Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

ZoDrEx, an European Endeavour for Optimising Zonal Isolation, Drilling and Exploitation of EGS Projects

Peter M. Meier, Frédéric Guinot, Falko Bethmann, Roland Faschingbauer, Andrés Alcolea, Françoise Liautaud, Jérôme Thanourey, Tiphaine Schott, Jesus Carrera, Victor Vilarrasa, Albert Genter, Nicolas Cuenot, Justine Mouchot, Martin Saar, Xiang-Zhao Kong, Rolf Bracke, Volker Wittig, Isabella Nardini, Waldemar Müller-Ruhe , Daniel Schindler, Andre Zucker, Florian Amann, Tobias Rausch, Alexander Wienzek, Alexander Buchner, Annabelle Molliet, Diana McMath, Peter Schnettler-Kristensen, Søren Hallundbaek, and Jørgen Hallundbaek

Geo-Energie Suisse AG, Reitergasse 11, CH 8004 Zürich, Switzerland

p.meier@geo-energie.ch

Keywords: EGS, deviated percussion drilling, zonal isolation, corrosion, inhibitors, environment.

ABSTRACT

The ZoDrEx project is a GEOTHERMICA ERA-NET co-funded project aimed at demonstrating drilling, completion and production products and technologies that will increase the technical and economical chances of success in geothermal energy applications. At the end of the project, ZoDrEx will have demonstrated that: (1) fluid driven percussion drilling can be used in highly deviated trajectories to improve drilling efficiency in crystalline rocks, and that the impacts of percussion drilling can be dampened to a level compatible with downhole measurement systems, thus leading to substantial cost reduction in geothermal well construction. The improvements will be demonstrated in the granite of the Bedretto Underground research Laboratory for Geoenergies (BULG) in the Swiss Alps; (2) zonal isolation is key to the efficient stimulation of EGS and that the selection of zonal isolation technologies can be performed efficiently. Additionally, ZoDrEx will have contributed to the development of more robust zonal isolation technologies, which will be demonstrated in boreholes of the BULG; and (3) operating EGS plants can be optimized through automated, protected against corrosion with more acceptable inhibitors, and thoroughly monitored facilities for ensuring the safety of the workers, the public and the environment. These optimizations will be shown at the Rittershoffen geothermal power plant in Alsace, France. In parallel, most tasks involve modelling exercises aimed at forecasting, e.g., the hydromechanical impact of different completion or stimulation schemes. Testing drilling, completion and stimulation technologies in the BULG allows a more precise control over experimental conditions, a reduced cost and a low risk environment when compared to testing in a deep wellbore. In the end, EGS operators will have a better understanding on how to improve well construction, EGS creation, production optimization and plant operation at a reduced technical and financial risk. The ZoDrEx project groups 10 partners from Denmark, France, Germany, Spain and Switzerland. These partners include 5 industry leaders in drilling, drilling fluid services, completion equipment, project management and geothermal operators, 3 engineering organizations active in both the public and the private sectors, and two prestigious academic research organizations.

1. INTRODUCTION

The temperature of about 98% of the earth mass is above 1000°C, which represents an enormous and renewable source of energy. However, only a small fraction of this sustainable and environmentally friendly energy source is converted into electrical power nowadays. The reason is that the transport and conversion of heat into power in an economic and profitable way is still challenging and not risk-free, which precludes major private investments in geothermal industry and its development.

To make things worse, geothermal energy is most profitable in geologically and tectonically favourable areas. To tackle this problem, the concept of Enhanced Geothermal System was devised from the old Hot Dry Rock concept and patented by the los Alamos National Laboratory in 1974. Since then, technical readiness levels (Figure 1) involved in the construction of an EGS have improved significantly in connection with the numerous successful EGS experiments in the last two decades, e.g., Soultz-sous-Forêts (France), the Cooper Basin (Australia) or those in the Upper Rhine Graben (Germany), to cite a few. However, the techniques to efficiently and consistently (in the sense of clonability or portability) construct an EGS are still in the development phase towards an industrially efficient and cost-friendly process. Thus, a first step aimed at reducing the risk and cost of EGS operations is precisely to identify the most sensible techniques, i.e., those with ample room for development. Testing new technologies or developing improvements to existing ones under real EGS conditions would be unaffordable in terms of cost and risk. Thus, pilot and demonstration projects are required.

