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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report dated 9.03.2023

ZoDrEx

Zonal Isolation, Drilling and Exploitation of EGS Projects

Source: ©Geo-Energie Suisse 2022

Date: 9.03.2023

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

Subsidy recipients:
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Reitergasse, 8004 Zürich
www.geo-energie.ch

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SFOE contract number: SI/501720-01

Zusammenfassung

Ziel des ZoDrEx-Projekts ist die Demonstration und das Benchmarking von innovativer Bohrtechnologie, Bohrlochausrüstungen und Stimulationstechnologien, die die technischen und wirtschaftlichen Erfolgsaussichten von Geothermie-, Wärmespeicher- und CCS-Anwendungen erhöhen.

Zu den innovativen Lösungen, die im unterirdischen Felslabor von Bedretto getestet und demonstriert wurden, gehören Hammerbohrungen von großen Bohrlöchern mit einem Durchmesser von 8,5 Zoll in der gleichen Größe, wie tiefe Geothermiebohrungen abgeteuft werden, sowie zonale Isolationstechnologien in diesen Bohrlöchern zur Stimulation einzelner Bohrlochabschnitte.

Im Projekt ZoDrEx konnte eindeutig nachgewiesen werden, dass die Hammerbohrtechnik auch bei stark abgelenkten und horizontalen Bohrungen mit Durchmessern von 8,5 Zoll bis zu Längen von mindestens 400 m auch ohne Richtbohrtechnik eine qualitativ gute und kostengünstige Alternative zu konventionellen Rotarybohrungen darstellt. Streng genommen gilt dies derzeit vor allem dort, wo klares Wasser als Bohrspülung eingesetzt werden kann. Als Einsatzgebiete sehen wir derzeit vor allem Wärmespeicherprojekte und mitteltiefe Geothermieprojekte im kristallinen Gestein. Die Zukunft der Hammerbohrtechnik für tiefe geothermische Anwendungen hängt jedoch noch davon ab, inwieweit es möglich sein wird, den Hammer auch mit Bohrspülung anzutreiben.

Es wurden verschiedene zonale Isolationstechnologien demonstriert und verglichen, die vor allem für die Entwicklung von EGS, aber auch ganz allgemein für die Erhöhung der Durchlässigkeit beim Anschluss von Bohrungen ans Reservoir in Hydrothermalen- und Wärmespeicherprojekten von großer Bedeutung sind.

ZoDrEx hat damit die Grundlage geschaffen, um die Energieerträge zum Teil erheblich zu steigern, die Einsatzrisiken verschiedener Technologien besser abzuschätzen und damit die Wirtschaftlichkeit geothermischer Systeme insgesamt zu erhöhen. Darüber hinaus können wir Reservoir- und Bohringenieuren Auslegungskriterien und Entscheidungsgrundlagen liefern.

Résumé

Le projet ZoDrEx vise à démontrer et à comparer les produits et technologies de forage, de complétion et de stimulation qui augmenteront les chances de réussite technique et économique des applications géothermiques, de stockage de chaleur et de CCS.

Les solutions innovantes testées et démontrées au laboratoire souterrain de Bedretto comprennent le forage à l'aide d'un marteau de grands trous de forage de 8,5 pouces de diamètre, de la même taille que celle des puits géothermiques profonds, et des technologies d'isolation zonale dans ces trous de forage pour la stimulation de sections individuelles de ces trous.

Dans le projet ZoDrEx, il a été clairement démontré que la technique de forage au marteau est une alternative qualitativement bonne et rentable au forage rotatif conventionnel, même pour les puits fortement déviés et horizontaux d'un diamètre de 8,5 pouces jusqu'à des longueurs d'au moins 400 m, même sans technologie de forage directionnel. À proprement parler, cela s'applique actuellement principalement là où l'eau claire peut être utilisée comme fluide de forage. Les projets de stockage de chaleur et les projets géothermiques de moyenne profondeur dans les roches cristallines sont actuellement les principaux domaines d'application. Cependant, l'avenir de la technologie de forage à marteau pour les applications géothermiques profondes dépend encore de la mesure dans laquelle il sera possible d'entraîner le marteau en utilisant également le fluide de forage.

Différentes technologies d'isolation zonale ont été démontrées et comparées, ce qui peut être d'une grande importance principalement pour le développement de l'EGS, mais aussi plus généralement pour augmenter la perméabilité lors de la connexion des puits avec le réservoir dans les projets

hydrothermaux et de stockage de chaleur. ZoDrEx a donc fourni la base pour augmenter les rendements énergétiques, dans certains cas de manière significative, et pour mieux évaluer les risques de déploiement des différentes technologies, ce qui permet d'améliorer l'économie globale des systèmes géothermiques. En outre, nous pouvons fournir aux ingénieurs de réservoir et de forage des critères de conception et une base pour la prise de décision.

Summary

The ZoDrEx project aims at demonstrating and benchmarking of drilling, completion and stimulation products and technologies that will increase the technical and economical chances of success in geothermal, heat storage and CCS applications.

The innovative solutions been tested and demonstrated at the Bedretto underground rock laboratory include hammer drilling of large 8.5 inch diameter boreholes in the same size as deep geothermal wells are drilled, and zonal isolation technologies in these boreholes for the stimulation of individual borehole sections.

In the ZoDrEx project it was clearly demonstrated that the hammer drilling technique is a qualitatively good and cost-effective alternative to conventional rotary drilling even for highly deviated and horizontal wells with diameters of 8.5 inch up to lengths of at least 400 m, even without directional drilling technology. Strictly speaking, this currently applies primarily where clear water can be used as drilling fluid. We currently see heat-storage projects and medium-depth geothermal projects in crystalline rock as the primary areas of application. However, the future of hammer drilling technology for deep geothermal applications still depends on the extent to which it will be possible to drive the hammer using drilling fluid as well.

Different zonal isolation technologies were demonstrated and compared, which can be of great importance primarily for the development of EGS, but also more generally for increasing the permeability when connecting wells with the reservoir in hydrothermal and heat storage projects. ZoDrEx has thus provided the basis for increasing energy yields, in some cases significantly, and for better assessing the deployment risks of different technologies, thus boosting the overall economics of geothermal systems. In addition, we can provide reservoir and drilling engineers with design criteria and a basis for decision-making.

Main findings

- conditions, borehole breakouts, borehole stability, temperature, equipment reliability, deployment risks, equipment availability and costs.

  For a greenfield project without pre-existing information from exploration drilling such as the Haute-Sorne project, it is now possible to plan for a stimulation well from the outset with a cemented and perforated casing. For a second well, probably a production well, it can be decided based on the results of the first well whether it is better to use an open-hole multi-packer completion or also to equip the second well with a cemented and perforated casing. These results are of great importance to reduce the operational, technical, and therefore also financial risk of projects that will depend on stimulation measures because sufficient water permeability cannot be expected on the basis of the available data before drilling.

- Within the framework of ZoDrEx, the micro-drilled side-track developed by Fraunhofer IEG could be used successfully for the first time in-situ in granite and for the first time at depths of approximately 300 m. A with a typical geothermal diameter of 8.5 inch and a cemented casing, could be well connected to the fractured rock with the micro-side-tracks and subsequently stimulated. This technology is first in certain cases a very good alternative for the classical perforation technology based on explosives, and secondly it allows completely new perspectives for applications to drill several meters long micro-sidetracks, which are impossible to reach with the classical perforations. This technology can significantly contribute to greatly increase the hydraulic connectivity between the wellbore and the reservoir and therefore has a significant contribution to increase the overall economic viability of geothermal and heat storage projects. It also minimizes the exploration risks. If the permeability of the sandstone at the on-going heat store project in Bern will not be sufficiently high, the drilling of micro-side-tracks will be an important risk mitigation measure. Because of the ZoDrEx project this technology could now be applied.

Contents

1 Introduction

1.1 Background information and current situation

On May 2017, the people of Switzerland has approved massively (58% for) the energy act that sets the pace toward ending nuclear power generation in the country.

On 5 October 2016, the required international consensus for the Paris Agreement was achieved. That agreement entered into force on 4 November 2016. It was eventually ratified in June 2017 by the Swiss senate by 39 votes against 3. In this agreement, Switzerland commits by 2030 to lower its CO_2 emissions by 50% when compared to the 1990 level.

In this context, Switzerland must replace its about 40% nuclear electricity generation by a CO_2 free emission technology that does not depend on meteorological factors and that can be flexible enough to allow intermittent renewable energy sources to feed the grid when available.

Geothermal power generation is the only technology currently on the market that can meet the above requirements. With 97% of the earth mass at temperatures exceeding 1000°C an enormous amount of thermal energy is available inside our planet. Because of its potential and its availability regardless of time, seasonal and else factors, it sets it apart from all renewable energy sources. However, bringing this underground energy from its source to the surface in an economic way and a usable form is still challenging. Indeed, accessing the deeply buried energy requires expensive drilling operations, and bringing that energy to the surface in sizable amounts, when compared to population and industrial's needs, is still considered too risky for private investments alone. Therefore, we must identify and demonstrate the technologies needed to significantly reduce the risks and costs associated with well drilling and completion, with geothermal fluids production and with enhanced geothermal systems (EGS) operations to make deep geothermal projects a sound economical proposition. This is the ambition of the ZoDrEx project.

Associated solutions include energy storage and energy efficiency improvement, both necessary at better utilizing the currently available power, but not able to tap into new and locally available resources. Geothermal power generation, energy storage and energy efficiency efforts are not in competition but complement each other toward achieving the set energy strategy targets. The combination of these technologies and the large Swiss capacity to produce and store electricity from hydraulic power infrastructures are a viable solution for an independent and continued power supply.

Once the risk associated with geothermal power generation is reduced to an acceptable level, this energy source can be made available to the larger world for domestic, industrial and development needs. Along the ZoDrEx project, the adaptation of existing equipment to geothermal applications will contribute to the necessary risk reduction goal while creating industrial opportunities

The ZoDrEx project aims at reducing the risks currently plaguing geothermal projects. Therefore, ZoDrEx will not directly bring new energy into the Swiss supply. To make the energy transition of Switzerland and Europe a reality, with geothermal energy playing its part in that transition, deep geothermal resources must be accessed at a lower risk through EGS implementation. The proper resources able to deliver that low risk engineered process, previously scattered across Europe are assembled into this consortium to demonstrate that a full-scale project can be confidently undertaken.

Deep geothermal power generation via enhanced geothermal systems (EGS) is still in its infancy. In Switzerland, the attempt in Basel (2006) was stopped for various reasons that do not need being debated here. In France, Soultz-sous-Forêts has demonstrated that these projects can reach a successful outcome. However, they all show that the risks (industrial and financial) associated with these projects are a major factor affecting EGS development.

Geo-Energie Suisse holds a construction permit in Haute-Sorne (Jura) and is working on a number of similar projects throughout Switzerland. Learning from the previous experiences, Geo-Energie Suisse has developed models and techniques with major Swiss research institutions such as ETH Zürich to mitigate these risks. However, before embarking on a full-size project, some of these ideas and developments must be tested under controlled conditions. Indeed, with well costs hovering in the CHF 100 million range for a project like in Haute-Sorne, ensuring that stimulation placement, hence production targets in low permeable rock can be met is an overarching priority.

The findings of ZoDrEx are not only applicable to EGS projects, but also to hydrothermal projects to increase or ensure a successful outcome in case not enough permeability has been found (the latest example being the AGEPP project in Lavey-les-Bains). Furthermore, the technologies tested in ZoDrEx are not only applicable in crystalline rock (granite, gneiss) but also in sediments and therefore in principle to any geothermal project irrespectively of depth. In addition, these technologies go even beyond the pure geothermal sector, because they can also be applied to heat storage projects and CCS projects.

ZoDrEx results are necessary to expand the geothermal, heat storage and CCS market from its current pilot and demonstration playground into a technology available for industrial and profitable applications, thus becoming attractive also to private investment. In this report we present mainly the results of the activities performed in the underground rock laboratory of Bedretto.

1.2 Purpose of the project

The ZoDrEx project aims at demonstrating and benchmarking of drilling, completion and stimulation products and technologies that will increase the technical and economical chances of success in geothermal, heat storage and CCS applications. The following innovative solution have been demonstrated by ZoDrEx:

I. Fluid driven percussion drilling can be used in highly deviated trajectories to improve drilling efficiency in crystalline rocks and evaluate the readiness and benefits of hammer drilling on one side for deep geothermal projects and on the other side for shallower heat-storage projects.

II. Zonal isolation is key to efficient EGS stimulation and that zonal isolation technologies selection can be performed efficiently. Additionally, ZoDrEx has contributed to the development of more robust zonal isolation technologies and has allowed a benchmarking of different systems.

All the activities within ZoDrEx were aiming at selecting or extending, testing and implementing existing technologies to adapt or prove them in the context of geothermal projects. By testing some of these technologies in an underground laboratory, ZoDrEx allowed a more precise control over experimental conditions, a low-risk environment for trying new technologies and reduced cost when compared to testing in a deep wellbore. In the end, operators have now a better understanding on how to improve well construction, EGS creation and stimulation at a reduced technical and financial risk.

The ZoDrEx project groups 8 partners from Denmark, France, Germany, Spain and Switzerland. These partners include industry leaders in completion equipment, project management and geothermal operators, engineering organizations active in both the public and the private sectors, and two prestigious academic research organisations. Note that in this report we present mainly the results of the activities performed in the underground rock laboratory of Bedretto.

To make the energy transition of Europe a reality, deep geothermal resources must be accessed at a lower risk through EGS implementation. The proper resources able to deliver that low risk engineered process, previously scattered across Europe are assembled into this consortium to demonstrate that a full-scale project can be confidently undertaken.

1.3 Objectives

The main objectives of ZoDrEx at the Bedretto Lab are A) to improve and demonstrate horizontal drilling efficiency in crystalline rocks using hammer drilling and B) to evaluate and demonstrate reliable zonal isolation techniques (equipment and stimulation performance). These objectives are described in more detail in the following.

A) **Improve and demonstrate horizontal drilling efficiency in crystalline rocks** in the Bedretto gallery:

Drilling deep geothermal wells is expensive, in part because of the difficulty of penetrating crystalline rock with conventional drilling tools. Projects have demonstrated that drilling speed in crystalline rocks can be improved by a factor of 10 when using percussion drilling in comparison to standard rotary drilling. A vertical well was drilled with a rate of penetration (ROP) of up to 15 m/hour to circa 4500 m using air hammer drilling at the ST1 project in Helsinki. In contrast, conventional ROPs range around 1.5 m/hour for rotary drilling in crystalline rocks (e.g. Basel). However, today's attractiveness of hammer drilling is still limited for long laterals in deep crystalline rocks wells, mainly because hammer drilling is not steerable and because downhole measurements while drilling (MWD) tools cannot withstand the strong shocks exerted by the hammer up the drill string.

The project shall demonstrate that drilling of two horizontal 8 ½" diameter strongly deviated boreholes with 45° and 65° from horizontal and with a length between 300 and 400 m from the Bedretto gallery into granite is feasible.

Furthermore, drilling data concerning the deviations from the planned trajectories, the rate of penetration and the ability to infer fracture frequency information from drilling data are analysed in order to evaluate the readiness and benefits of hammer drilling on one side for deep geothermal projects and on the other side for shallower heat-storage projects.

B) **Evaluate and demonstrate reliable zonal isolation techniques** in the Bedretto gallery:

Harvesting the geothermal resources implies an efficient technique for stimulating the geothermal reservoir. Large efforts have been devoted to hydraulic and chemical stimulation technologies. However, little has been done on the efficient placement of these treatments. Existing techniques, developed for oil production, tend to produce concentrated (unstable) stimulation, which is not appropriate for EGS. Yet, the method and location stimulation treatments are paramount to achieving a successful EGS project for which the connection between the borehole and geothermal reservoir must be achieved and maintained for maximising injection and production.

Pinpoint injection of stimulation treatments requires a corresponding zonal isolation technology, able to efficiently segment a wellbore under deep geothermal conditions. The white paper "Zonal isolation for geothermal wells" of the International Partnership for Geothermal Technology (2012, [1]) describes the issues and a number of potential technology solutions to achieve the required zonal isolation.

Several EGS reservoir creation and development concepts (Geo-Energie Suisse AG for Haute-Sorne, US D.O.E. FORGE at Utah Milford site), rely on zonal isolation techniques to individually stimulate multiple isolated sections. The oil and gas industry has developed a number of zonal isolation concepts for multi-zonal stimulation, but none of them has ever been applied for EGS reservoir creation. However, a reliable multi-zonal isolation technique is critical to EGS operation and crucial for the whole investment of projects requiring several tens of millions of Swiss Francs.

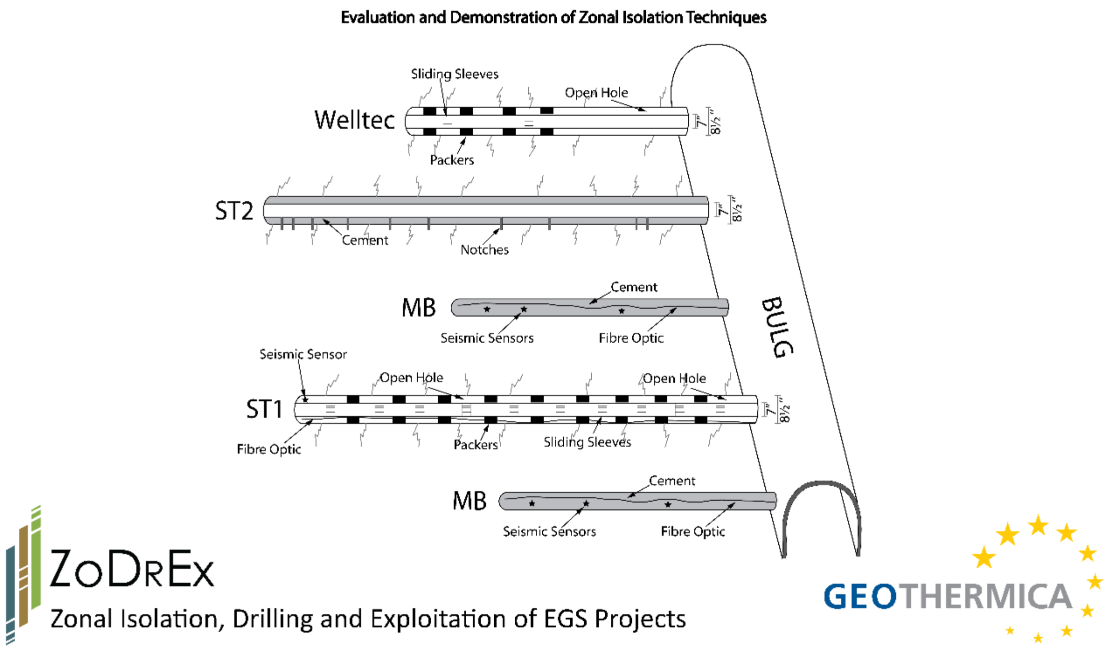


Figure 1. Concept of the ZoDrEx Project.

The multi-zonal isolation techniques benchmarked in ZoDrEx are shown schematically in Figure 1.

Borehole ST1 is completed with an open-hole multi-packer system and sliding sleeves. The sliding sleeves can be opened and closed individually to pressurize natural fractures within the isolated open borehole sections.

Borehole ST2 in Figure 1 is cased and cemented. The borehole is perforated in its left part. Notches are created in the middle of the borehole using short-radius multilateral, small diameter boreholes (micro drillings) to access the formation out of the cased main borehole. The isolated sections can be pressurized either using a double-packer system (not shown) introduced trough the central liner or each section is created from the end to borehole head sequentially, pressurized and isolated from the rest of the borehole with a plug (not shown).

The advantage of open-hole isolation techniques with packers (in ST1) is that all natural fractures intersecting the borehole between two packers are readily available for stimulation. These zonal isolation packer solutions can involve swellable elastomer, mechanical, inflatable, solid inflatable, as well as a combination of those and with various setting mechanisms. Major drawback of packer solutions is that they are expensive, may show operational problems during installation and that packers can only seal in relatively good borehole wall conditions (very stable boreholes, small and few borehole breakouts or washouts). Especially for a first well the borehole conditions are generally unknown in advance. Therefore, in comparison to a multi-packer system a cemented and perforated casing is easier to plan for and associated with lower risks in view of borehole breakouts or washouts. The main risks of deploying a cemented and perforated casing are bad cementation and bad access to the reservoir for stimulation and production.

