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Table of contents

Natural isotopes as tracers for the evaluation of Mae Chan fault zone geothermal system in Northern Thailand

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Six mediums to low potential hot springs exist in the granitic basement along the NE-SW Mae Chan fault zone in northern Thailand. These hot springs have been continuously scrutinized for geothermal energy production. However, the low potential hot springs along the Mae Chan fault line have been yet studied. The hydrogeological cycle of these hot springs is still considered ambiguous as little knowledge about these systems is available. These hot springs have been continuously scrutinized for geothermal energy production. However, the low potential hot springs along the Mae Chan fault line have been yet studied. The hydrogeological cycle of these hot springs is still considered ambiguous as little knowledge about these systems is available. This study utilizes Sr compositions, and 87Sr/86Sr isotope compositions of the thermal water and rock samples to understand the water-rock interactions. The rock samples were analyzed for petrology and mineral separation. The results show that Sr concentration in thermal water ranges between 43.27 and 90.97 μgL-1 and 87Sr/86Sr ratio varies between 0.7179 and 0.7364. The minerals rock samples have Sr concentration between 22 and 1,063 μgL-1 and 87Sr/86Sr ratio between 0.7230 and 0.7418. The mixing model shows that hot springs near the fault have 73.11 to 75.10% Sr with rock origin, while the hot springs located far from the fault core have 82.50 to 86.31% Sr. The amount of Sr is controlled by porosity and permeability of the crystalline basement rock, which varies with the distance of the fault core from the hot springs.

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A review of the petrophysical properties of the granite reservoir and overlying sedimentary units (Buntsandstein and Muschelkalk) from the Soultz-sous-Forêts geothermal site (France)

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Geothermal energy projects within the Upper Rhine Graben, a 350-km-long and 50-km-wide Cenozoic rift valley, exploit anonymously high geothermal gradients (> 80 ∘C/km) that are attributed to crustal thinning and efficient large-scale hydrothermal convection. Indeed, more than fifteen geothermal wells have been drilled in the Upper Rhine Graben since the 1980s. The geology of the region consists of a fractured granitic basement overlain by a sequence of Permian and Triassic sedimentary rocks (Buntsandstein, Muschelkalk, and Keuper), Jurassic sedimentary rocks, and Tertiary to Quaternary graben fill. The petrophysical properties of the fractured granitic reservoir and the Buntsandstein and Muschelkalk units, sampled from exploration borehole EPS-1 at the Soultz-sous-Forêts geothermal site (France), has been the subject of a collection of recent studies. Such petrophysical data are of value for reservoir prospection, stimulation, and optimisation strategies at existing and prospective geothermal sites throughout the Upper Rhine Graben. We present here a review of the petrophysical properties of these rocks (e.g., density, porosity, permeability, P-wave velocity, Young's modulus, uniaxial compressive strength, thermal conductivity, and thermal diffusivity), and a detailed description of their microstructure and mineralogy, and outline methods available to upscale these laboratory measurements to scales more suited to large-scale modelling designed to better understand, for example, large-scale fluid circulation and borehole stability.

*Speaker

Thermo-reporting nanoparticles for accurate sensing of geothermal reservoir conditions

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The inaccessibility of geological reservoirs makes detection of reservoir properties and conditions a key problem in the field of reservoir engineering. We present an approach for the development of messenger nanoparticles for the determination of reservoir conditions, with a proof of concept example of temperature detection under controlled laboratory conditions. Silica particles are synthesized with a two-layer architecture, an inner enclosed core and an outer porous shell, each doped with a different fluorescent dye to create a dual emission system. Temperature detection happens by a threshold temperature-triggered irreversible release of the outer dye, thus changing the fluorescence signal of the particles. The reported particle system consequently enables a direct, reliable and fast way to determine reservoir temperature. It also displays a sharp threshold for accurate sensing and allows detection at concentration ranges as low as few nanograms of nanoparticles per milliliter.

*Speaker

The Value of performing Play Based Evaluation in Geothermal Resource Assessment and Development

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Abstract: Play Based Evaluation (PBE) is more than just making colourful maps. It is a widely used exploration methodology in the oil and gas industry around the world. With just a small change of key elements it can also be used for mapping geothermal resource potential. Geological trends are defined and mapped in a consistent manner within a given area, thereby identifying the segment(s) with the highest chance of success for geothermal resource potential. The resource and corresponding geothermal effect at surface is highly dependent on the subsurface geology; it is not always a given that the available subsurface resource corresponds to what is desired at surface. As a result, play based evaluation is a powerful assessment tool and aids decision making in the early stages of geothermal resource development.
A play based evaluation is a phased process where identification and understanding of specific subsurface elements is undertaken to perform an assessment of the available geothermal resources. For geothermal resource mapping, the following elements are typically evaluated:

- Reservoir presence and properties
- Cap rock
- Reservoir flow capacity
- Temperature

In the example presented, these elements are mapped for a sandstone interval, however any kind of fractured system can be mapped including volcanic, igneous, and metamorphic rocks. Within the selected area of interest, the first step in the evaluation is to define a main target (reservoir) followed by data mining and QC of available information (left part of figure), including data confidence for each data set.

Following this, trends are mapped with the same conditions for each element, to assign a chance of success to each segment (CoS, right part of figure), creating a Common Risk Segment (CRS) map for each element (middle part of figure).

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The final step is multiplication of the CRS maps creating a Composite Common Risk Segment (CCRS) map: a map that displays areas with highest CoS for desired geothermal resource potential.

This PBE activity is carried out independent of the desired surface geothermal effect and the resulting CCRS map delivers a clear understanding of the resource potential, the confidence in the resource based on the available data, and what kind of data should be obtained within a certain area to reduce the uncertainty. The final CCRS play map is also suitable for adding non-geological, surface-related information to highlight existing population centres, infrastructure, and potential end-user compatibility, from electrical power generation through to thermal energy to industrial, agricultural, or residential consumers.

Microanalytical Analysis of Reservoir Scaling in Fractured Geothermal Systems

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The microstructural and microchemical properties of minerals precipitated in fractured geothermal reservoirs can record significant information concerning reservoir scaling and the evolving conditions within the geothermal reservoir over time. It is vitally important to characterize these microscale signatures as they can potentially provide insight into a range of factors that control the onset of fracture scaling and scaling rates, including temperature, pressure, and geothermal fluid composition, as well as provide insight into changing fluid compositions, temperatures, and pressues associated with geothermal field evolution. By investigating examples of sealed fractures from geothermal systems with a range of microanalytical techniques a deeper understanding of the processes operating during fracture scaling can be obtained. Information on nucleation and growth of scaling minerals in geothermal fractures is crucial in order to incorporate reservoir scaling accurately into reservoir models, and defining fully the influence of secondary permeability in geothermal systems. Here we present findings of microanalytical studies of calcite and quartz scaling in geothermal systems from New Zealand and Uganda that show a variety of vein mienral nucleation and growth processes and controls responsible for reservoir scaling.

*Speaker

3DHIP-Calculator. A new tool for developing deep geothermal resource assessments from 3D models using the 'Heat-In-Place' method and Monte Carlo simulations. Preliminary results in the Empordà Basin case study, (NE Catalonia) - GeoERA HotLime project.

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A new tool called '3DHIP-Calculator' to perform geothermal resource assessment of deep hot aquifers from 3D geological and thermal voxel models have been developed by the 'Institut Cartogràfic i Geològic de Catalunya (the Geological Survey of Catalunya)' and the Department of Geology of the 'Autonomous University of Barcelona (UAB)'. The software has been delivered in the framework of an industrial doctorate program.
The new software written in MATLAB (v2019), was delivered at February 2020 and is distributed in a compiled executable standalone program for Microsoft Windows™ (3DHIP-Calculator.exe). The software is free downable from the ICGC website. It can be of interest for those companies, geological surveys and research institutions dedicated to the assessment of deep geothermal resources. The version allows assessments of deep geothermal potential by calculating the USGS "Heat-in-Place (HIP)" (Muffler and Cataldi, 1978; Garg & Combs, 2015) and thermal energy recoverable (Arkan and Parlaktuna, 2005; Trumpy, et al. 2016; Limberger et al. 2018) on 3D geological models using a probabilistic or stochastic approach with Monte Caro simulations. 3DHIP-Calculator is shown with an intuitive graphical user interface (GUI) that help their utilization. The results are presented in different graphs (histograms and cumulative probability functions) and 2D maps. The output data can then be exported to Geographic Information Systems (GIS) for more detailed 2D mapping to show probabilities of the available resource (for example, 10% HIP (P10)), HIP (P50) or HIP (P90). The software will be presented.

The new software is currently being used in the GeoERA HotLime project (co-financing H2020). The project addresses the mapping and assessment of geothermal plays in deep carbonate rocks in different pilot areas in Europe. The applicability of the software will be briefly presented with

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the preliminary results obtained by the 'Empordà Basin' pilot case located in NE, Catalonia (Spain). The study addresses the evaluation of the deep geothermal potential of the fractured limestone aquifer of the Lower Tertiary called 'Girona limestone formation'.

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Estimation of geothermal potential for an Enhanced Geothermal System taking into account geological uncertainty and the risk of induced seismicity: a case study in Acoculco, Mexico

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Within the H2020 GEMex project, the potential for Enhanced Geothermal System (EGS) development at the site of Acoculco (Mexico) has been investigated. At the site, two exploration wells were drilled in the past, which showed high temperature (_˜300 ∘C at 2 km depth) but very low permeability. In this report, the production is estimated based on EGS stimulation concepts from GEMex task 7.2 (Hofmann et al., 2020). The stimulation concepts were translated into field development scenarios using different assumptions on how the stimulation might affect the permeability in the subsurface. In total, 12 scenarios were defined based on 4 different stimulation concepts for 3 depths each. The stimulation concepts are: hydraulic fracture (tensile), stimulated fracture network, stimulated fault (shear) and a combination of stimulated fractures and a fault. The three defined target depths are 800 m, 1500 m and 1800 m. At 800 m depth the open hole part of the well starts and this area is the most likely to be stimulated if the well is stimulated without further completions. At 1500 m, the target is (fractured) marble which could be stimulated and at 1800 m, the contact zone between the skarn and the granites would be the target.

For these scenarios, production was simulated for 20 years and the resulting heat production analysed. For all the hydraulic fracture scenarios, premature cold water breakthrough was an issue. In these scenarios, the stimulated rock volume is too small to sustain the temperature for more than a few years. In the scenarios in which it was assumed that a connected fracture network was stimulated, heat production is much better. A main question is if such a network of fractures is present. In case a fault is stimulated, also the stimulated volume is estimated to

*Speaker

be much larger than for a hydraulic fracture and thermal breakthrough is delayed. The achieved width of the stimulated fault zone has a large impact on the production. If the fault intersection with the well is limited, the required drawdown for inflow into the well can be considerable, which also negatively impacts the heat production. The combination scenario of stimulated fractures and a fault can also give good heat production, provided cross flow across the fault is assumed. Whether this is realistic depends on the fault architecture.

For each scenario, uncertainty about the stimulation results was incorporated by simulation of 50 realizations rather than one. To parametrize the realizations, the values for the size and permeability of the stimulated area were sampled from a probability distribution. Other uncertainties were not included in the analysis. This limited uncertainty analysis already gave a large spread in cold water breakthrough and produced heat. The analysis of induced seismicity demonstrates for both the strike-slip fault model and normal-slip fault model, that induced thermoelastic stress changes can lead to a high relative rate of induced seismicity (R$>$ 104, where R is the relative increase in natural seismicity rate). A clear risk of induced seismicity by cooling of the pre-existing faults is identified in this study, given the assumption made in this study. Our analysis predicts a higher level of induced Coulomb stress and induced seismicity for the normal-slip fault model than for the strike-slip fault model. The number of events at each magnitude is expected to be higher for the normal-slip fault model than for the strike-slip fault model.