Ideally, pilot and demonstration projects are best executed and most informative under favourable conditions aimed at minimising costs and risks. For instance, drilling from deep tunnels excavated along igneous rocks (the usual target of EGS) is advantageous because (1) drilling is best monitored, (2) different drilling techniques can be tested at low cost, and therefore (3) the risks of failure are alleviated. The same can be said about other techniques required for the construction of an EGS, e.g., well completion, zonal isolation, hydraulic stimulation, monitoring, etc. In this context, the ZoDrEx project, supported by the EU ERANET-GEOTHERMICA co-fund activity, runs nowadays in the Bedretto Underground research Laboratory tunnel (BULG). ZoDrEx (ZOnal isolation, DRilling and Exploitation of EGS projects) aims at demonstrating drilling, completion and production products and technologies that will increase the technical and economical chances of success in geothermal energy applications.

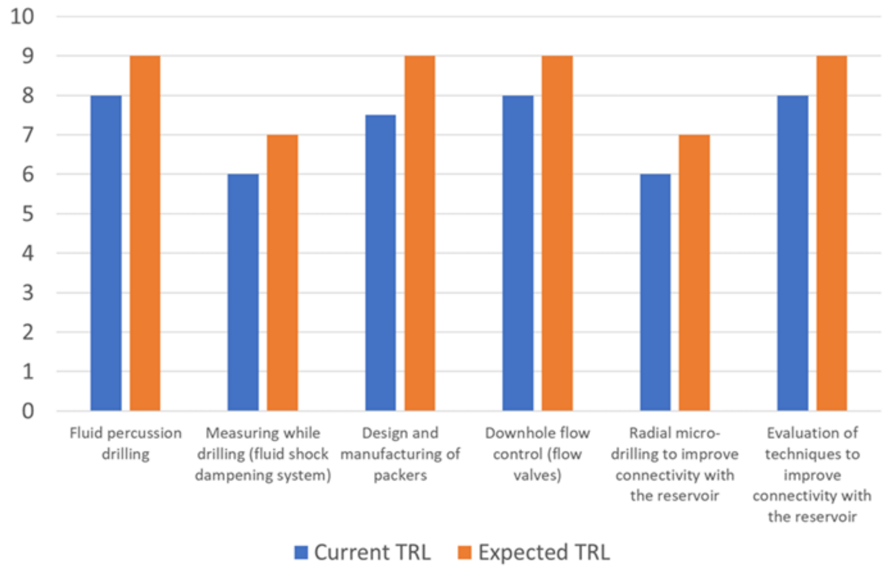

Figure 1: Current and expected technical readiness levels before/after the experience in the Bedretto Underground Laboratory for Geoenergies (BULG).

2. THE NEW BEDRETTO UNDERGROUND LABORATORY FOR GEOENERGIES (BULG)

The purpose of the BULG 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, approximately 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 masl.). It is excavated within the Rotondo granite, a late Variscan intrusion in the Gotthard massif. It shows as a fine to medium-grained, relative homogeneous light-grey granite with weakly developed sub-vertical NE-SW striking foliation, mostly visible in ductile shear zones (Lützenkirchen and Loew, 2011). The age of the Rotondo granite is approximately 294 Ma (Sergeev and Steiger, 1995). On surface, it outcrops over an area of 20-25 km2 (Labhart, 2005).