One of the main objectives of ZoDrEx is to test and benchmark these two systems. Each of them has its own merits and drawbacks, but none has been sufficiently qualified in the field for EGS to be confidently applied in a real project.

The field tests were jointly supported by Fraunhofer (drilling of micro-side-tracks) and RWTH (Minifrac tests) and our academic partners CSIC (Spain), RWTH (Germany) and ETH (Switzerland), who adapted hydro-mechanically coupled numerical models and laboratory tests to help design the field experiments and to analyze the data gathered during the field experiments. The numerical models are built on state-of-the-art codes from the academic partners.

The ZoDrEx project has the ambition of taking the zonal isolation technologies from a TRL 7 to 9 through extensive testing in the Bedretto underground laboratory (Ronco, Val Bedretto, Canton Tessin, Switzerland) offering a direct access to crystalline rock. The rock laboratory is operated by ETH Zürich, which holds also the licence to operate, from the owners, and the permits, from the authorities.

2 Description of facility

The purpose of the Bedretto Lab (or *"BULG":* Bedretto Underground Laboratory for Geosciences and Geoenergies) is to host reduced scale in-situ experiments in crystalline rocks, with focus on drilling and completion, hydraulic stimulation, monitoring and seismic risk mitigation during the construction of an EGS. The BULG is located in an enlarged section of the Bedretto tunnel between tunnel meters 2000-2100 from the south entrance. The Bedretto tunnel, a branch of the Furka railway tunnel (Figure 2), trends ~N43W at ~1500 m below the Pizzo Rotondo (3190 m a.s.l.). Further information can be found under http://www.bedrettolab.ethz.ch/en/home/.

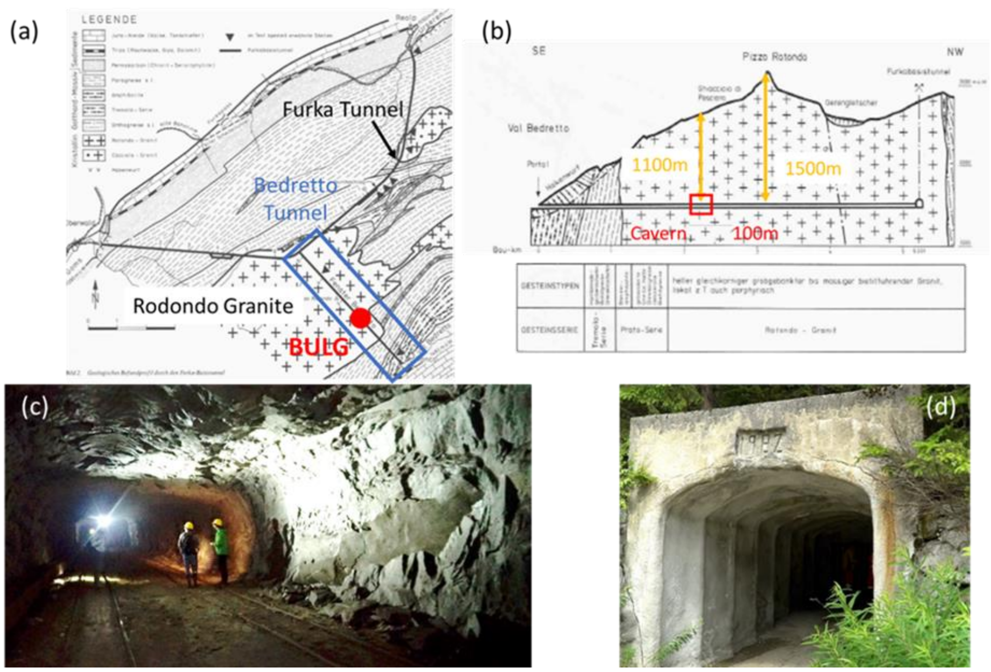


Figure 2. (a) Geological map of the surroundings of the Bedretto tunnel (blue inset) and location of the Bedretto Lab ("BULG" red point); (b) NW-SE profile along the Bedretto tunnel, depicting the location of the cavern hosting the BULG; the approximate overburden is depicted by yellow arrows (panels a and b modified from Keller and Schneider, 1982); (c) inner view of the tunnel; (d) south entrance of the tunnel. From [2].

3 Procedures, methodologies and results

3.1 Improve and demonstrate horizontal drilling efficiency in crystalline rocks

Drilling deep geothermal wells is expensive, in part because of the difficulty of penetrating crystalline rock with conventional drilling tools. Projects have demonstrated that drilling speed in crystalline rocks can be improved by a factor of 10 when using percussion drilling in comparison to standard rotary drilling. A vertical well was drilled with a Rate of Penetration of up to 15 m/hour to circa 4500 m using air hammer drilling at the ST1 project in Helsinki. In contrast, conventional Rates of Penetration range around 1.5 m/hour for rotary drilling in crystalline rocks with roller cone bits (e.g., Basel project). However, today's attractiveness of hammer drilling is still limited for long laterals in deep crystalline rock wells, mainly because hammer drilling is not steerable and because downhole Measurements While Drilling tools cannot withstand the strong shocks exerted by the hammer up the drill string.

The goal of ZoDrEx is to demonstrate that drilling of horizontal 8 ½ inch (215.9 mm) diameter strongly deviated boreholes with a length up to 400 m from the Bedretto gallery into granite is feasible (Figure 3). Furthermore, drilling data concerning the deviations from the planned trajectories, the rate of penetration and the ability to infer fracture frequency information from drilling data are analysed in order to evaluate the readiness and benefits of hammer drilling on one side for deep geothermal projects and on the other side for shallower heat-storage projects.

At the Bedretto Lab three wells were successfully drilled as production or injection boreholes with 8 ½ inch diameter, with a length of 400 m and an inclination of 45° (ST1), with a length of 350 m and an inclination of 35° from horizontal (ST2) and with a length of 120 m and an inclination of 6° from horizontal (Welltec borehole). Furthermore, for monitoring, eight boreholes were hammer drilled with diameters of 6 ½ inch (165.1 mm), inclinations of 20 to 45° from horizontal and lengths of 100 to 300 m (Figure 3). These wells were originally named with the abbreviation CB, later the wells were given the abbreviation MB (MB = **M**onitoring **B**orehole; MB1 to MB8).

The most in-depth data analysis and evaluation of the drilling performance has been done for the ST2 borehole. In the following we summarize these results.

All drilling and drilling related work were conducted by Züblin AG and were consulted as well as directed by both Fraunhofer IEG and Geo-Energie Suisse. During the actual drilling work, Geo-Energie Suisse was continually present in the Bedretto Lab overviewing the operation; Fraunhofer IEG was on site at times to consult with the proceedings, however, at the time, the COVID-19 situation started to become increasingly prevalent, rendering desired further presence and participation of Fraunhofer IEG in the actual drilling operation unfeasible.

In close cooperation, Züblin AG employed percussion hammer technology to drill through the hard granite rock of the Saint-Gotthard Massif. For this, a so-called Down-the-Hole drill was utilized in conjunction with 3 m drill pipe and water as a drilling fluid. Borehole ST2 has an initial angle of 35 degrees from the horizontal, a borehole diameter of about 8 ½ inch at a measured depth of about 350 m. Please note, that in hammer drilling the diameter slightly decreases with depth because of the wear of the hammer. Therefore, to reach a diameter of 8 ½ inch at final Measured Depth the borehole needs to be started with a slightly increased diameter.

In the past, percussion drilling technologies have proven to significantly increase the Rate of Penetration. As Rate of Penetration is the crucial measure for the assessment of operational success or failure, much focus lies on improving and maximizing it. Due to the percussive action on the rock surface, Down-the-Hole technology allows for especially high Rates of Penetration in hard formations like the Saint-Gotthard granite, rock delineating reservoir characteristics suited for geothermal exploitation; conventional rotary drilling employs either point-load crushing (Tri-Cone) or sole shearcutting (PDC) action on the rock surface resulting in lower Rate of Penetration in hard rock. This is the reason for the investigation of percussion hammer technology for application in geothermal wellbores.

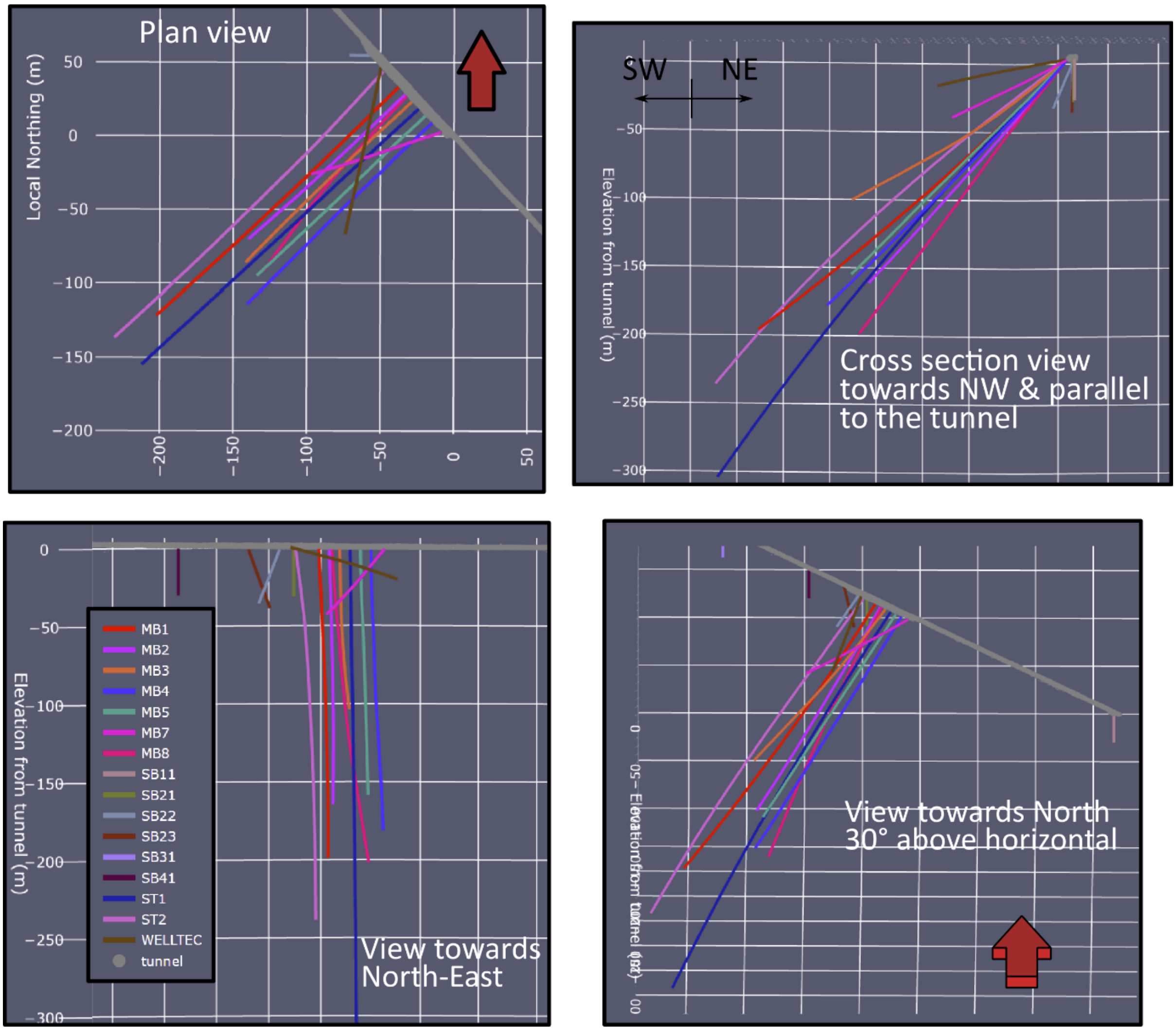


Figure 3. View from different perspectives of the boreholes drilled in the Bedretto Lab. Three boreholes were drilled as production or injection boreholes with 8 ½ inch diameter (ST1, ST2 and Welltec). Monitoring boreholes were hammer drilled with diameters of 6 ½ inch (MB1 – MB8). Geological characterization analysis was done in the boreholes SB1 - SB4.

At Fraunhofer IEG, many wellbores were drilled employing conventional percussion drilling technologies, with Rates of Penetration ranging from 1.03 m/min to 0.74 m/min for shallow deviated wellbores. General trends for percussion drilling were demonstrated and can be summarized as follows: Rate of Penetration decreases with increasing depth and necessary circulation time rises with depth; this is also because distance between bottom hole and surface increases. Rate of Penetration does not include downtime due to tripping or other operations-related activity, which prohibits drilling, i.e., rock breaking by the bit.

Drilling at Fraunhofer IEG has also proven that cuttings transport and circulation flow are proportional: a volume increase for the one necessitates a likewise increase for the other. In the reference case, 260 and 320 cubic meters of circulation water removed 4.3 and 5.3 cubic meters of cuttings from one 6 ½ (165.1 mm) and 7 ¼ inch (184.15 mm) borehole, respectively.

Also, when distinguishing between circulation time versus drilling time, it is evident from drilling data that more than half of the overall time required to drill to Total Depth is allotted to hole cleaning and fluid circulation for cuttings removal: Non-Productive Time. This is especially true for depths beyond 80 meters and for high cuttings velocities in the range of 1.2 to 3.2 m/s, which are conventionally not encountered in deep drilling. Only prior to 80 meters, more time is allocated to percussion drilling than water circulation according to the data.

As deviated or horizontal well sections represent an especially powerful mean to connect wellbore and reservoir with predominantly sub-vertical fractures and as due to the nature of reservoir rock being hard rock in hot dry rock and Enhanced Geothermal Systems (EGS), it is necessary to show that Down-the-Hole drills are capable of delivering deviated and directional wellbores with high quality. This inclined drilling operation with no deviation control whatsoever allowed for assumptions to be drawn regarding trajectory behaviour and well path compliance of Down-the-Hole drilling technology in very hard rock.

For a Measured Depth of 350 meters, an inclination drop of 13.7 degrees could be determined for the bottom hole of the wellbore ST2. Furthermore, at Total Depth a deviation from the initial orientation (azimuth) of 220 degrees at the wellhead was determined to be 222.8 degrees. The Horizontal Displacement of the wellbore was calculated to be 254.82 m, True Vertical Depth is approximately 226.64 m. Considering the Horizontal Displacement and the initial inclination at wellhead, this deviation is acceptable for no deviation control and good with regard to wellbore deviation in rotary drilling. In fact, it is very presumable and probable that rotary drilling under the exact same conditions would have resulted in higher deviation both in inclination and orientation. Nonetheless, wellbore deviation encountered in rotary drilling is in part a result of the tendency of the bit to move due to its rotation. Therefore, the interpretation of the well trajectory data as well as suggestions in the literature allow the assessment that, for percussion drilling technology, smaller wellbore deviation may be anticipated.

Additional logging verified the general smoothness of the wellbore through various employed post-run devices including Optical Televiewer, Acoustic Televiewer, caliper log and video-image camera log; both well trajectory and wellbore wall were determined to be generally smooth especially visually through color video-recording of the entire borehole. Dogleg severity (DLS) is approximated to be 1.23 degrees per 30 m for the ST2 wellbore. Nevertheless, a few large washouts were determined at Measured Depths of 194, 260, 280 and 323 m. They were attributed through the logs to faults in the formation and thus were not regarded because of poor or inadequate drilling. In the initial open hole state of the wellbore, however, these washouts had to be considered for workover operations like the Radial Jet Drilling stimulation. Necessary Run in Hole and Pull Out Of Hole of drill pipe for the Radial Jet Drilling operation was planned accordingly.

One major purpose of drilling fluid is the transport of cuttings from bottom hole to surface. Common drilling fluids embrace properties such as thixotropy and adequate viscosity through additives. Today’s downhole percussion drilling tools still are rather sensitive to impurities and abrasive materials in the drilling fluid. Therefore, it is necessary to facilitate cuttings removal and appropriate hole cleaning with nearly clear and ambient water, which has not been intensively enriched or altered with additives.

Drilling fluid comprises an integral part in the making of the borehole. It is part of the circulation system and amongst many others, it facilitates hole cleaning, wellbore integrity and well control. Moreover, it may be utilized to convey hydraulic power to the bit in addition to mechanical power through pipe rotation and weight on bit. Good hole cleaning means the removal and evacuation of cuttings from the vicinity of the bit and the subsequent transport of cuttings from downhole to surface via the annulus; both through the properties and the energy of the drilling fluid during the well drilling process. Inadequate cuttings removal from the wellbore will eventually impede drilling. For drilling fluids of conventional deep drilling, cuttings removal from the wellbore is most severely affected by flow rate, hole angle, pipe rotation, Rate of Penetration and eccentricity.

Especially in deviated or horizontal boreholes, hole cleaning issues are persistent as cuttings accumulate along and around the pipe on the low-side of the borehole: the pipe remains on the low-side and creates an uneven annulus distributing it into high-flow and low-flow zones, thereby altering flow characteristics. Rotation prohibits cuttings accumulations from building up and generally homogenizes the flow. However, it is when a pipe connection is made to allow for the further extension of the borehole, that pumps are stopped and the drilling fluid circulation system comes to a halt, impairing both cuttings transport and hole cleaning. Conventional drilling fluid restricts cuttings from falling back to the bottom hole through fluid-thickening and viscosity-increasing thixotropic additives. However, it is currently not possible to utilize this type of thixotropic drilling fluid, employed in conventional drilling, in combination with percussion drilling technologies: various mechanical components inducing the percussion mechanism are prone to failure when driven through a medium other than clean water. It is therefore necessary to facilitate cuttings transport and hole cleaning through clear water with no additives when utilizing percussion drilling technology. This makes flow velocity and adequate circulation of the borehole even more important. Industry practice suggests a velocity of 0.3 to 0.8 m/s for good hole cleaning.

For the assessment of cuttings transport, particle slip velocity was determined considering for buoyancy, drag resistance and gravitational acceleration. For the ST2 drilling operation, the fluid was just water and the cuttings particles were fine-grained granite. Under ideal conditions, the slip velocity of the particle would be equal to the necessary cuttings transport velocity, though, for a realistic approximation, influences like particle size inhomogeneity, pipe rotation, wellbore wall roughness and others must be considered. This is achieved through the introduction of another factor accounting for all geological and drilling related issues, which further impair cuttings transport to surface.

The drilling of the ST2 borehole in the Bedretto Lab has proven the viability and feasibility of percussion drilling with clear water as drilling fluid in a pilot up to 350 m of Measured Depth. Though the inclination of the well was rather high at 35 degrees from horizontal, the remaining of the above-mentioned most important parameters affecting cuttings transport were optimized to facilitate adequate hole cleaning. Flow rate was increased whenever needed, pipe rotation was upheld except when making-a-connection and pipe eccentricity was ensured through centralizing elements (stabilizers or centralizers) along the drill string. High circulation rate was maintained, and cuttings size was kept low to facilitate adequate hole cleaning at all times. Moreover, additional fluid circulation was conducted after drilling halt and before new pipe connection. This was to transport the cuttings in the borehole to the surface post drilling of a 3 m joint of pipe. The contrary, the immediate halt of the pumps after the conclusion of drilling, would have resulted in the cuttings in the borehole to sink to the bottom of the well, potentially clogging and plugging downhole equipment. Furthermore, the drilling resulted in favourable wellbore wall conditions, evident especially through visual imagery of the video-image camera log shown in Figure 8, due to formation (very hard rock) and the nature of the percussion drilling technology.

The geothermal energy industry is interested in detecting smaller scale fault zones intersected by boreholes that can be targets for hydraulic stimulations without to run expensive and technically demanding logs. We investigated the utilization and value of Rate of Penetration data from borehole hammer drilling for the characterization of a geothermal reservoir in fractured granite.

