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From Underground to Surface: Energy provision and Distribution

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From Underground to Surface: Energy provision and Distribution

Event organized by the Research Department of Subsurface Modeling and Engineering (RD SME) from Ruhr-Universität Bochum

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Deputy Speaker: Prof. Dr.-Ing Markus Thewes

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Preface

This document presents a compilation of abstracts that have been submitted and accepted for presentation at the workshop entitled "From Underground to Surface: Energy Provision and Distribution," scheduled for November 30, 2023. The increasing emphasis on minimizing the global carbon footprint necessitates collaborative scientific endeavors across diverse disciplines. To confront this intricate challenge, interdisciplinary scientific cooperation emerges as indispensable for gaining a comprehensive understanding of potential energy sources, associated hazards, and the efficient distribution of energy for advancing human activities. Among the potential approaches are exploiting geothermal reservoirs or temperature variations linked to seasonal changes, storing heat underground and extracting raw materials crucial for the energy transition found in waste materials from mining activities. Mitigating hazards requires an in-depth comprehension of structure and composition of both the deep and shallow subsurface, achievable through a combination of experimental work, numerical analysis, and theoretical modeling. Once the potential energy sources are identified, and the requisite modeling is conducted, the effective distribution of energy through efficient systems becomes the final step in the global efforts to reduce carbon emissions. This holistic approach, encompassing exploration, hazard reduction, and efficient distribution, underscores the significance of interdisciplinary collaboration in navigating the complexities of sustainable energy provision and distribution.

Abstracts

Giant carbonate veins as traces of hydrothermal fluid pathways in exhumed analogues of geothermal reservoir

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The potential geothermal reservoir of Western Germany is represented by Devonian carbonates underlying a vast portion of North Rhine-Westphalia at depths between 1.3 km and 6 km. To reduce uncertainty regarding the structures that can control hydrothermal fluid flow in the buried Devonian reservoir, here we studied the orientation and textures of giant calcite-dolomite veins in Devonian carbonates exposed in the Steltenberg and Donnerkuhle quarries, near Hagen. These veins represent a fossil geothermal system and can provide a snapshot on paleo-structure/stress orientations that controlled geothermal fluid circulation in the potential Devonian geothermal reservoir. Calcite-dolomite veins are mainly subvertical, N-S- to NNW-striking, and up to 10 meters thick (common thicknesses between a few tens of centimeters and 2-3 meters). Accordingly, these orientations represent past flow directions of hydrothermal fluids. Subvertical, or steeply SSW- to NNE-plunging vein intersections were additional enhanced, pipe-like fluid flow directions. Veins probably filled strike-slip and extensional faults generated during late to post-Variscan orogeny. Veins formed by multiple crack-and-seal events through hydrothermal fluid flow and mineral precipitation and opened under a main E-W to ENE extension direction. Calcite crystals grown roughly perpendicular to vein walls and show elongated-blocky to blocky textures, indicating precipitation into open fractures that remained open until their sealing. Vein filling is also characterized by host rock slivers that are not in contact each other, floating within calcite-dolomite crystals. All this evidence suggests that newly created fractures were zone of low pressure, where the surrounding fluids were suddenly sucked into, and the subsequent pressure drop favored the fast precipitation of calcite-dolomite crystals keeping clasts in suspension, as typically occur in co-seismic hydrothermal breccias. Such textures and large vein opening are also common in veins from epithermal mineral deposits and points towards lithostatic load and low differential stress during vein development at shallow depth environments.