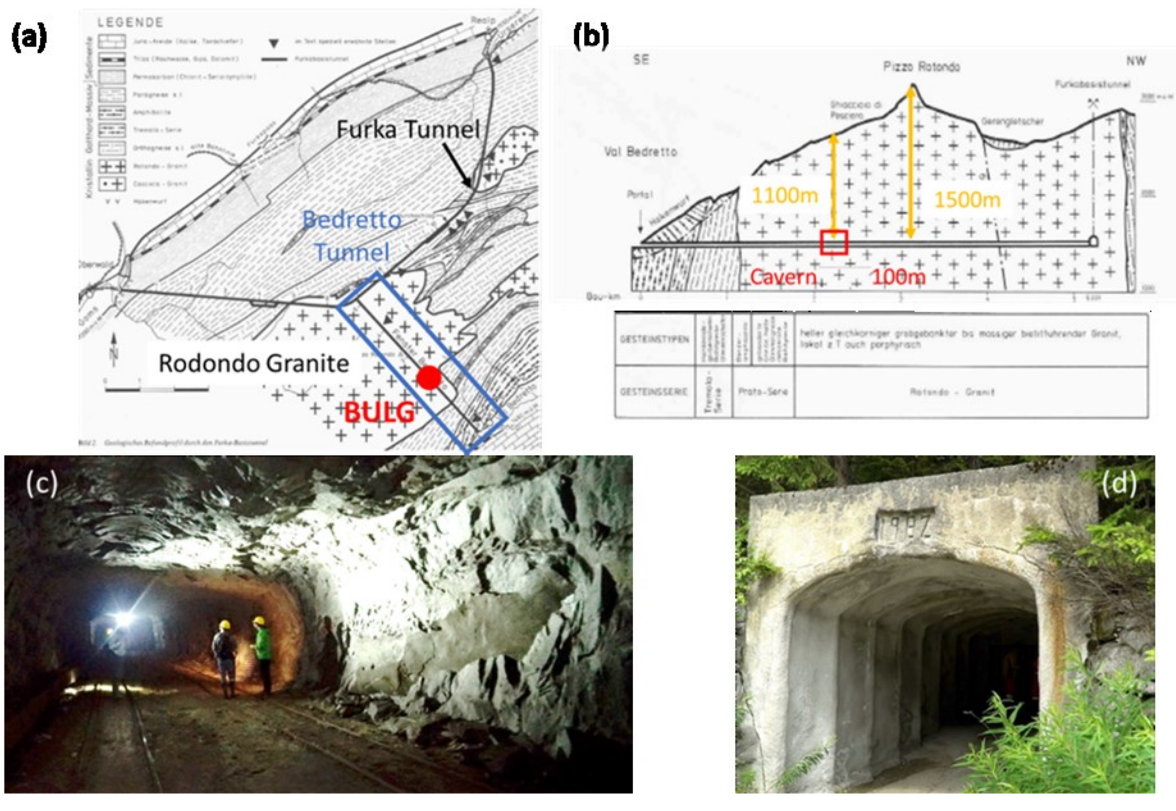

Figure 2: (a) Geological map of the surroundings of the Bedretto tunnel (blue inset) and location of the BULG (red circle); (b) NW-SE profile along the Bedretto tunnel, depicting the location of the cavern hosting the BULG; the approximate depth is depicted by yellow arrows (panels a and b modified from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

The regional stress state in the Swiss Alps is synthetized in Kastrup et al. (2004). These authors analyze focal mechanisms to observe a predominance of strike-slip or strike-slip to normal faulting regimes towards North and Northwest, whereas normal faulting is predominant to the South (Figure 3). In Bedretto, stress-induced failure is observed along certain sections of the tunnel, which may indicate that the local stress regime is strike-slip and/or normal faulting (Ma et al., 2019).

Faults and fractures along a ~600 m-long tunnel section encompassing the BULG have been mapped (Meier, 2017) and are presented in Figure 4. Three main fracture families have been identified, all of them sub-vertical and striking N-S, E-W and NE-SW, the latter being approximately orthogonal to the tunnel axis. The sets of fractures N-S and E-W intersect sometimes, forming "en-echelon" structures (Figure 4b). All three sets display slickensides, which indicates past shear episodes. Notably, fractures are often mineralized, possibly with biotite (Serbeto, personal communication).

As observed, the structural geology of the Bedretto tunnel is similar to that expected at 4-5 km depth underneath the Swiss Plateau, target of future EGS in Switzerland. As such, and in spite of scale effects, the BULG is a well-suited candidate for testing new techniques aimed at reducing risks and costs of true-scale EGS projects.