A method of Rate of Penetration (ROP) picking and a back analysis with all the fracture and fault zone structures detected in the Acoustic Televiewer and Optical Televiewer logs of boreholes ST1 and ST2 allows to compare how many structures were picked up with respect to all known structures (Figure 4). For every increase in ROP, the maximum value in the period was taken before a reduction in ROP was seen. The maximum values of ROP are taken because these are most easily seen and the larger the value, the more likely it is to correspond to the center of a fracture or fault zone structure. The threshold was determined to be 10 – 25 m/h for ST1 and 16-25 m/h for ST2. The thresholds are defined in ranges because for certain depths within the boreholes, the base value varied depending on the section being analysed, either the upper limit or lower limit of the threshold ranges were used. Any increases in ROP below the lower limit thresholds were considered to be noise. Base values of ROP were also defined for drilling through intact rock. The base ROP values for ST1 and ST2 are 5- 20 m/h and 12- 17 m/h, respectively.

It is a mixture of using thresholds and the relative size of increases in drilling maximums to determine where at what depth the increase is taken. There are some cases where peaks were more rounded of larger amounts of time, and there were some cases where they were clear. This must be taken into account in the analysis. Utilizing the drilling speed to see if a peak is also present there as well was a method to reaffirm the drilling peak pick locations. This is illustrated in Figure 4 where "zone 1" shows a rounded increase in ROP but does not meet the threshold value of 20 m/h, "zone 2" shows a rounded increase in ROP and meets the threshold, a marker is placed at the maximum before a reduction is seen, "Zone 3" shows a distinct increase and max. ROP value also marked with a marker [3].

The best characterized structures from the Rate of Penetration-data were small fault zones that were detected in 90 – 100 % of cases, in contrast to smaller and sometimes closed individual fractures that were detected only in 25 – 38 % of the cases. We conclude that in the absence of Acoustic Televiewer or Optical Televiewer logs, Rate of Penetration data can provide important and sufficient information for the approximate locations of smaller fault zones as targets for hydraulic stimulation.

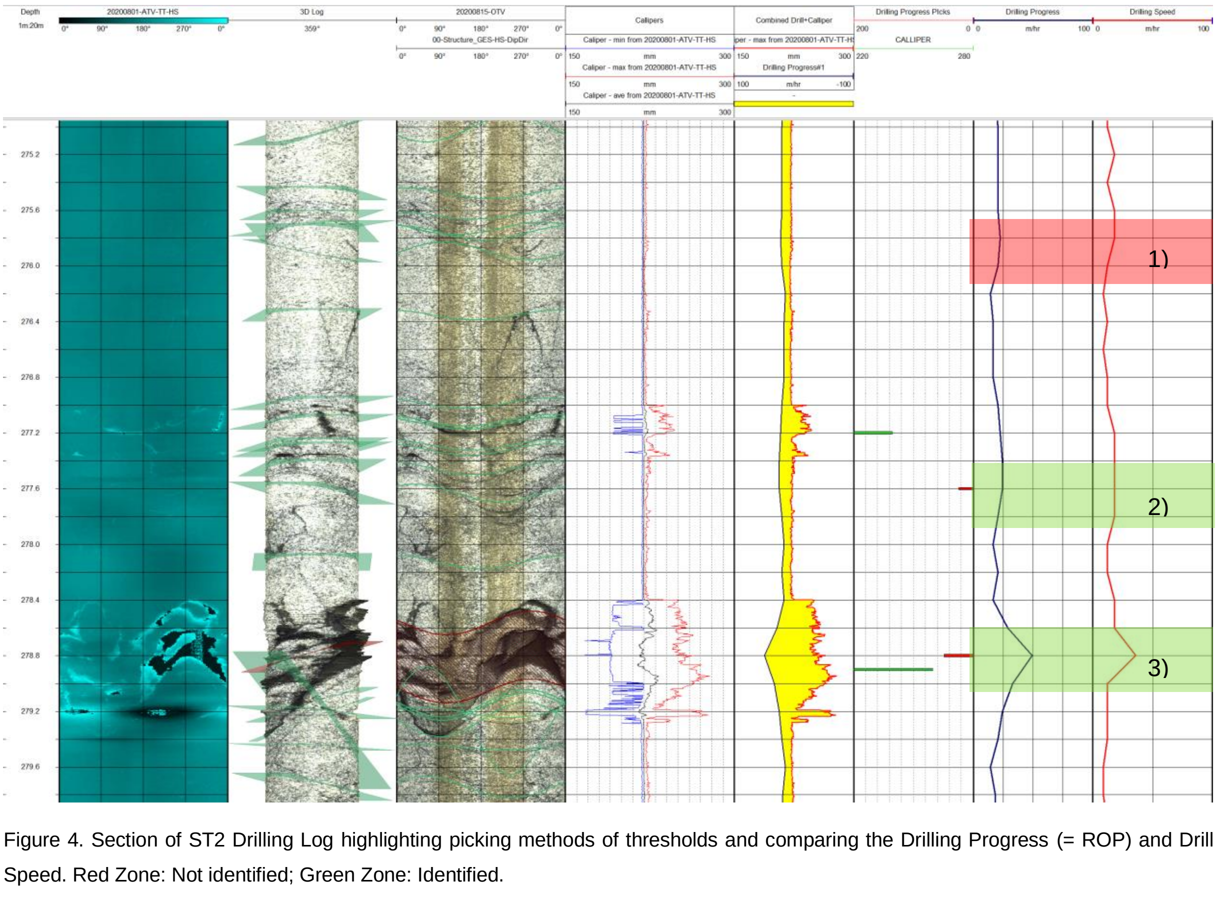


Figure 4. Section of ST2 Drilling Log highlighting picking methods of thresholds and comparing the Drilling Progress (= ROP) and Drill Speed. Red Zone: Not identified; Green Zone: Identified.

3.2 Evaluation and demonstration of reliable zonal isolation equipment

After the boreholes ST1, ST2 and Welltec were drilled with a percussion hammer, the boreholes were characterized by ETH, GES, RWTH and CSIC to choose the test intervals for the different zonal isolation techniques and to define the geo-mechanical conditions of the reservoir. Thereafter, different zonal isolation technologies have been installed and tested by GES and the partners Fraunhofer IEG and Welltec. These include a temporary double packer system utilized in the open ST1 and ST2 boreholes and in the cemented and perforated casing in ST2, a multi-packer system installed in ST1, cementing a 7-inch casing in ST2, radial jet micro-drilling through the casing in ST2 and installing a metal packer system in the Welltec borehole (Figure 1).

3.2.1 Borehole and reservoir characterization prior to stimulation

The borehole and reservoir characterization prior to stimulation included a structural fracture analysis, stress and breakout analysis, measurements of deformation modulus and elasticity modulus, and hydraulic testing.

The stress state was estimated with mini-frac tests and dry (packer) reopening tests at five depth intervals, yielding a minimum horizontal stress of 13-16 MPa and maximum horizontal stress about 0.8~1 of vertical stress. The fracture closure pressure was analysed with several techniques, including G-function, square root of time, bilinear pressure-decay, and jacking pressure. In most cases, the applied techniques give consistent results within an uncertainty range of 1 to 2 MPa.

The dilatometer test yielded the modulus of deformation and modulus of elasticity of the in-situ rock mass. The average elastic modulus is, also considering the dilatometer test in the vertical borehole, 42 MPa ± 18 MPa. The overall average of the deformation modulus from the loading cycle is 12 MPa ± 4 MPa and from the reloading cycle 45 MPa ± 25 MPa.

The in-situ stress analysis and borehole breakout analysis included an azimuth log, tilt log, and caliper log that were collected from the Acoustic Televiewer logs. Breakouts along the boreholes were identified based on the Acoustic Televiewer logs: 262 breakouts were identified in monitoring borehole MB1 between 120-220 m; 136 breakouts were identified in monitoring borehole MB2 between 120-220 m. Discussions were made on variations in breakout presence, orientation and shape, and the underlying processes that cause these variations. The direct link between borehole orientation, borehole tilt, and breakout presence is investigated, as well as the influence of the rate of change of the orientation and tilt. Estimations were made on the rock strength in areas with breakout presence.

Fibre-Optic Distributed Temperature Sensing was used to identify hydraulically active zones along the boreholes ST1 and ST2. Cooling effects indicative for formation water influx could be identified between 109.5 and 112.5 m borehole depth in ST1 and at 179 m in ST2. These observations can be related to a set of pre-existing fractures in ST1 and a single natural fracture in ST2 that are clearly visible in the optical televiewer logs.

Many hydraulic tests were conducted in monitoring borehole MB1, and the stimulation boreholes ST1 and ST2 to estimate the transmissivity and injectivity prior to stimulation, and to measure the hydraulic head profile along the boreholes. The transmissivity is rather small in the order of 1E-9 m^2/s in the first 100 to 120 m of the boreholes intersecting an almost intact granite with only few and typically closed fractures. At around 100 to 120 m all boreholes at the Bedretto Lab intersect the same larger shear-zone with moderate transmissivity values between 1E-8 to 1E-7 m^2/s. After crossing this shear-zone to a depth of about 350 m transmissivity values of the intervals containing open fractures range from 1E-8 to 1E-6 m^2/s, a range that is representative for the crystalline basement under the molasse basin in Switzerland. Only in ST1 highly transmissive fracture zones were intersected from 350 to 400 m with transmissivity values of up to 1E-5 m^2/s. At the time of the hydraulic measurements in ST1 and ST2 most of the boreholes in the reservoir were flowing freely and the hydraulic heads were influenced by borehole drainage in addition to the permanent drainage of the tunnel. Therefore, in all boreholes the hydraulic heads of the tested intervals with respect to the atmospheric pressure at the tunnel were ranging between 50 and 250 m, with the higher values typically in the deeper (measured depth) borehole sections. However, about 6 months after installing the multi-packer completion system in ST1 and closing most of the other wells, hydraulic heads increased from 0 at the well head of ST1 to over 700 m at a measured depth of about 400 m.

3.2.2 Temporary double packer system in the open boreholes ST1 and ST2, and in the cemented and perforated (micro-drilled) casing in ST2

Temporary double-packer systems rated to up to 30 MPa provided by Solexperts AG have been utilized with water inflatable packers in ST1 and ST2 prior to the installation of the permanent multi-packer system in ST1 and prior to cementing the casing in ST2. The deployment and operation of the temporary double packer system followed standard procedures of the industry and are not reported in more detail here, since all operations were successful and without issues. The double packer configurations were run with interval lengths of minimum one to two meters for hydraulic fracturing and interval lengths of up to about 10 m for shear stimulations.

The objective of running temporary double-packer systems before installing permanent borehole completion systems was to identify alterations at the borehole wall after and because of notching, hydraulic fracturing and stimulation. These alterations resulted generally in permanent increase of transmissivity (see discussion in 3.3) and were identified and imaged utilizing borehole logging tools, primarily Acoustic Televiewer, but also Optical Televiewer, camera, temperature- and salinity-logging.

In several high-pressure step rate injection tests (also called hydraulic jacking tests) bypass within the fracture system was observed as an increase of flow rates out of the annulus (void between the injection pipes and the borehole wall). In these cases, the bypass started generally after the jacking pressure of the fractures within the injection interval had been reached. The bypass occasionally reached values of more than 50% of the injection flow rates. In these cases, the injection has been terminated soon after such high levels of bypass was attained. We are confident that the observed bypass predominately did not occur along the packers but around the packers within the fracture system.

Please note, that packer bypass within the fracture system is not an issue with multi-packer completions in terms of high flow rates at the annulus. With a multi-packer system bypass within the fracture system will result in an increase of pressure in the neighbouring intervals. Of course, bypass along a packer may still occur if the packer has been set at an unfavourable location or a too high inflation pressure may have induced fractures along the packer.

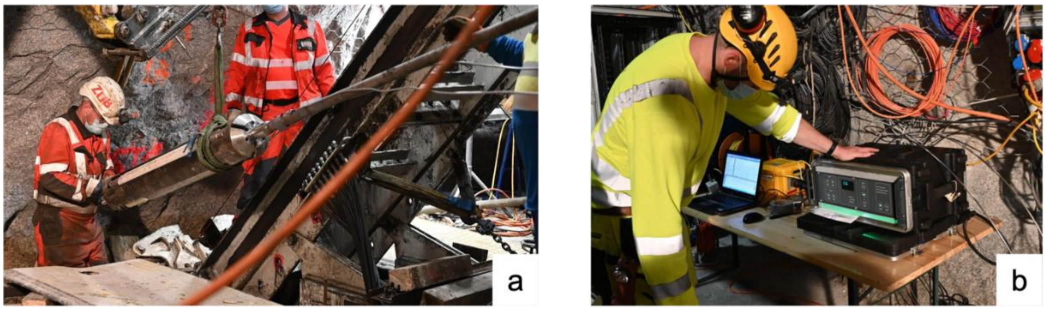
In the case of a cemented casing that is perforated at several locations along the well, bypass within the annulus can occur in case of a bad cementation or if the spacing between the perforations is too small. This happened in two out of four tests in ST2 where the distances between the perforations are in the order of only 10 to 20 m, and the cementation was not very good. However, the issue of bypass within the annulus is believed to be rather negligible in case of a good cementation and larger spacing between the perforations.

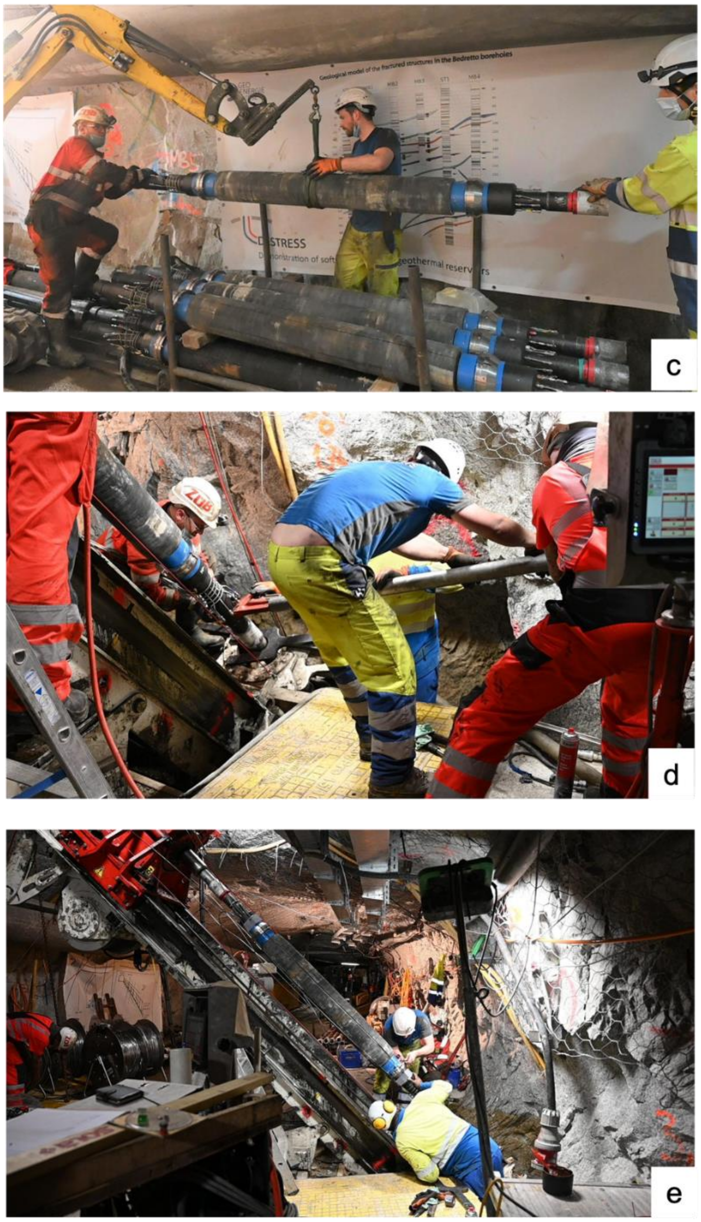
3.2.3 Multi-packer system in ST1

A multi-packer borehole completion system from the oil and gas industry was installed in the 400 m long ST1 borehole with 14 water inflatable packers (rated to 30 MPa) and 14 valves in between the packers (also called sliding sleeves), worked reliably and as expected. Opening or closing of valves located between the packers, allow to inject, or withdraw water from the individual stages. These valves are opened or closed by a key, that is lowered, attached to rods run inside of the 3 ½ inch diameter central tubing. The key is activated at the surface by applying water pressure inside the rods. The lengths of the intervals were chosen based on the previous characterization of the fractures along the borehole. The shortest interval was 7.5 m isolating a larger fracture zone, the two longest intervals in the order of 55 m isolated one section with very low permeability and low fracture density, and another section with multiple fractures of intermediate permeabilities that could not be subdivided further because no more packers were planned for.

Innovative fibre-optic technology installed together and attached to the multi-packer system performed very well. The Distributed Acoustic Sensing measurements provided valuable information on the open/close positions of the valves between the packers (characteristic noise indicates the correct opening/closing). This is important for applications in deep wells, where virtually no control is possible from surface to the 4 - 6 km deep installed and mechanically moved sliding sleeves. The Fibre-Optic Distributed Temperature Sensing measurements and especially the heat pulse measurements allowed us to identify flowing fractures within the intervals isolated by two packers.

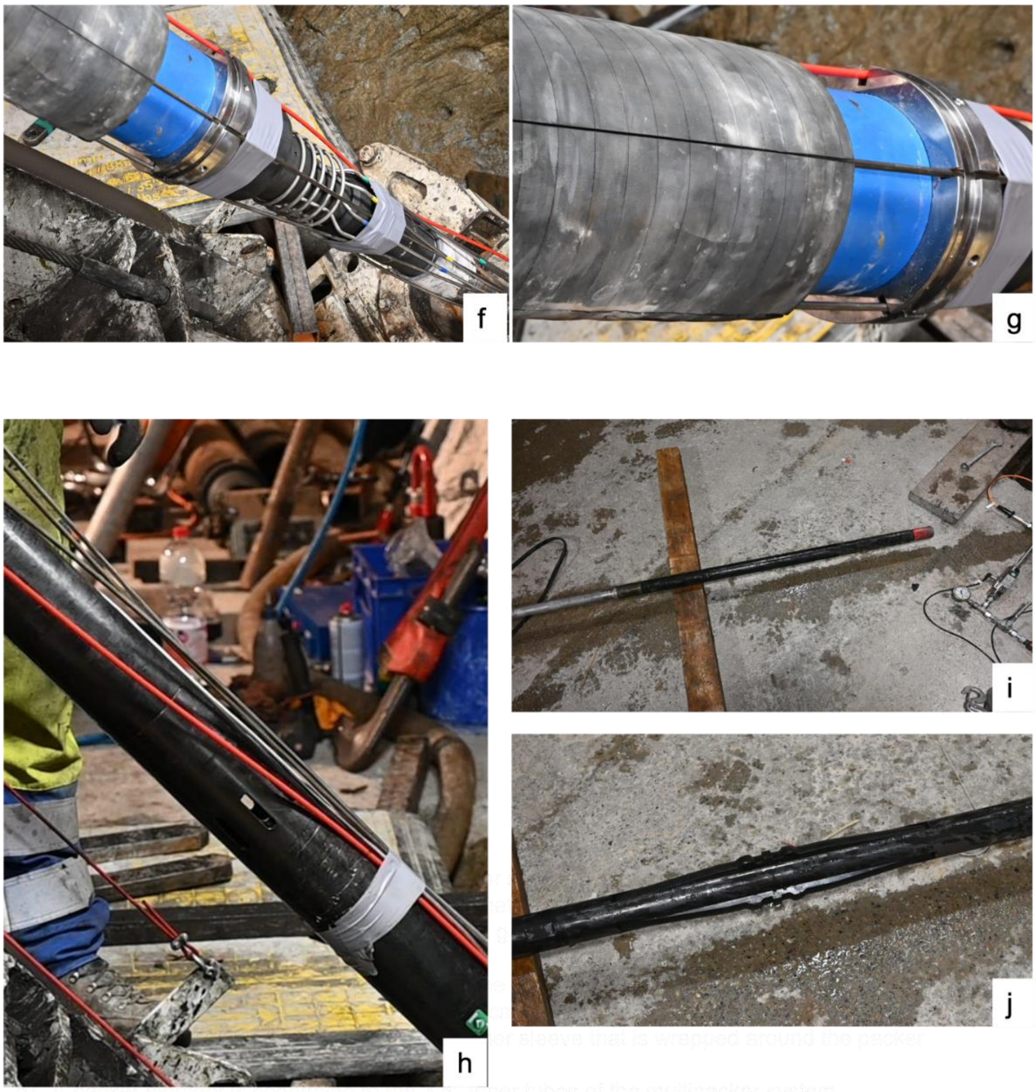
The seismometer installed at the toe, in the last stage of the multi-packer system, performed well, and was of great use for the precise localization of micro-seismic events, except when water was injected into the same interval, resulting in flow noise disturbing the measurements.





a) Installation of the first piece of the multipacker system containing a 3-component geophone that is clamped to the borehole wall by a small diameter inflatable packer inside the tool (not visible).
b) Data acquisition system for the 3-component geophone installed at the toe of the multipacker system.
c) Packer elements prepared for installation. The packer inflation lines pass inside through the packer whereas the fibre optic cable, the geophone cables and the cables for the downhole pressure sensors are led within slots along an elastomer sleeve that is wrapped around the packer elements.
d) A packer element is connected to the 3.5'' inner tubes of the multipacker system.
e) The packer is inflated temporarily to enable mounting the lines into the slots along the outside elastomer sleeve that is wrapped around the packer. This solution mimics the behavior of passing lines along swellable packers for a deep geothermal project. Instead of inflatable packers, swellable packers will be used preferably at much higher downhole temperatures.