Amethyst-agate geodes deposit from Uruguay: insights from one-phase fluid inclusions and stable isotopes

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The amethyst and agate geode deposits from Los Catalanes Gemmological District in Uruguay correspond to one of two main deposits of its kind in the world, and their production and export play an important role in the economy of Uruguay. The geometry of the deposit is horizontal, with an irregular distribution of geodes within basalt lava flows and strong variations in their abundance as well as quality, geometry, and shape. Reliable exploration guides are scarce, and the limited knowledge on the geological parameters controlling its occurrence means that the exploration is unpredictable, and the estimates of remaining reserves are unclear. Based on novel applications of cutting-edge methods including nucleation-assisted microthermometry of single-phase fluid inclusions and triple oxygen isotope analysis of different minerals of the deposits and of water hosted inside the geodes we are able to constrain with unprecedented detail the crystallization temperatures of the mineralization, and composition and origin of the mineralizing fluid. The mineralization of the geodes corresponds to a secondary process that took place in a low-temperature environment between 15 and 60°C, after the emplacement of the complete basalt pile, as indicated by the coincidence of the fluid inclusions and isotope data independent of the stratigraphy of the three mineralized lava flows. The mineralizing fluid present isotopic signatures consistent with meteoric water and very low salinities from pure water up to 3.8 wt% NaCl-eq, likely sourced from the groundwater hosted in the aquifers in the basaltic sequence and underlying units. Based on the insights provided by the new data, we propose a mineralization model for the Los Catalanes deposits that involves a combination of open- and closed-system crystallization inside pre-existing cavities during episodic injections of fluid in a rather stable geological context.

Keywords: Amethyst geodes; Fluid inclusions; Triple oxygen isotopes; Los Catalanes Gemmological District; Paraná-Etendeka LIP

Thermochronology and geothermal systems: from nuisance to exploration tool and the challenges to overcome

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Thermochronology is an increasingly common study area that uses different techniques to reconstruct a variety of geological processes in the upper crust, such as the exhumation of active orogens and passive margins, or the thermal history of Phanerozoic basins and their potential as hydrocarbon systems. It is a sub-area of geochronology that is based on the thermal sensitivity of geochronometers to reconstruct the T-t (time-temperature) paths of the analyzed sample. In other words, it uses the classical concept of closure temperature to track the transition from open- to closed-system behavior. However, the closure temperature of a thermochronometer is not a "hard" boundary, but instead represents a temperature interval that is dependent on the cooling rate of the studied sample, which means that the T-t histories modelled from the available data are non-unique solutions. In this context, geothermal systems are typically seen as "nuisances" for earth scientists interested in reconstructing the regional evolution of a study area, and are not uncommonly invoked as catch-all solutions to explain (and discard) outlying data. Recent studies, however, have demonstrated the usefulness of thermochronology as a geothermal exploration tool capable of determining the lifespan of hydrothermal systems, i.e., by investigating the longevity of hot springs. This presentation illustrates these concepts and presents recent examples of this application. In addition, it discusses how common causes for uncertainty in thermochronology act as important challenges for more widespread application, and gives examples of the methodological work necessary to address them.

Getting the big picture right: tunnel lining safety prediction based on measurements deploying an AI-FEM-based concept

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The expansion of the underground infrastructure and the necessity to maintain the full functionality of the existing tunnels highlights the role of structural health monitoring in keeping track of the behaviour of the structure over time.
In the presented study, the focus is on segmental tunnel lining for deep and long tunnels. The idea resides in exploiting the availability of strain measurements on-site to predict the full stress field in the lining in real-time by combining finite element analyses and machine learning algorithms. The issue of the discrepancy between numerical models and reality is discussed and some strategies are proposed for the detection of the aforementioned mismatch using the available measurements. The application of the concept is accomplished on a full-scale experiment, wherein piled lining rings are tested under a geostatic-like loading condition.

Underlined name denotes presenter

A Deeponet Approach for the Fusion of Simulations and Monitoring to predict Settlement Field in Mechanized Tunnelling

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The assessment of surface settlements during mechanized tunnelling is of importance and remains a challenging research topic. Generally, the surface settlement can be predicted using different paradigms: either a physics-driven approach utilizing computational models, or a data-driven approach employing machine learning techniques to establish mappings between influencing factors and ground settlement. In this work, we introduce a multi-fidelity deep operator network (DeepONet) framework to combine the advantages of both approaches and assimilate the data from different sources. The presented framework, which leverages the recently developed operator learning methods, comprises two components: a low-fidelity subnet that captures the fundamental ground settlement patterns obtained from finite element simulations, and a high-fidelity subnet that learns the nonlinear correlation between numerical models and real engineering monitoring data. The results show that the proposed method can capture not only the physical laws governed by numerical simulations, but also accurately fit measured data as well. Remarkably, even with limited noisy measurement data, our model can still provide rapid, precise, and robust reconstruction of the full-field surface settlement in real-time during mechanized tunnelling.

