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Eight years of geoenergy research in SCCER-SoE

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Zusammenfassung

Ende 2020 kamen die acht Schweizer Kompetenzzentren für Energieforschung (SCCER) zum Abschluss. Diese betrachteten die wesentlichen Aspekte des zukünftigen Energiesystems, wie Gebäude, Mobilität, Stromnetze usw. Eines der SCCER (SoE – Supply of Electricity, www.sccer-soe.ch) hatte das Ziel, die Forschung im Bereich der Geothermie voranzubringen. Diese könnte als nahezu unerschöpfliche einheimische Energiequelle einen wichtigen Beitrag in den Bereichen Strom und Wärme leisten. Ein weiteres Ziel war die Erschliessung von unterirdischen Lagerstätten für CO2, auch hier leistete das SCCER-SoE wichtige Beiträge.

Der vorliegende Bericht fasst die wesentlichen Erkenntnisse unserer Forschung zusammen. Die grösste Herausforderung jeder geothermischen Aktivität ist das in der Regel unzureichende Wissen über die geologischen Strukturen im Untergrund. Die GeoMol Datenbank von swisstopo unterstützte die geothermische Exploration im Sedimentbecken unterhalb des Schweizer Mittellands. Wasserführende Strukturen innerhalb des Sedimentbeckens, sog. Aquifere, wurden in Demonstrationsprojekten in Genf und Bern durch Tiefenbohrungen weiter untersucht, in diesem Fall mit dem Ziel einer saisonalen Speicherung von Wärme im Untergrund.

Unterhalb des Sedimentbeckens schliesst sich der kristalline Untergrund an. Dort finden sich in der Regel keine wasserdurchlässigen Schichten, die sog. Permeabilität muss künstlich erzeugt werden. Dies kann durch kontrolliertes Einpressen von Wasser erfolgen, wodurch entweder existierende oder neue Bruchnetzwerke geschaffen werden. Entscheiden dabei ist, das Risiko induzierter Erdbeben zu minimieren. Entsprechende Strategien wurden und werden in unterirdischen Feldlaboren in Grimsel und Bedretto untersucht.

Schliesslich wurde auch das Potenzial der unterirdischen CO2 Speicherung in Schweizer Sedimentbecken untersucht. Frühere Schätzungen mussten deutlich nach unten korrigiert werden. Das bedeutet einerseits, dass eine weitergehende Exploration der Schweizer Untergrund dringend nötig ist – sowohl für die Geothermie als auch für die CO2-Speicherung. Andererseits muss die Schweiz alternative Wege der CO2 Speicherung im Ausland entwickeln.

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1 Introduction

The eight Swiss Competence Centers for Energy Research (SCCER) were launched in 2013 with the aim to strengthen the energy related research in Switzerland and to improve the scientific and technical basis for the Energystrategy 2050. One key element was the replacement of nuclear power by renewable sources, mostly by hydropower, photovoltaics and wind but also by adding geothermal electricity production to the mix. The obvious advantage of the latter technology is the capability to deliver baseload generation, similar to nuclear power plants. The SCCER Supply of Electricity (SoE) aimed at the two key technologies, hydropower and geothermal. This paper gives an overview on the achievements in the geothermal field. Here we consider the full spectrum of usage, including also the extraction and seasonal storage of heat, and in addition the permanent storage of CO2 in the subsurface.

The target of the geoenergy activities was to provide scientific understanding and practical tools to support industry's exploration for and exploitation of geoenergy in Switzerland. We covered various aspects from base technology development to pilot and demonstration projects. The most promising type of geothermal resources for power production in Switzerland are deep Enhanced Geothermal Systems (EGS). The key question here is how reservoir permeability can be successfully, reproducibly, and safely enhanced by hydraulic stimulation at several km depth to guarantee commercially relevant circulation rates. Consequently, a major focus was on experimental and theoretical research on hydraulic stimulation methods. Hydraulic stimulation was demonstrated on different scales within two P&D projects, first in the Grimsel lab, later in the Bedretto laboratory.

The supply of geothermal energy for direct heating and interim heat storage in aquifers have received attention as a means to avoid and minimize CO2 emissions from buildings. SCCER-SoE researchers were involved in a major program of the Canton of Geneva on the potential for direct hydrothermal heat use and storage, utilizing this opportunity as a stepping stone towards developing geothermal power production in Switzerland [24]. Last but not least, we evaluated the potential of regional aquifers for CO2 storage that will be needed to achieve the net-zero target of Switzerland. This requires identification of sufficiently porous and permeable rock formations at depth that are capped by impermeable seals.

2 Prospection, exploration and drilling

GeoMol. Geothermal energy can only be exploited at reasonable costs if there is sufficient knowledge on the subsurface. The 3D geological model of the Swiss Molasse Basin (GeoMol) [31] created by swisstopo provides a simplified representation of the subsurface of the Swiss Midlands located between the Jura Mountains to the north and the Alps to the south (see Figure 1). The model features the major fault systems and 12 basin-wide geological horizons based mainly on geophysical data, wells and surface geology.

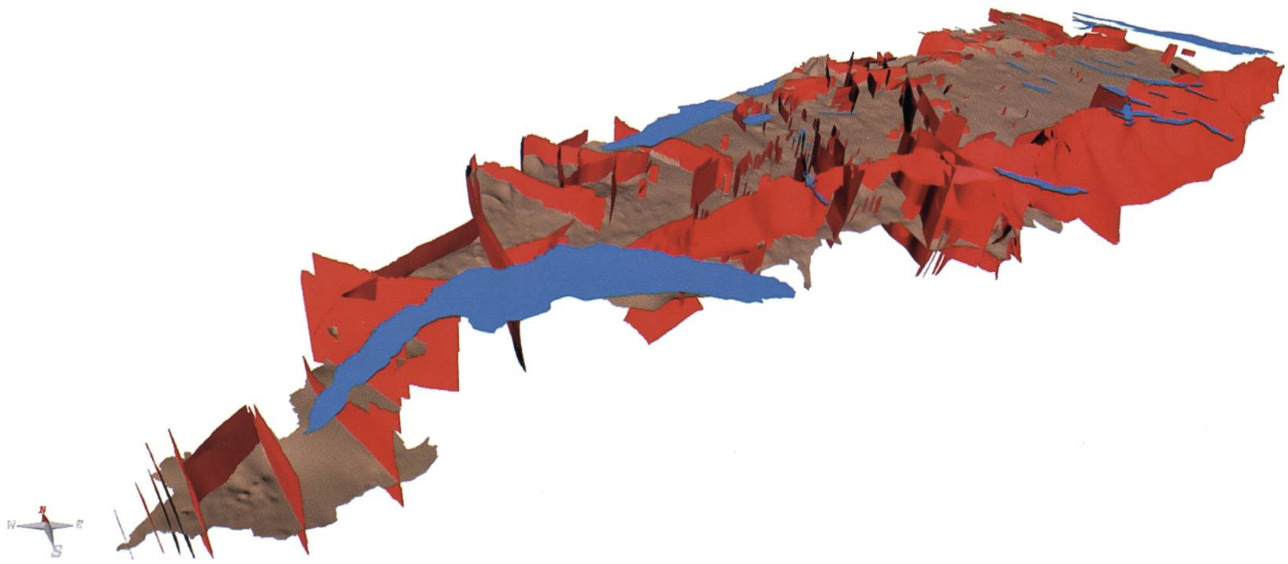

Fig. 1: Representation of the «Top Dogger» surface (brown) and fault zones (red) from the GeoMol19 model. View is from the SSW to NNE with a 3x vertical exaggeration. The model terminates along the southern edge of the Jura Mountains to the north, the Alps to the south, Lake Constance to the NE and Lake Geneva & France to the SW.

The anticipated use of the model lies primarily in the early phases of geothermal and and CO2 storage exploration as well as the visualization of the subsurface. While it cannot provide detailed information, we are aware of the model being used in the planning stages of six different geothermal projects. The uppermost layer of the model – Top Bedrock – came to use in three projects related to transporta-tion. Academia has also shown interest in the model and has applied it in three studies regarding subsurface exploration. GeoMol can be accessed through https://viewer.geomol.ch.

Fairways analysis for deep geothermal in Switzerland. Subsurface models like GeoMol provide opportunities for identifying geothermal plays and assessing the suitability for geothermal development. Valley & Miller propose such an analyzes in a quantitative play-fairway approach for Switzerland [27]. The objective of the study is to value the available data within a systematic, evolutive quantitative framework. After a first review of the available data sets, a conceptual classification of those geological and structural settings was proposed, that are favorable for deep-seated fluid circulation in Switzerland. Available data was used to determine best-estimate stress models, which are then used to compute slip and dilation tendency on the main faults identified in the database. All available information was combined to provide quantitative mapping of the fairway score (favorability maps) for geothermal exploration.

