3D Modelling and Uncertainty Evaluation of the Northern Upper Rhine Graben

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Keywords
Geological modelling, Uncertainty modelling, heat transition, Upper Rhine Graben

ABSTRACT
The Upper Rhine Graben is an important source for geothermal energy with its elevated geothermal gradient and highly faulted structural system. This is proven by a drive to unlock these resources by several projects since the 1980's. However, not all projects come with the projected results. This stems from the structural complexity which comes with a lot of subsurface heterogeneity. Faults formed under different stress regimes and syntectonic sedimentation created a network of different unit geometry throughout the graben. And it is this complexity that therefore limited certainty of the models which projects are based on. The ultimate result in an increased risk for the success of a geothermal exploration project.

In order to reduce production risks, the uncertainty of geological models need to be understood. This is where uncertainty models come into play. With an uncertainty workflow for geothermal models based on a Monte Carlo simulation. First a base model was created for the northern Upper Rhine Graben, which is based on previous interpretations, seismic data, lab measurements and intrinsic borehole data (e.g., porosity, density, specific heat capacity). Next, the uncertainty workflow takes all known uncertainty components of the base model input data and their error probability distribution. Based on their probability of occurrence, uncertainty fields are generated, and many models are created based on their input parameters. The results are combined to provide a new model and maps with insight into the uncertainties of the geological model, which can subsequently be used for risk assessment and mitigation.

DeepStor – a blue print for heat storage in urban areas

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Abstract

The subsurface condition of the Upper Rhine Graben is favorable for developing novel geothermal utilization concepts. In particular, they allow for an optimization of the energetic use for variable heat production and storage scenarios. The fact that former hydrocarbon reservoirs are involved, perfectly describes the transition to the future use of renewable CO_2-neutral energies.

The planned DeepStor research infrastructure is intended to investigate the technical feasibility of high-temperature heat storage in the deep subsurface. The need for high-temperature thermal storage arises from seasonal fluctuations in heat demand, which often result in excess heat in the summer. With the use of a depleted hydrocarbon field, we use the extensive knowledge from it for the development of a heat storage system with the aim of supplying the district heating network of KIT Campus North in winter, thus creating a real geoenergy transition.

The Campus North of the KIT is located in the central-eastern Upper Rhine Graben. Seasonal heat storage experiments are envisaged in the Tertiary calcareous fine-grained sandstones of the Niederödern and Froidefontaine Formations. Loading and unloading experiments in the potential storage sites at the edge of the former Leopoldshafen oil field will enable calibrated investigations of the associated coupled thermal, hydraulic, mechanical and chemical processes in the thermal water cycle. In scientific experiments, further fundamental questions concerning the development of this technology will be examined in depth.

Here, we investigate potential up-scaling of such heat storage to urban areas. We present a case study for the city of Karlsruhe that needs to handle a difference in demand of 200 MW between peak and base load.

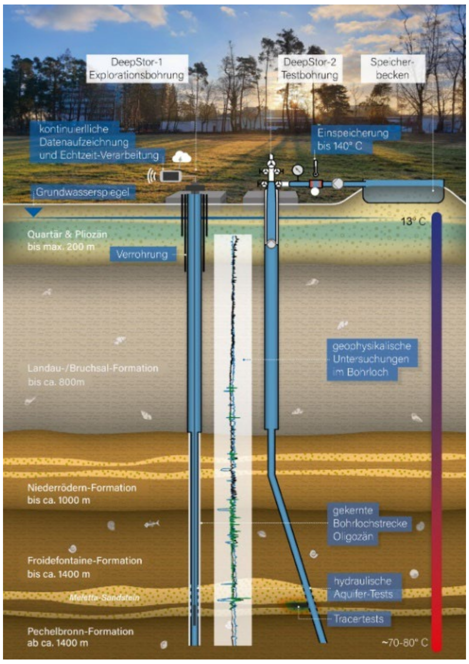

Figure 1: Design of the Helmholtz Research Infrastructure DeepStor at KIT Campus North

MINING HEAT IN A REGIONAL BRITTLE SHEAR ZONE: THE POTENTIALITY OF THE GAVORRANO AREA (SOUTHERN TUSCANY, ITALY)

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Abstract

In the frame of the H2020- HOCOLOOP project, the portability of a specific coaxial tool permitting internal water flow circulation in deep boreholes, is evaluated to transfer heat from rocks to surface. Whereas most applications assume heat extraction from tight or matrix-porosity formations, we study the potential of this approach in wide, permeable, fractured shear zones, constraining the numerical modelling with field-based outcrop measurements. In the Gavorrano example the geothermal heat flux is about 80mW/m2 (geothermal gradient of about 150°C/km).

The Gavorrano area is located in central Italy, in the inner zone of the Northern Apennines (southern Tuscany), where a Neogene monzogranite body (estimated as3 km long, 1.5 km wide, and 0.7 km thick) was emplaced in the early Pliocene. This magmatic intrusion, known as the Gavorrano pluton, is partially exposed in a ridge bounded by regional faults delimiting broad structural depressions. A widespread circulation of geothermal fluids accompanied the cooling of the magmatic body and gave rise to an extensive Fe-ore deposit (mainly pyrite) exploited during the past century, thus the area is characterized by abandoned boreholes that might have a new life as geothermal wells, hosting the coaxial tool. Structural analysis was carried out in a quarry where the regional shear zone is exposed. The adopted methodology is based on virtual 3D outcrop models by photogrammetry and scan lines.

Data from the fieldwork permits us to define those parameters (e.g., fracture density, permeability and connectivity) necessary to properly model the heat transfer in the presence of geothermal fluids.

Different scenarios of heat extraction were simulated. We used a numerical model based on cylindrical symmetry, which applies a finite volume method that conserves the energy in the system. The fluid is assumed incompressible with a constant heat capacity, heat conductivity, and viscosity. Based on the geological data of the site, we simulated heat production over a time span of 20 years with three different flow rates 0.5, 2 and 8 kg/s, and an injection temperature of 20 °C. For the case of a circulation rate of 2 kg/s, we obtained a power of 180 kW, and an output temperature that stayed above 42 °C. The coaxial heat exchanger shows a very gentle decline in produced power over several decades after a short initial transient. These reference simulations did not account for heat convection by fluid flow in the rock.

DTS Monitoring of Cold-Water Injection Tests in Litoměřice: Understanding Flow Patterns in EGS Development

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Abstract

An essential aspect of EGS (Enhanced Geothermal Systems) development is hydraulic testing, primarily aimed at assessing and further enhancing permeability within the reservoir rock formation. In the context of the RINGEN research infrastructure located in Litoměřice, Czech Republic, two cold-water injection tests were conducted in a 2111 meters deep pilot borehole during the year 2020. These tests reached flow rates of 50 l/min, resulting in the creation of fracture within the Carboniferous ignimbrite layer at depths between 880 to 890 meters above the cataclastic zone. The fracture behaviour was monitored with a DTS (Distributed Temperature Sensing), which was installed in the well, allowing for the identification of the dynamic temperature changes. These measurements contributed to the localization of the fracture and the detection of an atypical flow pattern, which remained unanswered, as there is an immediate cold-water inflow from the parts above the fracture after the well is shut in. Since no seismicity was detected during these tests, the temperature data is basically the only source of information together with borehole lithology. Based on the analysis of the temperature distribution and its evolution during the tests we propose a flow model which is verified by thermal modelling to explain the observed anomalous behaviour of temperature data.

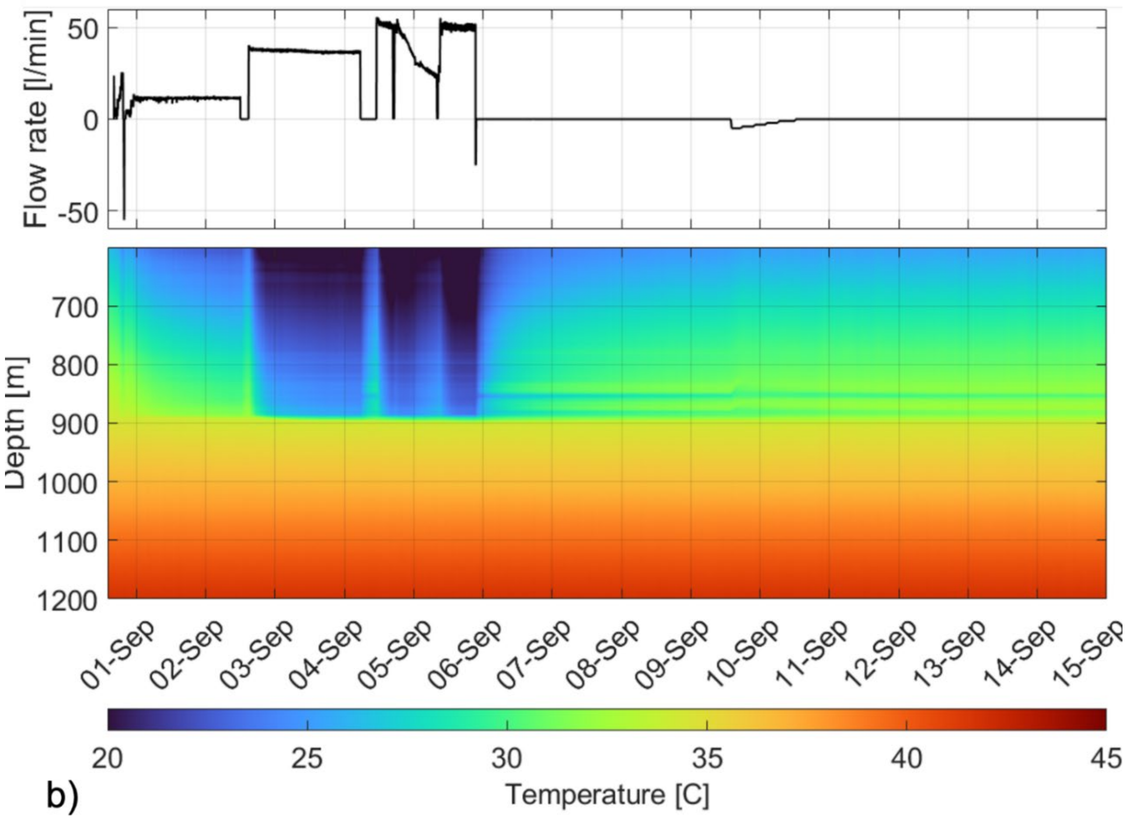

Figure 1
Flow rate (upper panel) and temperature map (bottom panel) for the August/September 2020 injection tests in the Litoměřice PVGT-LT1 borehole.

Push pull tests for aquifer parameterization of ATES systems: lessons learned from parameter optimization

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Abstract

A comprehensive characterization of aquifer parameters plays an important role in making accurate long-term predictions regarding the functionality of an Aquifer Thermal Energy Storage (ATES) system. Push-Pull Tests (PPTs) with different tracers combinations have gained widespread acceptance as a means to ascertain key aquifer properties. These PPTs enable the determination of effective porosity, flow velocity, dispersion coeffiecient, sorption coefficients, and the critical parameter of heat storage capacity within the aquifer. Over the course of more than five decades, a multitude of analytical and numerical approaches have been derived to validate PPT data and to assess the sensitivity of various models. However, it is imperative to recognize that the primary challenge in calibrating PPTs lies in the non-uniqueness of the inverse problem solution. This challenge is particularly pronounced in the context of ATES systems, where limited data availability and parametric uncertainties call for the application of stochastic parameter optimization techniques.

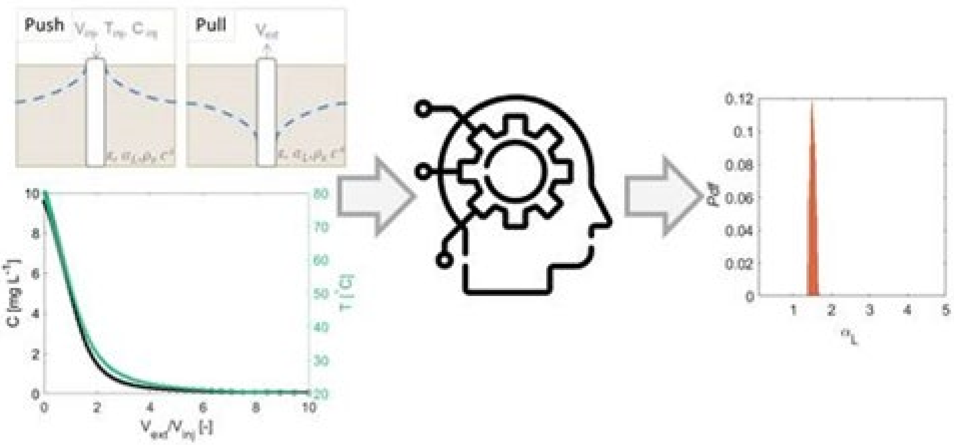

Figure 1: Graphical scheme of the modelling approach

In response to these challenges, a meta-modelling optimization approach for stochastic parameter optimization has been developed (Fig. 1). Applying the analytical solution for heat and conservative tracer transport and using the total normalized Root-Mean-Square-Error (RMSE) as an objective function, an optimization process has been proposed to calibrate the PPT data. This optimization approach has undergone rigorous validation against synthetic dataset, incorporating parameters typically observed in real-world scenarios, along with measurements taken at one of the ATES sites in Berlin.

The outcomes of this study underscore the critical importance of carefull selecting fit criteria such as the measurement error and possible parameter ranges, and thus optimizing data resolution. These choices have a profound impact on defining the calibration precision, thereby reinforcing the significance of meticulous attention to detail in ATES system characterization.

Do salt diapirs promote the geothermal potential of shallow depth aquifers?

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Abstract

There is an increasing interest in the exploration of geothermal energy as a replacement for fossil fuels. If developed properly geothermal energy systems could become a more sustainable solution for direct heat usage. Geothermal closed loop systems already exist in the Netherlands at deeper depths. At shallower depths the presence of salt pillars or other salt structures could be a region of interest for geothermal energy. Salt has a much higher thermal conductivity than other sedimentary rocks, (6.5 W/m K for salt versus 1.6 W/m K for shale and 4.0 W/m K for sandstone). Salt diapirs therefore could act as good local conductors of heat from deep to shallow depths, resulting in locally elevated temperatures of reservoirs overlying a diapir. To investigate this, the Onstwedde salt dome, located in NE Netherlands, is used as a case study for thermal modelling (Fig. 1.). Firstly, a detailed 3D seismic interpretation of the Onstwedde pillar and surrounding areas. The 3D static model was depth-converted, so that it could be used as input for numerical thermal modelling. The modelling code developed by Van Wees et al. is based on a multi-1D probabilistic tectonic heat flow model which can be converted into a 3D model by incorporating the horizontal heat flow.

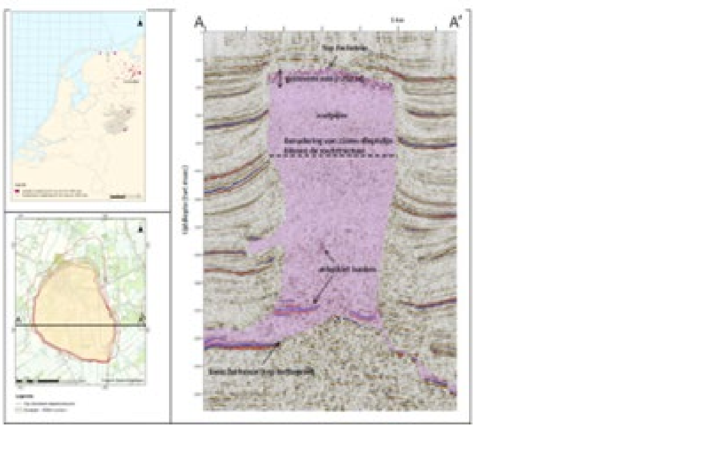

Fig. 1. (left top) Location of the Onstwedde salt diapr. (left bottom) Depth contours of the top of the salt diapir. (right) Seismic cross section, showing the shape of the diapir and the surrounding and overlying (deformed) sedimentary layers.

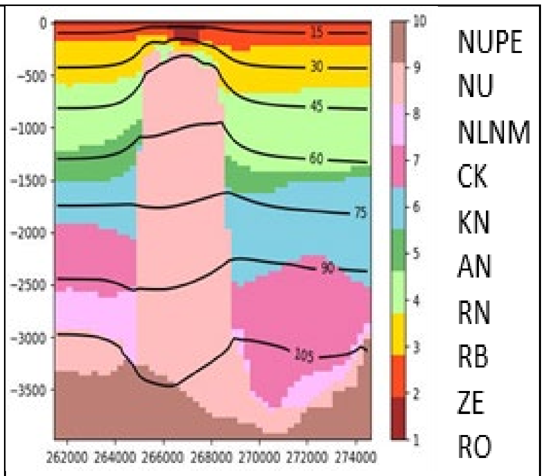

Fig. 2. Isotherms around the salt dome

The first results of the thermal modelling show lateral temperature anomalies exist above the salt dome of up to 20 degrees Celsius higher than the surrounding subsurface (Fig. 2.). At the bottom of the salt dome a negative lateral anomaly in temperature can be seen. The modelled positive temperature anomalies above the salt dome suggest that it would be possible to drill at much shallower depths to reach the same temperature (up to a few 100s of metres). With drilling being the most expensive part of the process of generating of geothermal heat, a shallower well can contribute largely to cutting exploitation costs. However, due to the lack of accurate temperature data of the subsurface around the Onstwedde salt dome, the model can not yet be callibrated accurately. Several exploratory wells are needed to acquire more data on the temperature-depth distribution above and away from the diapir. Moreover, a further parameter study is needed to asses the different effects of thermal rock parameters and boundary conditions on the 3D temperature distribution in the depth range down to 500m.

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The REFLECT project – improving the availability of data on the characteristics and behaviour of geothermal fluids

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Abstract

The efficiency of geothermal utilisation depends strongly on the characteristics and behaviour of the fluids that transfer heat between the geosphere and the engineered components of a power plant. Changes in equilibrium conditions during thermal water production can cause chemical reactions such as degassing or mineral saturation, which can lead to precipitation or corrosion, with potentially serious consequences for power plant operation and project economics.

The EU-H2020 project REFLECT (2019-2023) aimed to improve the availability of data on geothermal fluids in order to avoid the above-mentioned problems. This included (1) developing an improved sampling technique for deep fluids at very hot temperatures (>300°C), (2) collecting existing and new data from geothermal fluids across Europe through field measurements, including microbiological studies, and (3) simulating processes in thermal water through detailed laboratory experiments under in-situ conditions to collect kinetic and equilibrium data of relevant reactions. In addition, numerical simulations were also performed to predict mineral solubility and precipitation risk of minerals. These data were (4) implemented in case-specific predictive models simulating processes at geothermal sites and (5) integrated into a European geothermal Fluid Atlas. This atlas includes query and filter tools to explore the database with a GIS-based map visualisation. The atlas makes the data accessible to the geothermal community and the general public.

In the project, 14 partners from geothermal research, industry, and geoscience associations worked together to narrow the knowledge gaps for geothermal fluid properties and processes during geothermal utilisation, leading to more reliable predictions of geothermal performance.

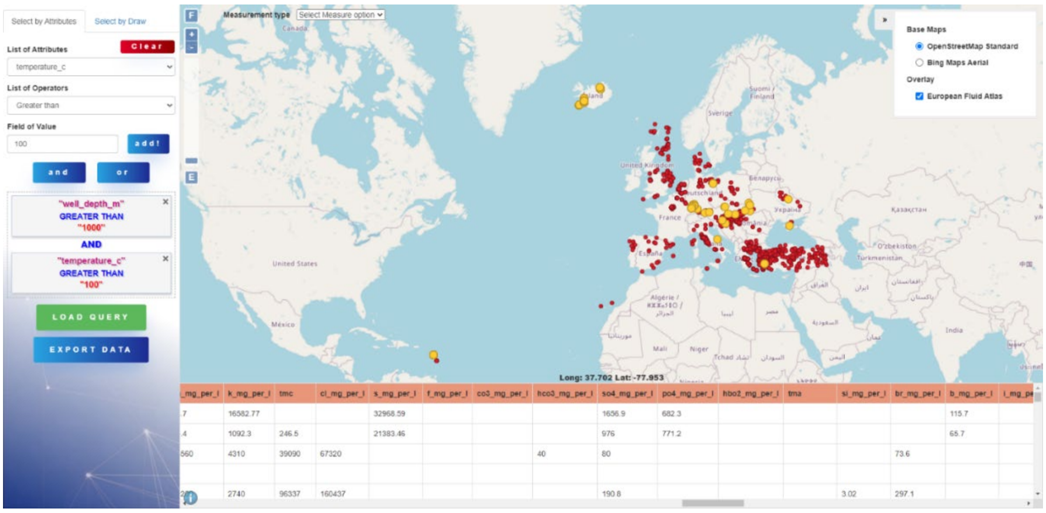

Figure 1: Screenshot of the European Geothermal Fluid Atlas with location of the 2,400 wells where already existing well, fluid, rock and reservoir data were collected. The example shows the query for wells with depth > 1,000 m and temperature > 100°C, resulting in the locations on the map marked with yellow dots.

Developing a marginal reservoir for urban heating in Zwolle (NL): integrating advanced 3D reservoir characterization models and well technology options for concept select

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Abstract

Geothermal reservoirs are prospected to be developed in many urban areas with the intent of replacing fossil fuel fired heating. In many urban areas the development of geothermal reservoirs can be challenging due to suboptimal (marginal) reservoir conditions. In this study we present a concept select case study for the clastic Rotliegend reservoir in Zwolle (Netherlands), which aimed to demonstrate that geothermal flow performance can be increased by 30-100% relative to conventional sub-vertical wells, by considering advanced well design options, including sub-horizontal and multilateral well designs.

The robustness of concept select outcomes considering (more) complex well designs is critically dependent on the quality of 3D reservoir characterization models and uncertainty assessments used in performance simulation (Figure 1). By performing geological, analysis, structural analysis and supplementing this with temperature (and fluid) analysis, a detailed transmissivity map, temperature and depth map have been constructed on which local areas of interest can be identified where the subsurface is most convenient for geothermal development. From this geological analysis a static model with multiple stochastic realizations has been built which represents a probable representation of the subsurface, and includes detailed fault geometries and cementation zones. For the concept select, flow performance of different well concepts has been tested for all stochastic realizations, indicating favorability for sub-horizontal well and multilateral well designs marked by a consistent and significant (more than double) increase of flow performance compared to a conventional subvertical well design. In addition, the enhancement of flow performance comes at a moderate additional investment cost for well engineering and increased operational costs, effectively reducing the Levelized Cost of Energy.

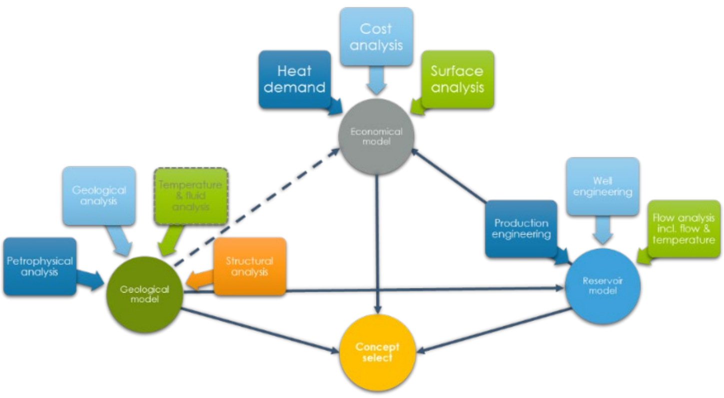

Figure 1: Overview of concept select for a geothermal project. Note that heat demand and surface analysis are not part of the scope of this study; temperature and fluid analysis have been included under reservoir model as well.

Acknowledgements

This study has been performed as part of the RESULT project (Enhancing REServoirs in Urban deveLopmenT: smart wells and reservoir development). RESULT has been subsidized through the ERANET Cofund GEOTHERMICA (EC Project no. 731117), by the Ministry of Economic Affairs and Climate Policy (the Netherlands), Rannis (Iceland) and GSI (Ireland).

Understanding native Hydrogen generation in granitic geothermal reservoirs of the Upper Rhine Graben, an experimental and geochemical modeling approach

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In the current global context of addressing climate change and transitioning to low-carbon energy sources, the search for alternatives to fossil fuels is important. Hydrogen has emerged as a promising option, as its combustion only produces water without emitting carbon dioxide. Although hydrogen is already being used as an energy vector in various industries, the existing methods of hydrogen production, such as steam methane reforming or water electrolysis, are expensive and either contribute to CO2 emissions or require high electricity consumption. An alternative approach to obtain hydrogen is through the extraction of native hydrogen found naturally in certain geological settings. In this study we investigate the potential for native hydrogen generation in the geothermal reservoir of Soultz-sous-forêts (Upper Rhine Graben, France) as this gas has been detected in its fluids. While the exact origin and contributions are not yet fully understood, one of the hypotheses is that water-rock interactions occurring at depth within the geothermal reservoir could constitute a source. The Soultz-sous-forêts reservoir is composed of a biotite-rich fractured granite, and the circulation of geothermal fluid within the reservoir leads to the hydration of biotite, resulting in the oxidation of ferrous iron to ferric iron. Our hypothesis is that natural hydrogen is produced during this oxidation process. Initial geochemical modeling using the KIRMAT code has shown promising hydrogen production. However, further research and validation through experimental approaches are needed to test this model. The objective of this project is to gain a better understanding of hydrogen generation in granitic reservoirs by conducting batch experiments in gold capsules in parallel with geochemical modeling. We worked with granitic samples from the reservoir (at 1800 m depth) as well as pure iron-rich minerals found in the granite (biotite, hornblende), and synthetic wurtzite (FeO). An important aspect of the project is setting up the experimental protocol at the ITES laboratory. The first set of experiments demonstrated that the protocol successfully reproduces iron oxidation and hydrogen production, especially for the FeO compound. However, minor adjustments are needed to measure hydrogen in the natural samples. The next step will involve a second set of experiments to measure hydrogen in the natural samples and compare the results to the corresponding simulations.

On the Structure and Geothermal Energy Potential of the Sedimentary Basins of Africa

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Abstract

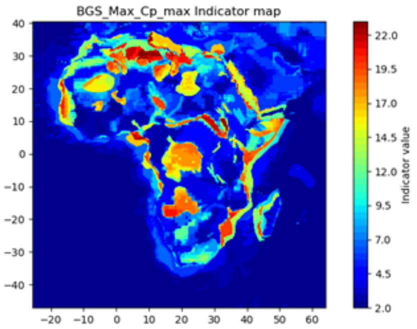

Figure 2: Results of qualitative analysis. Higher indicator values indicate higher estimated geothermal energy potential.

The need for sustainable and renewable energy alternatives is growing rapidly and more relevant than ever before. To address this challenge for African countries and promote cooperation between European and African institutions the Long-term Europe-Africa Partnership for Renewable Energies (LEAP-RE) was initiated. The Geothermal Atlas for Africa (GAA), as part of this larger initiative, focusses on the exploration, development and visualization of geothermal energy potential of the African countries. TNO and Utrecht University, as partners of the GAA, aim to perform qualitative and quantitative analysis, via numerical modeling (gravity, temperature and geothermal potential) to provide estimates on the geothermal energy potential of Africa.

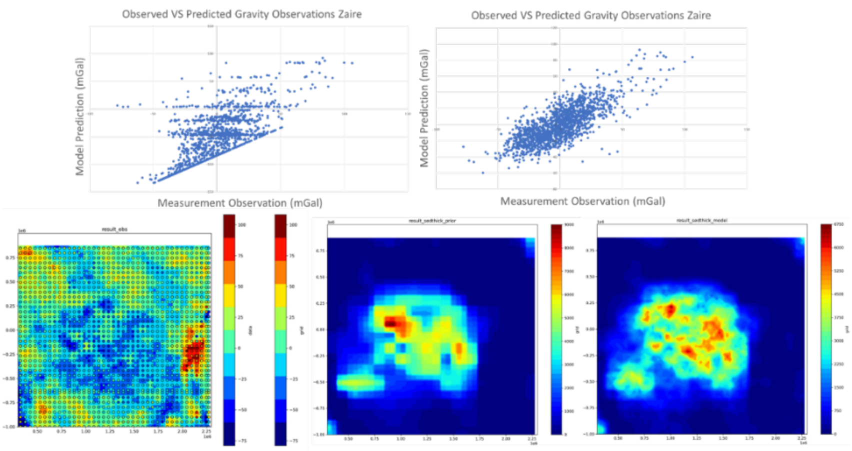

Figure 2: Gravity inversion results of the Zaire basin (Democratic Republic Congo). Top: gravity observations (satallite data) vs modeled gravity values of prior model (left) and our model (right). Bottom left: spatial differences between gravity observations and our model. Bottom right: sediment thickness map prior model (left) and our model (right).

In this study we present different approaches to improve current sedimentary basin models for Africa by incorporating geothermal energy potential related parameters (e.g., porosity, temperature, reservoir thickness etc.). This includes improvement of the resolution of publicly available sedimentary thickness models via gravity inversion, and temperature modeling of the African sub-surface. The jointly compiled data of the Geothermal Atlas of Africa and modelling studies will allow us to make more robust predictions of the geothermal potential of Africa (Fig. 2).

Searching for hot rocks & water with lukewarm results: Lessons learnt from 30 years of geothermal E&P activity in Switzerland.

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Abstract

Switzerland enjoys an exceptional favorable social and political support on energy transition policies aimed at eliminating 12 million tons of CO2 per year in order to meet the 2050 objectives and thus maintaining the target of zero carbon emissions.

Geothermal energy is indeed considered by society and both the federal and cantonal governments as one of the viable ways to meet that ambitious target.

If from one side Switzerland is a world's leader in installation of heat pumps which have contributed greatly to reduce the consumption of fossil fuels for heating both for domestic, industrial and agricultural use, the quest for high temperature rocks and water in the deep Swiss subsurface over the last 30 years has somehow not provided the expected results. The outcomes of wells such as Thônex drilled 30 years ago (1993), followed by Basel (2006), Triemli (2009), St Gallen (2013) and more recently Lavey-les-Bains (2022), Venzel/La Côte and Yverdon (2023) have clearly demonstrated that the Swiss subsurface geothermal potential is still not been exploited as initially hoped. Unexpected success such as the one of the GEo-01 (2018) well in the Geneva Basin and the repurposing of some of the deep wells such as Triemli and Thônex have however demonstrated that the geothermal potential exists and that providing a successful second life to initially disappointing results is a viable option.

Overall, the last 30 years of deep geothermal industry projects in Switzerland offer a large number of lessons learnt which will analyzed and presented in this paper. Will the Swiss industry and regulatory agencies learn from these past experiences ? Will these lessons learnt be taken into account ? Only the future will tell.

Two important lessons seems however to stand out:1) A successful geothermal energy industry, similarly to other business dealing with natural geo-resources exploitation, requires a consolidated and experienced geo-energy exploration mind set supported by courageous large upfront investments; 2) As per the hydrothermal potential, the Swiss subsurface is not yet known well enough to be able to take a stand. Like for the hydrocarbon industry, the understanding of the main controls on porosity and permeability needs to be worked out properly both at basin and reservoir scale. This is only possible with a thorough regional exploration approach and it is not possible when dealing with a 'one shot approach' in a spatially limited area.

Developing conceptual model for geothermal reservoir exploration in Northern Alsace (France)

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Context of the study

Lithium de France (LDF) is the first independent French operator who aims to extract heat and geothermal lithium. The project consists in producing hot and Li-rich fluid naturally circulating inside a fracture network related to fault zones in the Upper Rhine Graben. In the context of the exploration campaign conducted by LDF in its exploration license named "Les Sources" (Figure 1), 3D seismic campaigns have been acquired to better image the various fault networks that influence the geothermal resource. The production of this original 3D image of the reservoir is an essential tool for geothermal exploration. However, understanding and predicting these brines circulations inside the fault network are key parameters for the success of geothermal projects.

The development of a conceptual model of fracture and fault zones, as well as permeability distribution at the field scale, will provide input for numerical modeling, target selection, and well trajectory studies. This study represents a multidisciplinary approach involving geological, geophysical, and geochemical data for geothermal resource assessments and geothermal reservoir modeling within the exploration license area "Les Sources".

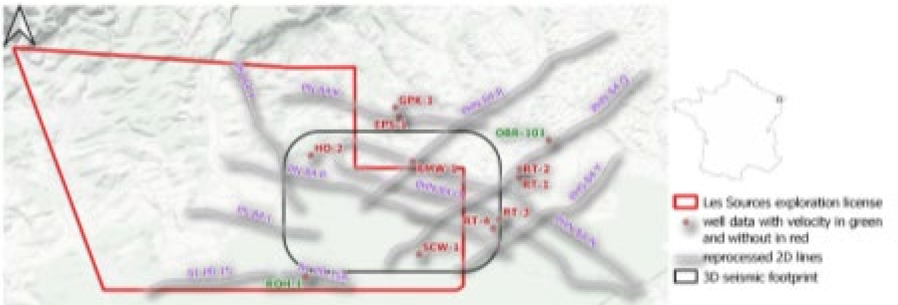

Figure 1: Exploration license Les Sources with 3D seismic footprint, vintage 2D lines acquired and reprocessed by LDF, and historical wells used for the 3D seismic interpretation.

Methods and outcomes

The study gathered geological, geophysical, and geochemical data acquired by LDF since 2022, along with available data from the national database of the French geological survey. Initially, a geological model was constructed, utilizing the original 3D seismic cube covering 60 km^2, in addition to reprocessed 2D seismic lines. This approach allowed for the creation of a 3D representation of a complex reservoir affected by multiple lithologies and tectonic structures. A comprehensive review of 13 offset wells helped to identify lithological formations within the area, as well as permeable zones, borehole instabilities, and gas occurrences. Available logs and mineralogical observations were integrated to interpret the fault zone architecture and permeability distribution. It seems that fracture distribution and clay minerals play crucial roles in the reservoir's permeability. These findings were then incorporated into the Thermo-Hydro-Mechanical modeling to predict the reservoir's behavior during future exploitation.

Perspectives and concluding remarks

Geological and dynamic modeling, coupled with the offset well review, significantly enhanced our understanding of permeability distribution associated to fault network. Targets and borehole trajectories were meticulously designed based on these observations. Conceptual models play a crucial role in ensuring the success of well planning, field development, and resource assessment. The assessment of lithium resources relies on the study of fluid-rock interactions and reactive transport. Geochemical analyses are scheduled to be conducted by the end of the year and will be integrated into the reservoir modeling.

ABSTRACT BUIJZE

Developing a Novel Downhole Sampler for Geochemical Monitoring of High-Temperature Geothermal Reservoirs

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Abstract

The monitoring of a geothermal reservoir during its development and production stage is crucial for sustainable and long-lasting utilization. Production wells can cut through several feeding aquifers resulting in discharging of a mixture of fluids originating from these different zones. As such, a sample obtained from a well head during conventional sampling represents an average chemical composition of the subsurface fluids. In contrast, a downhole sampler can collect fluids at precise depths and therefore providing an information about fluid properties at individual feed zones. As it has been observed in high temperature geothermal fields, lack of such a knowledge can lead to a decreased production efficiency and high cost of utilization. For example, extreme corrosion rates of perforated liners have been observed at specific depths due to localized mixing of fluids characterized by distinct compositions. Such damages could be avoided by identifying of such mixing depths before well flow test and by casing off these mis-matching feed zones through cement plugs or tiebacks, and/or provide input for design of future wells. Similarly, scaling induced by fluid mixing, could be reduced by assessing appropriate casing depth, and therefore preventing the inflow of problematic fluids into the well.

A downhole sampler that is capable of collecting fluids from high temperature wells at up to 300-400°C during every stage of the geothermal utilization has been designed and is currently undergoing tests. The chemical data obtained from fluids at different depths will not only help to select the most energy efficient discharge fluids for improved productivity of the well. It will also contribute to the conceptual models of the reservoirs, hence, to better understanding of hydrothermal reservoirs through their production lifetime.

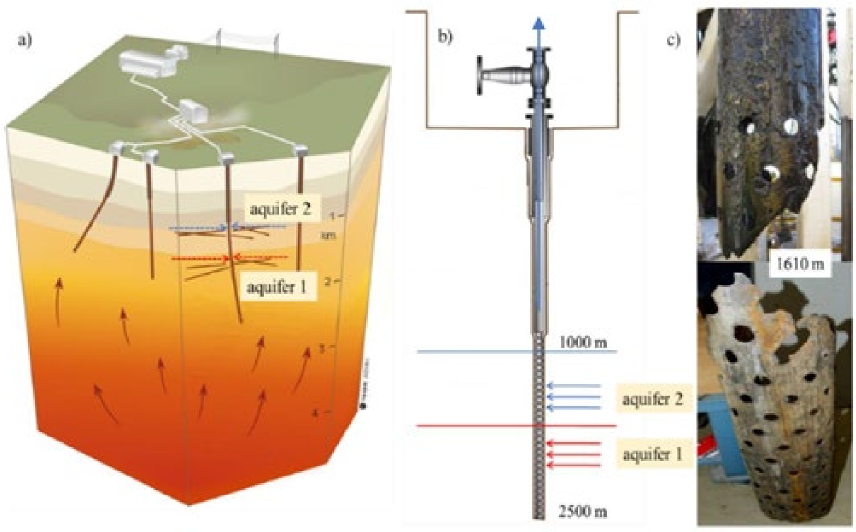

Figure 1: Schematic drawing of a high temperature geothermal system (a) and a well bore with two feeding aquifers (b) for demonstration of a liner corrosion (c) example at 160 m depth within well KJ-39 (Krafla, Iceland). Extensive damage of the liner was caused by mixing between high temperature fluids from aquifer 1 (hot steam containing HCl gas) and aquifer 2 (colder instream) causing formation of HCl acid and corroding 12 mm liner down to 0 mm in a few months (Karlsdottir & Thorbjornsson, 2013).

Distributed Temperature Sensing measurements for exploring Borehole Thermal Energy Storages in Scandinavia

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Abstract

Borehole thermal energy storages are useful for seasonal heat storage, but costly installations. It is therefore desirable to achieve good use/operation of them through monitoring and use of detailed on-site knowledge.
Three BTESs have been equipped with optical fibres in some of the boreholes, which enables distributed temperature sensing (DTS), that is, monitoring of the temperature in the boreholes as a function of both space and time.
Results from DTS monitoring are presented here. The results reveal the achieved thermal stratification, downwards heat losses and temperature level at all times, which is useful for charging/discharging strategies, especially in medium/high temperature BTESs. valuable information is also found for low temperature BTES, such as: The presence and changes in groundwater level, location of fractures and variations in ground thermal conductivity and the temperature difference between collector and borehole wall. These observations were only apparent when heat was injected/extracted. Hence, more information is obtained if DTS is used during operation than if used before operation for smaller tests such as thermal response test. Overall, DTS during operation is useful for monitoring of BTES, especially HT-BTES, and for improving operation and design of future BTESs.

Developing a marginal reservoir for urban heating in Zwolle (NL): Optimized well and completion design

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Abstract

In this study we optimize previously defined favorable well design concepts for the clastic Rotliegend reservoir in Zwolle (Netherlands) complementary to (Leewis et al., 2023). For this purpose TNO's in-house optimization technology (EVEReST), built upon the recently developed stochastic gradient-based optimization technique StoSAG (Fonseca et al., 2017) has been used. EVEReST allows to perform robust optimization including both many design parameters as well as subsurface uncertainties in a computationally efficient manner – i.e. with much fewer numerical simulations required when compared to alternative techniques. Figure 1 (left) depicts schematically the robust optimization process.

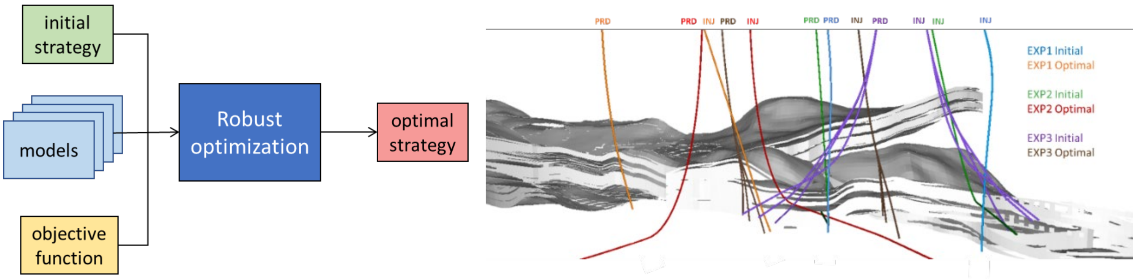

Figure 1: (left) Schematic representation of the robust optimization process in terms of input and output. (right) initial and optimal well designs: both well design and placement parameters have been included in optimization, subject to surface development constraints.

Three well location/trajectory optimization experiments have been performed resulting in different solutions (Figure 1 - right). Each experiment was started with different initial well concepts: (1) slightly deviated, (2) strongly deviated (sub-horizontal) and (3) multilateral wells. In the first two experiments, the optimizer had the freedom to explore more broadly different well shapes (from almost horizontal to almost vertical).

The robust optimization confirmed favorability for sub-horizontal well and multilateral well designs (Leewis et al., 2023) marked by a consistent and significant increase of flow performance, and shows very low uncertainty compared to a conventional subvertical well design. In addition, the enhancement of flow performance comes at a moderate additional investment cost for well engineering and increased operational costs, effectively reducing the Levelized Cost of Energy.

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Acknowledgements

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Reservoir analysis and characterization of the temperature and chemical changes in the Ellidaárdalur low temperature field, Reykjavík, Iceland as a part of the RESULT project

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Abstract

The aim of the RESULT project is to demonstrate the potential for increased performance of geothermal reservoirs for direct heating in urban areas of northern Europe. One of the goals of the project is to enhance the lifetime and heat recovery of such reservoirs. The Ellidaárdalur geothermal field is located within the city of Reykjavík, Iceland. The field has been in production for the local district heating system since 1968. There is a wealth of data relating to drilling, well completion, production history and temperature development available for the area. The production has varied from 1 GL/year in 1968 up to a high of 5.6 GL/year in 1983. Since 1983 the production from filed was lowered due to falling temperatures and water quality. Production during the last 10 years has been between 1.6 and 2.6 GL/year.

Substantial cooling has been observed in the field from the start of production with produced water temperature from wells in the field decreasing from over 100°C in many wells down to around 80°C or even lower in some wells. This has been accompanied by changes in chemical components. In general, the pattern seen in all wells is that the concentration of Cl, CO_2, Ca and O_2 increases with time as the temperature decreases. The concentration of SiO_2 and F decreases with decreasing temperature. The increased oxygen content in the produced water has been an issue, as oxygen causes corrosion of material and equipment. This has led to production from specific wells being decreased or stopped. The importance of this system has however been increasing again in the last few years due to rapid increase in hot water demand in the capital region.

Various processes contribute to the cooling and change in chemical composition, e.g., drawdown in the hottest aquifer causing a greater portion of produced water to come from cooler aquifers, downflow of colder water into the lower, hotter, aquifers through fractures or idle wells and possibly lateral inflow of cooler water from the system edges. Temperature measurements taken within the RESULT project from two wells that were sealed with a monitoring tube in 1991 to stop downflow of colder water show that temperature has gradually increased back to original formation temperature values. The data from the field suggests downflow of colder water from shallower aquifers through idle wells has contributed substantially to the cooling in the field, at least since production from the field was decreased. This indicates that the cooling in the field can, at least to some extent, be reversed by changing the production scheme and re-casing and/or sealing more wells. A tracer test will be carried out in near future to get better information on flow paths in the system. Downhole chemical additive trials are scheduled for the fall of 2023 to remove oxygen and prevent damage of equipment. Furthermore, the possibility of a more stable production scheme to reduce cooling due to downflow will be evaluated as well as the benefits of drilling new wells in the area.

Coupling of thermo-hydro-mechanical modeling with seismicity modeling in a faulted geothermal reservoir

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Abstract

Geothermal energy has been considered as an effective factor in energy transition worldwide for providing heat and electricity. In order to reach high amount of geothermal energy, deep geothermal reservoirs with high temperature should be targeted. The operation of such geothermal reservoirs can be performed by doublet injection-production systems within faulted geological formations. The operation within such faulted system generates seismic events, which sometimes can be felt by humans, the origin of the events being the complicated thermo-hydro-mechanical and chemical response of the system against operational and geo-reservoir parameters, e.g. flow rate of injection-production, fault properties, etc. Hence, numerical simulation of the exploitation of faulted geothermal systems can provide operators and public insights about the likely occurrence of seismic events during the life span of the site. Considering seismic event as an additional response of the system to the THMC response in the numerical model makes the simulation more complicated with more parameters involved.

In this study, to solve such complexity in simulation, we propose to couple two finite element numerical codes, one based on the MOOSE framework and SeisSol. The former is used to simulate the reservoir THM response (chemical effects are not considered) to the site operations and the latter is applied to simulate the dynamic seismic response of the fault(s). For the coupling, a bash script is written to call and run each code, manage the feedback of the corresponding results and loop over time. Hence, the coupled modeling starts with the MOOSE-based code to simulate THM behavior against the operation up to the fault failure. For the time being, the Mohr-Coulomb failure criterion is used. Once failure took place, the bash calls SeisSol for simulating the seismicity based on the MOOSE outputs, e.g. stress, and propagates the rupture in the fault system. The outputs of the SeisSol, e.g. stress, will be imported into the MOOSE simulator to proceed the simulation following the seismic event. Therefore, the outputs of each code are considered as initial conditions of the counterpart for the next step of the loop. The looping will continue over the predefined duration of the field exploitation.

Enhancing Subterranean Building Thermal Energy Efficiency through Ground Heat Transfer.

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Abstract

The demand for energy consumption is substantial in cold climate countries. The expanding construction sector has spurred a heightened focus on enhancing the energy efficiency of heating buildings. In line with national legislation and EU directives, significant investments have been directed to improve the thermal efficiency of the buildings. However, primary energy consumption continues to constitute a significant portion of global energy. Innovation is crucial to reduce energy consumption in buildings and achieve greater energy efficiency and sustainability. It can bring about new solutions that are smarter and more natural energy generation to reduce greenhouse gas emissions. The ground can serve as an effective and sustainable heat accumulator for heating and cooling. The temperature of the ground is higher than that of the ambient air in the colder period and lower in the warmer period. The building deep in the soil could use less thermal energy compared to the above-ground buildings that provide the same amount of thermal comfort. The temperature difference between the soil and the air inside the building decreases as the temperature of the soil increases. In progress, this process generates the condition that acts against heat loss. However, heat dissipates further to consecutive layers and reaches thermal equilibrium. The charging of the ground by heat and its dissipation through the adjacent soil layers was investigated. The results of this research showed that 31% of energy savings in completely underground buildings were derived from heating the space.

A new 3D geological model of the Upper Rhine Graben for medium-depth geothermal energy assessment

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Keywords
3D modelling, medium-depth geothermal resources, heat transition, reservoir assessment

ABSTRACT
The majority of geothermal projects in Germany have focused on deep geothermal systems, while resources at intermediate depths (~400 – 1500 m) have been little explored so far. However, medium-depth geothermal reservoirs possess a high potential for heat generation, even in areas previously considered less favorable for geothermal energy utilization, and could make a significant contribution to Germany's heat generation. In order to accelerate the heat transition and to become independent of fossil fuels, the ArtemIS project aims to assess the medium-deep geothermal potential in Germany, covering all play types and providing regionalized information for different geothermal applications. For this purpose, a 3D geological model of the play type "Upper Rhine Graben" was created. Modeling results from previous projects (GEORG, Hessen 3D, and DGE-ROLLOUT) were used to create an initial fault model of the study area. Newly acquired 2D and 3D seismic interpretation was applied to update the fault model, revealing a complex fault framework and synsedimentary tectonic activity. Geophysical well logs were digitized and used to define the model horizons. Subsequently, a first heat-in-place evaluation was performed for the northern Upper Rhine Graben. In addition, new outcrop analog studies are underway to provide new laboratory measurements for model parameterization of the shallower units within the Upper Rhine Graben. The results will form the basis for further numerical reservoir simulations (e.g., performance of hydrothermal doublets) and will be integrated into the publicly available internet platform "Geothermal Information System - GeotIS". This will facilitate the planning of new projects for municipalities and energy suppliers.

Geothermal potential of Ukraine can play a key role in accelerating the transition to net-zero energy target

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The geothermal potential of Ukraine can play a key role in accelerating the transition to clean energy, enhancing its energy security and independence. Analysis of the distribution of deep heat flux values on the territory of Ukraine, which varies from 40 to over 120 mW/m2, allows to identify Transcarpathian depression is one of the most prospective zones. There are 38 geothermal facilities within the depression with estimated resources about 10,424 million kWh/year. Despite the high geothermal background of this territory (the magnitude of the deep heat flow of the Transcarpathian depression vary from 61.4 mW/m2 to 111-112 mW/m2, the average geothermal gradient is 5 ºC/100 m, and for some fields it is equal to 7-8 ºC/100 m. The predominant reservoir temperature of geothermal volumes of sites ranges from 40 to 70 ºC and include: subthermal (warm, T=20-35°C), thermal (hot, T=35-42°C) and high-thermal (very hot, T more than 42°C) of hydrothermal resources and brines. First of all, this can be explained by the shallow drilling depth of the wells, the depth of which varies on average from 1000 to 3000 m.
The considerable strain of the deflection geothermal field is associated with the high tectonic mobility of the area. The deep thermal processes associated with the differentiation and redistribution of magma proceeded very intensively here.
In addition, the formation of thermal aquifers limits the high location of the crystalline basement. The regional area of feeding of deep aquifers is the zone of the Folded Carpathians, through the faults and disturbances of which cold atmospheric waters enter the aquifers and cool the latter.The vast majority of reservoirs have a crack-pore or crack-vein type with very uneven filtration properties both in the section and along the extension. Water-bearing rocks are represented by volcanogenic formations, rarely metamorphic and carbonates. Thermal aquifers are limited to fractured zones.
Territorially, thermal water fields are concentrated in the Uzhgorod, Mukachevo, Berehove, Irshava, Khust-Vynohradiv, Tyachiv (Solotvyno), and Svalyava recreation zones. In our study were analyzed numbers of wells and their wireline logging, coring and testing data. Petrophysical evaluation of the key wells was performed in the area of study. According to this data interpretation we can highlighted main reservoir properties: porosity ranges main geothermal targets is from 6-13%, fractures and losses during drilling this formations were noted. Lithology of this rocks characterized by sandstones, siltstones, breccia's, limestones and conglomerates. This data shows that the area of study (Trancarpathia region) possess a huge potential in wide range ap of geothermal application – direct use (heat), power generation projects, ATES as well as balneological one.

Geothermal potential of the Miocene Breda Formation in the Netherlands

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Abstract

The Breda Formation is the oldest and deepest unit in the Upper North Sea Group. Because of its relatively shallow burial (top depth <600 m) the temperature is generally low. However in the Roer Valley Graben (RVG) and the Zuiderzee Low (ZZL), the depth of the base exceeds 1000 meter. This corresponds to temperatures of more than 40°C, which makes it a potential target for shallow geothermal production.

Because the depth range of the Breda Formation is deeper than most ground water wells but shallower than the intervals studied in oil and gas exploration wells, little is known about the lithological content. The Regional Geohydrological Information System (REGIS) only predicts sand in the Breda Formation south of the line Rotterdam – Utrecht – Zwolle – Arnhem, and clay to the north. In the North this hypothesis is supported by sparse lithological well information. The information on aquifer flow properties porosity and permeability is even less.

The Zuiderzee Low (ZZL) and the Roer Valley Graben (RVG) were depocenters during the deposition of the sediments of the Breda Formation, which is reflected by the deep burial of the base. The hypothesis was formulated that both the RVG and ZZL acted as areas where sand accumulated. In order to test this hypothesis, cuttings from 5 wells in the ZZL were evaluated. Further, petrophysical evaluations were done on 16 O&G exploration wells in the ZZL, and 9 in the RVG. The cuttings show that the Breda Formation is sandy in the ZZL, although the fines content is hard to determine due to mixing with drilling mud. Well tests on the Naarden-120 well, which is located on the edge of the ZZL permeabilities around 300 mD. The petrophysical evaluations suggest permeabilities between 100 and 3000 mD. The main cause for the high uncertainty is the lack of information on the porosity-permeability relation.

The geothermal potential was calculated using the ThermoGIS approach with the operational settings as described on www.thermogis.nl. Because of the relatively shallow burial compared to those of other geothermal aquifers, the return temperature was lowered to 20 °C instead of the more commonly used 30 °C. Using these settings, the geothermal power was estimated to reach up to 9 MW_{th}, which could be improved further with a heat pump. The scenario assumes that the entire thickness of the formation is completed, which might not be realistic. The shown power map must therefore be viewed with caution. Concluding, the Breda Formation can be an interesting target for shallow geothermal exploration, but more details regarding the flow properties are needed.

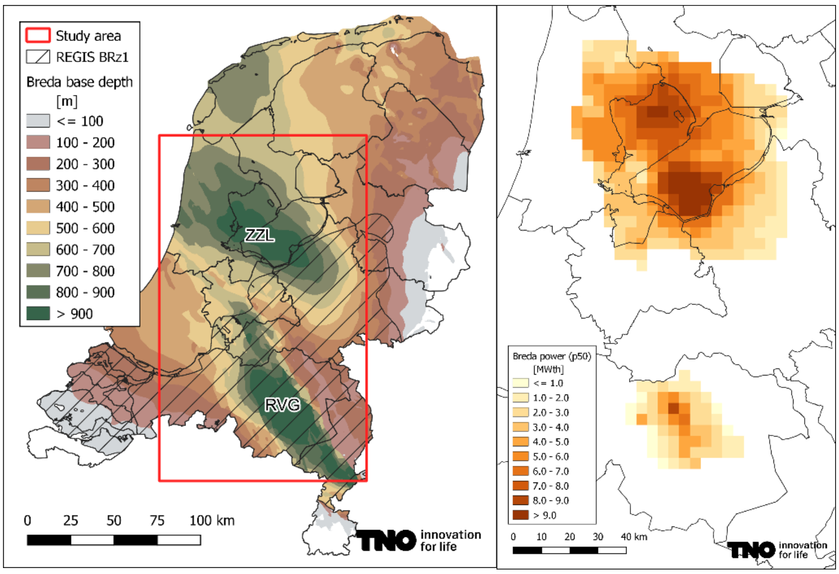

Figure: Left: Breda Fm depth showing Zuiderzee Low and Roer Valley Graben depocenters. Right: Calculated geothermal potential

Assessing High-Temperature Aquifer Thermal Energy Storage (HT-ATES) in the Upper Jurassic reservoir of the German Molasse Basin

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Abstract

High-temperature aquifer thermal energy storage (HT-ATES) systems provide high capacity for thermal energy storage of surplus energy by incorporating seasonal phases of charging and discharging a reservoir. In the present work, we emphasize on the karstified and fractured Upper Jurassic reservoir of the German Molasse Basin (North Alpine Foreland Basin). Even though multiple geothermal plants operate currently at this reservoir, the potential for heat storage has not been yet sufficiently analyzed. The estimated heating capacity obtained by feasible operational parameters is ca. 18 MW over half a year. Our approach highlights the evaluation of HT-ATES development in the Malm reservoir by means of numerical modeling.

The performed numerical analysis focuses on a subset of the Upper Jurassic reservoir which is governed by karst-dominated fluid fluxes, and further exhibits favorable reservoir temperature for heat storage. While we develop synthetic numerical models, those are based on a series of discrete investigations and datasets (i.e. field tests, well logs and investigations of rock cores) of three operating geothermal systems of the Malm aquifer, at depths of ca. 2000-3000 m TVD. In this regard, the numerical models are constrained by known Upper Jurassic reservoir properties and locally feasible operational parameters (e.g. flow rates, injected/produced fluid temperatures), and are thus considered representative of the ca. 500 m thick Malm reservoir at this subregion of the Molasse Basin. The proposed distance of the two vertical wells is 400 m, i.e. approx. twice the maximum estimated thermal radius, deciphered by assuming fluid injection solely in the thinner reservoir unit.

Simulation results illustrate the thermal perturbation that develops initially in the rock volume directly adjacent to the wells and progressively advances radially into the reservoir rock matrix. The geometry of the thermally affected reservoir rock is significant since heat losses occur at the interface between host rock and propagating thermal front. Furthermore, the models consider, through the IAPWS thermodynamic property formulations, density and viscosity variation induced by the temperature contrast between the injected fluid and the reservoir. Apart from investigating potentially arising buoyant fluxes that may trigger considerable thermal losses, the integration of density and viscosity variance additionally enables to examine its effect on the productivity and injectivity indexes. The computations allow to capture the relevant thermal and hydraulic effects of heat storage, and promote further a better understanding of the Upper Jurassic reservoir behavior.

Mechanical and microstructural characterization of spatially heterogenous simulated fault gouges, derived from the Dutch Rotliegend

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Human interventions in the subsurface have effects on its dynamic behaviour. Having a better understanding of how the subsurface responds to such interventions is crucial for an efficient and safe use of reservoirs at depth for future applications including the production of geothermal heat. A lack of fundamental knowledge of the processes that occur due to human induced stress changes has already proven to cause negative societal impact as seen in Groningen in the northeast of the Netherlands.

Gas production from the Groningen gas field causes compaction and induced seismicity within the reservoir and overlying/underlying lithologies. Recent earthquake localization studies show that seismicity dominantly occurs on complex normal fault systems that juxtapose lithologies of contrasting mechanical properties. However, little is known about the effects of along-fault heterogeneity on the frictional behaviour of these faults.

This study aims at understanding how material mixing and clay-smearing in fault gouges affects the mechanical strength and stability of faults that juxtapose contrasting lithologies (clay-rich vs quartz-rich) by performing friction experiments in a rotary shear configuration. Experiments are performed under normal stresses ranging between 2.5 and 10 MPa and imposed velocities ranging between 10 and 1000 µm/s. The rotary shear configuration allows for the large shear-displacements required to study the effects of lithology mixing.

This study shows that the frictional strength and stability of spatially heterogeneous gouges highly depends on the amount of shear-displacement. The frictional strength is characterized by subsequent phases of displacement-weakening and strengthening, whereas the frictional stability only increases with shear-displacement. This eventually leads to relatively strong but also frictionally stable faults at large displacements. The results have important implications for modelling earthquake nucleation, propagation, and arrest and apply to faults in geological settings that exhibit induced seismicity, like the Groningen gas field, but are also relevant for tectonically active faults located elsewhere.

Fluid dynamics in rough rock fractures

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Abstract

Crystalline rocks in deep geothermal reservoirs have a virtually impermeable rock matrix. The fluid is transported along rock fractures with high flow rates near the borehole. Hydraulic simulations in reservoir modeling mostly make use of approximations when dealing with flow behavior through rock fractures. Common simplifications such as the (Local) Cubic Law reduce the required computational cost, but often cannot fully reflect the fluid dynamics in this setting. More accurate models, on the other hand, typically require prior parameterizations (problem fitting) and/ or lead to a high simulation effort.

To test and validate these approximations for rough fractures, they are experimentally investigated in the F^4aT-Hydraulic Laboratory (Forced-Fluid-Fracture-Flow and Transport Laboratory). It comprises a flow-through test stand, where hydraulic experiments can be conducted with fracture surfaces of a defined roughness. This roughness can either be reproduced by a high-resolution scan of a real rock fracture or synthetically generated by a theoretical roughness definition. For the experimental tests, these rough surfaces are then printed with a highly accurate 3D printer. Additionally, the fracture flow is numerically simulated as Navier-Stokes-Flow, which helps analyze the fluid dynamics in the rough surface in a higher resolution. With these two methods combined, the approximations can be validated, and accruing effects in rough fractures, such as channeling, can be investigated. The channeling effect describes the occurrence of preferential flow paths with a higher flow rate and other fracture areas with nearly no flow, which could affect the hydraulics and thermodynamics of a geothermal reservoir. The occurrence of this effect as well as its impact on the transport processes in these complex fractures is still an ongoing scientific question.

Using Machine Learning-based Workflows to quantify the effects of the Geological Uncertainty in Geothermal Applications

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Abstract

The evaluation of possible uncertainties in underground processes requires numerical simulations based on probabilistic geological models. In this study, 50 geological models are used to simulate the tracer breakthrough curve (BTC) in a geothermal doublet. Simulation results revealed that a negligible perturbation in the structural model causes a 26 and 30 percent variation for peak arrival time and tracer magnitude, respectively. To establish a more robust method for quantifying structural uncertainties, three different machine learning (ML) models are used. Decision tree regression (DTR) and random forest regression (RFR) methods are deployed to predict the target variable, i.e. BTC, merely based on the structural model. The input features for the ML model were defined as the coordinates of the four corners of the perturbed structural element (a planar fault). Then, the model correlated these coordinates with its target variable which is the BTC. DTR and RFR methods generated all the values of the BTC time series at once. DTR and RFR methods suffered from the most typical issue in ML: over-fitting and under-fitting. Then, a chain of gradient boosting regression (GBR) is developed to add the formerly predicted values to the list of input features. The chain model predicts every time step of the BTC as a unique target variable. The acceptable increase in RMSE from train to test data confirmed the ability of the chain model to capture both the general trend and small-scale heterogeneities. Using the ML model instead of the numerical solver, the computational time decreased by six orders of magnitude. Thanks to the time efficiency of ML, BTCs for 2000 different geological models are calculated to enable a more comprehensive uncertainty quantification.

Evaluation of the geothermal potential in the Acque Albule Basin (RM) through a multidisciplinary approach

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Abstract

Low and medium enthalpy geothermal energy has been widely exploited in the last years, due to the need for green transition in the overall human development. This study presents new findings about the geothermal potential of the Acque Albule Basin (AAB). This area is located in the Latium region, about 40 km NE of Rome. The AAB is a subsiding basin tectonically controlled and characterized by a volumetrically huge hydrothermal manifestation. The deep hydrothermal activity is testified by the presence of large and thick travertine deposits and several mineralized springs (Tmax at surface of about 23°C) in which warm fluids rise up from the geothermal reservoir. These hot fluids circulate through the Meso-Cenozoic carbonate succession, highly affected by dissolution and brittle deformation. To this purpose, the main goal of this work is to develop a methodology to evaluate the permeability distribution in the deep carbonate reservoirs, and to evaluate the geothermal potential of the AAB through a multidisciplinary approach. First of all, several geophysical prospections have been carried out in the AAB (passive and active seismic techniques) in order to identify the depth (3D model) of the main lithological layers. Based on this geophysical survey, the measurement of diffuse soil CO2 emissions is being planned, to define a model for the permeability in the geothermal reservoir. Finally, we are running several laboratory experiments on the carbonates rocks to evaluate the mechanical and hydrological behaviour of this lithologies under different fluids pressure condition. A preliminary model for the exploitation will be set up, combining structural field data, geophysical data, geochemical data, and laboratory experiments.

Keywords: geothermal energy, green transition, sustainability, hydrothermal circulation.

Geological Characterization and Modeling of Maastrichtian Calcarenites in the North German Basin Regarding Their Potential as a Medium-Depth Geothermal Reservoir

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Abstract

The untapped potential of mid-depth geothermal resources in the North German Basin (NDB) offers a sustainable and carbon-neutral heat supply opportunity. The Maastrichtian Calcarenites, in particular, show promise, yet their geothermal potential remains insufficiently explored. Numerous wells from the hydrocarbon industry have intersected these Calcarenites in the past, occasionally serving for wastewater disposal within the oil and gas sector, indicating substantial porosity and permeability. The primary objective of this research is to cartographically document the distribution of Calcarenites, characterize their geological properties, and assess their geothermal potential. The planned workflow and first results are primarily to be presented.

To achieve this, data from the hydrocarbon database, a 3D seismic survey, and a 3D subsurface model will undergo collection, analysis, and re-evaluation. The primary focus is a meticulous examination of well data to classify facies types, characterize rock properties, and analyze geological structures for precise identification and delineation of potential reservoir zones. Additionally, core samples will analyzed to determine petrophysical properties, like porosity, permeability, pore size, and diagenesis. Seismic data will be interpreted to detect geological patterns, such as fault lines, rock types, and subsurface layer variations. Subsequently, all acquired data will integrate into a detailed geological model. Using this model, numerical simulations will evaluate economic reservoir parameters for doublet operation, considering thermodynamics, hydraulics, and mechanics. From these results, strategies for harnessing the geothermal potential of the Maastrichtian Calcarenites will be derived. Finally, the findings of this study will be made accessible to the public through the GeotIS platform.

A thorough analysis of well reports confirms the facies distribution inentified in previous studies. Accordingly, in northwestern Germany the Maastricht deposits exhibits a facies transition from southeast to northwest, delineating three distinct facies: the proximal Steinförder facies, the intermediate Reitrooker facies marked by the presence of Calcarenites, and the distal Schreibkreide facies consisting of chalk. Based on the well log data the Calcarenite can be divided into two zones: the Upper and Lower Calcarenite, separated by a marl-rich layer, which can consistently observed and correlated across the study area. Furthermore, there is a noticeable trend indicating that the higher stratigraphic Calcarenite exhibits greater porosity and permeability. Thus, the Upper Calcarenite appears to be potentially suitable as geothermal reservoir rocks. The thickness of the reservoir hinges on the preserved Upper Calcarenite during the Tertiary transgression. Halokinesis and associated condensation and dilation processes significantly impact diagenesis, structure development, and reservoir rock quality, including pre-Tertiary erosion. Seismic analysis promises to provide additional insights.

Exploring Future Geothermal Potential in the Ruhr District, Germany: A Borehole Study on Two Diverse Reservoir Rock Types

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Abstract

In Germany, resources for deep geothermal energy have so far been limited to a few provinces, and some of them are well developed, with power plants in operation. However, other parts of Germany have hardly been explored, despite high population densities with high energy demands in some regions (e.g., the Ruhr District in North-Rhine Westphalia).

Deep wells at reservoir depths (at least 2500 m and deeper) are seldom available or not surveyed for geothermal purposes. Research projects involving deep boreholes are rarely realized and typically focus on single sites. For this reason, shallow boreholes offer an alternative as an analogue study, providing a first insight into deep fracture networks. Therefore, more studies on deep hydrogeology in fractured reservoirs need to be conducted in the future to provide an initial estimate of geothermal potential. Depths greater than a few hundred meters allow assessments of fracture systems that are unaffected by meteoric weathering and therefore not altered by surface processes.

For this study, a naturally fractured Carboniferous sandstone and a karstic dolomitic limestone reservoir of the Devonian were investigated using geophysical borehole measurements, hydraulic and hydrochemical experiments, and acoustic/optical televiewer recordings. Shallow exploration wells with a depth of a few hundred meters have proven useful for providing an initial estimation of the in situ permeability. Additionally, transmissive fractures as well as karstified structures could be located and evaluated using borehole probes.

The sandstone formation studied showed low overall permeability, likely due to the presence of fractures that are numerous but not hydraulically effective. In this geology, fault zones should be drilled as a priority target, potentially revealing increased apertures of connected fractures. Alternatively, permeability can be improved through stimulation (hydraulically, if seismic risk is kept low, or chemically by dissolving fracture fillings to enlarge fracture apertures). Chemical enhancement of permeability was attempted using CO2 to dissolve carbonate fillings in fractures via a borehole injection experiment, but further research is needed to evaluate the effectiveness of this method. Alternatively, low-permeability layers can be geothermally exploited using the recently demonstrated EAVOR-Loop™, as drilling in the tight Ruhr Carboniferous formations can be accurately achieved with minor mud losses.

The dolomitic limestone formation exhibits exceptional permeability due to large fracture apertures, cavities, and vuggy porosity resulting from karstic processes, making it a promising reservoir for hydrogeothermal purposes. However, further confirmation is required at reservoir depths (e.g., 2500 – 4000 m).

In summary, deeper geothermal reservoirs in the Ruhr region have not been explored enough so far, and further field studies are necessary to evaluate their potential for geothermal energy production.

Geothermal projects in Litoměřice, Czech Republic

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Abstract

The town of Litoměřice, Czech Republic, has been the object of geothermal exploration for nearly two decades, with the pilot exploration well being drilled in 2007. Fifteen years later, more geothermal drilling is planned to take place at the site. Here we introduce two geothermal projects, SYNERGYS and PUSH-IT, that are about to commence in late 2023 at the Litoměřice geothermal site. PUSH-IT (Piloting Underground Storage of Heat In geoThermal Reservoirs) is an international project with many international partners led by TU Delft and funded by the Horizon Europe programme and aims to demonstrate various Underground Thermal Energy Storage technologies (borehole - BTES, aquifer - ATES and mine - MTES). Litoměřice is the follower site for demonstration of the BTES technology. SYNERGYS is funded by the Just Transition Fund to aid former coal regions with energy transition. SYNERGYS stands for the synergies of various energy resources (deep geothermal - EGS, shallow geothermal - BTES, and photovoltaic on the surface). Two exploration wells are planned to be drilled in October 2023 under PUSH-IT. The deeper (500 m) well is a fully-cored and logged exploration well, later to be equipped with a fibre-optic cable for future monitoring. The shallower (200 m) well is designed as a hydrogeological monitoring well. Results from these boreholes are essential for the design of the three proposed BTES fields aimed at depths of 100 m (low temperature), 200 m (medium temperature) and ~450 m (high temperature). Drilling of the BTES fields is planned for 2024, establishing the largest and most complex geothermal development in the Czech Republic.

MAJOR CHALLENGES ON ENHANCED GEOTHERMAL SYSTEM PROJECTS

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Abstract
The sustainability of the energy supply can only be achieved to use long-term energy transformation of renewables. Major renewable energy sources are solar, wind, geothermal, and hydroelectric power. Geothermal energy apart from other renewables with its higher efficiency rates. The fundamental purpose of geothermal energy is to generate electricity by transferring the earth's heat to the surface via geothermal fluid. Although the major focus for geothermal energy was conventional production, recent studies are mainly dealing with the non-conventional geothermal application which is called Enhanced Geothermal Systems (EGS). EGS, derived from Hot Dry Rock (HDR), can play an important role in meeting energy demands. EGS is considered as a valuable energy production method to achieve carbon free goals of all countries. However, it brings many new challenges on drilling, well integrity, and hydraulic fracturing. In the current study, an overview will be demonstrated about significant challenges on EGS.

A Coupled Thermo-Hydro-Mechanical Simulation of Borehole Heat Storage in the Nordic Climate: A Case Study from Norway

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Abstract
The efficient design and long-term stability of borehole thermal energy storage (BTES) systems require a thorough understanding of the interplay of thermal, hydraulic, and mechanical processes, particularly when it comes to high temperature storage. Heat injection in subsurface environment not only changes the temperature of the surrounding medium but can also affect fluid dynamics through the expansion or contraction of the porous medium. Coupled thermo-hydromechanical (THM) simulation offers a holistic approach to capture these interrelated phenomena and evaluate the long-term efficiency of the thermal storage system. In this paper, the potential consequences of high temperature BTES on the surrounding porous media are analysed using THM simulation. The results obtained indicated that the expansions and contractions caused by heat storage and extraction can induce stresses in the rock, which may reduce the efficiency of the system in the long term due to the changes in permeability. These stresses can also cause heat to migrate away from the storage zone, potentially affecting neighbouring structures, groundwater sources or ecosystems. Elevated temperatures can also alter the mechanical properties of the rock, affecting its strength and ductility, which in turn can have implications for the stability and longevity of the borehole system. It appears that coupled THM simulation is an indispensable tool to ensure the safety, reliability, and performance optimisation of borehole heat storage systems, offering guidance for design, operation and maintenance strategies.

Thermal properties of unconsolidated sediments and borehole back fill materials for ground source thermal energy systems

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Abstract

The performance of Ground source heat pump systems (GSHP), and heat losses along well bores of high-temperature aquifer thermal energy storage systems (HT-ATES) and geothermal wells is strongly affected by conductive properties. The anticipated growth of the geothermal and HT-ATES in line with global potential of geothermal energy production of between 125 and 1793 EJ yr-1 (1) augments to the relevance of in-depth understanding of conductive properties. Apart from heat losses affecting performance, shallow groundwater used for drinking water could be affected by the heat transfer (2). This can result in (bio)chemical changes in the water composition and can potentially reduce the amount of suitable drinking water reserves for future use. In addition, too much heat loss in the cold subsurface could yield a risk of the formation of thermal plumes, which could in turn compromise the production of neighboring geothermal wells in urban areas (3).

Uncertainties in the thermal conductivity of an aquifer can affect the efficiency estimations of a single HT-ATES doublet. Using DoubletCalc (4), it was determined that this especially plays a role during the initial three loading cycles with a difference of up to 3.5% in efficiency. Others have shown even larger impacts, where an increase of 12.5% of the thermal conductivity reduces the total aquifer technical potential with 25–33%, while decreasing by 12.5% results in a 29–49% increase (3).

Understanding and being able to measure and predict the thermal properties both on the centimeter- and meter scale is challenging. Experimental determination is typically on the millimeter scale, most numerical simulations use solid rock-, oil and gas- and construction industry values and well thermal response tests lumpsum many different sediment types into one value.

A semi-automated setup was developed based on the needle-probe method to create an experimentally based understanding of the influence of different interrelated physical properties of unconsolidated sediments, such as grain size, shape, porosity and mineralogy, on the thermal properties of such sediments.

For separating the bulk thermal conductivity measured in the lab, into a thermal conductivity value for fluid and solid individually, an ensemble smoother with multiple data assimilation (ES-MDA) tool was used. This tool applies an inverse fit of the analytical thermal conductivity model, derived from Fourier's law of heat, to the experimental data. Results include the most likely solid and fluid thermal conductivities and sample porosity, with a given uncertainty range.

The combined experimental-numerical approach provides a reliable and reproducible method for determining the thermal properties of unconsolidated sediments and porous media in general and a means to determine the validity of the forward model calculations. In most recent developments, results from the experimental set-up and ES-MDA tool are used in a numerical model, representative for a closed-loop ground source heat pump system. This way, configuration and efficiency analyses of the system are performed.

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Risk assessment of fault reactivation and induced seismicity for the high-temperature heat storage demonstrator, DeepStor, in the Upper Rhine Graben

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Abstract

HT-ATES (high-temperature aquifer thermal energy storage) systems have the objective of seasonal storage of significant amounts of thermal energy, enabling to cover the demand of e.g. industrial processes or district heating. Nevertheless, due to the elevated temperatures or pressures associated to HT-ATES systems, thermo- and poroelastic stress changes occur in the proximity to the injection well. These stress changes could potentially lead to fault reactivation and seismic activity. This study centers on the evaluation of the probability of fault reactivation and induced seismicity for the planned HT-ATES demonstrator DeepStor, situated near Karlsruhe in the Upper Rhine Graben in Southwest Germany. DeepStor aims to prove the concept of the utilization of a former oil reservoir for HT-ATES. The risk assessment is based on a geological model of the intended storage site as input for thermo-hydraulic numerical modeling. The resulting variations in reservoir pressure and temperature are then integrated into a semi-analytical computation to determine stress changes along a fault close to the HT-ATES system. Through a sensitivity analysis of parameters followed by a Monte Carlo simulation comprising 1000 iterations, it becomes clear that the most influential factors are related to uncertainties concerning stress conditions, particularly the ratio between horizontal and vertical stresses, as well as the orientation of the maximum horizontal stress. However, the calculated slip tendency on the fault next to the injection well surpasses the friction coefficient in only around 4% of all parameter combinations of the Monte Carlo analysis. Essentially, this occurs solely under highly unfavorable combinations of reservoir and operational variables. Consequently, the anticipated risk of fault reactivation and subsequent induced seismic activity associated with HT-ATES operations at the DeepStor demonstrator is presumed to be relatively minimal.

A sensitivity analysis of stress changes related to geothermal direct heat production in clastic reservoirs and potential for fault reactivation and seismicity

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Keywords: geothermal energy, stress arching, fault reactivation, induced seismicity.

ABSTRACT

Accurate and efficient predictions of three-dimensional subsurface stress changes are required for the assessment of geothermal operations with respect to fault stability and the potential risk for induced seismicity. The effects of long-term cooling on the reactivation and seismicity potential of faults near a geothermal doublet in matrix permeability dominated geothermal systems require quantification and management for safe and effective application of geothermal energy (e.g. Marelis et al., 2022, 2023). This work presents a detailed analysis of the sensitivity for fault reactivation and induced seismicity based on different scenarios for reservoir characteristics and production parameters. To this end, MACRIS (Mechanical Analysis of Complex Reservoir for Induced Seismicity) (Van Wees et al., 2019) is introduced as a computational method for high-resolution stress predictions and reactivation potential of faults in structurally complex reservoirs. By adopting a mesh-free approach adapted to industry standard flow simulation topologies, MACRIS is capable of preserving the complex 3D hydraulic development of the injected cold-water volume and the 3D geometrical complexities of the reservoir grid. The workflow has been applied to a three-dimensional model representative of a low enthalpy geothermal system with a clastic reservoir. The model is marked by a single fault, subject to no and normal offset. Key elements in the dynamic and mechanical behaviour of the reservoir are varied, along with different production scenarios. Simulated stress evolutions in MACRIS show a predominant sensitivity for fault reactivation to the thermo-elastic parameters, i.e. the Young's modulus and thermal expansion coefficient. Results show the effects of stress arching to increase as a result of fault throw and fault related reservoir flow compartmentalization. Furthermore, in cooling reservoirs, the intersection area of the cold-water volume in direct contact with the fault plane is shown to be the main driver for fault reactivation and subsequent seismic potential.

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GeoLaB - Geothermal Laboratory in the Crystalline Basement

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Abstract

The imperative to address climate change and the evolving geopolitical landscape highlights Europe's need to break free from fossil fuel dependency and prioritize a genuine energy transition. Geothermal energy emerges as a pivotal player in this endeavor, particularly concerning heat supply and storage. The primary untapped potential lies within the crystalline bedrock, notably concentrated in tectonically active regions. However, harnessing this vast potential sustainably, efficiently, and securely necessitates a profound expansion of our scientific comprehension and the formulation of innovative, science-driven strategies.
Endorsed and funded by the Helmholtz Association, the subterranean GeoLaB (Geothermal Laboratory in the Crystalline Basement) research facility will confront foundational challenges inherent in deep geothermal projects, specifically reservoir technology and borehole safety. This initiative bridges the divide between laboratory or small-scale field assessments and full-scale reservoir operations. Its focus is on gaining fresh insights into the intricate, nonlinear interplay of processes connected with substantial flow rates in crystalline reservoir formations (anticipated to exceed 1 liter per second). Through cutting-edge interdisciplinary research and visualization methodologies, complemented by the creation and application of advanced monitoring and analytical tools, this endeavor will yield crucial new knowledge pivotal for the ecologically safe and responsible exploitation of deep geothermal resources.
Officially started in January 2023, the project aspires to evolve into an interdisciplinary and globally collaborative research platform upon completion. However, even during the exploration and construction stages, it will serve as a frontier for state-of-the-art research and development. The geoscientific community is wholeheartedly invited to partake in the GeoLaB initiative.

Figure 1: caption

GeoLaB (Geothermal Laboratory in the Crystalline Basement) is a planned Helmholtz large-scale infrastructure. The international and interdisciplinary research platform focuses on the thermal-hydraulic-mechanical-chemical (THMC) processes of deep geothermal reservoirs and reservoir engineering issues. The overarching aim of the research is a safe and ecologically sustainable use of the most important geothermal resources in Germany and worldwide. For this purpose, a generic underground geoscientific laboratory in the fractured crystalline basement of the Schwarzwald-Odenwald complex shall be built.

ABSTRACT VARDON

Simulation of the Delft campus geothermal wells constrained by the producer well logs

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Abstract

The Delft campus geothermal well is responsible for extracting subsurface heat the campus buildings and parts of the Delft city. This heat extraction process is subject to significant uncertainties, coming from both operational and geological factors. The injection well Bottom Hole Pressure (BHP) forms an operational uncertainty and is dictated by geological uncertainties such as facies or porosity realizations of the same reservoir geometry. Injection well BHP is largely influenced by the discharge rate and the connection between an injection and production well. The production well's trajectory log data is employed to assess the connection in the vicinity of the production well, thus constraining the geological model and geological uncertainties.

In this work, 900 large geological models (approximate 6.0 million grid blocks) are utilized to simulate the heat production. We present the Delft campus geothermal well models simulation with production well log constraint using the open-source software Delft Advanced Research Terra Simulation (DARTS). The DARTS platform enables accurate and efficient sensitivity and uncertainty analysis. Our work demonstrates that, considering the variations in porosity realization, there can be a significant variation in the lifetime of a geothermal system, exceeding 15 years, when the total simulation time is extended to 30 years. This underscores the substantial uncertainty that can be attributed to geological property models. Furthermore, when we introduce the constraint of matching production well logs, we are able to identify 19 geological models out of a pool of 900 that exhibits favourable porosity alignment within the production well trajectory blocks compared to the actual production well logs. Additionally, our study reveals that the majority of geological models exhibits injection well BHP values below the SodM threshold. Our study highlights the need for Uncertainty Quantification in direct-use geothermal systems to accurately predict their lifetime and operational range.

A digital twin for the TU Delft campus geothermal project: First concepts

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Abstract

A digital twin denotes a virtual representation of a physical product, process or facility, and is used to understand and predict the physical counterpart's performance. Geothermal energy can provide clean and sustainable energy base load. The TU Delft campus geothermal project ("Geothermie Delft") has been initiated to provide a unique research environment with the vision to scale-up the deployment of geothermal energy as well as providing and storing heat for the TU Delft campus. Here we propose a concept for a Digital Twin for Geothermal Energy that will be tested and validated at Geothermie Delft. Multiple geological models will be expeditiously constructed for the reservoir. The production data will be used for updating the geological models in real-time, constrain reservoir uncertainties, and adapt operational strategies to boost performance. The concept will encompass several stages (Figure 1). Well logs and seismic data will be utilized to design multiple reservoir models that capture possible geological scenarios, using the Rapid Reservoir Modeling (RRM) software. Likely property distributions will be assigned to the various geological domains to capture uncertainty in the petrophysical data. The Delft Advanced Research Terra Simulator (DARTS) will be combined with machine learning techniques to create a proxy model that enables fast production forecasts. As new production data becomes available, data assimilation techniques such as ESMDA and RML will be applied to update property distributions for each scenario and improve the corresponding proxy models. This iterative process will result in better constrained geological and production uncertainties, both of which are key to optimize operational strategies. Overall, the geothermal digital twin is envisioned to decrease operational risks, reduce maintenance costs, extended reservoir lifetimes, and enhanced overall sustainability of a geothermal resource.

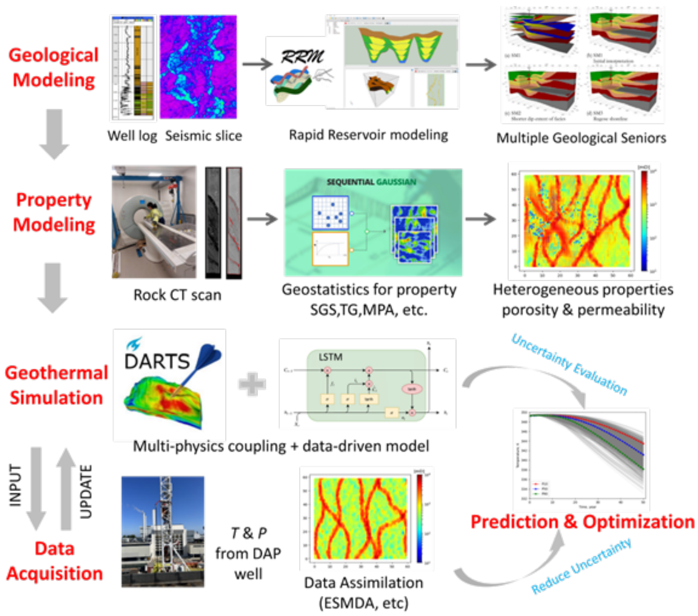

Figure 1: The concept for the Digital Twin for Geothermal Energy

MALEG - Machine learning for enhancing geothermal energy production

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Abstract

To improve the efficiency of geothermal energy production the reinjection temperature has to be reduced. Yet in most cases, the geothermal fluid composition is counteracting this temperature reduction. Whilst pressure relief or cooling, highly mineralised geothermal fluids tend to rise uncontrolled mineral precipitation (scaling). This is a strict limiting factor for the efficient and continuous operation of geothermal power plants. The complex and site-specific hydrochemistry of the fluids complicates the prediction and quantification of scalings using deterministic geochemical models. In the MALEG project, geochemical models are complemented by artificial intelligence, which is trained with hydrochemical data provided by on-site experiments.

For this purpose, a demonstrator is built resembling a hardware twin of the geothermal power plant, which is capable of representing the thermodynamic processes in the system. The demonstrator will be connected to the power plant via a bypass to conduct hydrochemical precipitation experiments. Continuous monitoring of fluid and solid samples accompanies the experiments to evaluate potential mineral precipitation. These precipitation processes are dependent on the chemical milieu of the fluid. Changing system parameters such as pressure, temperature, pH, or ion concentration enable the formation of scaling. The application of the demonstrator and the corresponding hydrochemical experiments are planned for three geothermal systems involving different reservoir conditions. The collected and analysed data will set up a diverse hydrochemical database, which will be used to develop the AI-based prediction tool "MALEG". In addition, a digital twin consisting of deterministic geochemical models will validate the predictions of "MALEG". Thus, the impact of changes in the fluid chemistry can be predicted more accurately. Evaluating scaling formation will allow optimisation of geothermal power plant operating parameters for improving efficiency, the introduction of cascade utilisation, integration of mineral extraction processes, or cost reduction of routine hydrochemical monitoring.

EGRISE 2.0 an empowered tool to figure geothermal sector status and needs

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Abstract

There is a large number of geothermal information providers, such as scientists, operators, consultants, public entities and funding agencies. Their documents, often available on request, are stored and served by various systems, which are not necessarily and organically connected.

Capitalizing the geothermal knowledge is a priority clearly recognized in the Strategic Research and Innovation Agenda (SRIA) issued by the European Technologies and Innovation Platform (ETIP) on geothermal, with the scope of promoting RD&I in the geothermal sector. A detailed and comprehensive collection of information from past and actual RD&I projects and geothermal activities is crucial to figure out the status of geothermal sector. Information on funds of research projects, performance indicators, prototypes, patents, publications, datasets and EU project deliverables aid scientists in setting up innovative project proposals, investors in discovering potential market opportunities, and policy maker in allocating resources or defining regulations to boost the development of the sector.

To such aim ETIP Geothermal developed the first release of the European Geothermal Research and Innovation Search Engine (EGRISE) in 2018. EGRISE is a web-based platform enabling users to discover documents related to the geothermal sector in a catalogue of over 260 resources. The majority was represented by EU funded project deliverables. With the development of the constantly updated EU OpenAIRE scientific knowledge aggregator, the static repository created with EGRISE became obsolete. In the frame of the Geotherm-FORA EU project, we are implementing EGRISE 2.0, expanding the original EGRISE back-end and empowering its capabilities.

EGRISE 2.0 builds on top of the OpenAIRE harvesting information on EU funded geothermal projects and relate public deliverables. Furthermore, it retrieves datasets from different repositories (e.g., Zenodo, Pangea) and scientific journals reaping meta information of each single research product. Research products related to the geothermal sector are identified by queries based on specific keywords. EGRISE users can access the resulting huge amount of documents (actually over 8000) and search them, e.g., by type of publication, type of resource access, year range, funder, country, language, source.

Moreover, EGRISE 2.0 is linked to a dashboard showing statistics on the available research products, such as publication number, publication openness over the time, and top organization producing research products. These are important information on matureness of specific sectors or topic, for example for the funding agencies defining topics to be supported.

EGRISE will be soon available, for free, in the frame of ETIP-Geothermal web portal.

New closed loop well solution for geothermal heat extraction

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Abstract
A new closed loop solution for extracting geothermal energy provides stable, reliable and clean energy for district heating and other applications (Figure 1). The solution differs from the conventional open geothermal solutions by being more environment friendly, can be implemented almost anywhere, and has low operational risk and maintenance cost.

The solution is based on an arrangement where one or several horizontal wells are drilled to a suitable depth, normally up to 4 km vertical depth and a similar length horizontal section. The wells are completed with a new patented production string solution, DualVac, which supplies the geothermal energy to fex. the district heating network.

The solution is based on heat exchange between the rock and the circulating water in the well. The water is heated from the rock as it is pumped down the well. The heated water returns to the surface through the inner DualVac pipe with minimal heat loss as the pipe works as a thermoflask.

The development of DualVac and the closed loop solution is part Hocloop, funded by the Horizon Europe, EU research program and funded by the Norwegian Innovation Fund.

The closed loop solution avoids requirements for the permeability and porosity of the rock formation. The solution avoids that fluid enter into the formation, i.e. avoid risk of subsurface water pollution, induced seismicity and there is no need for fracking the formation.

The energy output per well can typically be up to 4 MW. The flow rate can be adjusted to control the temperature and thermal power output. The power output capacity per well depends on various factors, such as the temperature and thermal conductivity of the formation, the temperature of the circulating water and the length of the horizontal well section.

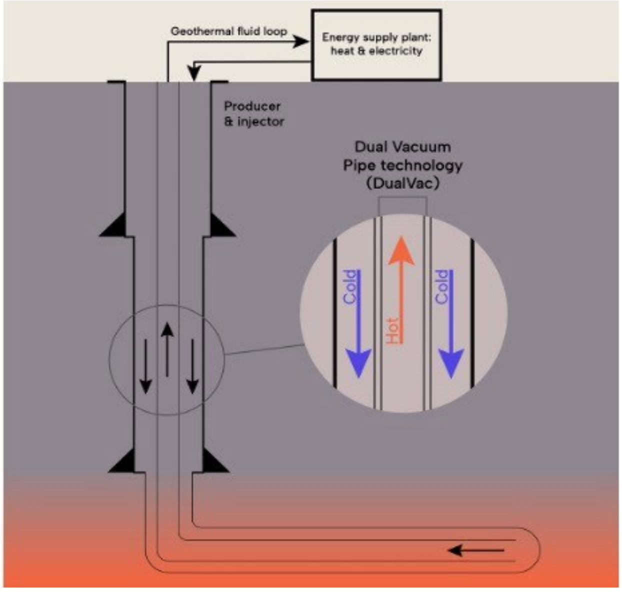

Figure 1: Single well closed loop geothermal well solution.

Experimental Investigation of the usage of CO2 in closed loop systems: the HOCLOOP Project

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Abstract

The HOCLOOP project focused on the feasibility study of the development of a closed loop geothermal system based on the REELWELL DualPipe technology. In the scope of this project, a specific work-package (WP3) explores the possible usages of fluids different than water for heat extraction, with specific focus on CO_2 and CO_2 mixtures. An experimental campaign has been planned to study the behaviour of CO_2, and the possible usage of ionic fluid for heat-extraction properties enhancement. The experimental campaign will be jointly conducted by the Universities of Bari and Florence. The University of Bari will study the properties (viscosity and heat capacity) of CO_2 and ionic fluids mixtures while the University of Florence will study the heat transfer behaviour of such mixtures. The authors will present the test benches preliminary design and the planned experimental activities.
A schematic of the test equipment is shown on figure 1

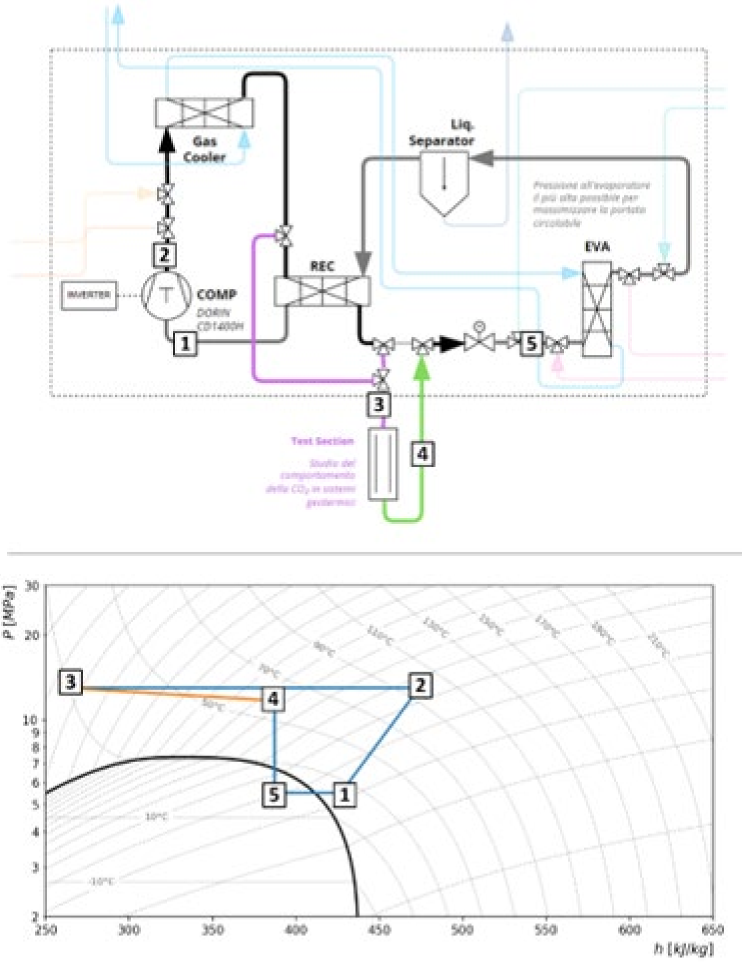

Figure 1 – schematic of the test equipment and CO_2 transformation in the test section

On novel binary power plant configurations for the exploitation of two-phase geothermal resources

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Abstract
The design of a geothermal power plant exploiting a two-phase geothermal resource is a demanding task, due to the fact that different technologies, plant configurations and working fluids must be considered. Moreover, the impact and cost of handling non-condensable gases (NCG) must be taken into account.

This study investigates the performance of novel ORC power plant configurations specifically designed to exploit two-phase geothermal sources, and subsequently benchmarks their performance against the more common flash power plants. Further, a parametric study on the geofluid inlet conditions and NCG content, heat exchanger pinch-point temperature difference and other fundamental design inputs is carried out to compare the performance and define the application envelope of the different technologies.

Preliminary Life Cycle Assessment, Exergo-economic and Exergo-environmental analysis of the Qualtra geothermal power plant

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Abstract

Qualtra is an innovative 10 MW geothermal power plant proposal with a closed-loop design that prevents emissions into the atmosphere. This approach employs a binary cycle system where the geothermal resource, consisting of steam at 10 bar and 180°C, heats a synthetic fluid (R1233zd), which operates in a Rankine cycle arrangement. An air-cooled condenser recovers the condensed working fluid, which is then pressurized and returned to the main heat exchanger (MHE). In the MHE, the resource condenses under high pressure - the recovered liquid brine preheats the working fluid, and is then reinjected into the reservoir.

The non-condensable gas (NCG) stream, primarily composed of CO_2, is collected at the MHE's dome and extracted using intercooled compressors. This high-pressure NCG stream is directed to an innovative reinjection well, which employs a novel two-phase flow reinjection concept, mixing the liquid brine and the compressed NCG stream at significant depths using a coaxial pipe arrangement and reverse-gas lift valves to guarantee entrainment of the gas with the liquid brine stream. This ensures stable two-phase flow even during startup or closure, allowing the NCG stream to be entrained into the reservoir. Overall, Qualtra's design minimizes the environmental impact by containing emissions and efficiently harnesses geothermal energy for power generation. A comprehensive environmental analysis was performed for this plant: Life Cycle Assessment (LCA) and Exergo Environmental Analysis (EevA).

The results obtained from the LCA (carried out using the ReCiPe 2016 midpoint methodology) are 18 different environmental impacts. Each of them has its own unit and refers to the functional unit, that is, the kWh of energy produced over a 30-year plant lifetime. It should be emphasised that the Qualtra power plant has no direct emissions into the atmosphere. For this reason, the environmental indicators sensitive to atmospheric emissions are only affected from indirect emissions during the life cycle. The life cycle Global Warming Potential indicator is given as a reference, with a value of 6.56 g CO_2/kWh which is very low compared with traditional systems. An analysis of the contributions shows how for each category the main impact comes from the construction phase, in fact it exceeds 90% of the impacts for all categories. The main contribution are machinery and wells drilling.

A single score analysis was also conducted for each process, applying normalization and weighting of environmental indicators.

These single score results are the input for the Exergo-Environmental Analysis (EEvA), which shows that for the Qualtra power plant the system of wells is the most impactful contribution, accounting for approximately 45% of the total impact. Other significant contributins to the environmental impact are represented by the condenser (21% of the total), the turbine (17% of the total), and the HEGeo (14% of the total).

The plant analysis included the evaluation of costs, which were processed through an Exergo-economic analysis evaluating the cost buldup along the major plant components. This included the evaluation of the cost of electricity generated by the power plant, which is expected to be 8.3 cents per kilowatt-hour (cPts/kWhe).

The largest induced earthquakes during the GEOVEN deep geothermal project, Strasbourg, 2018–2022: from source parameters to intensity maps

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Abstract
Between 2019 November and 2021 July, four induced earthquakes of local magnitude equal to or greater than three were felt by the population of Strasbourg, France. These events were related to activity at the deep geothermal site GEOVEN located in Vendenheim in the nor ther n suburb area of the city of Strasbourg. The first earthquake, with a local magnitude (*M*lv) of 3.0, occurred on 2019 November 12, at the same depth as the bottom of the wells (approximately 4 km) but 5 km to the south. The second (*M*lv 3.6) occurred a year later, on 2020 December 4, below the wells, and led to the termination of the project by the authorities. The third (*M*lv 3.3) was initiated three weeks after shut-in on 2021 January 22, while the largest earthquake to date (*M*lv 3.9) occurred on 2021 June 26, more than 6 months after shut-in. We constrained these four events' absolute locations using a 3-D velocity model of the area and here present regional intensity maps. We estimated moment magnitude and focal mechanism trough waveform inversion and inferred the fault plane acti v ated during the largest event from an analysis of rupture directivity effects in the recorded waveforms. Our analysis highlights the existence of a critically stressed fault that hosted three of these widely felt events. We show how the derived source properties of these four earthquakes are directly linked to ground shaking observations at the surface. Notably, we demonstrate how earthquake moment, location, direction of rupture and stress drop impact the regional intensity distribution. Our results suggest that the traffic light system could benefit from including ground shaking scenarios based on realistic subsurface properties and potential earthquake source models.

A pragmatic approach to monitoring induced seismicity and subsidence at geothermal operations

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Abstract

Geohazards such as induced seismicity and subsidence are commonly, and often wrongly, associated with geothermal operations. Due to the vastly different types of geothermal plays and variable local geologic conditions, the public perception of risk related to a geothermal system is regularly misinterpreted. The public's perception of subsurface or mining activities can put a geothermal project's social license to operate at risk but may not fully account for the conditions that have the greatest impact on geohazards such as geothermal reservoir characteristics (*e.g.*, matrix permeable sands, fractured carbonates, or enhanced/engineered fracture networks) or local geological setting (*e.g.*, tectonically active region, presence of faults).

In the Netherlands, geothermal heat from sand matrix permeable reservoirs has been produced for over a decade. During this time, no induced seismic activity has been conclusively associated with geothermal operations producing from sandstone aquifers. One exception of induced micro-seismicity associated with a geothermal project – now closed –was operating from a fractured carbonate reservoir. Similarly, no cases of significant subsidence have been associated with geothermal operations. This includes the relatively shallow mine water project in the south of the Netherlands, where a perceived hazard of sinkholes has been identified associated with the risk of potential shallow mine gallery collapse.

Public perception of geothermal operation has been negatively influenced by subsurface activity involving onshore wells and the occurrence of limited seismicity and subsidence resulting from depleted gas reservoirs in the northern part of the Netherlands. This has led to very conservative regulations for all subsurface mining activities, even though the mechanisms that impact the risk potential of geohazards at these activities are vastly different. Currently all potential geothermal projects must evaluate the geohazard risk according to a rigid guideline to obtain necessary permits. Furthermore, many projects have to abide by a strict seismic risk management plan that includes a seismic risk protocol with a traffic light hazard quantification system to mitigate risk.

Geothermal operators can bring in specialists to set up systems such as local seismic networks to monitor geohazard risk. However, the expense and sensitivity of these services are commonly disproportionate to the actual risk presented by the project. To reduce both the cost of installing a high-resolution monitoring system, and the subsequent operating costs, we have developed a pragmatic solution to monitoring geohazards using publicly available data. Seismic activity is monitored from the international seismic monitoring network; subsidence is measured using public Interferometric Synthetic Aperture Radar (InSar) data from the Sentinel-A satellite of the European Space Agency.

Potential geohazards are characterized using Python-based data processing and visualization scripts. These geohazard monitoring tools provide geothermal operators with a cost-efficient solution that aligns with responsible geohazard management. This internationally scalable monitoring approach is currently being deployed at twelve (prospective) geothermal operations across the Netherlands, providing project operators with effective and transparent geohazard management for government regulators and the public.

New methodology for assessment of the induced seismicity monitoring network

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Abstract

Seismic monitoring is essential for the safe development of geothermal resources. n the absence of important pre-existing seismicity, the monitoring performance of a network must be determined by modelling of seismic waves. Such modelling is dependent on both P-wave and S-wave velocity and attenuation models. While P-wave velocities are usually known (reflection surveys or sonic logs and sometimes even P-wave attenuation), S-wave models require additional constraints, especially in the shallow part of the model where there are no constraints from sonic logs.

We use seismic noise interferometry to obtain Rayleigh surface waves between receivers of a sparse array. We invert the Rayleigh wave dispersion curves for the S-wave velocity structure beneath the array with additional constraints on layer boundaries derived from the P-wave velocity model. The observed data constrain low S-wave velocity at the shallow depths resulting in high P-to-S-wave velocity ratio (Vp/Vs).

This velocity model is significantly different from the starting model derived from extrapolated S-wave velocity information. We show that the monitoring network with the new model is able to detect events with magnitude lower by 0.4 than with the starting model (see Figure 1 for the new model modelling, the starting model showed magnitudes 0.4 higher).

This methodology and data example illustrate the need of good knowledge of the near-surface structure in the geothermal areas to correctly appraise the seismic monitoring network performance. A more accurate magnitude evaluation provides a saving in cost, since the more precise magnitude determination in the new model prevents potential false triggering of the red light protocol at an earlier stage. In addition, the study indicates that the network performs better than anticipated based on its initial design.

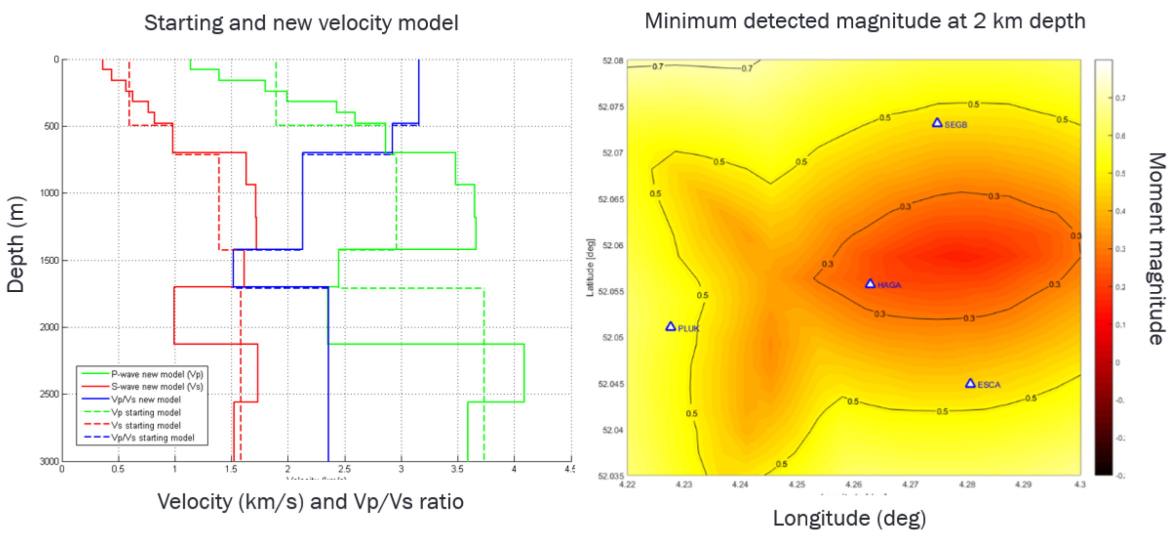

Figure 1 The new and old velocity models (left plot, solid and broken line) and Minimum magnitude detectable for 90th percentile of noise level recorded over 12 months on the 4 stations represented by white triangles (right plot).

Detection of seismic velocity changes from THM modelling at DeepStor demonstrator

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Abstract

In Central Europe, a substantial emitter of CO2 in the energy sector corresponds to the thermal energy required for heating and cooling. Seasonal underground heat storage presents a viable option for storing excess heat generated during the summer months for usage in winter, reducing the need for conventional sources of energy. Today, high-temperature aquifer thermal energy storage (HT-ATES) systems are attracting large interest as they represent a sustainable means of meeting heat demand.

In HT-ATES systems, hot water is injected into a reservoir during summer, while exchanged cold water is injected over the winter season. These fluctuations in temperature and pressure have an impact on the geomechanical and thermo-hydraulic properties of both the reservoir and the surrounding layers. Monitoring the changes in the reservoir properties is a critical aspect of running a heat storage system safely and efficiently. We try to determine whether active seismic imaging could be a suitable method to characterize the temporal and spatial evolution of the reservoir.

In order to design future geophysical monitoring systems, we first perform thermo-hydro-mechanical (THM) modelling to estimate the variations in the poroelastic properties due to the geothermal processes. Our modeling is based on the characteristics of the DeepStor demonstrator, currently under development in the north of Karlsruhe (Germany), at the Karlsruhe Institute of Technology. The model comprises three layers, each with different mechanical properties, and incorporates a single borehole. The simulation of cyclic hot water injection and production over time allows to quantify its effect on the underground material properties. In addition to assessing the expected operational parameters of the DeepStor demonstrator, we test additional injection schemes with varying underground properties to simulate the different ranges of porosity changes and look at their effects on the elastic properties.

Parameters from the THM model are linked to seismic sensitive variables, such as velocities and impedances, through empirical equations. Hence, we are able to quantify the effects of cyclic injection on these variables and determine under which conditions active seismic surveys could detect them.

Hybrid heating system (geothermal energy and gas) for an innovative greenhouse in NW Italy: how to optimize investment and operative costs.

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Abstract

Greenhouses are one of the higher energy-consuming sectors in farming, representing an important source of the energy demand. Heating accounts for 70/85% of the total energy consumption as one of the largest operating costs for the maintenance of a greenhouse, after labour and plant materials. The amount of thermal energy needed for heating mainly depends on the climate of the specific area, as well as on the greenhouse design and on the cultivated crop. In this framework, geothermal energy plays a very important role in maintaining the desired temperature and reducing energy consumption.

This work deals with the design of a hybrid heating plant (97% geothermal energy and 3% gas-condensing boiler, Fig. 1) for the innovative Plant Phenotyping Greenhouse at the University Campus in Grugliasco (few km West of the city of Turin).

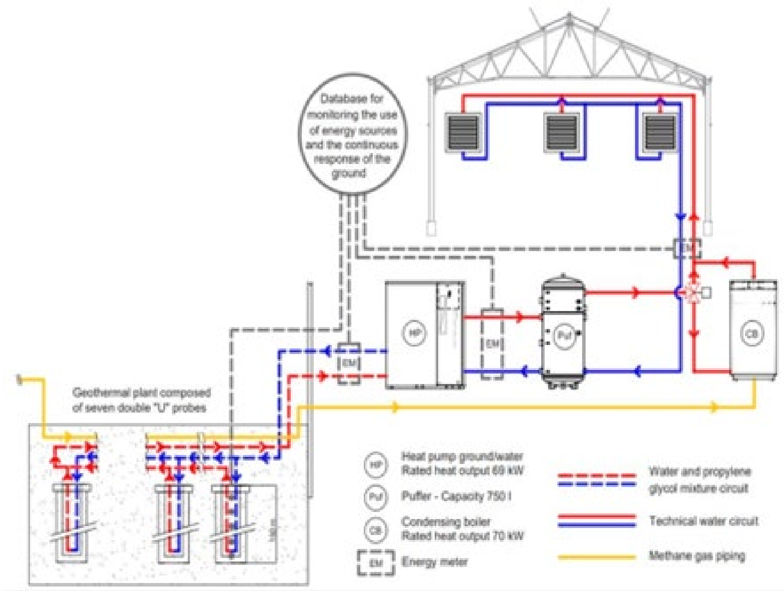

Figure 1: Hybrid heating system project for the plant phenotyping greenhouse at the University Campus in Grugliasco (a few km from Turin, NW Italy).

This work aims at testifying the energy efficiency of this kind of hybrid plant and its economic sustainability, as well as to optimize both investments and operative costs comparing with conventional heating systems.

It mainly focused on the geological, hydrogeological, and thermo-physical characteristics of the ground, which are useful to correctly size the geothermal plant. Furthermore, numerical simulations also provided data about the thermal energy storage and production during on and off plant cycles. The results show a thermal power of 50.92 kW over 120 days of plant operation, in line with the expected energy needs to meet the base load demand. Long-term results further ensured a negligeable impact on the ground, with a thermal plume between 5 and 10 m from the plant, reducing substantially in a few months after switching off the plant.

A specific economic analysis based on the costs before the year 2022 and, thus, before the current European geopolitical situation, was also conducted. This analysis was supported by a detailed design of the shallow geothermal plant, which allowed the right number of the geothermal boreholes (BHEs) to be deduced, as well as their depth and their distance, while limiting the initial investment costs and meeting almost all the energy needs.

PrESENCE & Sismocité

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Abstract
The seismic events that affected the Eurometropole of Strasbourg (France) between 2019 and 2021 led to extensive media coverage of the seismological data diffused by the national seismic monitoring network (BCSF-RéNaSS). Numerous articles published in the local press have provided technical information to characterize the events and document their effects. Sociological observations highlight significant variations in the social appropriation of seismological data and the impact of deep geothermal energy projects. The PrESENCE and SismoCité projects, which bring together geophysicists and social sciences researchers, aim to implement a citizen science initiative focusing on seismic monitoring. These projects will give civil society a better understanding of the environmental impact of industrial projects, enabling them to form their own opinions and make informed decisions.

A number of actions are being taken in this context:
Implementing a concertation process involving scientists, municipalities, and associations
The aim is to involve citizens, municipalities and association in the deployment and optimisation of a citizen science initiative dedicated to seismological monitoring. Alongside the installation of seismometer in private homes (the Alsace seismo-citizen network), several sensors are installed in town halls and association premises, enabling participants to uptake the initiative. The concertation will be carried out in several steps: preliminary interviews, focus group sessions, expert hearings, and redaction of proposals on the design of the seismic monitoring system (with a focus on its scope, governance, communication tools and openness to society). A monitoring committee will be set up, whose role will evolve as the project progresses.

Enhance dialogue between science and society
Two different approaches will be used for exchanges between scientists, volunteers and the general public. First, thematic public meetings involving different categories of stakeholders: EOST researchers will present reports on seismological observations; in other sessions, researchers and/or members of civil society will open the debate by tackling other issues (related to economy, energy policy, environment).
Second, existing mediation spaces would be mobilized to present the approach to a wider audience. In these venues, a seismic sensor similar to those used in the sismo-citoyen network will be presented with a range of information about the SismoCité project and seismological monitoring. A mediator from each of these structures will explain, at set times, how the sensor works and its value for seismological monitoring.

In this paper, we will go back over the objectives of this project and present in detail the progress of our work, as well as the methodology used to organize this concertation.

Options for drinking water protection close to a deep drilling site, using the example of the planned HT-ATES research infrastructure, DeepStor-1.

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Abstract

In densely populated and high-water demand areas, deep geothermal energy, especially for heat production, can compete with drinking water protection, as both uses of the subsurface are tied to local consumers. So far, the Water Resources Act does not provide for the possibility of deep drilling within designated drinking water protection zones. However, due to the increasing number of projects for the development of deep geothermal energy and its importance for the regional heat transition, decisions on the approval of deep drilling in drinking water protection zone 3 in Baden-Württemberg are currently made on a case-by-case basis.

Using the example of the planned deep drilling project DeepStor-1 on the premises of the KIT Campus Nord north of the city of Karlsruhe, measures for the protection of the drinking water source near the drilling site are determined and coordinated with the approving authorities. The basis for the risk assessment is a 3D flow and solute transport model, which covers the unconsolidated rock aquifers down to the base of the Pliocene at a depth of approximately 140 meters. Drinking water is extracted from the upper two gravel aquifers, with their high transmissivities totaling over 6e-2 m^2/s allowing for high extraction rates of 200 m^3/h per well and ensuring the water supply for the research center.

The analysis of potential contamination pathways shows significant differences in risk for the construction phases of the drilling site with an unsealed surface and, in particular, the drilling cellar, as well as the drilling phase and subsequent operational phase. The drinking water protection concept includes a spatially highly resolved monitoring system, which includes groundwater monitoring wells equipped with sensor chains that measure groundwater level, temperature, and electrical conductivity oriented to depth. Additionally, fiber-optic temperature measurements are taken. The measurements are integrated into an alarm and response scheme. Furthermore, the groundwater monitoring wells downstream of the drilling site can hydraulically isolate any contaminants due to extraction operations and serve as remediation wells.

Review of concepts that combine geothermal energy and CCS: comparing performance and sustainability

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Abstract

Geothermal energy production and CCS (carbon capture and storage) represent promising technological solutions to help mitigate climate change and aid the current global energy crisis. In recent years, the number of concepts that propose to combine and mutualize these technologies has exploded. An extensive literature review was carried out of the concepts (over 150 pertinent publications). Here we present a synthesis of that work based on infographics for each concept. Concepts were classified (figure 1) and fall into the following categories: 1) where supercritical CO_2 is used as a heat vector for geothermal energy production; 2) water-driven geothermal concepts with CO_2 injection/reinjection, generally dissolved in the geothermal brine (either an external source for CCS or re-injection of CO_2 emitted by geothermal brine exploitation for near-zero emissions); 3) other synergetic uses with only slight hybridization. Another possibility to classify concepts is to separate the concepts that are intrinsically linked to specific geological features, and another pool of concepts that require similar geological features (porous and permeable aquifer overlain by a caprock). To compare the concepts, key performance indicators were proposed with semi-quantitative ranking. A visual comparison aid was developed in the form of a series of eight infographics, including all the concepts and based on key criteria, such as amount of CO_2 stored and/or energy produced (heat or electricity), features of the underground and of the external CO_2 emitters, readiness of the concept, etc.

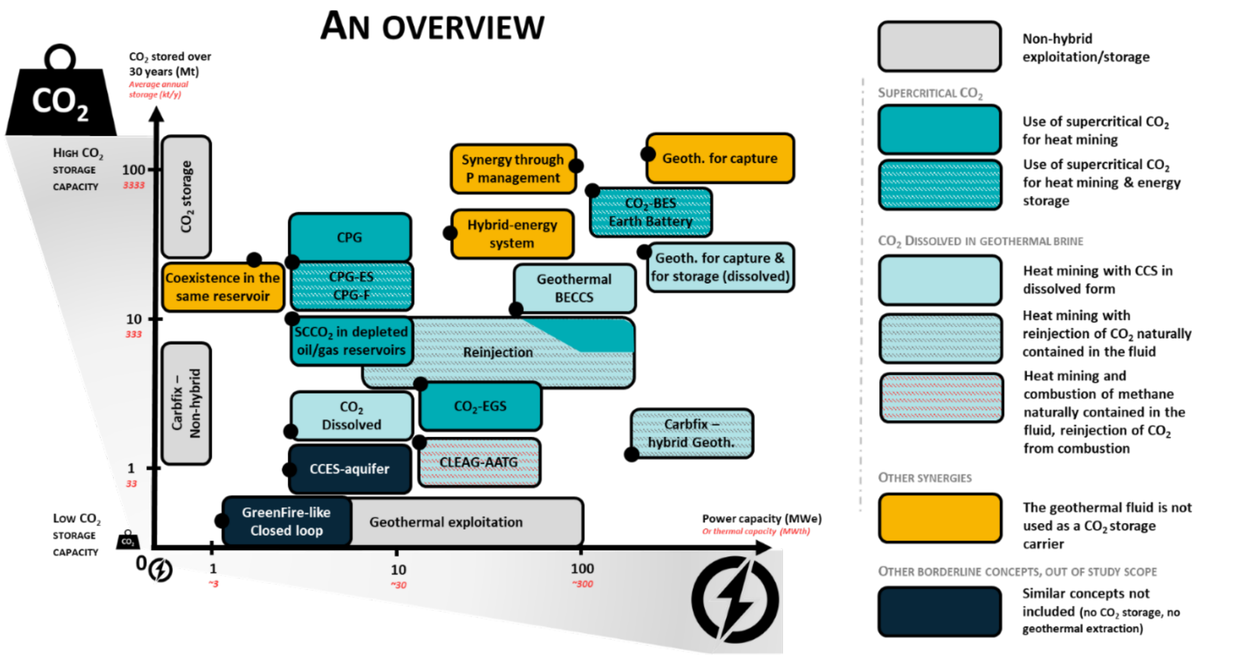

Figure 1: Overview of concepts according to CO_2 storage capacity and power capacity and depending on the kind of synergies (different colors).

Acknowledgements: we are grateful to IEAGHG for proposing and funding this topic and for interesting scientific discussions and debates as part of this work. The work has been published in the report 'IEAGHG, "Prospective integration of Geothermal Energy with Carbon Capture and Storage (CCS)", 2023-02, August 2023'

Tentative Mass Budget 2019-2022 at Theistareykir Geothermal reservoir (Northern Iceland) by means of time-lapse gravity measurements

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Abstract

Since 2017 a hybrid gravity monitoring program is performed at Theistareykir geothermal field (Northern Iceland) to contribute to the study of the underground mass transfer induced by geothermal harnessing. According to the hybrid concept, both absolute and relative gravity measurements are repeated over time in different operating modes. Relative measurements are yearly collected on a network of 27 sites spanning the area as well as by means of continuous recordings at three selected sites, close to the extraction and injection zones, where two superconducting gravimeters and a g-Phone spring meter, specifically designed for continuous gravity recordings, operate. Moreover absolute measurements are also yearly repeated at the 3 recording sites as well as at the site used as reference for the relative network, the latter to detect possible gravity changes therein. InSAR and GNSS monitoring of the ground deformations is used to separate geometric (due to height changes) and mass-dependent contributions to the observed time gravity changes.

After reducing the contribution of the vertical ground displacement from the recorded signals, gravity residuals are analyzed.

In this study we focus on the most recent gravity measurements collected in 2019 and 2022. Three approaches are followed to retrieve the underground mass changes assuming the most simple Mogi's point source: a) forward modeling of gravity changes inferred from the absolute gravity measurements. b) application of the Gauss integral procedure on the spatial gravity changes as inferred from the repetition network data and c) least-squared inversion of the time-variable gravity field. Our modelling is validated with the extraction and injection data. Based on gravity, geodetic and extraction/injection data, we assess a tentative mass budget in terms of mass discharge into the atmosphere, recharge of the geothermal reservoir and net mass loss. Such a mass budget might contribute to discriminate potential harnessing scenarios and provide sustainability clues for the geothermal field use.

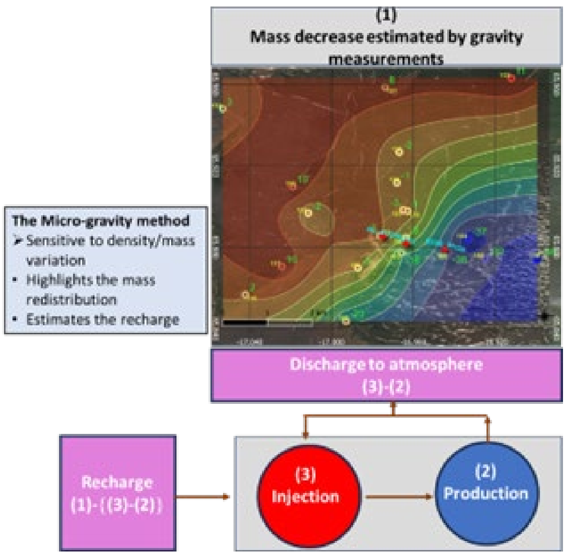

Figure 1: Conceptual model: Gravimetry as a tool for Geothermal reservoir monitoring.

An assessment of environmental impact, safety and CO_2 footprint and outlook for application of the Eavor Loop in the Netherlands

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We present results of a feasibility study of the Eavor Loop in the Tilburg area in The Netherlands focussing on the assessment the environmental impact, safety and CO_2 footprint. Input to the study are geological and geomechanical interpretation and numerical simulation of the Eavor Loop™ technology over its lifetime. The study assessed the possible occurrence of undesirable effects (i.e., leakage, well bore collapse, induced seismicity) and compared the carbon footprint of the Eavor Loop technology with conventional geothermal applications. As part of the evaluation, thermal performance and Eavor Loop construction / operational characteristics were analyzed through a Life Cycle Assessment (LCA) and quantitative assessment of the CO_2 per GJ produced. The layout of consist of 12 laterals, each about 70m apart. For the operation of the Eavor Loop it is assumed that inlet temperatures will be ~60°C and flow rate of 60 kg/s with the assumption that the water density at 60°C is 1000 kg/s. A dedicated numerical thermal model has been used to calculate the thermal response of the Eavor Loop for 10 years at constant flow rate conditions. The grid sizes in radial direction have been chosen such that the logarithmic value of the cell centers radial coordinates is linearly increasing from sub cm-size at the well bore to few meter size at a radial distance of 70 m, which is sufficient to fully cover the transient heat flow over the simulated lifetime, as well as to assess well bore integrity and thermally induced stress changes further away from the well bore. The predicted thermal power is in excess of 7 MWth.
The simulations indicate that the Eavor Loop has a long lifetime marked by a very moderate linear decline of the production temperature and power over a lifetime of 10s of years, with minor thermal interference of laterals if placed with a spacing of ca 70m. The Eavor-Loop emissions are 20% improved compared to conventional systems, saving over 2kg CO_2-eq/GJ. Based on the thermal simulations, stress changes were analyzed with a semi-analytical approach, assessing underlying sensitivities. Results indicated that potential leakage due to issues with borehole-stability and reactivation of pre-existing faults is not likely to be risks for safe operation of the Eavor Loop over its full life-time.

Acknowledgements:
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New data types added to the CDGP: GNSS and geological data

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Abstract

The Data Center for Deep Geothermal Energy (CDGP-Centre de Données de Géothermie Profonde, https://cdgp.u-strasbg.fr/) was launched by the LabEX G-EAU-THERMIE PROFONDE (http://labex-geothermie.unistra.fr) in 2016, now Interdisciplinary Thematic Institute for Geosciences for the Energy System Transition (https://geot.unistra.fr/). The CDGP aims to archive, preserve and distribute geothermal site data in the Alsace region. Specific procedures have been implemented since the beginning of the project to respect international requirements for data management. FAIR recommendations are utilized to distribute data that is Findable, Accessible, Interoperable, and Reusable.

The CDGP distributes seismological (waveforms, catalogs, focal mechanisms) and hydraulic data from simulation and circulation phases at various geothermal sites (Soultz-sous-Forêts, Rittershoffen and Vendenheim). Furthermore, seismic, geological, and other data related to anthropogenic hazards are distributed.

A new challenge for CDGP is to add new type of data. Since August 2022, geodetic data can be found directly on the CDGP website. A map of the different stations and their raw data availability are presented.
Within the context of the Geo-INQUIRE project, which aims to improve access to data ,we have gathered all the information needed to characterize these stations, and we added these metadata to Metadata Management and Distribution (https://gnss-metadata.eu/) so that we can include these stations to the TCS GNSS network. The goal is to be able to offer services such as daily averages.

CDGP will also supplement Episodes with new data, such as geological data. We have generated several geological sections and prognostic drilling profiles around the geothermal sites from GeORG (https://maps.geopotenziale.eu/). Theses data will also be available on the EPISODES platform, since the CDGP is an internal node of EPOS-IP Anthropogenic Hazards.

The CDGP plans to add other types of data, such as InSAR or laboratory data, in the near future.

Responses of the subsurface thermal field to the paleoclimate history in Germany

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Abstract

Understanding the underground temperature distribution is required to determine geothermal energy potential, heat flow, mechanical properties of lithological units, and the long-term safety of heat producing waste in repositories. Recent studies suggest that the Last Glacial Period and the Holocene Climate Optimum present the largest contribution to the climate impact on the modern subsurface temperature distribution in Germany. Previous studies, mainly in Northern Euope, have shown, that an additive effect of the Pleistocene Glaciations can be observed, with a total cooling of several K in up to two km depth.

As temperature observations in the subsurface are sparse, numerical modelling is utilized to make sound predictions and risk-assessments. In contrast to statistical models, numerical physical approaches can account for local heterogeneities in thermal properties, given well informed structural and parametrical models of the subsurface. The common approach of modeling stationary solutions has the disadvantage of not accounting for the paleoclimatic effect on the modern-day subsurface temperature field. However, thermophysical parameters are sparse, especially for less commonly utilized stratigraphic units and rock types like clay and salt. Herein, the regional effects of paleoclimate on the subsurface thermal field in Germany is not fully understood.

To improve the parameterization for numerical thermal modelling of the sedimentary basins in Germany, the variation of thermophysical properties within formations, and the sensitivity to temperature and pressure is being determined on a wide range of collected core material using a multi-stage testing scheme.
Furthermore, Global Circulation Models (GCM) and most paleoclimate proxies provide surface-air-temperatures (SAT). However, SAT may not convert directly into Ground Surface Temperatures (GST), as glaciers and local variations in soil type, vegetation and precipitation cause different buffering (e.g. phase transition/latent heat) and insulating effects (e.g. snow coverage).

Forward models of the 1D borehole temperature profiles using GSTH inferred from GCM and novel thermophysical parameters are computed and the results are compared against observations of undisturbed and continuous borehole temperature logs. The goal is to determine the sensitivity and regional covariation of subsurface temperature to transient GST in German sedimentary basins. Thereby, obtaining spatiotemporal ground surface temperatures for large scale numerical simulations of thermo-hydro-mechanical processes.

Using Machine Learning to Characterize Fluid Flow Behaviour in Fractured Geothermal Reservoirs

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Abstract

Geothermal reservoirs are recognized as a promising sustainable energy resource with a potential to play a crucial role in the shift to net-zero emissions. To maximize their potential, it is essential to understand the dynamics of heat and fluid flow within these reservoirs. Many geothermal reservoirs contain fractures, which enhance permeability and often comprise the primary reservoir permeability. Predicting heat and fluid flow behaviour in fractured (geothermal) reservoirs is notoriously challenging because fracture properties are difficult to constrain.

Well testing and pressure transient analysis are key methods for reservoir characterisation and can help to quantify flow geometries in fractured reservoirs. However, existing methodologies for fractured reservoirs often provide limited insights, restricting a more in-depth characterization of fracture properties. In this study, we address this limitation by applying machine learning to classify pressure responses, aiming to offer a more comprehensive characterization of fracture properties and enhance the overall understanding of reservoir behaviour.

We use an in-house Discrete Fracture Network generator to create diverse fracture network realizations representative of real-world scenarios. Advanced fluid flow simulations, facilitated by DARTS (Delft Advanced Research Terra Simulator), produced a dataset of synthetic pressure response data. These pressure responses were grouped using machine learning and clustering to extract key fracture characteristics that are representative of more complex fracture geometries and associated flow behaviours. First results indicate that this approach is effective in identifying and classifying pressure responses and hence provide deeper insights into the links between fracture properties and fluid flow.

Future work aims towards maturing this methodology and aspired to develop a comprehensive framework for understanding the nuances of fracture network properties and their impact on pressure transient dynamics and heat flow in fractured geothermal reservoirs.

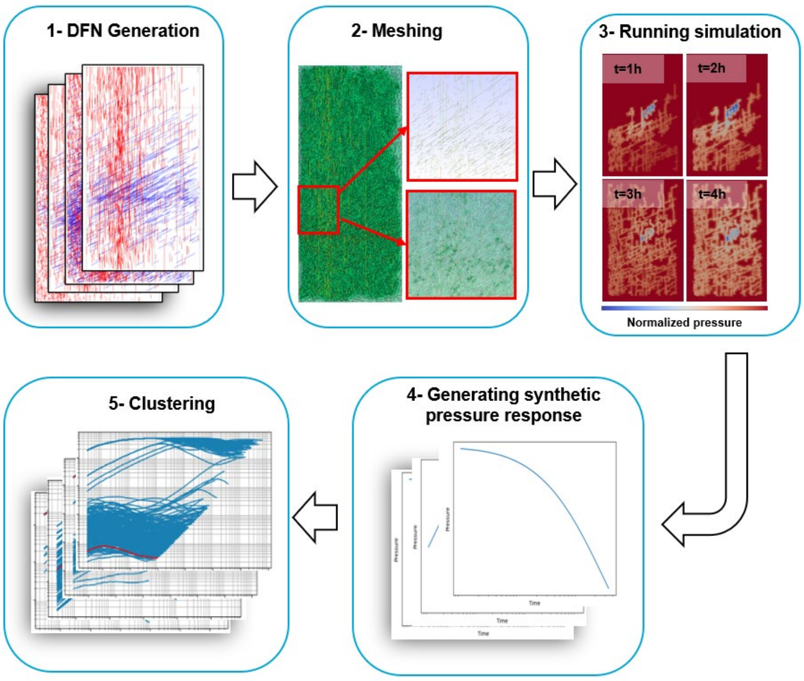

Figure 1: Methodology of the research

Validation of thermodynamic databases for geochemical modeling in geothermal environments

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Advances in geochemistry in recent decades have been supported by an increasing number of geochemical models to help understanding brine behavior and scaling occurrence. Geochemical modeling is based on thermodynamic databases that are compiled from experimental and calculated thermodynamic data. The data gathered in these databases is subject to limitations that are subject to the experimental thermodynamic conditions present during the experiments. The key parameters for solubility problems are temperature and pressure, as well as pH and salinity. Therefore, the same model results can diverge when using different thermodynamic data or by applying data that is not valid for the chemical conditions and/or rely on interpolation from existing data.

PHREEQC is one of the state-of-the-art modeling programs which is used in this work. Several new PHREEQC databases have recently become available for geochemical modeling, such as geothermal.dat by Zhang et al. (2020), carbfix.dat by Voigt et al. (2018), or the imported YMP and soltherm databases from TOUGHREACT by Alsemgeest et al. (2021), which are compiled specifically for geothermal modeling. In addition to the previously mentioned problems with inconsistent modeling results, there are two cases involving pressure in PHREEQC. The first one is a pressure correction for the solubility product based on the addition of the molar volume and the usage of the Redlich-type equation, however this is not integrated in every database. The second one is about the equation to calculate the gas pressure. Either the ideal gas law or the Peng-Robinson equation of state is used. The recently developed geothermal databases were compared with existing ones to evaluate the best suited thermodynamic data for degassing pressure and geothermal power plant modeling. The evaluated data will be compiled in a new PHREEQC thermodynamic database.

In order to compare the databases, a set of scaling minerals was defined. This set includes the most abundant sulfides, sulfates, oxides, and carbonates regarding scalings in geothermal power plants. The molal concentrations of these minerals were modeled at solubility equilibrium over a temperature range from 0.1 to 300 °C, a pressure of 1 bar or less and in low salinity (<0.1 M_{NaCl}) solutions. The results were comparable to experimental data to determine the best-fitting database for each specific mineral. Additionally, the degassing pressure of brines with known chemical composition was evaluated for the different databases. The modeled gas phase consisted of CO_2, CH_4, N_2 and H_2S which were completely dissolved in solution at elevated temperature and pressure. The time at which a free gas phase began to form was determined by a controlled decrease in pressure. Furthermore, experiments are planned to compare the modeled results for the degassing pressure and the newly developed database at different geothermal power plants with the help of special power-plant-demonstrator facility.

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ABSTRACT PIJNENBURG

EXPERIMENTAL MODEL INVESTIGATING POTENTIAL OF GEOTHERMAL ENERGY IN RECYCLING POLYETHYLENE TEREPHTHALATE: CASE STUDY OF OLKARIA

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Key Words: experimental model, geothermal energy, recycling and polyethylene terephthalate

ABSTRACT

Geothermal energy is one of the clean, sustainable and renewable resources, which provide heat energy that is derived from radioactive decay elements within the earth's crust. The non-electric utilization (direct use) of geothermal heat has been reported in various domains that have a need for sustainable supply of heat energy. Adoption and direct use of geothermal energy in Kenya is one way which can enable waste control to enhance environmental protection and optimize the use of this resource. In this research, heat energy from the geothermal well was simulated using an experimental model in which polyethylene terephthalate (PET) pieces were melted and moulded into usable products under suitable pressure conditions. The objective of this study was using mathematical model to investigate the potential of using geothermal heat in recycling PET plastics. The ground plastic waste material was exposed to heat and the resulting molten medium was subjected to selected polymer processing techniques to obtain desired products. The suitability of geothermal conditions in recycling PET was investigated through numerical analysis. In the design, the study performed experiments on controlled factor of temperature. The data collected was analyzed by use of MATLAB. This study established, through experimental model that the least intrinsic melting temperature for recycling PET was 180 oC, the study further noted that the maximum recycling pressure for PET through experimental was 1 bar and for effective velocity flow of molten plastic viscosity index of 0.1 to 0.8 was needed. All the conditions these conditions are attainable at Olkaria after steam has been used for generation of electricity before reinjection to the ground. Therefore, geothermal energy can be used for recycling PET as one way of controlling environmental pollution and create job opportunities.

Investigation of dry and wet cooling at the supercritical ORC MoNiKa

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ABSTRACT

The Modular Low-Temperature Cycle Karlsruhe (MoNiKa) was built at the Campus North of the Karlsruhe Institute of Technology to investigate the optimization possibilities of supercritical Organic Rankine Cycle (ORC) power plants for geothermal energy production. Several research tasks have been carried out on this plant, focusing on individual components such as the turbine, heat exchanger, condenser and pump.

This work focuses on the condenser of the Monika cycle. As one of the main components, this heat exchanger releases the heat from the working fluid(propane) to the ambient air. The temperature level of this heat extraction directly determines the output of the power plant. Since geothermal power plants in Germany are operated with a constant flow rate in the thermal water circuit, this leads to a lower heat demand in the summer months and the possibility to compensate this with an increased electricity production. Unfortunately, this seasonal shift in heat and power production does not match the fluctuation in outside air temperature, so that in summer, when cooling air temperatures are high, less electricity can be produced despite a low heat demand.

Therefore, the hybrid cooler of the MoNiKa plant has the ability to spray water on the finned tubes at the air intake duct in order to reduce the cooling air temperature.

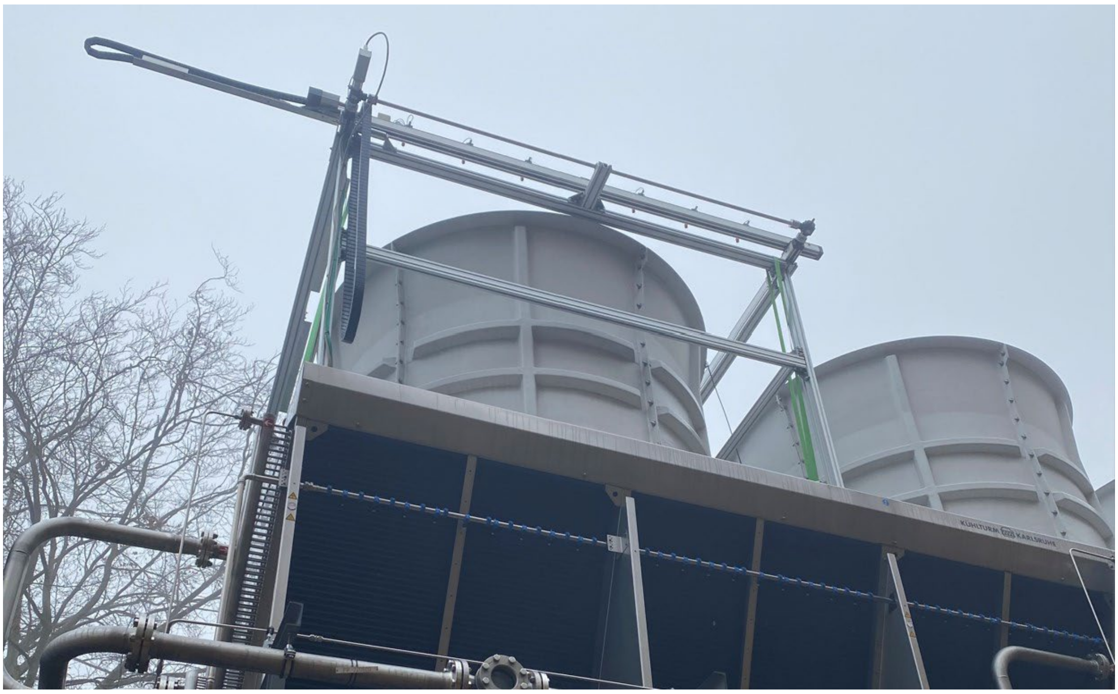

Figure 1: Hybrid cooler MoNiKa and velocity and temperature sensors at the diffusor outlet

In a first study water injection were examined. Comparing the condensation temperatures in dry operation at full fan speed with the wet tests at reduced fan speed shows a reduction in power consumption of 48% respectively in wet operation.

In a more detailed study, the velocity and temperature profiles at the cooling air inlet and outlet were measured and used to calculate the air and propane energy balance. The difference in the energy balance was determined to be 9,4% for the 69% load point of the power plant. These investigations make it possible to improve the operation of the condenser, which is essential for the economic operation of geothermal power plants.

Hybrid gravity monitoring at Theistareykir geothermal field, Iceland

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Abstract

Geothermal fields need to be continuously monitored, for optimal and sustainable harnessing of the associated hydrothermal reservoir. Such assessment can be achieved by modelling the mass and fluid displacement within the hydrothermal system, taking into account the injection and production parameters.
In this study, we aim at assessing the subsurface mass displacement model at Theistareykir geothermal field, in the Icelandic north volcanic zone, through the use of the hybrid gravity technique.
Hybrid gravimetry, is a method which consists in the combination of micro-gravity time lapse measurements, repeated every year on a pre-designed network of points and integrated with continuous gravity measurements, recorded continuously at several multi parameters stations, deployed within and outside the geothermal field. The stations are equipped with a superconducting or a spring gravimeter as well as a GNSS antenna, a broad band seismometer and hydrological and weather sensors. These measurements are integrated with absolute gravity measurements, collected yearly, in order to constrain the instrumental drift of the relative gravimeters. Finally, the results are compared with mass movement estimated from the injection and production rates, provided by the operating energy company.
We present here the complete time series obtained from the three superconducting gravimeters that have been measuring at Theistareykir, since 2017 (year of the start of the power plat operation), and a local tidal model obtained from the analysis of these time series. In addition, we show the time-lapse micro gravity maps, obtained from the field measurements. These enable us to understand the mass displacement in the subsurface within the geothermal field and assess the sustainability of the energy production.

Preliminary characterization of leachable organic matter and naturally-occurring radionuclides in the reservoir rocks of the Balmatt geothermal site, Mol, Belgium

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Abstract

Geothermal energy installations in Europe generate naturally-occurring radioactive materials (NORM) associated with naturally-occurring radionuclides (NORs) in mineral scales. The NORs present in geothermal brines such as ^{226}Ra, ^{210}Pb, and ^{210}Po, represent the decay products of ^{238}U and may be affected by different fractionation processes (e.g. sorption, precipitation, volatilization) during their transport and migration through the geothermal system. Dissolved and particulate/colloidal organic compounds are present in geothermal brines and could influence NORs fractionation, but a mechanistic understanding of this process is fairly lacking. The source of these organic compounds may be natural organic matter (NOM) from the reservoir rocks and organic moieties of scaling and corrosion inhibitors (Leins et al., 2022). In order to characterize the leachable fractions of NOM and NORs from the reservoir rocks, static leaching experiments were conducted at 125°C using representative well cuttings of the Loenhout Formation (3,470 m depth) of the Balmatt geothermal site in Mol, Belgium. The leaching experiments were conducted using a 3.5 M NaCl solution at a fixed solid-liquid ratio of 1:5 g/mL, and a fixed leaching time of 14 days. NOM concentrations of the cuttings were determined using Total Organic Carbon (TOC) analysis showing an initial concentration of 11.4 ± 2.0 mg C/g, while the average dissolved organic carbon (DOC) concentration of the leachate is ~236 ± 24 mg C/L analyzed through Liquid Chromatography-Organic Carbon Detection (LC-OCD). This demonstrates that ~10% of the TOC were mobilized during the leaching process. Furthermore, the main constituents of the DOC are low molecular weight acids (47-49%), low molecular weight neutrals (27-28%), hydrophobic organic carbon (23-25%), and biopolymers (0.5-0.6%). Humic substances and their hydrolysates are absent. Qualitative characterization of the possible organic moieties in the leachates by Attenuated Total Reflectance-Fourier Transform-Infrared spectroscopy (ATR-FTIR) shows indications of alcohols, alkanes, alkenes, carboxylates/ethers/esters, phenols, and amines but needs to be confirmed due to the low absorbance and high signal-to-noise ratio. Preliminary results of the NORs analysis of the leachates by α-spectrometry and Lucas scintillation method (Lucas, 2004) reveal the relatively higher leachability of ^{226}Ra (3.2-3.4 Bq/kg) as compared to ^{210}Po (0.06 mBq/L), while 210Pb was not analyzed due to insufficient sample volume. TOC analysis of the cuttings after leaching, and NOM leaching at 70°C is ongoing. The leaching procedure will also be performed using cuttings from the Chokier and Souvré Formations to estimate their NOM and NOR contribution to the Balmatt geothermal brine. These results will then be compared to the thermal degradation products of chemical inhibitors, to help distinguish which organic matter types (i.e. NOM or synthetic) represent the main source of the DOC in the brine.

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Geothermal Reservoir Deformation Monitoring Based on Coda Wave Interferometry

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Abstract

Monitoring of geothermal reservoir deformation is essential for the normal development of the Enhanced geothermal system (EGS). Coda wave interferometry (CWI) with ambient noise is regarded as an effective and low-cost reservoir monitoring technique and draws more and more attentions. But the connection between the obtained CWI measurements and the undergoing physical changes of deep reservoir is still not clear. In this study, we use the Rittershoffen geothermal site (France) as a case study and conduct a series of forward simulations of scattered wavefield propagation through the deformed reservoir due to hydraulic stimulation, considering acoustic-elastic effects. The simulation is built on *Code_ASTER* (mechanical loading) and SPECFEM2D (wave propagation). The model is two dimensional with a scale of 12km (width)×20km (height), in which the upper reservoir model contains 8 layers to mimic Rittershoffen geothermal reservoir geology, the lower sub model with multiple circular inclusions is set to scatter the waves emitted from a point source located at bottom of the model that produces scattered wavefield; two synthetic seismic stations are located at the top of the model. The model is reproducing the seasonal variation of relative wave velocity changes obtained from ambient noise cross-correlation functions (ANCCF) induced by the underground water table elevation changes. We also study the effect of in-situ reservoir deformation on CWI measurements by modelling the case of hydraulic pressure increase in an open hole and the case of aseismic slip along an embedded fault, which mimic hydraulic injection of GRT-1 well, Rittershoffen. The result indicates that the induced small reservoir deformation in both situations can be detected by CWI measurements, which helps us to have a better understanding about the connection between the obtained CWI measurements and the undergoing deformation of deep geothermal reservoir.

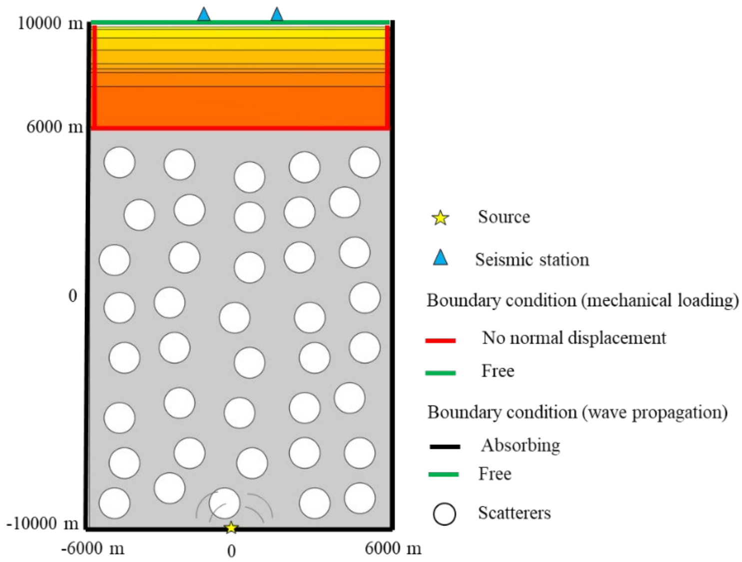

Figure 1: 2-Dimensional numerical multiple layered model of Rittershoffen subsurface (the top 4 km with 8 layers) and the sub-model (16km in depth), located below the subsurface model as a virtual scattering domain.

Developing a new Geothermal industrial Infrastructure Database based on INSPIRE UML Model in Tuscany, Italy

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Abstract:
Geothermal energy has emerged as a sustainable and reliable source of renewable energy, offering significant potential in mitigating climate change and reducing dependence on fossil fuels. The successful operation of geothermal systems is crucial for maximizing energy utilization, optimizing efficiency, and ensuring long-term sustainability.
Following the request of the Tuscany Region, we are building a database of the geothermal industrial infrastructure in Tuscany, Italy, utilizing the UML language to design its structure. The database is based on the INSPIRE UML model and uses standard features to create a robust information model that can handle geographic data.
This database serves as a valuable data infrastructure to organize a comprehensive dataset, enabling open access for most of the data, data sharing, analysis, processing, and knowledge dissemination. It acts as an indispensable tool for supporting policy-makers and aiding decision-making processes related to geothermal industrial infrastructure management.
It is designed to include relevant information associated with each lease such as power plant, plant types, commissioning dates, installed and running capacity, electrical production data, and general information about wells. The database also incorporates data related to the geothermal fluid transport infrastructure, and all the documentation relating to the authorization procedures. Furthermore, it encompasses information on economics, regulations, energy policies, energy production, and environmental monitoring stations. This database also covers personnel employed and mobile facilities involved in geothermal operations, offering a comprehensive overview of the industry's operational processes.
The services provided by the database will be accessed through user-friendly web-based interfaces, as well as web-based protocols such as WMS (Web Map Service), and WFS (Web Feature Service). However, the confidentiality of private data will be guaranteed, and only public data will be made available, enabling stakeholders to utilize the database effectively and efficiently.

Keywords: geothermal industrial infrastructure, Database, INSPIRE UML Model, Geothermal energy, user interface