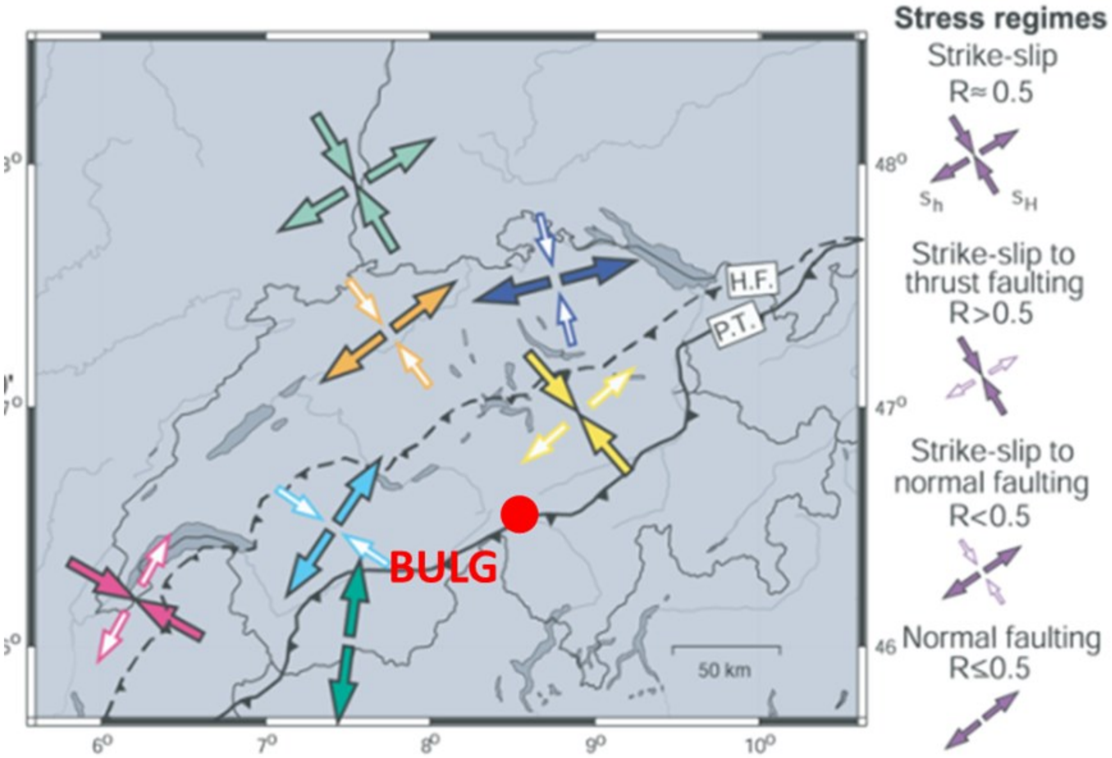

Figure 3: Regional stress map at the Swiss Alpin area. Modified from Kastrup et al. (2004).

3. OBJECTIVES OF THE ZODREX PROJECT

The expected technical readiness to be achieved after the ZoDrEx project are displayed in Figure 1. ZoDrEx agglutinates 10 partners from Denmark, France, Germany, Spain and Switzerland, including 5 industry leaders in drilling, drilling fluid services, completion equipment, project management and geothermal operation, 3 engineering organizations active in both the public and the private sectors, and two prestigious academic research organisations. The objectives of the ZoDrEx project are to demonstrate that:

- Fluid driven percussion drilling can be used in highly deviated borehole trajectories, which will improve drilling efficiency in crystalline rocks,
- the impact of percussion drilling can be dampened to a level compatible with downhole measurement systems, thus leading to a substantial cost reduction in the construction and monitoring of geothermal wells.
- zonal isolation is a key to success in the efficient stimulation of EGS; additionally, ZoDrEx will contribute to the development of robust zonal isolation technologies,
- the costs during the operational cycle of the geothermal plant are lowered by protecting equipment (e.g., pumps) against corrosion with optimally designed inhibitors, and
- operating geothermal plants can be optimized through automation and continuous monitoring to ensure the safety of the workers, the public and the environment.