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Conceptual model of heat transfer near volcanic geothermal heat sources

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Traditional conceptual models of the roots of volcanic geothermal systems rely on the assumption that the main mechanism for heat transfer from heat sources (believed to be cooling magma chambers or intrusions) is driven by a Convective Downward Migration (CDM) process: a cooling front, driven by convecting water, migrates into hot rock through fractures that open up due to thermo-elastic contraction by cooling of the rock. The vertical energy transport is facilitated by water convection in opened fractures. The CDM process has been implemented in numerical models by increasing the permeability near the heat sources. Simulated heat transport in the roots, enhances convection of fluids at less depths, explaining the existence of geothermal systems above magmatic sources. In this study, a conceptual model of an active CDM process above a magmatic intrusion (heat source) based on existing literature and IDDP (Iceland deep drilling Project) field example is given. The mathematical model presented is used to study possible effect of the CDM process on the observed heat transfer during production testing of the IDDP-1 well in Krafla, NE Iceland. Based on the conceptual model, possible thermal and mechanical conditions in the hot rock are modelled to study the proposed conditions that enhance permeability and favour convection by opening of fractures in the hot rock.

*Speaker

Review on the Exploration and Development of Yangyi Geothermal Reservoir

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In Feb 2019, the Yangyi geothermal power plant achieved its 16 MW full capacity electricity generation, which is the second industry scale geothermal plant in China in the last 30 years. The exploration of Yangyi geothermal reservoir can be traced back to the 1980s. Nevertheless, the project was not receiving enough investment and technical support until recent years. Since 2015, the new owner of Yangyi reservoir has invested considerable resources into this project and completed a series of supplementary geochemical and geophysical exploration work. Based on gravity, electrical resistivity, magnetotelluric and also geochemical survey results, a 3D reservoir concept model was constructed to identify the location of both shallow porous and deep-cutting hydrothermal conduits. Following these information, a series of logging and well-testing operations were performed, as well as a three-month long tracer injection and monitoring program in 2017. Besides the reservoir engineering work, a specific scale-prevention program was designed based on the geochemical characteristics of the Yangyi geothermal fluid. In order to improve the success rate of well drilling in the future, Acoustic Borehole Imaging (ABI) tool was employed to produce ultra-sonic wellbore surface images, which serves as a solid indicator on the depth, location and inclination of producing fractures and feed zones. The final production plan was concluded with two production wells from the south (ZK203 and ZK208) and one injection well (ZK403) in the north. A 16-MW Organic Rankine Cycle (ORC) power plant was purchased from Ormat Technologies Inc. The power plant equipment installation was completed at the end of 2018. After testing and optimization work, Yangyi power plant was commissioned and reached full-capacity power output in 2019. This talk will summarize and introduce the experiences gained and also lessons learned from the exploration and development of Yangyi project.

*Speaker

Geothermal Exploration Program for the DeepStor Project

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The worldwide unique infrastructure DeepStor aims at the development of high-temperature heat storage in the deep underground as a new element in the future CO2-neutral global energy mix. The advantage of this technology over other types of thermal energy storage is the broad coverage of natural storage capacity, e.g. in former hydrocarbon reservoirs and saline aquifers in the largely accessible sedimentary basins.
Applying storage systems for water-based district heating or for industrial process heat systems requires raising the ATES temperature of max. 50 ∘C to temperatures up to 150 ∘C in high temperature systems (HT-ATES). This involves considerable technology development such as optimal reservoir development, solutions to damage of the natural reservoir by thermo-hydro-chemical interaction, or materials sustaining chemically harsh condition of the thermal water. To overcome current temperature limitation, the scientific infrastructure "DeepStor" has been designed.

In 2019, geophysical exploration started including gravity and seismic investigations combined with borehole data. In the former oilfield Leopoldshafen in direct neighbourhood to the KIT-Campus North, a total amount of 188'000 t of oil with only little amount of gas was produced in the period between the 1957 to 1986. More than 20 boreholes were drilled for hydrocarbon exploration and production. The resource is characterized as a stacked reservoir consisting of at least three Oligocene units with the sandstone layers and lenses of the Bunte Niederrödern beds, Cyrena marls, and Meletta beds at depths between approximately 900 m to 1250 m. This situation provides some flexibility for the planned heat storage regarding depth, temperature, and flow rates. Given the geological and geophysical characteristics, the specific assets for energetic efficiency in the area North of Karlsruhe are:

- Reservoir sandstones occur as layers and lenses sandwiched between thick shale-rich rocks that due to their generally lower heat conductivity most likely insulate the quartz-rich sandstones contributing to energy efficiency of the heat storage system.
- The elevated ambient temperatures in the subsurface of the northern area of Karlsruhe are favourable in terms of energetic efficiency if compared to other potential areas in Germany as cooling effects are reduced.

*Speaker

In summary, the existence of (1) a geothermal temperature anomaly, (2) former hydrocarbon reservoirs of potential suitability for thermal storage, (3) a comprehensive local geoscientific expertise, (4) a unique data situation, and (5) an ongoing dialogue with the public create optimal framework conditions for the realization of the DeepStor project. Furthermore, these conditions allow for a possible future up-scaling and extension of the storage project by geothermal heat production to implement an advanced heat management system together with other renewable technologies.

fLUXtec./ project – Surveying natural gas emissions in geothermal exploration

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Convection-dominated geothermal systems in regions with active tectonism and volcanism comprise vast amounts of thermal energy suitable for power generation and direct use applications. The structural control on permeability and fluid flow in these systems has a substantial influence on the geothermal potential. Fault- and fracture networks facilitate the infiltration of meteoric water into the reservoir, but also the upward migration of hot geothermal fluids. Geophysical surveys (e.g., magnetotelluric methods) are commonly used in geothermal exploration to detect large resistivity structures as a result of intense fluid-rock interaction, with the limitation that they cannot resolve single permeability structures. In this context, soil gas surveys can substantially complement established geophysical exploration techniques by i) providing direct information from the subsurface across large areas, and ii) serving as an indicator of recent volcanic-geothermal activity and the presence of an active geothermal system. The spatial variability of natural gas emissions at Earth's surface is a proxy for structural discontinuities in the subsurface. Increased gas emission rates indicate most permeable sectors of fracture networks, which are connected to deep hydrothermal systems. We perform comprehensive soil gas surveys in a variety of geothermal projects worldwide driven by different research and industry-related questions. Our approach integrates the assessment of gas composition, emission rates and isotopes of different natural gases to complement conventional geothermal exploration methods and reduce the risk of unsuccessful drilling. Furthermore, we could prove the successful identification of 'blind' geothermal systems, where no active surface expressions (e.g. hot springs, fumaroles) exist. We will present a summary of selected case studies from geothermal systems worldwide, highlighting the great potential of this approach not only in reservoir assessment, but also in reservoir monitoring. New projects, like fLUXtec./, will focus on the optimization and advancement of this exploration and monitoring technology, which should be more commonly applied in geothermal projects for a safe and sustainable exploration and management.

*Speaker

Geochemistry characteristic of Southern hot springs, Thailand

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Hot springs can be found in most region in Thailand. There are about 40 hot springs in Southern and around 120 hot springs altogether which are related to non-volcanic geological setting. Most hot spring were mainly developed as local tourist destination and for tourism purposes such as spas. However, for further development a better understanding of the geological setting and characteristic is. The Krabi, Nakhon Si Thammarat, Phang Nga, Suratthani, Chumphon and Ranong hot springs are presented here as case studies located in Southern, Thailand. Geochemical analysis water samples were collected from natural pools, groundwater wells and sea water from eastern and western coast. The hot springs discharge thermal water of temperatures between 35.7 – 70.0 ∘C and mostly alkaline pH around 6.6 – 8.1. The major cation and anion results indicate that hot springs in the study area can be classified into four types: NaCl, NaHCO3, CaHCO3 and CaCl type. The oxygen stable isotope displays a meteoric origin of thermal water moreover the salinity in some hot springs are from sea water intrusion. Meteoric water is flow downward and heat up through the main pathway relate to fault zone.

*Speaker

Numerical simulation on kilometer-scale fault-related thermal anomalies in tight gas sandstones

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Large-scale natural convections systems in a faulted sandstone reservoir are investigated using the finite element code TIGER. The selected illustrative research location (Piesberg quarry, Lower Saxony Basin, North Germany) has a thermal anomaly, evidenced by a variety of geothermometers studies (including thermometry, fluid inclusion, etc.), in the reservoir outcrop analog of circa 300∘C, which is approximately 90∘C-120∘C higher compared to outcropping rocks of a similar stratigraphic position some 15 km to the west. The origin and development of this anomaly are investigated within this study, targeting the analysis of natural convection systems. The transient 3D models are based on idealized structural models that characterize all geological features during Late Jurassic rifting (162 Ma) including realistic fluid (temperature-dependent density and dynamic viscosity, etc.) and rock properties. Sensitivity analyses including effects of fault thickness, fault transmissivity, and fault dip angle were carried out, respectively. The results show that all parameters affect the structure, temperature anomaly, and kinetics of the natural convection systems in a faulted sandstone reservoir. In sum, a vertical 400m thick fault with a permeability of 1e-13 m2 yields a maximum 99∘C-125∘C higher temperature in the sandstones reservoir according with the thermal anomalies detected in the Piesberg quarry. The resulting over 40∘C thermal anomaly has extensions of more than 1.6km at the fault boundary to the overlying host rock.

This study demonstrates that the local thermal anomalies are presumably provoked by circulating hydrothermal fluids along the fault damage zone of a large NNW-SSE striking fault, laterally heating up the entire exposed sandstone reservoir. Results suggest that this thermal event was reached prior to peak subsidence during Late Jurassic rifting (162 Ma). Owing to the idealized nature of the presented models, the numerical results and the associated analytical solution can be applied to petroleum and geothermal system models to avoid overestimating of burial depth and reservoir quality, etc.

Keywords: Numerical simulation; Thermal anomaly; Natural convection; Fault; Tight gas sandstones; Upper Carboniferous; Lower Saxony Basin

*Speaker

Hydro-mechanical modeling of the year 2000 hydraulic stimulation of GPK2 well, Soultz-sous-Forêts, France

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Hydraulic stimulation of pre-existing fractures and faults plays a significant role in improving hydraulic conductivity of the fracture network around injection and production wells in geothermal reservoirs. It is therefore important to characterize the hydro-mechanical behavior of the faults against fluid injection. The Soultz-sous-Forêts site (France) has been an EGS pilot site where several major hydraulic stimulations have been performed and are well documented (https://cdgp.u-strasbg.fr/ and https://tcs.ah-epos.eu/). Here we use the 3DEC numerical modeling tool (Itasca) to analyze the year 2000 stimulation of GPK2 well where large scale seismic anomalies have been evidenced during the different stages of the stimulation using 4D-P-wave tomography (Calo et al, 2011). The specificity of the approach is to combine two modeling at different scales. First, a small scale model (100x100x100 m3) is built to analyze the effective mechanical response of a stochastic discrete fracture network (DFN) following the statistical features of the observed fracture network (Massart et al, 2010). Second, a large scale numerical model of the Soultz-sous-Forêts reservoir (5000x5000x5000 m3) containing the largest faults of the reservoir defined by Sausse et al., 2010, is developed including regional stresses. The objective is to constrain the large scale mechanical properties of the embedding matrix around the fault from the small scale model, in particular, its hydro-mechanical behavior in terms of non-linear elastic response related to the stochastic DFN. As a first step only the largest fault (FZ4770) is considered (Figure 1B). The first stage of the stimulation (green rectangle at figure 1A) is modelled as a constant flow rate of 30 ls-1 of water injected into the fault at the depth of approximately 4.5 km. We explored the effect of the normal and shear stiffness of the fault on the dynamical response of pore pressure along the fracture and the onset of slip. t is found that the increase of the aperture of the fault during the injection shows a slow migration (_˜10 cm/s) owing to poro-elastic effects that is compared to the observed seismicity migration. Also generated fluid pressure throughout the fault shows a long period oscillating behavior (_˜5 hr) sensitive to the relative magnitude of the fracture normal and shear stiffnesses.