Figure 5. Experimental impressions of the multipacker system installed in ST1, with 14 water inflatable packers and 14 valves in between the packers. The length of the intervals between the packers varies from 7.5 m to 55 m. A key which is attached to rods and run inside of the central tubing of the multipacker system opens or closes the valves.



f) Enlarged section for better illustration of the line routing along and through the packer elements.
g) Enlarged section for better illustration of the line routing through the slots within the elastomere sleeve around the packer elements (packer deflated).
h) Sliding sleeve (valve) in open position installed between two packers. The sliding sleeves were all installed with an open position. The sliding sleeves can be opened and closed by installing a special shifting tool (see next figure) at the depth of the sliding sleeve inside the 3.5'' inner tube and activating the shifting tool to pull or push the sleeve with an inside mechanism applying a force of several hundreds of kilograms.
i) Shifting tool in deactivated position runs inside the sliding sleeves for opening or closing the sliding sleeves.
j) Enlarged picture of the shifting tool in activated position runs inside the sliding sleeves for opening or closing the sliding sleeves.

Figure 6. Experimental impressions of the multipacker system installed in ST1, with 14 water inflatable packers and 14 valves in between the packers. The length of the intervals between the packers varies from 7.5 m to 55 m. A key which is attached to rods and run inside of the central tubing of the multipacker system opens or closes the valves.

3.2.4 Cementing a 7-inch casing in ST2 and drilling micro-sidetracks with the IEG Radial Jet Drilling technology

A 7-inch casing was cemented in ST2 in May 2021. From the beginning it was clear that cementing of the annulus will be a challenge since the natural formation pressure is increasing along the 350 m long borehole from atmospheric pressure at the tunnel to over 4 MPa at the end of the borehole. Therefore, the conductive fractures along the borehole are all at different pressures. These fractures producing an inflow to the annulus will either dilute the cement in the case that the pressure in the annulus during cementation is too small, or cement will be lost to the reservoir in case of a pressure higher in the annulus than in the reservoir.

This challenge had been studied in detail by the two experts from the oil and gas industry in charge of the planning. One of them was already leading the cementations of the neighbouring boreholes instrumented with complex monitoring equipment (acoustic emission sensors, fibre optics, geophones). The optimal mixture and types of cement and lost circulation materials had been defined previously in laboratory experiments and cementation was successfully carried out for several monitoring boreholes with the same pressure challenges before cementation of the casing in ST2.

Despite the very carefully planning and preparation, the cement quality turned to be very poor from 0 to about 270 m. Therefore, only the section from 270 m to about 340 m could be utilized for the tests, because remediation of the first 270 m of the borehole was not possible within the ZoDrEx project timeline and budget.

Radial Jet Drilling is a stimulation treatment, which targets the boosting of wellbore-reservoir contact through the creation of small-caliber, radially-oriented lateral micro-drain holes along the production or injection zones of the borehole. It is essentially a treatment employing actual drilling for the purpose of reservoir stimulation. For this, Radial Jet Drilling combines a series of technologies to enhance the communication between wellbore and reservoir, and to increase productivity or injectivity: directional drilling, short-radius wellbore deviation, whipstock-like deflection, side-tracking, coiled tubing technology, jointed pipe technology, hydraulic rock penetration and downhole bit drive techniques constitute what is referred to as Radial Jet Drilling.

Initially, the whipstock-like downhole tool or deflector shoe, which induces a deflection from the wellbore axis, is lowered into the wellbore via jointed pipe employing a small workover rig. Once the deflector shoe and other Bottom Hole Assembly components like stabilizers reach the target zone, coiled tubing is deployed to lower a hose with attached nozzle through the jointed pipe into the deflector shoe. During this process and thereafter, the jointed pipe maintains the deflector shoe in place. This allows for the deflection of the nozzle as it travels through the deflector shoe toward the wellbore wall or casing. At this interface, the nozzle initiates the side-track out of the wellbore to create the lateral. That said, the deflection toward the wellbore wall occurs solely within the gauge of the wellbore, rendering it an ultra-short deviation procedure with an inclination of up to 90 degrees. In cased boreholes, an ancillary casing milling operation precedes the side-tracking. Moreover, the nozzle is equipped with forward-oriented and backward-oriented orifices facilitating rock erosion and propulsion, respectively; the former drills (jetting) the lateral and the latter advances the nozzle along the lateral. Contrary to conventional drilling, the nozzle and trailing hose and coil are in tension downhole. Figure 7 is a schematic of Radial Jet Drilling showing the most important components.

Upon completion of the micro-drain hole, nozzle and hose are pulled out of hole. By turning the drill string, it is possible to change the direction of the deflector shoe exit to subsequently drill additional micro- drain holes under other azimuth angles. In this case, the turning is usually performed as coiled tubing and nozzle are pulled out of hole and after inserting a gyroscope into the drill string via wireline. The gyroscope is used to determine the new direction of the deviation shoe and transmits this to the surface through the wireline. This information is what makes turning from surface for direction change and reorientation underground possible in the first place. The precise orientation of the deflector shoe ensures information about the azimuth of each micro-drain holes.

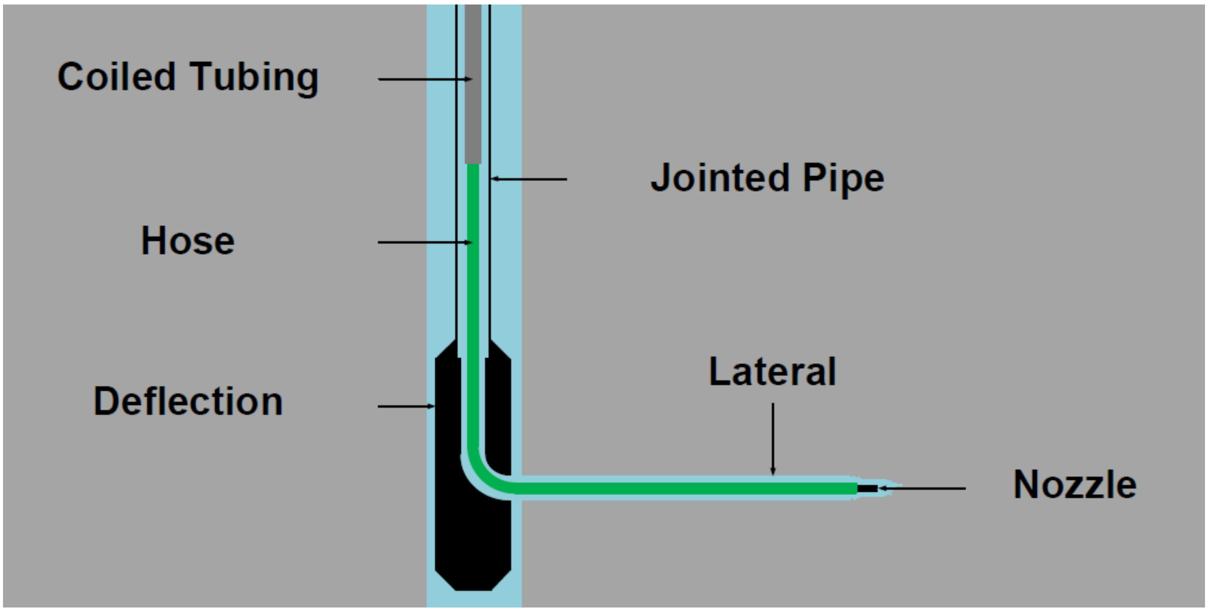


Figure 7. Coiled tubing-based radial jet drilling: hose and nozzle comprising the jetting Bottom Hole Assembly, jointed pipe holding the deflector shoe.

A mechanically supported, downhole jet bit drive is being developed at Fraunhofer IEG and gradually finding its application within Radial Jet Drilling operations. It is a successive invention out of the high-pressure rotating nozzles having been widely used within Radial Jet Drilling so far. It finally became even a separate project called Micro Turbine Drilling to further develop this technology. Fundamentally, the so-called micro turbine converts the stored, hydraulic energy within the water into rotation necessary to turn a special bit. Subsequently, this makes for mechanical milling as the bit is in contact with the rock surface that needs to be cut or milled away, also requiring some force or Weight On Bit (WOB). The micro turbine is rather compact and comprised of all standard pieces like bit, stator and rotor with impeller and drive shaft. The main body and function of such a turbine is to convert the fluid´s hydraulic energy into rotation and thus, mechanical energy. The drive shaft then transmits this rotation to the bit, allowing for normal, mechanical drilling and milling of the minerals or rocks. The required Weight On Bit necessary for the milling or drilling is simply induced hydraulically through backward oriented thruster nozzles, the commonly known technique within any Radial Jet Drilling system, rendering it also a self-propelled operation.

The micro turbine milling operation was commenced when the desired depths in borehole ST2 had been reached. For that, the high-pressure pump was connected by flow lines with the coiled tubing unit at surface. The coiled tubing, being connected to the turbine Bottom Hole Assembly downhole, was Run in Hole through the pipe into the deflector shoe. Then, the mechanically supported side-tracking was initiated by milling a hole through the steel casing first. The same bit and jetting Bottom Hole Assembly then allow for continued jetting and milling into the surrounding rock, saving already one round trip out of the hole as is necessary otherwise within usual Radial Jet Drilling operations, as normal casing milling is conducted differently and much slower. Upon conclusion of the radial lateral, the coiled tubing string with Bottom Hole Assembly was pulled out of hole. The downhole orientation of the deflector shoe was determined and verified post run utilizing a downhole camera; being lowered through the pipe to the top adapter, which had been marked and prepared prior for basic orientational directions. As the downhole camera was compact enough to also pass through the deflector shoe, it allowed for rather good assessment and evaluation of the micro side-tracks having been produced previously. Visualizations of any micro laterals, boreholes, or notches and pathway approximations thereof were possible in this way.

Several micro-boreholes and notches were created through the micro turbine in an attempt to establish communication between wellbore and reservoir through the cemented casing. High-angle and low-angle exits were made from the deflector shoe to create side-tracks with differing orientation angles (azimuth); this likewise resulted in the variation of the side-track inclination angles as the ST2 wellbore is deviated. The length of the side-tracks was purposefully limited to the vicinity of the wellbore in an attempt to focus on the near-wellbore damage. Figure 8 is an image of a side-track from the ST2 wellbore directly into the granite from the open borehole (left), and through the casing, the cement into the granite (right). Figure 9 shows the ATV and OTV log of the micro-side-track shown in the left of Figure 8. In general, the micro-boreholes were drilled into low permeable slightly fissured rock. Because of the long testing time necessary for hydraulic tests, no such tests were performed before fracturing or stimulation.

The data show the success of the mechanical rock destruction process in hard rock like the Bedretto granite. However, there is room for improvement of operational capabilities as field trials were limited at a handful during the project. An issue which occasionally occurred and must be resolved is the tendency of the drilling tool (this is also true for the jetting tool) to jam downhole, rendering Pull Out Of Hole very difficult at times. For the micro turbine this has led to complete deadlock with much effort going toward Pull Out Of Hole. It is believed that the interface between deflector shoe and the wellbore may have provided a state which allowed for such jamming of the turbine. This interface is essentially comprised of the deflector shoe exit, the wellbore wall and a gap between both. Investigations into resolving the issue are ongoing and are part of the Micro Turbine Drilling project. Another issue, which was observed during the Bedretto Lab tests, was the creation of tortuous side-tracks with ledges. This is the result of the turbine to recentralize after the creation of an initial window, possibly because of whirling of bit and turbine or the effect of the hose on the drilling dynamics.

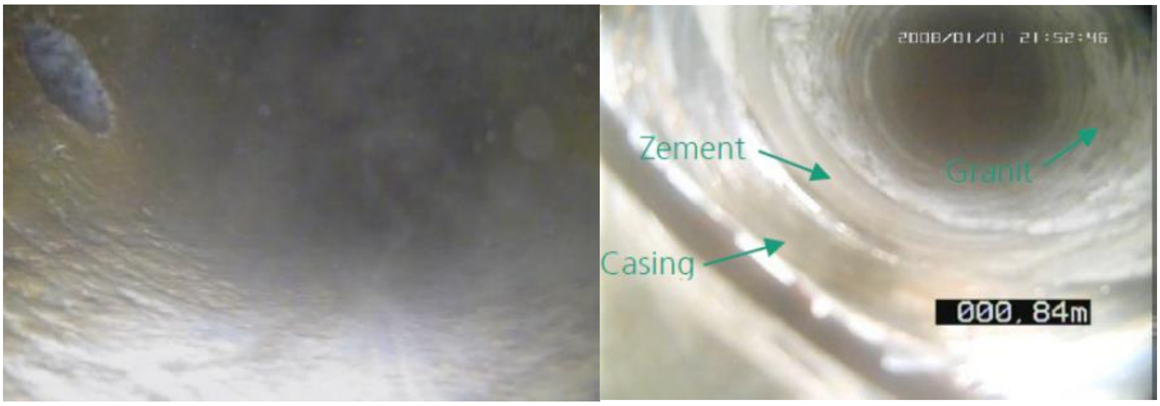


Figure 8. Milled side-track in ST2 borehole wall before running and cementing casing (left) and through casing and cement into the granite (right). The side-tracks have a minimum diameter of 3 cm and lengths typical of several decimetres with maximum lengths of around 2 m.

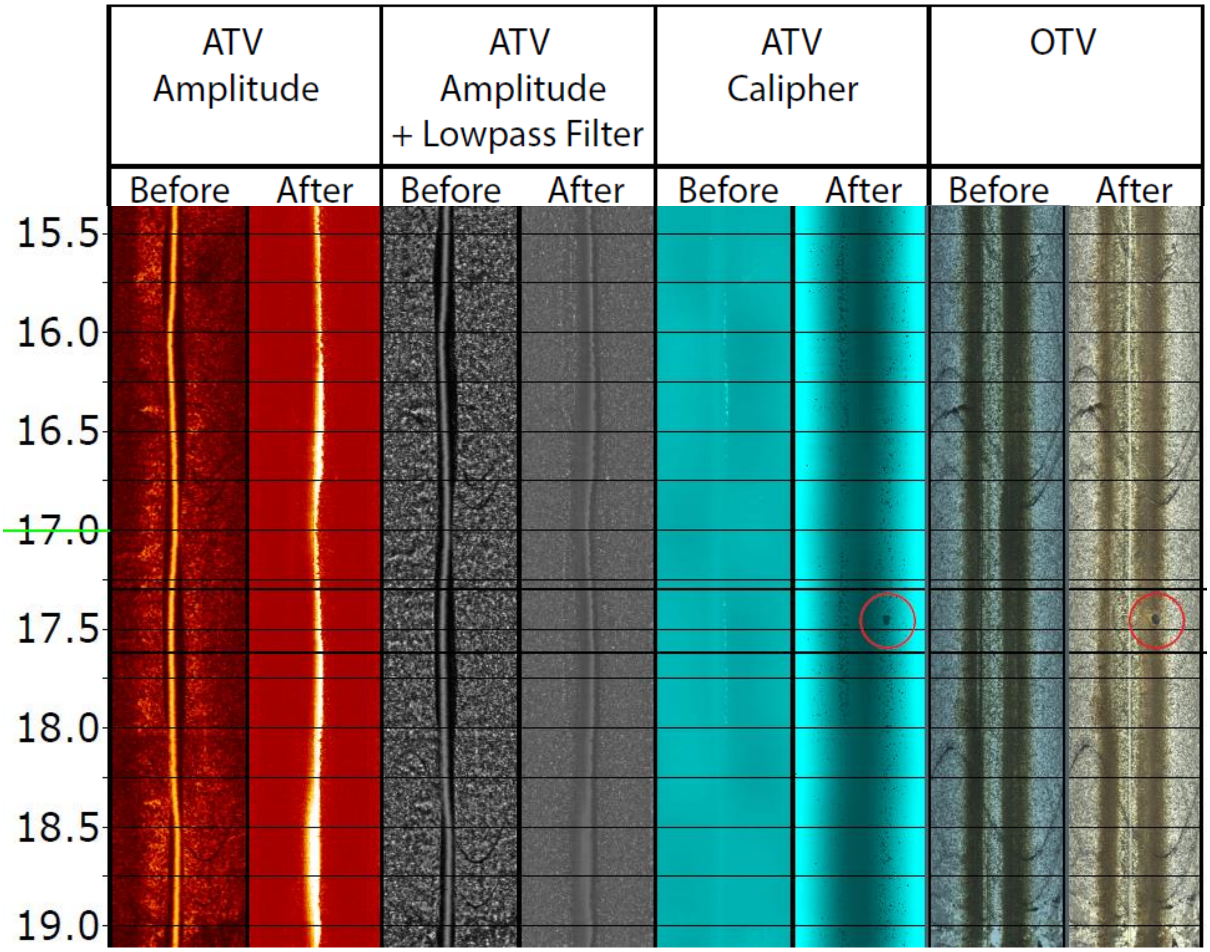


Figure 9. Comparison of ATV and OTV-Logs before and after realizing the side-tracks and notches. The red circles highlight the localization of a realized notch, visible on the ATV- and OTV- logs.

Moreover, current Radial Jet Drilling operations like in the Bedretto Lab demonstration necessitate the allocation of a substantial amount of time to the azimuth-specific reorientation of the deflector shoe for respective micro-side-tracks, rendering Non-Productive Time a real issue as up to twenty percent of the operation time is lost in this way. Additional Non-Productive Time arises from the necessary change of the depth position of the deflector shoe to treat the entirety of the reservoir thickness or target formation; only this ensures maximum possible contacting of the reservoir by the wellbore, preventing inflow performance issues from problems like partial penetration etc. The abovementioned Non-Productive Time is a direct result of extra tripping of coiled tubing and ancillary equipment, i.e., at least two trips are required for the reorientation of the deflector shoe and one trip is required for the changing of the deflector shoe's depth position. This issue of tripping Non-Productive Time must be addressed to foster Radial Jet Drilling technology and make is more attractive.

3.2.5 Design and installation of the Welltec metal packer system

Based on Welltec Annular Barrier (WAB) technology, a new high expansion packer was designed by Welltec for improved management of ovalization and breakout. With the objective to develop a high expansion packer to provide better, more robust zonal isolation to manage breakout in crystalline formations. The WAB is a metal expandable packer, a non-retrievable packer mounted directly onto the liner to create a permanent seal of the well's annulus (void between the liner and the borehole wall).

The WAB is hydraulically set, which causes the metal membrane to deform, sealing the annulus (Figure 10).

