7th European Geothermal Workshop - Characterization of Deep Geothermal Systems

Report of Contributions

Contribution ID: **85** Type: **Poster**

Analysis of the applicability of ambient noise based techniques on the monitoring of deep geothermal reservoirs by numerical modelling

Wednesday, October 9, 2019 9:55 AM (15 minutes)

A challenge in deep geothermal projects based on the Enhanced Geothermal System (EGS) is to ensure their successful development and the durability of the operation of deep underground heat exchangers while controlling the risk of inducing potentially seismic events. The management of these risks calls for the development of monitoring methods which could contribute to recognize an unexpected reservoir dynamic. Recently, the development of seismic noise correlation methods has contributed to the use of Coda Wave Interferometry (CWI) to compare daily stacked ambient noise cross-correlation functions (or ANCFs). The application of such ambient noise-based monitoring techniques opened perspectives to follow the fine-scale evolution of complex geological structures. In particular, the methods have been applied to the ambient seismic noise recorded since 2012 in the vicinity of the Rittershoffen deep geothermal power plant. The measurements highlight an annual variability repeated from year to year, but the trend is still not well understood as the physical process at the origin of the measurements are not well identified. Surface phenomena, such as annual temperature variations or changes in the water table elevation, are among the natural processes unrelated to the reservoir evolution, that could explain the annual variability but also potentially bias the monitoring of the reservoir changes.

Our study aims first at a better understanding of the processes deduced from the measurements. Second, we study the applicability of passive monitoring techniques based on the ambient noise to support the management of the reservoir in various geotechnical contexts and to monitor unexpected evolutions. To this purpose, we developed a 2D numerical model that describes the signature of annual surface temperature and water table elevation variations, on the interferometry measurements. By modelling the contribution of a local evolution in the reservoir, we investigate whether if the contribution to the measurements of surface perturbations could shadow the one of a local change in the reservoir.

Our measurements show that the annual variability measured from the ambient seismic noise recorded in the vicinity of Rittershoffen is retrieved in the numerical measurement. The time-serie of the ANI is correlated to the water table elevation variation. We show that the transient deformation introduced in the medium at depth has a clear impact on the measurements. The numerical modelling of the effects highlighted infield opens perspectives for the removing of unwanted effects related to natural surface processes in the monitoring of the deep geothermal reservoir.

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Session Classification: Poster Session

Track Classification: Topic 4: Resource Development

Contribution ID: **86** Type: **Poster**

Impact of Heat Transfer Unit Distribution Characteristics on the heat extraction from EGS with horizontal wells using multistage fracturing

Wednesday, October 9, 2019 12:30 PM (20 minutes)

By referring to the volume fracturing technology widely used in shale gas and other unconventional oil and gas resources with low-permeability, the segmented multistage fracturing technology of horizontal wells can be introduced to construct the EGS (Enhanced geothermal system) artificial reservoir. Since the EGS reservoir fracturing exhibits in a form of strong non-uniformity, a horizontal dual-well non-uniform multistage fracturing model is constructed. By adjusting the thickness and distribution types of heat transfer unit (HTU), several sets of cases are designed respectively to study the influence of HTU distribution characteristics on heat extraction performance of EGS using multistage fracturing in horizontal wells. In order to characterize the non-uniformity characteristic of HTU distribution, the new concept of preference thickness ratio is introduced. The results show that in non-uniform fracturing EGS reservoirs the production temperatures are not strictly positively correlated with the reservoir fracturing stage, and is also affected by the distribution characteristics of HTU. Moreover, the production temperatures are negatively correlated with the preference thickness ratio. In the EGS reservoir with non-uniform fracturing, the heat extraction performance can be enhanced by plugging the inferior HTU or strengthening the fracturing of the reservoir to make an homogeneous HTU. This study has certain guiding significance for the fracturing of reservoirs and the construction of artificial thermal reservoirs in EGS geothermal field.

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Session Classification: Poster Session

Track Classification: Topic 4: Resource Development

Contribution ID: **88** Type: **Poster**

Design and Safety Considerations to Perform Coiled Tubing Operations in Large-Diameter, High-Temperature Geothermal Wells

Wednesday, October 9, 2019 5:40 PM (20 minutes)

With limited CT operations in HT, large-diameter geothermal wells across the world, planning and executing interventions under those conditions can be challenging. As such, equipment failure risk is high, preventing successful nitrogen lift operations. To gain further understanding of operations in HT and cold water downflow environments, CT simulations were combined with simulations from geothermal reservoir to overcome modeling limitations. The outcome helped designing customized downhole tools (e.g., nozzles) and a new cooling loop system; they also allowed optimizing the nitrogen lift technique. As a result, two large-diameter geothermal wells were lifted safely and successfully with 2-in. CT.

Best practices extracted from this study will be best applied as a reference to design, prepare, and safely perform CT jobs in wells with large-diameter casing and high bottomhole temperatures.

Engineering methods and steps taken to prepare and execute successful CT operations under those conditions are provided so that operational setup can be optimized to minimize risk and improve efficiency. This study specifically focuses on CT operations performed in South-East Asia and aiming to lift geothermal wells with nitrogen. It details how the equipment—such as bottom-hole nozzles, surface cooling loop designs, pressure control equipment, bottomhole assembly seal material—was engineered to perform under the harsh conditions encountered in HT, large-completion geothermal wells. The optimum kickoff depths along with N2 rates from CT simulations were combined with the results from geothermal reservoir simulations, which led to very good results. Specifically, on-job temperature readings showed effectiveness of the new design, in particular for the cooling loop system utilized on surface with heat exchange riser to maintain wellhead stack temperature below 200 degF, thus allowing safe working conditions in HT wells. The comparison between downhole tools such as normal spherical nozzles along with customized tapered nozzles with appropriate standoff shall also be discussed.

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Session Classification: Poster Session

Contribution ID: **89** Type: **Poster**

Petrophysical properties of the Muschelkalk from the Soultz-sous-Forêts geothermal site (France), an important lithostratigraphic unit for geothermal exploitation in the Upper Rhine Graben

Wednesday, October 9, 2019 5:40 PM (20 minutes)

The Muschelkalk, composed of Triassic limestones, marls, dolomites, and evaporites, forms part of the Permo-Triassic cover of sedimentary rocks that directly overlies the fractured granitic reservoir used for geothermal energy exploitation in the Upper Rhine Graben. Petrophysical data for this lithostratigraphic unit are sparse, but are of value for reservoir prospection, stimulation, and optimisation strategies at existing and prospective geothermal sites throughout the Upper Rhine Graben. To this end, we present here a systematic microstructural, mineralogical, and petrophysical characterisation of the Muschelkalk core (from the Middle to Lower Muschelkalk; from a depth of ~930 to ~1001 m) from exploration borehole EPS-1 at Soultz-sous-Forêts (France). First, we assessed the microstructure and mineral content of samples from six depths that we consider represent the variability of the available core. The majority of the core is composed of fine-grained, interbedded dolomites and marls; however, anhydrite and a dolomitic sandstone bank were found in the Upper and Lower Muschelkalk core, respectively. A larger suite of samples (from fifteen depths, including the six depths chosen for microstructural and mineral content analysis) were then characterised in terms of their petrophysical properties. The matrix porosity of the measured Muschelkalk samples is low, from ~0.01 to ~0.1, and their matrix permeability is below the resolution of our permeameter (« 10-18 m2). P-wave velocity, thermal conductivity, thermal diffusivity, specific heat capacity, Young's modulus, and uniaxial compressive strength range from 2.60 to 5.37 km/s, 2.42 to 5.72 W/mK, 1.19 to 2.46 mm2/s, 1.63 to 2.46 MJ/m3K, 9.4 to 39.5 GPa, and 55.1 to 257.6 MPa, respectively. Therefore, and despite the narrow range of porosity, the petrophysical properties of the Muschelkalk are highly variable. We compare these new data with those recently acquired for the Buntsandstein unit (the Permo-Triassic unit immediately below the Muschelkalk) and thus provide an overview of the petrophysical properties of the two sedimentary units that directly overly the fractured granitic reservoir.

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Session Classification: Poster Session

Contribution ID: **90** Type: **Oral**

Sensitivity analysis of the total reinjection geothermal plant in Castelnuovo

Thursday, October 10, 2019 10:10 AM (15 minutes)

Geothermal power is one of the renewable energies which is extensively used in Italy, especially in Tuscan region, and which is becoming very discussed all around Europe. Geothermal energy exploits the geological heat sources, which are naturally present and it is considered as a renewable energy when the short time period is taken into account. However, the continuous exploitation of the geothermal resource can affect its conditions and particularly its temperature, reducing the production rate of the power plant.
In order to reduce the impact of the geothermal power plant on the resource, a total re-injection configuration of the power plant is taken into account in this study. Particularly, a closed-loop ORC power plant layout including complete gas reinjection is studied for the geothermal location of Castelnuovo Val di Cecina, Italy.
The resource condition is saturated vapour, with a high content (8%) of non-condensable gases (NCGs); therefore, a suitable configuration of the power plant is analysed, both from design condition, as well through the development of a sensitivity analysis of the main operating conditions, such as temperatures, mass flow rates and pressures, both of the power plant and of the NCG reinjection compressor train. The re-compression train configuration is comprised of a 3-stage compressor with one precooler and two intercoolers; the NCG stream is directed downwards in the external annulus of the reinjection well, while the liquid brine flows through the inner pipe section developing progressively the piezometric head. Mixing is achieved at a certain depth (400-600 m) through the use of a reverse gas lift valve. Various operating conditions are analysed, finding the optimal design point, both from an energy and exergo-economic point of view.
Furthermore, the interaction between the binary cycle and the geothermal resource is studied through a dynamic simulation. The compressor train conditions are defined and the conditions of the fluid at well-head are assessed. The flow conditions under various operating transients are analysed, especially regarding the time required in order to achieve steady state conditions. The operational requirements are determined in terms of height of the water column and depth of the NCGs reverse gas-lift mixing valve in the reinjection well in order to match the compressor outlet pressure.

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Session Classification: Session 5: Energy Conversion Systems

Track Classification: Topic 5: Energy Conversion Systems

Contribution ID: **92** Type: **Poster**

Hydrogeological, hydrogeochemical and isotope geochemical features of geothermal waters of Salavatlı in the continental rift zone of the Büyük Menderes, western Anatolia, Turkey

Wednesday, October 9, 2019 10:30 AM (20 minutes)

The geothermal field of Salavatlı is located in the north of the middle part of the continental rift zone of the Büyük Menderes within the Menderes Massif, western Anatolia, Turkey and consists of Paleozoic metamorphic rocks and Miocene to Pliocene sedimentary rocks. Paleozoic marbles and quartzites form the geothermal water reservoir in the area with 35 production and reinjection wells in a depth up to 3249 m and 5 geothermal power plants in a capacity of 70 MWe. During the present study, we measured in-situ parameters and collected samples at 19 production and reinjection wells for hydrogeochemical and isotope geochemical analyses. The geothermal waters of Salavatlı in meteoric origin can be considered as Na-HCO3 type water and have reservoir temperatures up to 200 ℃. In Salavatlı, the sampled groundwaters and mixed geothermal waters lie along the meteoric water line (MWL) in plot of $\delta^{18}O$ versus $\delta^{2}H$, whereas the high-temperature geothermal waters deviate from the meteoric water line (MWL), suggesting a fluid-rock interaction.
In the drainage area of Salavatlı, the geothermal waters percolate at faults and permeable clastic sediments into the reaction zone of the roof area of a magma chamber, situated at a probable depth of up to 4 km, where meteoric fluids are heated by the cooling magmatic belt and ascend to the surface due to their lower density caused by convection cells. Besides, some subvolcanic rocks from Middle Miocene to recent in age occurred in the continental rift zones of the Menderes Massif.

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Session Classification: Poster Session

Contribution ID: **93** Type: **Oral**

A new mine water geothermal research facility: the UK Geoenergy Observatory in Glasgow, Scotland

A new subsurface mine water geothermal research facility, part of the UK Geoenergy Observatories, is being constructed in the Clyde Gateway area of Glasgow City, UK. The facility will enable scientists to take forward research that is vital to understanding the role and potential of abandoned mine systems as heat source/ sink, such as integration into district-wide heating/cooling networks, the risks involved in mine water energy developments and the environmental management regulation needed. By reducing subsurface uncertainty associated with these systems and by providing a test site for new technologies, the project aims to encourage the widespread development of coal mine geothermal resources in areas close to former coalfield communities. In 2019, baseline and continuous monitoring data from the Observatory boreholes will start to become available via an online portal. This talk will describe the rationale for the research facility and design, summarise the planned data acquisition and offer a first glimpse at some of the data obtained to date.

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Session Classification: Keynote 4: A new mine water geothermal research facility: the UK Geoenergy Observatory in Glasgow, Scotland

Contribution ID: **94** Type: **Oral**

RESERVOIR CHARACTERIZATION AND NUMERICAL MODELING OF ALUTO-LANGANO GEOTHERMAL FIELD, ETHIOPIA

Wednesday, October 9, 2019 10:10 AM (15 minutes)

Aluto-Langano geothermal field is located within the central southern portion of the Main Ethiopian Rift (Lake District), approximately 200 km southeast of Addis Ababa. Geothermal explorations began in the mid-1980s with the drilling of eight deep exploratory wells (maximum depth of 2500 m). The full potential of this field has not been fully exploited and therefore there is a need for further study and understand the geothermal reservoir system. Currently, plans are underway to develop fully Aluto-Langano geothermal field. Therefore, to achieve the full development program, further studies of the reservoir system is needed. The main objective of my study is to develop a 3D reservoir model for simulation studies to better reflect and understand the geothermal system of the Aluto-Langano geothermal field.

Characterization requires an understanding of the physical processes that govern the flow of mass and energy through the reservoir. As for most reservoir modeling endeavors, the inability to measure the actual value of the properties in the geothermal system makes it necessary to strike a balance between what is included in the reservoir model and what is known about the physical processes that need to make based on the model.

Numerical simulations are important tools for the exploration of the geothermal reservoir since they can predict thermal and hydraulic reservoir conditions and are able to simulate the development of a reservoir while exploitation. However, reliable forecasts are possible only if the subsurface geology of the area is known and the corresponding thermal and hydraulic properties are well defined. Therefore, all information available will be integrated in order to develop a geothermal model. Data from geophysical methods (MT and Gravity) for the heat source and structural investigation, information from existing wells in the Aluto will be collected then analyzed. The numerical model will be based on a conceptual model, which will provide the structures and geometries of the subsurface. Numerical simulation tool (Tough2) will be used to predict the current steady-state conditions as well as their development in time. The expected outcome of this study will be to understand hydraulic and heat transport processes in the reservoir, which is necessary to assess the geothermal potential and to define the optimum exploitation and plant operation strategies for the study area. The long-term environmental impacts of the operation have to be further investigated with the help of reservoir modeling.

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Session Classification: Session 1: Assessment of Geothermal Resources

Track Classification: Topic 1: Assessment of Geothermal Resources

Contribution ID: **95** Type: **Oral**

Mapping Geothermal: A planning instrument for power and heat generation in Germany

Thursday, October 10, 2019 9:40 AM (15 minutes)

Germany defined an ambitious social and economic plan in order to cut 80 % of CO2 emissions by 2050. In this context, geothermal energy can play a key-role, since the high capacity factor and the possible heat and power configuration. Several power plants and district heating systems are currently running in Germany on geothermal sources.
In this work, an extended techno-economic analysis of several geothermal binary solutions in Germany is proposed. Six organic Rankine cycles (ORC) power plant models are developed and analysed in order to provide a planning instrument for geothermal energy exploitation. This planning tool aims at power and heat generation and considers different energy system characteristics and distinct geothermal reservoir properties. The investigated examples are here listed:
1. Traunreut supercritical
2. Traunreut (subcritical)
3. Kirchstockach in double-stage configuration
4. Kirchstockach in single-stage configuration
5. Insheim with high performance components
6. Insheim with low performance components.

The investigated solutions cover the whole range of geothermal reservoir properties and power plant technical features available in Germany. Each example is firstly developed according to on-design analysis, where the evaporating pressure is varied in order to maximize the turbine power output. Later, each simulating model has been extended according to the implementation of off-design correlations for each component of the ORC power unit. Real ambient temperature data are therefore implemented and each model is hourly simulated. For each power plant model, three different configurations are evaluated: power-only and heat and power, with respectively 5 and 10 MW as maximum heat demand. Techno-economic analyses according to annual input data are therefore developed for the CHP configurations.
The double-stage Kirchstockach power plant shows the highest on-design turbine power output (4910 kWel), followed by Insheim high performance with 4427 kWel. The thermal efficiency results in 12.51 % in Insheim high performance, while only 8.21 % in Traunreut supercritical. In fact, the very high auxiliary power requirement affects the overall power unit efficiency. An economic analysis on the component level is applied to calculate the levelized cost of electricity (LCOE) of each ORC power plant. In power-only configuration, Insheim with high performance shows the lowest LCOE (10.79 €ct/kWh) while the highest value is reached by the supercritical case study in Traunreut (19.40 €ct/kWh). This solution requires the highest-cost and longest-term total investment. In general, the obtained results show how a very high geothermal well-head temperature could improve the techno-economic results. Current calculations show how an increasing maximum heat demand negatively affects the LCOE and the BEP but increases the Net Present Value at the end of the investment.
The results enable operators and planers to identify the most suitable power plant configuration in dependence of reservoir conditions and specific heating demand. In this work, Aspen V8.8 has been chosen as simulating environment.

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Session Classification: Session 5: Energy Conversion Systems

Track Classification: Topic 5: Energy Conversion Systems

Contribution ID: **96** Type: **Poster**

GIS-based LiDAR-DEM5 lineament analysis in crystalline basement rocks of the central and northern Black Forest, SW-Germany

Wednesday, October 9, 2019 12:10 PM (20 minutes)

Favorably oriented brittle fault zones in a regional stress field are major targets for geothermal exploration and production. Particularly, knowledge of spatial distribution and orientation of brittle fault zones in crystalline basement rocks contribute to our understanding of structural relationships, fault kinematics, and to natural and induced seismicity in EGS reservoirs. In order to quantify distribution and orientation of fault zones in crystalline basement rocks a Geoinformation System (GIS) based lineament analysis has been carried in the central and northern Black Forest as a first follow-up study of Meixner et al. (2018) who provided a lineament analysis for the southern Black Forest. Data base for lineament analysis are LiDAR-DEM5-data that were transformed into raster datasets, hillshaded and analysed in GIS. Inclined faults intersecting with a topography with different orientation than the strike direction of the fault will appear as curvilinear features at a map surface and hence will not be mapped as lineaments Subvertical faults instead will be mapped as lineaments independent either of topography or orientation of the fault. Hence inclined faults will commonly be underrepresented by a regional lineament analysis. For statistical consistency and comparability, e.g. for evaluation of the lineament orientation distribution, each lineament was cut in 500 m long segments. The remaining end pieces of each lineament length below 500 m are statistically regarded as equivalent to the regular 500 m segments.
The orientation distribution of mapped lineaments shows maxima for NE-SW-(040-065°), NNW-SSE-(155-170°), and N-S-(170-010°) trends and minima for E-W-(080-095°) and ESE-WNW-(100-125°) trends. The predominant NE-SW- and NNW-SSE-trending lineaments can be referred to late Carboniferous-early Permian volcano-sedimentary basins (e.g. Rupf & Nitsch, 2008). This is in marked contrast to the southern Black Forest where WNW-ESE-trending lineaments prevail (Meixner et al., 2018). As NE-trending lineaments display little reactivation potential in the regional stress field natural seismicity is distinctly less than in the southern Black Forest where NW-trending faults with high reactivation potentials prevail (Meixner et al. 2018).

References

Meixner J, Grimmer JC, Becker A, Schill E, Kohl T (2018) Comparison of different digital elevation models and satellite imagery for lineament analysis: Implications for identification and spatial arrangement of fault zones in crystalline basement rocks of the southern Black Forest (Germany). Journal of Structural Geology, v. 108, p. 256-268, doi: 10.1016/j.jsg.2017.11.006

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Session Classification: Poster Session

Contribution ID: **97** Type: **Poster**

Numerical modeling of thermal front propagation caused by fluid injection in a fractured reservoir for forecasting thermal-induced seismicity

Wednesday, October 9, 2019 9:00 AM (20 minutes)

In this work, the propagation of a thermal-hydraulic front caused by cold fluid injection is investigated, using a finite element (FE) model. The objective of the work is to simulate the propagation of temperature changes in the subsurface and to quantify the resulting thermally induced stresses. The model is based on a typical setup of a geothermal powerplant in the greater Munich area. In the vicinity of the injection well of the powerplant seismic events occurred five years after commissioning.

The powerplant uses the Malm aquifer as a geothermal reservoir and reinjects cold fluid in the vicinity of a fault zone. In order to approach to the complex reservoirs'hydrogeology and the fault zone characteristics, a mesh generator was created using MATLAB. The generator creates a model based on regular cube-shaped elements, which can be separately parameterized and thus grouped to geological units. Furthermore, the cube's surfaces can be integrated as discrete, two-dimensional elements, which can also be separately parameterized. Thus, a 3D model was created with a reservoir containing a regularly distributed fracture network and fault zone. A scenario analysis was used to investigate the influence of the fault and the fractures on the thermal-hydraulic front propagation.

The results of the simulations show that especially the fracture network can significantly influence the range of the area influenced thermally by fluid injection. The fluid flow within the fault zone can lead to temperature changes in several hundred meters underneath the transition zone from the reservoir to the crystalline basement of several degrees. To quantify the resulting thermo-hydraulic stresses analytical approaches were used. The results show that the thermal-induced stresses exceed the hydraulic induced stresses clearly. In total, the changes of the stresses caused by the fluid injection are ranging in orders of magnitude which can affect a fault's integrity.

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Session Classification: Poster Session

Track Classification: Topic 4: Resource Development

Contribution ID: **98** Type: **Oral**

Sustainability of Geothermal Systems

Geothermal energy is classified as a renewable resource, where "renewable"describes a characteristic of the resource: the energy removed from the underground resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological/societal systems. Consequently, geothermal exploitation is not a "mining"process. The production of geothermal fluid/heat continuously creates a hydraulic/heat sink in the reservoir. This leads to pressure and temperature gradients, which in turn generate fluid/heat inflow to reestablish the pre-production state. The regeneration of geothermal resources is a process, which occurs over various time scales, depending on the type and size of the production system, the rate of extraction, and on the attributes of the resource.

Time scales for re-establishing the pre-production state following the cessation of production have been examined using numerical model simulations for the main geothermal technologies: 1) Heat extraction by geothermal heat pumps, 2) The use of a doublet system on a hydrothermal aquifer for space heating, 3) The generation of electricity on a high enthalpy, two-phase reservoir and 4) EGS: enhanced geothermal system for co-generation. The results show that during production intermissions or after production stops, recovery driven by natural forces like pressure and temperature gradients take place. The recovery typically shows asymptotic behavior, being strong at the start, and then slowing down subsequently, and theoretically taking an infinite amount of time to reach its original state.

However, practical replenishment (up to 95%) will occur much earlier, generally on time scales of the same order as the lifetime of the geothermal production systems. In more detail: 1) Any "balanced"fluid/heat production that does not exceed the natural recharge can be considered fully sustainable, 2) Production rates that exceed the rate of recharge will eventually lead to reservoir depletion, thus stopping economic production. 3) Geothermal resources will attempt to reestablish their pre-production states following termination of production, 4) The post exploitation recovery exhibits an asymptotic behavior reaching a "practical"replenishment on time scales of the same order as the lifetime of the geothermal production system, 5) Geothermal resources are renewable on timescales of technological/societal systems (~30-300 years), 6) Sustainable production secures the longevity of the resource at a lower production levels, 7) The level of sustainable production depends on the utilization technology as well as on the geothermal resource characteristics and 8) Production from geothermal resources should be limited to sustainable levels.

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Session Classification: Keynote 5: Sustainability of Geothermal Systems

Contribution ID: **99** Type: **Oral**

Drilling Induced Borehole Breakouts - New Insights From LWD Data Analysis

Wednesday, October 9, 2019 3:05 PM (15 minutes)

Logging while drilling (LWD) borehole images are widely used for the analysis of borehole breakouts. These breakouts develop when the circumferential stress around the borehole exceeds the compressive strength of the rock. Furthermore, they can show a temporal development. The aim of this thesis was the investigation whether a causal relationship between drilling operations and the development of breakouts exists.

For this purpose, a software tool has been developed, as an add-in for the Baker Hughes proprietary software JewelSuite, to interpret the data. The observations displayed a general relationship between breakouts and tripping operations as well as events with switched-off pumps. Various pressure reductions have been identified in breakout sections. The pressure reductions of the highest magnitude are caused by the switch-off of pumps during connections. A sensitivity analysis, examining the influence of the observed pressure changes on the stresses around the wellbore, has shown a strong dependency on the borehole orientation. Further, it became visible that the downhole temperature responses negatively to drilling operations. Switched-off pumps are responsible for the temperature reductions of the highest magnitude as well.

An investigation of the temporal development of breakouts has shown that breakouts tend to grow both azimuthally and depth-wise. Pressure changes between relogs may be an explanation for this time-dependent behavior. A causal relationship between breakouts and drilling operations could not be proven on the base of the investigated data set. Future research based on the findings of this work, however, may clarify this relationship by using relog data of higher quantity and quality or data from multiple imaging tools of the same run.

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Session Classification: Session 3: Constructing Geothermal Wells

Track Classification: Topic 3: Constructing Geothermal Wells

Contribution ID: **101** Type: **Oral**

Characterization of a Geothermal Reservoir in Denmark based on Seismic Inversion Results

Wednesday, October 9, 2019 11:55 AM (15 minutes)

The geophysical characterization of reservoir properties, such as lithofacies, porosity and other petrophysical variables, is essential for the exploitation of subsurface reservoirs. Indeed, reservoir lithofacies classification provides significant information about the petrophysical behavior of reservoir rocks and their degree of compartmentalization (Bosch et al., 2002). Furthermore, the porosity of reservoir rocks determines the storage capacity of energy resources such as hydrocarbon and water (Keelan, 1982). Here, we present a methodology to infer lithofacies and porosity in an onshore geothermal reservoir located at the north of Copenhagen, Denmark, based on seismic attributes obtained from seismic inversion. As for the majority of Danish deep basins, Lower Jurassic –Upper Triassic potential geothermal reservoirs are found (Mathiesen et al., 2010; Poulsen et al., 2017; Røgen et al., 2015).
The inversion of seismic data provides acoustic impedance (AI) and the ratio between P-wave and S-wave velocity (Vp/Vs). The goal of this method is to predict the lithofacies distribution from these seismic attributes. To account for the dependency in the lithofacies along the vertical direction, a first-order stationary Markov chain is introduced. The relationship between seismic variables (AI and Vp/Vs) and reservoir parameters (lithofacies and porosity) is modeled using an Artificial Neural Networks (ANN), to overcome the non-linearity of the relation and the non-Gaussian distributions. ANN is a machine learning approach based on weights and biases in the synaptic nodes to mimic the behaviors of neurons and is suitable to model complex unknown physical relations. Three different lithofacies are defined based on observations in nearby wells: sand, shaly-sand and shale. Sand is characterized by high AI and low Vp/Vs, whereas shale exhibits the opposite behavior. First lithofacies are classified based on elastic attributes; then, porosity is predicted using the classified lithofacies as constraints. The classification is based on an integrated method combining ANN and HMM (ANN-HMM) using the seismic inversion results as input. The ANN-HMM algorithm is trained using data from well logs and core samples. The integrated ANN-HMM approach provides better results compared to ANN and HMM, applied separately. In particular, the classification results show an improved continuity in the sand layer between the lower Jurassic reservoir unit and the Gassum Formation. The integrated approach also reduces the non-uniqueness. The results have been compared to those obtained from a standard approach where porosity is estimated without the lithofacies constrained; in the proposed approach, the predicted porosity is generally more accurate. However, the correct prediction of porosity strongly depends on the accuracy of the lithofacies prediction. Because the Markov model only accounts for transitions in the vertical direction, a future research direction will focus on the horizontal correlations between lithofacies (Feng et al., 2018).

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Session Classification: Session 2: Exploration of Geothermal Reservoirs

Track Classification: Topic 2: Exploration of Geothermal Reservoirs

Contribution ID: **102** Type: **Poster**

Optimization of heat extraction from sedimentary reservoirs for CPG electricity generation

Wednesday, October 9, 2019 5:40 PM (20 minutes)

The primary goal of the present work is evaluation and comparison of vertical and horizontal well placements and their impact on the power output of a CPG (CO2 Plume Geothermal) system. Performances of vertical and horizontal wells arranged in a repeated five-spot pattern are evaluated for single- and multi-phase flow cases. Numerical models were developed in MOOSE (Multiphysics Object Oriented Simulation Environment), tested and compared against each other and previous studies. Simulations show that the reservoir will respond differently to different well configurations, with buoyancy playing a major role in its response. The study discusses the accuracy of present models, the effects of buoyancy, phase mobilities and different well placements on the power output of CPG systems.

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Presenter: RAVILOV, Marat (ETHZ)

Session Classification: Poster Session

Contribution ID: **103** Type: **Poster**

Reactive Reservoir Systems - Crystallization and Filter Processes of Barite in Geothermal Systems

Wednesday, October 9, 2019 2:10 PM (20 minutes)

During geothermal energy generation, the change of temperature and pressure conditions can lead to supersaturation of the extracted fluids and therefore to the precipitation of crystalline phases. Well-documented crystalline deposits on the inner walls of pipes are the consequences. In addition, turbulence-induced inhomogeneities and mechanical disturbances also lead to the spontaneous formation of free-floating crystal nuclei. A significant part of them are carried along and reinjected into the reservoir. There, the crystal nuclei are possible centers for crystallization and cementations processes or can accumulate by filter effects. Both processes contribute to scaling effects which limit the permeability of the geothermal reservoir and therefore the profitability of a geothermal power plant. So far, such effects have been barely considered in previous studies.

Our investigations focus on a better understanding of the formation and growth of crystal nuclei in saturated geothermal solutions during thermal and pressure relaxation, and their role in decreasing permeability of fractured geothermal reservoirs. For this purpose, a high-pressure-high-temperature apparatus is built and used which is based on the working principle of a geothermal cycle. Circulating flow-through experiments with fractured reservoir rocks, i.e., two sandstones, and barite-supersaturated fluids are conducted under geothermal conditions with the option to simulate heat extraction and injection of colder crystal-contaminated fluids. Furthermore, the size and morphology of precipitated barite crystals are studied as important factors influencing the potential filter processes in fractures. First results show substantial change in barite morphology with different sodium chloride concentrations in solution. To minimize the scaling effects, the goal is to develop approaches to control crystal nucleation.

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Presenter: Mr ZUBER, Philipp

Session Classification: Poster Session

Contribution ID: **105** Type: **Poster**

Geothermal Power Generated from UK Granites (GWatt)

Wednesday, October 9, 2019 5:40 PM (20 minutes)

Geothermal Power Generated from UK Granites (GWatt)

Exploitation of the UK underground thermal resource has been held back by; 1) knowledge gaps about permeability and fluid/heat flow within the fractured hot rocks, and 2) a perception that the uncertainty associated with drilling problems or limited fluid flow from deep boreholes are too high for the potential financial reward. The recently-started NERC-funded GWatt project seeks to address these barriers to uptake of EGS by:
- Increasing knowledge of the geological conditions needed for deep fracture-controlled fluid flow within granitic rocks.
- Developing a quantitative understanding of the heat resource and sustainability of the geothermal reservoir.
- Constructing robust geological risk assessments based on well-established oil & gas uncertainty quantification and optimisation methods, with a view to reducing perceived risks.
- Applying the integrated results of site-specific research to new geothermal exploration models for other granites, particularly those in SW England.

GWatt will link with the developing United Downs Deep Geothermal Power (UDDGP) project, a 2 borehole EGS in the Carnmenellis granite in Cornwall. This will provide a unique resource; downhole fluids, rock samples, geophysical logs, flow data and seismic data. GWatt will maximise the scientific potential from these data, and carry out innovative further analyses and interpretation, combining site-specific observations with regional studies and state-of-the-art uncertainty quantification, to address the challenges associated with EGS development within SW England. Other UK crystalline basement rocks show fracture-controlled groundwater flow, so the lessons learned from GWatt will ultimately benefit understanding of the rest of the UK deep subsurface. A background to the aims and initial findings of the project will be provided.

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Presenter: Dr ROCHELLE, Chris (British Geological Survey)

Session Classification: Poster Session

Contribution ID: **106** Type: **Poster**

Geothermal brines as mineral resource, new scopes beyond lithium extraction

Wednesday, October 9, 2019 5:40 PM (20 minutes)

Geothermal fluids are used as sustainable, alternative energy source for electricity and heat generation in geothermal power plants. Two general settings are distinguished, using hot fluids in active volcanic regions or using lower temperature geothermal brines in sedimentary basins. It has long been known that the geothermal fluids in active volcanic areas are enriched in e.g., Au, As, Sb, Ag and Cu. In the 1980s, chemical and physical data from geothermal power plants in New Zealand have been used in order to develop genetic models for the formation of Au-Ag-(Cu) deposits, the so-called epithermal gold deposits. Geothermal basin brines, for example in the Upper Rhine Graben, have temperatures of ~90-300°C and often have high salinity (up to 40 wt.% total dissolved solids). Such high-salinity basin brines are able to transport divalent transition metals as chloride complexes and are involved in the formation of sedimentary rock-hosted mineral deposits, such as Mississippi Valley Type (Zn-Pb) and Kupferschiefer Type (Cu) deposits. Mining these deposits produces several important byproducts, such as Ag, Ga, Ge, In, Co, PGE and Te. We, thus regard geothermal brines not only as heat carriers but also as metal carriers in sedimentary basins.

It is now well known that some geothermal basin brines like in Cornwall (UK) or Salton Sea (USA) are enriched in Li and several lines of processing technologies for Li extraction are being developed and tested. Recently, several exploration licenses for Li extraction from geothermal brines have been granted in the Upper Rhine valley. Although the data set for geothermal brines from the Upper Rhine Graben is incomplete, some metals other than Li are recognized as enriched in the fluids, including Zn, Sb, Be, Cs, Ge and Rb. Such elements also have the potential for economic extraction from the produced geothermal brines.

Although Zn is an economically important metal and it is enriched in the brine, the geothermal fluids are not considered a promising Zn resource, because of the low annual extractable amount in comparison to the large-scale global production (13 Mt in 2018) from sulfide deposits. Antimony (fire-retardant chemicals), Be (extreme light-weight alloys), Cs (cell phone, GPS), Ge (fiber optics, solar cells, LED) belong to the so-called technology elements and are produced at much less volume or as byproducts of large volume commodities. Rubidium is very rare on the market with special applications in biomedical research, special glasses and electronics. Many of these elements are not mined in Europe at all. Thus, Europe and Germany are completely dependent on a free market and the possibility to import these raw materials. The large volume of fluids (ca. 30-100 l/s) passing through the various geothermal power plants in the Upper Rhine Graben grants a significant supply of geothermal fluid as a carrier of raw materials from deep sources to the surface. Technologies need to be developed to make this resource available to the society.

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Session Classification: Poster Session

Contribution ID: **107** Type: **Oral**

Time-lapse magnetotellurics and micro-gravity monitoring of the Theistareykir geothermal field (Iceland)

Thursday, October 10, 2019 11:25 AM (15 minutes)

The Theistareykir geothermal field is located on the path of the Mid-Atlantic ridge in Northeastern Iceland. A power plant in the area produces 90 MWe since autumn 2017 using 13 production wells of around 2 km depth and 3 injection wells of about 450 and 100 m depth.

We monitor the spatial and temporal evolution of the geothermal reservoir using time-lapse magnetotellurics (MT) and micro-gravity methods. Surveys were performed before and after the beginning of the electricity production in summer 2017, 2018 and 2019.

9 MT stations were used to image the resistivity variations. Repeated MT measurements may help identifying the geothermal fluid path and characterizing the evolution of the reservoir, such as alteration of the medium or changes in water salinity or temperature. 5 components i.e. the horizontal electric field (Ex, Ey), the horizontal magnetic field (Hx, Hy) and the vertical magnetic field (Hz) components, were recorded simultaneously by METRONIX ADU-07e stations during 48 to 96 hours with a sampling rates of 512 Hz, 8,192 Hz and 65,536 Hz. Then, filtered time series were processed using the Bounded Influence Remote Reference Processing (BIRRP) program to derive apparent resistivity and phase sounding plots. Preliminary results indicate that the geothermal production increases the resistivity of the medium. No clear resistivity change is observed near the injection area.

27 gravity stations were measured with a relative Scintrex CG5 gravimeter in summer 2017, 2018 and summer 2019 to highlight the subsurface mass changes induced by the geothermal operations, and hence, help estimating recharge of the geothermal reservoir. These surveys were combined with Micro-g Solutions Inc. FG5#206 absolute gravity measurements and continuous gravity measurements to apply a fully hybrid micro-gravity method. In this context, GFZ Potsdam deployed three iGrav superconducting gravimeters and one gPhone spring gravimeter at the Theistareykir geothermal area since autumn 2017. The time-lapse gravity data are corrected for instrumental drift and vertical displacements deduced from GPS measurements performed by the University of Iceland. First results show a gravity decrease near the production area which can be explained by the extraction of 6.5 Mt at 1.6 km depth. We do not observe any significant gravity change near the injection area which suggests that the reinjected geothermal fluid is drained by faults.

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Session Classification: Session 6: Operation of Geothermal Systems

Track Classification: Topic 6: Operation of Geothermal Systems

Contribution ID: **108** Type: **Poster**

The United Downs Deep Geothermal Power project, Cornwall, UK

Wednesday, October 9, 2019 5:40 PM (20 minutes)

The United Downs Deep Geothermal Power (UDDGP) project is the first geothermal power project in the United Kingdom. It aims to develop the geothermal resources in the heat-producing granites that lie beneath Cornwall in SW England. Financial support has come from the European Regional Development Fund and the local authority (Cornwall Council) who, together, have provided £13m of the £18m project budget.

Two wells have been drilled to intersect a target fault structure that, it is hoped, will provide enough natural permeability to allow circulation between the wells at flow rates between 20 and 80l/s. The wells intersect the fault at vertical depths of approximately 2,000m (injection well) and 4,000m (production well).

The bottomhole temperature is expected to be in the region of 190 Deg C which should support electricity generation of between 1 and 3WMe (net). Drilling began in November 2018 and was completed at the end of June 2019. The production well reached a depth of 5,275m (MD) and the injection well 2,393m (MD).

The objective of the project is to prove the concept of operating a system with a very large well spacing, within an organized natural fracture system, and to demonstrate the viability of producing electricity so that the necessary private investment can be attracted to further develop the geothermal resources in Cornwall.

In parallel with the technical programme, Geothermal Engineering Ltd (GEL) has given a high priority to the implementation of a diverse and inclusive programme of education and public outreach in the local and wider community. The education programme has so far reached approximately 3,000 students.

The community outreach programme has built and strengthened GEL's relationship with the community and aims to provide reliable and objective information about geothermal energy in general, and the United Downs project in particular. Public open days are held at regular intervals to encourage people to come and view the site, ask questions and learn about geothermal energy. GEL has also attended numerous community events, public meetings and county-wide shows, spreading the message to thousands of members of the public.

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Presenter: Mr LEDINGHAM, Peter (GeoScience Ltd)

Session Classification: Poster Session

Contribution ID: **109** Type: **Oral**

Modeling of High-Enthalpy Geothermal Projects in Fractured Reservoirs

Wednesday, October 9, 2019 4:45 PM (15 minutes)

In general, high-enthalpy geothermal systems are characterized by a presence of vapor or coexistence of vapor-liquid phases. There is a complex phase transition (condensation) process during its development with cold water re-injection. Also, high-enthalpy geothermal reservoirs either contain naturally developed fractures or need induced fractures for fluid to flow at economically relevant rates. Simulation of heat production in high-enthalpy geothermal fracture systems is associated with solving complex physical process in complicated fracture networks. Besides, the existence of fracture networks magnifies the uncertainty of reservoir properties due to its wide range of scales and complex geometry, which can increase reservoir heterogeneity to a large extent.

In this work, a discrete fracture-matrix (DFM) model is used to describe the geothermal reservoir with fractures. Fractures are explicitly characterized in the model with individual grid cells. The numerical scheme is implemented within the Delft Advanced Research Terra Simulator (DARTS), which can provide fast and accurate flow response of the geothermal field. This simulation framework uses the Operator-Based Linearization (OBL) technique. In DARTS, the molar formulation is selected with pressure and enthalpy as primary variables. Besides, a fully implicit two-point flux approximation on an unstructured grid is implemented to solve the mass and energy conservation equations.

We use a realistic fracture network in this study. To achieve both accuracy and computational performance, firstly a reasonable resolution of grid discretization is determined through the comparison of solutions and convergence analysis among different sets of grid discretization. With the optimal grid resolution, we investigate the influence of geo-static and thermal parameters on thermal breakthrough and heat production. We find that the thermal production and distribution are sensitive to fracture-matrix permeability ratio, rock heat conduction and heat capacity, which can provide insights for the development of high-enthalpy geothermal reservoirs with fractures.

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Presenter: Mr WANG, Yang (TU Delft)

Session Classification: Session 4: Resource Development

Track Classification: Topic 4: Resource Development

Contribution ID: **110** Type: **Poster**

Global application of Aquifer Thermal Energy Storage (ATES)

Wednesday, October 9, 2019 5:40 PM (20 minutes)

While the share of renewables in the power generation sector steadily increases, less attention is paid to the decarbonisation of the heating and cooling sector. Since most industrial nations are located within the moderate climate zone, the global heating and cooling supply is less a matter of energy shortage than a matter of seasonal storage. Aquifer Thermal Energy Storage (ATES) is considered to bridge this seasonal gap between times of highest energy demand and times of highest energy supply. With more than 2,800 ATES in operation, 90 % of all systems are operating in the Netherlands and Scandinavia. At the same time, more than 99 % of all ATES system are low temperature (LT) systems storing temperatures below 30 ℃. In contrast, there are currently only two high temperature (HT) ATES (>50 ℃) in operation worldwide. As early HT-ATES projects had to be abandoned due to significant geochemical problems, several research projects in Central Europe and North America strive to demonstrate technical feasibility. This talk provides an overview of ongoing HT-ATES projects in Germany, Switzerland, the Netherlands and the US.

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Presenter: Mr FLEUCHAUS, Paul (Karlsruhe Institute of Technology (KIT))

Session Classification: Poster Session

Contribution ID: **111** Type: **Poster**

In-situ stress and rock mass characterisation via mini-frac tests at the Bedretto Underground Laboratory

Wednesday, October 9, 2019 10:10 AM (20 minutes)

ETH Zurich has established the Bedretto Underground Laboratory for Geoenergies (BULG) in the Swiss Central Alps (http://www.bedrettolab.ethz.ch), where hydraulic stimulation techniques and associated induced seismicity will be studied. Purpose of the experiments is to improve the understanding of hydromechanical processes linked to the creation of a deep geothermal reservoir. The BULG is located in relatively homogeneous granite with an overburden of around 1000 m. In context of the initial in-situ stress field and rock mass characterisation campaign, several hydraulic mini-frac tests were conducted. Four 30 m-long vertical and two 40 m-long inclined boreholes were analysed in detail to complement preliminary reported stress magnitudes. Several measurement protocols were utilised within the mini-frac tests conducted at five depth intervals in each borehole.

Mini-frac tests can provide extensive information about the stress magnitudes, stress directions and rock properties like permeability or stiffness. The pressure decay analysis after pump shut-in was used to infer fracture closure pressure, whereas dry packer reopening tests gave an estimation of the fracture reopening pressure and system stiffness. Shut-in times were varied from several minutes to one hour or overnight (12 to 14 h) to display effects on the fracture closure analysis and obtain the local pore pressure. The latter ranges between 2.4 to 5.3 MPa, an indication of tunnel drainage effects. Since fracture closure pressure determination, an approximation to the minimum horizontal stress, is controversial in the literature, several analysis techniques were compared: G-function, square root of time, bilinear pressure-decay and jacking pressure. In most cases, the applied techniques give consistent results in a range of 1 to 2 MPa, but sporadically differences are larger. The fracture compliance method was used to identify the point where the stiffness of the fracture increases, related to the beginning of its closure. Therefore, it is the most accurate indication of minimum principal stress, which ranges between 12.6 to 15.2 MPa. Derived magnitudes for the maximum horizontal stress lie between 17.8 to 23.8 MPa.

Increasing fracture stiffness was correlated to a linear or bilinear flow regime on log-log scale plots of the pressure derivative. Like the fracture closure pressure, the formation breakdown, fracture reopening and instantaneous shut-in pressures show intra- and inter-borehole variations. The proximity to naturally fractured regions, which were located on borehole logs, seems to influence the data quality and pressure values. Slip-tendency calculations indicate that the pressure range reached during the mini-frac tests is sufficient to reactive these fractures. As the induced tensile fracture propagates further away from the borehole with every injection cycle, it becomes more and more likely that it intersects pre-existing fractures. This is seen as multiple closure signature on several of the used diagnostic plots, where it is beneficial to have extended observation times (≥ 1 h) to fully characterise the different closure behaviours.

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Session Classification: Poster Session

Track Classification: Topic 2: Exploration of Geothermal Reservoirs

Contribution ID: **112** Type: **Oral**

Thermo- and petrophysical rock properties of the Los Humeros geothermal field (Mexico): comparison of outcrop analogues and reservoir formations

Wednesday, October 9, 2019 11:25 AM (15 minutes)

The Los Humeros geothermal system is an operating steam dominated field with 65 wells (23 producing). With temperatures above 380 ℃, the system is characterized as a super-hot geothermal system (SHGS). The development of such systems is still challenging due to the high temperatures and aggressive reservoir fluids, which lead to corrosion and scaling problems.
For better reservoir understanding and prospective modeling of the Los Humeros caldera complex, extensive geological, geochemical, geophysical and technical investigations are performed within the scope of the GEMex project (EU-H2020, GA Nr. 727550). Relatively little is known about the petro- and thermophysical rock properties in the study area. This data is critical for i) processing and interpreting geophysical data and ii) for parameterizing reservoir models. Therefore, outcrop analogue and reservoir sample studies have been carried out in order to define and characterize all key units from the basement to the cap rock. Thus to identify geological heterogeneities on different scales (outcrop analysis, representative rock samples, thin sections and chemical analysis) enabling reservoir property prediction.
More than 200 rock samples were taken from representative outcrops inside of the Los Humeros caldera, the surrounding area and from the exhumed 'fossil'system Las Minas. Additionally, 64 core samples covering 14 wells of the Los Humeros geothermal field were obtained. The samples were analyzed for petrophysical (e.g. density, porosity, permeability) and thermophysical properties (thermal conductivity, thermal diffusivity, heat capacity) as well as ultra-sonic wave velocities and magnetic susceptibility.
Based on the outcrops and petrological analysis, the unit's geological heterogeneity, which controls the rock properties, can be addressed. Hydrothermal alteration of different intensities was observed on borehole core samples resulting in high heterogeneity in terms of sample appearance, chemical composition and rock properties. Likewise, hydrothermal alteration can be observed in outcrops in the vicinity of dykes, igneous bodies and fault zones. An extensive rock property database was created comprising more than 20 parameters analyzed on more than 1200 plugs altogether. The results enable the classification of different lithofacies types with distinct properties, which is essential to define geothermal model units within a 3D geological model. Based on statistical analysis, 19 lithostratigraphic units were defined for the Los Humeros geothermal field.

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Session Classification: Session 2: Exploration of Geothermal Reservoirs

Track Classification: Topic 2: Exploration of Geothermal Reservoirs

Contribution ID: **113** Type: **Poster**

Assessment for geothermal utilization of the Upper Devonian Leduc and Nisku Formation in the Alberta Basin, Canada

Wednesday, October 9, 2019 10:50 AM (20 minutes)

The Canadian province of Alberta has the highest per capita CO2-equivalent emissions in Canada, predominantly due to the industrial burning of coal for the generation of electricity and mining operations in the oil sand deposits. The use of Alberta's geothermal potential could reduce CO2 emissions by substituting at least some reasonable amounts of fossil fuels.
Geothermal research in Alberta started back in the '60s mainly focusing on the determination of heat flow, geothermal gradients and reservoir temperature in the basin. Based on recent feasibility studies, the Upper Devonian carbonate aquifer systems within the Alberta Basin were identified as promising target formations for geothermal energy. To assess their geothermal reservoir potential, detailed knowledge of the thermo- and petrophysical rock properties is needed. The presented analogue study compared drill core rock properties from the Southesk-Cairn Carbonate Complex and the Rimbey-Meadowbrook Reef Trend with selected outcrop samples from stratigraphically correlative outcrops in the Rocky Mountains. Samples from the Leduc and Nisku Formations were analyzed for thermal conductivity, thermal diffusivity and heat capacity, as well as density, porosity and permeability. These data suggest that the extensively dolomitized and highly fractured reef zones with permeabilities of up to 10−12 m2 and thermal conductivities of > 4 W m−1 K −1 are the most promising reservoirs for geothermal utilization.
Besides, our dataset is complemented by open-file core and reservoir data retrieved from the AccuMap database for mapping of reservoir temperature, TDS, sour gases (H2S, CO2, N2) and petrophysical core data (density, porosity and permeability). A preliminary 3D geological model of the Nisku and Leduc aquifers in the western part of the Rimbey-Meadowbrook reef trend was created with GOCAD/SKUA to determine the potential for geothermal utilization on a local scale (e. g. on the scale of a few townships). Preliminary findings confirm those from previous studies that the Upper Devonian carbonate aquifers are worth investigating as geothermal reservoirs.

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Presenter: Mrs WEYDT, Leandra (TU Darmstadt)

Session Classification: Poster Session

Contribution ID: **114** Type: **Poster**

Constraining caldera structures to understand geothermal fluid migration: insights from analogue modelling, and implications for the Los Humeros Volcanic Complex

Wednesday, October 9, 2019 1:50 PM (20 minutes)

In the frame of the GEMex Europe-Mexico cooperation project (Horizon 2020 Programme; grant agreement No. 727550), we have performed a series of analogue models investigating the influence of pre-existing faults on caldera collapse and subsequent caldera resurgence. This experimental work aims at investigating the development of caldera collapse and resurgence structures, which may represent viable pathways for the migration of geothermal fluids. Although these models have addressed the process for a general point of view, they were designed using the geometrical parameters known for the Los Humeros volcanic complex (Puebla state –Mexico), which is currently exploited for energy production, and is likely related to the structural evolution of the caldera complex. Caldera collapse and resurgence are complex geological processes that remain elusive to investigate. Several numerical and analogue modelling experiments have attempted to analyse this process during the last decades (e.g., Acocella, 2007; Geyer & Martí, 2014, and references therein). Particularly, analogue models allow to monitor the progressive evolution and the deformation pattern resulting from caldera collapse/resurgence processes at a reduced scale (both of time and geometry). A general model integrating analogue models with geological evidence suggests that caldera collapse is accommodated by early outward-dipping reverse faults and subsequent inward-dipping normal faults, but some aspects remain barely addressed, such as the role of inherited structures during caldera collapse and resurgence processes. In our modelling, we have induced caldera collapse by draining out (and afterwards re-injecting in case of intra-caldera resurgence) an analogue magma from an analogue magma chamber, emplaced below a brittle sedimentary cover simulated by a multi-layered sand mixture. Pre-existing faults have been simulated either at the caldera margin(s) and/or above the caldera depression. The shape of the magma chamber was varied by imposing straight sides, simulating pre-existing fault discontinuities, and in some models the sand pack was pre-deformed by artificial dilation zones in different positions, simulating inherited fabrics within the brittle crust. Our models show that discontinuities may induce caldera ring-faults to deviate from standard evolution and that inherited fabrics may influence significantly the caldera collapse deformation pattern (by modifying and/or inhibiting the formation of specific caldera collapse structures), and eventually caldera resurgence. This may bear important implications for migration of geothermal fluids and consequently for their detection, providing insights into caldera collapse processes and associated geothermal reservoirs, helping to better constrain variables associated with reservoir investigation.

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Session Classification: Poster Session

Contribution ID: **115** Type: **Poster**

Geological controls on upper crustal heat flow for deep geothermal energy

Wednesday, October 9, 2019 11:10 AM (20 minutes)

The United Downs Deep Geothermal Project is the first geothermal power project to commence in the UK, situated near Redruth, Cornwall, SW England. Two deep deviated geothermal wells have recently been completed to measured depths of 2393 m and 5275 m (2214 m and 5054 m true vertical depth) in June 2019. The wells target the NNW-SSE-trending Porthtowan Fault Zone (PTFZ) which cuts an Early Permian granite batholith and is hoped to form a natural fault-hosted geothermal reservoir.

SW England is a particularly favourable region for geothermal power production because it has the highest heat flow values in the UK, c. 120 mW m-2 at on-granite locations. Challenges exist for modelling the high surface heat flow values due to uncertainties relating to the radioelement concentrations at depth and the volume and distribution of the granites. The granites have a heterogeneous U, Th and K content controlled primarily by the temperature and degree of source rock partial melting and fractional crystallisation processes. Secondary to this, fluid rock interaction can leach and redistribute radioelements.

The aims of this research are to resolve the heat flow issues by investigating the radioelement concentration and thermal conductivity of the granite using data from the United Downs Deep Geothermal Project. Detailed mineralogical and geochemical analyses will be carried out to define different granite types and understand the host minerals of U and Th. These analyses in combination with wireline spectral gamma data will allow a detailed characterisation of the radioelements with depth and allow a high-resolution heat production profile to be produced. In addition to this, coupled thermal conductivity measurements will be carried out to examine the temperature dependence of thermal conductivity and characterise thermal conductivity with depth. The results of this will improve the thermal resource and sub-surface temperature evaluation of the granites.

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Session Classification: Poster Session

Contribution ID: **116** Type: **Poster**

Simulation of temperature logs in high-temperature well

Wednesday, October 9, 2019 2:50 PM (20 minutes)

In the frame of the EU Horizon 2020 DEEPEGS project and the IDDP2 project, the well RN-15 located in the Reykjanes geothermal field (Iceland) was deepened. So far, this well, namely RN-15/IDDP2 is the deepest geothermal well drilled in Iceland with a final depth of 4659 m and a measured bottom-hole temperature of 427℃ and fluid pressure of 34 MPa. During drilling, several temperature logs were run whilst water was injected continuously to cool down the equipment in the borehole due to the high-temperature environment. The objective of our work, as part of the DEEPEGS project, is to apply numerical simulation methods to estimate the formation temperature and fluid loss along the well path, based on the recorded temperature logs acquired under dynamic conditions, during and after drilling. This is of particular interest for the development and understanding of the deep geothermal reservoir.

Our approach comprises the development of a transient thermal model in which the temperature evolution of the well and the surrounding formation is simulated. The numerical tool enables the use of the whole history fluid circulation data. In this work, we first evaluate synthetic data that reflect possible different technical logging conditions such as permanent cooling or fluid loss zones in the high-temperature environment. Concerns as to whether simple BHT type correction methods are still applicable to non-shut-in conditions of boreholes will be considered. Consequently, different application examples of temperature logs are presented. Firstly, we provide an example of estimating SFT in an extremely high-temperature well, which is continuously cooled down during logging, using the classic Horner-plot Method. The impact of using non-shut-in temperature logs for the SFT estimation is examined. Secondly, we demonstrate how temperature logs can be used for characterizing the fluid loss in the borehole. The results show that applying simple temperature correction methods on the non-shut-in temperature data could lead to large errors (24 ℃ to 74 ℃ at a flow rate of 0.7 L/s) for SFT estimation. Fluid loss leads to the local gradient increase in the vertical temperature profile. However, the amount of the temperature gradient increase and the percentage of fluid loss have a non-linear and non-monotonic relationship. This relationship depends on the flow rate and the lateral heat transfer between the fluid and the rock formation. As indicated by this study, under low fluid losses (< 30%) or relatively higher flow rates (> 20 L/s), the impact of flow rate on the temperature gradient increase can be ignored. The knowledge and experience gained from the synthetic models provide insights for the future work when the real temperature logging data are used to constrain the far-field formation temperature and to estimate the fluid loss. Herein, we also present some first results on the temperature analysis in the RN-15/IDDP2 well using real long-term drilling and logging data.

Keywords: RN-15/IDDP2, DEEPEGS, Numerical simulation, Formation temperature, Fluid loss

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Session Classification: Poster Session

Contribution ID: **117** Type: **Poster**

SWIR spectroscopy for the exploration of hydrothermal alteration in crystalline geothermal reservoirs (Alsace, France).

Wednesday, October 9, 2019 5:40 PM (20 minutes)

In the granitic basement of the Upper Rhine Graben (URG), fracture zones (FZs) are bearing the major permeability. The investigation of permeable hydrothermally altered FZs and their distribution in the well is a key issue for the understanding of fluid circulation in granitic rocks. Hence, it is crucial for the optimization of the fluid flow in existing geothermal wells and for the target of new geothermal projects. The innovative use of the short-wave infrared (SWIR) spectroscopy on drill cuttings is applied to Rittershoffen and Soultz-sous-Forêts wells for the investigation of the clay signature of FZs in crystalline rocks. SWIR spectra were acquired for more than 3000 cuttings samples in the granitic sections of the Rittershoffen and Soultz-sous-Forêts wells (GRT-1, 2 and GPK-1, 2, 3, 4 respectively). In this study several selected sections of those geothermal wells will be presented. The FZs of these wells were first characterized by mineralogical studies. Binocular loupe observations enabled to distinguish the several grades of hydrothermal alteration encountered by the granite. X-ray diffraction (XRD) analyses enabled to identify the secondary clay mineralogy corresponding to poorly crystallized illite (PCI) and illite-smectite mixed layers (I/S ML) which generally takes place within (FZs). The SWIR results correlate with the XRD results and the former binocular magnifier observations. For all wells studied, the area of the 2200 nm absorption band area correlates with the illitic minerals proportion and yields specific values for the several hydrothermal alteration facies in the granite: larger the 2200 nm absorption band area, higher the hydrothermal alteration. SWIR spectroscopy is therefore a promising tool to estimate the hydrothermal alteration intensity and to understand the FZ architecture. Beyond, SWIR spectroscopy helps to identify the extent of rock affected by past or present hydrothermal circulations around FZs. Using routinely field SWIR spectroscopy on crystalline cuttings could be a pioneer method to characterize FZs in the recent geothermal well drilled at 3.8 km deep in Illkirch (Strasbourg area).

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Session Classification: Poster Session

Contribution ID: **118** Type: **Oral**

Accelerating reactive transport simulations with on-demand learning algorithms

Thursday, October 10, 2019 4:15 PM (15 minutes)

Reactive transport simulations help us better understand how geochemical reactions affect complex geothermal systems. However, geochemical reaction calculations can be extremely costly, sometimes accounting for over 99% of all computing costs in the simulation. As a result, the common practice is to simplify chemical details of fluids and rocks in the computer model to make it more computationally feasible. To tackle this computing issue, we resort to an on-demand learning algorithm that can speed up geochemical calculations by orders of magnitude, and thus substantially accelerate reactive transport simulations. In this presentation, we show how these algorithms work and highlight the speed up obtained in some reactive transport problems. We also comment about the next steps we will undertake to make these smart algorithms more commonly used for numerical investigations of geothermal energy systems.

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Session Classification: Session 8: Computing and Data Management, Machine Learning

Track Classification: Topic 8: Computing and Data Management, Machine Learning

Contribution ID: **119** Type: **Poster**

An automated workflow to study parameter sensitivities in a geothermal reservoir

Wednesday, October 9, 2019 5:40 PM (20 minutes)

During the last two decades, a considerable effort has been made by the Oil and Gas industry to develop automated workflows to describe the uncertainty in the subsurface. The Ensemble Reservoir Tool, developed by the state-owned Norwegian company Equinor, has been a key tool to characterize and history-match real hydrocarbon reservoirs. The modelling goal has been to create repeatable, updatable and consistent reservoir models that capture the important uncertain parameters.
Our objective is to demonstrate how these same tools used for uncertainty characterization can be adapted to automate a sensitivity analysis of a geothermal reservoir. As an example, we consider a synthetic aquifer located at about 2000-meter depth. A simplified facies-belt model of three sands with their static properties (porosity, permeability and thermal conductivity) has been set up. The forward thermal simulations are carried out with Eclipse's thermal functionality. We address the sensitivity of the energy production in a production well after 50 years of production, as a function of well placement, injection-production rates and heterogeneous thermal properties. Due to the versatility of this workflow, it can be readily used on producing geothermal reservoirs to help history match complex production histories and forecast future production.

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Session Classification: Poster Session

Contribution ID: **120** Type: **Poster**

Local earthquake tomography of Los Humeros geothermal field

Wednesday, October 9, 2019 3:50 PM (20 minutes)

Los Humeros volcanic complex hosts one of Mexico's main geothermal fields, which is operated by the Federal Electric Comission (CFE, by its Spanish acronym). It is located at the eastern edge of the Trans Mexican Volcanic Belt (TMVB) forming the northern boundary of the Serdán-Oriental basin. The shallow subsurface has been studied extensively, but knowledge of the geothermal system at depths greater than ~2.4 km is still rather sparse. For this reason, in the framework of the European H2020 and Mexican CONACyT-SENER project GEMex, various geophysical, geological, and geochemical surveys have been carried out to better understand the structure and behaviour of the geothermal reservoir, and to investigate future development areas.

Between September 2017 and September 2018, a seismic network consisting of 23 broadband and 20 short period stations, was deployed to monitor and study the currently exploited Los Humeros geothermal field. In this study, we use the retrieved local micro-seismic events (Gaucher et al 2019) to derive a minimum 1D velocity model, which we later employ as starting model to obtain 3D velocity variations and seismicity relocations. We will present results of the derived P-wave velocity and Vp/Vs models highlighting new information of the geothermal field, along with an initial interpretation of main velocity anomalies and structures and compare them to previous geological and geophysical data.

References

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Authors: Ms TOLEDO, Tania (GFZ-Potsdam); Dr GAUCHER, Emmanuel (KIT); Dr JOUSSET , Philippe (GFZ-Potsdam); Prof. MAURER, Hansruedi (ETH Zurich); Prof. KRAWCYK, Charlotte (TU Berlin); Prof. CALO, Marco (UNAM, Mexico); Prof. FIGUEROA, Angel (UMSNH, Mexico)

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Session Classification: Poster Session

Contribution ID: **121** Type: **Oral**

Seismicity induced during thermal and hydraulic stimulation of the well GRT1 at the Rittershoffen deep geothermal site, France

Wednesday, October 9, 2019 12:10 PM (15 minutes)

In a geothermal reservoir, seismicity may be induced due to pressure changes in the underground as a result of drilling, stimulation or circulation operations. The induced seismic events are therefore strongly linked to the fluid flow and the geological structures that make this fluid flow possible. The development of the deep geothermal site at Rittershoffen (Alsace, France) was monitored continuously by different seismic networks covering various operational periods from September 2012 to October 2014, including the drilling of the well doublet GRT1/GRT2, the thermal, hydraulic and chemical stimulations of GRT1 and circulation tests between the two wells. The seismicity induced by these operations has the potential to give valuable insight into the geomechanical behaviour of the reservoir and the geometry of the underground fracture network. Here, we focus on the comparison of the seismicity induced during the thermal and hydraulic stimulation of the well GRT1 to highlight similarities and differences of the seismic response of a reservoir to different types of stimulation operations.

To obtain a robust database for this analysis, we first apply a template matching code to the continuous waveforms recorded by the seismic networks. This technique is based on the calculation of the correlation coefficient between continuous and template waveforms. It outperforms conventional STA/LTA detectors in terms of sensitivity to events with low signal-to-noise ratio and picking consistency for events with waveforms similar to the templates. As template database, we use a manually picked seismic catalogue covering the different stimulation periods of GRT1 and the drilling period of GRT2 described in Maurer et al. (sub.). This starting catalogue contains over 1300 events, 146 recorded during thermal stimulation of GRT1, 990 during hydraulic stimulation of GRT1 and 184 during the drilling of GRT2.

The application of the template matching algorithm to the continuous waveforms recorded during the stimulation periods resulted in the detection of about 300 events for the thermal stimulation and nearly 3000 events for the hydraulic stimulation. Hence, the event database was doubled for the thermal and tripled for the hydraulic stimulation compared to the original template database. All events are then relocated with HypoDD, using the travel time differences between the events to gain precise relative locations. This makes it possible to image the seismically active structures during the stimulation operations. The comparison of the spatial distribution of the seismicity can answer questions like whether the same structures in the same reservoir area were activated, how large the seismically active reservoir volumes during each stimulation were and if they can be approximated by the same fault plane. Additionally, the relative magnitudes for the newly detected events are calculated from the magnitudes of the templates to further characterize the seismicity during the two stimulation operations.

References

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Session Classification: Session 2: Exploration of Geothermal Reservoirs

Track Classification: Topic 2: Exploration of Geothermal Reservoirs

Contribution ID: **122** Type: **Poster**

Tintina fault core analysis for potential geothermal development

Wednesday, October 9, 2019 5:40 PM (20 minutes)

Drill core from the Tintina Trench was extracted near Ross River region, Yukon; Canada. The Tintina Trench is a late Miocene graben that was formed along the antecedent early Tertiary Tintina fault. The graben is a natural catchment for alluvial and glacial sediment. In 2018, the Yukon Geological Survey drilled a 500 m geothermal gradient well in the area. Core from the well was logged, and a variety of analyses were conducted to evaluate the subsurface in the study area. The following analyses were completed: qualitative XRD analysis, thin section analysis, and porosity measurements. In combination, the results collected enable a robust evaluation of target areas for potential geothermal development in the future. 73 samples were selected for XRD analysis. The results showed that detrital quartz, k-feldspar, and clays (kaolinite and smectite) are the most prominent minerals throughout the entire well core. In addition, 13 samples were prepared as thin sections and analyzed to examine the grain porosity characteristics. The most prevalent porosity characteristic observed was fracture porosity and similar highly interconnected hairline features striking throughout the samples, often parallel to bedding. Some of the fractures observed may have been from thin section preparation or the core log process. The grains tended to be angular to sub-angular, which is typical for detrital grains. The clays occupy the space between larger grains, generally quartz or k-feldspar. Porosity measurements determined the total grain volume in the core at depth. It was determined that the percent pore volume out of the entire bulk volume ranged in the samples from 2.6% to 24.5%. The highest observed porosity was at 366 m, reaching 24.5% porosity of the total bulk volume. The requested standard deviation for the pycnometry measurements was 0.05 with an average of 4-6 runs to achieve 3 within the requested standard deviation. The well has an average temperature gradient of 31 ⁰C/km. This gradient suggests marginal potential for electricity production and good potential for direct use of the heat.

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Session Classification: Poster Session

Contribution ID: **124** Type: **Oral**

Volcano-tectonic model guide for the geothermal exploration of the Los Humeros Volcanic Complex, Mexico

The Los Humeros Volcanic Complex (LHVC) is an important geothermal target in Mexico, hosting a geothermal field currently producing ca. 95 MW of electric power. The geothermal field is located in a Quaternary collapse caldera where resurgence occurs since ca. 50 ka. The analysis of the LHVC structure and its influence on secondary permeability and occurrence of thermal anomalies is important to get insights into the interplay between the volcano-tectonic setting and the characteristics of the geothermal resources in the area. In this study, we present a structural and morphostructural analysis of the caldera complex and geothermal field, integrated with thermal remote sensing and subsurface data, like well logs, seismological data and magnetotelluric imaging. The structural analysis suggests that volcanotectonic faulting and fluids-driven hydrofractures generated under a local radial stress field induced by the LHVC magmatic and hydrothermal systems. The volcanotectonic stress field and resurgence faults influence the distribution of secondary permeability, with the expected geometry of faults and fractures producing geothermal fluids varying with location and depth. The results of this study constitute a volcano-tectonic model guide useful to understand the structure of the Los Humeros geothermal field and support the exploration of deeper Super-Hot Geothermal Systems (SHGSs) and engineering of Enhanced Geothermal Systems (EGSs) in the LHVC and other active resurgent calderas.
The research leading to these results has received funding from the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550. The research also received support by Comisión Federal de Electricidad (CFE) of Mexico.

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Session Classification: Keynote 1: Volcano-tectonic model guide for the geothermal exploration of the Los Humeros Volcanic Complex, Mexico

Contribution ID: **125** Type: **Poster**

Simulation of temperature and pressure driven fracture deformation

Wednesday, October 9, 2019 3:30 PM (20 minutes)

Preexisting fractures may deform under the influence of changes in temperature or pressure during development and operation of a geothermal reservoir. Such deformation events are both of consequence in themselves, as they may be felt as earthquakes at the surface, and by virtue of the impact they may have on properties of the reservoir, such as the permeability. Using a discrete fracture matrix model explicitly accounting for processes and variables both in the fractures and in the matrix, we simulate the three-dimensional multiphysics problems of thermomechanical and hydromechanical fracture stimulation with a friction law at the fractures. The model is implemented in the open-source simulation tool PorePy, and its explicit representation of the fractures allows for high accuracy and spatial resolution of the fracture dynamics, including normal (fracture opening) and tangential (slip events) deformation.

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Session Classification: Poster Session

Contribution ID: **126** Type: **Poster**

Stabilization of Forced Heat Convection: Applications to Enhanced Geothermal Systems (EGS)

Wednesday, October 9, 2019 5:40 PM (20 minutes)

The natural permeability of geothermal reservoirs is low and needs to be enhanced to ensure an efficient use and economic viability. Next to chemical enhancement, the main technique used for that purpose is hydraulic fracturing. Here, hydraulic fracturing is introduced in a thermo-poroelastic framework. The main addition to this framework is a fracturing model, phrased in terms of Terzaghi's effective stress that governs the evolution of size and aperture of the fractures in all directions of space. At any geometrical point, a fracture-induced anisotropic permeability tensor is calculated: Next to the injection pressure and thermal shrinking, the directional properties of this tensor are strongly influenced by geological stresses. The fully integrated framework is henceforth used in simulating thermal recovery from enhanced geothermal reservoirs.
Evidently, the credibility of the numerical simulations cannot be sufficiently trusted with large spurious wiggles in the temperature field and consequently in those of the effective stresses. This paper provides several approaches to stabilize convection of heat due to extreme injection conditions at early stages, sudden increase in permeability due to hydraulic fracturing, and near the production wells at late injection stages. Emphasis is paid to the subgrid scale/gradient subgrid scale method where the transient problem is placed into a stabilized advection–diffusion–reaction problem.

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Session Classification: Poster Session

Contribution ID: **127** Type: **Oral**

MulT_predict –A multicomponent geothermometer with integrated sensitivity analyses

Wednesday, October 9, 2019 10:40 AM (15 minutes)

Keywords: MulT_predict, multicomponent geothermometry, sensitivity analysis, reservoir temperature estimation

ABSTRACT
For a successful geothermal reservoir exploration, an in-situ temperature estimation is essential. Since geothermometric reservoir temperature estimations using conventional solute geothermometers often entail high uncertainties, a new computational approach is proposed. The goal was to obtain high-accuracy multicomponent reservoir temperature estimations by only using standard geochemical data without the need of sophisticated gas analysis. Therefore, the new numerical tool MulT_predict is introduced. MulT_predict is a multicomponent geothermometer code with integrated sensitivity analyses to back calculate on in-situ conditions. The script is based on MATLAB, which interacts with IPhreeqc. The tool was calibrated and validated against in-situ reservoir temperature measurements. Hence, reservoir conditions are numerically reconstructed by varying various sensitive parameters (e.g. pH value, steam loss, aluminum concentration etc.) to reduce the uncertainties of the reservoir temperature estimation. The new method led to statistically robust and precise reservoir temperature estimations.
At first, a set of reservoir specific minerals is selected as the base of the multicomponent geothermometry. While calculating the saturations indices of the mineral phases over a defined temperature range, sensitive parameters are subsequently varied. As pH, aluminum concentration and redox potential are prone to interferences (e.g. measurement errors, secondary processes, etc.) as well as possible phase segregation due to boiling during the fluid ascent, reservoir conditions are numerically reconstructed to reduce the temperature estimation uncertainties. The variation of sensitive parameters minimizes the spread between the calculated temperature estimations of each selected mineral phase. The minimal range within the temperature estimations reflects the most plausible reservoir conditions. In this case, the geochemical equilibrium between mineral phases and the reservoir rock is reconstructed. The reservoir temperature estimations fitting the in-situ temperature measurements with a maximal uncertainty of 2.6% and an overall temperature accuracy of 0.5% while the average temperature spread is about 4.2% of the measured absolute reservoir temperature. Furthermore, the back calculated sensitive parameters match the results corrected via WATCH 2.4 (Bjarnason 2010). Especially steam loss and pH value now can be reconstructed with just a standard water analysis without the requirement for an additional gas analysis other approaches typically need. In addition, no supplementary software is needed to back calculate nor pH value nor steam loss. The outcome of the statistical evaluation is given as a box plot combining the temperature estimations of each mineral phase used in the multicomponent geothermometer. In conclusion, the developed method is a promising tool for the high precision estimation of reservoir temperatures. Since MulT_predict does not rely on a sophisticated gas analysis and geochemical data, which is often not available, the tool facilitates the usability yet calculating precise reservoir temperature estimations.

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Presenter: YSTROEM, Lars H

Session Classification: Session 1: Assessment of Geothermal Resources

Contribution ID: **128** Type: **Oral**

An efficient discrete fracture model for variably saturated flow in fractured porous media

Thursday, October 10, 2019 4:30 PM (15 minutes)

Flow in fractured porous media is encountered in a broad spectrum of industrial, environmental, and engineering applications. This covers, for example, geothermal systems and hydraulic fracturing, carbon dioxide sequestration, management of karstic aquifers, and oil production. For those and other applications, modeling has become an indispensable tool for several purposes, such as understanding physical processes, developing monitoring systems, and providing predictions. Most of the existing studies in the literature deal with saturated porous media while flow in variably saturated fractured porous media is marginally investigated and the related processes are not fully understood.

The flow in variably saturated porous media is often modeled using Richards'equation (RE) that incorporates nonlinear constitutive relations between pressure head, hydraulic conductivity, and water content. From a numerical point of view, accurate numerical solution of the RE remains a challenge, especially in the presence of formation fractures and sharp wetting fronts. Fractures typically introduce high complex geometry that requires dense meshes with fine elements to capture the high contrast in properties between the fractures and the adjacent matrix zones.

The Discrete Fracture Network (DFN) approach, in which the fractures are embedded as lower-dimensional elements, (n-1)-D, in higher-dimensional physical domain, n-D, is widely used to deal with the flow in saturated fractured porous media. To the best of our knowledge, the DFN approach has not been implemented for flow in unsaturated porous media, which is currently modeled using the traditional dual-porosity and equivalent porous media approaches. Thus the first objective of this work is to develop a new efficient model for variably saturated flow in fractured porous media based on the DFN approach.

In this model, we use Richard's equation for both the matrix and fractures. This can be encountered in the case of sediment-filled fractures or thin high permeable layers in porous media. To address challenges related to space discretization, the mixed hybrid finite element method with a new mass lumping technique is implemented to avoid spurious oscillations. Time integration is performed using an advanced solver based on a higher-order backward differentiation with adaptivity in time stepping. The proposed solver has the privilege of selecting time step sizes within the fractures different from those in the matrix. The newly developed DFN model is verified against an industrial FE-based simulator and showed significant superiority in terms of efficiency and robustness.

Keywords: Discrete Fracture Network; Variably Saturated Flow; Mixed Hybrid Finite Element method; Mass Lumping

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Session Classification: Session 8: Computing and Data Management, Machine Learning

Track Classification: Topic 8: Computing and Data Management, Machine Learning

Contribution ID: **129** Type: **Oral**

REGIONAL STRUCTURES IN THE LOS HUMEROS GEOTHERMAL SYSTEM: INSIGHTS FOR SUPER-HOT GEOTHERMAL FLUIDS LOCATION

Wednesday, October 9, 2019 9:55 AM (15 minutes)

The Los Humeros geothermal field is presently located inside a wide, almost circular caldera structure, collapsed during late Pliocene-Holocene (≤ 2.8 Ma). Geothermal exploration is targeted to exploitation of hot- to super-hot geothermal fluids, in order to improve the production of electricity.

With these aims, in order to investigate the deep part of the present active Los Humeros geothermal system, we have integrated information from the exhumed, fossil, Las Minas area (considered analogue of the deep part of the Los Humeros geothermal field) with gravity data and satellite images and digital topography. These latter finalized to the study of the monogenetic volcanoes distribution and other volcanic structures related to tectonics.

The studies from Las Minas area suggest that hot to super-hot fluids are mostly trapped at the intersection between NNW-SSE and NE-SW striking fault-damage zones affecting the Jurassic-Cretaceous calcareous volcanic basement. Such fluids, as inferred by fluid inclusions studies in quartz-hydrothermal minerals, display a clear magmatic imprinting, being strictly related to the cooling process of magma patches.

The analysis of gravity data indicates two main regional trends, along which clear and sharp changes of densities are recorded. These trends are NNW-SSE and NE-SW oriented, respectively. Some of them are delimiting the Los Humeros volcanic area, thus suggesting that the volcano location was controlled by pre-existing regional structures.

The satellite image analysis and digital topography, focused on the alignment of monogenic volcanoes, again indicated the NNW-SSE and NE-SW regional structures as the most significant for channeling magmatic fluids from depth, highlighting the control of crustal fractures on volcanism.

With this background, we suggest that the investigation of hot to super-hot geothermal fluids should be addressed to the intersection between the two fault regional systems, at depth compatible with the basement location.

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Session Classification: Session 1: Assessment of Geothermal Resources

Track Classification: Topic 1: Assessment of Geothermal Resources

Contribution ID: **130** Type: **Poster**

GeoLaB - Geothermal laboratory in the crystalline basement

Wednesday, October 9, 2019 4:10 PM (20 minutes)

Geothermal energy is one of the worldwide most important renewable and base load capable energy sources. It will play a major role in the German energy transition process. In Central Europe, the largest geothermal potential resides in the crystalline basement rock with important hotspots in tectonically stressed areas. To meet the necessary energy demand geothermal involves the production of relatively high-flow rates (>10 L/s) from fractured rock. To harvest the geothermal potential in an environmentally sound and economic way, new scientifically founded strategies and technologies are urgently needed.
The proposed new underground research laboratory GeoLaB (Geothermal Laboratory in the Crystalline Basement) addresses fundamental challenges of reservoir technology. The specific objectives of GeoLaB are 1) efficient and safe management of fractured reservoirs, 2) cutting-edge multidisciplinary and multi process research with visualization concepts, 3) developing new environmentally benign strategies for subsurface installations, and 4) transparent interaction with the public and decision makers. The planned experiments will significantly expand our fundamental understanding of processes associated with operational conditions in reservoir structures.

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Presenter: Prof. KOHL, Thomas (KIT)

Session Classification: Poster Session

Contribution ID: **131** Type: **Poster**

CDGP, a repository for geothermal data in Alsace

Wednesday, October 9, 2019 1:10 PM (20 minutes)

The Data Centre for deep geothermal energy (CDGP, https://cdgp.u-strasbg.fr) was launched in 2016 by the LabEx G-EAU-THERMIE PROFONDE (http://labex-geothermie.unistra.fr) to preserve, archive and distribute data acquired on geothermal sites in Alsace. More than 30 years of data were collected on the Soultz-sous-Forêts research site, providing an inestimable legacy wealth.

CDGP is part of the EPOS european platform EPOS-IP Anthropogenic Hazards (TCS-AH, https://tcs.ah-epos.eu/). It provides Episodes that are a set of comprehensive data of a geophysical (e.g. deformation) process, induced or triggered by technological activity, which under certain circumstances can become hazardous for people, infrastructure and environment. At CDGP, datasets related to stimulation episodes of 2004 and 2005 have been recently added. Episodes from 1993, 2000 and 2003 are also available, and datasets related to 2010 circulation will be available soon. The EPOS TCS-AH brings together a broad community interested in Anthropogenic Hazards related to induced seismicity. It is designed as a functional e-research infrastructure that provides access to a large set of relevant data and allows free experimentations in a virtual laboratory, promoting interdisciplinary collaborations between stakeholders (the scientific community, industrial partners and society).

From the very start of the repository, we decided to follow international requirements for data management, and used FAIR recommendations to distribute Findable, Accessible, Interoperable and Reusable data.

Legacy or more recent, academic or industrial, the data consist mainly of seismological and hydraulic data acquired during stimulation and circulation phases. They are collected from data providers and curated, converted into standardized (community-shared) formats and documented with metadata. Data are identified with a DOI, findable via a local geo-catalogue; metadata are also harvested by the EPOS TCS-AH platform.

As industrial partners provide some data, we set an AAAI (authentication, authorization, and accounting infrastructure); data are distributed in respect of (1) affiliation of the user (academic, industrial, etc.) and (2) distribution rules set by data providers. Interoperability is promoted with use of open or community-shared data formats: SEED, csv, pdf, etc. Open data are granted with a Creative Commons license (CC-BY or CC-BY-NC) to allow their broad use.

Despite the recent setup of CDGP, some data are vintage: we had to deal with obsolete tapes and formats to convert and archive on modern electronic supports. Identification of owners is sometimes difficult, but necessary to obtain the distribution rules. A Data Management Plan (DMP) defines all tasks and rules used to perform these tasks. We are on the track to prepare the CoreTrustSeal certification.

Examples of the use of the distributed data will be illustrated. One of them is the reinvestigation of the micro-seismicity development during the stimulation of 1993 that shows that in areas where aseismic slip on pre-existing faults has been evidenced, only small rupture sizes are observed whereas in part of the reservoir where seismicity is related to the creation of new fractures, a wider distribution and larger rupture sizes are promoted. Implications exist for detecting the transition between events related to pre-existing faults and the onset of fresh fractures.

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Session Classification: Poster Session

Contribution ID: **132** Type: **Oral**

Predictive Mechanical model for fracture stimulation in an enhanced geothermal system (EGS) context

Wednesday, October 9, 2019 5:00 PM (15 minutes)

Predictive Mechanical model for fracture stimulation in an enhanced geothermal system (EGS) context

Keywords: GEMex, Enhanced Geothermal System (EGS), scanline survey, Discrete fracture model (DFM), Finite Element Method (FEM)

ABSTRACT

The development of an EGS is one of the goals of the GEMex project, an international collaboration of two consortia, one from Europe and one from Mexico. The research is based on exploration, characterization and assessment of two geothermal systems located in the Trans-Mexican volcanic belt, Los Humeros and Acoculco.
Los Humeros has been a producing field for several years, but Acoculco is yet to be developed. Thanks to surface manifestations of hydrothermal activities, the existence of a geothermal system is evident. However, two wells reached very high temperatures, but did not find any fluids. For that reason, the Acoculco Caldera is foreseen as EGS development site, hoping to connect existing wells to a productive zone.
In this study, we develop a workflow that aims at assessing the feasibility of this EGS. The approach aims at generating a realistic predictive mechanical model for fracture stimulation from the well borehole.
The strength of the method stands in the combination of reliable data obtained from field work and experimental measurements on mechanical properties of the target rocks, used together to populate a numerical model.

The workflow starts with the identification and description of the surface discontinuities using the scanline survey method. These surveys are interpolated and extrapolated using the multiple point statistics method to generate geological discrete fracture networks. The results of these simulations are then evaluated in a finite element method program using a flow model for fractured media. Finally, combining the fracture flow model and the mechanical properties measured in the rock physics laboratory, the fracture propagation is calculated.

The method offers a physically sound prediction of the reservoir flow characteristics as well as an accurate mechanical model of the fracture propagation and the pressure distribution for well borehole stimulation. Because the workflow is based on easily accessible data and thanks to its simplicity, this approach could be applied in most EGS case studies.

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Session Classification: Session 4: Resource Development

Track Classification: Topic 4: Resource Development

Contribution ID: **133** Type: **Oral**

Impact of a partly sealed fault on hydro-mechanical properties of a granite reservoir

Wednesday, October 9, 2019 5:15 PM (15 minutes)

The fluid flow in Enhanced Geothermal Systems (EGS) is dominated by hydraulically stimulated fractures and faults which are the key elements of their hydraulic performance and sustainability. At the fault scale, the flow performance is influenced by the aperture distribution which is strongly dependent on the fault roughness, the geological fault sealing, the relative shear displacement, and the amount of flow exchange between the matrix and the fault itself. On the mechanical side, stiffness and strength of partly sealed fault might alter or reinforced the mechanical behavior of the fault zone in particular with respect to new stimulations. In order to quantify the impact of chemical soft stimulation in EGS reservoir on the hydro-mechanical properties of a fault-rock system that includes fault-filling material, we conducted numerical flow through experiments of a granite reservoir hosting one single partly sealed fault of size 512x512~m^2. In order to mimic the chemical alteration of the fault-rock system we sequentially changed the distribution pattern of the fault-filling material by means of a hydro-poro-elastic coupled simulation. Navier-Stokes flow is solved in the 3-dimensional rough aperture and Darcy flow in the related poro-elastic matrix. By means of this model, an evaluation of the local channeling effect through the fault for various degrees of sealing was performed. Based on the obtained results, we derived a macroscopic change of the hydraulic-mechanical behavior of the fault-rock system, e.g. permeability change, fracture stiffness modulus.

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Session Classification: Session 4: Resource Development

Track Classification: Topic 4: Resource Development

Contribution ID: **134** Type: **Oral**

Reducing the efforts to access deep geo-resources by thermally assisting the drilling process

Wednesday, October 9, 2019 2:50 PM (15 minutes)

In order to meet the increasing worldwide energy demand in the next decades, access to deep geothermal, oil or gas reservoirs will be key in the future global energy supply. Construction of deep wells, especially for deep geothermal energy, require major costs, mainly related to the involved drilling operations. Indeed, drilling costs are found to increase exponentially with depth and, furthermore, they occur in an early, considerably high-risk phase of the project. Drilling of deep wells into hard rocks represents a major challenge for conventional rotary drilling systems, featuring high rates of drill bit wear with consequent bit replacement and high non-productive time (NPT), low rates of penetration (ROP) and poor process efficiency. Thus, advances are needed to decrease the overall costs of drilling and therefore improving the project economics, by enhancing the overall drilling performance, specifically in hard granite rocks, commonly found formations in deep geothermal projects.

We propose to combine a thermal assistance, e.g., by flame jets, to conventional rotary drilling methods. We term this method combined thermo-mechanical drilling (CTMD). In this manner, the hard rock material is weakened thermally, prior to the mechanical removal by conventional cutters. This concept is expected to increase the removal performance and thereby intensify the drilling process in hard rock materials, enhance the overall bit lifetime, thus reducing the cost of drilling. In this work, we show laboratory evidence that the CTMD can effectively enhance the drilling process in hard granite rock. Further, the CTMD technology is field-tested under relevant process conditions. We provide conclusions on its advantages, technical feasibility and integration potential of this technology into conventional drilling systems. Finally, we also compare the removal characteristics of this approach against conventional mechanical drilling methods to discuss on the performance improvements to drill deep wells in hard rocks.

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Session Classification: Session 3: Constructing Geothermal Wells

Track Classification: Topic 3: Constructing Geothermal Wells

Contribution ID: **135** Type: **Poster**

Field methodologies aimed at geomechanical and geophysical characterization of faults zones in geothermal areas

Wednesday, October 9, 2019 5:40 PM (20 minutes)

During March 2018 field works were conducted in the Acoculco and Las Minas areas for both geomechanical and geophysical surveys at the outcrop scale. In particular, were performed: classical ISRM scanlines, photo acquisition for no-contact geomechanical surveys, Electrical Resistivity Tomography, Ultrasonic Pulse Velocity measurements. Moreover, samples were collected for some sites.
Unito team reached the field sites previously selected thanks to Domenico Liotta and Walter Wheeler descriptions and suggestions.
During field trip, the attention was dedicated to find situations (outcrops) permitting to find explanation to the problem of the fluid paths. Field geologist suggested us some (a dozen) interesting outcrops but, already from preliminary descriptions, only a few of them suited the necessity of standard methodology for rock mass characterization. Main problems were: the dimension and continuity of the outcrops, the meaning respect to depth circuits, the practical accessibility at instruments in certain places. Anyway, some consideration can be done, especially about rock mass behaviour after faulting and related hydraulic conductivity. Interesting was to couple geomechanical surveys (both field measurements and no-contact photogrammetric elaboration) to geophysical lines (high resolution electrical topographies).
In the report of each studied outcrop, hydraulic conductivity was estimated. As a matter of fact, most depends on joint opening and infilling, parameter very difficult to determine with precision in surface and subjected to meaningful variation with depth. It is possible to give some general consideration and in particular:
• Limestone range between 10-3 and 10-5 m/s, depending to joint density (faulting);
• Andesite show a brittle behaviour and consequently higher values (10-3 m/s);
• Fault and the surroundings can reach also 10-2 m/s.
Only in one site was possible to study a well-developed discontinuity and the related damage zone: the Rinconda fault. In this was possible to directly measure discontinuities only on one side of the fault, but the other part was investigated by geoelecrical survey. Results are the following:
• there is an evident decrease in fracturation moving away from the fault core: from more that 20 j/m near the fault to less than 5 in the sounding rock mass;
• this passage is not progressive but there is core of about 5 m of the fault characterized with more than 10 j/m, than there is a slightly deformed zone (about 5 j/m) of 6-8 m followed by a more fractured one that pass again to a less jointed "sounding"rock mass;
• the same situation is highlighted by geoelectric that "see"the same order of changes;
• due to these differences, also hydraulic conductivity changes from very high in the core (about 10-2 m/s, the orange box in the picture) to a less permeable zone (green, 10-5) to an increase for a couple of m (blue again) to the permeability typical for intact rock mass (usually very low, 10-6 m/s).
From a geothermal point of view, this situation depicts a zone damaged by a meaningful fault of about 30-40 m in which the permeability is definitely higher (orders of magnitude) than to rest of the rock mass.
Strong emphasis we would like to give also to the very good agreement between physical and

geophysical results: geoelectric, even if qualitative, couple very well direct observation and ca be used when field observation are not possible.
Also where there are only indirect observation of subsoil fluids emission, like near the Acoculco wells, near surface geophysics is able to give information about the origin of gas and/o brine: in that case, gas emission alignment well fit the resistivity anomaly highlighted by electrical topographies. Interpretation seem to give the idea that fluids came thought a fault strong dipping towards SW going towards the pass the road came into the valley.
Field surveys were useful to understand the technical characteristic of the rock mass outcropping in the geothermal area or in similar geological context (Las Minas). Traditional and no-contact methodology produced date usually well-fitting each other and permitting to do estimation about mechanical and hydrogeological properties. Moreover, was possible to give information about dimension of fault and related damaged zone. Meaningful information aimed at identifying geological structures came from geoelectrical tomography's. By the way, field measurements confirm that the fluid circulation is leaded by fragile structures where permeability is orders of magnitude higher than intact rock masses.

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Session Classification: Poster Session

Contribution ID: **136** Type: **Poster**

Effect of temperature on physical properties of carbonatic rocks.

Wednesday, October 9, 2019 12:50 PM (20 minutes)

Significant increased of temperatures affect large crustal volumes of carbonatic rocks often related to high temperature settings (e.g volcanoes sedimentary basements, geothermal areas within thick carbonatic sequences or thick sedimentary sequences in contact with large scale plutons). Forecasting carbonatic rocks physical evolution under temperature gradients is of the utmost importance for many rock-mechanics fields, such as rock-engineering applications (deep drilling, geothermal energy and oil exploitation, nuclear waste disposal, CO2 storage) but also preservation and restoration of cultural heritages damaged by fire as well as for weakening of volcano basements and decarbonation processes during earthquake ruptures.

This study has two main objectives: the first one is the quantitative estimation of the influence of high temperatures on physical properties of texturally different carbonatic rocks and the second one to provide an unified and more comprehensive relationship between physical features and temperature.

For these purposes, carbonatic rock specimens, coming GEMEX sites and some italian analogue, were tested before and after thermal treatment, with cycles from 105℃ up to 600℃, measuring porosity, ultrasonic pulse velocity (UPV) and electrical resistivity (ER).

The thermal treatment induced an increase of porosity due to generation of new cracks or reopening of existing ones. At first sight, limestones (RLM samples) showed a marked increment in porosity compared to other samples for temperatures higher than 400℃. A plausible explanation of this behaviour is due to the fact that limestones undergo deeper textural changes, as being not exposed to heating in their formation history differently to marbles, decalcination and decarbonation processes are more pervasive and diffused between grains increasing the cracks damage.

The increase in porosity is mirrored by decrease of P- and S-wave velocity and apparent resistivity in saturated conditions.

The general degradation of physical parameters also influenced the dynamic mechanical characteristics of rock samples.

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Session Classification: Poster Session

Contribution ID: **137** Type: **Poster**

Magnetotelluric phase tensor analysis and its significance for tectonic interpretation: Case studies of the Los Humeros and Acoculco geothermal resources, Mexico

Wednesday, October 9, 2019 2:30 PM (20 minutes)

A joint geothermal project of a European and Mexican consortium began in late 2016 with the purpose to develop geothermal energy in the easternmost region of the Trans-Mexican Volcanic Belt. Two sites that belong to the Comisión Federal de Electricidad (CFE) have been investigated. For both systems the phase tensor analysis from magnetotelluric data and its outcome for structural interpretation have been investigated.

The Los Humeros geothermal reservoir is a superhot geothermal resource that is exploited with a high number of wells. On the other hand, an enhanced geothermal system (EGS) is proposed to be developed in the Acocolco geothermal prospect. In order to explore the geothermal resource and guarantee a future sustainable exploitation, an extensive international research programm was initiated, aimed at investigating the characteristics of both areas, superhot conditions for Los Humeros and the potential of EGS development for Acoculco. Besides seismological and gravimetric techniques, the magnetotelluric method displays the subsurface resistivity structure allowing a hint about the reservoir architecure.

While data acquisition and processing as well as the inversion and interpretation are provided by other studies,here we evaluate the phase tensor of the 122 MT measurements in and around the Los Humeros caldera and the 68 MT recordings in the vicinity of the two Acoculco wells. In combination with geoelectric strike direction and induction arrows, preferantial orientations and structures of the subsurface conductivity distribution will become visible.
After analysis and interpretation of the phase tensor, a correlation with structural geological data is conducted to investigate the characteristics of the detected tectonic features.

This abstract presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu.

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Presenter: Dr HELD, Sebastian

Session Classification: Poster Session

Contribution ID: **138** Type: **Oral**

Bedretto Deep Underground Laboratory for Geoenergies –a new interdisciplinary research facility

Wednesday, October 9, 2019 4:30 PM (15 minutes)

The Bedretto tunnel in Ticino, Southern Switzerland has been identified to provide ideal conditions for underground in-situ experiments on the meso-scale related to geo-energies. The tunnel is located in the Rotondo Granite and comes with 1'000m plus overburden rock mass, for this reason providing a setting that is similar to typical deep reservoirs.
The Bedretto tunnel is a 5km long side access, built during the excavation of the Furka base tunnel. At about 2km from the entrance in Val Bedretto, a 6 m wide and 100 m long niche has been excavated during tunnel construction, providing the ideal conditions for an underground laboratory. The tunnel has been retrofitted with a new access road, power supply, ventilation, IT-infrastructure and an external laboratory. Additionally, it is equipped with a background basic monitoring system along the tunnel.
We present an overview about a series of experiments planned for the next years in the context of EGS. Stimulation experiments will be conducted in dedicated boreholes with specially designed borehole completions that allows the direct access to the rock volume in individually accessible intervals.
The first project is focusing on the development of a reservoir of 100 m scale, which is a significant larger scale than other in-situ stimulation experiments conducted i.e., by Zang et al. 2017, Amann et al. 2018, Renner et al. 2019 and Kneafsey et al. 2019. The experiment will test and monitor the concept of multi-stage segmented stimulation in EGS creation. The reservoir will be developed through two injection boreholes at distances 200m to 300 m from the tunnel, i.e. in rock volume where both stresses as well as hydrology is undisturbed from the tunnel excavation. A multi-component monitoring network will ensure the observation of induced seismicity (-6 < Mw < 2), aseismic deformation and pressure as well as tilt and temperature. Challenges in network installation, including deep borehole installation, high pore pressures of more than 10MPa and sealing of boreholes using advanced grouting techniques, require the development of novel monitoring techniques which is here introduced.
A second project aims at Mitigating induced seismicity for successful geo-resources applications (MISS). Within this project we will conduct the first-ever program to perform controlled 50-100m scale fault stimulation experiments in basement rock at over 1'000m depth. We will investigate how earthquakes nucleate, propagate and arrest and find answers on the role of pre-stress conditions and geometrical/rheological complexities (i.e., barriers) on earthquake nucleation.

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Presenter: PLENKERS, Katrin

Session Classification: Session 4: Resource Development

Track Classification: Topic 4: Resource Development

Contribution ID: **139** Type: **Poster**

Cold reinjection in the Soultz-sous-Forêts reservoir during geothermal exploitation based on 3D hydrothermal modelling

Wednesday, October 9, 2019 5:40 PM (20 minutes)

As a part of the European project called MEET, the geothermal powerplant of Soultz-sous-Forêts (Bas-Rhin, France) is investigating the possibility of producing more energy with the same infrastructure. This research project aims to study the potential increase of electricity production by reinjecting the geothermal fluid at lower temperature. Indeed, during the operation of the powerplant, the geothermal fluid is currently reinjected at 70℃, and the MEET project aims to test its reinjection at 40℃. This temperature drop could generate several impacts on the reservoir such as induced seismicity, scaling, and cooling. Thus, a 3D hydrothermal study was achieved in order to evaluate the spreading of the thermal front during colder reinjection and its impact on production temperature.

In a first step, to achieve this goal, a 3D structural model of the Soultz geology was created in software PETREL integrating different geometric models that have been done in previous studies from 2D vintage seismic profiles and calibrated with well data. Our project contains 5 major lithostratigraphic horizons from tops of Jurassic to Paleozoic granite layers. In parallel, fractures and faults datasets were compiled by Sausse et al. (2010). They have been collected thanks to geological studies, well logs, vertical seismic profiles and induced micro-seismicity clouds and gathered into a 3D model. About 50 fractures in the granite have been considered during this structural compilation.

In a second step, this first geometrical model was simplified in order to be able to run hydrothermal simulation. Previous studies demonstrated that the convection within the fracture system seems to affect the Paleozoic granite but also the Triassic sediments. Due to well completion, only Buntsandstein and granite tops were considered for circulation simulation. Each of 50 faults initially present in the model were assessed in term of permeability from various indicator such as: flow anomalies, temperature anomalies, mud losses and tracer tests results. The fracture extension was also considered as an input parameter according to the degree of hydrothermal alteration around the fracture network in the well or to the VSP and micro-seismicity data. Finally, the most elaborated 3D hydrothermal model contains five main fractures which were subject to thermal cooling.

In a third step, once the structural model is defined, the hydrothermal tests can be performed with the software FEFLOW: a finite-element simulation software able to model groundwater flow, mass and heat transfer in porous and fracture media, in 2D, tabular or fully unstructured 3D mesh. A3D hydrothermal model has been built based on the structural model. It has been calibrated with power plant operation data and interpretations of hydraulic tests, tracer tests, logging and core sample measurement. This model allowed estimating the impact over time of power plant operation with a colder reinjection in the fractured reservoir of Soultz-sous-Forêts. A sensibility study on main reservoir hydraulic and temperature parameters have been realized to better understand their influence.

Finally, the 3D model will be presented as well as the preliminary results of the hydrothermal simulation related to a colder reinjection in the deep fractured granite reservoir.

Reference:

Sausse J., Dezayes C., Dorbath L., Genter A., Place J., 2010. 3D model of fracture zones at Soultz-sous-Forêts based on geological data, image logs, induced microseismicity and vertical seismic profiles. C. R. Geoscience 342, 531-545, https://doi.org/10.1016/j.crte.2010.01.011.

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Session Classification: Poster Session

Contribution ID: **140** Type: **Poster**

Evolution of hydro-mechanical properties during shearing in an EGS reservoir using a DFN model

Wednesday, October 9, 2019 3:10 PM (20 minutes)

In geothermal systems such as Soultz-sous-Forets, the hydraulic stimulation will ensure the efficient hydraulic exchange between injection and production wells by improving hydraulic conductivity of the fracture network through shear of pre-existing fractures. Shear motion creates permanent changes in hydraulic conductivity because of dilation angle of asperities existed on both sides of fracture planes which in most cases do not match each other after stimulation and create a conduit of open space between. This operation is normally accompanied with microseismicity and is monitored by deploying surface and down-hole seismic receivers.
4-D P-wave tomography derived from seismic monitoring during hydraulic stimulation of well GPK2 of Soultz-sous-Forets, an unexpected occurrence in the P-wave velocity variation. In two steps of stimulation, when the injection flow rate was increased, the P-wave velocity in the stimulated area increased as well (Calo et al., 2011). This is vice versa with what experienced in the laboratory by lockner et al., (1974) and Rummel (1991), which may be caused by non-linear evolution of hydro-mechanical coupling of discontinuities as explained by Bandis et al, (1983).
Hence, the aim of current project is to numerically model the non linearity for the elastic response of fractures and to investigate the role of dilatancy associated with shear motions along fractures once they reach instability. 3DEC numerical modeling tools developed by Itasca Consulting Group is used to fulfill the aim of project, considering that dilatancy in 3DEC develops only if shear slip occurs. So far, to pace on abovementioned track, first a numerical model of stochastic discrete fracture network (DFN) on the basis of wellbore scale fracture network description (Massart et al., 2010) is created and after that its effects on mechanical behavior of a 100x100x100 m3 block is investigated.

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Session Classification: Poster Session

Contribution ID: **141** Type: **Poster**

Performance Evaluation and Operation Sustainability of Deep Borehole Heat Exchanger Coupled with Geothermal Heat Pump System

Wednesday, October 9, 2019 4:30 PM (20 minutes)

To achieve a low-carbon and sustainable future, the utilization of geothermal energy gains more attention all around the world, due to its sustainability, continuity and low carbon emissions. Avoiding the disequilibrium of ground temperature and large area requirement from application of traditional borehole heat exchanger (BHE, around 150 m), deep borehole heat exchanger (DBHE, down to 2500 m), a state-of-the-art and feasible apparatus, could extract deep geothermal energy efficiently.

In this paper, a Finite Volume Method (FVM) based numerical model was constructed to simulate the heat transport process in multilayers of rock & soil. The model was developed by considering the ground temperature gradient in the axial direction and multilayer thermal properties of rock and soil.The model has been validated by the experimental data in a demonstration project.The heat extracting performance of DBHE under different types of run-stop ratio (including different working conditions for several building characteristics) are evaluated. In the intermittent operation for 10 years, the decreasing proportions of the outlet temperature under four different operation modes with the run-stop ratio (i.e. the ratio of the running time to the stopping time in a day) of 8:16, 12:12, 16:8 and 24:0, were no more than 3.57%. The rock temperature profiles in the heating mode of both commercial and residential buildings were presented and the annual decreasing proportions were less than 4.0%.

Under the continuous operation of 10 years, the outlet temperature of the DBHE gradually decreased with a decreasing proportion of less than 3%. The temperature variation of rock and soil surrounding the DBHE under the continuous operation of 10 years decreased with the increase of the distance away from the borehole. For 1 year's intermittent operation under different run-stop ratios, the outlet temperature of the DBHE decreased with the augment of the daily running time. The total heat extraction increased with grow of the daily running time. For 10 years'intermittent operation under two typical operation modes (commercial heating and residential heating), the decrease rates of the outlet fluid temperature were not more than 2.92% and 3.57% yearly, respectively. For 10 years'intermittent operation for the two typical operation modes, the annual decreasing proportions of the temperature of rock and soil at the reference points were less than 4%. After 10 years'operation, the decrease of the temperature of the rock and soil will be no more than 10%.

The findings obtained from this study could be used as a reference for sustainability research of DBHEs under different working conditions and operation modes. The study will also provide a reference for the application of DBHE coupled heat pump systems.

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Session Classification: Poster Session

Contribution ID: **142** Type: **Oral**

An Integrated Approach in 3D/4D Modelling in Geothermal Development

Wednesday, October 9, 2019 10:25 AM (15 minutes)

Through all stages of development, a geothermal project is exposed to a range of challenges. These manifest in resource existence, size, suitability, sustainability and utilization challenges. As well as being highly susceptive to market, financing and commercial risks. The most important element used to overcome the challenges and in de risking of geothermal well targets or assessing geothermal resource capacity is the use of a conceptual model with the available information.

Stages of a geothermal development are divided into exploration, feasibility, development and operations. The conceptual model changes throughout these stages as more data, understanding and management needs change. During exploration a geothermal conceptual model will often consist of a geological, structural, geochemical, geophysical and most importantly a thermodynamic component derived from geoscientific data. Without detailed subsurface data, surface geochemical and resistivity often indicate temperature anomalies within the subsurface while structure and geological setting gives good indication of permeable and non permeable zones for reservoir delineation and well targeting. During the feasibility and development stages time dependent data such as temperature and chemistry will be incorporated into the conceptual model that forms a base for the numeric model, used for key decision such as well targeting, output forecasts and communication with local community and financiers.

Types of data collected during the first three stages of development vary slightly between each project. Once a geothermal project moves into the operational phase the behaviour of well performance as well as reservoir understanding, dictates the type of data collected and incorporated into the model. This in many cases includes time dependent data such as tracer testing, well flow rates and chemistry.

It is well known integrated software and workflows enables geoscientists, engineers and managers to collaborate for greater efficiency, productivity and understanding. Combining the right technology, data, knowledge, systems and people will lead to measurable gains and productivity. New technologies and software solutions are tackling this challenge in solving needs for integrated workflows. The use of Leapfrog Geothermal software has been instrumental in moving the conceptual model into a 3D and 4D space. While associated products are changing the way projects operate. We will look at the use of modelling in a geothermal context and look at global case studies where this solution is providing a platform for all disciplines to communicate, collaborate and form the basis for key decisions.

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Session Classification: Session 1: Assessment of Geothermal Resources

Track Classification: Topic 1: Assessment of Geothermal Resources

Contribution ID: **143** Type: **Oral**

The Development of a Coupled Wellbore-Reservoir Simulator for Geothermal Application

Thursday, October 10, 2019 4:00 PM (15 minutes)

Boreholes under dynamic conditions are a highly non-linear and complexly coupled thermo-hydraulic system. Multiple parameters, for instance, temperature, pressure, specific heat, enthalpy, viscosity, flow regime, heat transfer, degassing, steam quality and salinity are inter connected. Production and injection often entail several engineering challenges and operational problems, within the boreholes but also up and down stream (reservoir - power plant - reservoir), which can be very diverse in their character. Finding solutions or working on process optimization prerequisite a profound understanding and a reliable numerical tool to quantify the processes. In this context, we developed a wellbore simulator implicitly solving transient fully-coupled non-isothermal two-phase pipe flow. Since the hydraulic and thermal connection to the reservoir is a crucial and critical point at the same time, we overcome the "reservoir-mimicking"boundaries (e.g. inflow performance relationships, productivity index, etc.) by integrating a real reservoir. Since the development of the tool is an ongoing process in this work we present the current state of the tool and it's most important capabilities, such as non-isothermal compressible two-phase pipe flow and the integration into a real reservoir. Future development efforts will concentrate mainly on the coupling to an appropriate module for the quantification of the aqueous chemistry and reactive multicomponent transport.

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Session Classification: Session 8: Computing and Data Management, Machine Learning

Track Classification: Topic 8: Computing and Data Management, Machine Learning

Contribution ID: **144** Type: **Oral**

Life-Cycle Environmental Impacts of Individual and District Geothermal Heating and Cooling in Geneva

Thursday, October 10, 2019 2:45 PM (15 minutes)

In 2017, the energy delivered for heating purposes of buildings in the State of Geneva in Switzerland came from oil- and gas-fired boilers, which led to negative impacts on air pollution and global warming. The 2035 target of the State of Geneva is therefore to reduce the annual heat consumption to 29 GJ/capita, from which 34% should come from renewable energy or waste heat recovery. The State has identified geothermal energy as one of the most prominent sources of renewable energy. Since 2014, GEothermie 2020 program responds to this finding by carrying out projects to characterize Geneva's subsurface and to develop new geothermal projects. Exploration wells between 700 m and 1500 m are planned and being implemented. These projects are organized together with the district heating expansion program. As GEothermie 2020 program has environmental goals at its core, the geothermal developments are accompanied by Life Cycle Assessment (LCA) for evaluating the environmental sustainability.

Concerning geothermal heating and cooling applications, the available state-of-the-art LCA studies were systematically reviewed. Existing studies mostly cover ground-source heat pumps (GSHP), whereas the research on groundwater extraction from medium depth is still very scarce, despite the widespread deployment of such systems in Europe. The environmental impacts of GSHP highly depend on the energetic performance of the heat pump and the electricity mix of the country in question. As a result, the impacts of GSHP are not necessarily lower as compared to those of oil boilers. In contrast, the impacts of groundwater extraction systems are reported in the literature to be lower than those of oil boilers. More LCA results are yet to be obtained to conclude this finding.

Two LCA studies were carried out for a residential building and an office building in Geneva, benefiting from a shallow aquifer at a depth of 10 m and 30 m. The results of LCA with a lifetime of 30 years show that the operation phase contributes the most towards the environmental impacts. Geothermal energy from a shallow aquifer in Geneva reduces, among others, the global warming potential and air pollution (PM10) by 95% and 63% respectively, as compared to an individual oil boiler. It reduces the consumption of fossil fuel by over 95%. However, the impact on water depletion is higher on average by 45 times, owing to the consumption of electricity produced by Swiss hydropower. The use of heat pumps, heat exchangers, and piping leads to high depletion of abiotic resources.

LCA studies are also carried out to evaluate the environmental performance of geothermal energy applications in the context of district heating in Geneva. Concorde and Satigny projects are two of the GEothermie 2020's projects in the development phase. Concorde project aims to incorporate geothermal energy from the aquifer at a depth of 60 m into the district heating that supplies heat to eight buildings. The successfully drilled Geo-01well in Satigny (744 m) could be valorized to supply a district with heating and cooling. An LCA study is performed on a hypothetical installation based on the known parameters of this well.

Sensitivity analyses are performed to identify the parameters that influence the impacts the most. The results of Concorde's and Satigny's LCA study are to be compared with the impacts of conventional oil boilers and the impacts of previously analyzed individual geothermal energy systems. Recommendations of environmentally optimized configurations are to be constructed in order to support the implementation of GEothermie 2020 goals.

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Session Classification: Session 7: Sustainability, Environment and Regulatory Framework

Track Classification: Topic 7: Sustainability, Environment and Regulatory Framework

Contribution ID: **145** Type: **Oral**

Thermo-economic design of hybrid borehole thermal energy storage systems in district heating and cooling grids

Thursday, October 10, 2019 9:55 AM (15 minutes)

In Germany, heating accounts for approximately two thirds of the end energy consumption in private households. It is estimated that by about 2060 the amount of energy used worldwide in cooling will overtake that used in heating. Therefore, there is a need to design efficient energy systems to supply heating and cooling loads simultaneously.

A cooling cycle cools a heat source by dissipating its heat to the environment. The rejected heat can be stored in a heat storage medium for heating purposes. The utilization of Borehole Thermal Energy Storage (BTES) systems as efficient heat sinks as well as storage media in district heating and cooling (DHC) grids has gained a lot of attention during the previous years.

However, there are still challenges that need to be resolved to pave the way for the efficient integration of such systems into DHC networks. The most important ones include high investment costs and inefficient operation when they are not properly designed. The usage of hybrid BTES systems is a useful way of alleviating these issues. A hybrid system includes supplementary heating and cooling devices, like gas boilers and cooling towers, to cover the peak demands and to regulate the induced seasonal thermal imbalance in the ground. Consequently, proper design and sizing of hybrid grids is of great importance and needs to be conducted considering both technical and economic aspects.

Exergy defines an energy system's potential to interact with its environment. As BTES systems are in seasonal interaction with ground, the exergy analysis method can be utilized as a tool for their technical assessment. By utilizing the exergoeconomic analysis method, which combines both exergy and economic principles, important information can be derived for the design of hybrid BTES systems in DHC grids.

After selecting the DHC system on campus Lichtwiese, TU Darmstadt, as a case study, different scenarios of hybrid BTES systems are proposed based on internationally accepted design recommendations. Thereafter, the conceptual models are virtualized and parametrized in TRNSYS 18. To select the optimal configuration, levelized cost of exergy product and total average exergetic efficiency are chosen as economic and technical criteria respectively. After developing a MATLAB code, the simulated TRNSYS models are coupled with MATLAB to perform multi-objective optimization of the selected objectives using evolutionary algorithms. Optimization results of different scenarios are compared with each other and the best design scenario for the case study is selected. Finally, a parametric study of the selected scenario is done to evaluate further improvement potentials.

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Session Classification: Session 5: Energy Conversion Systems

Track Classification: Topic 5: Energy Conversion Systems

Contribution ID: **146** Type: **Poster**

The Los Humeros Superhot Geothermal Resource in Mexico: Results from an Extensive Resistivity Survey

Wednesday, October 9, 2019 5:40 PM (20 minutes)

GEMex, a joint geothermal project of a European and Mexican consortium, began in late 2016 with the purpose to develop geothermal energy in the easternmost region of the Trans-Mexican Volcanic Belt. Los Humeros superhot geothermal area, commissioned to the Comisión Federal de Electricidad (CFE), was chosen as a test site for a superhot geothermal system. Extensive geological, geochemical, and geophysical studies were carried out to gain a better knowledge of the subsurface physical conditions.

The resistivity survey was planned using results from previous work that had been carried out in the area, i.e., an existing resistivity model and geological maps. The resistivity campaign consisted of 122 co-located magnetotelluric (MT) and transient electromagnetic (TEM) measurements made in 2017 and 2018 through a joint effort by the European and Mexican partners. Geoelectrical strike analysis of the MT data was carried out and the result are in agreement with the main geological features of the area, adding to the tectonic information at depth in Los Humeros.

The co-located TEM and MT soundings were jointly inverted in one-dimension, where the TEM data were used to correct the MT data for static shift. Along with the results from the one-dimension inversion we present preliminary results of a 3D inversion performed on the full impedance tensor of the MT data corrected for static shifts, using different initial models. Two inversion codes were applied for comparison, the WSINV3DMT code was run in Europe and the ModEM code in Mexico.

The resistivity model has been compared with the main geological structures in the area revealing the location of a geothermal significance. Interpretation with other geoscientific results, such as gravity, passive and active seismics and geology, is ongoing within the GEMex project.

This abstract presents results of the GEMex Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 727550, and by the Mexican Energy Sustainability Fund CONACYT-SENER, Project 2015-04-268074. More information can be found on the GEMex Website: http://www.gemex-h2020.eu

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Session Classification: Poster Session

Contribution ID: **147** Type: **Poster**

Uncertainty Quantification for Basin-Scale Heat Flow Models with a Physics-Based Machine Learning Approach

Wednesday, October 9, 2019 5:30 PM (20 minutes)

In order to determine suitable locations for geothermal exploration, reliable predictions of the earth's subsurface temperature field are essential. For these predictions, it is necessary to consider the uncertainties of the involved parameters. However, with the current state-of-the-art simulations standard uncertainty quantification methods, such as Markov Chain Monte Carlo are computationally intractable for basin-scale models at high resolution. We thus require numerical methods that considerably accelerate the forward simulation to enable the use of uncertainty quantification approaches that can easily require up to a million forward simulations.

For this purpose, we introduce the reduced basis method, a physics-based machine learning approach. Our previous studies show that we obtain speed-ups of four to six orders of magnitude in comparison to standard finite element simulations.

One main advantage of the reduced basis method in contrast to other surrogate models is that we obtain temperature values at every point in the model and not only at the observation points. Consequently, we can generate uncertainty maps of the temperatures at the target depth of the geothermal wells for the entire extent of the basin.

We use the Brandenburg (Germany) model to illustrate the application and benefits of the reduced basis method for large-scale geological models. The numerical simulations are realized within the DwarfElephant package, an open-source high-performance application based on the Multiphysics Object Oriented Simulation Environment (MOOSE) developed by the Idaho National Laboratory. The DwarfElephant package offers a physics-independent and user-friendly access to the reduced basis method within a high-performance finite element library, allowing computations of spatially high dimensional models. In addition, we present how the method can be used for other inverse processes, such as automated model calibrations. Inverse problems are becoming rapidly extremely expensive computationally even without including all major sources of uncertainty. In that regard, the reduced basis method is very promising because it allows a significant reduction in computation time without introducing additional physical uncertainties.

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Session Classification: Poster Session

Contribution ID: **148** Type: **Oral**

A case study on the intensive shallow geothermal usage in a German neighborhood

Thursday, October 10, 2019 3:00 PM (15 minutes)

Ground source heat pump (GSHP) systems has become a renewable technology to provide space heating and cooling. An evident trend is the intensive exploration of shallow geothermal heat within a limited area, e.g. residential quarters. In such context, thermal interaction among nearby installations is often expected, which leads to concerns about the subsurface environment and the system performance.

This talk presents a case study to evaluate the thermal impacts and predict the long-term sustainability of intensive geothermal use in a typical urban neighborhood in Germany. Within this site, 50 GSHPs have been applied since around 2008 and are operating mainly for heating. Site investigations and monitoring campaigns have been carried out, while an unsaturated groundwater flow has been confirmed. In addition, a declining trend of the groundwater temperature was detected in the downstream direction.

A 2D numerical model was built using the OpenGeoSys program to simulate the coupled groundwater flow and heat transport processes at the study site. In particular, the individual GSHP systems are represented as thermal/hydraulic source terms which become active during the operating seasons. In order to determine the key model parameters such as hydraulic conductivity, thermal conductivity and heat extraction rates, a calibration procedure was performed until the numerical model was able to reproduce the monitored groundwater temperatures with sufficient accuracy.

Following the model validation, a long-term prognosis of the induced thermal impacts and feedback on the energy efficiency was performed on a 24-year basis. The predictive results of subsurface temperature indicate limited thermal impacts as the minimum temperature will maintain above 3 ℃ and that the area undergone severe temperature drop is less than 1% size of the neighborhood. Based on the temperature predictions, the evolution of the Coefficient of Performance (COP) of the individual installations was extrapolated using a novel estimation approach. The results showed that the energy performance of all installations will be quite robust since seasonal COPs are at least 3.8. Nevertheless, it is worthwhile to note the exacerbated ground cooling near the downstream installations as well as the associated deterioration of their COP factors with time. As a consequence, downstream installations consume more power than the upstream ones, leading to a maximum 92 EUR difference in annual expenditure on electricity.

Furthermore, a sensitivity analysis on the effect of groundwater flow velocity was also performed in which a bandwidth of one order of magnitude was considered. The results revealed that the temperature distribution and the GSHP performance rely strongly on the groundwater flow regime depending on the geometrical layout of installations. Particularly, for the conduction-dominating scenario, the groundwater temperature reaches ~0 ℃ after eight years, which is unsustainable in the long run.

To conclude, this study demonstrates that intensive utilization of geothermal heat is generally sustainable in refurbished living quarters, provided that sufficient groundwater flow exists. As a prerequisite for the optimal planning of such projects, site-specific information on the groundwater flow direction and magnitude needs to be accounted for especially when allocating the GSHPs. In addition, site-wise parameterized models should be applied more to support optimized development and management.

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Session Classification: Session 7: Sustainability, Environment and Regulatory Framework

Track Classification: Topic 7: Sustainability, Environment and Regulatory Framework

Contribution ID: **149** Type: **Poster**

Linear vs. Nonlinear flow laws in sheared and rough self-affine fractures

Wednesday, October 9, 2019 5:10 PM (20 minutes)

Developing and operating deep geothermal projects require a comprehensive understanding of the hydraulic properties of the reservoir. Structural features such as fractures have a crucial impact on hydraulic conductivity and thus on the geothermal reservoir sustainability. Therefore, reliable quantification of fluid flow through fractures is of high interest for reservoir engineering, especially for deep geothermal applications.
From a geometrical point of view, fractures are void spaces constraint by rough and sheared rock surfaces. The quantification of the relationship between pressure loss and flow rate for the flow along rough surfaces is a complex task and computationally expensive, particularly if it is considered on large scale and in three dimensions. Typically, Darcy-based 2D-local cubic law (LCL) simulations are used to reduce computational time. By increasing flow rates, the inertial forces, typically occurring near the borehole, have a significant effect on the pressure drop and cannot be neglected. In order to obtain realistic results for such systems, the flow has to be expressed in terms of Navier-Stokes equations. In this study, we compare widely spread LCL-based approaches and also present initial steps towards 3D-Navier-Stokes (NS) calculations on a single fracture scale.
For the application of the LCL, whose validity for small flow rates has already been confirmed, a defined fracture aperture is required. This aperture is often assumed to be the distance between the two fracture surfaces in the vertical direction, while shear effects, such as anisotropy, tortuosity and roughness, are neglected. It could be shown that this assumption leads to large uncertainties and that instead the fracture aperture should be described by an effective aperture determined by the measurement of the distance along surface normals. For higher flow rates, it could be shown that this simplification is no longer permissible and non-parallel flow and inertial effects must also be considered. In order to quantify the non-linear fluid flow, the Navier-Stokes equations must be applied to a three-dimensional fracture geometry representing the real fracture topology. A comparison of the LCL with NS shows that differences in anisotropy and channeling have to be expected even at low flow rates. These differences in anisotropy and channeling rise by increasing the flow rate.
The comparison of both approaches presented herein leads to valuable evidence to which extend LCL quantifications on rough surfaces provide results with tolerable uncertainties, and in which configurations (flow velocities, tortuosity, channeling, etc.) inertial forces have to be considered using Navier-Stokes.

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Presenter: Mr EGERT, Robert

Session Classification: Poster Session

Contribution ID: **150** Type: **Oral**

Geothermal Binary Demonstration Power Plant Pangolombian-Lahendong, Indonesia

Thursday, October 10, 2019 11:40 AM (15 minutes)

In order to successfully demonstrate geothermal binary power plant technology at an Indonesian site and to intensify the know-how transfer in this technology field a German-Indonesian collaboration project has been initiated in 2013 involving GFZ Potsdam (Germany), the Agency for the Assessment and Application of Technology in Indonesia (BPPT) and PT Pertamina Geothermal Energy (PGE). Geothermal binary power plants are not yet an established technology at Indonesian sites. The first commercial binary units have been commissioned at Sarulla field just in 2017. Due to their adaptability binary plants could however be implemented at much more sites and help to increase the geothermal capacity in Indonesia.
The binary demonstration power plant Pangolombian-Lahendong is a prototype that has been developed in order to meet different technical, but also non-technical constraints. The power plant cycle is integrated using two intermediate closed water cycles for heat supply and heat removal which is an untypical set-up for geothermal binary power plants. Technical components from Germany but also Indonesian suppliers have been used.
The binary demonstration plant started operation in September 2017. Since then more than 1.8 GWh (status September 2019) could be produced and a full-automatic and parallel grid operation could be proven. In January 2019 the demonstration plant has been handed over to an Indonesian partner. Besides the power supply for geothermal injection pumps the binary plant shall serve for education and research.
The presentation describes the technical concept and will summarize the operational experiences.

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Session Classification: Session 6: Operation of Geothermal Systems

Track Classification: Topic 6: Operation of Geothermal Systems

Contribution ID: **151** Type: **Oral**

Synthesis of manganese oxide adsorbent as a tool for selective Lithium extraction from geothermal brines

Thursday, October 10, 2019 11:10 AM (15 minutes)

Lithium (Li) is one of the crucial elements for the realization of electric mobility, energy transition and digitization, with rising demand and prices over the last decades. However, with an import rate of 86% (2010 –2014) and a contribution to global Li-production of less than 1% (2017), Europe depends almost entirely on Li-import. To reduce the dependency, Li deposits and new and unconventional sources are searched for within in the EU. One possible source are the geothermal brines of the Upper Rhine Graben with Li concentrations of up to 200 mg/L.

However, extraction of Li through evaporation cannot be applied in the Upper Rhine Graben because of an unsuitable climate and the need for huge evaporation ponds or a large amount of energy. Instead, one way for economic Li extraction is the application of synthesized manganese oxide adsorbents, which is based on the selective adsorption of the dissolved Li. The high selectivity towards Li is a result of a tunnel structure of the manganese oxide with diameters slightly larger than the ionic radius of Li, thus hindering competing ions to adsorb onto the inner surface of the adsorbent and simultaneously creating a high specific surface area. Lithium is desorbed from the Mn oxides through exchange with H+-ions, which is achieved by applying an acidic solution. From the resulting solution, Li can be precipitated as Li2CO3 or LiCl and the Li-free adsorbent can be reused. The adsorption and desorption capacity are influenced by brine-related parameters like pH, temperature, salinity and further depend on the chemical composition and mineralogical structure of the adsorbent. In our study, a manganese oxide adsorbent (Li1.6Mn1.6O4) was synthesised to prove the suitability of the approach for the geothermal brines of the Upper Rhine Graben.

XRD and SEM analyses of the synthesised adsorbent shows a comparatively high amount of amorphous phases (~12 ¬ 18% semi-quantitatively) covering and coagulating the adsorbent particles (diameter of <1 –2 µm) to aggregates with diameters >10 µm. The XRD analyses of the synthesised Li1.6Mn1.6O4 shows a mixture of a Li-Mn-oxide phase and a Mn2O3 phase, which is an intermediate product of the synthesis, indicating that the transformation of the synthesis educts is incomplete.

Experiments with LiOH solutions show that Li is readily adsorbed and desorbed but the Li adsorption capacity is lower than expected. Additionally, more Li is desorbed than adsorbed indicating that Li originating from the synthesis educts is still present. Reaction kinetics are fast with an adsorption and desorption of more than 50% in several minutes proving the suitability of the method for the application in geothermal power plants. However, since the presence of intermediate products and amorphous phases significantly lower the Li adsorption capacity, a revised hydrothermal synthesis for the manganese oxide adsorbents is developed. Thereby, the synthesis parameters calcination duration and temperature, Mn-Li-ratio and duration of crystallization period are optimized to reach a transformation rate of synthesis educts of >90% and an amorphous percentage <5% to produce an adsorbent with which Li can be produced economical from the geothermal brines.

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Session Classification: Session 6: Operation of Geothermal Systems

Track Classification: Topic 6: Operation of Geothermal Systems

Contribution ID: **152** Type: **Oral**

Meeting Site-specific Energy Demand With a Fully Renewable Power System

Thursday, October 10, 2019 3:15 PM (15 minutes)

In electricity grids, demand and generation must be balanced at all times. Modern electricity is primarily generated by constant power sources, such as nuclear and coal, and quickly dispatchable sources, such as gas fired power plants, which can be adjusted based on small demand variations. However, as anthropogenic total CO_2 emissions already make up almost 75% of the atmosphere's total carbon content, governments are increasingly implementing renewable energy mandates. These mandates limit a country's CO_2 emissions and reliance on fossil fuels. Therefore the electricity generation market is moving towards renewable power sources, which have no CO_2 emission.

Many renewable energies, such as wind, solar, and hydropower, are variable power sources. These power sources have a different power production capability at each moment in time depending on natural inputs, and these input variations cause their generation to fluctuate unpredictably. For example, on a cloudy day, a solar power plant will be able to generate only a fraction of its installed capacity. The field of energy optimization arose with the goal of calculating how to ensure full demand coverage with the least production. The optimization of variable power sources is thus an important problem to figure out how we can rely on variable power sources, such as most current renewable energy sources, to meet demand.

Two of the most widely used renewably power sources, wind and solar, have a mismatch in the timing of energy supply versus demand. In order to reconcile this mismatch, either a third energy source or an energy storage system has to be included to fully meet demand.
This study will optimize a purely renewable energy system to fully meet demand for the town of Minot, North Dakota. The renewable system considers CO_2 Plume Geothermal, in addition to wind and solar, as both a third power source and as a method of energy storage.

Geothermal energy production is dispatchable, as a specific amount of power can always be generated. Earth's thermal energy is always available, and a geothermal power system can extract this energy as needed. A CO_2 Plume Geothermal power plant runs like a geothermal plant, but with CO_2 instead of brine as the primary working fluid. This proposed technology therefore both generates power and provides a use for CO_2 sequestered in the ground.

This research finds the optimum sizes of wind, solar and CO_2 Plume Geothermal power plants to fully meet demand in a stand-alone system. CO_2 Plume Geothermal with Energy Storage (CPGES) is then implemented to store surplus energy and meet energy demand without supplemental gas turbine power generation. We find that using CPG energy storage reduces renewable energy overproduction by 80%, system capital cost by 75%, and the system remains fully renewable.

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Session Classification: Session 7: Sustainability, Environment and Regulatory Framework

Track Classification: Topic 7: Sustainability, Environment and Regulatory Framework

Contribution ID: **153** Type: **Poster**

Geothermal Systems Exploration in the Southern Chilean Volcanic Zone by Magnetotelluric Method: a case study at Villarrica Volcano

Wednesday, October 9, 2019 4:50 PM (20 minutes)

Understanding the subsurface behavior of the Earth is of high importance for the development of geothermal energy, especially in Chile, which has active volcanoes throughout the country. An area with great potential of geothermal development is the southern zone of Chile. Controlled by volcanic environment widely influenced by cortical fault systems. Several thermal spring manifestations of different temperature are proof of this control.
The study of geothermal systems in southern Chile began around of Villarrica volcano with the objective of exploring reservoirs for production of energy. The study in the area around the volcanic volcano was based on 31 magnetotelluric (MT) stations, deployed in two profiles, one oriented EW and perpendicular to the branches of the Liquiñe-Ofqui fault system (LOFS) and a second NS-oriented along LOFS and subsystems perpendicular to the Andean transversal fault (ATF) and the chain volcanic Villarrica-Quetrupillán-Lanín. The results correspond to inversion of MT data revealing a high anomaly of the electrical conductivity at 3km depth below the volcanic chain. In addition, anomalies of intermediate resistivity are observed that coincide with the location of thermal sources of low-medium temperature or monogenic volcanic activity. Possibly, fault systems would serve as fluid pathways.
The study of geothermal systems in southern Chile will continue with the investigation of the Tolhuaca geothermal system, located on the flanks of Tolhuaca volcano, influenced by LOFS and ATF as well. MT data measured in the surroundings of the Tolhuaca volcano will be analyzed, in order to know the influence of fault systems in a high temperature geothermal system.
These two studies will allow us to understand geothermal systems of different temperatures in the southern Chilean volcanic zone that are controlled by the same fault systems.

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Presenter: PAVEZ, Maximiliano (KIT - INE)

Session Classification: Poster Session

Contribution ID: **154** Type: **Poster**

Utilization of abandoned hydrocarbon reservoirs for deep geothermal heat storage

Wednesday, October 9, 2019 11:30 AM (20 minutes)

Energy transition involves an increasing demand for renewable energies. Room heating and hot water account for the majority of the energy demand of private households. Thus, seasonal storage of excess heat produced during the summertime and extracted during the wintertime is of paramount importance. High temperature heat storage in the subsurface may be realized in abandoned hydrocarbon reservoirs worldwide as these reservoirs have already been extensively characterized concerning their geology, geo- and petrophysical properties as well as their depths and geometries. Although these hydrocarbon reservoirs are relatively well characterized, their potential use for geothermal heat storage has not yet been investigated. Here we focus in a first approach on abandoned oilfields of the Upper Rhine Graben (URG) in SW Germany with the aim to assess their potentials for geothermal heat storage. While geothermal production commonly targets fractured reservoirs to obtain economically viable flowrates, geothermal heat storage will aim at reservoirs with high porosities. As the productivity of hydrocarbon reservoirs is commonly controlled by their porosities, they appear as viable targets for high temperature heat storage.

We have characterized 20 abandoned hydrocarbon reservoirs in the URG, which were productive for more than five years, in Cenozoic sandstones in depths of approximately 200 –1800 m. Our characterization is based on published data of their production histories, reservoir geology, and petrophysical properties. Most reservoirs in the URG are stacked reservoirs with inflow of hydrocarbons into the borehole from multiple stratigraphic units, as for example in Landau and Leopoldshafen, biasing an assignment of respective reservoir productivity. For heat storage injection pressure needs to be well controlled to avoid undesired hydraulic fracturing. Therefore (theoretically) infinite reservoirs with high transmissivities appear to be more attractive and less risky than confined reservoirs.

The production histories of the various hydrocarbon reservoirs show typical patterns with a rapid increase of the annual production, followed by a slower decrease of production (tailing) before hydrocarbon production was shut down. Most reservoirs in Cenozoic sandstones show porosities of 10 to 20% with some extreme values of up to 30%. Associated permeabilities vary from 0.1 to 100 mD with some extreme values of up to 1000 mD. Data show a non-linear relationship between porosity and permeability. During hydrocarbon production water-oil ratios increase until unalluring water-oil were produced. We evaluate the potential of abandoned hydrocarbon reservoirs in the URG for heat storage by developing generic numerical models to constrain limiting conditions. The uncertainties of input parameters and their impact on heat storage potential will be addressed by a sensitivity analysis. Potential reservoirs for heat storage may be defined based on energy recovered over invested energy (EROI).

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Presenter: STRICKER, Kai

Session Classification: Poster Session

Contribution ID: **155** Type: **Oral**

Geothermal heat storage in the Upper Rhine Graben –the DeepStor project at KIT Campus North

Thursday, October 10, 2019 10:55 AM (15 minutes)

The subsurface condition of the Upper Rhine Graben are 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 CO2-neutral energies.

The concept is tailored to the Campus North of the Karlsruhe Institute of Technology (KIT) that is located in the central-eastern Upper Rhine Graben. It includes multi-level utilization with heat recovery from the deep Mesozoic reservoirs (GeoHeat project) and seasonal heat storage in the Tertiary Sandstones above (DeepStor project). In the long term, the concept should cover a significant part of the basic heat load at the KIT Campus North in a climate-neutral way. The underground of the campus is characterized by the largest known heat anomaly in Germany, with temperatures of ≥ 100 °C at a depth of 2 km. In connection with the existing area-wide local heating network, the campus offers good conditions for the extraction, seasonal storage and distribution of heat from deep geothermal energy. The step-by-step development of deep geothermal energy at the KIT Campus North within the framework of the DeepStor storage project will include first the deep underground to Tertiary Basin. The high temperature storage of renewable heat involves the same Tertiary strata from which hydrocarbons have been extracted until the 1990s (Stricker et al, this issue) and will be supplied in a first step with heat from cogeneration as well as current renewable waste heat from scientific infrastructure projects such as “bioliq”.

The expected reduction of flow rates by seasonal storage in the later GeoHeat project should serve in particular to reduce induced seismicity, which is still one of the greatest obstacles for the industrial, deep geothermal development in the Rhine Graben.
DeepStor consists of three stages:
1) The establishment of a scientific demonstrator for high-temperature heat storage in the deep underground with the aim of validating the technical feasibility.
2) Coupling of the prototype to above-ground plants (e.g. CHP, bioliq) with feed into the local heat grid.
3) Integration into the regular operation of the KIT Campus Nord heat supply system.

For the interaction with public DeepStor will implement an inter- and transdisciplinary co-design. This represents a paradigm shift in the definition of the development concept and the operation of geothermal power plants. This innovative approach makes it possible to integrate civil society already in the concept development phase. In this way, constructive impulses from society can be made fruitful at an early stage in order to identify the challenges of deep geothermal energy and thus also of the local “heat transition” and to develop solution options.

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Presenter: SCHILL, Eva

Session Classification: Session 6: Operation of Geothermal Systems

Track Classification: Topic 6: Operation of Geothermal Systems

Contribution ID: **156** Type: **Poster**

Geological structures in the Acoculco geothermal area, Mexico: a background for EGS development

Wednesday, October 9, 2019 5:40 PM (20 minutes)

In the surroundings of Acoculco village in the eastern Trans-Mexican Volcanic Belt, two 2-km-deep geothermal exploration boreholes, 500 m apart, demonstrate a temperature gradient of nearly 150℃ per km and a tight reservoir. In this context, the GEMex project considered the Acoculco area as a study area for applying methodologies of analysis for Enhanced Geothermal Systems. The stratigraphy indicated by the boreholes consists of about 700 m thickness of volcanic deposits underlain by about 1000 m thickness of limestone and skarn, in turn underlain by granite.

One of the first approaches for predicting the natural fracture properties of the reservoir is to define the structural setting, highlighting the main regional trends and the intra-caldera characteristics in terms of fracture network and connectivity. Toward this goal, a new structural map was constructed and two main fault systems recognized, striking NNW-SSE and SW-NE respectively. Kinematic analysis of the outcropping fault slip-surfaces was carried out by structural stations located along the regional faults. The results indicate that the NNW-SSE striking faults are characterized by early dextral to oblique-normal movement characteristically overprinted by predominantly normal movement. In contrast, the SW-NE striking faults are characterized by normal movement. The fault activity is encompassed between late Pleistocene and Present, based on paleontological and stratigraphic evidence. Detailed fieldwork carried out in the area surrounding the boreholes confirms this structural framework and highlights northward migration of the deformation, indicated by stratigraphic relations, thermal springs and gas effusions. Outcropping fractures are typically mineralized.

The objective of these detailed outcrop studies is to assist the forecasting of existing fracture systems in the predominantly granitic reservoir. In the vicinity of the boreholes small fault-bounded sedimentary basins 200 to 500 m wide contain late Pleistocene sediments and are delimited by NE-trending normal faults and NNW-trending oblique-slip transfer faults. The fault exposures are typically in lava and highly-compact welded tuff and characterized by damage zones estimated to be three to 10 meters wide with fracture frequencies of up to 10/m. Several of the steep NNW-striking faults trend between or near the boreholes. Whereas the fault spacing and damage zone width is expected to change with depth and location in the fault network, the fault geometry and displacement indicates that the fault system cuts through the volcanic and underlying carbonate strata into the granite. The mineral sealing observed in outcrop is consistent with the lack of fluid loss when the wells were tested. However, for EGS purposes, the mineralized fractures can be expected to be weaker than non-fractured rock volumes and to open under pressure stimulation.

In conclusion, fieldwork produced geometrical and strength parameters, both at local and regional scale, to assist the simulation of EGS in a rock volume affected by a known fracture system.

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Session Classification: Poster Session

Contribution ID: **157** Type: **Oral**

Environmental aspects of geothermal technologies: the contribution of GEOENVI to the description of risks and impacts and related mitigation measures

Thursday, October 10, 2019 2:30 PM (15 minutes)

Despite the main contribution that deep geothermal technologies bring to the energy transition from fossil to renewable resources in many European countries, in some regions these technologies are confronted with a negative perception, particularly in terms of environmental performance, which could seriously hamper their market uptake.
The evaluation and effective communication of environmental issues is the main target of the European GEOENVI Project, launched in the framework of the H2020 programme (GA 818242) and started on November 2018. Among the various activities, a main part is currently focused on describing the adverse and benign effects on the environment that technologies potentially bring with their development, and providing accurate and current information about the best practices and available technologies to avoid, whenever, possible, or otherwise minimise the unavoidable adverse effects to the environment produced by geothermal development.
The environmental effects from geothermal development have been categorized based on safeguard subjects, i.e., endpoint indicators, emphasizing environmental burdens.
The analysed adverse environmental effects considered of relevance for the geothermal development and analysed for the project are:
• Effects of surface operations: energy and water consumption and emissions to the environment;
• Waste production from surface operations
• Surface disturbance, including vibration, noise, visual, land occupation and dust
• Leaks due to surface installations and operations
• Liquid/solid effusions and waste
• Degassing
• Radioactivity
• Ground surface deformation
• Seismicity
• Interconnection of aquifers and disturbance of non-targeted aquifers
• Reservoir physical and chemical modifications
The presentation will describe the mapping of the environmental risks and impacts as well as mitigation measures performed by the project, and how they are being organised on public Wiki pages and database.

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Session Classification: Session 7: Sustainability, Environment and Regulatory Framework

Track Classification: Topic 7: Sustainability, Environment and Regulatory Framework

Contribution ID: **158** Type: **Poster**

Effects of elevated confining pressure and temperature conditions on deeply buried sandstone reservoirs

Wednesday, October 9, 2019 5:40 PM (20 minutes)

Connected open pores forming the matrix porosity are important fluid pathways in siliciclastic geothermal and hydrocarbon reservoirs at 2-5 km depth. Therefore, grain rearrangement by mechanical compaction, authigenic mineral formation during early and late diagenesis, as well as chemical compaction have a profound impact on permeability (Taylor et al., 2010; Busch et al., 2017). Petrophysical measurements in combination with petrographic information was employed to characterize potential analogs to reservoirs in Rotliegend fluvio-eolian sandstone units.

Petrophysical measurements were conducted on plug samples with a diameter and length of 3.0 cm. Helium porosity was measured with a micromeritics® AccuPyc II 1340 gas pycnometer. Klinkenberg-corrected permeability under steady-state conditions was measured at 1.2 MPa confining pressure at room temperature (22° C) using dry, oil-free lab air as a permeant. Also, Klinkenberg-corrected permeability under steady-state conditions was measured at confining pressures of 2, 5, 10, 30 and 50 MPa at room temperature (22° C) during loading and unloading cycles. Permeability pressure sensitivity coefficients after David et al. (1994) were determined from the measured permeability hysteresis curves. Selected samples were also measured at reservoir temperatures of 140° C in order to evaluate the effect of elevated temperatures on the permeability in reservoirs compared to ambient measurements. Detailed mineralogical composition, the grade of compaction (Lundegard et al., 1992), and the impact of authigenic minerals on pore space reduction were derived from thin sections with point-counting adjusted to the maximum grain size.

Helium porosities range from 3.8-25.7 %, while ambient permeabilities range from 8.882*10-18 m² - 2.899*10-13 m². Dependent on the initial permeability under ambient conditions (1.2 MPa confining pressure, 22 °C), permeabilities are reduced from below one order of magnitude up to four orders of magnitude. Permeabilities for less compacted and less cemented samples are reduced by below one order of magnitude, permeabilities for highly cemented but not highly compacted samples are reduced by one-two orders of magnitude, and permeabilities for highly compacted sandstones are reduced by up to three orders of magnitude. Consequently, the permeability pressure sensitivity coefficient γ ranges from 0.5 –22.2 10-2 MPa-1. The temperature effect shows inconclusive results in regards to its effect on permeability. Results highlight the significant heterogeneity in production relevant properties like permeability and porosity, although the bulk mineralogical composition is very similar. Thus, detailed characterizations are necessary to evaluate different permeabilities in seemingly heterogeneous sandstones. This allows to better predict unexpected reductions of fluid flow rates and zones requiring stimulation in geothermal and hydrocarbon reservoirs.

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Session Classification: Poster Session

Contribution ID: **159** Type: **Poster**

New Geothermal Project Portfolio in the German part of the Upper Rhine Graben by Deutsche Erdwärme

Wednesday, October 9, 2019 5:40 PM (20 minutes)

Deutsche Erdwärme GmbH & Co. KG is today the largest German private geothermal project developer and future operator in the German part of the Upper Rhine Graben area. The company currently holds ca. 1000 km² of granted project concession area in the two federal states of Baden Württemberg and Rhineland-Palatinate. Backed with strong financial support by public (or strategic) investors Deutsche Erdwärme intends to realize and operate a portfolio of geothermal plants on the Upper Rhine in the coming years. At the same time, further exploration permits are to be acquired in order to develop additional, promising areas in the region for electricity and heat production from deep geothermal energy resources.
Currently the company's main activities are in the field of 3D seismic data acquisition, regional structural interpretation , execution of reservoir studies to identify favourable target zones and site selection for planned drilling activities. The reservoir assessment includes structural geological and geomechanical as well as thermo-hydraulic modelling based on 3D seismic data and all available borehole data in the region. After an initial quality check further acquirement of raw data and/or reprocessing will be performed to ensure the best data quality is available for the project portfolio. The aim is to understand the resource on different scales to optimize the exploration concept and well design. First results on reservoir studies and exploration concepts will be discussed. At present, DEW is preparing an own 3D seismic campaign in the Waghäusel concession north of Karlsruhe to be executed in November/December 2019. Furthermore, existing projects in the area, that have been ceased in the past for different reasons, will be re-evaluated with the aim of a reactivation. The current status of all these activities will be presented.

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Session Classification: Poster Session

Contribution ID: **161** Type: **Oral**

Spectral analysis of aeromagnetic data for geothermal exploration and assessment: the case of southern Italy

Wednesday, October 9, 2019 11:40 AM (15 minutes)

The best way to study the subsurface geothermal potential is by directly measuring the heat flow and temperature from boreholes. However, heat flow and temperature data are not uniformly distributed and not consistently deep; thus they are not enough in inferring deep thermal distributions. In this case, Curie depth isotherm may provide the deep thermal distribution which cannot be obtained otherwise. Estimation of Curie isotherm can be accomplished by assuming either a statistical ensemble of homogeneous sources or even a fractal sources distribution. The Curie isotherm, in combination with heat flow and temperature distribution data, may provide reasonable geological results, which can be used for further detail exploration. In order to assess the geothermal potential of the region, we have estimated the Curie isothermal surface of the Southern Italy trough spectral analysis. Spectral analysis in the Southern Italy suggests that the Tyrrhenian Sea is underlined by Curie isotherm that ranges from less than 10 km to 20 km, whereas the Apennines are characterized by relatively deep Curie isotherm. This variation is also consistent with the existing heat flow and temperature data, which shows high heat flow over the Tyrrhenian Sea and low heat flow values over the Apennine, with some local hotspots. Both the Curie depth results and heat flow data indicates that the Southern Italy is a promising area for further geothermal resources exploration and exploitation.

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Session Classification: Session 2: Exploration of Geothermal Reservoirs

Track Classification: Topic 2: Exploration of Geothermal Reservoirs

Contribution ID: **162** Type: **Poster**

Geological structures and analogue permeability studies in Los Humeros geothermal system

Wednesday, October 9, 2019 9:35 AM (20 minutes)

Caldera-related superhot geothermal reservoirs are in many cases underexploited. Primary exploration and production challenges, closely tied to investment risk, are predicting the reservoir and targeting the drilling. Our focus in this contribution is assessing the role of fractures in outcrops and their utility as analogues to the fractures in the geothermal reservoir. Our case study is the Los Humeros geothermal fields in the Central Mexican volcanic belt, as part of the H-2020 GEMex project (EU-MEX collaboration) to improved understanding of subsurface conditions.

Los Humerous are recent caldera (<3.8 Ma) characterized by high heat-flow related to granitoids intruded into the Jurassic-Cretaceous limestone basement. The Los Humeros reservoir lies below about 1300 m depth and consists of fractured lavas and ingimbrites and underlying limestone. The present caldera land surface is composed of volcanic edifices, tuffs and lavas. The reservoir lithologies are influenced by pre- and syn-caldera extreme temperatures and deformation, post-caldera burial, and pre-caldera to present hydrothermal alteration/metamorphism and magmatic intrusion.

Our database includes most of the lithologies present in the reservoir. Data were acquired using fracture scan lines and 3D quantitative outcrop models. Conventional interpretation and analysis were extended by stochastic fracture modelling to generate analogue 10-m scale “fracture boxes”. From these we infer relative fracture permeability based on fracture size, orientation, connectivity and spatial frequency. For application to the reservoir fluid flow modelling, we group these fractured-rock volumes into three categories: A) fault-related; B) background deep burial; and C) background shallow burial.

Fault-related fracture systems (A) are typical of damage zones along faults, in relays, and near fault intersections. Recently-active regional to intra-caldera faults cross-cut numerous caldera lithologies and some influence the caldera shape. These faults and their representative “fracture box” volumes are characterized by high fracture frequencies in lithified “tight” reservoir-analog lithologies (welded tuff/ignimbrite, lava, intrusive, metamorphic). Outcrops representative of deeply buried sections of syn-caldera faults (i.e. reservoir) typically show high grade alteration in the form of hydrothermal fracture fill and metamorphism (combined seal conduit systems).

Background fracture systems (B) in outcrops of granodiorite and marble (skarn) are inferred to have been generated under deep burial conditions similar to the reservoir. The low fracture frequency (0.1-0.3 f/m) indicates low network permeability. The typical fracture system consists of orthogonal regular-spaced joints of non-tectonic origin, including near-subsurface unroofing joints, cooling joints and hydrothermal veins.

Sedimentary and extrusive volcanic rocks (C) display a much higher fracture frequencies than deep-burial category. For syn- to post-caldera deposits these fractures formed in the near surface have been progressively buried to reservoir depths. For pre-caldera deposits this history is overprinted by caldera-related deformation. In general andesites and basalts show fracture characteristics consistent with good permeability and mostly high fracture connectivity both in background levels and in faults. Mesozoic limestone basement may also be present in the reservoir has a tight fracture network inherited from Laramide-age folding and thrusting followed by the uplift and unroofing during TMVB development.

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Session Classification: Poster Session

Contribution ID: **163** Type: **Poster**

Thermal modelling of magmatic geothermal systems: the role of deep-seated heat sources

Wednesday, October 9, 2019 11:50 AM (20 minutes)

High-temperature geothermal fields are mostly associated with the occurrence of intrusive and/or extrusive magmatic centers. We present the results achieved in different National and European research projects, i.e. Geothermal Atlas of Southern Italy, Descramble and Gemex projects. We applied an integrated approach in order to set-up numerical models able to simulate the conductive-convective thermal structure of selected high-temperature geothermal fields, i.e. the southern sector of Larderello area (Central Italy), the Ischia Island (Southern Italy), the Acoculco caldera complex (Mexico) and the Long Valley caldera (US). In the above-mentioned geothermal fields, both the high geothermal gradients measured in the impervious rocks and the thermal effects of the circulating hot fluids in the deep-seated reservoirs suggest the occurrence of young and shallow magma bodies acting as the main heat source of the overlying hydrothermal systems. In this context, the age of the last magmatic event, the emplacement depth and temperature are key aspects in understanding the geothermal system and assessing its potential. How long magma bodies persist in the mid- to upper crust is a fundamental information to understanding also the relationship of magmatism to geothermal resources in continental settings. We propose a numerical approach implemented in a Finite Element (FE) environment capable to evaluate the contribution of the main variables that characterize the heat source and the reservoir. The final 3D thermal models were achieved via the optimization of the available temperature measurements in deep boreholes tacking into account the thermal effects of the interplay between the free convection and the topographically driven groundwater flow, the reservoir permeability and the thermal load released by the parametrized heat source.

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Session Classification: Poster Session

Contribution ID: **164** Type: **Poster**

Forecasting Induced Seismicity for the geothermal UDDGP project –An ongoing experiment

Wednesday, October 9, 2019 5:40 PM (20 minutes)

The occurrence of induced earthquakes is a typical phenomenon in the development and exploitation of geothermal reservoirs targeting crystalline basement. Although most induced earthquakes are of low magnitude and can only be detected by sensitive recording instruments, some isolated earthquakes in the magnitude range ML3.5 have occurred in geothermal reservoirs. Due to their shallow depth, earthquakes of this strength can be felt by humans and can even cause slight damage to buildings. Although the physics leading to induced seismicity are well understood, the earthquake process is critically depending on details of the subsurface conditions. Therefore, forecasting the seismicity response to geothermal activities from a 'green-field'perspective is a challenging task.

We have developed a framework for assessing the range of a potential seismicity response given the subsurface information available at a certain time during geothermal project development. The approach rests on a physics based, dynamic earthquake simulator to study timing and magnitude of induced earthquakes assuming different subsurface conditions. As new information becomes available, the range of the potential seismicity response can be narrowed down. Our strategy provides a basis for seismic risk mitigation in two different ways: we can identify (i) which additional information is required to further narrow the range of the seismicity response and (ii) how geothermal activities need to be adjusted to minimize the seismicity response.

We apply the approach to the United Downs Deep Geothermal Project (UDDGP) in Cornwall, which is currently being developed. A first seismicity prognosis was made in the 'green-field' project phase, prior to drilling the first well. A structural, geological model was constructed from mapping at surface and within mines down to 400 m bgl. and from gravity modeling. Geothermal exploration is targeting a sub-vertical fault zone in granitic rock at a depth level between 2.5 km and 4.5 km. Width, geometry and hydraulic parameters of the fault zone were not well constrained at that time. The initial model, however, indicated that stress strength conditions on the target fault are near-critical with stress criticality increasing with depth. Numerical simulations indicated that seismicity induced during the initial development stage could be up to M3.5.

Subsequent to the initial seismicity prognosis, two geothermal wells were drilled to depth levels between 5 km and 2.5 km, respectively. Induced seismicity observed during drilling the deeper well are consistent with prognosed conditions such as the near-critical state of stress and that the flow is constrained to individual faults.

We are currently performing a parameter sensitivity study to investigate to what extend a pressure limit (rate reduction) impacts the maximum magnitude.

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Session Classification: Poster Session

Contribution ID: **165** Type: **Poster**

Predictive mechanical model for fracture stimulation in an enhanced geothermal system (EGS) context

The development of an EGS is one of the goals of the GEMex project, an international collaboration of two consortia, one from Europe and one from Mexico. The research is based on exploration, characterization and assessment of two geothermal systems located in the Trans-Mexican volcanic belt, Los Humeros and Acoculco.
Los Humeros has been a producing field for several years, but Acoculco is yet to be developed. Thanks to surface manifestations of hydrothermal activities, the existence of a geothermal system is evident. However, two wells reached very high temperatures, but did not find any fluids. For that reason, the Acoculco Caldera is foreseen as EGS development site, hoping to connect existing wells to a productive zone.
In this study, we develop a workflow that aims at assessing the feasibility of this EGS. The approach aims at generating a realistic predictive mechanical model for fracture stimulation from the well borehole.
The strength of the method stands in the combination of reliable data obtained from field work and experimental measurements on mechanical properties of the target rocks, used together to populate a numerical model.
The workflow starts with the identification and description of the surface discontinuities using the scanline survey method. These surveys are interpolated and extrapolated using the multiple point statistics method to generate geological discrete fracture networks. The results of these simulations are then evaluated in a finite element method program using a flow model for fractured media. Finally, combining the fracture flow model and the mechanical properties measured in the rock physics laboratory, the fracture propagation is calculated.
The method offers a physically sound prediction of the reservoir flow characteristics as well as an accurate mechanical model of the fracture propagation and the pressure distribution for well borehole stimulation. Because the workflow is based on easily accessible data and thanks to its simplicity, this approach could be applied in most EGS case studies.

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Geothermal Reservoir Characterization by Thermo-Reporting Nanoparticles

For a modular and comprehensive approach to characterization of reservoir properties such as temperature, pH or salinity, we present reporting nanoparticles with an architecture that forms a dual signal system in a core-shell structure. In this proof of concept example of thermo-reporting nanoparticles, the inner shell contains an inert signalling function, which enables the detection of the particles upon recovery at the exit point. The outer shell contains a reporting function, which undergoes an irreversible change that is triggered upon being exposed to a certain known and well-defined external stimulus that the particles experience while flowing inside the reservoir.

As a demonstration for our dual signal system, we synthesized core-shell silica nanoparticles, in which the core and the shell contain two different fluorescent dyes. The core encapsulates the dye in a tight and leak-proof manner, also protecting it for ambient conditions, in a way that ensures a stable and steady fluorescence-based signalling function even when the particles experience temperatures at least as high as 200 ℃. A second fluorescent dye is contained within the shell, where it is exposed to ambient conditions. Modification of the shell with different stimuli-responsive materials resulted in an irreversible change in the reporting fluorescence signal of the outer dye. Upon crossing the designated temperature threshold, the reporting signal either increased, decreased or shifted. In tests conducted in a closed system, this led to a distinguishable change in the ratio of reporting to signalling fluorescence emission signals and therefore to detection of an event of heating above the threshold temperature. The threshold could be detected at a resolution of 4 ℃ or less and was tried with 3 different materials for sensing of different temperatures.

The use of a dual signal system based on two different fluorescent dyes proved to have considerable advantages: The particles will be recovered in the geothermal fluids, which contain many different solutes, each with its own spectral features, making spectroscopic detection of tracers difficult. However, emissions from fluorescent dyes are only evoked by exciting the collected sample at specific wavelengths, giving the nanotracers a unique fingerprint. Fluorescent dyes also enable extremely sensitive detection, especially as many dye molecules are concentrated in a single particle. We were able to detect our particles in clean water with a sensitivity that translates to detection of 1.3 g of nanoparticles in 1,000,000 liters of water. Moreover, detection by fluorescence spectroscopy is fast, simple and cheap, and enables real time monitoring of geothermal fluids recovered at the exit point. The principle of an internal reference system makes the measurement direct and independent so that unambiguous data can be obtained without prior knowledge of reservoir parameters such as flow, without the need to conduct reservoir simulations or know reaction parameters to correctly analyse to results.

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