*Speaker

Optimising deep geothermal drilling efficientcy with respect to wellbore stability

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Managing cost and reliability is critical for successful deep geothermal well construction. This results in a balance between drilling speed and wellbore stability. Cost is directly related to the drilling duration, but a too high drilling speed will impact wellbore stability, increasing risk of cavings and packo, breakouts and tortuosity, and may cause challenges for the subsequent casing running and cementing as a results of wellbore irregularity and cuttings or cavings left in hole after cleaning.
Factors impacting wellbore stability are geological features, rock properties, in-situ stresses magnitude and orientation, formation pressure, wellbore pressure, orientation of drill trajectory, drilling vibrations, and drilling uid properties. Ideally all of these factors should be known and managed in operations. As the amount of downhole information in deep geothermal drilling operations is normally limited, as opposed to petroleum drilling operations with generally lower temperatures,softer rock, and greater cost margins, allowing for downhole instrumentation, other methods need to be developed to account for these factors, based on more limited information from surface measurements.

In order to use surface measurements for this purpose, better knowledge of downhole behaviour is needed, with respect to both drillstring vibrations and the mechanical response of the rock. With such knowledge, more reliable predictability of downhole behaviour may be achieved, allowing for better optimisation of the drilling process.

Advanced torque and drag models have been developed with the capability of accurately modelling drillstring vibrations while drilling. For application of such models for geothermal drilling, capability is needed of linking surface measurements to downhole behaviour. Although systems exist for damping mechanical vibrations, observed downhole problems indicate that knowledge of mechanical load on the wellbore wall is limited. Further, general rock mechanics models exist, but predictive capability of the mechanical behavior of rock in deep geothermal conditions as a function of mechanical and thermal load is today limited and needs further investigation.
It is proposed that the missing knowledge may be generated through laboratory and modeling

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studies using existing full-scale laboratory drilling infrastructure enabling drilling in rock samples for vibrations studies and subsequent studies of the drilled samples with respect to rock stability. Finally such increased knowledge may be used to improve model predictability for application in drilling optimisation with respect to both cost and reliability.

Numerical based filtering concept for feasibility evaluation and reservoir performance enhancement of hydrothermal doublet systems

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This study aims to introduce a filtering concept for evaluation and optimization of the feasibility and energy productivity for hydrothermal doublet systems. It also provides an intensive parametric study for several constraining geological- and engineering-related parameters which are selected based on limited available data at an early stage of geothermal projects. A new code, called TIGER, is introduced for modelling coupled thermal-hydro processes in porous media. Two reservoir conditions are studied and compared: a) homogeneous and b) fractured reservoirs. The effects of different fracture orientations and configurations are considered. For feasible and sustainable production over 30 years in the case of the homogeneous reservoir, reservoir permeabilities > 5x10-14 mˆ2 and sufficient reservoir thickness are required. While reservoir thickness is directly proportional to reservoir performance, increasing reservoir permeability will after a certain threshold reduce reservoir performance due to thermal break-through. To improve reasonably fluid circulation, either a direct connection of wells via a common fracture or indirect connection through fractures network is necessary. However, fast thermal break-through is a common thread, especially for well distances < 400 m and high transmissive fractures, and has to be considered during the design of reservoir operation. This study supplies several self-described and contourstyle charts, as guidelines, for project developers and decision-makers to initially evaluate sustainable geothermal potentials in different projects.

*Speaker

Active cross-well survey at the geothermal site Schäftlarnstraße

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Scientific research to assess the impact of geothermal exploitation on induced seismicity is carried out within the framework of the INSIDE project (supported by BMWi), focusing on several active and under-development plants in the Munich area (Germany, Molasse Basin). For the Schäftlarnstraße geothermal field, two fibre optic cables have been deployed thanks to Technische Universität München (TUM) and Stadtwerke München (SWM) – one behind the casing of the Th3 well and the other in the Th4 well. Distributed Acoustic Sensing (DAS) acquisition and processing techniques can therefore be applied, which opens interesting perspectives for the characterization of the propagation medium considering the distributed character of the sensors along the cables. To further constrain the seismic velocity model and achieve a more accurate location of any potential event, an active cross-well survey has been designed at the Schäftlarnstraße plant.
The primary purpose of the test is to "calibrate" the velocity model. With a shot positioned as deep as possible in the source-well, our goal is to mimic a seismic event that would occur at the reservoir level. Since real location and timing of the active source are controlled, our approach should enable to calibrate the velocity model between the source and the fibre optic cables. One other aspect of the survey is the achievement of a cross-well tomography. This approach goes beyond the calibration and aims to image the velocity model between the source and the receiver wells.
After presenting the design of the active campaign, which is planned for mid-October 2020, we will focus on the results of the feasibility studies that contributed to the conception of the survey, and highlight the major issues associated with this original test.

*Speaker

Fracture-matrix system under normal stress: The evolution of specific stiffness and permeability

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The sustainability of fractures in terms of permeability and fracture opening is of crucial importance in the fields of Enhanced Geothermal Systems (EGS). Both parameters are related to several features like aperture variation due to fracture surface roughness, relative shear displacement, the amount of flow exchange between the matrix and the fracture itself, fracture closure due to normal load, and others. In order to quantify constitutive relationships among the aforementioned aspects, we have conducted flow-through experiments for Flechtinger sandstones containing a single macroscopic fracture. Based on these experiments, we obtained a range of variations of intrinsic rock parameters, permeability and specific stiffness of the combined matrix-fracture system under hydrostatic loading. To evaluate the processes behind the laboratory observations, we carried out coupled hydro-mechanical simulations of the matrix-fracture system. Navier-Stokes flow was solved in the 3-dimensional open rough fracture domain, and back-coupled to the Darcy flow and mechanical deformation of the rock matrix. The results demonstrate that the numerical simulation could capture the elastic and inelastic behaviour as well as the related permeability alteration of the fracture domain. Both, the laboratory experiments as well as the numerical simulation indicate inelastic deformation of the single fracture even at low normal stress expressed by an increase of the fracture contact area and therefore fracture stiffness with increasing stress. The increase in the contact area is due to a reduction in mean aperture and is therefore accompanied by a reduction in the fracture permeability. The development of the contact area is irreversible and thus provides an estimate of the maximum stress applied to the sample. We call this behaviour "stress memory effect".

*Speaker

The evolution of fracture stiffness during constant and progressive cyclic loading

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The hydraulic performance and mechanical stability is crucial for several subsurface applications including fractured geothermal reservoirs. The potential of fractures to close under external load controls the aperture and thus the ability of a fracture to promote flow. This stress-related closure potential is defined by the fracture stiffness. Repeated loading may change the potential and possibly impacts the amount of elastic and plastic deformation. Especially for enhanced geothermal reservoirs this closure potential is crucial to maintain open fractures with sufficient permeability.

We carried out different cyclic loading experiments with fractured Flechtingen sandstone samples to up to 60 MPa hydrostatic stress. To achieve the full elasticity of the rock sample, the intact samples were pre-conditioned before fracturing. The Brazilian Disk setup was used to generate a tensile fracture that was manually displaced to 0.5 mm. For the actual experiment, two loading cycle scenarios were considered. During "constant cyclic loading" (CCL) experiments, the fracture was repeatedly loaded to the same peak load. During "progressive cyclic loading" (PCL) experiments, the peak stress was progressively increased in each cycle. The matrix and fracture deformation was monitored using axial and circumferential LVDT extensometers to obtain the corrected fracture stiffness. The permeability was continuously measured throughout the experiment. The fracture surfaces were scanned before and after the experiment to obtain the fracture topography. From this data, the aperture distribution and roughness was calculated.

From our experiments we found that fracture permeability and stiffness show a hysteresis effect. We could also show a stress-memory effect of fracture stiffness similar to the "Kaiser Effect" in intact rocks. It is characterized by a change from a non-linear stiffness trend at previously reached stress levels, to a linear trend at stresses that exceed any previous stress level. This effect allows for the identification of any previous stress levels and indicates the transition from a plastic to an elastic deformation mode. The self-affine roughness exponent above grain scale remained unchanged and suggests a large elastic component of fracture deformation. Relating stiffness and permeability, we found a stiffening of the fracture by progressive loading, leading to a more sustainable fracture permeability at same stress magnitudes. We therefore suggest that fracture permeability and the contact-area ratio are dependent on the stress-history of rock. Translating our results to the field scale, fracture permeability damage could possbily be minimized. This may be done by stiffening the fracture through a step-wise pressure function.

*Speaker

How well can we predict hydraulic fracture initiation and propagation in low-permeability rocks?

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6

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Numerical codes used for designing field-scale stimulation experiments are most often only validated using analytical models governing deformation and fluid flow in rock matrix and fractures. These models are very rarely validated using dataset obtained from experiments on real rock samples. We generated well-controlled experimental dataset in laboratory by hydraulically fracturing granite samples using high-pressure injection fluid to create a radial tensile fracture in a plane perpendicular to the direction of minimum stress. We used this dataset as benchmark to compare the predictions of two finite element hydraulic simulators: GEOS and CSMP. The simulation results indicate the importance of considering the system parameters such as compressibility of the injection set-up, viscosity of injection fluid and friction in the injection line to correctly model the pressure build-up process, which in turn influences the breakdown pressure and fracture initiation and propagation in the early-stage. Furthermore, permeability enhancement due to microcracking process before the main fracturing event can lead to fluid

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leak-off into the matrix, which not only influence the post-fracturing pressure-decay process in the reservoir, but also effect the pre-fracturing pressure build-up process.

Utilizing oil and gas industries' capabilities in exploring deep supercritical geothermal reservoir rocks

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1

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Global geothermal energy use lags far behind other energy sources, with geothermal comprising only 1% of overall energy production. The disproportionate use of this enormous, ubiquitous, clean and baseload source of energy is largely the result of a lack of technology transfer and expertise from the oil and gas industry. Geothermal energy exists today at a few hotspots. And looking at earth's total landmass, the number of places where those unique conditions occur is incredibly small. As a result, the resource is largely absent from the public energy debate, energy policy discussions, and strategic plans of major energy companies. New capabilities are enabled in drilling and exploration with the advent of hydraulic fracturing. Deep very hot geothermal development looks very approachable now. Technology base needs to be developed to exploit heat of reservoir rather than the fluid. If drilling for geothermal energy is carried in many places, instead of just where the resource is considered, the total calculus of the system changes. Then the geothermal projects may get scalability opportunities similar to oil and gas industry. The technologies and methodologies used in drilling for oil and gas and geothermal are similar; oil and gas companies have not optimized their operations for geothermal conditions and requirements. The very deep HPHT reservoirs could be exploited using three methodologies i.e. Open Loop Heat exchanger, Closed Loop Heat exchanger and Hydraulic Fracturing (HF).Areas like supercritical and closed loop systems would be a part of such complementary Enhanced Geothermal System (EGS). This paper discusses about the pros and cons of using such systems.