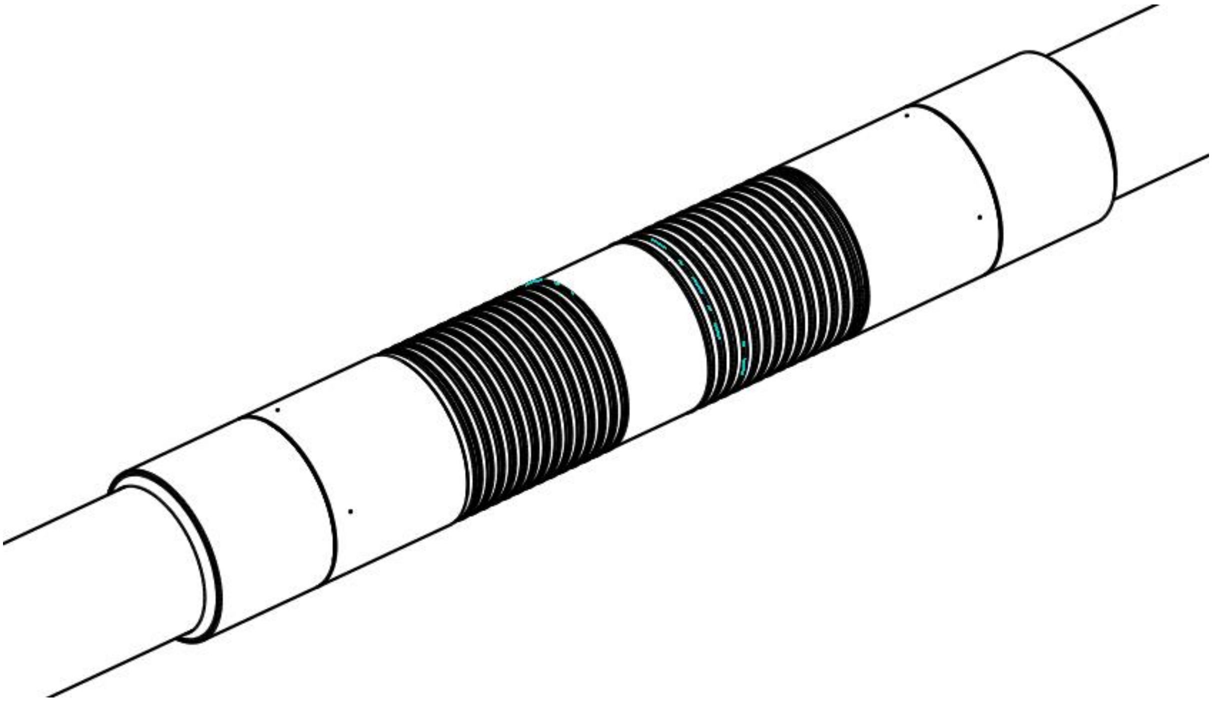


Figure 10. The new high expansion packer design with the new double sleeve in the center. The new design clearly standout from the old as it instead of one long seal stack it has two. With the two end pieces adding to the anchoring ability.

Welltec first designed and simulated an 8 ½ external casing packer for EGS application in high breakout boreholes capable of managing 260°C. This would be ideal for EGS deployment in European crystalline formations, but it could also function in the mid-temperature range hydrothermal systems elsewhere in the world.

The new sleeve is combined with an ultralow carbon, nickel alloy cable of managing both high temperatures and H_2S, as often seen in hydrothermal systems. As importantly, it was selected to withstand repeated thermal stress, as associated with geothermal workovers over life span. To ensure optimal sealing conditions for life of well, Welltec set the qualification to ISO 14310 V6 with V3 leak criteria.

Welltec has high confidence in expansion using Finite Element Analysis (FEA) modelling with years of fine tuning the mechanical material models with experimentation and testing. The design expansion limit was evaluated as the maximum stresses that the materials can support based on the minimum material properties of the packer's design. LS-Dyna was used to simulate expansion in two steps. The first step lasted from 0 to 0.1 seconds. Thereby the expansion pressure increased from 0 to 34.5 MPa. In the second step between 0.1 and 0.2 seconds, the expansion pressure increased less from 34.5 to 48.3 MPa (Figure 11).

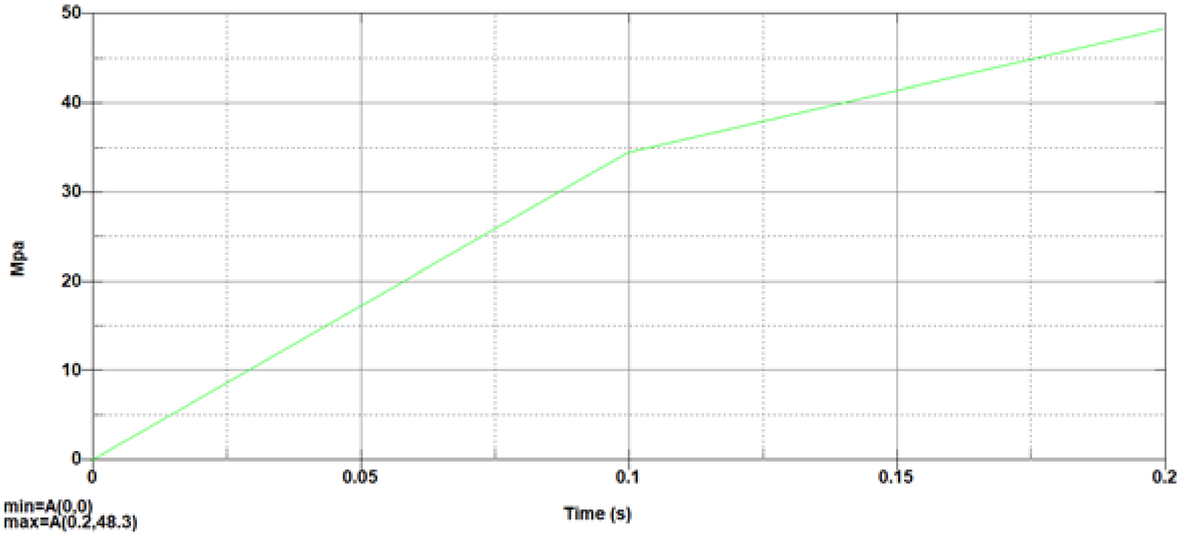


Figure 11. Displaying the LS-DYNA FEA simulation of pressure inside the packers during expansion.

Ultimately the expansion rate of the packer design was limited by the materials maximum acceptable stress. This was based on extensive laboratory testing performed with the material with UTM values above 800 MPa.

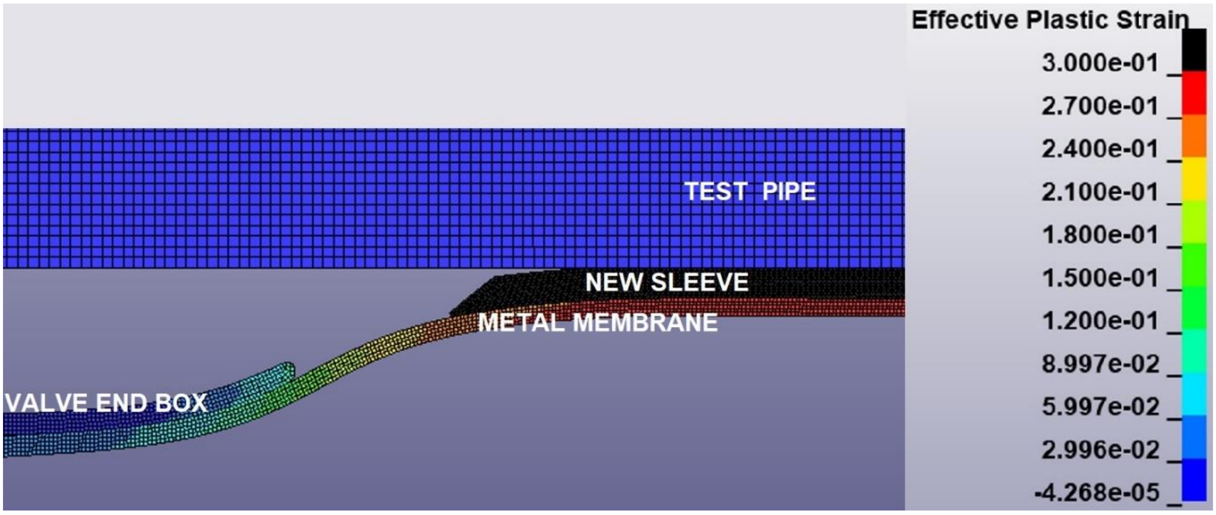


Figure 12. The above FEA simulation depicts one end of the packer during expansion of the new 8 ½ packer design inside of a hole. Displaying the contouring of effective plastic strain on the material of the new packer design.

Figure 13. The assembled new high expansion packer design.

Despite, the improved expansion ratio, it was concluded that, for a robust high temperature design with minimal leakage, packers should be set in less affected areas to ensure zonal isolation at the required qualification standard (i.e. to ensure an efficient seal above and below the chosen area to isolate it from the rest of the borehole). Some examples of breakout were indeed so extreme that it could not be expected of the material to handle the elongation let alone to seal the borehole annulus.

The work included the development of a 7-inch flow valve to function as both inflow and as stimulation gate. Historically valves have not been used in geothermal wells, as the instalment of valves was thought to reduce and restrict the flow of fluids to the well.

For the demonstration the used valve had a 110 percent capacity flow, which was selected to support the mass flow required in geothermal wells, although the capacity could be increased. Adjustments to the designs were made to the open/close mechanism to suit geothermal, primarily it was a question of adjusting the alloy managing H_2S conditions rather than temperature. A successful test of the mechanism was carried out to ensure it could be manipulated prior to deployment.

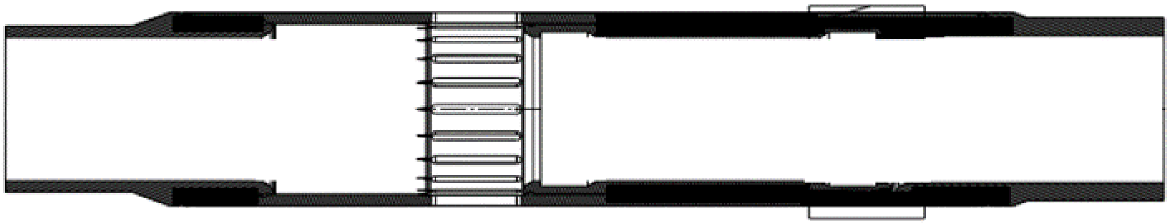


Figure 14. Schematic depiction of the 124 cm long 7-inch valve with 110 percent capacity flow allowing for full bore access, which allows it to be used for both injection and production.

Welltec theorized that, based on completion experience from oil and gas industry with the given completion system, it would be possible to perform stimulation more efficiently and with a greater degree of control if the well was drilled perpendicularly into the maximum stress direction in a part of the formation with less or no pre-existing fractures. Thereby allowing for a more controllable and uniform initiation of fractures using this system.

Therefore, at Bedretto a 120 meter deep horizontal well (Welltec borehole) was drilled with a 6 degree decline perpendicularly into the maximum stress direction. It intercepted a fractured zone at about 100 m that delivered an outflow measured at the wellhead of about 2.5 l/min in May 2021.

Based on data from an Acoustic Televiewer log, two sections of the borehole with little sign of pre-existing fractures were selected and the installation depth of the packers defined as described in the following figure:

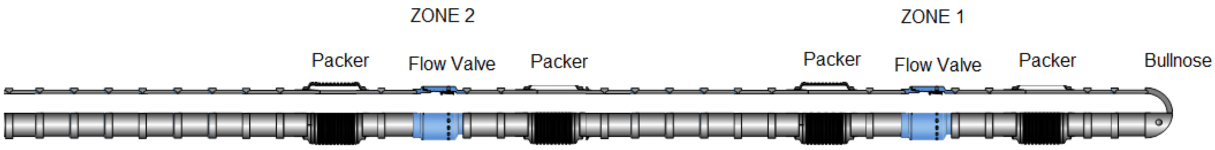


Figure 15. Well completion schematic with zone 2 at 66.81m to 61.92m and zone 1 at 80.63m to 75.68m.

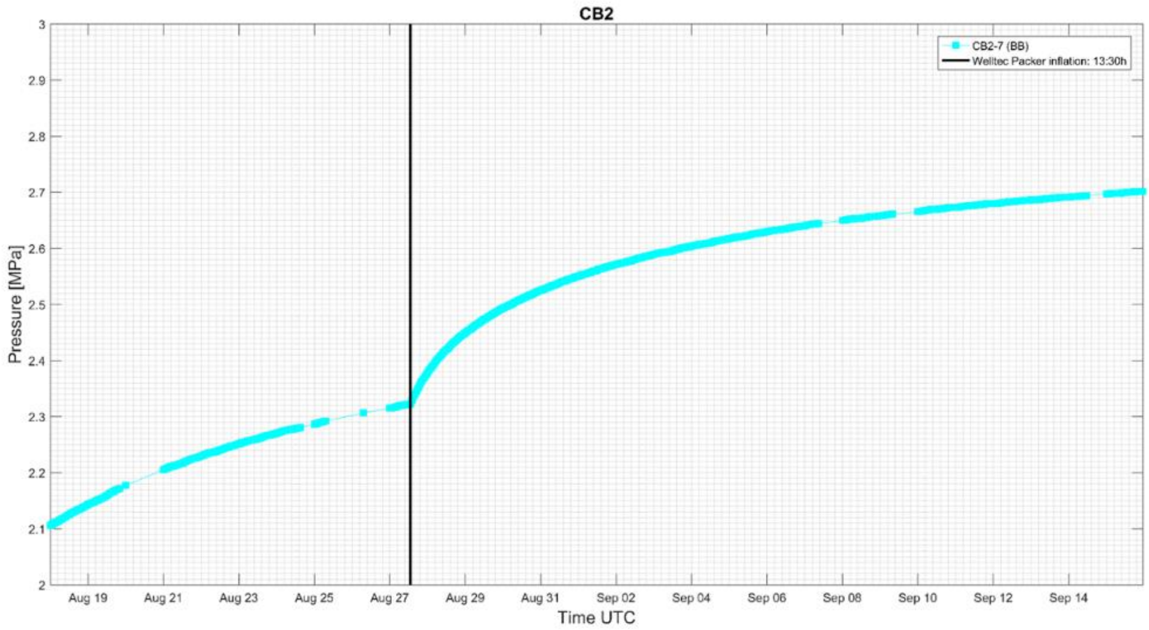
The cementation of the monitoring boreholes MB5, MB6, MB7 and MB8 in July resulted in a general pressure build-up in the reservoir causing an increase of the outflow at the wellhead of the Welltec borehole from 2.5 to 4.3 l/min (Figure 17), 4.3 l/min being the last outflow measurement before the installation of the packer system in August 2021.

The all-metal system consisting of 4 packers and 2 flow valves mounted on pup-joints (casing) with a bullnose at the end were successfully deployed and installed as described in Figure 15 in August 2021. The expansion of the packers was carried out in seven 2-minute intervals, slowly increasing the expansion pressure before increasing it to 34.8 MPa pressure (inside the packer) for 10 minutes to confirm setting. The packer deployment operations ended with the pressure inside the casing being relieved.

Figure 16. Flow valve (black, left) and packer (right) installation in Bedretto (August 2021)

The packer expansion was confirmed over the following 20 days, as pressure sensors in the neighboring wells, ST1 and CB2 registered a 0.35 MPa increase. However, after setting the packers, the outflow of around 2.5 l/min, as was previously detected, continued to be measured at the well head of the Welltec borehole in the annulus between the borehole wall and the central casing. Moreover, the pressure was increasing in CB2 and ST1 (Figure 17). This pressure increase in the neighboring boreholes and the outflow reduction at the annulus from initially 4.3 l/min to 2.5 l/min indicate a partial sealing of the system.

As the flow continued seemingly unaltered after installation, it is unknown, if the water is coming out of the annulus or through a natural fracture network, connecting to a larger network.



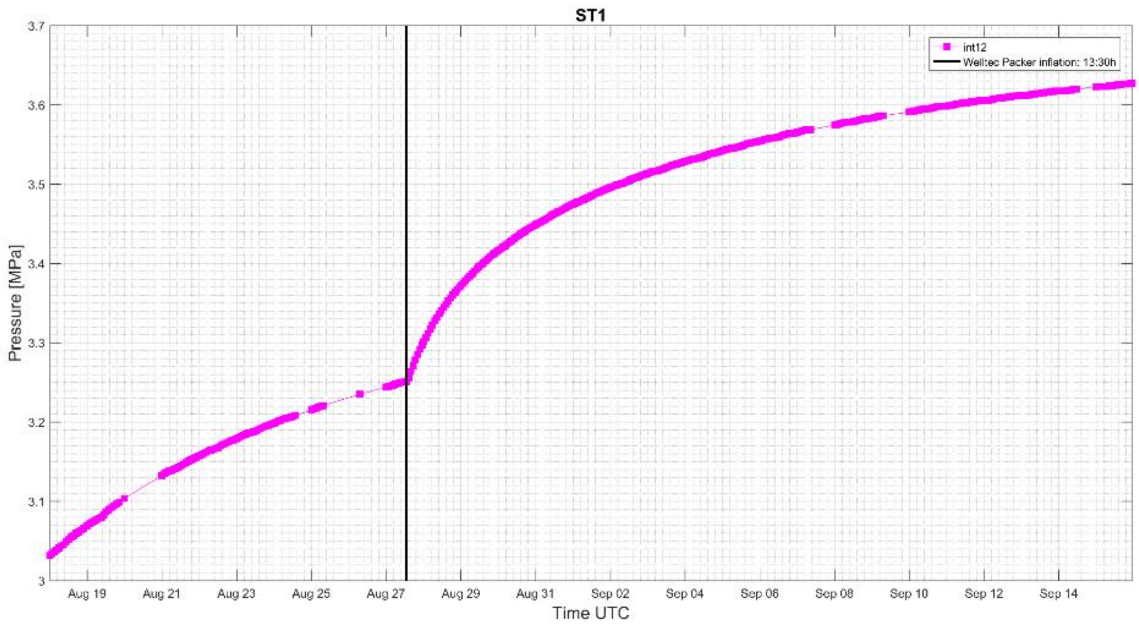


Figure 17. GeoMonitor data from sensors in CB2 (top; CB2 = MB2) and ST1 (bottom) show a pressure build-up in the reservoir before the packer expansion and an instant and consistent change in pressure in the formation following the packer expansion on August 27th.

Tests started in October 2021, but were inconclusive. Despite running multiple stimulation cycles in the upper zone (zone 2 at 66.81m to 61.92m in Figure 15), results were inconclusive. Once the valve in the lower zone was opened (zone 1 at 80.63m to 75.68m in Figure 15), water was immediately detected coming up through the casing in rates of 2.83 to 2.95 l/m, which stopped immediately once the zone was closed again, indicating the system's ability to isolate and separate zones with different flow. A five-step step-rate-test was carried out with initial rate of 0.5 and finally 7.5 l/m showed that the zone was in communication with an existing network, very likely connected by the well-documented nearby fault (commonly referred to as the Bad Boy), which had unexpectable been intercepted at 99 meters, when the well was drilled. This made further testing of the completion system difficult, as there was an indication of a cross-over flow in the formation, which pressed water across the formation around the bore hole, likely explaining the constant flow of 2.51 l/m. Nevertheless, the effects of the step rate test were briefly detectable by the ETH micro seismic sensors on a single channel in MB7.

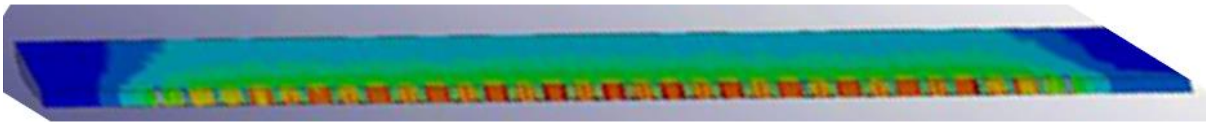


Figure 18. FEA model depicting the packer-to-rock using Bedretto's specific overburden stress along the 2.5m packer. The packer is made up of 15 small seals (along the bottom), each can be seen with contact stress. As the packer expanse from the centre-out, the outer seals apply less force to the formation, indicating a solidly sealed borehole.