The results obtained show that with the available data, sharp contrasts in favorability can be high-lighted on the Swiss plateau and these contrasts can guide exploration (see Figure 2). However, these results should be considered preliminary because of our simplifying assumptions, the paucity of data, and the scale of Switzerland which may not be appropriate for local scale exploration planning. Particularly, an attempt should be done to calibrate and validate the approach using appropriate data assimilation techniques. The difficulty is that direct evidence from geothermal projects or deep drilling on the Swiss plateau are sparse. The methodology and approach for generating favorability maps, however, can be applied in future studies with the availability of additional data, more sophisticated modeling and analysis, and findings from future exploration projects. Such should thus be seen as dynamic product that should evolve and be updated when new data and knowledge are collected.

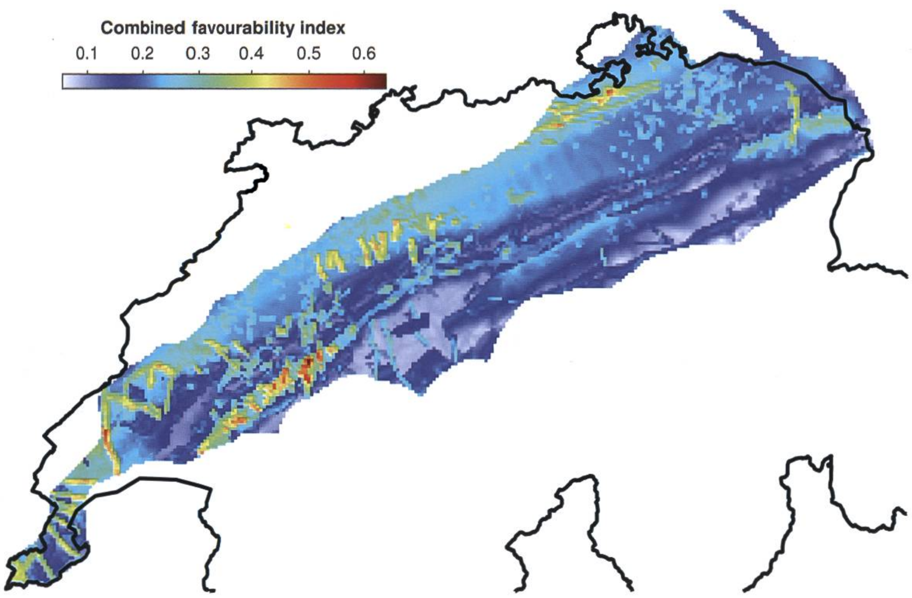

Fig. 2: Combined favorability index map for the target at 120 °C [26]

Wellbore trajectory optimisation workflow. An important performance factor for drilling is to ensure the stability of the borehole. When a borehole is unstable, more material needs to be carried back to the surface by the drilling fluids and rock fragments that are released to the borehole environment can cause operation difficulties like stuck pipes. Such difficulties generate costly delays. In addition, wellbore failure results in out of gauge boreholes with irregular wall geometries. This generates further difficulties for cementation and completion.

Borehole stability is a well-known issue in the oil and gas industry and solutions exist for this specific industry where many boreholes are drilled mostly in sedimentary rocks. Optimal drilling parameters for a field are estimated by trial and error on many wells. For the deep geothermal industry, the conditions are very different: boreholes are drilled in crystalline rocks with a failure mode that often differs from the sedimentary conditions encountered in the oil & gas industry. In addition, only few boreholes are drilled and they must be stable to enable the high rate production completions required for geothermal projects. The knowledge development by trial and error over many boreholes is not an option.

In a collaborative project between industry (GeoEnergie Suisse AG) and academia (University of Neuchâtel), a wellbore stability estimation workflow adequate for deep geothermal boreholes was developed. At the heart of the workflow, a systematic parameter estimation approach allows to calibrate both the stresses and the strength simultaneously. The approach is not delivering a unique solution but the range of possible parameters that are based on observations. It calibrates both the overall trends of strength and stresses – what we call first order calibrations – and the variability around these trends, i.e. second order calibrations. The output of these models give us a unique insight in the stress conditions and variability in the earth crust. They allow also to make stochastic predictions for subsequent wellbore sections and to optimize wellbore trajectory and drilling parameters to keep the risk of wellbore failure under an acceptable limit. To facilitate its deployment, the workflow has been implemented in a software tool that guides the user through the required workflow steps (see Figure 3).

3 Creation of permeability in crystalline rocks: from Grimsel to Bedretto

Developing and engineering geothermal reservoirs at depth has proven to be notoriously difficult in the past with failed deep geothermal projects outnumbering the successful ones. One problem lies in the challenge to establish fluid pathways between injection and production boreholes with optimal heat exchanger characteristics, while keeping induced seismicity below a harmful level. The outcomes of hydraulic stimulation operations – the key method to enhance the hydraulic conductivity and connectivity of the reservoir rock – has often been unpredictable. Thus, exploitation of deep geothermal energy relies on a more fundamental understanding of the stimulation processes and the improved ability to control them. Our current understanding of the seismic, thermo-hydromechanical and chemical processes during stimulations rely mostly on either decimeter-scale laboratory experiments or full-scale reservoir development projects. At the reservoir scale, indirect and sparse observations are usually recorded kilometers from where processes take place, and control of the stimulation processes is limited. Limited controllability and accessibility are eliminated at the laboratory scale, but scalability to the full-scale becomes an issue (Figure 4). Recently, worldwide initiatives attempt to overcome these research obstacles by bridging these scales with underground

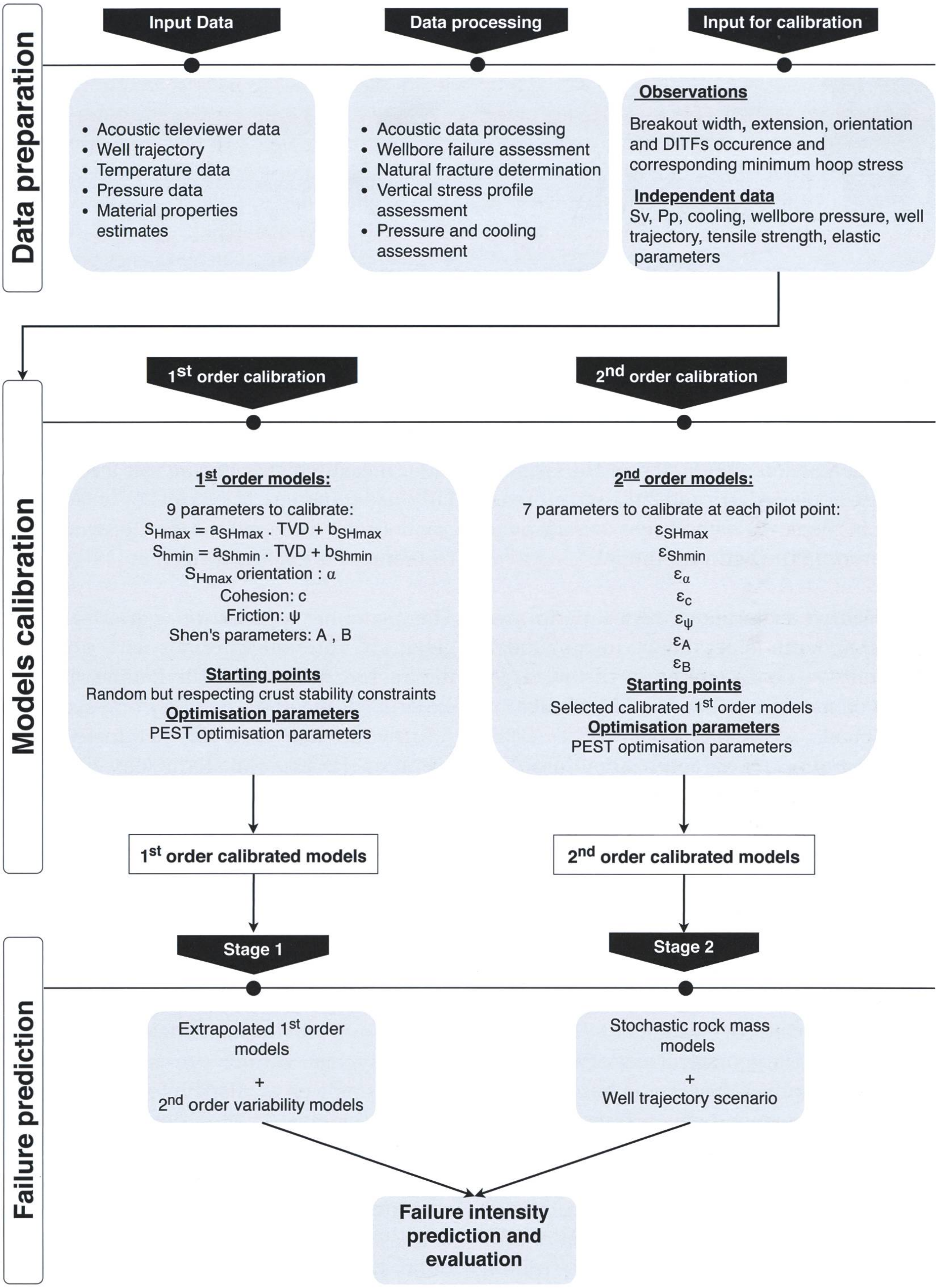

Fig. 3: Steps of the Deep Geothermal Well Optimisation Workflow (DGWOW) application.