*Speaker

3D Geomechanical Modelling of the Rhein-Ruhr Metropolitan Region - An Assessment of Fault Reactivation Risk

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In the interests of sustainable conversion of district heating systems across the densely populated metropolitan region of Rhine-Ruhr, progressive approach towards seismic risk assessment is essential, especially in the context of the development of deep geothermal reservoirs. Increased seismic risk concerns connected to exploration and exploitation of geothermal resources necessitate detailed understanding of the present-day in-situ stress state and its spatial variability. The local stress field directly affects, among others, wellbore stability, reservoir stimulation practices, permeability anisotropies, and reactivation potentials of faults. A well-informed analysis of the locally prevailing state of stress is, therefore, sought prior to any drilling activities. Based on the finite element method (FEM), this study aims at the development of a 3D geomechanical model of the Rhine-Ruhr metropolitan region for the assessment of the intrinsic risk of fault reactivation, associated seismicity, and to support safer and economically more efficient exploration and exploitation of deep geothermal energy resources. The collected geological and in-situ stress information from more than 700 yearlong coal extraction in the region allowed to considerably decrease the amount of uncertainties, make well-informed assumptions and provide comprehensive calibration datasets. Acting as a predictive tool, the developed model will provide an a priori large-scale understanding of the in-situ stress distribution, perturbations, and reactivation potentials of major deformation zones within the complex geological setting of the Rhein-Ruhr region.

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Fault Activation by Repeated Fluid Injection: Case Study of the Enhanced Geothermal System at Rittershoffen, France

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The development of the deep geothermal site at Rittershoffen (Alsace, France) was monitored continuously by different seismic networks covering various operational periods from September 2012 to October 2014, including the drilling of the well doublet GRT1/GRT2, the thermal, hydraulic and chemical stimulations of GRT1 and circulation tests between the two wells. The seismicity induced by these operations has the potential to give valuable insight into the geomechanical behaviour of the reservoir and the geometry of the underground fracture network. This work gives an overview of the spatial and temporal development of the induced seismicity during the GRT1 stimulation sequence and maps clusters of events with similar waveforms to give first insight into active structures in the reservoir.

To obtain a robust database for this analysis, we first apply a template matching code to the continuous waveforms recorded by the seismic networks. This technique is based on the calculation of the correlation coefficient between continuous and template waveforms. It outperforms conventional energy detectors in terms of sensitivity to events with low signal-to-noise ratio and picking consistency for events with waveforms similar to the templates. To decide when a new event is detected, adaptive threshold for the correlation coefficient is implemented. As template database, we use a manually picked seismic catalogue covering the different stimulation periods of GRT. This starting catalogue contains nearly 1000 events.

After running the detection with the template matching code, relative locations of all detected events are calculated. The visualization of the spatial and temporal evolution of the events can show, how the different operations influence the seismogenic development of the reservoir. Additionally, we perform a clustering analysis based on waveform similarity of the events and show the spatial distribution of these clusters in the reservoir. Such clusters can indicate the location of structures, which are repeatedly activated by the same processes, producing similar waveforms, and therefore dominate the geomechanical behaviour of the reservoir.

*Speaker

Heat storage in depleted hydrocarbon reservoirs of the Upper Rhine Graben

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Over 50 % of the German CO2 emissions are related to the demand for heating purposes and industrial processes. Especially the heating of buildings is subject to seasonal fluctuations. Therefore, the storage of excessive heat produced during summer times that can be extracted in winter times gains on importance. With current state-of-the-art technology and foreseeable developments, a significant amount of heat can only be stored in subsurface storage systems, utilizing the large available storage volumes. In contrast to the shallow "Aquifer Thermal Energy Storage" (ATES) systems, deep heat storage allows the storage of a larger amount of energy due to significantly higher injection temperatures. Depleted hydrocarbon reservoirs are well characterized by geological and geophysical exploration, thus providing excellent conditions for deep heat storage. We have characterized the petrophysical properties of 35 former oil reservoirs in the Upper Rhine Graben (URG). These data are the basis for the choice of suited parameters for a generic numerical study to assess the influence of flow rate, reservoir thickness, and permeability as well as the borehole geometry (vertical, horizontal) on the potential of deep heat storage. The recovery efficiency of such a heat storage system – defined as the ratio of extracted to injected energy – shows an increase from 66 % after one year to 82 % after a modeling period of ten years. The results of our modeling show a strong dependency of the storage potential on flow rate and reservoir thickness. Further can be shown that the majority of the investigated oil reservoirs (up to 90 %) have potential storage capacities of more than 2 GWh/a and can therefore be utilized for heat storage. Scaled to the URG, this points to potential storage capacity in depleted oil reservoirs of up to 10 TWh/a, which represents a considerable portion of the thermal energy needs in this area.

*Speaker

Thermal Performance Tests of Borehole Heat Exchangers with different lengths installed in a geothermal field

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In a geothermal field, the ground temperature increases more significantly with depth than the common field due to its higher ground temperature gradient. Generally, a Borehole Heat Exchanger (BHE) with a longer length has a higher depth-average temperature surrounding the BHE, favorable to the energy harvesting scenario. To identify how the BHE length will influence the heat extraction capacity of a BHE, short-term Thermal Performance Tests (TPTs) were conducted numerically in a validated numerical simulation framework. The results showed that a longer BHE improves the heat extraction rate of a BHE. Particularly, the heat extraction rate improves 7.65% when the installation depth increases from 20 to 30 m, and it would improve 27.63% when the installation depth increases from 20 to 60 m. Moreover, it was found that the improvement rate of the heat extraction rate generally stabilized at 0.5% per meter as the BHE reaches 40 m.

*Speaker

Design and optimization of geothermal binary plants: focus on methodology

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The successful exploitation of geothermal energy for power production relies on to the availability of nearly zero emission and efficient technologies, able to provide flexible operation: the binary cycle technology is of particular interest in this context. It consists of a loop for the geothermal fluid, flowing from the reservoir to the power plant through the production well and then back to the reservoir through the reinjection well; and of a power plant based on a closed thermodynamic cycle, generally an Organic Rankine Cycle (ORC). Often a downhole pump is required to assure an acceptable geothermal fluid mass flow rate.

The design and optimization process is generally conducted for the power plant, regardless of the geothermal fluid loop, with the aim to achieve the maximum net power output selecting the best cycle working fluid and the optimal cycle parameters. However, the optimization should be conducted by maximizing the net power of the overall plant, also including the down-hole pump consumption, which is usually not negligeable. This second approach implies the integrated calculation of the geothermal fluid loop and plant performance. The simulation model must reproduce different features of the overall plant: the thermodynamic properties of the geothermal fluid, the flow in the reservoir, the flow in production and injection wells, the thermodynamic properties of the cycle working fluid, the performance of the power plant components.

Aspen Plus, a commercial code widely adopted for the power plant simulation is selected to assess the ORC performances. Its application could be extended to the whole plant, including the geothermal fluid loop; however, the coupling of a simulation code for the power plant to a code specifically designed for the geothermal fluid loop can allow more accurate results. In this work, Doublet Calc (version 1.4.3), an open-source software for calculating the thermal power from a geothermal doublet exploiting a sedimentary aquifer, is coupled to Aspen Plus (version 10.0). The optimization process is carried out by means of an integrated, iterative approach, to maximize the overall net power of the plant.

The adoption of the integrated approach could be particularly profitable during preliminary performance evaluation. In fact, following the output results from the DoubletCalc simulation code, a probabilistic distribution for the electric power produced can be assessed.

Moreover, the adoption of a different software or more recent versions of the DoubletCalc software for the geothermal fluid loop could enlarge the capabilities of the integrated approach, by

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assessing the optimized plant performance over the full operating life of the plant.

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• Effect of Acidizing on Permeability, Strength and Stiffness of Veined Greywacke

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Acid stimulation is used as a permeability recovery technique in both injection and production geothermal wells to dissolve scale deposit at the well-rock interface. Different chemical blends are used depending on the minerals causing the scaling. Hydrochloric acid, and in some cases formic and nitric acid, is used for calcite while hydrofluoric acid is used for silica scaling. The reservoir rock at Kawerau geothermal field in New Zealand includes greywacke basement rock, a very fine-grained, lithic-rich metasandstone. The greywacke has very high intact compressive strength, but is typically highly fractured owing to the complex tectonic setting of the central North Island of New Zealand. In the Kawerau reservoir rocks many of the fractures are sealed by calcite.

We investigated the impact of acidizing on both permeability as well as strength of the greywacke by testing 20 mm diameter, 40 mm long cylindrical cores of Greywacke samples using the dosing protocol used during acid stimulation in active wells. When acidized with a 10% HCL solution for 65 minutes, the samples experienced, on average, a 30% relative reduction in strength, a 21% reduction in elastic stiffness, a 16% increase in porosity and a nearly 4000% increase in permeability, compared to as-cut control samples. When subsequently acidized with a 10% HCL + 5% HF solution for 98 minutes, the samples experienced, on average, a 38% relative reduction in strength, a 29% reduction in elastic stiffness, a 110% increase in porosity and a 14000% increase in permeability, compared to as-cut control samples.

This clearly demonstrates that, while acid treatment in these rocks will improve permeability at the sample scale, it will also decrease strength and stiffness. It is not clear from this small study if the changes in strength and permeability after the second acid treatment are due to additional dissolution of the calcite infilling by the HCL or if the HF also contributes to the changes. We propose that additional research be undertaken to fully explore the impacts of acidizing on fractured Greywacke. We also propose that research on the acidizing effect on strength and stiffness be investigated in European reservoir rocks to determine if this type of soft stimulation technique has the potential to affect wellbore stability.

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2017-2019 hybrid micro-gravity monitoring of the Theistareykir geothermal field (North Iceland)

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Geothermal energy represents around 30% of the produced electricity in Iceland with a cumulative capacity being equal to 755 MWe (Ragnarsson et al., 2020). In particular, the Theistareykir geothermal plant, which is located on the Mid-Atlantic ridge in North Iceland, produces 90 MWe using two turbines in operation since autumn 2017 and spring 2018. Here, we apply a hybrid micro-gravity monitoring to contribute to the sustainable management of this renewable energy. This method highlights the mass redistribution and, consequently, helps to quantify the recharge of the geothermal reservoir.
27 time-lapse micro-gravity stations were measured with a Scintrex CG5 gravimeter in 2017, 2018 and 2019 i.e. before and after the beginning of the geothermal production. In the frame of a cooperation project with GFZ Potsdam, continuous gravity changes were also recorded at 3 permanent stations with iGrav superconducting gravimeters calibrated with a FG5 ballistic absolute gravimeter. The combination of these instruments defines the hybrid micro-gravity method. Then, the gravity variations are corrected for the effect of vertical displacements deduced by InSAR analysis by the University of Iceland.

We observe a residual gravity decrease down to -38 +/- 11 μGal in 2019 with respect to 2017 in the production area. This variation is co-occuring with a subsidence of few millimeters. We discuss possible elastic models that could explain our observations.

