Assessment of Geothermal Well Productivity Improvement Technologies: an Overview from the DEEPEGS Project

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Proceedings World Geothermal Congress 2020
Reykjavik, Iceland, April 26 – May 2, 2020

Assessment of Geothermal Well Productivity Improvement Technologies: an Overview from the DEEPEGS Project

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Keywords: DEEPEGS, Stimulation, EGS, Well productivity, improvement, thermal stimulation, hydraulic stimulation, chemical stimulation

ABSTRACT

The H2020-DEEPEGS project aims to demonstrate the feasibility of the Enhanced/Engineered Geothermal System (EGS) Technology to produce electricity and/or heat. One of the main technological challenge is to optimize the well architecture and stimulation methods to get economically viable flow rate in deep hot reservoir initially little productive. The technologies are assessed for the two main demonstrators of the project: the IDDP-2/RN-15 Icelandic well and the VDH French doublet, taking into account the physical and geological specificities of each demonstrator.

The IDDP-2/RN-15 well is located in the Reykjanes peninsula, in SW of Iceland. It crosses the fractured sheeted dyke complex around 4500 m TVD (True Vertical Depth), to reach a temperature estimated around 500°C-530°C. The assessment of stimulation methods is focused on the thermal (Peter-Borie et al., 2018) and hydraulic stimulations.

The VDH doublet is located in the Upper Rhine Graben, in Eastern France. The target is a fault zone in the plutonic basement. The temperature around 4600 m TVD is estimated above 200°C. The initial injectivity/productivity index, below 1 l/s/bar, is far from the economically viable target. Several technologies are considered to enhance this index: the multi-drain well geometry and the hydraulic and thermal stimulations are assessed through numerical simulations.

1. INTRODUCTION

In some contexts, it is not possible to extract the Earth's thermal energy economically without implementing technological solutions (merged under the term "Enhanced/Engineered Geothermal System", abbreviated EGS) to increase the injectivity/productivity of the wells. To be able to generalize the exploitation of deep geothermal energy, these cases must be addressed through appropriate technological solutions. 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 (IDDP-2/RN-15) located in Reykjanes (Iceland) targets the sheeted dyke complex in a magmatic field. It is a high temperature reservoir (around 500°C-530°C) at around 4500 m TVD (Friðleifsson et al. 2017). The second demonstrator located in Vendenheim (France) is a doublet that targets a normal fault in the plutonic basement around 4600 m TVD, in the Upper Rhine Graben (URG), 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. 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 order to increase the well productivity/injectivity, it may also be possible to use sophisticated well architecture. Multilateral technology involves "multiple drilling or multi-branched drilling into the formation from a single well to maximize the productivity" (Kalita et al. 2015).

Within the H2020-DEEPEGS project, in order to study the impact of stimulation scenarios on the permeability development, we assess these different stimulation methods and well architectures for both demonstrators by numerical modelling. This paper aims to describe the studied and modelled technologies for both demonstrators and to sum up the main results. Companion papers detail numerical modelling implementation and results (Armandine Les Landes et al. 2020; Blaisonneau et al. 2020; Tran et al. 2020).

2. INJECTIVITY/PRODUCTIVITY ENHANCEMENT METHODS: AN OVERVIEW

Depending on the heat source and the geological controls on heat transport and thermal energy storage capacity, different geothermal play types can be defined: pure petrothermal system (very low permeability, no flow, heat transport is conduction-dominated), hydrothermal system (high permeability, heat transport is convection-dominated) (Moeck and Beardsmore 2014), or intermediate system.

Depending on the geothermal plays, different strategies could be used to increase the injectivity/productivity of a well:

- In hydrothermal systems, natural fluid can circulate through rock matrix porosity or through discontinuities; however, in hydrothermal EGS, flowrate is naturally too low for economic use and occurs mainly in fractures and/or faults. The main objective of the implementation of technological solutions is to enhance the connection of the well to the main natural pathways of the brine. Two kinds of strategy can be implemented:
    - Work on the well architecture, using multilateral well configurations,
    - Try increasing the permeability of pre-existing discontinuities in the well area mainly by methods resulting in discontinuities shearing.
- When no/very little circulation of the natural fluid exists, the system is defined as petrothermal, corresponding more to the initial concept of HDR (Hot Dry Rock). The basic idea of this system is that the heat is stored predominantly in rock, independently from fluid bearing structures. The implementation of technological solutions aims to create fluid pathways and to impose artificial (i.e. injected) fluid circulation. The stimulation consists of creating an artificial fracture network by fracturing the formation.

It should be noted that the stimulation methods used to increase the permeability are the same for both systems: mechanical, thermal or/and chemical processes are used. The distinction comes from the consequences of stimulations on the system: either increase of the permeability of pre-existing discontinuities (hydrothermal EGS) or generation of additional fractures (petrothermal EGS). Of course, the transition from petrothermal to hydrothermal systems is gradual, and some systems may present both increase of former discontinuities' permeability as well as generation of new fractures.