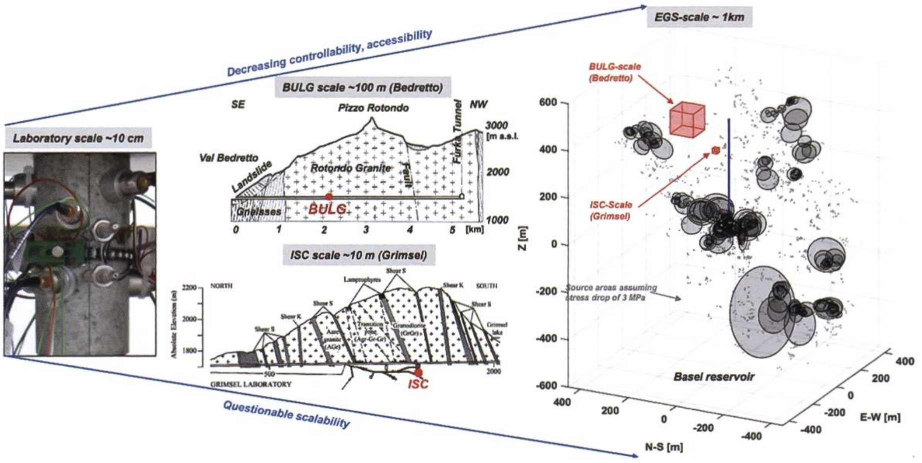

Fig. 4: Research on stimulation processes acts on different scales and at different depths.

in situ experiments, where process understanding and technological developments are advanced at the 10 to 100 m scales (Figure 4, [11]). As part of the SCCER-SoE, such experiments were conducted at the Grimsel Test Site between 2015 and 2017 and more recently in the newly established underground laboratory in the Bedretto tunnel.

The Grimsel experiment series performed at ~450 m depth in crystalline rock included an extensive characterization of the target rock volume, twelve hydraulic stimulation experiments, as well as a post-characterization program [1]. Characterization aimed at establishing a detailed 3D model of geological structures and rock properties, the stress field, and the hydraulic properties. Such a model provides indispensable information for both planning the stimulation experiment and analyzing the stimulation observations. Combining several methods for each characterization aspect was key to alleviate ambiguities and to improve validity of the results. For instance, the geological model was based on tunnel mapping, systematic borehole logging as well as ground penetrating radar and 3D anisotropic seismic tomography [19] [5]. Stress characterization included both stress relief methods, hydraulic methods, microseismic monitoring and numerical modeling [20] [12]. Hydraulic characterization involved single- and cross-hole tests [2][3], and a range of tracer tests [14][15][16][17]. At the same time, the characterization phase was a unique chance to explore innovative methods that go well beyond state-of-the-art: e.g. the utilization of DNA tracers [14]; 3D anisotropic seismic tomography [6]; time-lapse radar measurements during salt tracer tests [10]; using numerical models of anisotropic elasticity for the analysis of the overcoring tests for stress characterization [19]; etc.

The hydraulic stimulation experiment targeted six borehole intervals with pre-existing fracture so to induce hydroshearing (HS experiment in February 2017), and six intact (i.e. fracture-free) intervals to initiate hydrofractures (HF experiments in May 2017). For the six HS and the six HF experiments each, a standardized injection protocol was utilized, so that the variability in the observations must primarily originate from local conditions and not from the injection strategy. The stimulations were monitored with extensive high-resolution and multi-parametric sensor network that included both passive and active seismic monitoring, a deformation monitoring system, various pressure monitoring intervals as well as distributed temperature sensing systems. Thus, a rich dataset could be ac-quired that sheds light on various aspects of hydraulic stimulations with an unprecedented level detail. From the analysis of this vast dataset, a range of important insights have crystalized so far, while further analysis is still in progress. Some key results, interpretations and conclusions are summarized in the following (a-n):

a) Creation of new flow paths: Transmissivity enhancement of up to three orders of magnitude and creation of new connections between boreholes – in general the primary goals of hydraulic stimulations – were successfully achieved during the stimulation experiments, as hydraulic characterization before and after experiments revealed [2] [20]. Tracer tests after stimulation showed that the tracers accessed flow paths with larger hydraulic conductivities and thus swept larger volumes [15]. Interestingly, the stimulations did not enhance transmissivity throughout the reservoir; instead the target fractures showed a transmissivity decrease some distance from the injection [3]. In an experiment involving circulation of hot water (i.e. 45 °C warm water in 13 °C rock) longer tracer recovery times indicate that flow might be impeded through thermoelastic effects leading to flow being diverted to the far-field [16]. A detailed analysis of one stimulation experiment [21] showed how flow paths also changed during stimulation: propagation of the seismicity cloud as well as complex pressure and deformation transients revealed that different flow channels have been activated during two subsequent stimulation cycles.

b) Limiting injectivity and transmissivity: Stimulations led to a very variable transmissivity and injectivity increase between experiments with enhancement factors ranging from <10 only to more than 1000. It is noteworthy, that the injectivity after the HS stimulation reached similar values grouping around 1 l/min/MPa (range 0.4 – 1.7 l/min/MPa). Thus, the strong variability is owed to variable initial injectivities (0.0006 – 0.95 l/min/MPa) and not to a variable final injectivity [3]. Initial transmissivities of the HS intervals range from 8.3e-11 to 1.2e-7 m^2/s (>3 orders of magnitude), while the final transmissivities lie between a narrow range of 5.5e-8 to 2.3e-7 m^2/s (0.6 orders of magnitude). Similar observations are made for the HF experiments. The observation raises the questions if the achievable injectivity/transmissivity is a characteristic of the reservoir rock mass, possibly mediated by the ambient stress field or geological properties. The existence of such a limiting transmissivity would have important implications for full-scale reservoir stimulations. While transmissivity (and thus productivity) of a single stimulated volume is limited, more productivity could be attained by stimulating multiple adjacent intervals, e.g. through zonal isolation stimulations.

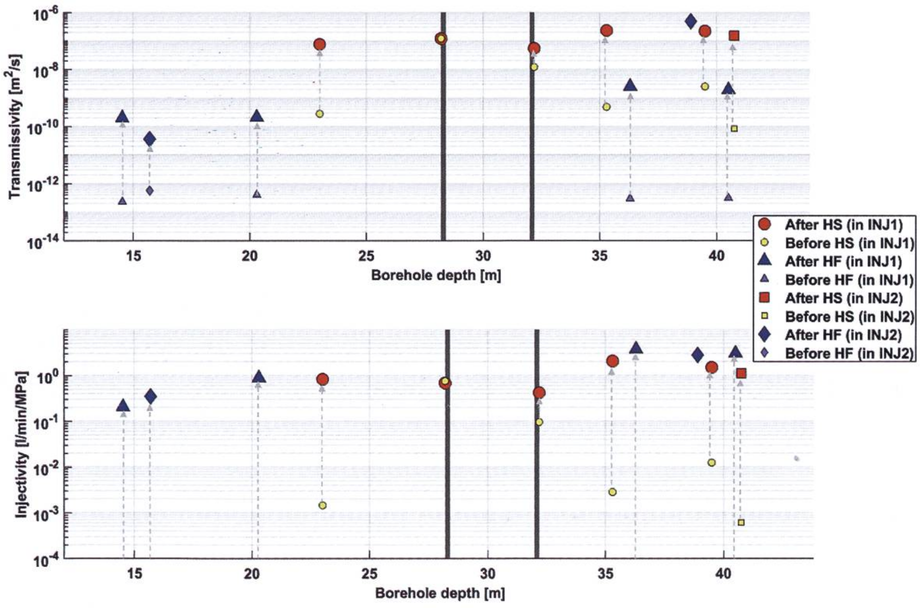

Fig. 5: Changes in transmissivity and injectivity during HS and HF experiments.

