CONTRIBUTION OF LARGE-SCALE FAULTS ON HYDROTHERMAL CIRCULATION IN DEEP GEOTHERMAL RESERVOIR IN THE UPPER RHINE GRABEN

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ABSTRACT

One assumption is generally made for the modeling of the deep EGS geothermal reservoir: the major geological structures such as the regional faults are the ones that control mostly the hydrothermal circulation at the reservoir scale (~10 km). We aim to study the relative influence of regional faults compared to the small-scale fracture network on the hydrothermal and mechanical states of the Rittershoffen geothermal reservoir (France). We develop a two-dimensional thermo-hydro-mechanical model (THM) at the reservoir scale. The representative elementary volume (REV) is at the scale of 100 m. The large-scale hydrothermal circulation and its associated observables are very well explained without large-scale faults. The regional "Rittershoffen" fault is then added in the model. Temperature, stress profiles and hydrothermal convection are only slightly disturbed by this large-scale fault. The regional fault is subsequently shown to have a weaker impact on the natural hydrothermal circulation than previously expected compared to the pervasive small-scale fracture network.

1. INTRODUCTION

The Upper Rhine Graben (called URG) has been shown to have a heterogeneous spatial distribution of temperature at depth which has been studied since the last century (Haas and Hoffmann 1929; Pribnow and Schellschmidt, 2000). High positive thermal anomalies such as in Soultz-sous-Forêts and Rittershoffen have been extensively studied and exploited as deep Enhanced Geothermal System (EGS) (Gérard et al 2006; Genter et al 2010). A large database of thermal, mechanical, geochemical, geophysical and geological measurements is available before, during and after exploitation for the EGS projects (Bresee 1992; Sausse et al 2010; Schaming et al 2016). Numerous modelling studies of these EGS sites have been performed in order to interpret available data (Sanyal et al 2000; Jain et al 2015; Tomac and Sauter 2017).

Typically numerical models are solving the physical balance equations including a more and less complex description of the fracture network in the reservoir via stochastic distributions (Cacas et al, 1990; Baujard and Bruel, 2006), or regular grid approach (Willis-Richards et al 1996; Kohl and Mégel, 2007) or based on deterministic set of faults (Guillou-Frottier et al 2013; Kohl et al 2000). They mostly describe simple physical interactions: some couple the thermal and fluid processes to describe the hydrothermal circulation (Guillou-Frottier et al 2013; Kohl et al 2000) and others couple the hydraulics and mechanical process to predict the localization of the shear events due to the exploitation of the reservoir (Baujard and Bruel, 2006; Gentier et al 2005).

When models are explicitly describing large-scale faults, they typically assume that faults are controlling the hydrothermal circulation in the reservoir. However, small-scale pervasive fracture network that are favorable to the fluid circulation is also known be present in EGS reservoirs.

In Soultz, the Ultra Borehole Image (UBI) logs and seismic measurements (VSP and microseismicity) have identified a dense network of more than forty small-scale areas in the granitic basement where some are clearly characterized as fluid pathways (Dezayes et al 2010, Cuenot 2006). The fractures have a mean aperture of 1.5 mm and a maximum aperture of 250 mm according to the core analyses (Traineau et al., 1991). The density of the open small-scale fractures is about 3.0 fractures.m^{-1} and 0.82 fractures.m^{-1} in the basement and sediments, respectively (Genter et al, 1997; Evans et al 2009).

In the closeby Rittershoffen site, the UBI logs highlight a strongly connected and permeable small-scale fracture network with a more highly fractured zone at the top of the granitic basement than at Soultz (Vidal et al 2016, 2017). In the present study, we aim to quantify the relative influence of the large-scale faults compared to the small-scale fractures on the hydrothermal circulation and the mechanical state of the reservoir. We focus on the case of the Rittershoffen deep geothermal site. To address the issue, a reservoir-scale model (~10 km) integrates thermo-hydro-mechanical

(THM) couplings in a two-dimension description. The Rittershoffen reservoir is homogenized at the scale of representative elementary volume (REV) about 100 meters (Vallier et al 2018).