Keywords: DeepONet, Multi-fidelity, Tunnel boring machine, Ground settlement prediction, Physics-informed machine learning

Water-assisted cracking in Anröchter sandstone

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Rocks are known to become weaker in the presence of water. The reduction in rock strength is due to water-assisted mechanical or physicochemical effects, or some combination of the two, and has important implications for geomechanical and geoengineering applications. Here, we present laboratory indentation tests that are designed to simulate the initial stage of mechanical excavation: the penetration of a cutting tool into a rock. We used a blunt indenter that mimics a section of a cutting disk, such as the ones used in tunnel boring machines, to indent Anröchter sandstone, which contains up to 64% calcite and has 4% to 10% porosity. The experiments were performed at room temperature, under oven-dry, water-saturated, and wetted-surface (by water or decane, which is chemically inert for our purposes) conditions, using 5 different loading rates spanning 4 orders of magnitude (8.3x10-5 mm/s to 8.3x10-1 mm/s). Our results show that the highest values of peak indentation force, the force required to break the specimen, were recorded for the oven-dry and the decane-wetted specimens. On average, the water-saturated specimens required the least peak indentation force to break. The absence of weakening in the decane-wetted tests suggests that water facilitates fast-acting physicochemical weakening, even at room temperature. Our findings suggest that excavation efficiency could be improved by controlling the chemical environment at the contact between the rock and the excavating tool.

Experimental investigation of coupled thermo-hydro-mechanical behaviour of Kaolin

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Due to developments in the field of renewable energies the geothermal use of geotechnical structures, which enables an environmentally friendly way of heating and cooling buildings, is gaining importance. Such structures no longer serve only to transfer loads into the ground, but also as heat exchangers between the structure and the surrounding soil. Advantages of this technology are the reduction of the CO2 emission for heating and cooling of new buildings up to 50%, the reduction of the consumption of fossil energy sources along with the reduction of energy transportation. Energy piles are the most prominent example of such geothermally used structures. The energy pile concept has been successfully applied in some countries such as the UK, Switzerland, Austria and Germany, while other countries are reluctant to accept this technique mainly due to concerns regarding the potential impact of temperature cycles on the load capacity and settlements. This applies specially to piles installed in fine-grained soils such as silts and clays since only few research studies have been conducted in these areas to date.
Former studies have shown that the response of fine-grained soils under thermal loads are dependent on the load history of the soil. It has been largely demonstrated that a normal consolidated material contracts mostly irreversible upon heating while a highly over consolidated material experiences a reversible volume expansion. In the scope of this study lies the soil behavior under coupled thermo- hydro-mechanical loading with temperature and suction varying in a cyclic manner. To address this issue an experimental campaign that covers numerous combinations of thermo-hydro-mechanical loading paths is conducted. Therefore, test devices that enable tests at elevated temperatures along with the control of suction and mechanical loads have been developed and will be presented. The tests comprise suction-controlled oedometric tests and triaxial tests with variation of temperature and initial state of compacted Kaolin samples. The experimental observations are further used to validate and enhance existing constitutive model for coupled thermo-hydro-mechanical loading paths.