c) Channelized heterogeneous flow: Only for few experiments (4 out of 6 HS experiments) and only at few monitoring locations, high-pressure signals away from the injection point (i.e. «pressure fronts») were observed, even though many non-linear pressure diffusion models of stimulations proposed in literature predict them [21]. We interpret the absence of such pressure signals as channelized flow within the fractures or fracture intersections. Analysis of hydraulic tests prior to the stimulations [2][3] support a conceptual model of strongly heterogeneous and possibly channelized flow field that is characterized by a fractional flow model with a flow dimension of 1.3 – 1.5 (i.e. between linear flow and radial flow symmetry). Further, the flow field is dominated by either fractures of the damage zone around the core of shear zones, where permeability and fracture density scale with a simple power law, or by single fractures that link subparallel shear zones, for which simple permeability/fracture density–relationships break down.

d) Stress heterogeneity: Similar as observed in deep reservoirs (e.g. [26]), the stress field orientation was found to rotate and the stress magnitudes to decrease towards the main shear zones in the target rock volume [19]. Both the HF and HS experiments imply that the shear zones may separate different stress compartments [9][20][7] leading to a difference in the stimulation characteristics. Meter-scale stress heterogeneity possibly leads to dramatic changes of the source mechanism along adjacent fractures as was observed from seismicity distributions and moment tensors of one HS experiment [29]. Transient stress redistribution during stimulation, evident from the complex deformation patterns, is superimposed on the heterogeneous static stress field and gives rise to diverse fracture interactions and dislocation modes that include opening and shearing as well formation of new fracture off pre-existing stimulated fractures. Often several adjacent fractures are observed to open simultaneously until one fracture opens faster and thus suppresses further opening or even closes neighboring fractures.

e) Mixed-mode stimulation: Various observations indicate that mode I (fracture opening) and mode II/III (slip) occur concurrently both during HS and HF stimulations as predicted by [23]. Formation of a new fracture was observed during a HS dominated experiment from seismicity that propagated away from the main seismicity cloud and from a strain sensor that opened by almost 400 µm [29]. Similarly, various HF experiments show that hydrofractures start out as clear mode I fractures, but quickly connect to the pre-existing fracture network, where mode II/III dislocations become evident [8] [9]. During HF, often not a single but several fracture strands propagate simultaneously. Similarly, during HS several fractures are pressurized and open together, but start competing with each other through stress interaction.

f) Noble gas release accompany fracturing: During the HF experiments an innovative in-situ gas equilibrium membrane inlet mass spectrometer was able to monitor transient anomalies in the helium and argon concentrations [25]. The anomalies are interpreted as originating from Helium and Argon-enriched fluids that were trapped in the pores of the rock mass and released by through fracturing processes. These intriguing and unique results demonstrate that geochemical monitoring complementing thermo- and hydromechanical observations may be of great value to understand stimulation processes.

g) Primary and secondary deformation field: Deformation and pressure observations from various distances around the stimulated rock volume suggest two deformation fields [20][7]. In the near-field of the stimulation, a so-called «primary field» exhibits the full complexity of the stimulation processes with transient and spatially variable extensional and compressive strain produced by fracture normal opening and slip dislocation and the stress redistribution related to these processes. These processes are primarily governed pressure diffusion. In the far-field, a «secondary field» is observed, which shows both more systematic compressive and extensional deformations that exceed deformation magnitudes that are expected from pressure diffusion. Here, far-field poro-elastic volumetric deformations govern.

h) Poro-elastic response: The poro-elastic near- and far-field reservoir response associated with high pressure fluid injection was studied in six fluid injection experiments at the Grimsel Test Site [7]. Based on the lag time and magnitude of pressure change obtained from pore pressure time series showed a near- and far-field response. The near-field response is associated with pressure diffusion. In the far-field, the fast response time and the pressure decay are related to effective stress changes in the anisotropic stress field. The experiments showed, on an unique spatial and temporal resolution, that fluid pressure perturbations around the injection point are not limited to the near-field and can extend beyond the pressurized zone.

i) Size of the stimulated volume: The aforementioned observation of a diffusion-controlled near-field and a poro-elasticity-controlled far-field raise the question of how the stimulated volume is to be defined. The question becomes even more compelling, because it was observed that the seismicity cloud in our case was much smaller than the pressurized volume estimated from 4D seismic tomography [5]. Based on clear correlations between seismic velocity and pressure found at the pressure monitoring locations, it was possible to delineate the volume that is likely affected by elevated pressure or – in the far-field – is compressed through volumetric expansion in the near-field. The seismicity clouds have been much smaller that the implied pressurized volumes. Furthermore, observations of transmissivity decreases some distance away from the stimulated intervals [3] additionally question if the pressurized volume or the seismically active volume encompass a rock mass volume with enhanced transmissivity.

j) Aseismic versus seismic deformation: A potentially larger stimulated volume as illuminated by the seismicity cloud may indicate that a large portion of the deformation – also the permanent one remaining after the stimulation – has occurred aseismically. In fact, a comparison of the total seismic moment per experiment with the total moment inferred from fracture dislocation magnitudes observed at the boreholes wall from acoustic televiewer images support the interpretation that seismic deformation accounts for only a small fraction of the total deformation [28]. Furthermore, fracture dislocation observed at various deformation sensors was found to be sometimes accompanied by seismicity and sometimes not [20].

k) Variable stimulation outcomes in a small rock volume: Generally, stimulation outcomes were found to be surprisingly variable within the relatively small experimental volume and defined by very local rock mass conditions like fracture orientation and architecture, hydraulic conductivity and connectivity or stress conditions. Apart from the aforementioned variable transmissivity changes per experiment, the seismic productivity, spatial distribution and magnitude distribution (expressed as a- and b-values) has been very diverse (Figure 6): for instance, while for one experiment only about ~100 seismic events were detected, more than >5000 events were located for another one [28].

l) Predictability of induced seismicity: The variability of seismicity characteristics between experiments is so large that predicting seismicity (or seismic hazard) for one experiment based on the in-formation from another seems futile. This raises the question to