The packers had been set in seven two-minute intervals, to limit stress on the rock, so to obviate effects of potentially causing mini fractures along the system, allowing for water to flow through the annulus. Further FEA modelling was carried out to demonstrate the effect of the packer sealing capability and the packer-to-rock stress contact. But incorporating the formation's specific vertical and horizontal overburden stress only indicated that there would have been minimal contact stress on the borehole, rendering the probability of borehole bypass low. Leaning towards the dominate assumption, that there is a crossflow in the formation connecting the lower zone to somewhere above the packers and that the packer sealed entirely. However, to further eliminate doubt, micro-localized stresses and expansion procedure could be further investigated when it comes to setting the packers in highly competent rock formations. Additional tests could in the future be caried out in the upper zone.

Although the rock laboratory offered a unique opportunity to test the equipment in a granite formation, and the completion system created a noticeable barrier with the lower zone demonstrating its basic function, further testing of the system was made difficult by time restraints and more importantly that the borehole was trapped between the tunnels stress plain and the large fault line in a lesser known section of the Bedretto formation.

3.3 Evaluation and demonstration of reliable stimulation performance with various zonal isolation techniques

The demonstration and benchmarking of multi-stage stimulation utilizing different innovative zonal isolation technologies was done at the Bedretto rock laboratory in Switzerland.

The multi-stage hydraulic stimulation concept proposed by Geo-Energie Suisse, based on lessons learned from the Basel EGS project [4], was successfully demonstrated at Bedretto Lab. The lessons learnt from Basel are basically twofold: firstly, a massive stimulation by injecting a large volume into a longer open borehole section does not result in a sufficient transmissivity increase because basically only one or a few preexisting fractures are stimulated, and secondly, a massive stimulation created a large, stimulated volume containing larger fracture areas that moved relatively to each other resulting in stronger magnitudes earthquakes. Both issues can be mitigated utilizing a multi-stage stimulation approach, because many smaller stimulations allow to increase transmissivity of a large number fractures and the areas of the individual fractures can be maintained enough small to prevent large magnitude seismicity.

The multi-stage hydraulic stimulation was demonstrated in two campaigns, the first in November and December 2020, the second in April and May 2021. The three main success criteria were met: first, a significant increase in flow rates and thus an increase in the energy output of an EGS project; second, detailed monitoring and mitigation of induced seismicity; and third, validation and qualification of advanced multi-stage stimulation devices from the oil and gas industry for geothermal applications.

The increase in flow rates predicted in 2016 [5], using numerical modeling by factors between 3 and 6 for the multi-stage stimulation concept compared to single-stage stimulation was demonstrated in Bedretto in-situ at a reservoir scale of 1:3 [6]. Scaling the results from the field work to a deep EGS project such as Haute-Sorne yields a range of flow rates from 78 to 160 l/s. This value significantly exceeds the success criteria set at 65 l/s for the Haute-Sorne EGS project. This is also a positive result given the inherent uncertainties. Applied to practice, this means that the electrical power of an EGS project can be increased from about 1.5 MW - if a single stimulation stage is carried out over the entire borehole reservoir section - to about 4.5 to 6 MW if a multi-stage stimulation approach is used.

Real-time monitoring and mitigation of induced seismicity and associated risks - the second main criterion for proving success - was also successfully demonstrated. The maximum moment magnitude of -1.6 within the stimulated rock volume was lower than naturally occurring seismicity (up to a magnitude of 0.0) at greater distances of about 1000 m from the stimulated reservoir. The natural seismicity occurred before stimulation began in November 2020 and may be a result of heavy rainfall, snowmelt, or other processes related to the transient hydrogeologic behavior of rock masses beneath alpine mountain slopes.

Finally, the oil and gas industry's advanced multi-packer system for zonal isolation along the 400 m ST1 borehole for multi-stage stimulation of a crystalline geothermal reservoir worked flawlessly. The operation of the valves between the packers also worked reliably. Instrumentation of the multi-packer system with fibre optic lines for Distributed Acoustic Sensing, Distributed Temperature Sensing and Heat Pulse Measurement provided very useful data for identifying flowing fractures between packers before, during and after stimulation. Fibre optic instrumentation also provided important information on operational aspects such as valve opening or closing and possible packer bypass. This is important for a deep EGS project where the valves are located at a depth of 3000 to 7000 m and the mechanical valve movement of only a few decimeters at the surface cannot be controlled.

To compare and benchmark the two principal multi-stage completion approaches “cemented and perforated casing” versus “open borehole packer completions” in view of connectivity from the borehole to the reservoir and regarding injectivity, we designed specific experiments and demonstrated that both systems work fine.

An experimental comparison of reservoir stimulation via open-hole packer systems with that via cased, cemented and perforated boreholes is not straight forward because of the heterogeneous rock properties, especially in fractured granites. One approach would be to perform a large number of tests at different locations in a reservoir using only one system at each location and compare the results statistically.

In our tests we only had two boreholes available and so could only perform a limited number of tests. Therefore, we chose a different approach and compared the hydraulic connectivity of the borehole to the reservoir at a few specific locations along one of the boreholes for each of the two systems.

Hydraulic connectivity was measured first with an open-hole double packer system isolating several meters of a borehole section before cementing the casing. Thereafter, the cemented casing was perforated within the same borehole section by single, micro-drilled mini sidetracks with a diameter of about 1.5” and a length of about 0.2 to 0.8 m. Lastly, the hydraulic connectivity was re-determined using a double packer system inside the casing to isolate the mini sidetrack.

The hydraulic connectivity of both systems was compared using two metrics: Injectivity was used as a measure of the hydraulic connectivity of the borehole to the immediate reservoir near-field in the first decimeters and meters from the borehole, and transmissivity was used as a measure of the connectivity to the reservoir in the decameter region from the borehole.

We conducted four tests. Here, we present the two most representative ones at around 307 m (Figure 19 and 20) and around 287 m (Figure 21 and 22) in the ST2 borehole with a length of 350m, an inclination of 35° from horizontal and a diameter of 8.5".

The test interval at 307 m contains a natural fracture (Figure 19) with very low transmissivity (T < 7E-9 m^2/s). In comparison the interval at 287 m contains a shear-zone (Figure 21) with a transmissivity of 2E-7 m^2/s, the highest natural transmissivity value measured in the entire borehole. These two conditions are considered to represent the two end members of stimulation targets of an EGS project.

Because of the very low transmissivity (T < 7E-9 m^2/s) of the natural fracture at 307 m a two-meter-long interval was isolated with a double packer system and a mini-fracturing test was conducted (Step 2 in Figure 19). After breakdown pressure was achieved some reopening cycles with a short duration of 5 to 10 minutes and a small total injected volume, in the order of 100 liters, were conducted. The increases of injectivity and transmissivity were only marginal and could not be determined with accuracy. An acoustic televiewer run did not reveal any newly created axial fractures within the interval.

Thereafter, a 5.5 m long interval from 305.1 to 310.6 m, including the previous hydraulic fractured interval, was isolated with a double packer system and two step-rate hydraulic jacking tests were conducted with a total injected volume of 58.4 m^3 (Step 3 in Figure 19). The two tests were phased in a 5 m^3 pre-stimulation and a 53.4 m^3 main stimulation.

A comparison of acoustic televiewer logs before and after this stimulation shows clear evidence of shear movements of the fracture [6]. An effective (average) transmissivity of about 6E-7 m^2/s was estimated for the stimulated area. The injectivity curves of the two open-hole injection cycles, that were performed in 2020, are presented in Figure 20.

About one year after these open-hole double packer stimulations a 7” steel casing was cemented (Step 4 in Figure 19) in the borehole and a mini sidetrack was drilled through the steel casing and the cement into the previously stimulated fracture at around 307 m (Step 5 in Figure 19). Finally, two step rate hydraulic jacking tests were performed that were similar to those in step 3. From these tests an effective (average) transmissivity of about 5E-7 m^2/s was estimated for the stimulated area. The injectivity curves of the two 2021 injection cycles through perforated cemented 7” casing are presented in Figure 20 together with the corresponding values of the 2020 open-hole injection cycles with the double packer system.

From the test results at 307 m, we conclude the following:

- In terms of hydraulic connectivity between the borehole and the reservoir there are no fundamental differences between open-hole packer systems and cemented casing perforated with a micro-drilled mini sidetrack. Firstly, because the injectivity curves of both systems are of the same order as shown in Figure 20, and secondly, the effective (average) transmissivity estimates of the stimulated zones are also very similar (6E-7 m^2/s and 5E-7 m^2/s).

- We currently have no conclusive explanation for the different injectivity curves. We suspect that this is related to the different flow geometry in the transition from the borehole to the near field of the reservoir.

- The good hydraulic connection of the borehole with only one mini sidetrack through the cemented steel casing is amazing. Unfortunately, we did not have time and resources to increase the number of mini sidetracks to see how much the hydraulic connection and injectivity could be improved with each additional mini sidetrack.

- We were also unable to test the extent to which these results are transferable to multiple perforations using perforation guns. In principle, however, we are optimistic in this respect.

- In all respects, however, we were surprised that we were able to permanently connect a small, closed and very low permeability fracture to the fractured reservoir via hydraulic stimulation and stimulate a reservoir zone via this fracture with a final transmissivity a factor of 3 greater (6E-7 m^2/s) than the most permeable natural shear zone in this well at 287 m (2E-7 m^2/s).

The procedure for testing the hydraulic connectivity of the borehole to the highly transmissive, natural shear zone at 287 m (Figure 21) was different from the tests at 307 m (Figure 19), because the shear-zone at 287 m was not stimulated before cementing and perforating the 7" casing.

In the fall of 2020 a natural, high transmissivity of 2E-7 m^2/s was derived from double packer hydraulic testing of the target zone (Step 1 in Figure 21). One year later, after cementing the 7" casing (Step 2 in Figure 21), a mini sidetrack was erroneously drilled 3 m above the target instead of directly into the shear-zone at 287 m (Step 3 in Figure 21), due to an error in counting the installation tubes for micro-drilling.

Three hydraulic jacking stimulation cycles were conducted (Figure 22) injecting a total volume of about 23 m^3. The radius of the stimulated area derived from micro-seismic measurements is about 55 m [6] and an effective (average) transmissivity of 3E-7 m^2/s was estimated for the stimulated area. The injectivity curves of the three injection cycles are presented in Figure 22.

From the tests on the shear-zone at 287 m:

- We confirm all the results listed above for 307 m and additionally demonstrated that a hydraulic connectivity of the wellbore to a fractured reservoir can work successfully even if a mini sidetrack (or possibly multiple perforations) is placed several meters away from a dominant fracture zone. This is particularly relevant in deep wells because the localization uncertainty is likely to be several meters.

- We cannot fully explain the significant improvement in injectivity in Figure 22 between the second and the third hydraulic jacking test at this time. There are two possible explanations: firstly, the cement on the 3 m long path between the mini sidetrack and the shear-zone was fractured and broken up; secondly the permeability of the flow paths through the reservoir near field between the mini sidetrack and the shear-zone (depicted with step 5 in Figure 21) was substantially increased from the second to the third injection cycle.

For years, there has been an intense debate among experts as to whether open-hole multi-packer systems or the classic cemented and perforated casing approach offer better hydraulic conditions for stimulation in fractured rocks. We have now been able to benchmark and demonstrate, within the usual uncertainties of subsurface work, that in principle both methods are good for multi-zonal stimulation.

This is good news for the geothermal industry. In planning borehole completions, drilling engineers can now focus on more reservoir-independent issues when deciding on one concept or the other, such as site-specific borehole conditions, borehole breakouts, borehole stability, temperature, equipment reliability, deployment risks, equipment availability and costs.

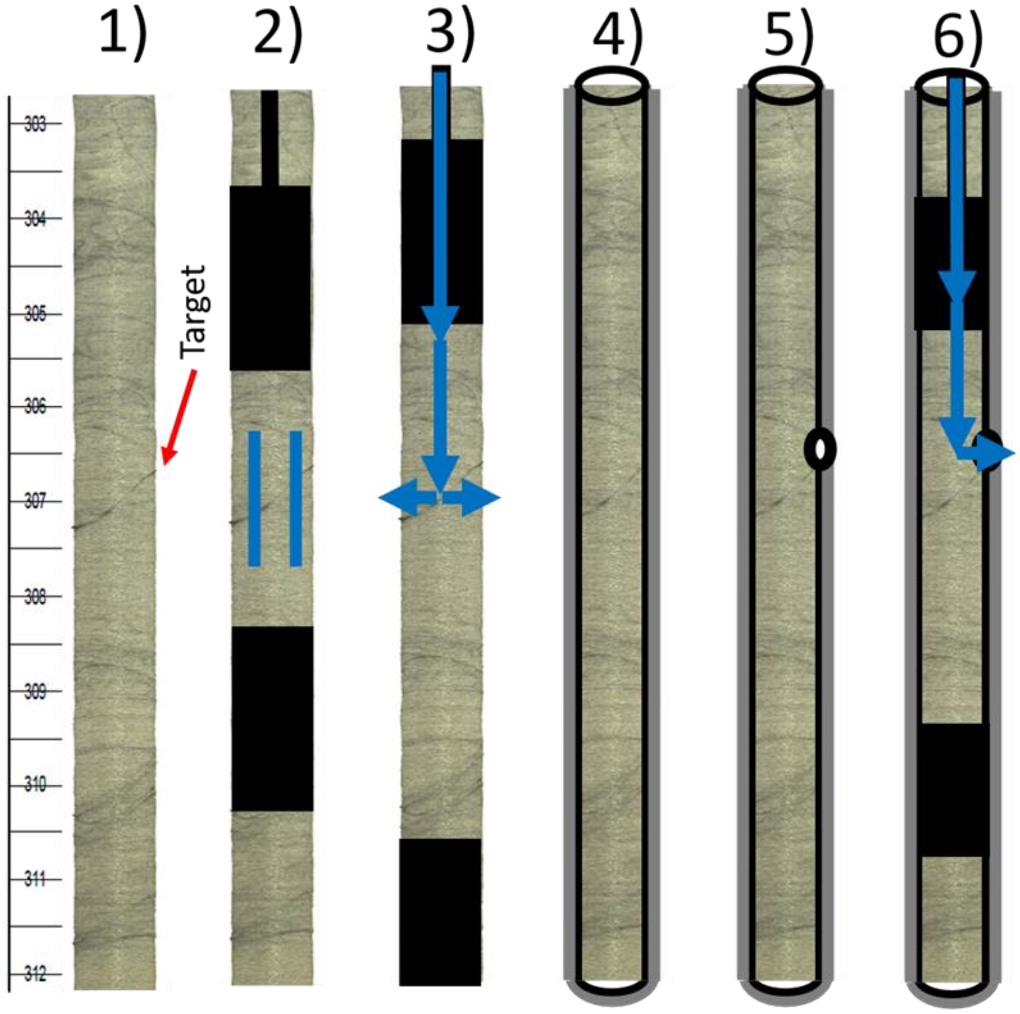


Figure 19. Benchmarking of zonal isolation technologies in borehole ST2: Stimulation first utilizing an open-hole 2 m double packer system isolating a very low transmissive target fracture (step 1) and performing mini-fracturing (step 2), followed by a hydraulic jacking stimulation (step 3); secondly cementing a 7-inch casing (step 4), drilling a micro-sidetrack with the newly developed microturbine by IEG (step 5), and re-stimulation by placing a double packer system inside the casing over the orifice of the micro-sidetrack (step 6). The injectivity data of steps 3 and 6 are presented in Figure 20.

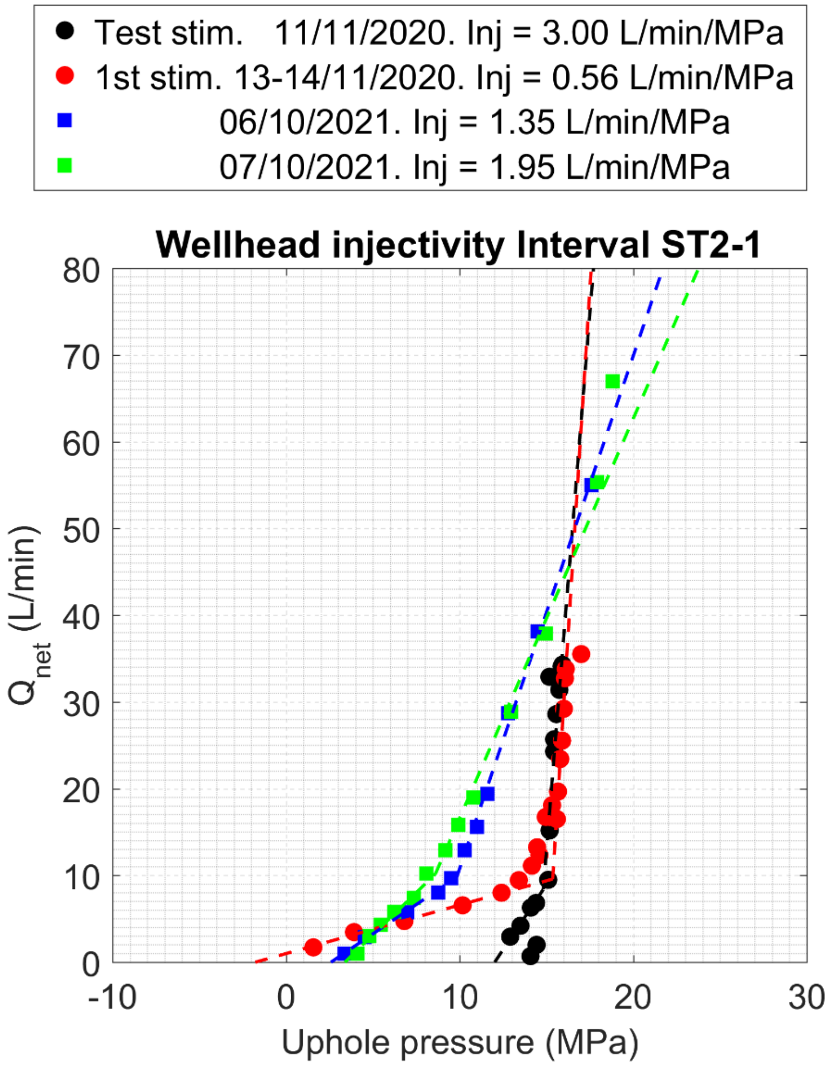


Figure 20. Injectivity for the experimental setup shown in Figure 19. The injectivity values are calculated using the initial part of the corresponding curve until it reaches the inflection point. The intersection between the two fitted lines of a stimulation (same colour) corresponds to the jacking pressure, at which the fracture opens. From that moment on, the pressure barely increases, even with a strongly increasing flow rate.

The injectivity values from step rate injection cycles are within a similar order for an open borehole zonal isolation with packers (black and red) at step 3 in the previous figure, and for the cemented and perforated (micro-sidetracked) casing (blue and green) at step 6 in the previous figure. The differences of the injectivity curves are not completely understood and may also be related to reservoir changes during the time of almost one year between both experiments. The reason why the injectivity of the test stimulation (red) is so much higher before reaching the jacking pressure and fracture opening than during the first stimulation (black) cannot be clearly determined. It is possible that after the test stimulation, fine components have clogged the flow paths.