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*Speaker

GeoLaB - Geothermal Laboratory in the Crystalline Basement

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In Central Europe, the largest geothermal potential resides in the crystalline basement rock with important hotspots in tectonically stressed areas. To better harvest this energy form under sustainable, predictable and efficient conditions, new focused, scientific driven strategies are needed. Similar to other geo-technologies, the processes for environmental sustainability in the subsurface need to be investigated in large-scale facilities. The proposed new underground research laboratory GeoLaB (Geothermal Laboratory in the Crystalline Basement) will address the fundamental challenges of reservoir technology and borehole safety. The specific objectives of GeoLaB are 1) to perform controlled high flow rate experiments, CHFE, in fractured rock, 2) to integrate multi-disciplinary research to solve key questions related to flow regime under high flow rates, or higher efficiency in reservoir engineering, 3) risk mitigation by developing and calibrating smart stimulation technologies without creating seismic hazard, and 4) to develop save and efficient borehole installations using innovative monitoring concepts. Planned experiments will significantly contribute to our understanding of processes associated with increased flow rates in crystalline rock. The application and development of cutting-edge tools for monitoring and analyzing will yield fundamental findings, which are of major importance for safe and ecologically-sustainable usage of geothermal energy and further subsurface resources. As an interdisciplinary and international research platform, GeoLaB will cooperate with universities, industrial partners, and professional organizations to foster synergies and technological and scientific innovations. GeoLaB is designed as a generic underground research laboratory in the crystalline rock adjacent to the Rhine Graben, one of the most prominent geothermal hotspots in Germany and France. GeoLaB is an analogue site representative of the world‘s most widespread geothermal reservoir rock, the crystalline basement. In an initial phase, the suitability of a site for GeoLaB located either in the Black Forest or the Odenwald, will be proven by geological, geophysical, and geochemical drilling exploration. At the selected site, a two km long gallery will be excavated, tapping individual caverns, from which controlled, high flow rate experiments will be conducted at depths of 400 m. The experiments will be continuously monitored from multiple wells, drilled from the underground laboratory or from the surface. This will create a unique 4D-benchmark dataset of thermal, hydraulic, chemical and mechanical parameters. Hence, GeoLaB will become a cornerstone for the target-oriented development of the enormous

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geothermal resource. With its worldwide unique geothermal laboratory setting, GeoLaB allows for cutting-edge research, associating fundamental to applied research for reservoir technology and borehole safety, bridging laboratory to field scale experiments and connecting renewable energy research to social perception. GeoLaB comprises a novel approach that will shape research in earth science for the next generations of students and scientists. Beyond the scientific and technological orientation of the infrastructure, GeoLaB forms a platform for science communication, participation and dialogue of stakeholders from industry, politics, administration and society. Complying public engagement, this aims at eliminating the asymmetry in terms of knowledge and communication. Early involvement of stakeholders with different roles in the innovation process may prevent proto-expertise from acquiring a life of its own. In this respect, geoethics employs concepts of open platforms for the engagement of all relevant stakeholders by exchange of knowledge and experience between the worlds of professionals, researchers, industry, authorities and the public. Such a platform needs to offer the possibility for open discussion on technical aspects such as site selection and risks, but also on related aspects such as regulatory and economic issues. This is ideally realized in a participatory process.

Life-cycle assessment of geothermal district heating and cooling networks

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Life-cycle assessment of geothermal district heating and cooling networks

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Strategies to decarbonize the building sector in Europe to reach climate goals increasingly include geothermal heating and cooling as an option, which is often applied in networks to benefit from the economies of scale. Under a program called GEothermies, the State of Geneva is actively increasing its understanding of geothermal potential from shallow and medium depth to decarbonize their heating and cooling supply. Life-cycle environmental impacts of geothermal heating systems are also critical to be assessed so that the environmental consequences can be acknowledged and managed. Our systematic literature review on geothermal heating and cooling revealed that shallow and medium-depth geothermal heating systems are underrepresented in terms of life-cycle environmental assessment studies, even though they are increasingly applied in Europe.

Our study addressed this research gap by quantifying the environmental impacts of geothermal heating and cooling networks on global warming, particulate matter emissions, terrestrial acidification, fossil and mineral resource scarcity, water consumption, land use, and total energy demand. We constructed six configurations that represent the key options for developing geothermal district heating and cooling in the State of Geneva from shallow and medium depth (10-3'400m). The options were first analyzed for the case where heating and cooling is entirely supplied by geothermal resources. This analysis also allowed for identifying the contribution of different life-cycle activities to the environmental impacts. Further, a bounding analysis was used to estimate the lower and upper bounds of the environmental impacts under uncertainty. We investigated the environmental impacts of combining geothermal resources with supplementary heating and cooling resources. Finally, these impacts were compared with those of other

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heating and cooling technologies that are used in the State of Geneva.
Our results show that, while most environmental impacts of geothermal heating and cooling are lower than those of fossil fuels, the impact on mineral resource scarcity is higher. The environmental impacts originate mainly from drilling of geothermal wells, construction of network pipes, and electricity consumption. While the extent of the contributions of these activities to the environmental impacts varies from one configuration to another, lower impacts were systematically found in the case of system with connected decentralized heat pumps and passive cooling. Also, supplying heat networks with a mix of geothermal and supplementary heating and cooling resources results in lower geothermal environmental impacts. This is specific to Geneva, where hydroelectricity constitutes a large share of the electricity mix. Nevertheless, the overall environmental impacts of heating and cooling networks highly depend on the type of supplementary heating and cooling resources.

Co-design of an implementation concept for a deep geothermal energy project at the Karls-ruhe Institute of Technology (KIT)

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We present a new approach to infrastructure planning for the production and use of renewable energy that better meets society's expectations (see figure below). The project aims for improved transparency and co-design at all stages. The implementation concept for the use of deep geothermal energy on the campus of the KIT includes a trans- and interdisciplinary co-design and is closely linked to the other scientists, citizens, and stakeholders to guarantee the integration of various interests and knowledge. The concept is oriented on public welfare and will fulfil criteria for societal acceptability. For this reason, criteria and scenarios for the use of geothermal energy will be developed together with stakeholders, scientists and citizens living and working near the planned facility. The various expectations, concerns and needs might lead to new conceptual ideas or adjustment requirements regarding the implementation concept. Since the construction of a deep geothermal energy plant is a long-term infrastructure project, which will change, e.g. the energy supply system, it is necessary also to include socioeconomic and landscape changes both in the planning and operational phase as well as beyond. We believe that our findings represent an essential step towards participation and transparency in the planning and implementation process of new technologies. The developed co-design concept can easily be adopted for similar infrastructure projects to facilitate the installation of renewable power plants for a more sustainable future of energy systems in Europe.

*Speaker

Use of co-produced waters from oil wells located in the Peruvian jungle to generate electricity through a Geothermal Binary Cycle Technology

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In the oilfields located in the Peruvian jungle, together with oil, large volumes of water are produced. The temperature of these geofluids extracted at the wellhead is around 100 ∘C, a temperature that can be used to generate electrical energy through the Geothermal Binary Cycle technology, in a process that does not consume fuel. There is a number of countries in the world where the hot water coming from oilfields can produce electricity in remote locations. The hot waters exchange heat with a low boiling point fluid which in turn pass through a turbine in a binary cycle.
Firstly, a binary cycle module in this thermodynamic system can replace some of the combustion generators of the power plants installed in the oilfields located in these remote locations. In the present, the oilfields use electric generator motors feed with fossil fuels (diesel or natural gas) for their daily activities. In contrast, a binary cycle system does not use fossil fuel; consequently, the environmental impact and greenhouse effect is zero or minimal.

Secondly, the communities surrounding the petroleum locations have poor living conditions where the lack of continuous electricity the 24 hours of a day is a widespread problem. The locals are reluctant to accept the extraction activities related to the oil activity because they complain that the benefits do not reach them. The use of the geofluids to produce electricity can also contribute with the development of the native communities and open the opportunities to utilise these geothermal fluids in agro-industry, fish farms, timber driers and more productive activities through cascade systems.
Overall, the geothermal technologies applied to produce electricity through a binary process using co-produced waters before being reinjected in the existent oilfield operations, mature fields and abandoned wells. These low-temperature waters (circa 100 C) can contribute to enhance the optimisation of the resources in the oilfields and benefit the communities with electricity

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and a source of energy to undertake economic activities.

Improving companies' engagement strategies with communities. Evidence from an Italian company in geothermal developments

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INTRODUCTION

Engagement strategies and practices can be considered as part of the concept and practices of Corporate Social Responsibility (CSR), since they help pursuing its main object, that is building a positive dialogue with stakeholders and avoiding potentially negative social and environmental impacts from business operation particularly project development. As the concept and practices of CSR have matured over time, engagement strategies and practices have been changing to cope with such modified CSR landscape. Despite that, research has often overlooked the study of the drivers able to promote such change.

THEORETICAL FRAMEWORK

The research presented grounds on the theoretical framework presented by Delannon et al. (2016). Such framework relies on the CSR literature to study company-community relations and identifies four engagement strategies with different intensities of engagement.

Then, the concept of *Conception* is defined as the ultimate purpose of companies-local communities' relationships (Lopez-Navarro et al., 2018). This concept ranges across four ultimate purposes and mirrors the strategy differentiation of Delannon et al. (2016) (Table 1), because when a company changes its engagement strategy, it is also inevitably changing the purpose to achieve the strategy.

Table 1. Strategies and relation to engagement and conception (see File attached)

Based on this theoretical framework, our research aims at identifying possible drivers able to determine a change of engagement strategy between company and community. Indeed, from the analysis of existing literature, despite the presence of studies on how companies adopt one strategy or another, there are no studies that identify the aforementioned drivers.

METHODS

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The study was conducted through a case study (Yin, 2017) and it investigates engagement strategies of company, in its experience of establishing and maintaining relationships with local communities across time. Those dynamics have been investigated through the case study of an Italian public company, operating in Italy and worldwide, considered an excellence at the global level regarding both technologies adopted in geothermal developments and commitment toward sustainability challenges represented by the 2030 Agenda for Sustainable Development. The analysis aims to e consider as *driver* any event, organisational change, regulatory change or any other modification within the company's modus operandi, as long as such modification was considered by the managers interviewed as crucial for a respective modification of the purpose the strategy.

Data collection was carried out through semi-structured interviews with 11 former and current company's managers (between January and April 2019), covering company's operation from the 1980s to nowadays. Besides interviews, a preparatory collection and analysis of documents was performed, including an analysis of grey a scientific literature, to provide contextual information as an informative basis for the subsequent interviews. After the transcription, a full analysis was performed, with the help of the Nvivo software.

PRELIMINARY FINDINGS

Preliminary findings provide insights on the presence of three main categories of drivers reported below.

- *Extraordinary negative events.* Special events have affected the geothermal developmentsy – i.e. accidents on the geothermal site, creation of committees against the geothermal developments, etc.

- *Regulatory evolution.* Relevant regulatory changes that, for example, impose a different environmental management of the geothermal site, thus leading to a different relationship with the local community.

- *Appointment of new upper-level managers.* The change of a CEO or a high-level manager has determined a modification in the role of the concept of conception (the ultimate purpose of the engagement strategy), therefore a consequent change of engagement strategy with the communities.

Our analysis also shows that the company does not always position itself clearly in one strategy or another at different times of its life, but rather straddles them. This depends on a total or partial implementation across various organizational dimensions, such as financial resources, human resources, measurement tools for evaluating the strategy, etc..

Furthermore, the drivers – and this concerns the most interesting and qualitative aspect of our research – often have a shared impact on the modification of a certain engagement strategy, usually with different magnitudes. For this reason, the degree to which organizational arrangements are modified in respond to a certain driver could represent an estimation of the ability of such driver to determine a change in the engagement strategy.

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Newspaper framing of deep geothermal projects in Alsace, France (2014-2019): news narratives at the service of promoters

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Abstract:

This article analyses how deep geothermal energy has been depicted in national and local Alsatian newspapers since specific projects were approved by the authorities in 2014. A previous analysis of national and local press coverage (Serrano et al. 2019) showed that during the period 2002 to 2018, journalists tended to focus on the positive aspects of geothermal energy, its contribution to the energy transition and climate change mitigation, and avoided referring to negative aspects, i.e. the high cost of geothermal projects, and the risks associated with different technologies. Negative media coverage of geothermal energy was generally linked to specific events, specifically, induced earthquakes. In the Alsatian press, negative coverage emerged during the public consultation on geothermal projects organized by the prefecture in 2015, when press coverage increased significantly.