After a presentation of the Rittershoffen EGS site, the meshing of the reservoir and the numerical resolution of the THM governing equations are developed. The observed trends of temperature and stress with depth are reproduced by adjusting the rock properties and the depth of the cap-rock by back-analysis. We discuss the impact of one large-scale fault on the hydrothermal circulation and mechanical state by explicitly describing the Rittershoffen fault inside the reservoir.

2. A RITTERSHOFFEN THM SIMPLE MODEL

2.1 An overview of the Rittershoffen site

The Rittershoffen site is located at 6 km South-East from Soultz-sous-Forêts and it is operated since 2016 (Genter et al 2015; Baujard et al 2017). The site is based on a doublet (GRT-1 and GRT-2) that targets the sediments-granite interface (Baujard et al 2015).

The knowledge concerning Rittershoffen is available thanks to the measurements from Soultz, the closeby site. The petrology is partially deduced thanks to cores from EPS-1 and GPK-1 wells (Aichholzer et al 2016). The stress field is assumed to be the same of the regional trends estimated at Soultz (Evans et al 2009; Cornet et al 2007). However, numerous specific geophysical, geochemical or stratigraphical studies have been conducted on the Rittershoffen site (Aichholzer et al 2016; Vidal et al 2016; Lengliné et al 2017; Sanjuan et al 2016).

Fig. 1a features the conceptual geology of the Rittershoffen geothermal site (Vallier et al 2018). The first 2.2 kilometers consist of the sedimentary cover (against 1.4 kilometers in Soultz) overlying a granitic basement. The shallowest granites are strongly fractured with about 2.5 fractures per meter (Vidal et al 2016). Two main natural fracture systems have been identified, one made of closely connected meso-fractures and the other of a set of large fractures crossing the former system (Dezayes et al 2014). After 2.5 km in depth i.e. below the wells, the characterization of the deep granitic basement is mostly based on the knowledge from the deep wells in the closeby Soultz site.

Fig. 1b illustrates the temperature-depth profiles from the GRT-1 and GRT-2 wells (Baujard et al 2017). Above the top of the Muschelkalk, the geothermal gradient is mostly constant about 85°C.km^{-1} then it sharply decreases at 1.65 km in depth until 3°C.km^{-1}. The constant gradient at the first kilometers has firstly been interpreted as indicator of a purely diffusive heat transfer. Its decline at 1.65 km deep is seen as an effect of a hydrothermal convection. Geochemical analysis evidences also a strong circulation between the wells (Sanjuan et al 2016). The Rittershoffen stress state is assumed to be consistent with the regional trends (Baujard et al 2017) and its evolution with depth has been estimated at the nearby Soultz site (Evans et al 2009; Cornet et al 2007).

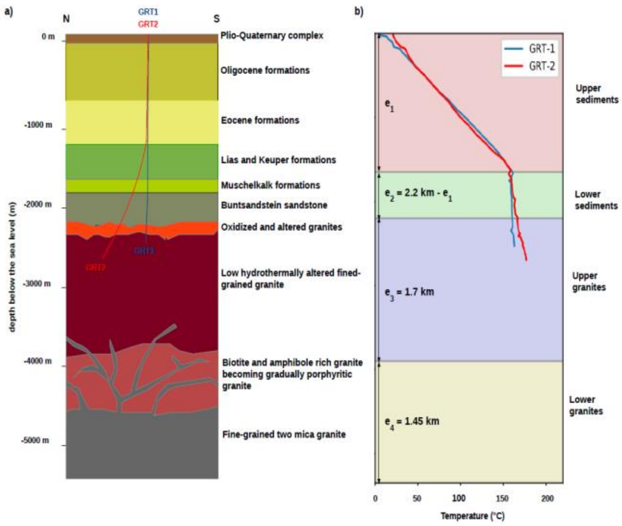

Figure 1: a) Conceptual geology of Rittershoffen inspired from Vidal et al (2017), Aichholzer et al (2016) and Dezayes et al 2005a. b) Temperature–depth profiles from the GRT-1 and GRT-2 wells (Baujard et al. 2017). The background colors correspond to the four layers homogenized in the model.

