materials does not seem to arrest or deflect the fracture at the material interfaces (see Fig. 8 and 9). However, this needs to be taken carefully since some simplifications are made in this modelling. For instance, it is known from field and laboratory observations that the interfaces themselves play a considerable role in fracture path. Under certain conditions, most likely at shallow depths, the boundedness of the interfaces may be not strong enough and the vertical hydrofractures, when hitting the material contacts, may continue along the material contacts, in the literature known as T-shaped fracture (see for instance Gudmundsson 2011, and references therein). At considerable depths, as is the case of the targeted depths in the GeneSys project such effect can hardly be expected.

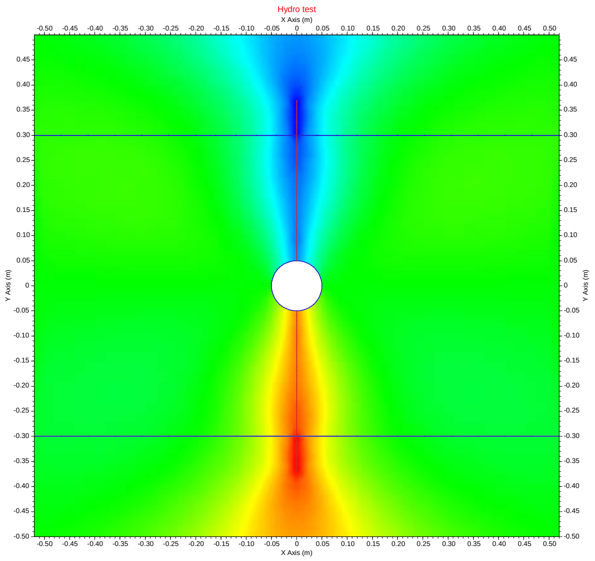

Figure 9: Deformation distribution related to fracture propagation. The corresponding colour bar is preferentially omitted and here explained. Maximum negative displacement (on the order of 6.0x10^{-5}m) is depicted with dark blue. As the displacement dies out the blue colour get lighter and lighter. Green colour denotes almost no deformation. The dark red colour corresponds to maximum positive displacement (also on the order of 6.0x10^{-5}m). As deformation lessens the red colour gets lighter and lighter and goes into yellow. Other picture features are explained in figure caption 8.

Another important aspect relates to the fracture aperture. Model results demonstrate that depending on the contrast in the elastic properties of the different material layers the fracture aperture may exhibit different values. In stiffer materials the fracture seems to suffer more squeezing, or in other words, the fracture conductivity seems to be slightly reduced. This may have significant implications for the spatiotemporal evolution of the hydraulic behaviour of hydrofractures and the different flow regimes (e.g. linear, bilinear and radial) in the injection and shut-in phases of hydraulic stimulation (Wessling et al. 2008).

Mechanical material properties such as fracture toughness (mode I and mode II of deformation) corresponding to the differently stratified sequences of sedimentary material seem to influence fracture path through material contacts and its hydraulic properties in the newly entered material domain. Values of fracture toughness in mode I and II of deformation were first taken from laboratory data on samples typical of the study area and later varied over a relatively broad range. Although some laboratory values are available, in general data on fracture toughness in mode II of deformation is very scarce.

Especially for a range of values of these two parameters close to one another the fracture path deviates from its initial orientation when crossing material interfaces (see Fig. 10 and 12). Besides, the fracture mode switches from a fluid-filled extensional fracture to a shear-dominated fracture. This has direct implications for the hydraulic properties of the through-going fracture. The hydraulic conductivity of the section of the fracture that has traversed through the material contacts has been drastically reduced (see Fig. 11).

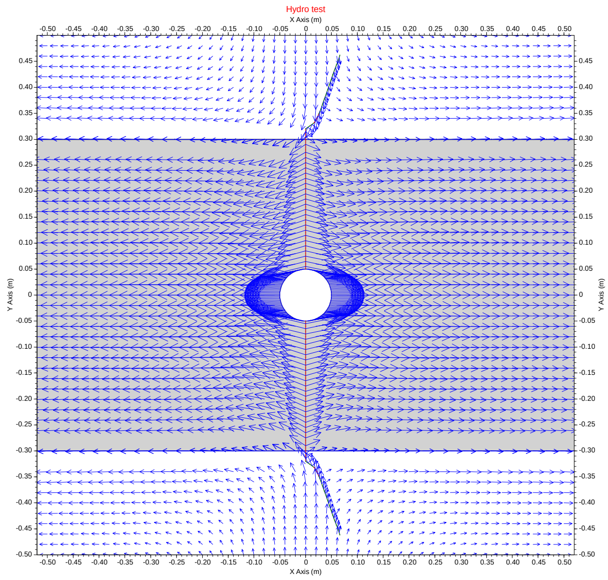

Figure 10: Similar to Fig. 8, the fracture-induced displacement field around an injection hole and hydraulically generated fractures is displayed. Red lines depict open, fluid-filled, hydraulically induced fractures. Green lines denote slipping fractures. Note the fracture deflection after crossing the material contacts and the switch to model of deformation II.

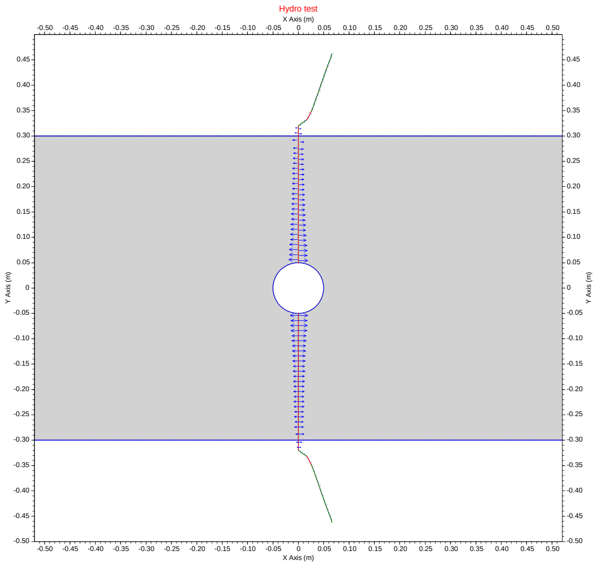

Figure 11: Fracture aperture or fracture-perpendicular displacement corresponding to the case displayed in Fig. 10. Blue arrows show the displacement field. Other features of this picture can be read in the figure captions 8, 9, and 10.

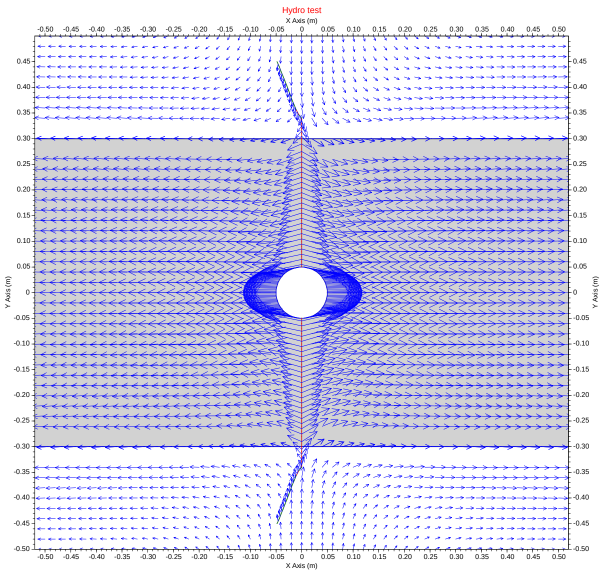

Figure 12: Displacement field and fracture path caused by a hydraulically generated fracture and its advancing through different sedimentary material. See previous figure captions of this section for other features of this picture.

Since dissimilar kinds of cracks/fractures originate in different orientations with respect to the *in-situ* or far-field stresses that apparently persist at the time of fracturing (e.g. Mutlu and Pollard 2008, and references therein), several scenarios were setup to model the hydro-mechanical interaction between multiple pre-existing fractures and a fluid-driven fracture. As mentioned earlier, these scenarios are relevant for deeper sections of the upper crust (e.g. vulcanite), also envisioned for future geothermal projects in the study area that equally requires hydro-fracturing. Properly classifying fracture types and fracture mechanical and hydraulic properties is a crucial component for assessing the orientation of fracture populations as an entire entity and hence for envisaging ideal drilling trajectories and designing reservoir models.

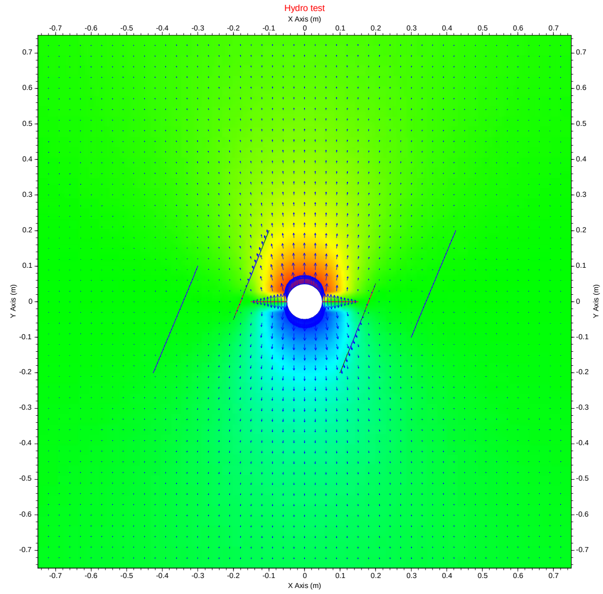

Figure 13: Initial displacement field concerning the scenario of multiple pre-existing joints and their interaction with a newly hydraulically generated fracture. Blue inclined lines depict natural pre-existing joints closed (both walls of the fractures are in contact, no fluid content). Red lines as well as explanations for the colour bar can be read in previous figure captions in this section.

As Fig. 13 shows, four natural cracks (blue solid inclined lines) are placed within the reservoir with a randomly selected orientation with respect to the *in-situ* stress field. As the hydraulically induced fractures advance, the pre-existing fractures walls already slide past each other as a result of the “pressure wave”. Some sections of the pre-existing cracks, close to the advancing hydrofractures tips, even experience fluid-filled extension deformation (see Fig. 13). Already at this stage of the advancing, hydraulically induced fracture, it is clear that different cracks/fractures or joints are characterized by different hydraulic properties (see Fig. 15). Although at the present stage of this work only one model material has been selected where fractures are embedded, it is expected that special kinds of fractures generate solely in specific rock types or in particular geologic settings.

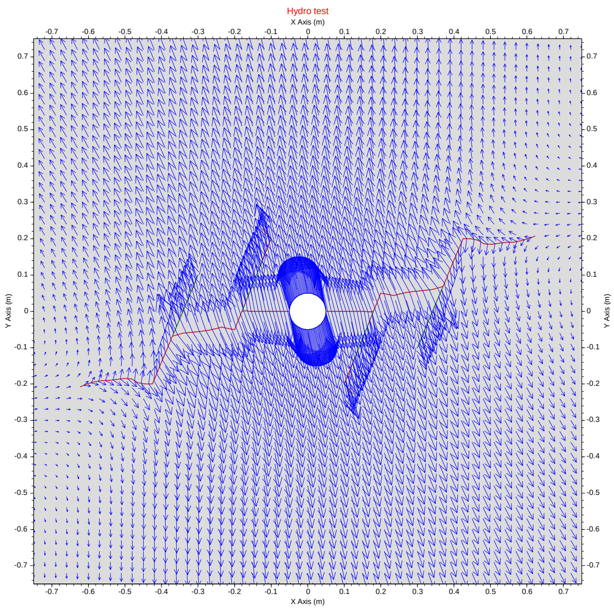

Figure 14: Displacement field at an advanced stage of modelling corresponding to an initial scenario illustrated in Fig. 13. Note how the newly hydraulically generated fracture coalescence with the pre-existing joints. See text and other preceding figure captions of this section for further details.

Fig. 14 displays the fracture interaction between four pre-existing fractures and a newly hydraulically induced fracture (see Fig. 13) in an advanced stage of the modelling. As shown in Fig. 13, at the beginning of pressurisation the hydrofracture propagates in the direction of one of the exerted boundary stresses. When running into the pre-existing joints the fluid pressure creates a fracture at the tips and the newly generated fracture tends to coalescence with the neighbouring pre-existing fracture (see Fig. 14). Furthermore, the new fracture created at the tip of the pre-existing joints, propagates in the direction of maximum shear applied to the entire host rock. Hence, the pre-existing cracks/joints or fractures exhibit a controlling character on the hydro-mechanical properties of the rock matrix. This is line with similar modelling previously performed by Shen et al. (2013).

Hydraulic properties, and in particular the fracture conductivity spatiotemporal evolution can be better seen in Fig. 15 and 16. Initially, the hydraulically induced fracture has much greater hydraulic conductivity than the pre-existing joints. As the hydraulically generated fracture advances and hits the pre-existing joints, different sections of the latter are hydraulically activated and show significant hydraulically conductivity (see Fig. 16). Especially the newly originated fractures stemming from the pre-existing joints tips take up a considerable part of the hydraulically conductivity of the fracture system, playing a hydraulically prominent role.

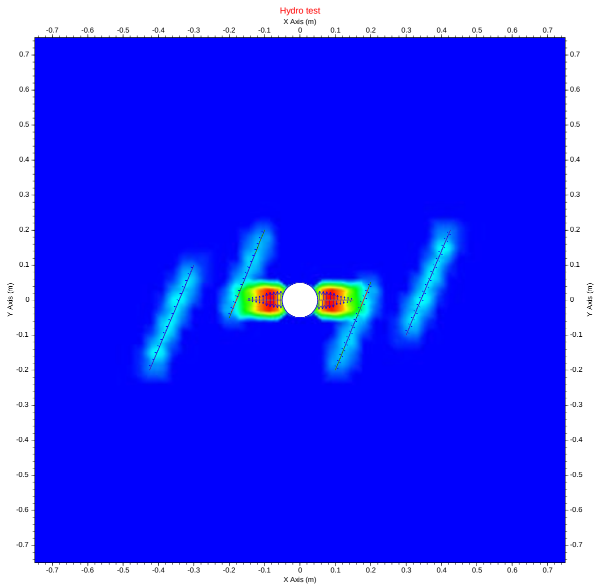

Figure 15: Hydraulic conductivity of fractures and porous rock matrix corresponding to the initial case displayed in Fig. 13. The colour bar has been preferentially omitted. Dark blue (background colour of rock matrix) corresponds to minimum permeability ($1x10^{-9}m^2$). Rock matrix permeability has been set to $1x10^{-19}m^2$. As domains gets more conductive the blue colour gets lighter ($6.3x10^{-9}m^2$). Highly conductive fracture domains (green to yellow colours) exhibit permeabilities on the order of $1x10^{-7}m^2$ – $2.5x10^{-6}m^2$. Maximum values are depicted with red colour and on the order of $1.6x10^{-5}m^2$. See text for details.

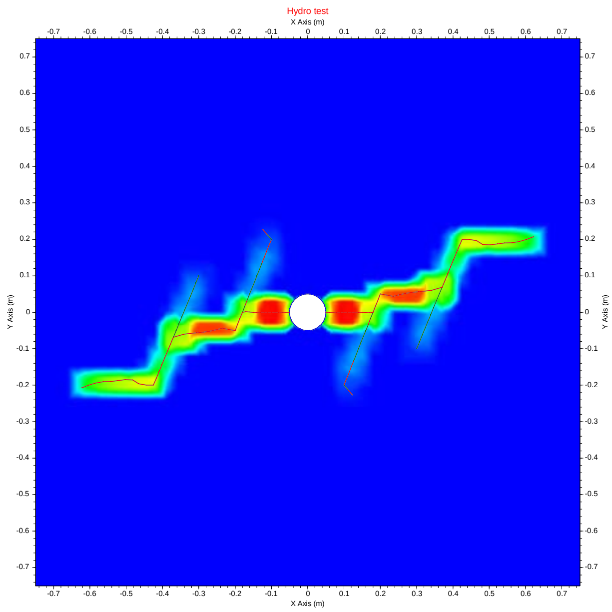

Figure 16: Hydraulic conductivity of fractures and porous rock matrix corresponding to an advanced stage of modelling case displayed in Fig. 14. Further details can be read in the preceding figure caption and other figure captions of this section.

Obviously, there are other mechanisms such as so-called stress barriers that may significantly contribute to fracture arrest. Extensive literature can be found about this issue (e.g. Naceur et al. 1990, Gudmundsson 2011, and references therein). Fracture arrest and confinement due to considerable stress differences between material layers is considered to be the most effective mechanism. However, this does not constitutes the focus of this study.

3. SUMMARY AND CONCLUDING REMARKS

Using FRACOD as boundary-element two-dimensional numerical tool, a variety of models was tested aimed at studying factors controlling hydrofracture path and geometry in different geological settings. Especially the hydro-mechanical response of fluid-driven fractures under region-specific mechanical and hydraulic loading conditions was investigated. Possible fracture trajectory and geometry controlling model parameters such as Young's modulus and Poisson's ratio as well as fracture toughness in mode I and II were varied over a broad range of region-specific values from laboratory experiments. Particular focus was given to scenarios involving lithologically layered sediment sequences typical of the North German Basin. Typical sediment layering (Middle Bunter) as encountered at targeted depths in the GeneSys-Borehole GT1 geothermal demonstration site was adopted for the numerical simulation since the GeneSys project provided valuable constraining data for the modelling. In addition, scenarios involving the hydro-mechanical interaction between multiple pre-existing joints and a newly hydraulically generated fracture were considered, as this would be the case of deeper laying vulcanite formations that may be the future targets of hydraulic stimulation.

First, preliminary model results reveal important features of the cracks/fractures growth pattern over a broad parameter range and loading conditions. Simulation results show that in scenarios considering sandstone sequences sandwiched between overriding and underlying sequences of claystone, halite or siltstone layers, elastic properties such as Young's modulus or Poisson's ratio do not seem to arrest hydrofractures growth at material interfaces. This means that as far as elastic properties are concerned, hydrofractures connecting different sediment layers as envisaged in the GeneSys project are realizable. However, the hydrofracture aperture may experience contraction while crossing material interfaces. This corroborates previous laboratory and field observations. Another fracture path and geometry controlling factor is the fracture toughness in mode I and II and their ratio. Model results demonstrate that considerable differences in this material property between adjacent material layers may lead to significant deflections of the fracture trajectory when crossing material contacts. Besides, the fracture deformation mode may switch from opening to shearing. This is in accordance with the obtained reduction in fracture aperture in lithologically layered reservoir. This has considerable implications for the dynamic hydro-mechanical behaviour analysis of hydrofractures.

Numerical simulations of the hydro-mechanical interaction of multiple pre-existing cracks with a newly, hydraulically created fracture clearly demonstrate that some shear displacement is accompanied by the opening mode of deformation in naturally pre-existing joints, ahead of meeting the advancing, hydraulically generated fracture. This is in line with previous modelling and theoretical considerations claiming that as pressure in the rock matrix grows, the effective principal stresses exerting on the natural cracks are reduced, facilitating shear movement along natural fracture walls. Moreover, model results show that when the newly, fluid-driven fracture encounters the pre-existing joints, it does not continue its previous path trend. Pre-existing fractures experience dramatic hydraulic and mechanical alterations, and they tend to propagate at their tips in the direction of the maximum shear stress. While initially propagating in the direction of the minimum stress component, the growth of the newly, hydraulically induced fracture is severely affected by the pre-existing fracture network. The fracture system experiences major hydraulic alterations. While the initial hydrofracture shows comparatively high values of hydraulic conductivity over the entire simulation time, only some sections of the pre-existing cracks significantly open and serve as valuable hydraulic paths, exhibiting considerable fracture aperture. Some others, however, show only shear mode of deformation.

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