Statistical approach to characterize stress field heterogeneity

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Stress tensor determination is of importance in many aspects of geothermal energy provision, from the understanding of the propagation orientation of newly created fractures to the control of the predominant stimulation mechanism, hydro-fractureing vs. hydro-shearing. Hydraulic stimulation experiments were carried out in a Gneiss formation penetrated by the research mine Reiche Zeche in Freiberg, Germany, in the framework of the STIMTEC and STIMTEC-X projects. Key objectives were to enhance hydraulic properties and characterize the stress field of the rock volume. Injection tests were performed in 28 intervals with 1 m length enclosed by y double-packer probe, either with pre-existing fractures or initially intact, distributed in 7 boreholes crisscrossing in a rock volume of 60×30×30 m^3. The data from the injection experiments typically used to determine components of the stress tensor comprise shut-in and jacking pressures and the orientation of the pressurized fracture. Impression packer testing and acoustic televiewer logging revealed multiple fracture traces for a number of intervals and thus we face ambiguity regarding the hydraulically relevant fractures. In total, the data set comprises 28 characteristic pressures assumed to correspond to the normal stress on a fracture and 60 fracture traces. Variability of recorded pressures and orientations shows that a uniform stress tensor cannot explain all the observed data but that the stress field is heterogeneous. To characterize the stress field in the rock volume, we developed a statistical approach consisting of a Monte Carlo analysis of random combinations of subgroups of intervals, i.e., including 5 to 28 intervals, with one fracture trace randomly selected out of the observed traces for each interval. The number of possible combinations is 1.3E+8 prohibiting a full inversion for each combination but motivating the Monte Carlo approach. Using the minimum number of intervals required to invert the stress field, i.e, 5 intervals since a constraint in the vertical stress is given by the overburden, the number of combinations reduce to 8E+4. We statistically investigate the influence of each particular interval and fracture trace in the probable stress regime.

Fault roughness controls injection-induced seismicity

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Surface roughness ubiquitously prevails in natural faults across various length scales. Despite extensive studies highlighting the important role of fault geometry in the dynamics of tectonic earthquakes, whether and how fault roughness affects fluid-induced seismicity remains elusive. Here, we investigate the effects of fault geometry and stress heterogeneity on fluid-induced fault slip and associated seismicity characteristics using laboratory experiments and numerical modelling. We perform fluid injection experiments on quartz-rich sandstone samples containing either a smooth or a rough fault. We find that geometrical roughness slows down injection-induced fault slip, and reduces macroscopic slip velocities and fault slip-weakening rates. Stress heterogeneity and roughness control hypocenter distribution, frequency-magnitude characteristics and source mechanisms of injection-induced acoustic emissions (AEs) (analogous to natural seismicity). In contrast to smooth faults where injection-induced AEs are uniformly distributed, slip on rough faults produces spatially localized AEs with pronounced non-double-couple source mechanisms. We demonstrate that these clustered AEs occur around highly-stressed asperities where induced local slip rates are higher, accompanied by lower Gutenberg–Richter *b*-values. Our findings suggest that real-time monitoring of induced micro-seismicity during fluid injection may allow identifying gradual localization processes occurring around highly-stressed asperities that can generate large induced events.

From outcrops to lab experiments and modeling: a multidisciplinary, multiscale approach to mitigate seismic hazard in deep geothermal energy applications.

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Deep geothermal energy (DGE) systems exploit heat at depths greater than 400 m. While energy production using DGE in southern Germany has been successful on a limited scale, significant factors have limited the widespread development of geothermal operations to date, including the socio-economic risks associated with possible induced earthquakes. One approach to reducing the risk of generating induced earthquakes is to conduct studies aimed at evaluating reservoir rocks' physical and hydraulic properties in efforts to predict the pore pressure and stress changes that could lead to fault reactivation. In addition, it is crucial to systematically quantify the frictional properties of faults at hydrothermal reservoir conditions to better predict their expected behavior upon reactivation (aseismic vs seismic).