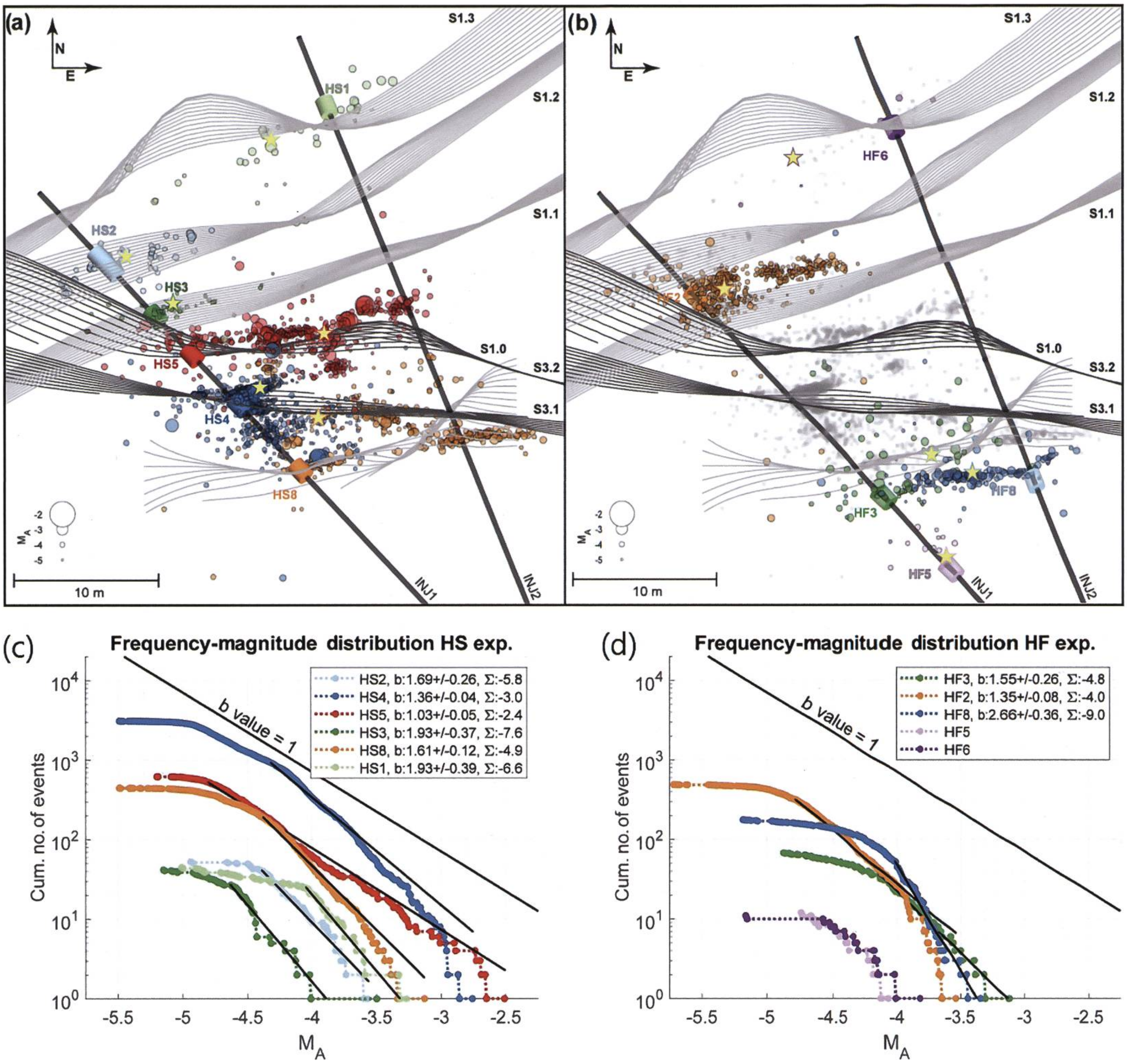

Fig. 6: Seismicity clouds of all stimulation experiments in map view. a) HS experiments, b) HF experiments [28]. c) and d) Magnitude distributions of all experiments.

what degree a priori forecasts of seismicity are possible at a certain experimental scale but also across scales. The meter-scale complexity found for the most seismically active experiments further challenges the predictability towards larger scales [29]. Moreover, this experiment exhibits an extraordinary tendency for repeating earthquakes that even lead to a partial breakdown of the anticipated Gutenberg-Richter distribution ([30] Experiment HS4 in Figure 6), which is the basis for seismic hazard forecasting. Here, further experimental work on different scales must tackle the question on scale-invariance of seismicity from the meter to the kilometer-scale.

m) A hypothetical open-hole stimulation: As most past reservoir development projects performed large open-hole stimulations, it is worth considering the following thought experiment [28]: What would have happened if instead of several 1 – 2 m long intervals, an extended borehole section including covering all intervals would have been stimulated at once? Most likely, the flow would have entered the most transmissive fractures. However, these correspond to the fractures of those intervals, for which the transmissivity and injectivity changed only marginally, and, at the same time, which were by far the most seismically active ones. Thus, an open-hole stimulation may have produced little gain in transmissivity/injectivity but a lot of seismicity. Stimulation using zonal isolation (i.e. of several selected intervals as done in our experiment series) may be a more advantageous strategy in terms of transmissivity gain and seismic hazard, if already transmissive and seismically active structures can be avoided. However, our experiments also indicate that hydraulic communication between adjacent stimulation zones is conceivable making it difficult to fully avoid hydraulically and seismically active fracture systems.

n) From Grimsel to Bedretto: The Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG) (http://www.bedrettolab.ethz.ch) has been developed in the Bedretto tunnel located in Bedretto, Ticino. The tunnel is a 5218 m long, connecting the Furka Base Tunnel and the Bedretto valley at its south portal. The tunnel axis runs N43°W, with a gentle slope of 0.2-1.7% down SE. The elevation at the tunnel south portal and the junction with the Furka Base Tunnel are 1480 m and 1562 m a.s.l., respectively. Correspondingly, the overburden of the tunnel gradually rises to a maximum of 1500 m. It has thus been identified as to provide ideal conditions for underground in-situ experiments related to geosciences and geoenergies. The tunnel of about 5 km length provides ventilation to the railroad tunnel connecting the Gotthard area to the Valais. Between TM2000-2100, the tunnel has been exca-vated and retrofitted into a 6 x 3 m^2 niche. The main focus of the BULGG is the research on enhanced/engineered geothermal Systems (EGS) and induced seismicity with a main focus on hydraulic stimulation, fluid circulation and seismic hazard mitigation.

Experiments are continued within the SFOE-funded project VLTRE. It addresses questions associated with the validation of stimulation procedures and sustainable utilization of heat exchangers in the deep underground. Stimulation concepts are tested in-situ while hydro-seismo-mechanical key parameter are monitored at a high spatial resolution, the objective being to answer following questions:

- Which stimulation concepts are appropriate for enhancing the permeability by orders of magnitudes while minimizing induced seismicity
- What are the relationships between the hydro-mechanical response, the stimu-

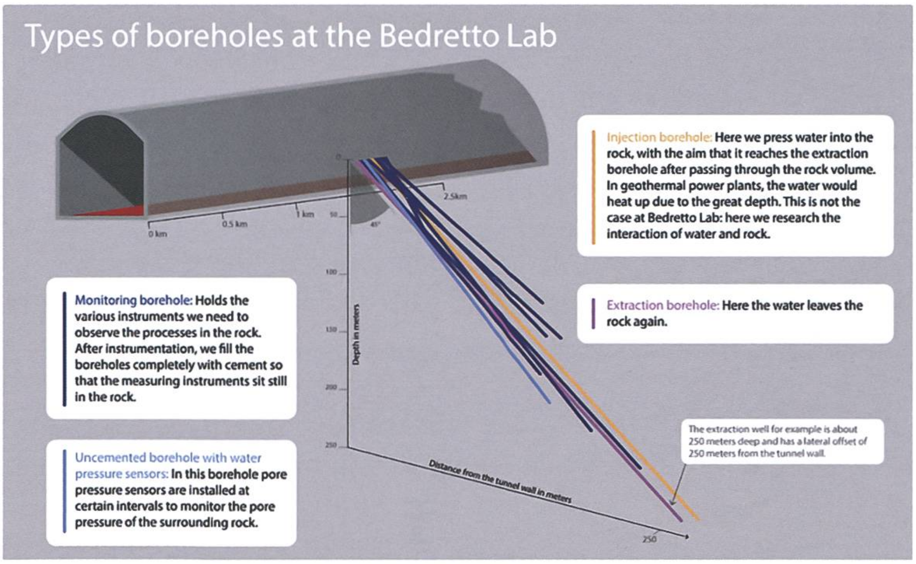

Fig. 7: Arrangement of boreholes and sensors for the Bedretto reservoir project.

lation concept, permeability creation, effective porosity and induced seismicity
- How can micro-seismicity be minimized
- What are the heat exchanger properties of the reservoir.

Other projects from various funding sources (EU, BFE, SNF and ETHZ) have similar or the same objectives as VLTRE. We joined these efforts to create the Bedretto Reservoir Project (BRP) which shall be the first fully controlled EGS at 300 m scale and 1.2 km depth. The main projects contributing to the BRP are the Geothermica project ZoDrEx and H2020 Destress. During 2019 and 2020, an array of injection and monitoring boreholes were drilled and equipped with a multitude of sensors (see Figure 7). Stimulation have started end of 2020 and will be reported in the years to come.

4 Heat production & storage and sedimentary basins

GEothermie2020. This geothermal development program driven by Services Industriels de Geneve (SIG) and the Canton of Geneva, aims at implementing geothermal energy in the Canton of Geneva with a stepwise approach starting from shallow installations to gradually move toward deeper targets to cover 20% of the cantonal heat demand by 2035. SCCER-SoE researchers from University of Geneva actively contributed to the prospection phase [24]. Two wells have been drilled into deep reservoirs in the Mesozoic carbonate sequence. The Geo-01 well is 744 m deep and produces at present 50 l/s of hot water at 33 °C which corresponds to 20-30 GWh of thermal power suitable to supply 2'000-3'000 households. A second well (GEo-02) reached ca 1400 m in depth. This well encountered carbonate reservoir at high hydrostatic pressure but lower permeability than expected and some differences in the predicted stratigraphy. The well will be re-entered, sampled and tested for a long period of time in order to assess well deliverability and reservoir connectivity. The mixed results obtained by the drilling campaign to date attest for the importance of continuing the efforts in exploring the subsurface in order to reach a satisfactory level of understanding to ensure high chance of drilling success.