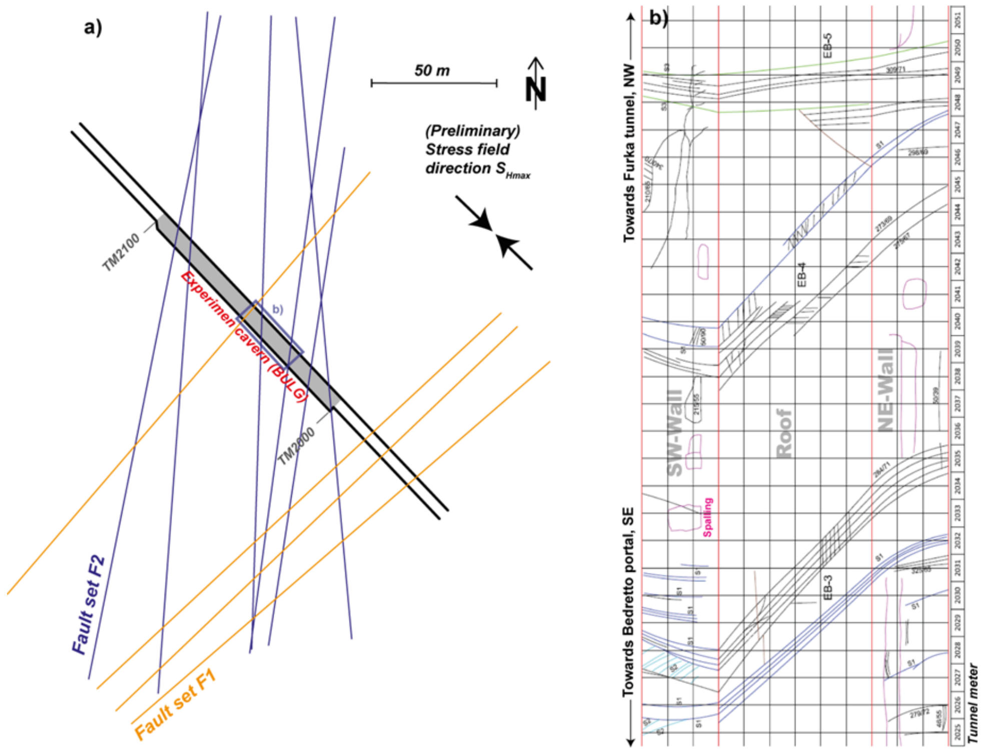

Figure 1: Structural geology at the BULG (Figure 2 in Gischig et al., 2019, adapted from Meier, 2017). a) Map of steeply dipping faults and fracture zones. b) Detail of structural mapping of tunnel walls and roof at the BULG.

The ZoDrEx project has been subdivided in four work packages, whose particular targets and expected challenges are described in detail the following subsections. Obviously, there are strong interactions between the different objectives and work packages, e.g., the design and development of optimal drilling and completion schemes and zonal isolation methods must bear in mind the subsequent hydraulic stimulations of the EGS and, at the same time, the hydraulic stimulation are meant to extend the operational lifetime of the EGS. An overall summary of drilling, completion and stimulation techniques is presented in Figure 5.