2.2 Towards a homogenized reservoir model

To study the impact of one regional fault, we initially develop a reservoir model as a 2D vertical cross-section without any large-scale fault. The small-scale fracture network is homogenized by assuming a REV of 100 m. Below the REV, faults and fractures are not explicitly described in the model but inverted from in-situ measurements by performing a back-analysis of the rock properties. As illustrated in Fig. 1b, the subsurface is split into four horizontal homogenized units: the upper, lower sediments and upper, lower granites. The depth of the transition between the sediments is an explored parameter during the back analysis of the observed profiles. The transition sediments-granite and between the granites are set at 2.2 km and 3.9 km in depth, respectively.

2.3 Coupled THM processes

The homogenized units are assumed to be a fully saturated porous medium with a single-phase brine. The model describes the coupled THM processes from a linear thermo-poro-elastic approach in the limit of the small perturbation as developed by Coussy (2004). The complete set of equations governing the THM coupling is presented in Vallier et al (2019). Here, the Cauchy stress is split into the effective stress and the hydraulic stress. Homogenized properties are depending on temperature, fluid pressure and porosity thanks to classic mixing laws.

One specificity of our THM model is that the brine rheology depends on temperature and/or fluid pressure using laboratory measurements of the rheology of a NaCl pure solution with a mass content of 100 g.L^{-1}

(Zaytsev and Aseyev 1992; Kestin et al. 1981; Rowe and Chou 1970). The temperature dependence of the brine rheology in particular for the fluid dynamic viscosity has been shown to have a strong influence on the hydrothermal circulation (Vallier et al 2019).

2.4 Numerical aspects

Direct model

The simulations are carried with the open-source finite element *Code_Aster* software (EDF 2014). The equations governing the THM coupling are solved with an Euler implicit scheme and the increment of the generalized displacements is calculated using the Newton-Raphson algorithm.

Initially, constant and uniform temperature and fluid pressure distributions are respectively set at 10.0°C and 0.1 MPa. The calculation is split up in three successive steps to improve the convergence of the process (Magnenet et al 2014): (i) during a short time period of 1000 years, the boundary conditions and gravity are progressively applied; (ii) next, during 100,000 years, the system freely evolves along constant boundary conditions; (iii) in one last increment, a steady-state solution is obtained by cancelling the time-dependent terms from the THM equations.

Fig. 2 sketches the Rittershoffen model with the four idealized units. Its height and width are respectively set at 5.35 km and 10 km in width. The typical size of the quadratic THM element is 100 meters. The boundary THM conditions are also illustrated in Fig.2: (i) for the thermal state, the temperatures are, respectively, maintained at 10.0 and 213.0°C on the upper and lower boundaries. The lateral boundaries are taken as adiabatic; (ii) for the hydraulic state, a fluid pressure of 0.1 MPa is set on the upper boundary; the other boundaries are assumed to be impermeable; (iii) for the mechanical part, the normal displacement is fixed to zero on the lower and lateral boundaries. The upper boundary is stress free.

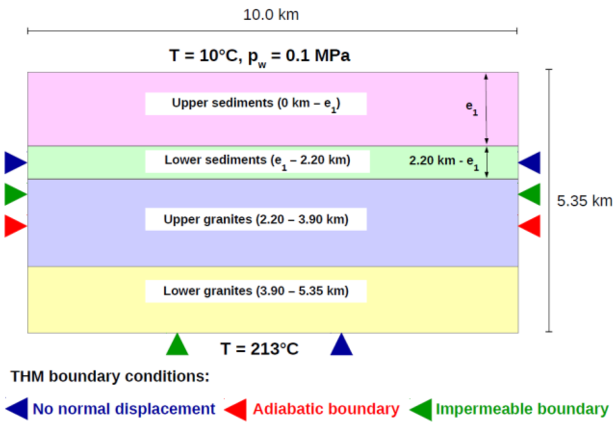

Figure 2: 2D vertical cross-section and THM boundary conditions. Here, the thickness of the first layer e_1 is evaluated during the back analysis.