Our work focuses on Devonian carbonate rocks in western Germany which represent a potential reservoir for DGE exploitation. We aim to quantify the geological structural properties on the reservoir scale, frictional properties on the laboratory scale, and use them as boundary constraints for modeling scenarios to explore the conditions under which faults are activated. Initially, we combine field structural analyses using scan lines with a 3D digital outcrop model and fracture characterization analysis using drone images to produce 3D Discrete Fracture Network (DFN) models. The DFN models help identify possible permeability anisotropy that could control fluid flow during geothermal operations. Next, in order to quantify the frictional properties of the reservoir rocks, we run a series of laboratory friction tests at realistic temperature and pressure conditions that are representative of a ~ 4 km deep geothermal reservoir. Finally, we use the permeability anisotropy inferred from fracture analysis and frictional properties inferred from lab as input for several injection/extraction modeling scenarios which can help us identify the necessary conditions for seismic or aseismic fault reactivation. We find that injection/production well locations with respect to the fault and injection rates strongly control the possible aseismic vs seismic fault reactivation.

Unlocking the Potential of Mine Waste in a Circular Economy: Innovative Tools, Challenges, and Opportunities

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Together with the high demand for critical raw materials (CRM) and metals to satisfy a climate neutral economy in our post-industrial societies, comes the waste generation and the entire chain of tasks concerning their efficient management and risk assessments. Over the past decades, we have gained some phenomenal knowledge of mine wastes based on a great diversity of characterization protocols and tests. Traditionally, the characterization of mine waste has primarily focused on assessing present and prospective environmental factors. This approach aligns with the conventional linear economy mindset of mining operations, which follows a "take-make-dispose" model. In contrast, a circular economy philosophy, characterized by a "make-use-return" approach, advocates for minimizing waste production in mining, reducing the loss of raw materials to waste streams, and characterizing any generated waste with the aim of potential reuse, recycling, or future mining activities. Indeed, mining has the potential to play a significant role in circular economy systems by actively working to eliminate waste from entire value chains and reintegrating mine waste materials into material cycles. In line with this responsible sourcing approach, historical mine waste piles containing a variety of mineral resources have gained attention as potential reservoirs of metals, industrial minerals, and CRMs. The efforts towards a greater confidence route for characterization of mine wastes will come from new macro approaches (e.g. remote sensing, monitoring of waste dumps), meso tests (e.g. infield analyses, spectral sensors), and micro laboratory analyses (e.g. computed tomography).The purpose of this contribution is to examine the diverse tools and methods that can be employed to assess mine wastes at both macro and micro scales within the context of circular economy systems and to present some demonstration scenarios.

A tailored model for sustainable control of ATES systems with mixed-integer programming

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Aquifer thermal energy storage (ATES) systems are used to temporarily store heat or cold in open aquifers in order to regulate building temperatures. Although the basic concept of storing heat in summer for winter (and vice versa) is simple, the efficient operation of ATES is non-trivial. For instance, ATES are necessarily combined with conventional heating systems or heat pumps to handle peak loads, which complicates their efficient operation. Moreover, it is important to maintain a certain heat balance in the underground to ensure long-term operation of ATES. Both challenges can be addressed with modern control technologies. In particular, model predictive control (MPC) enables to optimize the current operation while taking constraints and long-term requirements into account. The performance of MPC crucially depends on the quality of the model. In fact, the model should accurately capture the dominant system dynamics while being numerically cheap to evaluate. Existing approaches often address only one of these aspects. For instance, Rostampour et al. (2016) consider a simplistic battery-like model whereas Beernink et al. (2022) build on a complex MODFLOW model. In our contribution, we present a novel MPC scheme which reflects a sweet-spot between these extremes. More precisely, our model builds on linearizations of the heat transport equation for the three operation modes injection, extraction, and storing (or inactivity). Incorporating these modes in the MPC leads to a mixed-integer (optimization) program, which can be solved efficiently compared to an MPC utilizing a MODFLOW model. This is illustrated with a numerical case study showing the effectiveness of our approach.