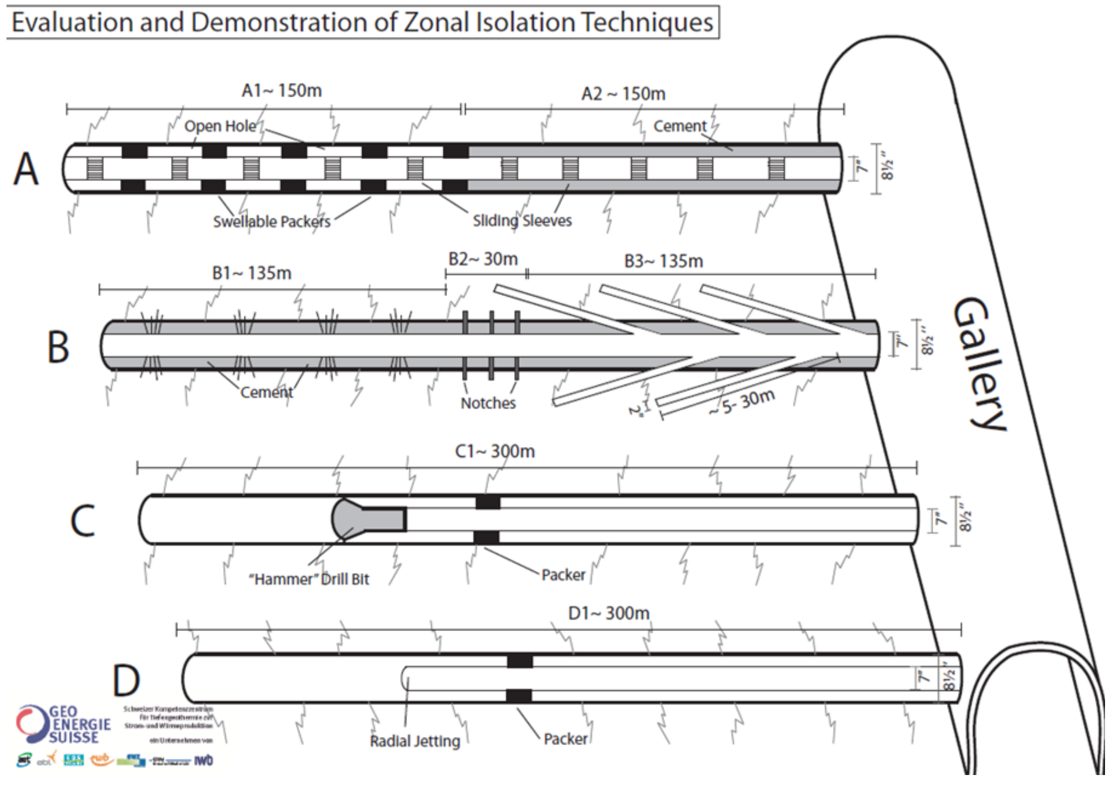

Figure 2: Sketch of the different drilling, completion and stimulation schemes used in Bedretto. From top to bottom: (A) stimulation of an openhole section (A1) and a cemented section (A2) with swellable packers and sliding sleeves; (B) example of lateral microdrilling and notches; (C) hammer drill bit with inflatable packer; (D) radial jetting with swellable packer.

3.1 Drilling and selection of drilling fluids

Percussion drilling with fluid hammer can substantially increase the ROP of standard rotary drilling methods by a factor 10. For example, a 4500 m depth borehole was drilled in Espoo (Finland, ST1 project) using an air powered "Down The Hole" (DTH) hammer, followed by a combination of a traditional rotary method and DTH hammer to the final depth of 6.4 km. The ROP achieved during the first phase (air-powered hammer only) was up to 15 m/hr, 100 times larger than the traditional ROP of rotary drilling in crystalline rocks (e.g., an average of 3 m/hr in Basel; see a survey in Baujard et al., 2017). Additional objectives are to demonstrate that (1) fluid hammer percussion drilling can be applied to highly deviated (i.e., pseudo-horizontal) sections and (2) that its impact on the drill string can be dampened to levels compatible with downhole instrumentation (measurement while drilling, MWD hereinafter). This demonstration combines research on the mechanical devices to be included in the bottom hole assembly and on the type of fluid and surface fluid management system to that end.

3.2 Zonal Isolation/Well completion

The zonal isolation must guarantee a "safe" travel of the circulating fluid from the injection to the production hole (i.e., generate a close circuit). In this context, borehole breakouts, inherent to boreholes in crystalline rocks, may put at risk any sealing isolation system, e.g., packers (Valley and Evans, 2009). The impact of borehole breakouts on packer design is particularly aggravated by thermal expansion (caused by the high downhole pressure and temperature) and corrosion/clashing along the operative lifespan of the packer. Thus, a first challenge is to properly identify and measure borehole breakouts. To that end, data out of the breakouts in borehole BS-1 in Basel (up to 13" width using an 8 1/2" bit) are being analyzed as worst-case scenario (Dahrabou et al., 2017).

Second, a proper selection of the completion scheme and corresponding materials is crucial to extending the operational lifetime of the system. Cement has consistently failed in geothermal applications due to the expansion/contraction of the steel tubulars caused by pressure and temperature variations, ultimately leading to cracks in the cement that compromise borehole integrity. Instead, metals have a higher tensile strength and tensile modulus than cement and should therefore better handle borehole breakouts. Metal alloy packers are an efficient way to achieve zonal isolation as they mould to borehole wall. However, standard packers in geothermal industry include rubber parts and are inherited from the oil-and-gas industry. Therefore, they cannot withstand the strenuous conditions of pressure and temperature at the great depth of an EGS. A full accelerated life test of the impact of downhole conditions on newly designed External Casing Packer (ECP) and flow valves will be undertaken, before the final development and the final testing in-house and in the rock.

Besides zonal isolation, well completion techniques aimed at connecting the borehole with the reservoir will be applied. Amongst them, we highlight the use of lateral drains drilled from the wellbore into the reservoir rock in an attempt to intersect more pre-existing fractures. A flexible assembly will be run into the wellbore and bent at the proper orientation using a previously installed whipstock system. In ZoDrEx, the technology does not only depend on standard hydro-frac hydraulic jetting but includes also a small diameter percussion drilling system. The lateral drill would be of a 2" nominal diameter. As in conventional lateral jetting, the assembly will use a whipstock tool run with coiled tubing (CT). An initial and extensive in-house testing technology will be carried out in an autoclave prior to the implementation in Bedretto, where reservoir conditions of high pressure and temperature can be reproduced. In addition, a preliminary modelling exercise to quantify the gain of connectivity between borehole and reservoir using different completion schemes has been carried out and is presented in section 5. ZoDrEx will also provide guidelines on the use of other zonal isolation options and their limitations.