Back-analysis

To characterize the hydrothermal circulation and the mechanical state of the reservoir, we aim to reproduce the observed thermal and stress data and estimate the rock physical and geometrical parameters at the reservoir scale. We proceed to a back-analysis using the open-source PEST software (Doherty 2005). The process is based on the Levenberg-Marquardt algorithm minimizing the error function i.e. the L2-norm of the discrepancy between simulated and observed temperature and stress-depth profiles according to a prior set of parameters. The four rock properties explored during the back-analysis are the permeability, thermal conductivity, Young's modulus and Poisson's ratio to reproduce the temperature and stress – depth profiles observed in Rittershoffen. The depth of the transition between the two sedimentary units is also adjusted during the back-analysis. The other rock properties and depths of interfaces are set as constant during the back-analysis. Low CPU time consuming, this method is however sensitive to its initial conditions i.e. the prior distributions. The knowledge from Soultz allows some constrains of the prior distributions for the rock properties.

3. RESULTS OF THE BACK-ANALYSIS WITHOUT ANY REGIONAL FAULT

3.1 Hydrothermal processes

Fig. 3a shows the excellent fit of the GRT-1 T-log after back-analysis, adjusting the rock-properties and the depth of the transition between the sediments. Without any large-scale fault, the homogenized THM model reproduces the main trend of the observed profile with values of rock properties consistent with laboratory data (Vallier et al. 2018).

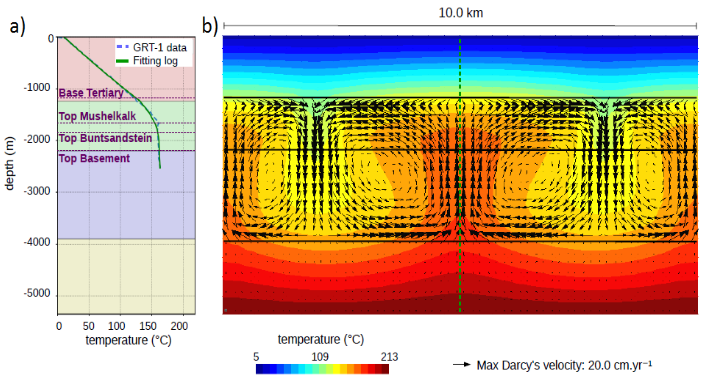

Figure 3: a) Comparison between the observed T-log in GRT-1 (dashed blue line) and the best fitting simulated vertical temperature-depth profile (green line). The purple dashed lines correspond to the lithological limits. b) Associated temperature and Darcy's velocity (black arrows) maps. The dashed green and black lines are respectively the position of the profile and the limits of the units.

Fig. 3b illustrates the temperature and Darcy's velocity maps associated with the best fit of the observed data. A large-scale convective system is obtained with convection cells having a width and height respectively of 3.0 km and 2.7 km. The maximum of Darcy's velocity is 20.0 cm.yr^{-1}, a value close to estimations from previous modelling and hydraulic tests (Clauser 1990; Guillou-Frottier et al 2013; Baria et al 1998). The thickness of the hydraulic cap-rock is obtained about 1.2 km, its bottom does not correspond to the breaking point of the T-log as previously expected (Baujard et al 2017).

3.2 Mechanical processes

Simultaneously, the observed trends of the stress principal components with depth are reproduced by a back-analysis of the elastic moduli (Young's modulus and Poisson's ratio). The stress-depth trends are taken from the measurements at the Soultz site (Evans et al 2009; Cornet et al 2007). They are assumed to be similar for the Rittershoffen site (Baujard et al 2017). The model is also assumed to be oriented along the direction of the maximum horizontal principal stress.

Fig 4 shows the best fit for each of three stress components. All stress-depth trends are well reproduced with elastic moduli rather consistent with the laboratory data.