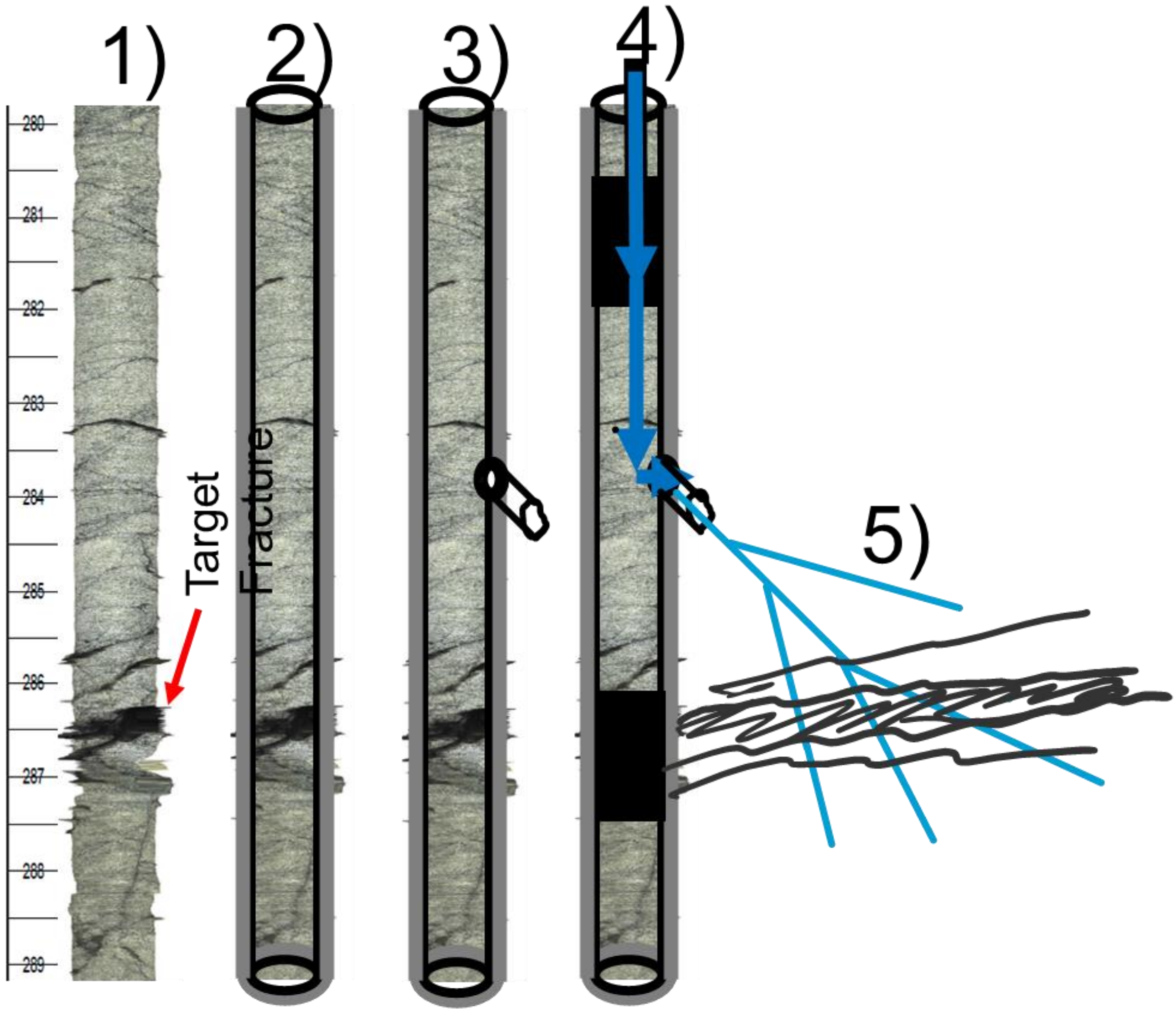


Figure 21. Testing of connectivity between the fractured reservoir and borehole ST2 completed with a cemented (step 2) and perforated (micro-sidetracked, step 3) casing. The micro-sidetrack consists of a single about 20 cm long microdrill with a diameter in the order of 3 cm. The micro-sidetrack has accidently been placed at about 3 m from the permeable target structure (step 3), instead of micro drilling directly into the fractured zone. Despite of the considerable offset, by stimulation it was possible to connect the fracture zone to the borehole (steps 4 and 5), demonstrated by measuring a slightly increased fracture zone transmissivity of 3E-7 m^2/s through the perforation compared to a hydraulic test with a double packer test straddling a 6 m interval over the fracture zone in the open borehole prior to cementing the casing (step 1). In steps 4 and 5 injectivity has been improved with each of the three consecutive step rate stimulation cycles (Figure 22).

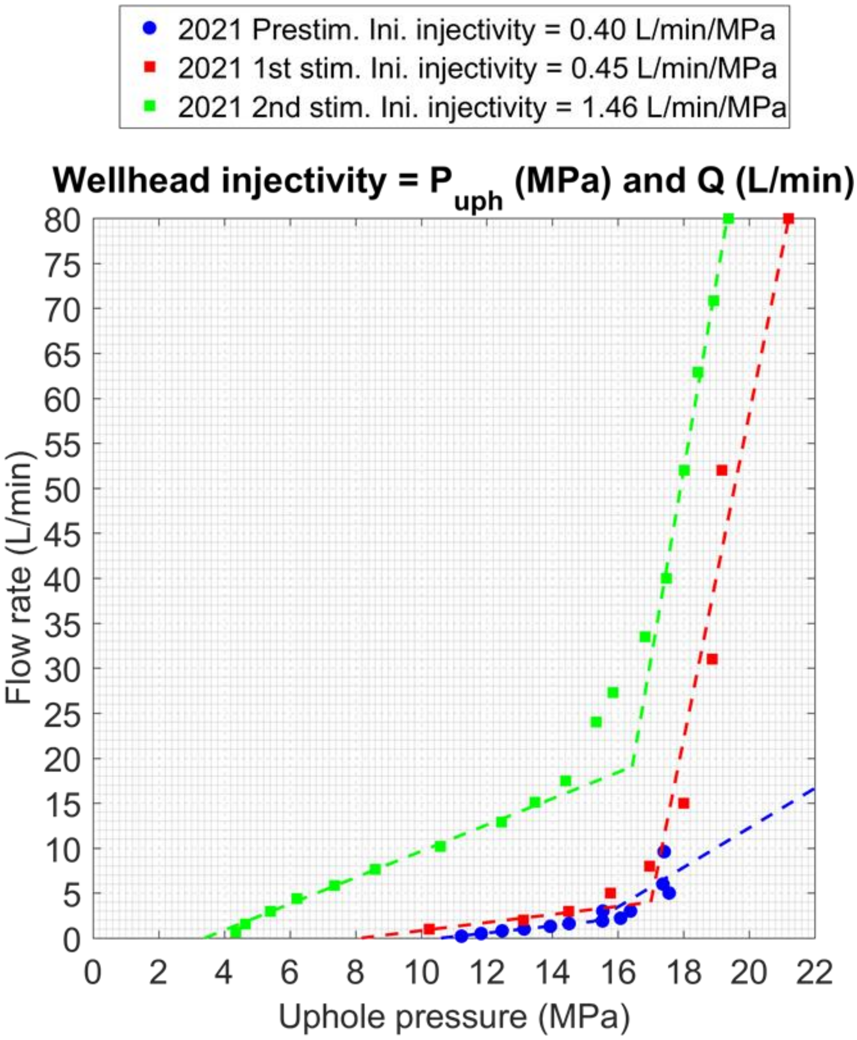


Figure 22. Injectivity was improved with 3 consecutive step rate stimulation cycles during steps 4 and 5 in Figure 21 to a similar value as shown for the interval in Figure 20.

In order to examine the geomechanical behavior at a decameter distance from the injection intervals during stimulation, CSIC and GES have built a large model with CODE_BRIGHT [7] that includes the Bedretto tunnel and the rock laboratory, with the drilled boreholes and the identified fractures (Figure 23). We have used three approaches with increasing complexity to finally reproduce satisfactorily the injection pressure evolution measured in the field (Figure 24). First, we have changed the permeability of the whole stimulated fracture coinciding with the changes in injection rate. This approach has the limitation that in reality permeability does not change homogeneously along the whole fracture and that it requires manual calibration of the permeability changes. Second, we have used an embedded model to calculate fracture permeability changes as a function of the volumetric strain based on the cubic law. This model, which considers the fracture to behave elastically, satisfactorily reproduces the early stages of the stimulation, but overestimates injection pressure at late times. The overestimation is because permeability enhancement occurs in the fracture due to dilatancy induced by shear slip, which opens up the fracture and produces additional permeability enhancement. To overcome this limitation, the third approach extends the previous one by considering for the fracture a viscoplastic constitutive model with slip weakening and dilatancy. With the viscoplastic model, permeability enhancement is one order of magnitude larger than with the elastic model (Figure 25), which means that the permanent permeability enhancement obtained as a result of the stimulation is of one order of magnitude, which improves injectivity. The extent of the reactivated fracture is of 40 m after 3.4 h of stimulation, which suggests that connecting a doublet is plausible for longer stimulation tests performed on the two wells.

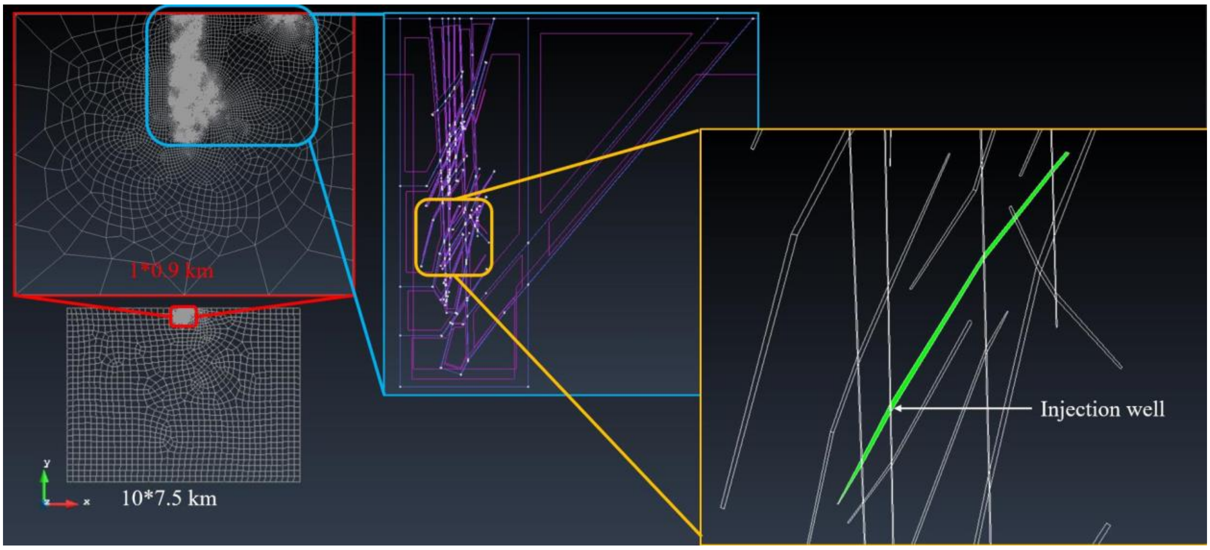


Figure 23. Model geometry and mesh

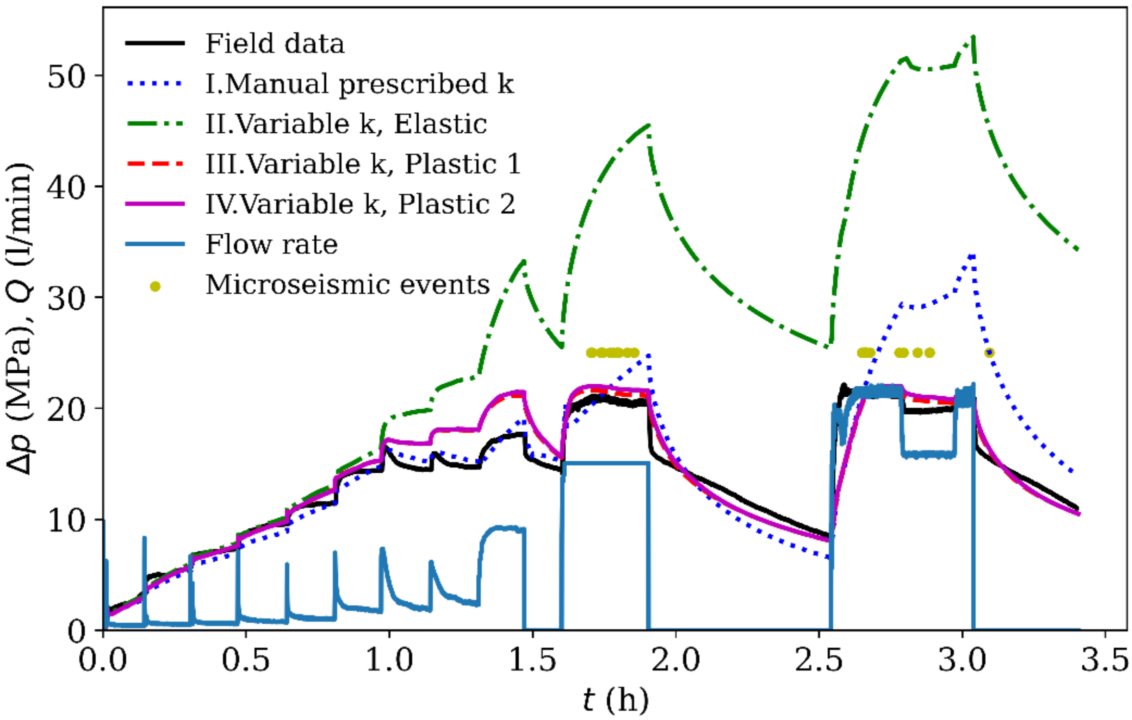


Figure 24. Pressure evolution at the injection well for the field experiment as well as the four numerical models; the solid blue line represents injection flow rate (lit/min); yellow circles indicate the time of the microseismical events.

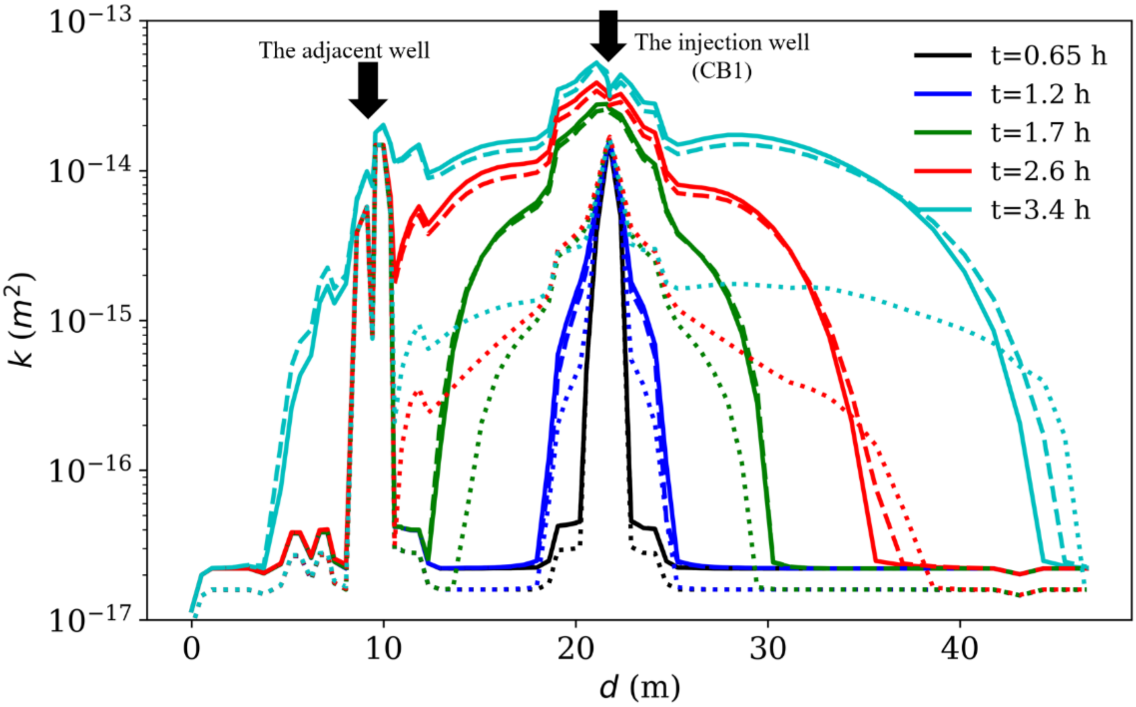


Figure 25. Comparison of fracture permeability profile for different models; Solid lines represent viscoplastic model III, hyphened-lines represent viscoplastic model IV, and dotted-lines are for elastic model II

4 Discussion and conclusions

The ZoDrEx project has been successful from the point of view of all participants and will have a significant impact on the one hand for the geothermal sector as a whole and on the other hand for the individual companies and organizations involved in the project.

In the ZoDrEx project it was clearly demonstrated that the hammer drilling technique is a qualitatively good and cost-effective alternative to conventional rotary drilling even for highly deviated and horizontal wells with diameters of 8.5 inch up to lengths of at least 400 m, even without directional drilling technology. Strictly speaking, this currently applies primarily where clear water can be used as drilling fluid. We currently see geo-storage projects and medium-depth geothermal projects in crystalline rock as the primary areas of application. However, the future of hammer drilling technology for deep geothermal applications still depends on the extent to which it will be possible to drive the hammer using drilling fluid as well.

In addition, the development of directional drilling technology for hammer systems will be necessary for boreholes with lengths significantly greater than 500 m that are strongly deflected from the vertical. As a by-product of the detailed drilling data analysis and the extensive investigations in the executed boreholes, we could show that the drilling progress (ROP) is a very good and reliable indicator for detecting small shear zones. Therefore, it is now conceivable to dispense with logging that is costly or difficult to implement or risky under technically very demanding conditions (e.g., very high temperatures). Overall, the results provide a clear basis for a cost reduction potential that can now be implemented by the geothermal industry.

Different zonal isolation technologies were demonstrated and compared, which can be of great importance primarily for the development of EGS, but also more generally for increasing the permeability when connecting wells in hydrothermal and heat storage projects. ZoDrEx has thus provided the basis for increasing energy yields, in some cases significantly, and for better assessing the deployment risks of different technologies, thus boosting the overall economics of geothermal systems. In addition, we can provide reservoir and drilling engineers with design criteria and a basis for decision-making. In particular, the following five results are worth highlighting:

1) ZoDrEx has contributed to the Bedretto Reservoir project demonstrating the multi-zonal stimulation concept - in our view the world's first project in crystalline rocks - to have an energetic advantage over single-stage stimulations in-situ. Previously, numerical models predicted a flow rate increase in the range of a factor of 3 to 6, which has now been experimentally proven on a scale of 1:3 compared to a deep EGS project, such as the one planned by Geo-Energie Suisse in Haute-Sorne in the canton of Jura in Switzerland. Applied to practice, this means that the electrical power of an EGS project can be increased from about 1.5 MW - if a single stimulation stage is carried out over the entire borehole reservoir section - to about 4.5 to 6 MW if a multi-stage stimulation approach is used.

2) For years, there has been an intensive debate among experts as to whether open-hole multi-packer systems or the classic cemented and perforated casing offer better hydraulic conditions for stimulation in fractured rocks. We have now been able to demonstrate, within the usual uncertainties of subsurface work, that both methods are good in principle for multi-zonal stimulation. This is good news for the geothermal industry. Planning reservoir and drilling engineers can now focus on more reservoir-independent issues when deciding on one concept or the other, such as site-specific borehole conditions, borehole breakouts, borehole stability, temperature, equipment reliability, deployment risks, equipment availability and costs.

3) Within the framework of ZoDrEx, the micro-drilled side-track developed by Fraunhofer IEG could be used successfully for the first time in-situ in granite and for the first time at depths of approximately 300 m. A well with a typical geothermal diameter of 8.5 inch and a cemented casing, could be well connected to the fractured rock with the micro-side-tracks and subsequently stimulated. This technology is first in certain cases a very good alternative for the classical perforation technology based on explosives, and secondly it allows completely new perspectives for applications to drill several meters long micro-sidetracks, which are impossible to reach with the classical perforations. This technology can significantly contribute to greatly increase the hydraulic connectivity between the wellbore and the reservoir and therefore has a significant contribution to increase the overall economic viability of geothermal and heat storage projects. It also minimizes the exploration risks. If the permeability of the sandstone at the on-going heat store project in Bern will not be sufficiently high, the drilling of micro-side-tracks will be an important risk mitigation measure. Because of the ZoDrEx project this technology is now ready to be applied.

The data show the success of the mechanical rock destruction process in hard rock. However, there is room for improvement of operational capabilities. An issue which occasionally occurred and must be resolved is the tendency of the drilling tool (this is also true for the jetting tool) to jam downhole, rendering Pull Out Of Hole very difficult at times. It is believed that the interface between deflector shoe and the wellbore may have provided a state which allowed for such jamming of the turbine. Investigations into resolving the issue are ongoing and are part of the Micro Turbine Drilling project. Another issue, which was observed during the Bedretto Lab tests, was the creation of tortuous side-tracks with ledges. This is the result of the turbine to recentralize after the creation of an initial window, possibly because of whirling of bit and turbine or the effect of the hose on the drilling dynamics.

Moreover, current Radial Jet Drilling operations like in the Bedretto Lab demonstration necessitate the allocation of a substantial amount of time to the azimuth-specific reorientation of the deflector shoe for respective micro-side-tracks, rendering Non-Productive Time a real issue as up to twenty percent of the operation time is lost in this way. Additional Non-Productive Time arises from the necessary change of the depth position of the deflector shoe to treat the entirety of the reservoir thickness or target formation; only this ensures maximum possible contacting of the reservoir by the wellbore, preventing inflow performance issues from problems like partial penetration etc. The abovementioned Non-Productive Time is a direct result of extra tripping of coiled tubing and ancillary equipment, i.e., at least two trips are required for the reorientation of the deflector shoe and one trip is required for the changing of the deflector shoe's depth position. This issue of tripping Non-Productive Time must be addressed to foster Radial Jet Drilling technology and make is more attractive.

4) As part of ZoDrEx, Welltec was able to further develop the WAB metal multipacker system routinely used for the petroleum industry in sedimentary rocks and test it in Bedretto in granite. The WAB system has an immense potential especially for the high temperature range of more than approx. 175°C, because approximately above this temperature elastomer-based packers can no longer be used. The experience gained in Bedretto enables specific challenges in crystalline rock to be mastered for further projects and processes to be optimized. Before the system can be used successfully, a further testing and optimisation of the packer setting is necessary.

5) From the point of view of the planning contractors and project developers, important experience was gained in Bedretto with the qualification of products and processes, which will contribute significantly to a more accurate assessment of the implementation risk of various technologies in deep boreholes. This is also a significant contribution to improving the economic viability of geothermal projects.

5 Outlook and next steps

The ZoDrEx results will be directly applied in the EGS projects and other projects (e.g., heat storage project in Bern) that Geo-Energie Suisse contracted for planning in Switzerland, especially for the Haute-Sorne project in Canton Jura.

The Haute-Sorne project aims to use geothermal energy to generate electricity and heat in a power plant fed by two 5 km deep boreholes. The main aim is to contribute to the provision of renewable and local energy in the Canton of Jura. If successful, the Haute-Sorne geothermal power plant will have a maximum electrical capacity of 5 MW and will be able to supply electricity to at least 6000 households. The project's total investment cost is estimated to be around 100 million Swiss francs. The development of Haute-Sorne will be based on the application of the multi-stage stimulation technology to enhance the rock properties that contribute to the geothermal energy production. The technology for Haute-Sorne is scalable and can be transferred to many other sites in Switzerland.

The following knowledge acquired through the ZoDrEx project will be integrated into the development of the Haute-Sorne project, the Bern heat storage project and other projects in Switzerland:

1) The most important ZoDrEx result for Haute-Sorne project and other projects world-wide is that both completion methods - the open-hole multi-packer systems **and** the classic cemented and perforated casing - are good in principle for multi-zonal stimulation. For a greenfield project without pre-existing information from exploration drilling such as the Haute-Sorne project, it is now possible to plan for a stimulation well from the outset with a cemented and perforated casing. For a second well, probably a production well, it can be decided based on the results of the first well whether it is better to use an open-hole multi-packer completion or also to equip the second well with a cemented and perforated casing. These results are of great importance to reduce the operational, technical and therefore also financial risk of projects that will depend on stimulation measures because sufficient water permeability cannot be expected on the basis of the available data before drilling.

2) Since we could show that the drilling progress (ROP) is a very good and reliable indicator for detecting small shear zones, we see a great potential for cost reduction of expensive borehole logging in Haute-Sorne, especially in long deviated sections and/or when high temperatures become challenging for

logging instruments. This result is not specific for EGS projects only and can be applied also to hydrothermal projects.

3) As a direct outcome of ZoDrEx, the micro-side-tracking technology is now available for heat storage (e.g., Bern) or hydrothermal projects. In case the sedimentary formations will not be sufficiently permeable, the access to the reservoir can be created artificially and the permeability increased by drilling a multitude of micro-side-tracks.

4) The future of the hammer drilling technology for deep geothermal applications still depends on the extent to which it will be possible to drive the hammer using drilling fluid as well, but depending on the technology development in the next years, hammer drilling may be considered as an alternative to rotary drilling during the development of the deviated section of the boreholes in Haute-Sorne.

5) The overall results of ZoDrEx have demonstrated that a reservoir can be created in granite or gneiss, and probably also in sediments. Such reservoirs could serve as a seasonal heat storage especially where crystalline formations are present at relatively shallow depth in the northern part of Switzerland and in many alpine regions of Switzerland.

6 National and international cooperation

The partners in ZoDrEx participating in the Bedretto demonstration tests include industry leaders in completion equipment, project management and geothermal operators, engineering organizations active in both the public and the private sectors, and prestigious academic research organizations.

The Swiss ZoDrEx partners are Geo-Energie Suisse (project coordinator) and ETH Zürich (research partner and operator of the Bedretto Lab).

The international ZoDrEx project partners involved with field work at Bedretto or analyzing data from Bedretto were from Germany Fraunhofer IEG (tool development, field work, data interpretation) and RWTH (field work and data interpretation), from Denmark Welltec (tool development, fieldwork and data interpretation) and from Spain CISIC (hydromechanical modelling).

The collaboration and coordination within the Consortium were especially challenging in the early stages of the project because of the large number of partners involved and many discussions evolved around the planning of the boreholes at Bedretto, especially also with ETH the site operator. Later the COVID pandemic situation made it difficult to meet with all members of the consortium. However, this was successfully addressed with regular telco project meetings as well as great efforts in multi- and bilateral communication both with the project coordinator and among partners.

The diversity of the project partners has helped to provide each other with invaluable insight into very specific topics that enlarged the awareness of the equipment manufacturers, service providers and research organizations for the requirements of the geothermal project developers and power plant operators.

The trans-nationality of ZoDrEx added great value to the project in creating new networks as well as strengthening existing ones between the consortium partners. This significantly contributed to the development and proposal of follow-up research and development projects within the field of geothermal energy and also to potential contracts between the providers of services and products, and project developing companies and power plant operators.

The annual meetings organized with all the project partners allowed the ZoDrEx partners to get an overview on the geothermal European actors and the issues they are facing at every step on the development of geothermal plants. Moreover, such meetings and the joint reports offered all the partners to present their competences. It will therefore be easier to identify and call on European structures for future projects. Finally, we want to mention that despite the fact that the project was strongly dependent on field work, the consortium was able to cope successfully with travel restrictions and the delays due to the COVID pandemic.

7 Publications

Social media

ZoDrEx Project description on GES website:
https://www.geo-energie.ch/forschung-entwicklung/felslabore-grimsel-bedretto/
https://www.geo-energie.ch/forschung-entwicklung/geothermica/zodrex-projekt/

Project description on CGE website:
https://www.cetimgrandest.fr/notre-rd-proprietes-dusage-des-materiaux-et-durabilite-des-produits-du-futur/

Project description on RWTH Aachen website:
https://www.lih.rwth-aachen.de/go/id/qwfd

Project description on CSIC website:
https://www.idaea.csic.es/project/zodrex-geothermica-era-net/

Press publications

Geo-Energie Suisse AG (2021): *Breakthrough for deep geothermal energy*, Press release (English,French,German,Italian):
https://www.geo-energie.ch/2021/01/21/durchbruch-f%C3%BCr-die-tiefengeothermie/
https://fr.geo-energie.ch/2021/01/21/perc%C3%A9e-pour-la-g%C3%A9othermie-profonde/
https://www.geo-energie.ch/bedretto2020-en/

Läubli, M., Häne, S. (2021): *Energie aus dem Untergrund, Wirksames Rezept gegen Erdbeben*, Tages-Anzeiger 21.1.2021
https://www.tagesanzeiger.ch/wirksames-rezept-gegen-erdbeben-760986462291

ETH/GES (2021): *Detective Work on earthquakes (2021)*, Website Bedretto
http://www.bedrettolab.ethz.ch/bs-imagewithtext/Detective-work-on-earthquakes/

ETH/GES (2021); *Second stimulation of the DESTRESS project, Website Bedretto*
http://www.bedrettolab.ethz.ch/bs-imagewithtext/Timeline-New-image-with-text-00018/

Swiss Italian speaking TV RSI: *Report on Bedretto Laboratory and work of GES for DESTRESS*
https://avenue.argusdatainsights.ch/Article/AvenueClip?artikelHash=8fd1e4bf5a984815a8639c7ff94a766d_D41E6C3CCB750AB3CB68C9A57D9925FD&artikelDateiId=286392938

Link, K. (2020): Bedretto Untergrundlabor für Geoenergien -Tiefengeothermische Energieforschung unter nahezu authentischen Bedingungen. *Geothermische Energie – Fachzeitschrift für geothermische Forschung und Anwendung in Deutschland, Österreich und der Schweiz. Nr. 96*. September 2020.

Meier, P., Bethmann, F., Alcolea, A., Ollinger, D., Serbeto, F., Dyer, B., Castilla, R., Christe, F. and Karvounis, D. (2021): Durchbruch für die Tiefengeothermie – Kleine Schritte mit großem Erfolg. *Geothermische Energie – Fachzeitschrift für geothermische Forschung und Anwendung in Deutschland, Österreich und der Schweiz. Nr. 99*. Juni 2021.

Publications

Kong, X.-Z., Wang, X., Ma, J., Saar, M. O., 2021. Shear and acidizing stimulation of carbonate-filled fractured granite. In preparation.

Li, Z., Ma, X., Kong, X.-Z., Saar, M. O., Vogler, D., 2021. Permeability evolution during pressure-controlled shear slip in saw-cut and natural granite fractures. Submitted to *Geomechanics for Energy and the Environment*.

Zareidarmiyan, A., Salarirad, H., Vilarrasa, V., De Simone, S. and Olivella, S., 2018. Geomechanical response of fractured reservoirs. *Fluids*, 3: 70, doi:10.3390/fluids3040070

Conferences

Bröker, K., Ma, X., Saar, M.O., and the Bedretto Lab Team, 2019. In-situ stress and rock mass characterization via mini-frac tests at the Bedretto Underground Laboratory. *7th European Geothermal Workshop Karlsruhe*, 9-10 October, 2019.

Castilla, R., Meier, P., Bethmann, F., Alcolea, A., Dyer, B., Serbeto, F., Christe, F., Karvounis, D., Ma, X. and Hertrich, M., 2022, Data integration and model updating in a multi-stage stimulation in the Bedretto Lab, Switzerland. Paper will be presented at the *ARMA 56TH US ROCK MECHANICS / GEOMECHANICS SYMPOSIUM Santa Fe*, New Mexico, 26-29 June 2022.

Johal, S. and Meier, P. M. (2021). Bedretto Underground Laboratory for Geoenergies (BULG) Borehole Fracture Identification: Drill Hammer Measurements Whilst Drilling (MWD). *Celle Drilling 2021 – Digital Edition, Tuesday, 14th September 2021.*

Kong, X.-Z., Ma, J., Grimm Lima, M., and Saar, M.O., 2019. Experimentally exploring permeability evolution induced by THMC-coupled processes. *2019 ARMA-CUPB Geothermal International Conference*.

Kong, X.-Z., Grimm Lima, M., Wang, X., Ma, J., 2021. Evolution of fracture permeability induced by THMC-coupled processes, *InterPore 2021*, Online.

Ma, X., 2019. Bedretto Underground Laboratory, Switzerland, and the planned in situ hydraulic stimulation experiments for EGS. *2019 ARMA-CUPB Geothermal International Conference*.

Ma, X., Gholizadeh Doonechaly, N., Hertrich, M., Gischig, V., Jordan, D., 2019, In situ stress characterization in the Bedretto Underground Laboratory: implications for induced slip of pre-existing fractures/faults. *3rd Schatzalp Workshop on Induced Seismicity 2019*.

Ma. X., Doonechaly, N. G., Hertrich, M., Gischig, V., Klee, G., 2019, Preliminary in situ stress and fracture characterization in the Bedretto Underground Laboratory, Swiss Alps: implications on hydraulic stimulation. *ISRM 14th International Congress of Rock Mechanics Rock Mechanics for natural resources and infrastructure development Foz do Iguassu*, Brazil, 13-18 September, 2019.

Meier, P. M., Guinot, F., Bethmann, F., Faschingbauer, R., Alcolea, A., Liautaud, F., Thanourey, J., Schott, T., Carrera, J., Vilarrasa, V., Genter, A., Cuenot, N., Mouchot, J., Saar, M. O., Kong, X., Bracke, R., Wittig, V., Nardini, I., Müller-Ruhe, W., Schindler, D., Zucker, A., Amann, F., Rausch, T., Wienzek, A., Buchner, A., Molliet, A., McMath, D., Schnettler-Kristensen, P., Hallundbaek, S. and Hallundbaek, J., 2020. ZoDrEx an European Endeavour for Optimising Zonal Isolation, Drilling and Exploitation of EGS Projects, *World Geothermal Congress (WGC 2020)*, 04 November 2021.

Meier, P. M., Serbeto, F., Christe, F., Alcolea, A., Castilla, R., Bethmann, F. and Dyer, B., 2022. Results from benchmark testing of zonal isolation borehole completions for multi-stage EGS stimulation in the Bedretto underground rock laboratory in Switzerland. 2022, Paper will be presented at the *ARMA 56TH US ROCK MECHANICS / GEOMECHANICS SYMPOSIUM Santa Fe*, New Mexico, 26-29 June 2022.

Vilarrasa, V., 2019. Process understanding of induced seismicity. *Workshop Quo Vadis Hydrogeology Group UPC-CSIC*, Sant Fruitós del Bages, Spain, 25-26 June 2019

Vilarrasa, V., 2020. Using geologic resources to mitigate climate change. *Inaugural Meeting of the InterPore Spanish Chapter*, Barcelona, Spain, 28 January 2020

Wu, H. and Vilarrasa, V., 2019. Numerical and analytical solutions to assess induced seismicity. *Workshop Quo Vadis Hydrogeology Group UPC-CSIC*, Sant Fruitós del Bages, Spain, 25-26 June 2019

Zareidarmiyan, A., Salarirad, H., Vilarrasa, V., Kim, K.-I-, Lee, J. and Min, K.-B., 2018. Comparison of numerical codes for coupled Thermo-Hydro-Mechanical simulations of fluid injection into fractured media. *International Conference on Coupled Processes in Fractured Geological Media: Observation, Modeling, and Application, CouFrac*, Wuhan, China, 12-14 November 2018

Zareidarmiyan, A., Salarirad, H. and Vilarrasa, 2020. The effect of discontinuities on the geomechanical response of carbonate reservoirs. *7th Iranian Rock Mechanics Conference*, Tehran, Iran, 21-22 April 2020

The project outline has been presented by RWTH as part of a keynote talk to a broad scientific at the 6th European Geothermal Workshop in Strasbourg, October 2018.

Master Thesis

Bröker, K., 2019. In-situ stress and rock mass characterization via mini-frac tests at the Bedretto Underground Laboratory. Master thesis. August, 2019.

van Limborgh, R., 2020. Borehole Indicators of In Situ Stress Field Heterogeneity at the Bedretto Underground Laboratory. Master thesis. August 2020, ETH Zurich.

Wang, Q.-H., 2021. Laboratory Experiments on Mud Cake Formation in the Single Natural Fractures. Master thesis. September 2021, ETH Zurich.

Deliverables

Castilla, R. (2021): Structural characterization of the Bedretto Underground laboratory for Geosciences (BULG).

Castilla, R., Meier, P., Bethmann, F., Christe, F. and Serbeto, F. (2021): The ST2 borehole in the Bedretto Underground Lab for Geosciences and Geoenergies (BULGG): Activities carried out in the framework of the GEOTHERMICA ZoDrEx research project.

Christe, F. (2022): Overview of Seismicity during injection Tests - Bedretto borehole Welltec.

Christe, F. and Meier, P. (2021): Installation of the Welltec packers in the Bedretto Underground Lab for Geosciences and Geoenergies (BULGG): Activities carried out in the framework of the GEOTHERMICA ZoDrEx research project.

Christe, F., Meier, P. and Serbeto, F. (2021): Hydrogeological characterization of the boreholes CB1, ST1 and ST2 in the Bedretto Underground Lab for Geosciences and Geoenergies (BULGG): Activities carried out in the framework of the GEOTHERMICA ZoDrEx research project.

Christe, F., Serbeto, F. and Meier, P. (2021): First Evaluation of stimulation tests in borehole ST2.

Fraunhofer IEG (2022): ZoDrEx – Zonal isolation, drilling and exploitation of EGS projects; 70160-44011; FINAL REPORT FRAUNHOFER IEG, JANUARY 1ST 2020 – NOV 30TH 2021

Johal, S. & Castilla, R. (2021): Integrated data analysis: ST2, CB1 and ST1.

Kong, X. and Saar, M. O. (2022): REPORT AND RESULTS OF ETHZ-INVOLVED SUB-TASKS (2.1, 3.1, 3.2, 3.4, 4.2, 4.3).

Meier, P. (2022): ZoDrEx: Zonal Isolation, Drilling and Exploitation of EGS projects. GEOTHERMICA Final Report. April 2022. http://www.geothermica.eu/media/call1/ZoDrEx_Final_Report_corrections_modifs-accepted_2_final-8_5_22v2.pdf.

Meier, P., Alcolea, A., Bethmann, F., Castilla, R., Christe, F., Dyer, B., Ollinger, D., Serbeto, F. with contributions from X. Ma, H. Krietsch, A. Shakas and M. Hertrich (2020): Reservoir stimulation tests in the Bedretto Lab (January 15th February 5th 2020).

RWTH Aachen University (2022): ZoDrEx - Zonal Isolation, Drilling and Exploitation of EGS Projects; Final report according to BNBest-BMBF 98.

Vilarrasa, V., Carrera J., Alcolea, A. and Meier P. (2022): Report and comparative results of Task 3.5.

Welltec Completions: WELLTEC – ZONAL ISOLATION - WORK PACKAGE 2.2 2.3 AND 3.3.

8 References

[1] International Partnership for Geothermal Technology (2012). Zonal Isolation for Geothermal Wells. August 2012. *https://ipgtgeothermal.org/assets/Uploads/FINAL-Zonal-Isolation-Packers-working-group-White-Paper-August-2012.pdf*

[2] Meier, P. M., Guinot, F., Bethmann, F., Faschingbauer, R., Alcolea, A., Liautaud, F., Thanourey, J., Schott, T., Carrera, J., Vilarrasa, V., Genter, A., Cuenot, N., Mouchot, J., Saar, M. O., Kong, X., Bracke, R., Wittig, V., Nardini, I., Müller-Ruhe, W., Schindler, D., Zucker, A., Amann, F., Rausch, T., Wienzek, A., Buchner, A., Molliet, A., McMath, D., Schnettler-Kristensen, P., Hallundbaek, S. and Hallundbaek, J., 2020. ZoDrEx an European Endeavour for Optimising Zonal Isolation, Drilling and Exploitation of EGS Projects, *World Geothermal Congress (WGC 2020)*, 04 November 2021.

[3] Johal, S. & Meier, P. M. (2021). Bedretto Underground Laboratory for Geoenergies (BULG) Borehole Fracture Identification: Drill Hammer Measurements Whilst Drilling (MWD). *Celle Drilling 2021 – Digital Edition, Tuesday, 14th September 2021.*

[4] Meier, P., Rodríguez, A., & Bethmann, F. (2015). Lessons Learned from Basel: New EGS Projects in Switzerland Using Multistage Stimulation and a Probabilistic Traffic Light System for the Reduction of Seismic Risk. *Proceedings World Geothermal Congress*.

[5] Meier, P., & Ollinger, D. (2016). Monte Carlo Flow Rate Simulations for the Multi-Stage EGS Stimulation Concept of the Haute-Sorne Pilot Project (Canton Jura, Switzerland*). In European Geothermal Congress. Strasbourg*.

[6] Domenico, G., Wiemer, S., Maurer, H., Hertrich, M., Meier, P., Alcolea, A., Castilla, R. and Hochreutener, R. (2022), Validation of Technologies for reservoir engineering (VALTER), Final Report January 15th, 2022.

[7] Olivella, S.; Gens, A.; Carrera, J.; Alonso, E.E. Numerical formulation for a simulator (CODE_BRIGHT) for the coupled analysis of saline media. Eng. Comput. 1996, 13, 87–112.