3.3 Stimulation and production optimization

It is widely accepted that segmenting the reservoir section by means of zonal isolation, and individually stimulating each section significantly reduces (1) the seismic risks associated with EGS reservoir stimulation (Baisch et al., 2009, Meier and Ollinger, 2016), and (2) the probability of short-circuiting the path between injection and production wells. In addition, segmentation allows to stimulate small fractures with overall equal (or larger) area than that of the single fracture attained after an "all-in" stimulation of an openhole section of a borehole (e.g., in Basel).

In this context, the objective of ZoDrEx is to systematically investigate, evaluate, and demonstrate stimulation procedures in boreholes which have been completed with state-of-the-art zonal isolation techniques on the proto-type (1:1) scale, employing both experimental (at the BULG) and numerical methods. Methods to be tested include Stimulation While Drilling (SWD), stimulation from cemented sliding sleeves, cemented liner through explosive and/or jetted holes, open borehole sections, and cased borehole sections (Figure 5).

On the optimisation side, ZoDrEx will contribute to the development of (1) a high temperature (>150°C) eco-friendly geothermal corrosion inhibitor for very saline brine, (2) the development of a geothermal downhole flow control device, and (3) the automation of pumping with an advanced monitoring system. The testing of these components will be carried out at the Rittershoffen geothermal plant (Alsace, France), one of the few geothermal plants in Europe operating with natural brine circulating along a fractured deep granite. The innovative approach in ZoDrEx targets both the energy production efficiency and the environmental performances, by combining the interaction between reservoir data (productivity, water level, gas content), operational data (pump performance, corrosion rate) and environmental data (induced seismicity, noise, gas emission, effluents).

3.4 Environmental protection

A comprehensive and exhaustive plan for the environmental protection of an EGS will be designed and implemented, including the sampling of gas emissions during exploitation, the collection and analyses of effluent liquids, noise monitoring, etc.

4. TIMELINE AND ON-GOING ACTIVITIES

The approximated timeline of activities in the BULG is presented in Figure 6. Preliminary results attained so far include the mapping of fractures along the BULG (Meier, 2017) and the execution of a number of mini-frac tests, summarized in Ma et al. (2019). The main conclusions of these studies are:

- the granitic massive is nearly critically stressed,

- the local stress regime is strike-slip and/or normal faulting. Vertical stress is S_v~26.5 MPa, the minimum horizontal stress is S_h~13-16 MPa, and the maximum horizontal stress is S_H~0.8-1.0·Sv, striking N100E. However, local perturbations are found,

- porewater pressures are 3-6 MPa, and

- the E-W striking sub-vertical faults are prone to slip by applying injection pressures of 8-10 MPa.

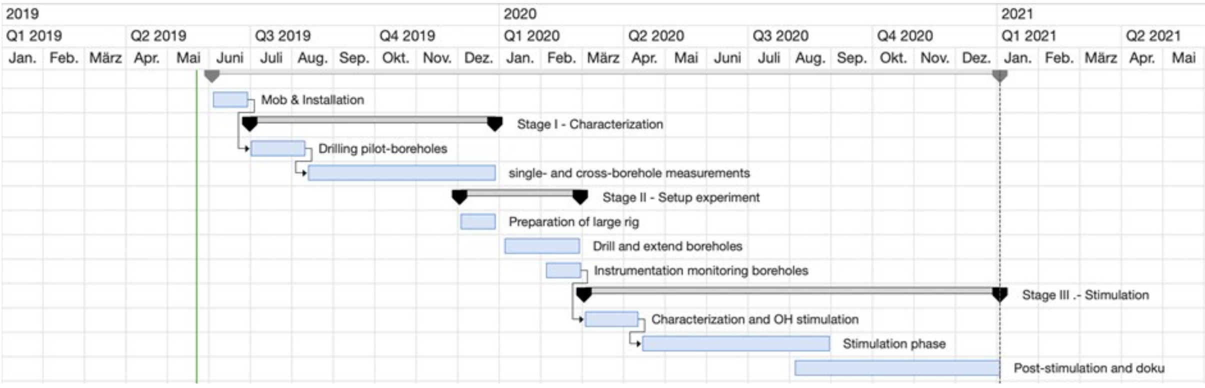

Figure 3. Approximate timeline of the ZoDrEx project.