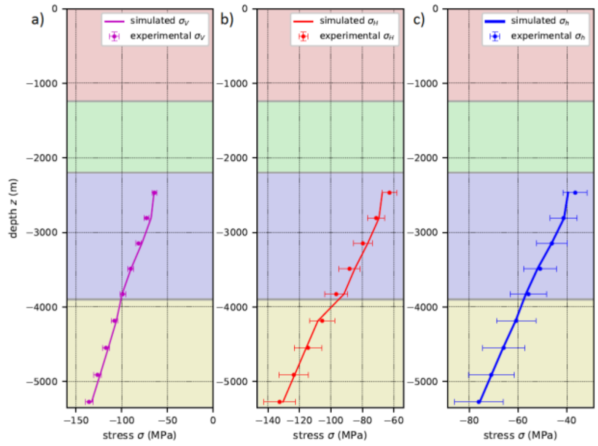

Figure 4: Comparison between the observed principal stress components (dashed lines) and the best simulated profiles (full lines): a) the vertical stress. b) the horizontal maximum stress. c) the horizontal minimum stress.

Overall, the model homogenizing the small-scale fracture network allows the description of most of the rock properties, thermal and mechanical observations by describing a reservoir-scale convective system.

4. IMPACT OF THE RITTERSHOFFEN FAULT

4.1 Characteristics of the Rittershoffen fault

Contrary to our assumption, many numerical studies consider that the hydrothermal circulation and mechanical reservoir state are mostly driven by the large-scale faults (Baujard and Bruel 2006; Kohl and Mégel 2007; Kohl 2000). To address this issue, we describe one of the main regional faults crossing the geothermal site: the Rittershoffen fault.

This major fault is extending from the surface to 3.5 km in depth with a N-S strike and 40 meters thick (GeORG 2013; Baujard et al 2016). From hydraulic tests, its permeability has been assessed: 5.34 x 10^{-14} m^2 (Baujard et al 2017). A rather large range of dip has been evaluated according to different measurements: 45° from 3D geological model (Baujard et al 2017); 74° and 83° respectively from fitting plane of induced seismic events (Lengliné et al 2017) and small-scale acoustic logs (Vidal et al 2016). The simulations are carried out for the three values of the dip to study the influence of the dip on the hydrothermal circulation.

4.2 Influence on the hydrothermal processes

Fig. 5 features the temperature and Darcy's velocity maps when the Rittershoffen fault is included and described with a dip of 45°. An ascending hydrothermal circulation is shown to exist along the fault. The associated maximum of Darcy's velocity is estimated to be of the order of 26.0 cm.yr^{-1}, slightly higher than in the case without fault. Importantly the perturbation is local. The reservoir-scale convective system shows the same number of convective cells with similar dimensions to the model without any large-scale fault.

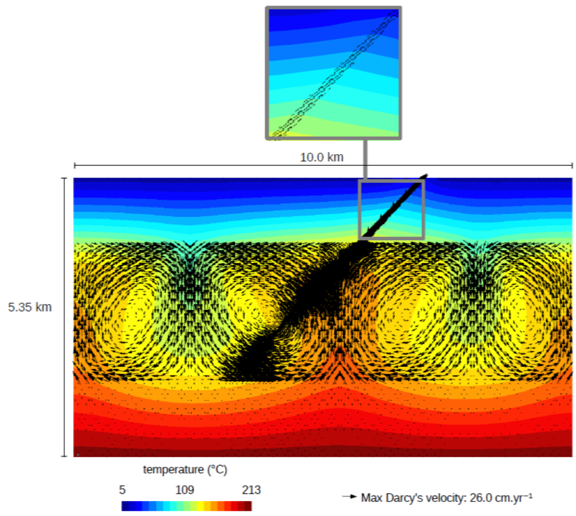

Figure 5: Simulated temperature and Darcy's velocity maps for the model describing the Rittershoffen fault with a dip of 45°. A closer zoom has been made near the fault in the sediments.

Fig. 6 illustrates the simulated temperature-depth profile when the Rittershoffen fault is described for the three different dips. The discrepancy between the different dips is less than 2°C. After adding a fault, the temperature shift is at maximum of about 6°C at 2.0 km in depth. The temperatures are slightly higher in the sedimentary cover and weaker in the basement, but the general profile trend stays mostly undisturbed.

