Thermal stimulation of the deep geothermal wells: insights from the H2020-DEEPEGS project

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Keywords: DEEPEGS, EGS, stimulation, thermal, Iceland, France

ABSTRACT

Enhanced/Engineered Geothermal System (EGS) generally requires well stimulation to enhance the injectivity to commercial levels. This stimulation step still constitutes a challenge to permit large-scale deployment of this renewable energy.

The present work is focused on thermal stimulation, which is often underestimated, and very little investigated. However, it may constitute a key effect especially in geothermal wells, for which temperature differences between the fluid and the formation are expected (either intentionally during dedicated stimulation, or less intentionally during drilling and operations).

Thermal stimulation can lead to both thermal shearing and thermal fracturing. We model both processes, respectively through analytical and numerical modelling, applied to two EGS demonstrators in the frame of the H2020-DEEPEGS project. The first demonstrator, located in Iceland, is characterized by very high rock temperature, and is likely to encounter high thermal stimulation (both by shearing and by fracturing). The second demonstrator, located in France corresponds to lower rock temperature. In spite of uncertain context (stress state, rock properties, etc.), it appears that thermal stimulation is likely to lead to the re-opening of the pre-existing sealed fractures.

1. INTRODUCTION

The Enhanced/Engineered Geothermal System (EGS) constitutes a promising renewable energy technology to produce heat and/or electricity from deep geothermal resources. White Paper published under the IPGT partnership (International Partnership for Geothermal Technology) states the following (IPGT, 2012): "Reservoir stimulation is the single most critical research area for enabling the development of commercial EGS technology. Stimulation also provides a method to increase production in conventional geothermal wells and low permeability regions of otherwise productive geothermal systems." The H2020-DEEPEGS project (grant agreement No 690771) aims at demonstrating the feasibility of EGS for delivering energy from renewable resources in Europe. In this framework, two deep geothermal wells in Iceland and in France were drilled to demonstrate the EGS technology in different geological contexts.

The first demonstrator (RN-15/IDDP-2) located in Reykjanes (Iceland) targets the sheeted dyke complex in a magmatic field. It is a high temperature reservoir (more than 450°C expected) at 4460 m TVD. The second demonstrator located in Vendenheim (France) targets a normal fault in the plutonic basement, in the Upper Rhine Graben, with temperature around 200°C. In both cases, short time injectivity index was estimated lower or equal to 3.1 $L.s^{-1}.bar^{-1}$ at the end of the drilling operation. This confirms the necessity of stimulation methods to enhance the injectivity to commercial levels.

Stimulation operations are commonly part of the completion programs of conventional geothermal wells worldwide, both in high-temperature volcanic environments and in lower temperature fracture-controlled convective systems and deep sedimentary systems. The purpose of such operations is to enhance the output of the wells, either by improving near-well permeability that has been reduced by the drilling operation itself, or to open up hydrological connections to permeable zones not directly intersected by the well in question. The methods generally used are based on the activation of mechanical, thermal and/or chemical mechanisms that drive to rock permeability enhancement (modified from Axelsson and Thorhallsson, 2009).

In this paper, we will focus on the thermal stimulations that can lead to pre-existing-fracture shearing and/or rock fracturing. We will discuss its effects on both demonstrators. Indeed, this potentially mixed-mechanism stimulation (using the term defined by McClure and Horne, 2014) has been used on the Icelandic well and it is planned for the French wells. Note that other technologies have been used or are planned for both demonstrators such as hydraulic stimulations (both demonstrators), chemical stimulations and dual-laterals drains (French demonstrator). Within the set of available technology, thermal fracturing is very attractive compared to the other options for cases for which flow can be restored or enhanced by the generation of a relatively near wellbore fracture network that will (hopefully) reconnect to a main reservoir flow system. The fluids commonly used during thermal stimulation of geothermal wells are indeed harmless, easy-to-prepare, with simple chemistry (compared to those used for hydraulic stimulations), low demanding in terms of equipment and usually low cost (Flores et al., 2005). Flores et al. (2005) claim that thermal fracturing is potentially the most attractive, but least understood, stimulation technique and that no well-founded methodology to design such well treatments was available at that time. For instance, a standard procedure for conducting thermal stimulation operations has not been established yet, and the mechanism of cold-water stimulation is still poorly understood. Even though some time has passed since the publication of their paper, a well-founded methodology is still lacking.

In this paper, after a state of the art on thermal stimulation, we present the method and the tools used for a first assessment of the efficiency of the stimulation depending on the suspected involved geomechanisms. In the fourth and fifth paragraphs, after a brief description of the demonstrators, we present the thermal stimulations (done or planned) and the results of the assessment of thermal stimulation potential efficiency. The results are then discussed.

2. THERMAL STIMULATION: STATE OF THE ART

2.1 Mechanisms

Covell (2016) describes what is involved in thermal stimulation, according to the most recent understanding: thermal stimulation is driven by thermal contraction caused by the significant temperature difference between cold injection of fluid and hot reservoir rock formation, which can enhance near wellbore permeability.

Several mechanisms that may enhance reservoir permeability through thermal stimulation include (modified from Covell, 2016): 1) the widening or reopening of pre-existing fractures due to thermal (cooling) rock contraction, 2) the shearing of pre-existing fractures after widening/reopening, 3) the creation of new fractures due to thermal contraction (thermal fracturing), or 4) the development of secondary fractures due to the contrast in the thermo-elastic properties of the mineral components of reservoir rocks. In-situ permeability increase linked to thermal stimulation is difficult to associate to fracturing or shearing. However, from a theoretical point of view, both mechanisms can be distinguished.

From a physical point of view, the injection of a fluid colder than the rock mass into a deep reservoir could potentially cause thermo-mechanical disturbances resulting in rock weakening. Indeed, the thermal solicitation induces differential strains at the origin of thermo-mechanical stresses. When these stresses exceed the mechanical resistance of the rock, microcracks and failures could appear (thermal fracturing). Strains at the origin of this process can be mainly due to (Siratovich et al., 2015): 1) microcracks between grains with different thermoelastic moduli or between similar, but misaligned anisotropic grains (differential and incompatible thermal expansion); 2) microcracks may also be initiated within individual grains at internal boundaries which are sites of thermal gradients; 3) thermo-chemical mechanisms may also be involved, such as bursting of fluid inclusions, mineral decomposition, devolatilization.

Thermal shearing is the shearing of a fracture (natural or induced by previous stimulation processes) due to thermal loading. This phenomenon is very under-studied as most authors attribute shear slip on fractures to an increase in the pore pressure field linked to water flow. But the pore pressure increase does not necessarily correspond to the existence of flow and several authors show that injection pressure in geothermal reservoirs is often insufficient to open a fracture, pointing the importance of thermal stresses as reported by Ghassemi et al. (2007). Under typical EGS field conditions, a substantial increase in fracture slip is observed when thermal stresses are taken into account. Theoretically, two physical processes can lead to thermal shearing: 1) fluid expansion (fluid warming; highlighted in Delage, 2013; Delaney, 1982; Palciauskas and Domenico, 1982 among others); 2) wall contraction (rock cooling).

2.2 Experience in geothermal fields

Thermal stimulation has already proven to be effective on several EGS and conventional geothermal fields. One of the oldest publications available explicitly discussing thermal stimulation of geothermal wells is written by Benson and Daggett (1987). They highlighted that three wells of the Los Azufres (Mexico) high temperature geothermal field indicated an increase in permeability during cold water injection. They could also model an increase in permeability by a factor of approximately 5 in the near-bore region after 2-3 h of injection. They also concluded that thermal contraction and thermal stress cracking of the formation were responsible for the permeability enhancement.

Flores et al. (2005) analysed field results and performed preliminary modelling to calculate effective permeability changes, with the objective to compare thermal stimulations with other stimulation methods. They concluded that thermal fracturing is fully applicable to geothermal environments, and is highly cost effective. Grant et al. (2013) developed an empirical formula to estimate the injectivity increase of geothermal wells with time when cold water is injected. They found that injectivity of a geothermal well generally increases with time at a rate proportional to t^n where n ranges between 0.4 and 0.7. The increase in permeability with time can be up to two orders of magnitude. Regarding time scale, they state that the increase cannot continue indefinitely, but has been observed to continue for a few years.

The increase is also strongly dependent on the temperature difference between the formation temperature and the injected water. Authors gathered information on a large number of wells (34) in New-Zealand and Iceland, and proposed statistical analysis to highlight the effect of temperature on injectivity. They show that the permeability ratio (defined as the permeability in cold conditions to the permeability in hot conditions) increases with the temperature difference (ΔT). The authors note that there is a strong variation but nevertheless detect a trend: the variation is close to ΔT^3. They also observed that most wells drilled with cold water were greatly stimulated through the effects of drilling and through operations at the end of drilling. According to them, the increase is due to thermal contraction of the rock, and causes permeability changes much greater than those due to pressure changes.

Within the literature, experience feedbacks are mainly from high temperature magmatic fields: in Iceland (Héðinsdóttir, 2014, Axelsson and Thorhallsson, 2009), at Los Humeros (Mexico, Flores-Armenta and Tovar-Aguado, 2008, and Luviano et al., 2015), at Bouillante (Guadeloupe, France, Tulinius et al., 2000), in Costa Rica (Zúñiga, 2010), in Japan (Kitao et al., 1990) and in Indonesia (Pasikki et al., 2010). The main conclusions of these stories are that it was generally not possible to identify whether the permeability increases were due to mode-1 opening, i.e. contraction of existing fractures or thermal fracturing, or shear initiation, because of the absence of sufficient experimental control, such as a repeat injection after the well had been allowed to fully recover to determine whether the improvements persisted. It was also impossible to distinguish between shearing and cleaning of drill cuttings, both of which are expected to produce irreversible increases in injectivity. It was found that thermal stimulation has a major influence in close vicinity of the wellbore. The case studies analysed show permeability enhancements caused by thermal effects, both through fracturing and shearing. The dominating mechanism caused by the thermal effects for short-term injections of cold fluid is believed to be shearing. It may furthermore be noted that fracture-filling material, near a wellbore, may crack during thermal stimulation, which may facilitate its removal with the fluid injected.

3. ASSESSMENT OF THE SHEARING AND FRACTURING UNDER THERMAL STIMULATION

3.1 Assessment of fault plane vulnerability to shear

One initial approach to assess if discontinuities are likely to shear or not is based on analysis of the normal and shear stress applied on a given discontinuity with regard to a failure criterion (*e.g.*: Moeck et al., 2009; Cuss et al., 2015). The three-dimensional Mohr diagram is plotted in Figure 1, and the in-situ effective stress field is displayed. For a given discontinuity, the shear and normal stresses on a discontinuity applying on it can be plotted (on the Figure 1, by a red dot and by a blue dot). A Mohr-Coulomb failure criterion (characterised by a friction angle and a cohesion) is defined for this discontinuity and plotted in this system. The points lying above the Mohr-Coulomb failure criterion are critically stressed and are likely to shear in the current state. In case of thermal loading, we can state:

1. that the normal stress on the discontinuity decreases if the fluid expansion drives the phenomenon (displayed by green arrows on Figure 1 shifting the dots; when the cold injected fluid goes through the discontinuities, it warms up, and then it expands) or,
2. that the internal friction angle decreases if the wall contraction drives the phenomenon (displayed by a black arrow and dashed failure criterion on Figure 1; true when the rock mass is cooled down).

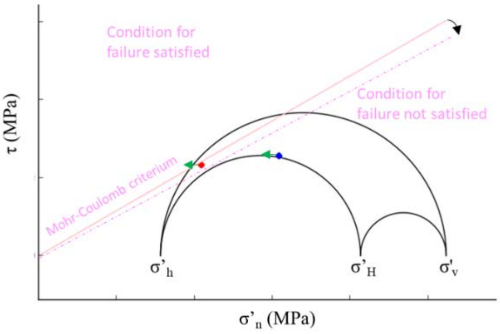

Figure 1: Three-dimensional Mohr diagram. The effective stress state is displayed by black semicircles; the red and blue dots display the shear and effective normal stresses on two discontinuities; the failure criterion is displayed by a pink line delimiting the stable and the unstable areas. Under thermal loading, the dots corresponding to discontinuities can cross the failure criterion if the normal effective stress decreases (green arrow) or if the criterion changes (black arrow and dashed pink line). See the text for more details.

In both cases, it leads to a further step towards the unstable area. Note that considering the high level of uncertainties, this study is qualitative (see below).

3.2 Assessment of thermal fracturing potential

Numerical simulations are performed to assess if thermo-mechanical stresses induced by thermal loading exceed the mechanical resistance of the rock. As strains at the origin of this process can be mainly due to thermal gradient in the rock mass and also to the heterogeneity of the grain contraction in the rock matrix, Discrete Element Method (DEM) has been chosen. Indeed, it is a useful approach to capture the cracking around a wellbore under stresses (*e.g.*: Karatela et al., 2016, Peter-Borie et al., 2018), as well as the physical phenomena at the granular phase level (micro scale), and to analyse their impact on the mechanical behaviour of the near wellbore zone (macro scale). This approach is implemented using the code PFC2D (Particle Flow Code - 2 Dimensions, Itasca Consulting Group Inc. 2008). The proposed numerical approach enables quantifying the depth and shapes of damages. Complementary information on the approach are available in Peter-Borie et al. (2018) and references therein.

The calculation set-up consists of a two dimensional cross-section perpendicular to the well or to a pre-existing discontinuity. The numerical simulations focus on the deepest part of the well. As far as possible, the conditions observed at the bottom of each well are used in the numerical simulations (rock and injected fluid temperatures, wellbore/discontinuity orientation, stress state if known…).

We focus our study on the behaviour of the matrix of the grained-textured rock. The description of the rock mass in the reservoir is used as a reference for the numerical rock model: dolerite for the Icelandic demonstrator and plutonic formation for the French demonstrator. The numerical simulation is performed stepwise. The aim is to reproduce, as far as possible, the state of the rock in the vicinity of the wellbore or of a pre-existing fracture before the thermal stimulation. The main steps are the borehole drilling (if any), which is simulated by removing the particles located on the wellbore surface, and the thermal loading, which is subjected to a hydraulic pressure (if any) and to a thermal loading. As a result of the thermal and mechanical loadings, cracks between numerical particles may appear. They are interpreted as rock damages; once cracks coalesce, a “macro”-discontinuity develops. If this discontinuity is connected to the borehole, then the injection pressure and the fluid temperature can penetrate into it.

If coalesced-cracks discontinuity connects to the borehole, the permeability of the rock mass in the surrounding of the wellbore increases. Here, we propose a method to estimate the permeability evolution in the near-wellbore due to modelled thermal fracturing based on the investigations of Jobmann et al. (2010), Zhou et al. (2016), and Tran et al. (2018). Assuming a given initial permeability of the intact rock mass constant, we can estimate that the permeability gain is proportional to the porosity gain in the rock mass. This porosity gain is estimated from the space gain between two particles separated by a coalesced crack (more details in Tran et al., 2018).

4. THERMAL STIMULATION OF THE ICELANDIC DEMONSTRATOR

4.1 Context

The Reykjanes geothermal system is located at the tip of the Reykjanes peninsula, SW Iceland at the landward extension of the Reykjanes Ridge (NNE-striking). From the surface to around 2.5 km depth, the lithology consists of sub-aerial basaltic lavas and to a lesser degree of hyaloclastites. Below, a typical sheeted dyke complex of an ophiolite is assumed, including a swarm of tectonic vertical to subvertical fractures and faults. Most of these discontinuities strike parallel to the ridge axis (Pálmason 1970; Gudmundsson 2000; Foulger et al. 2003; Karson 2016; Stefanson et al. 2017; Friðleifsson and Elders 2017).

Within the Reykjanes peninsula, the stress state evolves laterally from normal to strike-slip regime. At depth, the strike-slip regime seems to dominate (Sæmundsson et al., 2018, Keiding et al., 2009). Keiding et al. (2009) as well as Kristjánsdóttir (2013) found that $\sigma_2 \approx \sigma_3$. It appears that the admissible ratio $\sigma_{Hmax}/\ \sigma_{hmin}$ may be very high at 1.5 km depth (>2) (Batir et al., 2012). The major horizontal stress is oriented NNE-SSW to NE-SW. Note that the directions of stress at depth and the strain rate observed at the surface are in a good agreement (all seems to be driven by plate motion; Keiding et al., 2009).

4.2 The Reykjanes EGS demonstrator

The drilling of RN-15/IDDP-2 has been successfully completed in January 2017 (see more in Friðleifsson et al., 2019). The final measured depth of the well is 4650 m from the ground level (True Vertical Depth: 4460 m). Cores in the sheeted-dyke complex show mainly rocks with fine-grained igneous texture: micro-gabbro/dolerite to fine-grained basaltic intrusive, with heterogeneous grain size (Friðleifsson et al. 2017). The temperature measured at depth under disturbed conditions was 426°C, which gives an order of magnitude of the high temperature reached. Short time injectivity index was estimated to be around 3.1 L/s/bar at the end of the drilling operation (Weisenberger et al., 2017). Like the other shallower geothermal wells of the Reykjanes geothermal field (see Axelsson and Thorhallsson, 2009), thermal stimulation was performed after the end of drilling of RN-15/IDDP-2 by cold-water-injection-and-warm-up cycles, for several months (Sigurdsson, 2019).

4.3 Investigation of the potential thermal shearing

The set of discontinuities crossing the rock mass around the RN-15/IDDP-2 well has been characterised by Khodayar et al (2014). Figure 2 shows these discontinuities within the expected stress state. Regarding the uncertainties on the stress state, two extreme regimes are considered, a normal regime (Figure 2A) and a strike-slip regime (Figure 2B). In the case of a normal regime (A), the swarm of discontinuities does not seem prone to shear, unless the failure criterion is lowered. In the strike-slip regime (B), most of the discontinuities of the swarm lie in the unstable area, and thus should have sheared. Note that considering a non-zero cohesion would lead to reinforcement of the failure criterion, and would thus reduce the unstable area.

Seismic activity has been closely followed during this stimulation period, as discontinuities closed to the wellbore seem to be prone to shear under thermal and/or mechanical loading. Indeed, during drilling considerable induced seismicity has been observed in connection with fluid losses (Blanck et al., 2019). This seismic activity can be considered as an indirect proof of discontinuity shearing. However, due to uncertainties on the stress state, on the level of hydraulic stimulation (that shifts the Mohr's circles to the left), and on the effects of thermal loading, it remains difficult to identify precisely the origin of this discontinuity shearing.

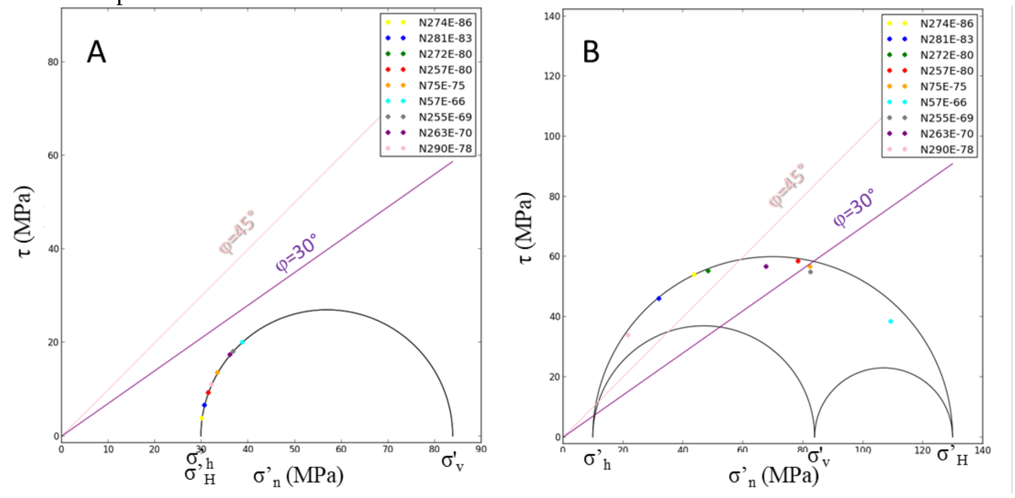

Figure 2: Three-dimensional Mohr diagram (for legend detail and explanation see Figure 1. The discontinuities plotted by coloured dots are from Khodayar et al. (2014). A: Result for a regional normal faulting regime; B: Result for a strike-slip regime.

4.4 Investigation of the potential thermal fracturing by numerical modelling

In this section, we present the results of the numerical investigations on the potential rock mass fracturing around the borehole under thermo-mechanical loading (more details available in Peter-Borie et al., 2018 and Tran et al., 2018).

A thermal difference of 400°C at the bottom hole is considered in this study. No overpressure is considered in the well as a first evaluation of the impact of the thermal loading. The normal and strike-slip regimes are still considered and give insights on the shape of the potential induced damaged. In both cases, induced fractures develop under thermal loading (Figure 3). In the most isotropic cases (Figure 3A), fractures develop around the wellbore without preferential direction, following the path of least resistance defined by the local mineral distribution. With the largest 2D deviatoric stresses (Figure 3B), the fracture propagates in the direction of the 2D maximum stress. In the vicinity of the wellbore, and still under thermal loading, permeability of this induced discontinuity can be estimated (Figure 4). Fracture permeability has a downward trend from the wellbore (main branch permeability up to 10^{-11} m^2) to the tip of the induced fracture.

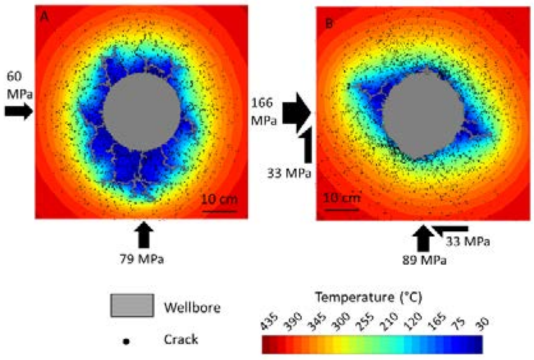

Figure 3: Thermal fracturing modelled after 4 hours of thermal loading. The front colour corresponds to the temperature (see legend). Each dot corresponds to a crack between two grain-modelling particles. Grey uniform colour corresponds to the area connected to the wellbore (penetration of thermal loading). A: Result for a regional normal faulting regime; B: Result for a strike-slip regime (modified from Peter-Borie et al., 2018).

Results from numerical modelling argue in favour of potential permeability increase around the wellbore due to thermal cracking and subsequent fracture development.

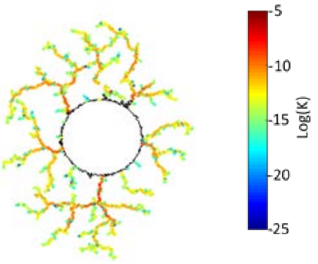

Figure 4: Logarithm of the permeability (K [m²]) of the coalesced-cracks discontinuities resulting from the numerical modelling of the thermal loading of the dolerite in the surrounding of the RN-15/IDDP-2 wellbore (see Figure 3A; modified from Tran et al., 2018)

5. PERSPECTIVES FOR THERMAL STIMULATIONS OF THE FRENCH DEMONSTRATOR

5.1 Context and reservoir model

The second demonstrator located in Vendenheim (France) targets a N10°E-striking and 82°W-dipping fault in the plutonic basement in the Upper Rhine Graben (URG).

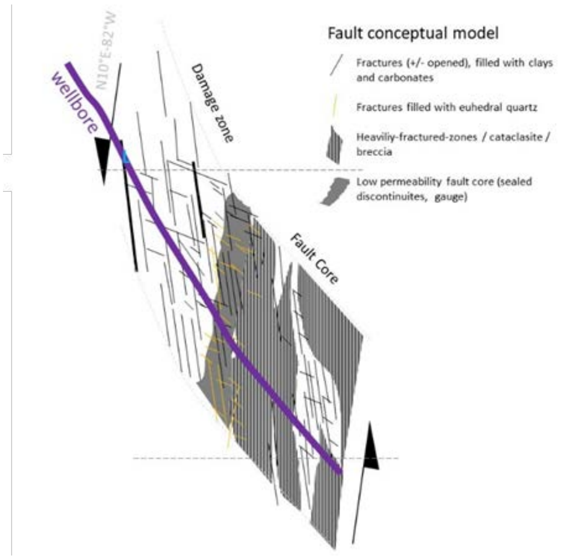

Figure 5: Conceptual model of the geometry of the targeted fault zone based on the drilling data

The targeted fault zone in the basement of Vendenheim has probably been created during Permo-Carboniferous times (sinistral shearing assumed) and submitted to a repeatedly changing stress field leading to its reactivation since then (Schumacher, 2002; Edel et al., 2007, among others). A conceptual model of the fault zone is proposed in Figure 5; it is based on drilling data and cutting analyses. This regional fault of order 2 is composed of a damaged zone (in the upper part of the hole) and of a fault core, that can be split in a low permeability zone (probably gauge), and in a heavily fractured zone. Euhedral quartz has been found in the cuttings, probably linked to hydrothermal sealing of discontinuities.

Currently, the URG is assumed to be globally an Andersonian system, i.e. the vertical stress is a principal stress. The faulting regime varies from normal faulting (mostly in the sedimentary part) to strike-slip regime. Vendenheim is located in the permutation area between a strike-slip-regime farthest North and a normal regime farthest South (e.g. Meixner et al., 2016); it is a quite area in term of natural seismicity. The main horizontal stress is roughly oriented NW–SE, with local variations from N130°E to N180°E (Meixner et al., 2016, Cornet et al., 2007). It is well-admitted that the orientation of the main horizontal stress is closer to N130°E in the Northern part of the URG and to N145° to N160° in the Southern part/Northern Switzerland (Plenefisch and Bonjer, 1997). First analyses of the breakouts observed in the Vendenheim well are consistent with a major horizontal stress between N150° and N170° (unpublished data and analyses).

5.2 The Vendenheim demonstrator

The drilling of the well doublet has been successfully completed in February 2019. The final measured depth of wells are respectively 5308 m (True Vertical Depth: 4426 m) and 5393 m (True Vertical Depth: 4650 m). The temperature measured at depth under disturbed conditions was around 200°C. The injectivity at the end of the drilling operation and after a first chemical stimulation is less than the targeted injectivity, which confirms the necessity of stimulation methods.

5.3 Investigation of the potential of thermal shearing

In this paper, we assume that the fault has been created under the Palaeozoic-time stress state. Assuming a Riedel-shear zone (main direction Y-Shear), main discontinuities subsets are the synthetic R-shears and the antithetic R’-shears as plotted in Figure 6. In this study, we also considered the traction subset bisecting the R-shears and the R’-shears.

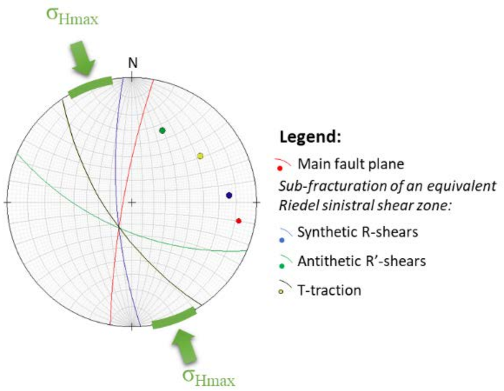

Figure 6: Plot of the targeted fault on a Wulff net (in red). Theoretical sub-fractures (Riedel shear structure) in the main fault zone assuming a structuration based on a sinistral faulting in the basement during the Permo-Carboniferous time: Synthetic R-shears (blue), anthitetic R’-shear (green), and traction direction at the bisecting line (black). The estimated direction of the major horizontal stress is plotted in green (arrow and thick line).

Figure 7 displays the three-dimensional Mohr diagram for this fault and the associated subsets of discontinuities for a current normal regime (Figure 7A) and current strike-slip regime (Figure 7B). For the selected failure criterion of the discontinuities (friction angle between 35° and 45°), all the discontinuities are in the stable area. It is consistent with the absence of natural seismicity. However, the R-shear planes, T-traction planes and Y-shear planes are close to the chosen lower failure criterion. Consequently, the discontinuities appear likely to shear with a slight decrease of the normal effective stress or of the failure criterion. This is even more critical for a strike-slip regime. The micro-seismic events (with magnitude lower than 1.4) that have been recorded during injection in the first well in March 2018 and localised in the reservoir area are likely an evidence of the proximity to failure of the discontinuities. This micro-seismicity may have been induced by hydro-mechanical effects due to the overpressure and/or of the thermal loading. Note that quantifying the stress induced by the cooling remains very uncertain.

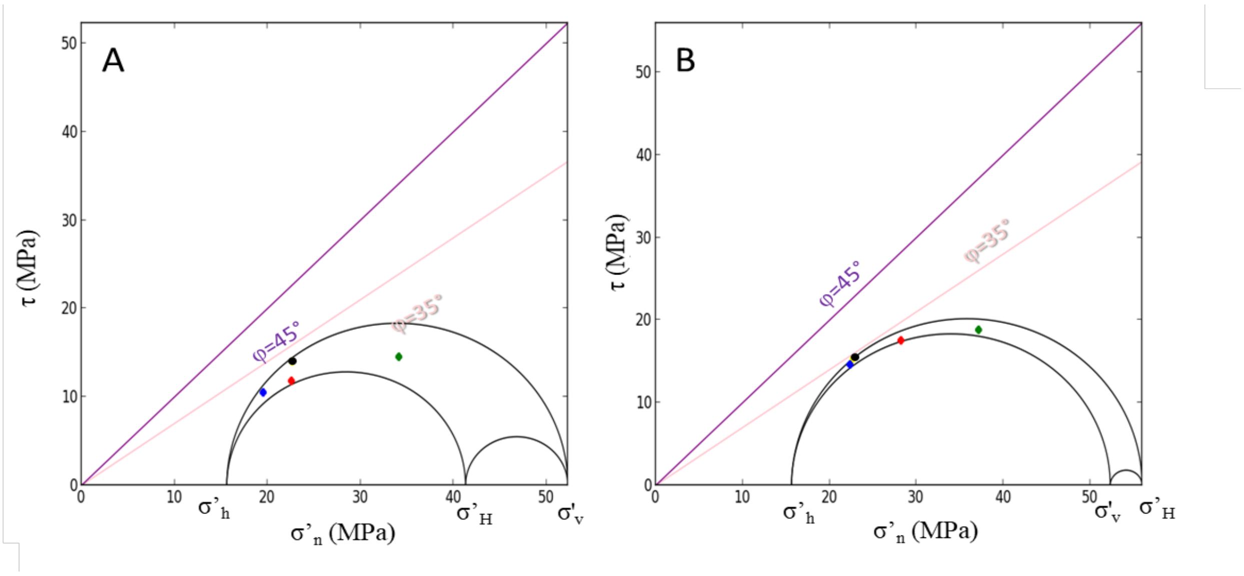

Figure 7: Three-dimensional Mohr diagram (for the legend details and explanation see Figure 1; legend of the colour of the dot is in Figure 6). A: Result for a normal faulting regime; B: Result for a strike-slip regime.

5.4 Investigation of the potential of thermal fracturing by numerical modelling

First insights in the potential of plutonic formation fracturing within the context of the central part of the URG is based on the numerical modelling performed for the neighbouring Soultz-sous-Forêts EGS (Peter-Borie et al., 2015). In both cases the nature of the rock mass, the bottom-hole depth (4.5 to 5 km depth) as well as the stress state are so far comparable. Peter-Borie et al. (2015) investigated the thermo-mechanical failure in the granite at 2 km-depth and 5 km-depth for several temperature differences between the injected fluid and the granite. The main conclusion is that the temperature difference expected in the reservoir (up to 150°C) is insufficient to create new fracture at 5 km depth in the granite. Note that thermal fracturing has been obtained in simulations at shallower depth (2 km depth), for a temperature difference at least equal to 120°C without overpressure in the well, and less when overpressure is considered.

Present data from the first well drilled in Vendenheim suggest that discontinuities are more or less sealed by hydrothermal quartz. Simulation of the cooling of such a discontinuity is performed to assess its cracking potential. Figure 8 displays the thermally induced cracking around a discontinuity perpendicular to the minimum horizontal stress, with quartz sealing (Figure 8A) and without sealing (Figure 8B, plutonic walls lie directly around the discontinuity).

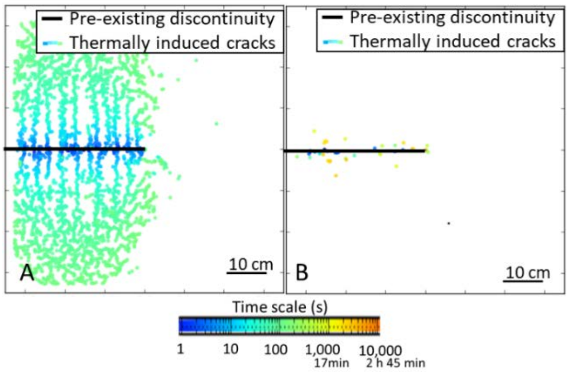

Figure 8: Thermal failure in a quartz vein (A) and in the plutonic formation (B) at 4775 m depth from the tip of a discontinuity perpendicular to the minimum horizontal stress. The temperature difference between the rock mass and the fluid in the fracture is 150°C. The colour scale refers to the simulated time from the cold fluid injection in the discontinuity (M. Peter-Borie, unpublished results from Soultz-sous-Forêts investigations).

The temperature difference between the rock mass and the fluid in the fracture is 150°C. In the presence of a quartz vein partially sealing the discontinuity, numerous coalescing cracks are induced, while in the other case, only few cracks are induced in the vicinity of the discontinuity. These numerical simulations argue in favour of a localised induced thermal fracturing within the sealed discontinuities. Thermal stimulation appears to be source of a potential enhancement of fluid circulation and/or creation of new fluid paths within the sealing, while it seems that no fracturing can be induced in the granite at the considered depth.

6. DISCUSSION AND CONCLUSION

The thermal stimulation efficiency is assessed on the two demonstrators of the H2020-DEEPEGS project. The two demonstrators target fractured/faulted tight reservoirs at similar depth, but the geological contexts and the formation temperatures are different.

Within the “young” rock mass of Reykjanes, all conditions are met to an efficient thermal stimulation because:

- the current stress state drives the discontinuities creation and these discontinuities are likely to shear under a slight stress increase that can be induced by thermal loading ;
- the high temperature of the rock mass temperature allows high temperature difference with the injection fluid, then thermal fracturing is possible within the rock mass at the considered depth.

As a result, the Reykjanes demonstrator can quite easily develop a mixed-mechanism stimulation involving both shearing and fracturing under thermal loading. In this context, both new discontinuities and pre-existing ones would be involved in the development of the geothermal fluid flow path. McClure and Horne (2014) suggest that in this case, propagating new fractures may terminate against pre-existing fractures, preventing the formation of large, continuous fractures. Note that the induced fractures are from a tensile mechanism, and need then to be propped to stay open when the fluid warms up.

The case of Vendenheim demonstrator is more complicated:

- this plutonic basement has been structured under a stress state quite different from the current one. There is currently low natural seismicity, due to lack of natural loading. Nonetheless, the basement is prone to shear if the pore pressure increases. In this context and considering high uncertainties, it is difficult to assess the potential effect of thermal stimulation, and if it would lead to induced seismicity or not. Further analyses and feedbacks are needed.
- the temperature of the reservoir is, comparatively to the Icelandic demonstrator, twice lower. It appears to be insufficient to create large induced fractures as in Iceland. However, the plutonic basement undergone numerous hydrothermal phases and quartz seals currently a part of the discontinuities of the reservoir. Veins of quartz appear to be prone to crack under “low” thermal loading. The flow path in the pre-existing sealed discontinuities can consequently be enhanced.

Hence, the Vendenheim demonstrator can also be enhanced by thermal stimulation, however, for a similar stimulation implementation, involved mechanisms will be different. The thermal loading will principally result in the unsealing of pre-existing discontinuities by cracking the quartz veins. This process should enhance the flow path within the subsets of discontinuities of the fault zone. At first, minimal shearing mechanisms are expected, leading to few and low micro-seismic events. However, more investigations are needed to prove this point.

To conclude, this first insight on the efficiency of the thermal stimulation, we can say that, unsurprisingly, the knowledge of geological context is necessary to assess the involved mechanisms and their efficiency. Beyond the two main processes dealing with thermal stimulation, shearing and fracturing, the way to enhance the reservoir can differ a lot: in our cases, the fracturing in the Icelandic reservoir will create new paths while in the French context it leads to the re-opening of the pre-existing sealed fractures.

In the different cultural and societal contexts of Iceland and France and considering the associated sensibilities to induced seismicity or to fracturing, knowing which mechanism will be involved during stimulation and at which scale is key for an EGS success story. In France especially, the thermal stimulation plan and induced mechanisms are likely to lead to the re-opening of the pre-existing sealed discontinuities in a soft way. However, further investigations are in progress to quantitatively assess the impact of all the possibly involved mechanisms.

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Acknowledgements

This study was part of the DEEPEGS project, which received funding from the European Union HORIZON 2020 research and innovation program under grant agreement No 690771.

The authors would like to thank the two anonymous reviewers of the abstract for advising to focus on one stimulation type for this paper.