This particular study of the media focuses on a sub-corpus of 382 articles published between

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January 2014 and February 2020 in Alsatian newspapers (n = 329) and in national newspapers (n = 53) in which the main subject is geothermal energy or Alsatian projects. We analyzed which sources are preferred by journalists, and how they depict geothermal energy and Alsatian projects.

We consider the news reported by the media as one of the public discourses that tend to legitimize the voice of specific social actors (to the detriment of others) concerning geothermal energy. Consequently, it conveys a particular and biased image of this renewable energy and of the actors, citizens, or authorities involved in -or concerned by- geothermal projects. More concretely, although journalists commit to being neutral, to presenting factual reports and more globally to objectivity, their professional practices and the sources on which they rely lead them to write about certain facts or events, while others are set aside or simply ignored. In their daily practice, journalists prefer sources that can be considered as authorities in the field: prefectural experts, industrialists, scientists, or elected representatives. They then 'reconstruct' facts based on these sources by choosing specific words and images rather than others. This whole process leads to a particular framing of geothermal energy that involves narratives about geothermal energy, featuring both promoters and opponents. But these narratives may undermine democratic dialogue on specific geothermal projects.

The analysis presented in this paper is part of a larger research project conducted in the framework of the Risk Governance package of the H2020 DESTRESS programme in connection with *Labex G-EAU-Thermie profonde* [1]. The aim of our research is to understand how public perceptions of deep geothermal energy are formed in diverse political, cultural, and sociological contexts.

http://www.destress-h2020.eu/en/what-we-do/wp3/

Added value of local geothermal resources utilization.

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Introduction

Among the renewable energy resources geothermal is specific to a local production and consumption. Next to the heat and energy production, geothermal energy presents with opportunities for rural and suburban areas linking sustainable development goals with expansion of new local economy sectors. Therefore, we assume that local exploitation of geothermal resources delivers a local added value other than energy generation. Moreover, a change of a municipality socioeconomic structure is presumed while geothermal establishments are introduced. The aim of this research is to fill in the gap in the literature and establish an empirical link between the use of the geothermal renewable and measures of local development. The assumed added value of the geothermal can be analysed as direct, indirect and induced effects on a municipality of exploitation. This research attempts to provide a methodology that measures the induced impact related to the socioeconomic development. The theoretical conceptualization underpinning this studies is reflected in endogenous growth theories as well as in regional economics approach.

Approach

This study attempts to establish a methodology that is able to measure geothermal resources impact on local development. Our approach is to implement the added value analysis of the locations where the renewable is used in multiple forms. Municipalities in Poland are chosen as the main object of the research because of particularly high geothermal potential and private sector experience in bringing up geothermal enterprises. The developed model is to demonstrate the statistical relation between exploited geothermal energy and parameters of local development. The versatility of this study lies in the fact that exercised on the Polish municipality cases our model is applicable for analysis to any geothermal municipality in the world.

Results

Throughout the selected statistical methods we have already obtained significant results to justify our research assumptions. We produced studies where the competitive advantage of using geothermal resources in the local economies is econometrically illustrated. In addition, we observed a faster development of the geothermal municipalities compering to the referred regions. Moreover, we built a local development model with geothermal parameters that we reckon is replicable in further studies about the local geothermal energy impact.

Discussion

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The research aims to deliver statistical argument for the expansion of geothermal resources extraction in Poland and worldwide.
Keywords: geothermal energy resources, local development, comparative advantage, Analytical Hierarchy Process, Principal Component Analysis, Shift-Share Analysis.

CROWDTHERMAL: Community-based development schemes for geothermal energy

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CROWDTHERMAL is a 36 months long project, funded under the European Union's Research and Innovation programme Horizon 2020 (grant agreement n∘857830). One of the major drivers of the project is to support the EU's strategic objective to decrease dependence on fossil fuels, to create a stable energy market, and to reduce the environmental impact of its energy supply. By creating new financial services and communication strategies, CROWDTHERMAL will contribute to the increase of geothermal energy in the gross final consumption, and consequently to the EU's Green Deal to become climate neutral by 2050 and the EU's energy challenge for 2030 to increase the use of renewable energy.
CROWDTHERMAL aims to empower the European public to directly participate in the development of geothermal projects with the help of alternative financing schemes such as crowdfunding and social engagement tools. In order to reach this goal, the following actions will be taken:

- Study the requirements for social licencing and develop a Social Licence to Operate (SLO) model for the different geothermal technologies and installations
- Review any successful case studies, as well as national/EU bottlenecks to alternative financing of geothermal energy in all EU countries
- Formulate new financial models for crowdsourcing on a national and trans-national basis, covering individual member-states and Europe as a whole
- Develop recommendations for a novel risk mitigation scheme that will be complementing the alternative financing solutions while also protecting private investors' interest
- Develop core services for social-media based promotion and alternative financing of geothermal projects, working closely with existing structures & conventional players

At the heart of the project is the innovative solution to tap into alternative finance for geothermal development, strengthening the European portfolio of economically feasible geothermal projects and demonstrating a stronger form of public engagement for the promotion of geothermal energy.

CROWDTHERMAL's core services are designed from the very beginning with long-term sustainability in mind and to continue to exist beyond the EC-funded period, helping geothermal

*Speaker

projects to tap into alternative finance during the years to come.

Led by the European Federation of Geologists, CROWDTHERMAL is implemented by a consortium of 10 partners from 7 European countries, combining extensive experience in large-scale geothermal project development, alternative finance, social media engagement, innovation, education, and international networking on geothermal energy. In addition, 17 EFG Linked Third Parties support the extension of the project database and the dissemination in 18 countries. 10 Advisory Board members support the project with extensive experience in geothermal energy, finance and social engagement.

CROWDTHERMAL consortium:

European Federation of Geologists (EFG), Belgium

Institute for Future Energy Systems (IZES), Germany

University of Glasgow (UoG), UK

GeoThermal Engineering GmbH (GeoT), Germany

La Palma Research Centre (LPRC), Spain

CrowdfundingHub (CFH), Netherlands

Szeged District Heating Co (SZDH), Hungary

Spanish Geothermal Technology Platform (GEOPLAT), Spain

Geothermal Research Cluster (GEORG), Iceland
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Intelligent model for prediction of methane solubility in marine environments

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The solubility of methane in freshwater and marine environments has been intensively investigated over the past decades because of its importance for many geological and hydrogeological studies, e.g. methane-dominated fluid inclusions, geothermal systems and hydraulic fracturing. Data-derived models can find the relation between the value of methane dissolution in the liquid phase and effective parameters. This study describes the application of a Gaussian process regression (GPR) model to estimate methane solubility in aquatic systems containing Na+, K+, Ca2+, Mg2+, Cl-, and SO4-2 over wide ranges of temperature (273.15 to 799 K) and pressure (1 to 2630 bar). Bayesian regularization algorithm was used for the optimization of hyperparameters in GPR model. A dataset including 1674 experimental data of methane solubility was employed for the model development. The predictive performance of GPR model was evaluated based on the statistical criteria. The coefficient of determination (R2) between experimental and predicted values is 0.986 and mean absolute error (MAE) is 0.000246. The results indicate the promising capability of GPR model in prediction of methane solubility in mixed aqueous systems that exists in marine environments.

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How well do we know our models?

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In Geosciences, we face the challenge of characterizing uncertainties to provide reliable predictions of the earth surface to allow, for instance, a sustainable and renewable energy management. In order, to address the uncertainties we need a good understanding of our geological models and their associated subsurface processes.
Therefore, the essential pre-step for uncertainty analyses are sensitivity studies. Sensitivity studies aim at determining the most influencing model parameters. Hence, we require them to significantly reduce the parameter space to avoid unfeasibly large compute times.

We distinguish two types of sensitivity analyses: local and global studies. In contrast, to the local sensitivity study, the global one accounts for parameter correlations. That is the reason, why we employ in this work a global sensitivity study. Unfortunately, global sensitivity studies have the disadvantage that they are computationally extremely demanding. Hence, they are prohibitive even for state-of-the-art finite element simulations.

For this reason, we construct a surrogate model by employing the reduced basis method. The reduced basis method is a model order reduction technique that aims at significantly reducing the spatial and temporal degrees of freedom of, for instance, finite element solves. In contrast to other surrogate models, we obtain a surrogate model that preserves the physics and is not restricted to the observation space. As we will show, the reduced basis method leads to a speed-up of five to six orders of magnitude with respect to our original problem while retaining an accuracy higher than the measurement accuracy.
In this work, we elaborate on the advantages of global sensitivity studies in comparison to local ones. We use several case studies, from large-scale European sedimentary basins to demonstrate how the global sensitivity studies are used to learn about the influence of transient, such as paleoclimate effects, and stationary effects. We also demonstrate how the results can be used in further analyses, such as deterministic and stochastic model calibrations. Furthermore, we show how we can use the analyses to learn about the subsurface processes and to identify model short comes.

*Speaker

Stochastic evaluation of the flow regime on rough and sheared fractures

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The detailed knowledge of the hydraulic properties is crucial for the assessment of geothermal reservoirs. In the case of Enhanced Geothermal Systems (EGS), fluid flow occurs along complex networks of faults and fractures that connect two or more boreholes. The geometric appearance and properties of these fractures are highly variable. They can be e.g. open or closed, altered and/or filled, smooth and rough. All these factors lead to unknown difficulties in predicting fluid pathways and quantifying flow behavior in the fractured reservoir and in the creation of numerical models.
In these numerical models, often highly simplified assumptions regarding flow behavior and geometry are used to project a fracture in 2D. The most common cubic law (CL) allows the calculation of the total fracture flow, while the local cubic law (LCL) considers the local pressure gradient as well as a local aperture. However, both flow laws pose the same problems: 1) The law is only valid for simple 2D geometries, 2) the aperture is defined and measured differently and 3) laminar Darcy flow is assumed. If these boundary conditions are no longer valid, e.g. during hydrotesting or in the vicinity of wells during production/injection, the complex and nonlinear Navier-Stokes equations must be solved.
We present the results of flow modeling in rough and sheared fractures by solving the Navier-Stokes equations. Using thirty statistically generated tortuous fracture geometries, the effects of different pressure gradients and flow directions on the formation of preferential fluid pathways and expected flow rates are investigated. The results show a strong dependence on aperture definition and shear direction with respect to flow rates and the formation of preferential fluid pathways. The flow perpendicular to the shearing is about 45 % higher than parallel to it. First nonlinear effects are detectable for a mean Re about 1. Within the identified channels, a laminar flow field can be maintained much longer, while outside the channels, mainly due to irregular geometries, nonlinear effects occur even for Re far below 1. The LCL leads to a mean overestimation between 5 and 15 %, depending on whether the fracture is flowed through perpendicularly or parallel. These differences mainly occur outside the identified channels, while inside the channels the parabolic flow field leads to reduced deviations.

*Speaker

Sensitivity analysis of an iterative ensemble Kalman filter method to interpret geothermal well logging

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The objective of drilling geothermal wells is to produce a flow of hot water, so formations with high porosity and permeability are targeted to place wells; well loggings such as density, neutron porosity, gamma ray and resistivity logs provide valuable information about the location of boundaries, lithology and permeable zone of the formation. To interpret the formation parameters from well logs, an inversion algorithm will be applied. The inversion model is started from an initial set of formation parameters. A forward physics-based model will simulate (forecast) the well logs. The simulated results will be updated (analyzed) by assimilating the well logs.
However, well logs are uncertain, and several parameters contribute to their quality, which must be quantified before making a decision about well placement.