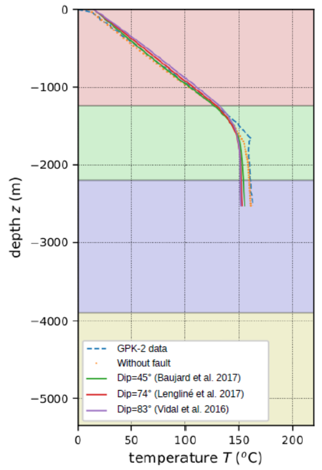

Figure 6: Comparison between the simulated temperature–depth profiles from models including the Rittershoffen fault with different dips and the model without the fault. All the profiles are extracted at the location of the maximum of the ascending flow.

4.3 Influence on the mechanical processes

Fig. 7 shows the comparison of the stress-depth profiles between the cases including the Rittershoffen fault and the previous one without any major fault. Once again, the influence of the dip on the simulated profiles is very negligible and the introduction of the fault does not show an important impact on the mechanical state. The maximum difference is about 1 MPa for the maximum horizontal stress at the interface between the granites.

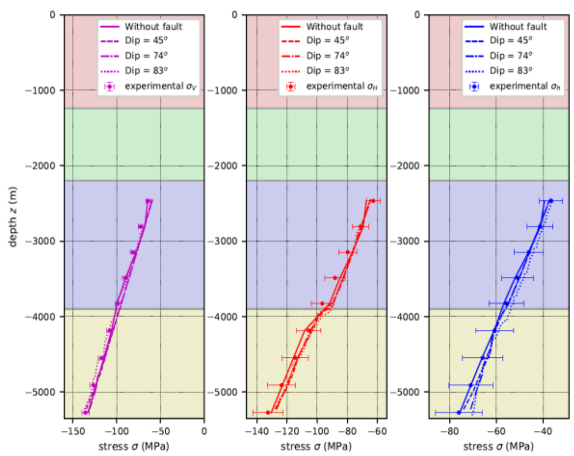

Figure 6: Comparison between the simulated principal components of the stress trends with depth from models including the Rittershoffen fault with different dips and the model without the fault: the vertical stress (purple), horizontal maximum stress (red), horizontal minimum stress (blue).

To summarize, for both the hydrothermal circulation and the stress state, the influence of a regional fault is not important compared to the pervasive small-scale fracture network.

5. CONCLUSIVE REMARKS

Applied to Rittershoffen, the THM model has been able to reproduce the observed thermal and mechanical profiles associated with a large-scale convective system. This accordance between the model and the observations has been obtained without explicitly describing any major fault. To study the impact of one regional fault on the natural reservoir state, the “Rittershoffen” fault with different values of dip has been added into the deep geothermal reservoir. The temperature disturbance is less than 6°C after describing the fault. A circulation is obtained along the fault, but the reservoir-scale convective system is only slightly perturbed. Concerning the stress state, the trends of the observed profiles reveal a discrepancy of less than 1 MPa owing to the Rittershoffen fault. In both cases, the influence of the fault dip can be negligible. The study allows us to validate that the regional faults are not significantly controlling the hydrothermal circulation which supports the homogenisation approach of our THM model.

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REFERENCES

Aichholzer C, Duringer P, Orciani S, Genter A. New stratigraphic interpretation of the Soultz-sous-Forêts 30-year-old geothermal wells calibrated on the recent one from Rittershoffen (Upper Rhine Graben, France). Geothermal Energy. 2016 ;4(1):13.

Baria R, Baumgärtner J, Gérard A, Jung R. The European HDR programme 1992-1995. Technical Report; Joule III Programme, final report EUR 18925 EN; 1998.

Baujard C, Bruel D. Numerical study of the impact of fluid density on the pressure distribution and stimulated volume in the Soultz HDR reservoir. Geothermics. 2006;35(5):607–21.

Baujard C, Genter A, Graff J.J, Maurer V, Dalmais E. ECOGI a new deep EGS project in Alsace, Rhine Graben, France In: Proceedings world geothermal congress. 2015.

Baujard C, Genter A, Dalmais E, Maurer V, Hehn R, Rosillette R. Temperature and hydraulic properties of the Rittershoffen EGS reservoir, France In: European geothermal congress. 2016.