The effectiveness of exploration approaches, concepts and models developed for the Geneva Basin – thanks also to other projects such as GECOS, UNCONGEO and HEATSTORE – will provide a solid framework to assist the continued effort to explore for direct heat production and subsurface storage potential in sedimentary basins at shallow to medium depths and demonstrate again the great potential and value of geothermal energy amongst the renewable energy portfolio available in Switzerland.

HEATSTORE aims at developing High Temperature (~25 °C to ~90 °C) Underground Thermal Energy Storage (HT-UTES) technologies, which are crucial for the energy system transformation to be successful. Storing heat underground will allow to manage variations in heat supply and demand and store energy for use in winter. In Switzerland, HEATSTORE focuses on two demonstration projects for High Temperature Aquifer Thermal Energy Storage (HT-ATES) in Geneva and in Bern. Scientists from the Universities of Geneva, Bern, Neuchatel and the Swiss Federal Institute of Technology in Zurich (ETHZ) are working on this project in collaboration with industrial operators (Services Industriels de Geneva SIG and Energie Wasser Bern EWB) within the framework of the SCCER-SoE to assess the feasibility of HT-ATES systems in Switzerland.

The scientists will combine (a) the energy system configuration in terms of excess heat availability and heat demand, and (b) the subsurface conditions to produce a set of

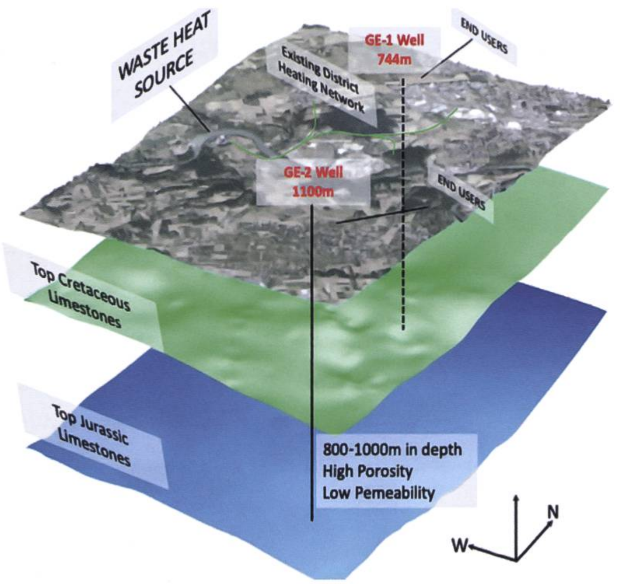

Fig. 8: Illustration of the Geneva project aiming to assess the heat storage potential for the devel-opment of an HT-ATES system connected to a waste-to-energy plant operated by Services Industriels de Genève (SIG).

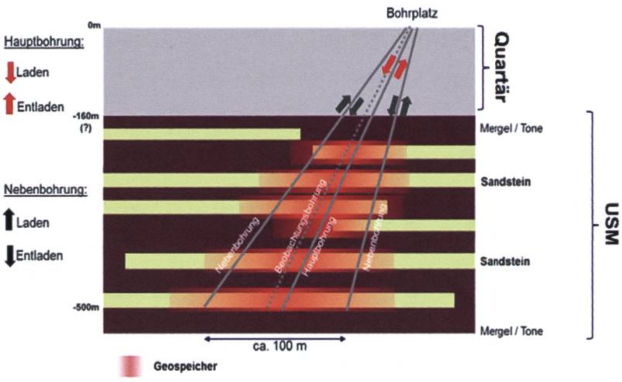

Fig. 9: Schematic representation of the pilot project in Bern aiming to store waste heat from the nearby Bern-Forsthaus power plant.

ATES systems scenario models. The results allow the scientists to assess the technical feasibility of HT-ATES systems at the two pilot sites. The models are calibrated according to the data resulting from field operations carried out by the industrial partners to eventually 1) define the most promising scenarios, 2) evaluate the value of the new information provided, 3) evaluate the economic performances of the identified scenarios and 4) link to boundary regulatory and environmental conditions to assess the overall technical, economic, legal and social feasibility of the projects.

HEATSTORE has the objective of accelerating the uptake of geothermal energy in Switzerland by: (i) Advancing and integrating ATES systems under different geologic conditions and energy system configurations, (ii) Providing a means to maximize geothermal business case performances, and (iii) Addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

The GECOS (Geothermal Energy Chance of Success) project, supported by Innosuisse (Project n. 26728.1 PFIW-IW), SIG and Geo2X aims at improving the way exploration inves-

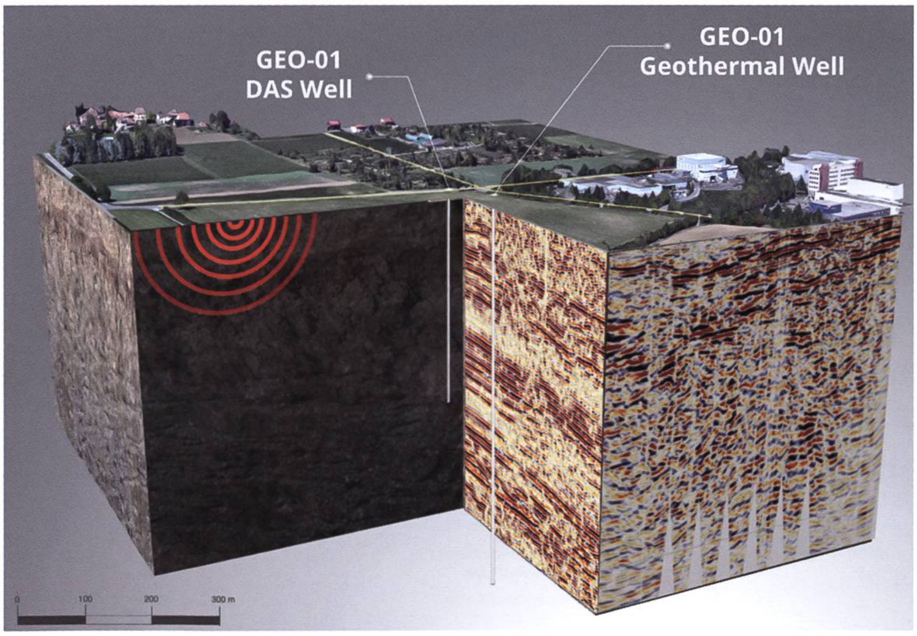

Fig. 10: Cartoon showing the multi-component approach developed in GECOS for high resolution geophysical data acquisitions.

tigations are designed and implemented in the context of exploration and development of geothermal resources and underground thermal energy storage (UTES) projects. The GECOS project is based on the need of industrial partners to reduce the uncertainty of subsurface exploration and reduce the risks associated in particular with drilling operations. The Geneva Basin subsurface as well as the whole Swiss Molasse Plateau, shows favourable conditions for geothermal heat production (and storage where possible) from the fractured and karstified Mesozoic carbonates. However, despite being potentially highly productive targets (as demonstrated by the GEo-01 well in Geneva), the uncertainties related to fault architecture, fracture network might still be high despite investing in standard geophysical exploration (i.e. active seismic). Additionally, the Geneva Basin is proven to be an active petroleum system, therefore hydrocarbon occurrence is an element of risk that can hinder the development of geothermal projects if not properly constrained and managed.

Therefore, to provide solutions to solve the mains questions listed above, the main research axes of GECOS are focussing on: 1) Reduction of subsurface uncertainty through the acquisition of high-resolution and cost-effective data such as 3D DAS VSP, S-waves and high-resolution gravity; 2) un-certainty quantification of subsurface data through the integration of geophysical and geological data using geostatistics; 3) reduction of the interpretation times and overall project costs, through the application of machine learning techniques that allows integrating new with already available data and improve the subsurface understanding in cost-effective manner (see Figure 10).

5 Carbon capture and storage

Recent scenarios for achieving net-zero emissions in Switzerland agree that the target cannot be reached with CO2 capture and storage (CCS). A first thorough and comprehensive study on the potential CO2 storage capacity had been carried out within the CARMA project [4]. Five potential aquifer/seal pairs in the Swiss Molasse Basin have been identified as potentially interesting in a depth range of 800-2500 m, the most promising of which is a carbonatic Triassic formation (Upper Muschelkalk) overlayered by a shaly/evaporitic formation (Gypskeuper). The potential of storage on the Muschelkalk alone was estimated to be about 700 Mt of CO2, the total for all five formations was 2500 Mt.