Practical implementation of a stimulation method is actually a complex process in which multiple physical phenomena are coupled: for example, hydraulic stimulation requires fluid injection, and the injected fluid is mostly colder than the rock mass and its chemical composition probably different from the natural local brine. Consequently, the result of a hydraulic stimulation is not only linked to the fluid overpressure, but also to the associated thermal and chemical stresses. This effect has been highlighted in the Geysers geothermal field by Stark (1990) among others: half of the earthquakes in the field appear to be related to cold water injection rather than to critical injection pressures.

3 SETTINGS OF THE DEMONSTRATORS

3.2 The Reykjanes demonstrator

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; Friðleifsson and Elders 2017; Stefanson et al. 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 (Keiding and Lund 2009; Sæmundsson et al. 2018). It appears, from borehole stress model, that the admissible ratio σ_{Hmax}/ σ_{hmin} may be very high at 1.5 km depth (>2) (Batir et al. 2012). The least compressive horizontal stress is oriented ESE-WNW. Note that the directions of stress at depth and the strain rate observed at the surface are in a good agreement (all seem to be driven by plate motion; Keiding and Lund 2009).

The drilling of IDDP-2/RN-15 has been successfully completed in January 2017 (see more in Friðleifsson et al. 2018). The final measured depth of the well is 4659 m from the ground level (True Vertical Depth around 4500 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.

The reservoir spreads over an area of approximately 1 to 1.5 km² and is located within a NE/ENE graben (Khodayar et al. 2014). Surface geological evidences and observations from wells drilled up to approximately 2 km TVD highlight a dense network of fault zones. The drilling status reports highlight a couple of higher permeability zones in the deeper part of the IDDP-2 well: a major one at 3409 m TVD, and smaller feed zones at 4285 m and 4326 m TVD. It is uncertain whether these higher permeability zones are related to material heterogeneity or natural fracturation. However, given the low permeability of the basaltic rocks and the substantial permeability increases at those depths, it is more likely that these feed zones are due to intersection with fault zones. The reservoir falls in an extrusive magmatic play, dominated by convection, in Moeck's definition (Moeck and Beardsmore 2014).

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 IDDP-2/RN-15 by cold-water-injection-and-warm-up cycles, for several months.

3.2 The Vendenheim demonstrator

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

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. 2006, among others). A conceptual model of the fault zone is proposed in Figure 1. 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 borehole) 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. The reservoir falls in the extensional domain plays, dominated by convection, in Moeck's definition (Moeck and Beardsmore 2014).

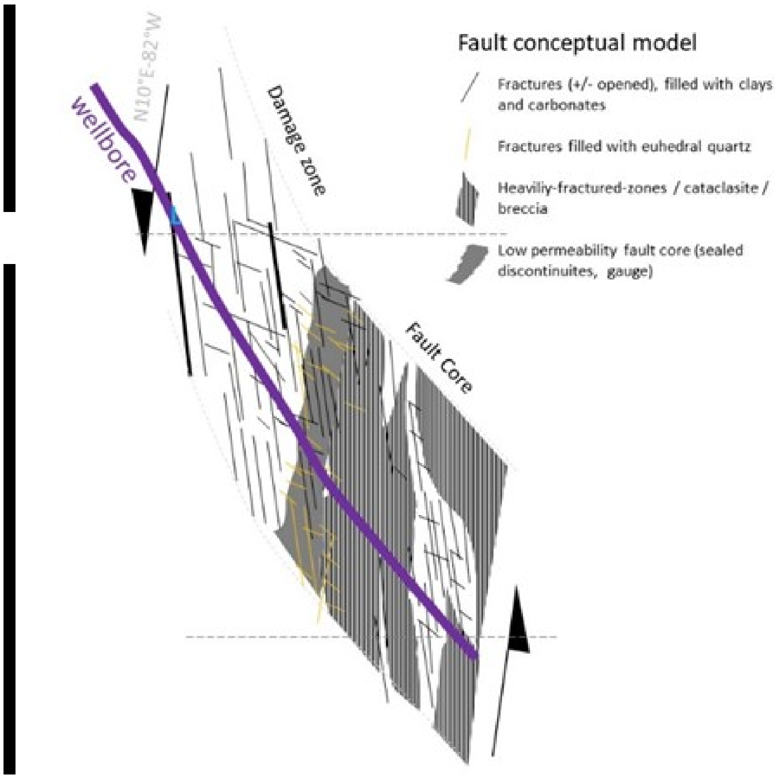


Figure 1: Conceptual model of the geometry of the targeted fault zone based on the drilling data

Currently, the URG is assumed to be globally an Andersonian system, i.e. the vertical stress is a principal stress. 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 (Cornet et al. 2007; Meixner et al. 2016). 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).

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. Soft hydraulic stimulation has been performed during the spring and the thermal stimulation is implemented since last June, by cold-water-injection-and-warm-up cycles, planned for several weeks.