The traditional Monte Carlo has been method used for uncertainty quantification, which requires thousands of forward simulations. In modern well placement, which aims to be used in real-time operation, a computationally efficient and robust log interpretation algorithm is required; In this study we propose to apply an iterative variant of standard Ensemble Kalman Filter (EnKF), which is a Monte Carlo approximation to the well-known Kalman Filter, to interpret well logs.

We validated applicability, robustness, and efficiency of the ensemble Kalman filter method by interpreting density logs for different constructed synthetic cases contains 40 formation layers with varying thicknesses. We chose the density log due to its simplicity and because we have access to its forward simulation. Density logs measure the number of electrons in a formation volume, which is proportional to bulk density and in combination with other logs can indicate the formation fluid and its porosity.

The results of several synthetic cases verified that the applied iterative ensemble method is applicable to analyze the model parameter, bulk density, by employing as few as 50 ensemble members and with three iterations, for a total of 150 forward simulations. We concluded that the ensemble-based method of the Kalman Filter is computationally efficient and robust for density

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logs. The updated model parameters have low and acceptable uncertainty in all synthetic cases; the method is applicable and robust in log interpretation in real-time operation.

Aspects of charge balance in modeling reactive transport of aqueous species in porous media

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Geochemical reactions can play an important role in geothermal operations, e.g., in mineral scaling or mineral recovery from produced brine. Brines in geothermal reservoirs consists of multiply-charged species. When applying standard tracer transport models to problems with multiple ions, an unrealistic build-up of charge can occur. The typical way to avoid this problem is to assign the same diffusion coefficient to all charged species. However, this approach does not provide the same results as a full treatment of electrical migration (Steefel, 2008).
The key to address this problem is including charge conservation to the transport model. The Nernst-Planck-Poisson approach explicitly solves the electrostatic potential. Sprocati et al. (2019) and Agnaou et al. (2020) implemented such an approach to model reactive transport in porous media. Another approach uses a concentration-dependent diffusivity (Boudreau et al., 2004) to ensure electroneutrality. This concentration-dependent diffusivity can be easily implemented in forward time-stepping numerical methods. We implement this method in our reactive transport solver based on FEniCS (Alnæs et al., 2015) and Reaktoro (Leal et al., 2017). We benchmarked our code using advection-diffusion of salt using different diffusivities for sodium (Na+) and chlorine (Cl-). Furthermore, we present preliminary results of modeling chemically driven convection in porous media (Almarcha et al., 2010). Our results show that the conservation of charge is essential in modeling reactive transport in porous media.

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Effect of fracture closure on hydraulic diffusivity

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The hydraulic diffusivity describes how the pressure diffuses in fractured porous medium, which is of great importance for numerous fields of research and industrial applications like induced seismicity related to deep geothermal energy. Since fractures or fracture networks dominate the fluid flow in impermeable rock mass, it is important to know the hydraulic diffusivity of natural rough fractures. To quantify it, we conducted finite element numerical simulations of transient fluid flow in a single fracture at the reservoir scale ($\sim$ 500 m). Geometry of synthetic fracture apertures were built from a self-affine model with isotropic Hurst exponent derived from fault surface observations (Candela et al, JGR, 2012). An effective hydraulic diffusivity of the fracture was estimated by fitting the pressure field with the analytical solution of an equivalent parallel plate model (i.e. with the same mean aperture). We performed the forward pressure diffusion modeling in rough fractures varying the degrees of openness and observed that the roughness and the related contact area could significantly affect the effective hydraulic diffusivity of the fracture. Fractures with large opening are similar to the parallel plate model with the same hydraulic aperture, and the effective hydraulic diffusivity is close to the one predicted by the 1D analytical solution. As we close the fracture, the effective hydraulic diffusivity deviates more and more from the parallel plate model and shows either isotropic or anisotropic behaviors by enhancing or reducing the diffusivity according to the orientation of the pressure drop and the development of the channeling effect. Owing to the self-affine property, large residual opening exists even with small hydraulic aperture. Furthermore, based on a fully plastic model of the asperity contact, we observe that the effective diffusivity of the fracture decreases by 7 orders of magnitude when closing the fracture to the fluid percolation threshold, which can be comparable to the field observed values.

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The EPOS Anthropogenic Hazards platform (TCS-AH) : a virtual laboratory for geothermal studies

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The EPOS Thematic Core Service on Anthropogenic Hazards (TCS-AH, https://tcs.ah-epos.eu/) is designed as a functional e-research infrastructure that provides access to a large set of relevant data and allows free experimentations in a virtual laboratory, promoting interdisciplinary collaborations between stakeholders (the scientific community, industrial partners and society).
The platform provides datasets as Episodes, which comprehensively describe Anthropogenic Hazards (AH) cases for infrastructures, people and/or environment. They are grouped in several categories of subsurface exploitations, one of them being geothermal energy production. Datasets describe various projects, including Soultz-sous-Forêts, Cooper Basin, Gross Schoenebeck, St. Gallen, The Geysers, and Carbfix. Users can access relevant datasets (e.g. seismic waveforms and catalogue), industrial data (e.g. well path, injection rates, wellhead pressure), and other geodata (e.g. geological section, velocity model, faults). The platform grants access to an application portfolio, designed for the AH area, from basic services (data integration and handling, physical modeling) to probabilistic assessments of anthropogenic seismic hazard and to simulator for multi-hazard/multi-risk assessment in exploration/exploitation of geo-resources.

Two local data centers (eNodes: IG-PAS/Poland and CDGP-EOST/France) provide the metadata and data to the TCS-AH platform in commonly used standards and formats (e.g. miniSEED, GeoTIFF, and Matlab). A registration/authorization is mandatory to access some data covered by restriction imposed by data industry providers or shared data embargoed by running projects.
TCS-AH is one of the 10 TCS forming the EPOS infrastructure.

*Speaker

Data relative to recent geothermal exploration sites in Alsace

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The Data Center for Deep Geothermal Energy (CDGP – Centre de Données de Géothermie Profonde, https://cdgp.u-strasbg.fr) was launched in 2016 by the LabEx G-EAU-THERMIE PROFONDE (http://labex-geothermie.unistra.fr) to preserve, archive and distribute data acquired on geothermal sites in Alsace.
Data currently available on the CDGP consist mainly of seismological and hydraulic data acquired at the Soultz-sous-Forêts geothermal plant pilot project. Data on the website are gathered in episodes. Episodes 1993, 1994, 1995, 1996, 2000, 2003, 2004, 2005 and 2010 from Soultz-sous-Forêts are available on the CDGP. All data are described with metadata and interoperability is promoted with use of open or community-shared data formats: miniSEED, csv, pdf.

CDGP is currently adding data from recent geothermal sites in Alsace near Soultz-sous-Forêts or around Strasbourg: Ritteshoffen development phase (RITD, ECOGI, 2012-2014), Vendenheim development phase (VDHD, 2016-, Geoven-Fonroche), Illkirch development phase (ILLD, 2018-, ÉS Illkirch Géothermie). The VDHD episode includes seismological data related to the triggered swarm below Strasbourg on November 2019. In a first step we provide published and open data collected by observatories, but operators were asked to make hydraulic and other data available, at least for academic research.
Data are curated and therefore may differ from published data available on editor's sites, are described with metadata, and are distributed according to rules set by data owners.

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Modelling and minimisation of the thermal interference effect of neighbouring geothermal licenses

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In a future scenario, the successful development of geothermal industry, will result in the large scale deployment of new deep geothermal projects. In highly populated areas, such as the Netherlands, such a development will lead to a dense grid of neighboring licenses. In such situation a new project requires careful design and planning as the available subsurface space can become scarce, leading to the potential interference with the neighboring licenses and competing usage of the resources. Interference can cause the reduction of lifetime, produced energy, and the profitability of neighboring projects. Therefore, it becomes important to consider the thermal interference while designing these systems in such dense areas to be able to obtain maximum energy and profit without hindering neighbors. Our research project assesses this question of thermal interference in neighboring geothermal systems and possible solutions for the long-term efficiency in geothermal energy provision using a numerical simulation approach.
To generate a numerical model capable of describing and predicting the effect of thermal interference we used the software package COMSOL Myltiphysics 5.5. The physics of fluid flow and heat transfer in porous media are applied to the reservoir model, and the finite element method is used to approximate the solution of these equations. Sensitivity analyses are performed on all input parameters as a post-processed simulation to control their influence on the output performance. The input parameters are divided into two categories; operational-controlled parameters: injection temperature, flow rate of injection, well spacing, well distance to border of the license area, and well location; and natural-controlled parameters including permeability and its anisotropy as kx/ky ratio. At the end of the parametric sensitivity analysis, an economic model is used as an instrument to evaluate how these input parameters can affect the long-term project feasibility.
The main finding in this study is that a careful design of the doublets' distance from each other, flow rates, and injection temperature is needed (adjusted to the natural control parameters) in order not to hinder neighbors profitability (produced energy and economic benefit). The results of this project can be used as a preliminary input informtion for geothermal system designers and decision makers for the licensing in densely spaced subsurface developments.

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Source parameters of the Ml3.0 Strasbourg Earthquake (12th November 2019)

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On the 12th of November 2019, a sequence of earthquakes, culminating at 13h38 (UTC) with anevent of magnitudeMl= 3.0 (called herafter the M3 event) , occurred just 5 km north of Strasbourg(identified and considered by the R éNaSS as an induced event). The largest event was widely felt inthe area and raises several questions about its origins, the fault structure on which it takes place andits mechansim. Here we investigate the source properties and the focal mechanisms of the largestevents of this sequence. We take advantage of the numerous recordings of the events to gather aset of seismic waveforms for all the largest events. By applying a spectral decomposition technique(Shearer & al., 2006), we are able to separate the source term of the M3 event from an attenuationterm and a station term. We show that the source displacement spectrum can be adequately fittedby a simple spectral model from Brune, 1970. The inferred moment is M0= 6 1013N mequivalent to Mw= 3.1 (using the Hanks & Kanamori, 1979 moment magnitude scale). This methodis only efficient in recovering the source property of the M3 event and failed to properly estimatethe source spectrum of the smaller events. In order to estimate source properties for the other largeevents of the sequence we turn to a spectral ratio approach (Lenglin e & Got, 2011). As all events ofthe sequence are located in a compact region (relative to the distances to the stations), at a commonstation, the recordings of the two events will differ only by their respective source terms all the othercontribution being similar will cancel out when computing the spectral ratio. We apply this method for each available recording of the S-wave for all events in the sequence with a localmagnitude higher than Ml= 1.7. Each event is compared to the spectrum of the M3 event. We obtain for the M3 event a corner frequency of 5.4 Hz suggesting a rupture length of 175 m (assuming a typical rupture velocity of 1015 m/s). For the other events, nine in total, we find that their respective corner frequencies and moment are all in agreement with a constant stress drop of 3.9 MPa.These results give some useful information for characterizing the fault network associated with thissequence of events.

*Speaker

Investigation of the Uncertainties in the Thermal Modeling of the RN-15/IDDP-2 Well in Iceland

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During the drilling of geothermal boreholes, the determination of down-hole and earth temperatures is often a challenging task due to the fact that the temperatures are a function of various variables such as borehole geometry, flow rate, shut-in times, penetration speed of the drilling bit, fluid and formation properties etc. To account for these complexities of heat transfer in a well, numerical modeling techniques are needed. Herein, an in-house simulation tool was applied to a high-temperature geothermal well-RN15-IDDP2, in Reykjanes, Iceland. The well was drilled for 168 days during which nearly total drilling fluid loss was encountered below 3.4 km. Several temperature logs were recorded under transient flow conditions. We chose one of the temperature logs which was measured after 145 days' cooling of the borehole and performed semi-synthetic thermal modeling analysis. Three major uncertainty factors affecting the outcome of the borehole temperature prediction were investigated. The first aspect is the time averaging scheme for the long-term flow history which would mainly affect the accuracy of the input data for the boundary condition at the wellhead. Specifically, three different flow rates were chosen: a constant flow rate averaged over 145 days' period (S1), daily averaged flow rates (S2) and daily averaged flow rates for the first 131 days followed by every-ten-minutes-averaged flow history over 14 days' period (S3). The results show that using S1 lead to a maximum error of 19 ∘C in temperature predictions along the borehole. Whereas using S2 result in negligible errors (max.0.07 ∘C) which implies that only S2 can be used as proxy of fine time scale data S3. The second aspect is the change of the well depth during the drilling. Comparisons were made between two scenarios where a pre-existing well and a well under development were assumed. The results indicate that assuming a pre-existing well would under-estimate the temperatures, with the maximum error occurring at the bottom-hole (_˜15 ∘C). The last aspect is the temperature logging speed which is an additional modeling constraint due to time-dependent spatial sampling. Our study shows that in cases where instantaneous picture of the temperature distribution in the borehole have to be assumed due to the missing of the information on the measurement time, a large error up to 40 ∘C in the temperature predictions can be made. In summary, this study has clearly demonstrated that the accuracy of the input data, i.e. the flow rate history, drilling progress and the spatial-temporal record of the temperature measurements, plays very import role in the numerical modeling of the borehole temperature logs, especially in highly dynamic drilling conditions.

*Speaker

Seasonal temperature forecasting for geothermal wells using Artificial intelligence: conceptual design for Dholera, Gujarat

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A hybrid geothermal plant has been setup in the Dholera city of Gujarat, India which utilizes solar and geothermal energy for power production via an Organic rankine cycle. Frequent use of geothermal water reduces the temperature of the reservoir and hence reduces the efficiency of the power generation system. The Artificial intelligence(AI) has established itself as an effective tool which utilizes current data for predicting future data and providing solutions to mitigate any problems associated with present system. Authors have collected large amount of data of geothermal water on the surface data based on seasonal variations. The concept of artificial intelligence may be utilized to predict the seasonal changes in the geothermal temperatures of the reservoir. The AI can be used to predict the most optimal time for the usage of the hybrid system so that the system works at its maximum capacity. The power thus generated can be stored in batteries or thermal storage devices and can be utilized during either night time or any other time when both the renewable energies are not present. The short comings of such system are several but with more data collected, the system will become more robust and practical. These types of systems can also be implemented in oil and gas wells to predict the production and troubleshooting.

*Speaker

Upscaling of Geothermal Processes in Heterogeneous Formations: Application of Thermal Taylor Dispersion

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Transverse thermal conduction in geothermal processes causes extra spreading of the cooling front: thermal Taylor dispersion. We derive a model from an energy balance for effective thermal diffusivity, αeff, to represent this phenomenon in layered media. Accounting for transverse heat conduction, αeff is much greater than the longitudinal thermal diffusivity, leading to a remarkably larger effective dispersion. A ratio of times is defined for longitudinal thermal convection and transverse thermal conduction, referred to as transverse thermal-conduction number NTC. The value of NTC is an indicator of thermal equilibrium in the vertical cross-section. Both NTC and αeff equations are verified by a match with numerical solutions for convection/conduction in a two-layer system. For $NTC > 5$, the system behaves as a single layer with thermal diffusivity αeff. When $NTC > 5$, a two-layer system can be combined and represented with αeff and average properties of the constitutive two layers. Then, an upscaling approach is developed for simulations of geothermal processes in stratified formations, by grouping layers based on the condition of $NTC > 5$ and αeff model. Specifically, NTC is calculated for every adjacent pair of layers, and the paired layers with a maximum value of NTC are grouped first. This procedure repeats on the grouped system until no adjacent layers meet $NTC > 5$. The upscaled layer properties of the grouped system are used as new inputs in the numerical simulations. The effectiveness of the upscaling approach is validated by good agreement in numerical solutions for thermal convection/dispersion using original and average layer properties, respectively (Figs. 1 and 2 in the Supplementary Data File). The upscaling approach is applied to well-log data of a geothermal reservoir in Copenhagen featuring many interspersed layers. After upscaling, the formation with 93 layers each ranging from 1 – 3 meters is reduced to 12 layers (Fig. 3 in the Supplementary Data File). The effective thermal diffusivity, αeff in the flow direction is about a factor of 10 times greater than original thermal diffusivity of rock. This greatly simplifies the description of a geothermal reservoir and provides a more accurate representation of convection/dispersion processes.

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‘Where to drill the next well?’ and ‘How to operate a geothermal system in the most efficient and safe manner?’

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These are the most important and urgent questions after a geothermal resource has been identified. The drilling success in geothermal systems can be enhanced through a better understanding of the subsurface. Here, the location of permeable fluid pathways is a key strategic step. Once the geothermal system is running, the sustainable operation is most essential also for the payback. The sustainability is mainly depending on the interaction between fluids, rocks and layout of power-plant components. Additionally, every geothermal project highly depends on the perception in the public. Factors influencing the perception are, among others, media and politics.
Two recently granted projects will answer these questions from different perspectives and give high-level training to PhD students.

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A triggered seismic swarm below the city of Strasbourg, France in November 2019

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On Nov 12, 2019, a Ml3.0 earthquake was felt by the whole population of the city of Strasbourg, France. It was located by the BCSF-RéNaSS (EOST) in the northwestern part of the town (Robertsau area) at a depth of 5.5km. Its location in the vicinity of the deep geothermal wells (GEOVEN), the temporal correlation with the injection activity on site, the similarity of the depth between the bottom of the wells and the hypocenter of the event, the lack of local seismicity before the event occurrence, the known geological structures including crustal faults in the area, immediately questioned the possible triggering of the event by the deep geothermal activities despite the relatively large distance (4-5km). In order to assess the origin of the Ml3.0 event, we report here on the data analysis performed from the seismological monitoring of the local area using the catalog produced by BCSF-RéNaSS and the regional public seismic networks. The main result is that the event is part of a remote triggered swarm that was initiated at least six days before the main shock and lasted more than three months. Template matching has been applied and allowed for a significant improvement of the detections. Double-difference relocations evidenced a set of conjugated faults in the swarm area that extends over 800m. Focal mechanisms of the two main events are very consistent with the known regional fault in the area. The regional stress field in combination with the fault orientation and a Coulomb failure criterion shows that the swarm location is in an unstable domain if the cohesion of the fault is weak, particularly sensitive to stress perturbations. Recent reactivation of the swarm after new geothermal activities confirms the proposed triggering process. *This presentation is dedicated to the memory of Prof. François Cornet.*

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Hydrothermal alteration research in geothermal systems: any news for the future?

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Active geothermal systems constitute a unique natural laboratory for the analysis and characterisation of heat-fluid-rock interactions. The possibility of sampling using drilled wells, in some cases up to 2-3 km depth, in a same geothermal field allow the possibility to model hydrothermal alteration processes both in a vertical as in lateral dimensions, allowing tracking fluid-flow processes. Also, if depth wells are available, it is possible to model and understand how thermal fluids react with the hosted rocks and how both, fluids and rocks, could change their composition. On the contrary with fossil geothermal systems, or with exhumed hydrothermal altered areas, active geothermal systems allow direct sampling of thermal fluids and host rocks that are currently reacting. In this sense, Browne (1978) suggested that active geothermal systems may be regarded as large-scale, uncontrolled, open-end natural experiments. Several papers were published after that excellent review and a particularly good summary about the parameters controlling hydrothermal minerals in geothermal systems was provided by Reyes (1990). Temperature, permeability, pressure, fluid composition, initial host-rock composition, duration of hydrothermal activity and number of hydrothermal regimes seems to be the main controls on the formation of hydrothermal minerals in geothermal systems. Consequently, the analysis and precise identification of the hydrothermal mineral paganesis existing in a precise geothermal system will provide us qualitative and, even in some cases, quantitative information about these forming variables. Moreover, Henley & Ellis (1983) proposed the understanding of ancient, already exhumed geothermal systems, as an extra way to approach our constraints to the active ones.

Different techniques have been currently used for the identification of hydrothermal mineralogy, including optical microscopy, X-ray diffraction (XRD), electron microscopy (EMPA and SEM) and fluid inclusions. Probably XRD studies are particularly relevant in geothermal exploration because allow to identify the clay mineralogy progression, in particular de I/S and C/S reaction progress that is responsible for the change in resistivity of country rocks, allowing the MT identification of the clay cap (dominated by smectite and illite/smectite mixed layer) in contrast with the reservoir domain, characterized by propylitic alteration and where chlorite is present. However, the reaction progress of these clay minerals is not so straightforward as evidenced by detailed high-resolution transmission electron microscopy (HR-TEM) suggesting more complex interlayering mechanism not only temperature controlled. Kinetic of interlayering mechanism must be considered and local host rock composition, texture and permeability seems to control the progression of clay minerals under typical disequilibrium conditions that dominate geothermal systems.

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Future advances in geothermal research must include the precise quantification of one of the main factors of fluid-flow: the permeability. It is a real challenge how to quantify effective permeability under reservoir conditions. Moreover, the comprehension of how permeability change along fractures zones open new concepts about fluid-flow-fractures. Recent experimental work in several advanced laboratories begin to give critical information about the fluid and heat pathways along fractures, opening a new window for the research. In this same sense, recent advances of the micro-CT technique highlight interesting and exiting results allowing to understand how hot fluid react with host rocks. Experimental works in some research labs, as GNS in Wairakei (New Zealand) are also providing interesting results because the can reproduce reservoir conditions at the laboratory scale, obtaining challenging data.

And, of course, one of the major open question is in relation with the timing and duration of geothermal systems. Conventional radiometric dating methods are not so precise for dating active hydrothermal processes. However, interesting results could be obtained using high-spatial resolution U/Th dating in calcites. This technique is currently used for dating corals, speleothems and Quaternary calcite filling fractures. The possibility to apply this technique to geothermal system could open a new look about the duration of hydrothermal alteration and its timing.

The future of hydrothermal alteration research in geothermal systems is completely open. New high-resolution analytical techniques will allow us to move from the micro and nano-scale to the conceptual model. Moreover, the possibility to expand our researchers to ancient exhumed systems will allow to take a look at the past for understanding present-day geothermal reservoirs.

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Research community contribution to the Deep Geothermal Implementation Working Group

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The Implementation Plan (IP) for the research field Deep Geothermal Energy formulates the strategic research and innovation goals of the European Member States and the Commission in this sector. It contains concrete Research and Innovation activities and proposes relevant financing options for their realization, which are considered essential for achieving the agreed objectives.
The session is dedicated to the ongoing revision of the IP and the role of geothermal research in Europe. The elaborated amendments of the IP will be presented by the Joint Programme Coordinator of the EERA Geothermal Joint Programme, Inga Berre.

To give a broader overview of European geothermal research, we will welcome a representative of the European Commission, Matthijs Soede, with his presentation on deep geothermal research in the context of the Green Deal.
We will also discuss the EERA Joint Programme Geothermal, its importance in the European geothermal landscape and the advantages for the participating scientific institutions.

*Speaker

Author Index