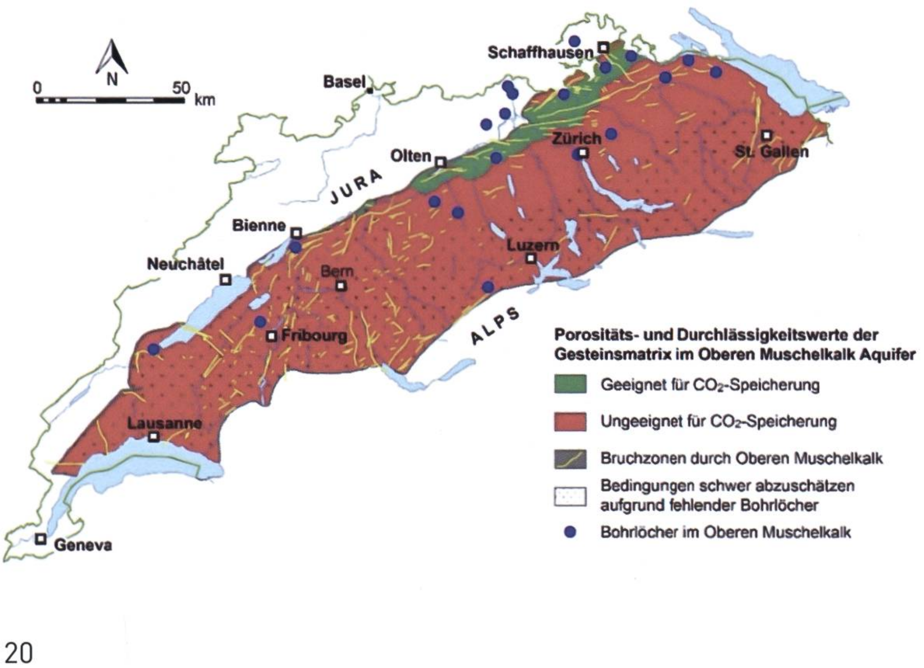

Fig. 11: New map of reservoir properties of the Trigonodus Dolomit (green + red areas) in the Upper Muschelkalk, Swiss Molasse Basin. Green area without faults has properties nominally suitable for industrial-scale gas sequestration. Red area is unsuitable.

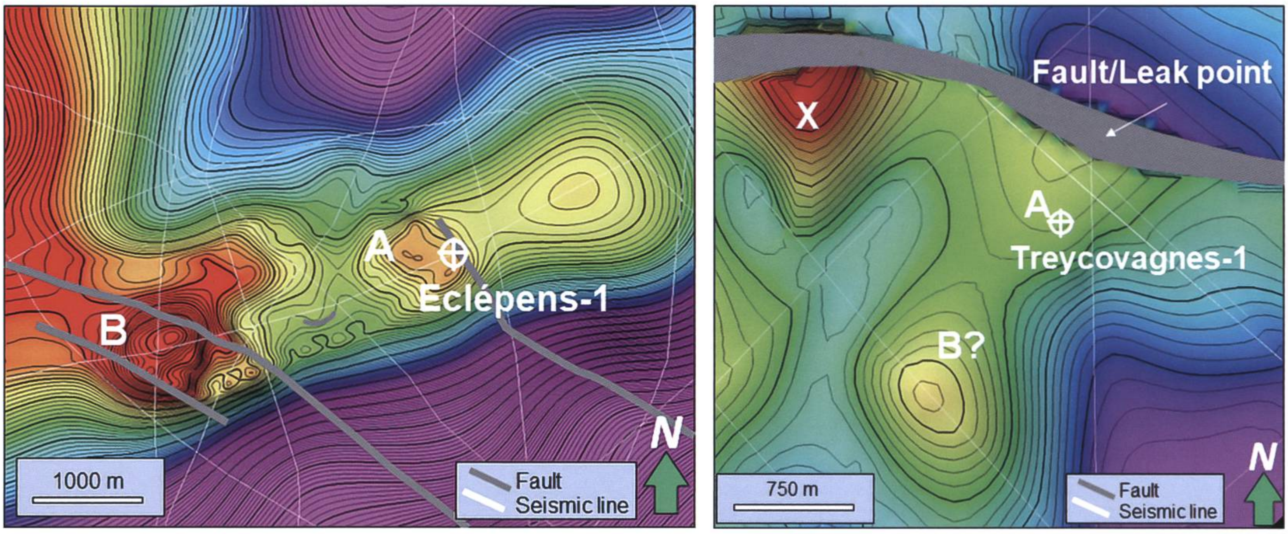

Fig. 12: 3D top reservoir structure of the target interval for storing CO2 at the Eclépens and Treycovagnes sites.

Within the SCCER-SoE these first estimates were revised by the same authors, on the basis of new data acquired in the last decade. The main factors determining whether an aquifer formation can serve as an industrial-scale reservoir for gas storage are rock-matrix porosity, rock-matrix permeability and the porosity and permeability of any fracture networks. Current industrial techniques require rock-matrix porosities >10 vol.% and permeabilities >10 mD to efficiently inject gas. Considering these factors, the most promising part of the Upper Muschelkalk is the 20–30 m thick layer known as the Trigonodus Dolomit, which is hydraulically sealed above by the Gipskeuper layer. The Trigonodus Dolomit occurs throughout the Swiss Molasse Basin between <100 m depth in the north and >5000 m in the south (combined green and red areas in Figure 11).

Regarding gas storage, it appears that the Trigonodus Dolomit exceeds the minimum useful matrix porosity and permeability values only at depths <1130 m. Applying the technical limit of 800 m minimum depth for gas injection, a feasible depth window of 800–1130 m results. This combination of depth and matrix properties is attained only within the green area (640 km^2) in Figure 11, between Olten and Schaffhausen. This area is cross-cut by discrete faults (yellow lines in Figure 11), which may or may not be potential gas-leakage pathways through the overlying Gipskeuper seal. Some of the faults are flanked by networks of fractures that enhance porosity and permeability of the Trigonodus Dolomite and that do not breach the overlying Gipskeuper seal, but whose distribution is difficult to quantify. The theoretical CO2 storage capacity of the unfaulted green regions (300 km^2 at 5.5% injection efficiency) is 52 Mt. The red area in Figure 11 is unsuitable for CO2 storage.

The next steps were taken within the Eranet-ACT project Elegancy. A site screening process was defined which involves quantifying the key geological properties necessary for CO2 injection by identifying and quantifying the key parameters (i.e. reservoir storativity, sealing integrity etc.) and assessing their uncertainties in order to predict and mitigate the risk associated with them [22]. The proposed workflow was tested for three sites in sub-regions of the Swiss Molasse Basin with moderate to high data density and subsurface knowledge (well penetrations with good quality logs and/or seismic and a pre-existing knowledge of the geological structure with storage and sealing potential.

Figure 12 shows a 3D view on the upper boundary of the potential reservoir for two

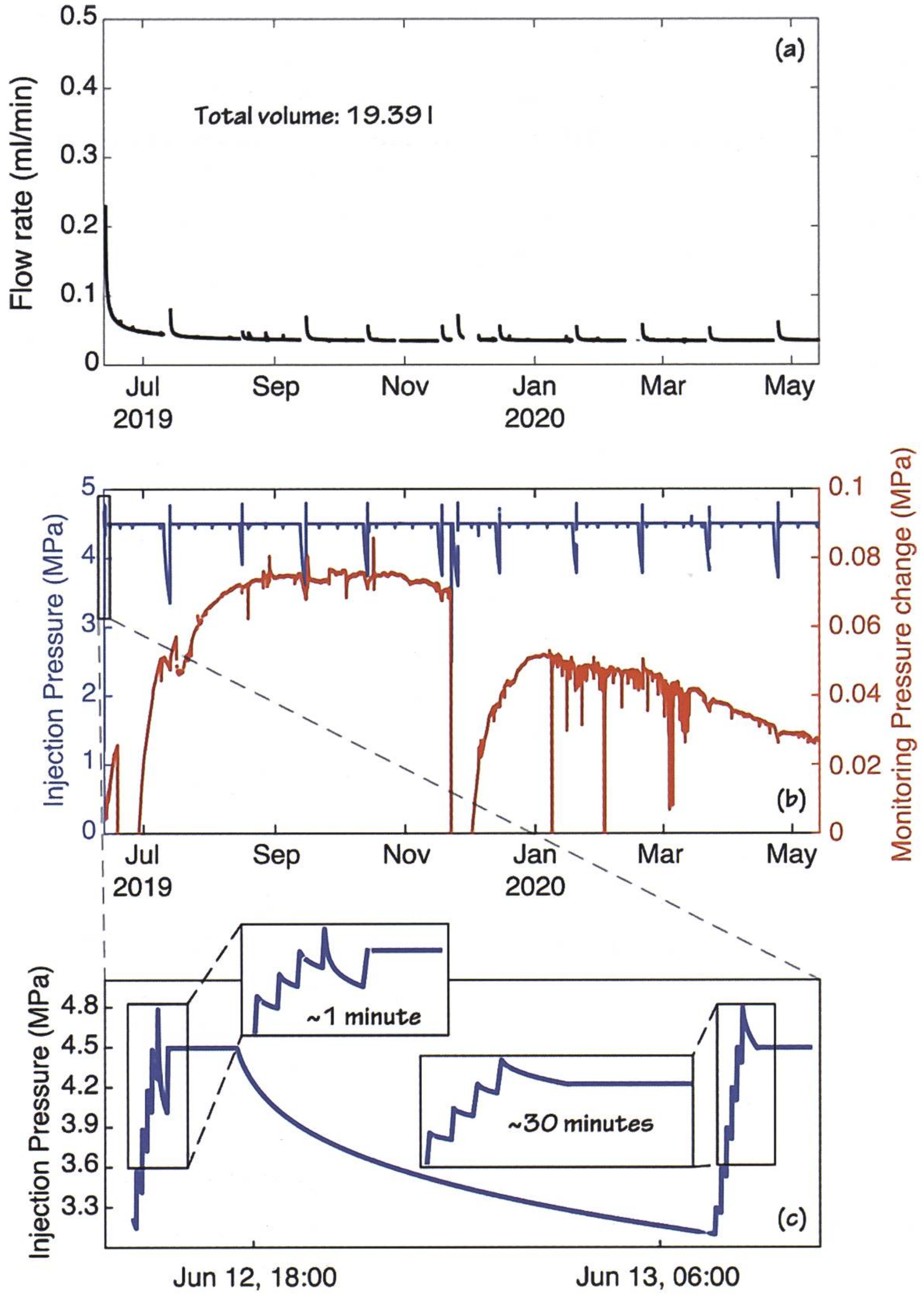

Fig. 13: (a) Flow rate recorded during the one year-long injection of CO2 saturated fluid. (b) Pressure at injection interval (blue line) and pressure changes recorded at the monitoring interval (red line). See Figure 1b for relative distances. (c) Zoom on injection pressure in the first days of injection.

of the sites. The red areas indicate traps that can be used to store CO2. Unfortunately, the combined storage volume for all three sites was found to be less than 1 Mt of CO2. Based on these results and considering this situation one might argue that further research and exploration should be made with the goal and the hope to find better sites for CO2 geological storage in Switzerland. This will come at a cost obviously and will carry the risk of not finding one. Another approach, less expensive and less risky, would be that of combining all lessons learnt from CARMA to ELEGANCY, and to make a better and more accurate prediction of the potential for CO2 storage in Switzerland, on which - if encouraging - one can base further exploration activities.

The last step towards a realization of CO2 storage was the study on cap-rock integrity undertaken within ELEGANCY ([32] [33] [34]). The injection experiment was performed in a fault hosted in clay at the Mont Terri underground rock laboratory (NW Switzerland). The experiment aimed at improving our understanding on the main physical and chemical mechanisms controlling the migration of CO_2 through a fault damage zone, and the impact of the injection on the transmissivity in the fault. To this end, we injected a CO_2-saturated saline water in the top of a 3 m think fault in the Opalinus Clay, a clay formation that is a good analogue of common caprock for CO_2 storage at depth. The mobility of the CO_2 within the fault was studied at decameter scale, by using an integrated monitoring system composed of as a seismic network, pressure temperature and electrical conductivity sensors, fiber optics, extensometers, and an in situ mass spectrometer for dissolved gas monitoring.

Figure 13 shows the full time series for the flow rate and recorded pressure for one year of injection. The flow rate drops in the first few days of injection from an average value of 0.2 ml/min to about 0.05 ml/min, then slowly decreases up to a steady-state value of about 0.035 ml/min (Figure 13a). In one year, only about 20 litres of CO_2-saturated water were injected into the fault zone.

The injection pressure is overall constant at 4.5 MPa (Figure 13b – blue line), while the pressure monitored at the interval M1 is first increasing to a maximum change of 0.08 MPa, then starting a slow decrease with a negative trend at time of writing (Figure 13b – red line). Worth to note that the two major pressure drops in the monitoring interval in June and December 2019 were due to incorrect manoeuvres of the operators, while the «jumps» observed in the period January - March 2020 where poroelastic effects caused by a nearby excavation. Overall, the pressure at the monitoring interval reaches a maximum around October/November 2019 and decreases afterward: this could be indicative of a compressive front with pressure increasing before the fluid from the injection breakthrough in the monitoring interval and decreasing afterwards. The pressure at injection is set constant, but at regular interval (every 30 days), we perform a little shut-in/ restart cycle to check for possible reactivation of the micro-fractures in the fault (Figure 13b – blue line). Figure 13c shows an example of these tests, at the start of the injection activities. The time of pressure decay of 0.3 MPa (from 4.8.to 4.5 MPa) is of 1 min on June 12th, 2019, and 30 min on June 13th, 2019. All following tests show a progressive increase in the decay time, as expected for a pressure front propagating further away from injection point.

Modelling of pressure observations indicate some potential porosity decrease in the near injection region. This would represent a sort of healing mechanism, that in the long term would prevent the leakage to happen. Upscaling of the results to large scale and assuming far-worst conditions than CS-D experiment (i.e. much more permeable fault) show relatively large leakage only if the permeability is above 10-17 m^2. In the worst simulated case (permeability 10-15 m^2, distance injection well-fault of only 50 m), about 0.1%/year of injected CO_2 migrated at shallow depth. Worth to mention that here we do not simulate a seismic reactivation of the fault, and therefore assume the permeability changes are negligible.

6 Summary and recommendations

The original Energy Strategy 2050 from 2012 set the target to produce 4.4 TWh of electricity through geothermal energy. It is clear that electricity generation requires as high as possible temperatures, otherwise the thermal efficiency of the power generation process becomes too low to be economic. Therefore, technologies are needed to extract thermal energy from the subsurface at a depth of several kilometers, which is generally in areas of crystalline rocks with very low natural permeability,

Consequently, a significant portion of the SCCER-SoE research went into the development of Enhanced Geothermal Systems (EGS), i.e. how to create permeability in otherwise tight rocks by hydraulic stimulation, avoiding if possible induced seismicity that can be felt at the surface. Experiments in deep underground labs, first in Grimsel, later in Bedretto allowed to make significant progress towards this goal, however, it is also clear that a full industrial deployment of EGS will need more effort to become reality.

The energy transition is more than an electricity transition. The majority of CO2 is emitted in the heating and mobility sectors. To appreciate this fact, we broadened the perspective on geothermal energy at the beginning of Phase II of the SCCER. Within the collaboration with SIG in Geneva, exploration techniques were developed and applied for the drilling of two exploration wells. The objective of this work was twofold: (i) to allow for the extraction of heat for district heating and (ii) to store thermal energy from summer to winter, for instance from a waste incineration plant. SCCER-SoE researchers contributed significantly to the success of these campaigns.

Last but not least we made significant progress on the question of underground CO2 storage. On one hand, researchers showed that CCS has to be part of the future energy strategy, otherwise the goal of net-zero emission cannot be reached. On the other hand, we re-evaluated the opportunities for geological storage in Switzerland, that were first assessed within the CARMA project. The previous estimates had to be corrected down, which led to the conclusion that Switzerland must evaluate alternative options for CO2 storage, for instance by joining European initiatives such as the Northern Lights project.

In the short to medium term, the exploitation of geothermal energy should focus on the extraction or seasonal storage of heat. The main advantage of such approach is that much shallower structures within the Swiss Molasse Basis can be targeted, using exploration, drilling and reservoir creation techniques that are state-of-the-art. Use cases are district heating networks or low temperature industrial processes. The latest update of the Energy perspectives suggests some 10 TWh/a of heat to be produced by the middle of the century. This goal is far less ambitious than the aforementioned 4.4 TWh/a of electricity, but it can be achieved. The long term ambition of geothermal energy must be to access increasing depth, allowing to deliver medium temperature heat (150-200 °C) to industrial processes, or to even generate electricity. Such depth will like require the hydraulic stimulation techniques which are developed in the Bedretto Lab. In order to ensure smooth transition to practice, a continued collaboration with industry is highly recommended.

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