5. CONCLUDING REMARKS

We have presented a summary of the ZoDrEx project and an overview of the on-going activities in the Bedretto Underground Research tunnel for Geoenergies. ZoDrEx aims at testing and developing new products and technologies that will increase the technical and economical chances of success in geothermal energy applications. Amongst them, we highlight fluid driven percussion, zonal isolation, corrosion inhibitors and monitoring systems.

6. ACKNOWLEDGMENTS

This work was supported by the Swiss Federal Office of Energy SFOE under the contract SI/501720-01 (Swiss partners) within the ERAnet GEOTHERMICA jointly funded by national Funding Organisations.

REFERENCES

Baisch, S., Carbon, D., Dannwolf, U., Delacou, B., Devaux, M., Dunand, F., Jung, R., Koller, M., Martin, C., Sartori, M., Secanell, R. and Vörös, R. (2009). Deep Heat Mining Basel - Seismic Risk Analysis. SERIANEX study prepared for the Departement für Wirtschaft, Soziales und Umwelt des Kantons Basel-Stadt, Amt für Umwelt und Energie, http://www.wsu.bs.ch/geothermie, 553 pages.

Baujard, C., Hehn, R., Genter, A., Teza, D., Baumgärtner, J., Guinot, F., Martin, A. and Steinlechner, S. (2017). Rate of penetration of geothermal wells: a key challenge in hard rocks, *Proc. 42nd Workshop on Geothermal Reservoir Engineering*, paper SGP-TR-212.

Dahrabou, A., Valley, B., Ladner, F., Guinot, F. and Meier, P. (2017). Optimization of geothermal well trajectory in order to minimize borehole failure. *Proc. American Geophysical Union, Fall Meeting 2017*, New Orleans (USA), abstract #MR13B-0318.

Gischig, V., Bethmann, F., Hertrich, M., Wiemer, S., Mignan, A., Broccardo, M., Villiger, L., Obermann, A.and Diehl T. (2019). Induced seismic hazard and risk analysis of hydraulic stimulation experiments at the Bedretto Underground Laboratory for Geoenergies (BULG). *Report of the Swiss Competence for Energy Research – Supply of Electricity (SCCER-SoE).*

Kastrup, U., Zoback, M.L., Deichmann, N.K., Evans, F., Giardini, D. and Michael., A.J. 2004. Stress field variations in the Swiss Alps and the northern Alpine foreland derived from inversion of fault plane solutions, *Journal of Geophysical Research*, 109, B01402

Keller, F. and Schneider, T.R. 1982. Geologie and Geotechnik, *Schweizer Ingenieur und Architekt,* 24: 512-520.

Labhart, T. (2005). Erläuterungen Zum Geologischen Atlas Des Schweiz 1:25000, Val Bedretto, Atlasblatt 68. ed. Bundesamt für Wasser und Geologie.

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

Lützenkirchen, V., & Loew, S. (2011). Late Alpine brittle faulting in the Rotondo granite (Switzerland): deformation mechanisms and fault evolution. *Swiss Journal of Geosciences*, 104(1), 31-54.

Meier, M. (2017). Geological characterization of an underground research facility in the Bedretto Tunnel, *BSc Thesis*, ETH Zürich.

Meier, P. M. and Ollinger, D. (2016). Monte Carlo flow rate simulations for the multi-stage EGS stimulation concept of the Haute-Sorne pilot project (Canton Jura, Switzerland). *Proc. European Geothermal Congress*, Strasbourg, France.

Sergeev, S. A., and Steiger, R. H. (1995). Caledonian and Variscan granitoids of the Gotthard massif: new geochronological and geochemical results, *Schweizerische Mineralogische und Petrographische Mitteilungen*, 75, 315-316.

Valley, B., and Evans, K. F. (2009). Stress orientation to 5 km depth in the basement below Basel (Switzerland) from borehole failure analysis". *Swiss Journal of Geosciences*, 102(3), (2009), 467–480. doi:10.1007/s00015-009-1335-z