Keywords: aquifer thermal energy storage (ATES), model predictive control (MPC), mixed-integer programming (MIP)

Two-well dipole test for aquifer characterization

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Heat and cold storage in the subsurface as well as geothermal energy provision intrinsically involve cyclic pumping operations, often in fields of several boreholes. We investigated the pressure and flow rate fields resulting from the simultaneous periodic operations in two boreholes. The interference in pressure experienced by a third monitoring borehole can be assessed by an analytical solution when assuming radial flow from the pumping wells. The solution is simply gained by superposition relying on the known solution for periodic pumping in a single well. An injectivity analysis, i.e., relating spectral characteristics of flow rate and pressure in a pumping well requires numerical solution even for simplifying assumptions. We compare our analytical and numerical results to observations from field tests conducted in four boreholes located close to the northwestern banks of an artificial fresh water reservoir, called the Kemnader See, at the southern city-limits of Bochum, Germany. The derived solutions allow us to assess, for example, how pumping periods and phase shifts affect hydraulic penetration of the exerted perturbations and whether simultaneous pumping operations can improve the yield of a producing well. Solving and investigating the hydraulic problem constitute the necessary first step towards a thermal performance analysis.

Numerical simulation of geomechanical experiments on granite

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Numerical modeling of subsurface processes is required for upscaling of laboratory experiments with respect to space, time and complexity in the context of energy provision, storage and its optimization. In this study, the time-dependent geomechanical properties of two different granites are carefully investigated with conventional laboratory experiments. Here we present results from conventional uniaxial and triaxial deformation experiments that are performed at various strain rates. The results are simulated with two different 'standard' modelling approaches using COMSOL Multiphysics and RS2 to obtain the predictive potential of these approaches, in a first step for rather simple changes in experimental boundary conditions and consistent material properties. The experimental dataset developed in this study aims to be capable of benchmarking a wide range of numerical codes.

Evaluation of transparent coating on metal surfaces

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This study focuses on materials inspection on corrosion against coatings, which found as the common technique in conserving industrial heritage. Our targeted inspection is on transparent coating on metal surfaces because of its efficient coating properties and maintaining the original identities and appearances of heritage sites. The coating layer thickness of customized samples will be measured by using different analytical measurement methods such as Optical Coherence Tomography (OCT), Electro Impedance Spectroscopy (EIS), Fourier Transform Infrared Spectroscopy (FTIR), Hyper Spectral Imaging Camera and Scanning Electron Microscope (SEM) in order to verify the lifetime of the coatings. Moreover, robotic algorithms for inspection and maintenance for metal monuments, and computation systems are also implemented to laboratory coating inspection methods and modified to be able to use in the heritage sites to give the real time non-destructive monitored coating conditions. The algorithms should, after the basic process is well understood be exchanged by machine-/ deep learning techniques to create an automatic inspection tool for materials and coatings. Finally, it is intended to create an affordable and easy to use handheld tool based on a combination of reliable analytical measurements and machine learning, which can also be possible for onsite inspection application for untrained personal directly.

SIEGFRIED – A New Interdisciplinary Project for Seismic Hazard Assessment to Accelerate the Geothermal Transition in the Lower Rhine Embayment

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Achieving the global climate goals requires accelerating the energy production from renewable sources. An effectively unlimited potential source of renewable energy that also has minimal climate footprint lies in deep geothermal energy. However, the growth of the deep geothermal energy sector is challenged by long profit return times and non-negligible socio-economical risks, including the potential of inducing seismicity. The latter is particularly relevant at site where permeability enhancement may be required. One potential site that offers a suitable geothermal and profitable conditions without the need of permeability enhancement is the Lower Rhine Embayment (LRE). The LRE is a tectonically active extensional faulting system with moderate seismicity rates and potentially suitable permeability properties for optimal geothermal energy production.

Here we present the objectives and preliminary work of our joint research project "SIEGFRIED – Seisimc Hazard Assessment of the Lower Rhine Embayment for Deep Geothermal Energy Utilization". SIEGFRIED is an interdisciplinary seismotectonic pilot project with the following objectives: (i) investigate physical processes in the fault activation, (ii) estimate the ambient stress in the crust based on seismological observations, (iii) model the stress state and stability of existing faults, and (iv) incorporate results into guidelines for developing regulation related to seismicity rates at the geothermal site.