Baujard C, Genter A, Dalmais E, Maurer V, Hehn R, Rosillette R, Vidal J, Schmittbuhl J. Hydrothermal characterization of wells GRT-1 and GRT-2 in Rittershoffen, France: implications on the understanding of natural flow systems in the Rhine Graben. Geothermics. 2017; 65:255–68.

Bresee, J.C.. Geothermal Energy in Europe: The Soultz Hot Dry Rock Project. CRC Press, 1992.

Cacas M, Ledoux E, de Marsily G, Tillie B, Barbreau A, Durand E, Feuga B, Peaudecerf P. Modeling fracture flow with a stochastic discrete fracture network: Calibration 1. The flow and validation model. Water Resour Res. 1990; 27:479–89.

Clauser C, Villinger H. Analysis of conductive and convective heat transfer in a sedimentary basin, demonstrated for the Rheingraben. Geophys J Int. 1990;100(3):393–414.

Cornet FH, Bèrard T, Bourouis S. How close to failure is a granite rock mass at a 5 km depth? Int J Rock Mech Mining Sci. 2007;44(1):47–66.

Coussy O. Poromechanics. Chihester: Wiley; 2004.

Cuenot N, Charléty J, Dorbath L, Haessler H. Faulting mechanisms and stress regime at the European HDR site of Soultz-sous-Forêts, France, Geothermics, Vol. 35, No. 5-6, 561-575. 2004.

Dezayes C, Gentier S, Genter A. Deep geothermal energy in Western Europe: the Soultz project. Orleans: Technical Report; 2005a.

Dezayes C, Sanjuan B, Gal F, Lerouge C, Fluid geochemistry monitoring and fractured zones characterization in the GRT-1 borehole (ECOGI project, Rittershoffen, Alsace, France). In: Deep Geothermal Days, Paris, France. 2014.

Doherty J. Model independent parameter estimation. 2005. http://www.pesthomepage.org.

EDF R. *Code_Aster* Open Source - general FEA software. 2016. http://www.code-aster.org.

Evans K, Valley B, Häring M, Hopkirk R, Baujard C, Kohl T, Magel T, Andrè L, Portier S, Vuataz F. Studies and support for the EGS reservoirs at Soultz-sous-Forêts. Centre for Geothermal Research CREGE CHYN: Technical report; 2009.

Genter A, Castaing C, Dezayes C, Tenzer H, Traineau H, Villemin T. Comparative analysis of direct (core) and indirect (borehole imaging tools) collection of fracture data in the Hot Dry Rock Soultz reservoir (France), Journal of Geophysical Research, vol. 102, B7, 15419-15431. 1997.

Genter A, Evans K, Cuenot N, Fritsch D, Sanjuan B. Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS). Comptes Rendus Geosci. 2010 ; 342(7):502–16.

Genter A, Cuenot N, Graff JJ, Schmittbuhl J, Villadangos G. La géothermie profonde en France : quelles leçons tirer du projet pilote de Soultz-sous-Forêts pour la réalisation d'un projet industriel à Rittershoffen. Revue Géologues. 2015 ; 185:97-101.

Gentier, S, Rachez, X, Dezayes, C, Blaisonneau, A, Genter, A., 2005. How to understand the effect of the hydraulic stimulation in terms of hydro-mechanical behavior at Soultz-sous-Forêts (France). GRC Trans. 29, 159–166.

GeORG Potentiel géologique profond du Fossé Rhénan supérieur. Parties 1 à 4. 2013. http://www.geopotenziale.eu.

Gérard A, Genter A, Kohl T, Lutz P, Rose P, Rummel F. The deep EGS (enhanced geothermal system) project at Soultz-sous-Forêts (Alsace, France). Geothermics. 2006;35(4):473–83.

Guillou-Frottier, L., Carre, C., Bourgine, B., Bouchot, V., Genter, A. Structure of hydrothermal convection in the Upper Rhine Graben as inferred from corrected temperature data and basin scale numerical models. Journal of Volcanology and Geothermal Research. 2013; 256:29-49.

Haas, IO, Hoffmann, CR. Temperature gradient in pechelbronn oil-bearing region, Lower Alsace: its determination and relation to oil reserves. AAPG Bulletin 1929;13(10):1257–1273.

Jain C, Vogt C, Clauser C. Maximum potential for geothermal power in germany based on engineered geothermal systems. Geothermal Energy. 2015;3(1):15.

Kestin J, Khalifa H.E, Correia R.J. Tables of the dynamic and kinematic viscosity of aqueous NaCl solutions in the temperature range 20-150°C and the pressure range 0.1-35 MPa. J Phys Chem Ref Data. 1981;10(1):71–88.

Kohl T, Mègel T. Predictive modeling of reservoir response to hydraulic stimulations at the European EGS site Soultz-sous-Forêts. Int J Rock Mech Mining Sci. 2007;44(8):1118–31.

Kohl T, Bächler D, Rybach L. Steps towards a comprehensive thermo-hydraulic analysis of the HDR test site Soultz-sous-Forêts In: Proceedings world geothermal congress. 2000. p. 2671–6.

Lengliné O, Boubacar M, Schmittbuhl J. Seismicity related to the hydraulic stimulation of GRT-1, Rittershoffen, France.Geophys. JInt. 2017; 208 (1) :1704–15.

Magnenet V, Fond C, Genter A, Schmittbuhl J. Two-dimensional THM modelling of the large scale natural hydrothermal circulation at Soultz-sous-Forêts. Geotherm Energy. 2014;2(1):17.

Rowe AM, Chou JCS. Pressure–volume–temperature-concentration relation of aqueous sodium chloride solutions. J Chem Eng Data. 1970;15(1):61–6.

Sanjuan B, Scheiber J, Gal F, Touzelet S, Genter A, Villadangos G. Inter-well chemical tracer testing at the Rittershoffen geothermal site (Alsace, France). In: European Geothermal Congress. 2016.

Sanyal SK, Butler SJ, Swenson D, Hardeman B. Review of the state-of-the-art of numerical simulation of enhanced geothermal systems. Trans. Geotherm. Resourc. Council. 2000; 28:181–6.

Sausse, J., Dezayes, C., Dorbath, L., Genter, A., Place, J. 3d model of fracture zones at Soultz-sous- Forêts based on geological data, image logs, induced microseismicity and vertical seismic profiles. Comptes Rendus Geoscience 2010;342(7):531–545.

Schaming, M., Grunberg, M., Jahn, M., Schmittbuhl, J., Cuenot, N., Genter, A., Dalmais, E. CDGP, the data center for deep geothermal data from alsace. In: EGU General Assembly Conference Abstracts. 18; 2016. p. 9897.

Tomac, I., Sauter, M. A review on challenges in the assessment of geomechanical rock performance for deep geothermal reservoir development. Renewable and Sustainable Energy Reviews 2017.

Traineau, H., Genter, A., Cautru, J.P., Fabriol, H., Chevremont, P. Petrography of the granite massif from drill cutting analysis and well log interpretation in the geothermal HDR borehole GPK-1 (Soultz, Alsace, France). Geothermal Science and Technology 1991;3(1):1–29.

Vallier B., Magnenet V., Schmittbuhl J., Fond C., THM modeling of hydrothermal circulation at Rittershoffen geothermal site, France. Geothermal Energy. 6:22. (2018).

Vallier B., Magnenet V., Schmittbuhl J., Fond C., Large scale hydro-thermal circulation in the deep geothermal reservoir of Soultz-sous-Forêts (France). Geothermics. 1:78. (2019).

Vidal J, Genter A, Schmittbuhl J. Pre- and post-stimulation characterization of geothermal well GRT-1, Rittershoffen, France: insights from acoustic image logs of hard fractured rocks. Geophys J Int. 2016a;206(2):845–60.

Vidal J, Patrier P. Genter A, Beaufort D. Occurrences of clay minerals in permeable fracture zones in the granitic basement of geothermal wells at Rittershoffen, France In: 42nd Workshop on geothermal engineering Stanford University, