Technische Universität München

Lehrstuhl für Hydrogeologie

Geothermal Energy Group

Geothermie-Allianz Bayern

Inverse Estimation of Hydraulic Properties Using Real-World Pumping Test Data of Deep Geothermal Wells

Mohamed Moursy[1], Kai Zosseder[1], Florian Konrad[2]

[1] Chair of Hydrogeology, Technical University of Munich – In the frame of the "Geothermal Alliance Bavaria" project – Subproject: "Longterm"

[2] Stadtwerke München (SWM)

Motivation & Aim

Accurate characterization of the hydraulic properties of geothermal reservoirs is important in understanding and improving their performance. Numerical models are crucial in simulating geothermal systems, and their reliability depends on calibration using real-world data. Pumping tests provide valuable information for calibrating numerical models and improving their predictive capabilities.

This study focuses on inversely estimating the hydraulic properties of a complex reservoir characterized by two fault systems including the fracture zones around them, three matrix blocks, and six deep geothermal wells (Figure 1). This is done by calibrating simulated pumping tests with real-world ones conducted in the six wells. To calibrate the model, a large number of Monte Carlo simulated pumping tests were conducted to allow enough parameter combinations to match the real pumping tests. After running the simulations on a well, the pressure measurements recorded at the surrounding wells are compared with the real-world interference tests to validate the model. Pressure history, Bourdet derivative, and interference curves were plotted for all the runs and the fitting simulations were ultimately derived based on the visualization of these curves. Finally, the calibrated and validated model, which forms the basis for conducting predictive simulations, can be further used in sensitivity and parametric studies.

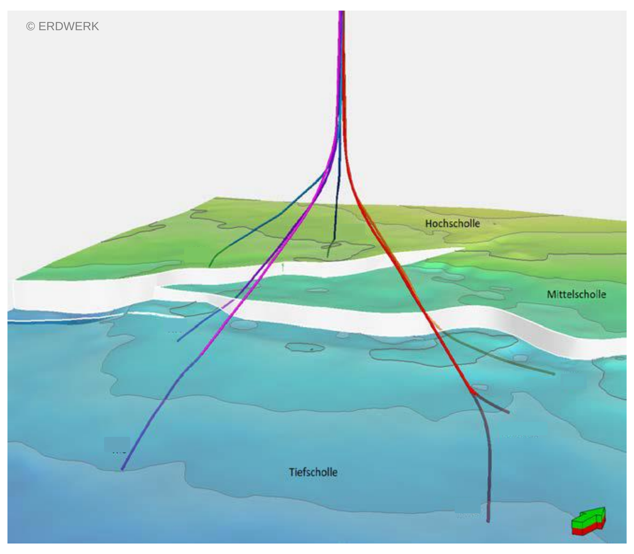


Figure 1: Reservoir components

Model Geometery

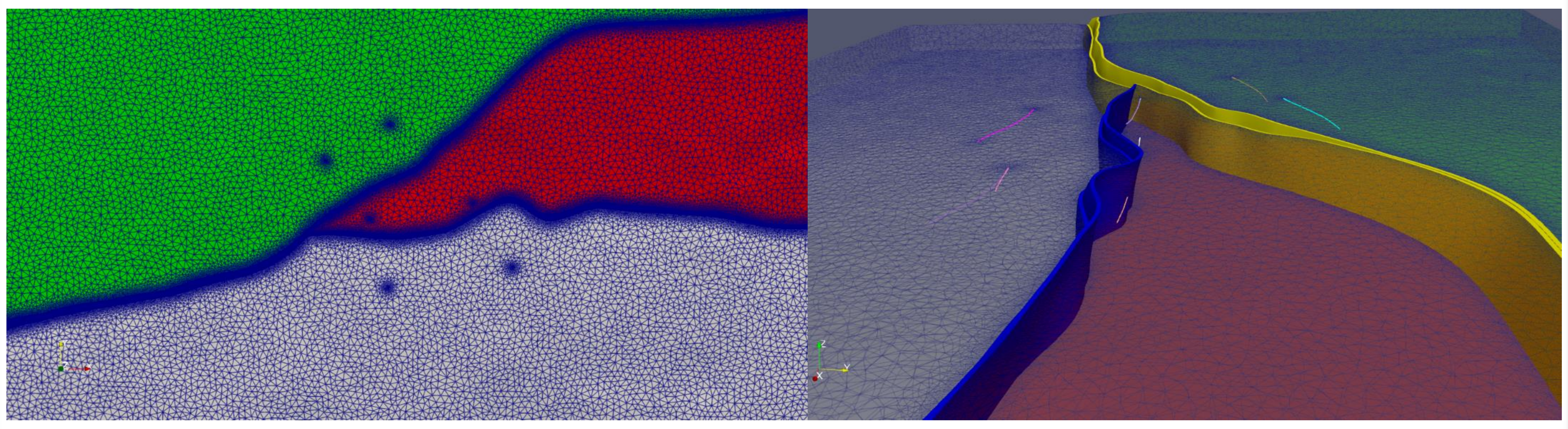
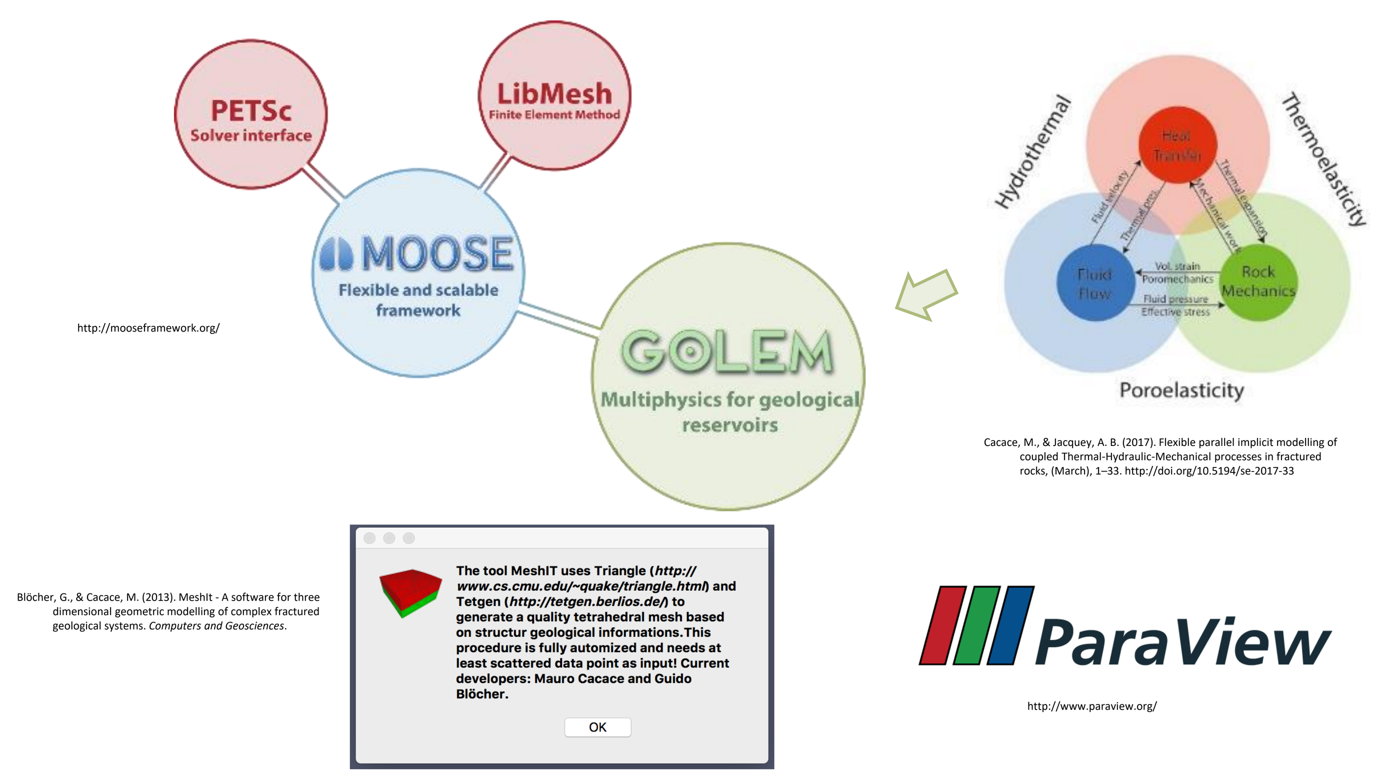


Figure 2: Mesh showing the reservoir components.

- An approximately 500 m thick reservoir is separated by two faults into three matrix blocks.
- Each fault core is surrounded by a fault zone of 70 m.
- Two wells in each matrix block, with a total of six wells.

Methodology



In this study, our numerical approach is comprised of using a combination of open-source tools including the numerical Multiphysics simulator Moose framework (Gaston et al. 2009), the finite-element reservoir simulation app GOLEM (Cacace and Jacquey 2017), the visualization-plus-pre-/post-processing-tool Paraview (Ahrens et al. 2005), and the unstructured tetrahedral mesh generator MeshIT (Blöcher et al. 2015). Together these tools allow for a continuum approach together with state-of-the-art numerical solvers and preconditioners, as well as parallelization capacities, suitable for high-performance supercomputers (Konrad et al. 2019). Since a large number of simulations is needed to satisfy enough parameter combinations for calibration, the open-source geostatistical tool RAVEN (Alfonsi et al. 2017) is used along with the available HPC cluster [LRZ Linux cluster (Leibniz-Rechenzentrum 2017)].

Spatial data for constructing the model were obtained from picked data points of the reservoir boundaries and main faults provided by 3D seismic surveys done in Munich city and were implemented in MeshIT to construct the mesh. The MOOSE simulator app GOLEM was then used to simulate pumping tests where the production conditions, the global parameters, and the water-table depths were adjusted to match that of the real-world pumping tests while changing the specific storage and the transmissivity of the rock matrices and the faults. Bohnsack et al. (2020) used different experimental methods and well-log data to provide the range of permeability and porosity values used in the simulations while information about the fluid properties was obtained from the NIST Chemistry Webbook (Lemmon et al. 2018) and McCain et al. (2011). A list of the parameters included in the GOLEM app is shown in Table 1. Using RAVEN, simulations with varying reservoir parameters were generated using a Monte Carlo approach, typically preferred in complex simulations due to its efficiency in exploring a multi-dimensional parameter space.

Table 1. Parameters included in the Golem app for hydraulic simulations

Global parameters	Material properties	Initial and boundary conditions	Pumping conditions	Simulation output
Solid density	Porosity	Initial pore pressure	Pumping rate	Change in Pressure
Fluid density	Permeability		Drawdown duration	
Fluid viscosity	Fluid modulus		Buildup duration	

After constructing and running the simulated pumping tests, the transient flow regimes were compared to those of the real-world pumping tests, through the pressure history and the Bourdet derivative (Bourdet 1989) curves of both tests. Interference tests, a form of multi-well tests, took place in our study site, i.e., when one well was in production (active well), pressure was measured at the surrounding wells (observational wells). These tests are sensitive to reservoir heterogeneity and they are very helpful in assessing the well-to-well pressure communication (Kamal 1983). For these reasons, the interference tests are used in our multi-well study after a fit of the pressure history and the Bourdet derivative curves is achieved between a simulation and the real-world pumping test. This process was repeated for all active wells until matching slopes of the pressures of the observational wells (between simulated and real wells) were realized.

Results

After several thousand simulation runs of single-well pumping tests, We found multiple simulations with a combination of hydraulic parameters that resulted in very close fits of pumping pressure curves and build-up analysis curves. In Figure 2 we show an example of these successful simulations.

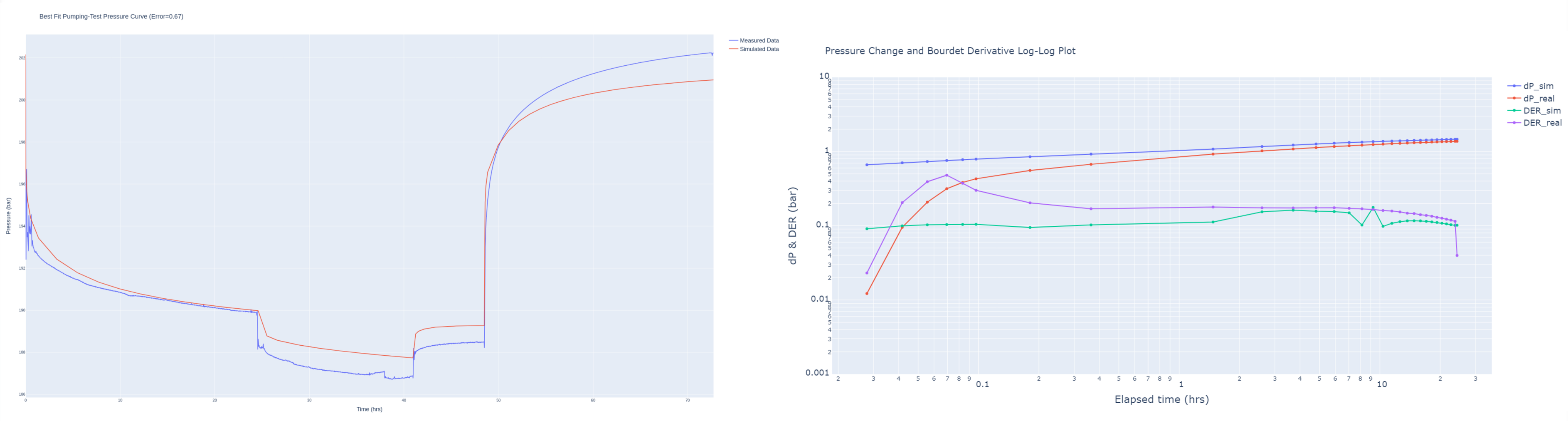


Figure 3: Left: Pumping pressure curve of measured Vs simulated pumping tests. Right: Pressure change and Bourdet derivative curves during the recovery phase.

The mean error percentage of the pressure curve for this simulation is around 0.67%.

However, best-fitting curves of pressure, pressure change, and Bourdet derivative can not be the only indication of a well-calibrated model as these similarities in the curves could also result from multiple combinations of hydraulic parameters (mainly transmissivity and specific storage). This is why we compare the pressure readings at the surrounding observational wells when one well is in production as shown in Figure 3.

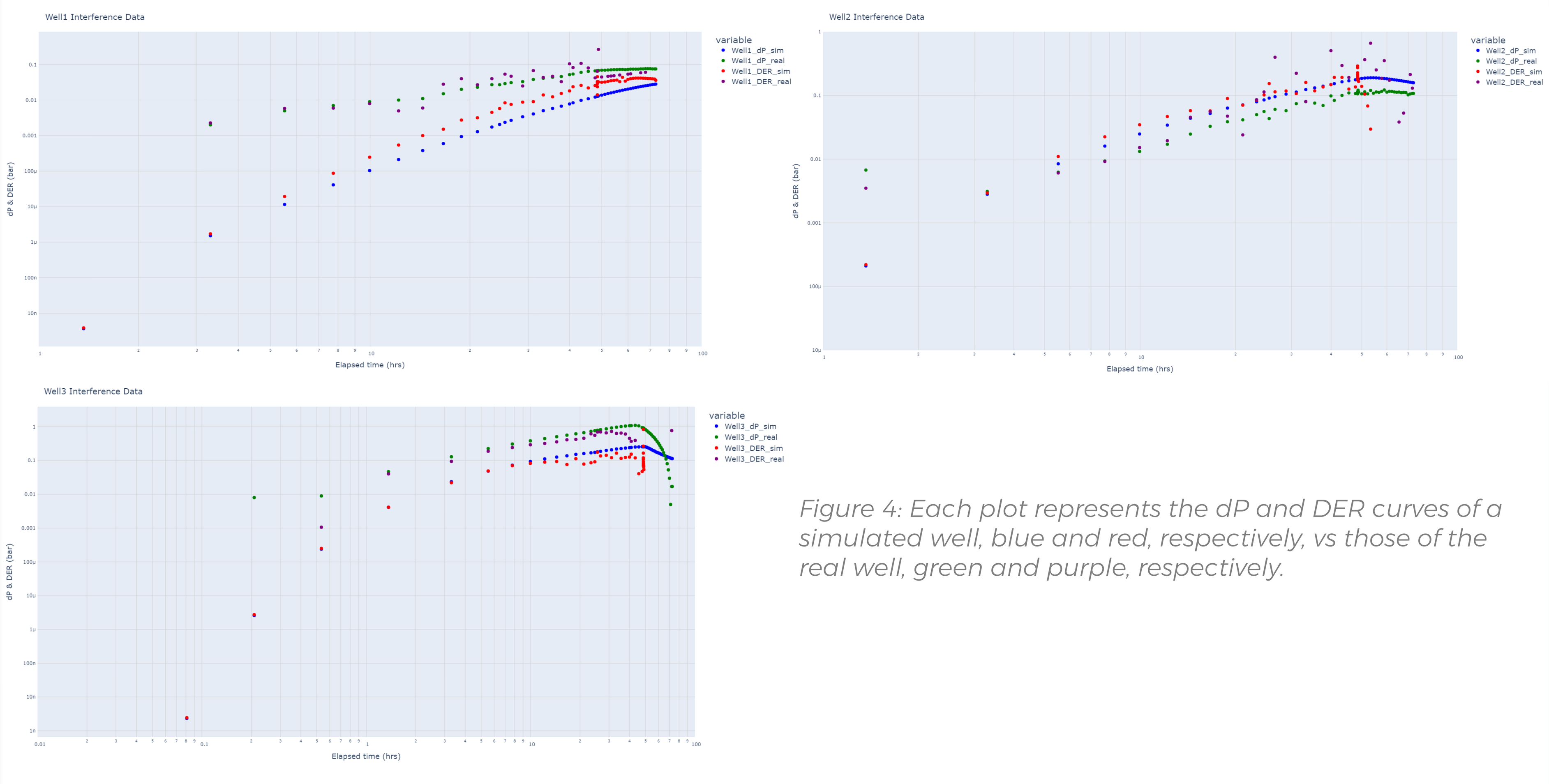


Figure 4: Each plot represents the dP and DER curves of a simulated well, blue and red, respectively, vs those of the real well, green and purple, respectively.

For the three wells, pressure change and Bourdet derivatives curves are in good alignment with the real data, especially after enough time has passed from the start of the pumping since it takes some time for the observational wells to detect pressure change resulting from the test..

These results can be then cross-checked with the other surrounding wells when each of them is solely active, i.e. undergoing a pumping test, and the pressure is recorded at the surrounding wells.

Conclusions

In a multi-well site, the use of pumping and interference tests together with a suitable combination of tools and sufficient computing power can effectively estimate the hydraulic parameters of a highly complex reservoir. In addition, the resultant parameter ranges from the calibration process of the simulated pumping tests can be further used for parametric studies

References

Ahrens, J., Geveci, B., & Law, C. (2005). ParaView: An End-User Tool for Large Data Visualization. Visualization Handbook. Elsevier.
Alfonsi, A., Rabiti, C., Mandelli, D., Cogliati, J., Wang, C., Talbot, P. W., . . . Smith, C. (2017). RAVEN Theory Manual and User Guide. Idaho National Laboratory.
Blöcher, G., & Cacace, M. (2015). MeshIt - A software for three dimensional volumetric meshing of complex faulted reservoirs. Computers and Geosciences, 74(6), 5191–5209. doi:https://doi.org/10.1007/s12665-015-4537-x.
Bohnsack, D., Potten, M., Pfrang, D., Wolpert, P., & Zosseder, K. (2020). Porosity–permeability relationship derived from Upper Jurassic carbonate rock cores to assess the regional. Geothermal Energy, 8(1). doi:https://doi.org/10.1186/s40517-020-00166-9.
Bourdet, Dominique, Ayoub, J. A., and Y. M. PIrard. "Use of Pressure Derivative in Well-Test Interpretation." SPE Form Eval 4 (1989): 293–302. doi: https://doi.org/10.2118/12777-PA
Cacace, M., & Jacquey, A. B. (2017). Flexible parallel implicit modelling of coupled thermal-hydraulic-mechanical processes in fractured rocks. Solid Earth, 8(5), 921–941. doi:https://doi.org/10.5194/se-8-921-2017
Gaston, D., Newman, C., Hansen, G., & Lebrun-grandié, D. (2009). MOOSE : A parallel computational framework for coupled systems of nonlinear equations. International Conference on Mathematics, Computational Methods & Reactor Physics, 239, 1768–1778. doi:https://doi.org/10.1016/j.nucLemmon, E. W., McLinden, M. O., & Friend, D. G. (2018). Thermophysical Properties of Fluid Systems. In P. J. Linstrom & W. G. Mallard (Eds.), NIST Chemistry WebBook, NIST Standard Reference Database Number 69. National Institute of Standards and Technology. doi:https://doi.org/https://doi.org/10.18434/T4D303engdes.2009.05.021
Konrad, F., Savvatis, A., Wellmann, F., & Zosseder, K. (2019). Hydraulic behavior of fault zones in pump tests of geothermal wells : a. Geothermal Energy [Internet]. Springer Berlin Heidelberg. doi:https://doi.org/10.1186/s40517- 019- 0137-4
MCCAIN, W.D., SPIVEY, J.P., JR. & LENN, C.P. (2011): Petroleum Reservoir Fluid Property Correlations. – 219 S. Oklahoma (PennWell).

M.Sc. Mohamed Moursy – TU München – m.moursy.ahmed@tum.de