The pre-operational seismotectonic background study will conduct seismic monitoring using 12 permanent stations in Germany, the Netherlands, and Belgium, operated by the seismological observatory Bensberg (GER), the Royal Netherlands Meteorological Institute (KNMI; NL), and the Royal Observatory of Belgium (ROB; BE), a dense array of 48 seismic stations around Eschweiler-Weisweiler from 2021 to 2022, and a longer-term deployment of 8 stations deployed between the Feldbiss and Sandgewand faults. We use the continuous seismic records to build an enhanced seismicity catalog employing machine learning packages that will be fundamental to identifying active fault structures. In addition, we are conducting a dynamic triggering study to quantify triggering threshold bounds and identify critically-stressed faults. We will also combine seismic observations with low-frequency ground-motion measurements of Distributed Acoustic Sensing and GNSS to search for evidence of aseismic deformation. Finally, we will estimate rock frictional properties based on exhumed analogs of potential reservoir rock to quantify their frictional properties under reservoir PT conditions. The measured frictional properties will serve as constraints for Rate-State friction models under various injection and well geometry scenarios to test conditions for (a)seismic fault (re)activation and maximum magnitudes.

Impact of thermal comfort driven building controls on the dimension of geothermal-heatpump-systems under consideration of different building types

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The assessment of human thermal sensation plays a vital role in the demand-oriented air conditioning of buildings. The aim is to supply as much heat as the occupants need to experience thermal comfort. Current heating and cooling thermostats are controlled by the present air temperature in the room. The corresponding set-temperatures were derived using comfort models for seated individuals with light activity and a predetermined clothing combination. However, since thermal comfort is a state that cannot solely be described by the air-temperature for controlling the thermal environment, this will only lead to an approximate coverage of heat and cold in buildings. Especially for different building types, the incorporation of comfort indices from thermal comfort models, that assess the thermal environment by using additional indoor climate parameters and physiological properties of the human body, can lead to a more precise sizing of the heating system, particularly for ground-source heat pump-systems. Suitable indices for that purpose have shown to be the operative temperature and the predicted mean vote (PMV), that is obtained by Fanger's thermal comfort model. The subject of this study is to examine the effects of the presented alternative controls on the load profile and the energy demand of the different building types and to estimate their influence on the sizing and the design of ground-source heat pump-systems. The results show that the thermal environment that is controlled by comfort indices leads to specific investment costs that are up to 13% lower than an air-temperature-based regulation, especially in old and existing buildings.

Environmental and Economic parameter study of Air-Source and Ground-Source Heat Pump Systems for existing Buildings

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The majority of final energy in Germany is used for heating and cooling buildings. Existing buildings typically have a relatively high heating demand, as over half of these buildings were constructed before the first heat insulation regulations, and less than 10% of them have been fully renovated. Heat pump systems could make a significant contribution to providing buildings with climate-friendly heat. However, the efficient use of heat pump systems strongly depends on the technical and economic conditions. Consequently, there is currently a controversial discussion about whether such systems can be economically used in existing buildings and how significant their climate benefits are.

The parameter study presented here investigated the influence of the building's heating demand, the supply temperature of the heating system, and the site conditions on the economic efficiency and climate benefits of the heat pump system. Air-source heat pumps with and without electric heating rod, ground-source heat pumps with and without electric heating rod or with solar thermal coupling were investigated. Various economic and ecological scenarios were considered. The systems were compared with gas heating.

The parameter study shows that the considered systems can be economically viable under certain conditions. The most crucial parameter for evaluation is the supply temperature of the heating system, site conditions have a significantly smaller impact on the results. Both the use of an electric heater and coupling with solar thermal systems result in cost reduction.

From an ecological and energy point of view, an improvement is to be expected with all heat pump systems compared to gas heating. In general, measures that reduce the supply temperature of a building are advisable. However, an energy-efficient renovation is not a prerequisite for the economical use of heat pumps in existing buildings.