4 ASSESSMENT OF GEOTHERMAL WELL PRODUCTIVITY IMPROVEMENT OF THE DEMONSTRATORS

4.1 Fractures shearing by hydraulic stimulation

Two different fracture stimulation mechanisms may occur during a hydraulic treatment and should be distinguished: during hydroshearing, over-pressure induces slip along pre-existing fractures that are favorably oriented in the stress field for reactivation in shear while during hydrofracking, new tensile fractures are generated (Gischig and Preisig 2015). Both demonstrators cross heavily fractured rock masses that constitute the reservoirs. As naturally opened fractures exist, numerical simulations focus on the assessment of the hydroshearing mechanism.

Hydroshearing is a well stimulation operation whose main objective is to increase well injectivity and/or productivity and create circulation pathways through the rock mass by reactivating pre-existing geological structures (fractures or fault zones, depending on scales). The injected fluid is usually water with no or few additives (Hirschberg et al. 2015) due to the self-propped nature of the "hydrosheared" structures.

To perform hydroshearing, pressurized water (usually less than 250 bars) is injected within the fractures and/or fault zones cutting the well. This increase of liquid pressure reduces the effective normal stress acting on the structures, which can no more resist the natural in situ stresses and so shear. The success of flow path creation relies on the irregular nature of the structures walls:

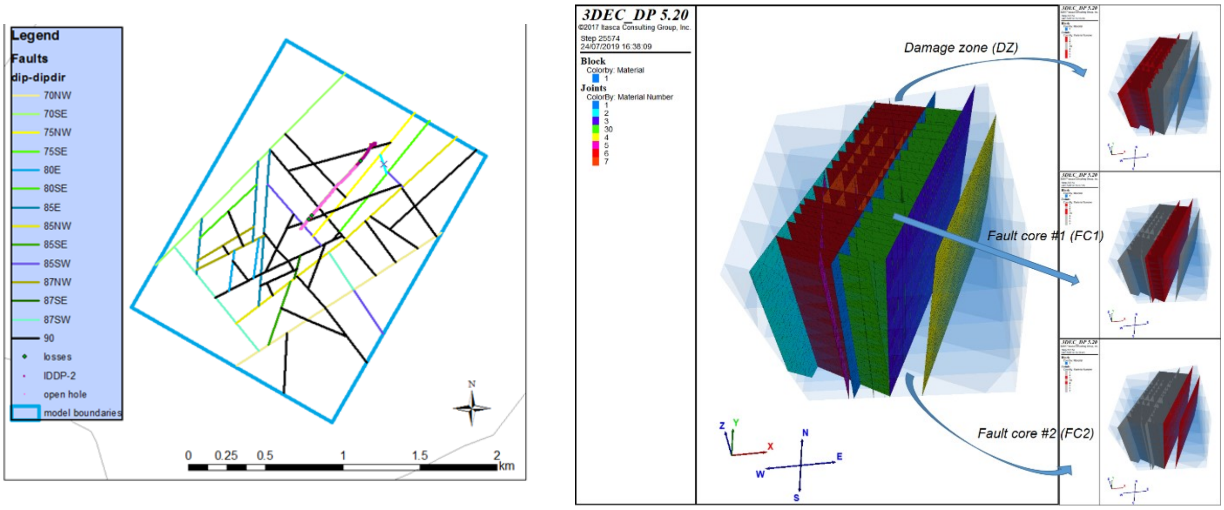
- during shearing, dilatational opening occurs and is mainly impacted by the walls irregularities of larger scales and larger wavelengths;

- at well shut-in, i.e. when overpressure is released in the well, the structures close, but their irregularities cause the walls to be misaligned.

The combined effect of dilatational opening and misaligned closing results in an irreversible opening of fractures/fault zones where injected fluids can then circulate.

From the geomechanical perspective, and irrespective of their scales, the pre-existing geological structures are weak points in the rock mass. If the orientation and amplitude of in-situ stresses, as well as the rock properties, are favorable, these weak points are likely to cause hydroshearing prior to rock mass fracturing, and may require lower levels of well overpressure.

In order to assess the injectivity gain by hydroshearing, hydro-mechanical numerical simulations are performed. For both cases, a Discrete Fracture Network is considered to reproduce the geological setting and the dominant flow pathways. We assume no flow in the rock matrix (as porosity of these plutonic rocks is very low): flow occurs only in the discontinuities. The hydraulic stimulation is modelled as a multi-step fluid pressure increase. Modelling process details are available in the companion paper (Blaisonneau et al. 2020).



a b

Figure 2: a. 2D view of the considered fault network for the numerical simulation of the hydraulic stimulation of IDDP-2/RN-15 (Iceland); b. View of the considered fracture network for the numerical simulation of the hydraulic stimulation of Vendenheim well (France)

<u>4.1.1 The Reykjanes demonstrator</u>

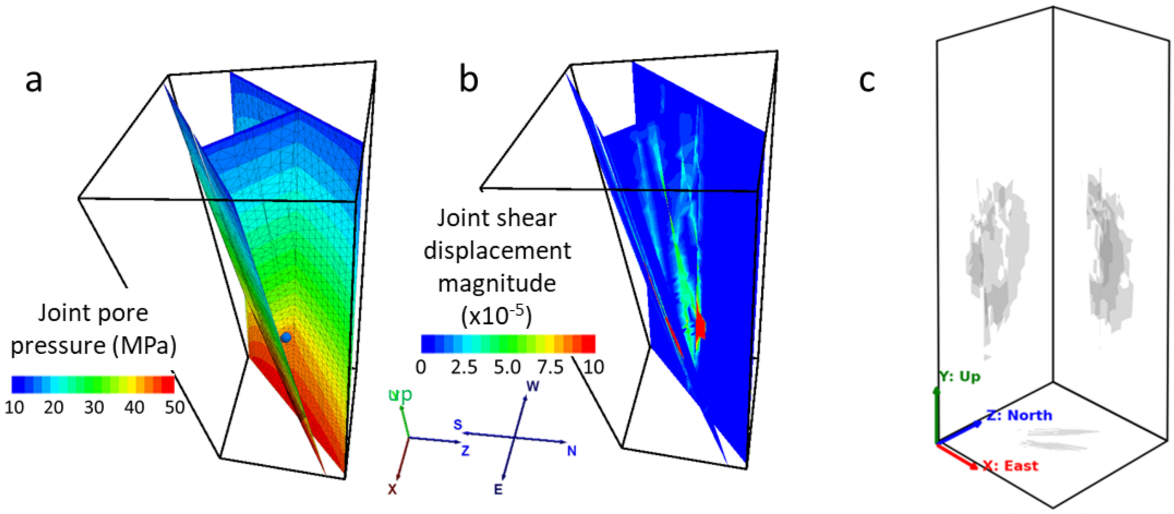


Figure 3a illustrates the evolution of the pore pressure and of the shear displacements at the highest level of overpressure stimulation in the wellbore (18 MPa). The shear displacements induced by the hydraulic stimulation are localized (

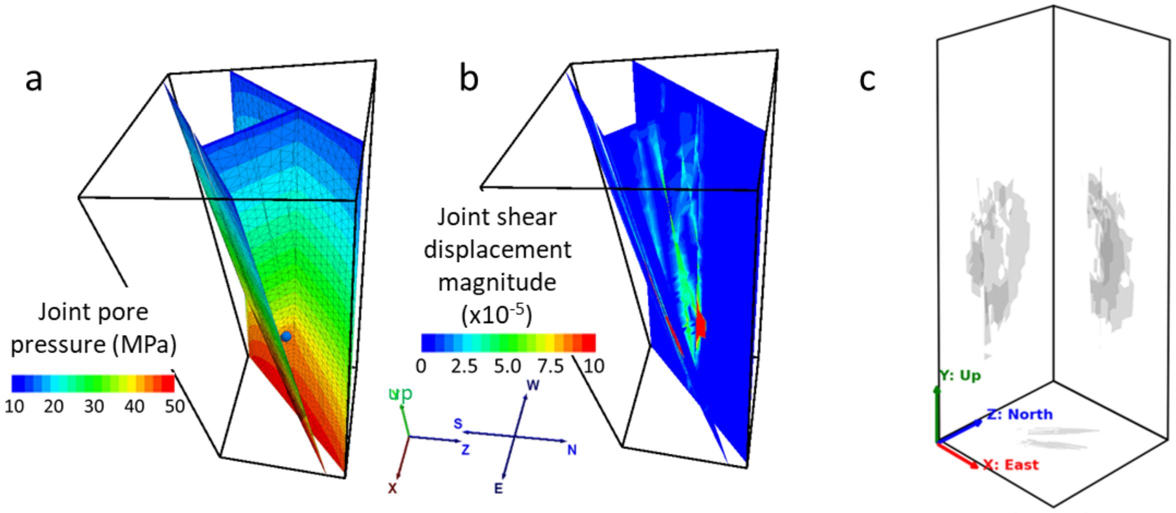


Figure 3b) and concentrated at the intersections of fractures on the whole height of the model. The highest magnitude is observed for regions on well-oriented fractures near the injection points. Considering the hydraulic criterion “irreversible residual apertures” (after the pressure shutdown) to assess the efficiency of the hydraulic stimulation (Figure 3c), it appears that the hydraulic stimulation would affect mainly a vertical area, promoting down to up flow paths. However the irreversibly opened area is quite limited within the reservoir.

To conclude this work detailed in Peter-Borie et al. (2017), it appears that hydroshearing alone might not be relevant for enhancing the injectivity of the Reykjanes reservoir, but might be a good kick-off for other stimulation scenarios by enhancing the higher-permeability area connected to the well (chemical, thermal).

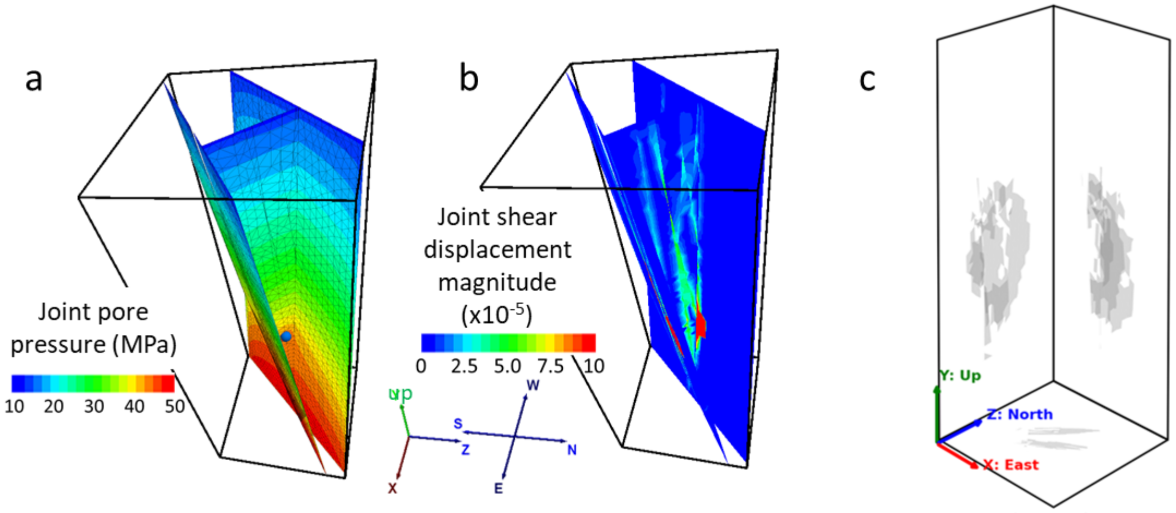


Figure 3: Pore pressure distribution (a) and shear displacements (b) in the three most relevant fractures at the highest level of overpressure in the well (18 MPa). The blue dot represents the wellbore. c: Projection of the 3D halo of an increase of the hydraulic aperture upper than 1.5 X the initial hydraulic aperture. Considered stress regime is normal to strike-slip, with σ_V=134 MPa, σ_H=134 MPa, and σ_h= 60 MPa.

4.1.2 The Vendenheim demonstrator

The Vendenheim reservoir is considered as a fault zone composed of three main areas: a damaged zone (permeable), a low-permeability fault core, and a medium-permeability fault core. The simulation of the hydraulic stimulation is performed considering two different assumptions:

- in the first one, the low-permeability-fault core has been assumed to be a highly brecchified plutonic rock with clay material, characterized by a soft mechanical behavior;
- and in the second one, this fault core have been assumed to be mainly governed by quartz-sealed fractures with a stiffer mechanical behavior.

Figure 4 illustrates the aperture increase of the discontinuities of the fault-reservoir at the highest level of simulated overpressure in the wellbore (10 MPa). The maximal aperture gain and the subsequent discontinuities with highest hydraulic apertures are located upstream of the low-permeability fault (in the damaged zone), whatever the mechanical behavior of the low-permeability area.

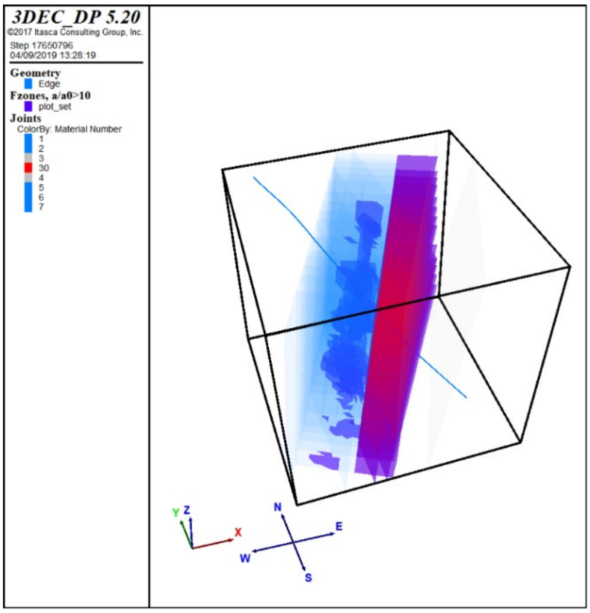


Figure 4: 3D halo of the increase (blue patches) of the hydraulic aperture larger than 10 X the initial hydraulic aperture of the joints (in blue the well trajectory). Transparent blue planes represent the location of the associated fractures (simulated overpressure: 10 MPa).

Figure 5 illustrates the 3D halo of the ratio increase of the hydraulic aperture (larger than 10 X the initial hydraulic aperture of the joints) for this two assumptions. First simulations show that the efficiency of the hydraulic stimulation in the damaged zone (defined as the gain in discontinuity aperture) is lower with an argilleous-breccia fault core (soft mechanical behavior; Figure 17 b) than in a fault core governed by sealed discontinuities (stiffer mechanical behavior; Figure 17 c).

To conclude this work detailed in Blaisonneau et al. (2030), it appears that hydraulic stimulation might be relevant for enhancing the injectivity of the Vendenheim reservoir. The stimulated area is mainly controlled by the presence of a low-permeability zone, and the fracture aperture gain is closely link to the mechanical behavior of this area.

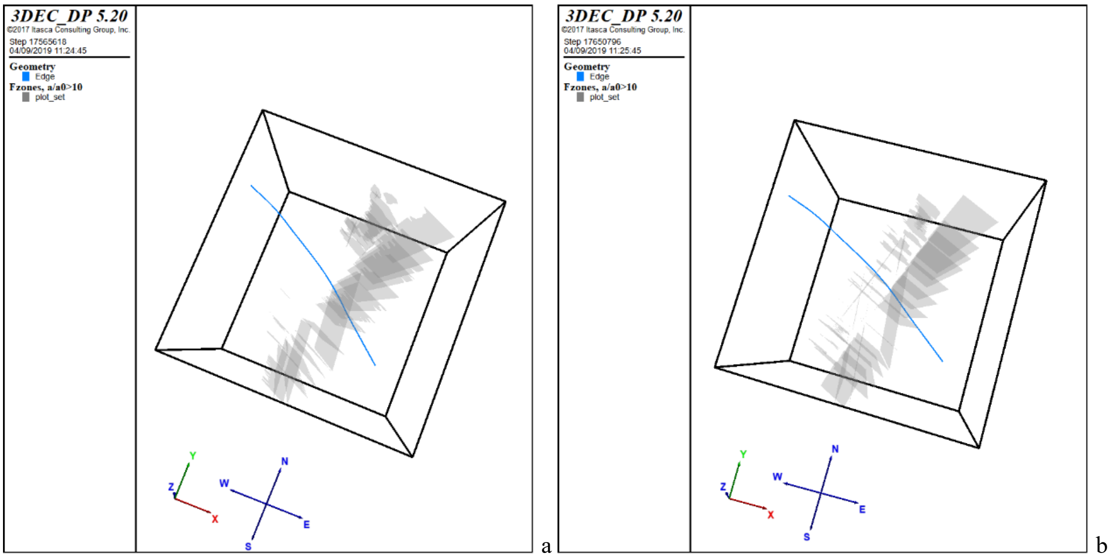


Figure 5: Simulation of the hydraulic stimulation of the fault zone of Vendenheim (simulated overpressure: 10 MPa). a/ Detailed view for a low permeability fault core considered as an argillaceous brecchia with soft mechanical behavior, b/ Detailed view for a low permeability fault core composed by sealed fractures with rigid mechanical behavior (Blaisonneau et al., 2020).

4.2 The thermal stimulation

The high temperature in the Reykjanes reservoir and the quartz fracture sealing in the Vendenheim reservoir associated to the high thermal expansion potential of this mineral lead us to consider the thermal stimulation for both demonstrators.

4.2.1 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.

The mechanisms involved in thermal stimulation are under-studied. From a theoretical point of view, we can distinguish (modified from Covell 2016):

1. permeability increase due to creation of new fractures (thermal fracturing).
2. permeability increase in existing fractures:
    a. widening or reopening of pre-existing fractures due to thermal rock contraction,
    b. shearing of pre-existing fractures after widening/reopening,

Concerning thermal fracturing, 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. 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.

Concerning thermal shearing,theoretically, two physical processes can be involved: 1) fluid expansion (fluid warming; highlighted in Delaney 1982; Palciauskas and Domenico 1982; Delage 2013 among others); 2) wall contraction (rock cooling). Most authors attribute shear slip on fractures to an increase in the pore pressure field linked to water flow, and thus the mechanism is very under-studied. 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.

4.2.2 Application to the demonstrators

The analytical analyses of thermal shearing potential (based on analysis of the normal and shear stress applied on a given discontinuity with regard to the Mohr-Coulomb failure criterion) and of the thermal fracturing potential (based on Discrete Element Method thermo-mechanical modelling of the rock behaviour under thermal loading) is developed in Peter-borie et al. (2019). Detailed analysis for the Vendenheim demonstrator is also available in the companion paper Tran et al. (2020).

The effect of the thermal stimulation differs with the geothermal play type. Although the two demonstrators target fractured/faulted tight reservoirs at similar depth (convection dominated systems), the geological contexts and the formation temperatures are different.

Within the “young” rock mass of Reykjanes, all conditions are met for 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 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 has 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 confirm this point.

To conclude on the efficiency of thermal stimulation, unsurprisingly, a good knowledge of the 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 will more likely lead to the re-opening of the pre-existing sealed fractures.

4.3 The two-legs geometry

4.3.1. Concept

Multilateral well configurations are sophisticated well architectures developed to increase the well productivity/injectivity. A multilateral well consists of one primary well and one or more secondary wells issuing from the first (Aubert 1998). Different configurations are possible for the number and orientation of the secondary wells (e.g. Vij et al. 1998): dual opposed laterals, stacked dual laterals, multilateral, branched multilaterals, splayed multilateral or fork type of dual lateral. Each configuration is adapted to a specific context (geological, economical and so on). The development of this technique comes from the oil & gas industry principally because it can reduce the economic costs of field development (Longbottom et al. 1997). Multilateral well configuration were developed because it allows reaching more targets with less surface development. Other benefits are an increase in production per platform, more reserves (reach fields considered not economically viable using classical techniques), production from target not easily drained otherwise because of their geology (e.g. natural fracture systems) and economy (Vij et al. 1998).

Few publications can be found about multilateral configuration in the case of geothermal systems. Song et al. (2018) did a numerical model study comparing performance (in terms of heat extraction) of a doublet against three different multilateral configurations. They found that during a 30-years heat extraction period, multilateral-well EGS has higher average production temperature, output thermal power, heat extraction ratio and accumulative extracted thermal energy than the conventional EGS doublet. However, this result is dependent on the model setup and on model assumptions (e.g. the reservoir consists of a low permeability rock and three artificial fractures).

Nair et al. (2017) report one example of multilateral well configuration in geothermal context. The Klaipéda well in Lithuania is composed of two injectors and two producers into a reservoir composed of fine-grained friable sandstone. The well has been losing injectivity since the start-up of the production in 1996 due to chemical interaction. In 2014, radial jetting technology was identified as a potential solution. Twelve horizontal laterals of 40 m length were planned in a sidetrack of the second well. The planned laterals were set to kick off in three different layers into the most productive reservoir. Post-drilling data suggest a 14% improvement in injectivity. However, from model a 57% improvement was suggested. The discrepancy is attributed to uncertainty in kick off depth, lateral length and so on that all together sum up. This is explained by the geology of the site that is formed of thin extremely permeable sand layers and moderately permeable sand layers interspaced by nearly impermeable clay layers. This configuration makes the injectivity very sensitive to the positioning of the laterals. However, this positioning is quite uncertain due to the jetting technique; indeed, after the start of the jetting inclination and azimuth are not controlled. This example shows multilateral can improve a well; however, limitation of the technology used and the geologic environment can limit this effect.

4.3.2 Application to the Vendenheim demonstrator

The fault-zone reservoir of Vendenheim seems to be a reasonable candidate for multilaterals configuration: this kind of well architecture will allow the increase of surface contact between the wellbore and the reservoir and consequently, may lead to productivity/injectivity increase. The two-legs (Figure 6) configuration is first assessed by numerical modelling, detailed in the companion paper Armandine Les Landes et al. (2020).

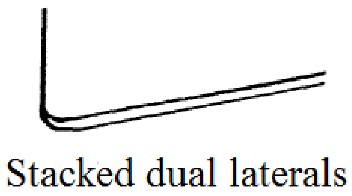


Figure 6: Geometry of a stacked dual laterals or “two-legs” configuration (modified after Vij et al, 1998)

Based on the hydrothermal model of the fault zone reservoir of Vendenheim, an injection test is performed for the reference model (one primary well) reproducing the initial injectivity index. Then the results of this simulation (injectivity index and pressure and temperature differential) can be compared with the results of the same injection test realized with a two-legs configuration. The implementation of the secondary well in the numerical model of the fault zone reservoir of Vendenheim results in an increase of the injectivity of a factor 1.4. These results demonstrate the ability of this kind of methods to enhance the injectivity/productivity of geothermal reservoir. The hydrothermal model is also used to import the results of the hydraulic stimulation (Blaisonneau et al. 2020) and then assess its impact as well as the combined effect of the hydraulic stimulation followed by the implementation of the two-legs configuration, which results in an increase of the injectivity of a factor 1.4 and 3, respectively. To finish this numerical model is used to simulate the injection of “cold” water (related to the reservoir temperature) in the longer term. The resulting temperature field could then be used in combination with the modification of permeability provided by the study of thermo-mechanical modelling of the rock behaviour under thermal loading (presented in Tran et al. 2020) to assess the impact of thermal stimulation.

5 CONCLUSION

In order to optimize the productivity/injectivity of deep geothermal wells initially not economic, a number of techniques are available. On the one hand, the architecture of drilling can be improved to increase the contact between the well and the reservoir. On the other hand, once the drilling is fixed, the connection with the reservoir can be improved through hydraulic, thermal and/or chemical stimulations. All these techniques (including architecture improvement) can be combined to reach the targeted production rate. In the DEEPEGS project, these techniques were tested on two demonstrators, in different geological contexts: a very hot one in Iceland (IDDP-2/RN-15, around 500°C-530°C, in a fractured sheeted dyke complex) and a more temperate one in France (above 200C, in a plutonic basement), both of them around 4.5 km depth.

In order to investigate the potential improvement that can be expected from the different technologies, a number of simulations approaches was deployed. The following results were obtained:

- Using hydraulic stimulation to produce hydroshearing is not sufficient to reach sufficient permeability in the Icelandic context. It can however constitute an interesting companion technique, if used in combination with another one.
- Thermal stimulation appears as a promising technique, especially in contexts with high temperature difference between the rock and the cooling fluid, and with favorable stress state, as in Iceland. In this case, thermal stimulation could lead to the apparition of new fractures. In less favorable cases, thermal stimulation could nevertheless be efficient to produce cracks in particular features of the rock, such as in veins of quartz in the French context.
- The use of improved well configurations appears as a good way to increase the productivity, especially when used in combination with other techniques.

Figure 7 corresponding to the Vendenheim demonstrator, illustrates these statements: in the case of a faulted geothermal reservoir, thermal stimulation can create new pathways by fracturing the quartz sealing of discontinuities; chemical stimulation increases the porosity of preexisting fractures by sealing dissolution (not presented in this paper); soft hydraulic stimulation leads to permeability enhancement through fractures shearing and the "two-legs" geometry increases the connectivity between the wellbores and the reservoir.

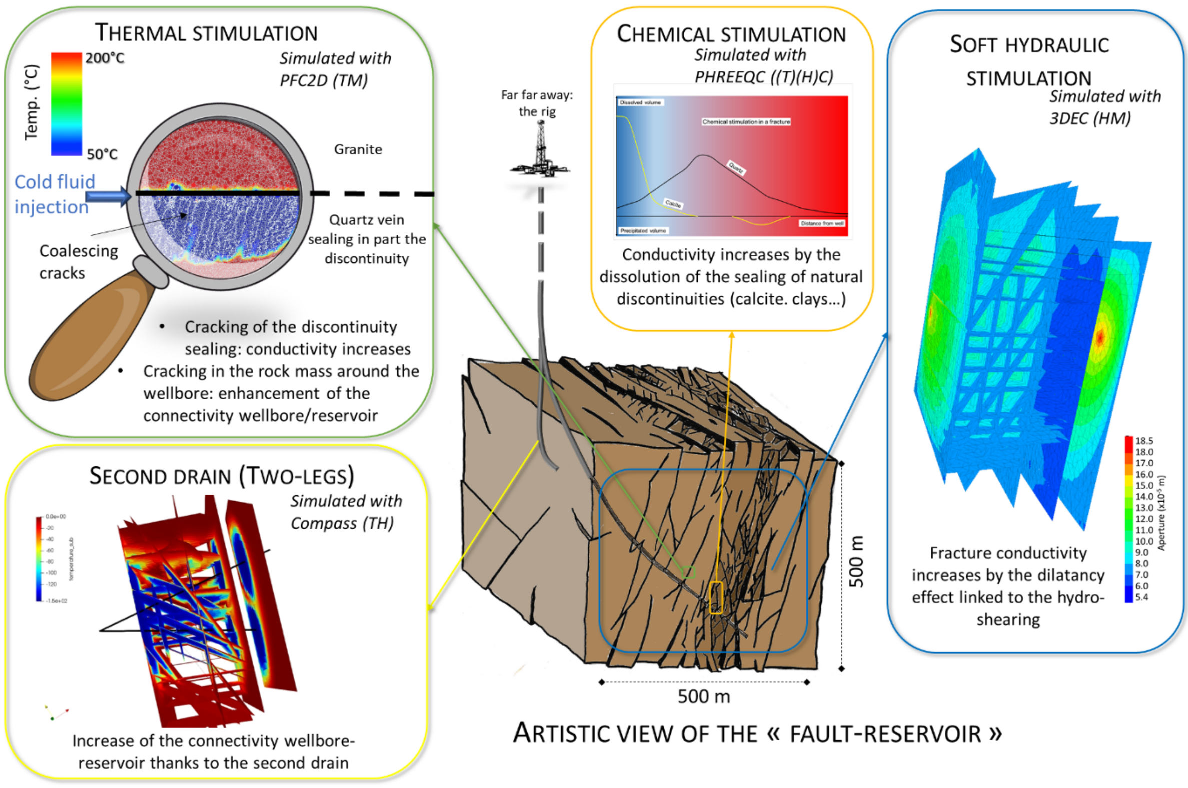


Figure 7: Artistic view of the faulted geothermal reservoir of Vendenheim and of the assessed technologies to improve the injectivity of the wells.

ACKNOWLEDGEMENTS

The work was performed in the framework of the DEEPEGS project, European Union's HORIZON 2020 research and innovation program under grant agreement No 690771. We would like to thank HS-ORKA for providing access to the datasets over the Reykjanes geothermal field and Fonroche Géothermie for providing access to the datasets over the Vendenheim geothermal field.

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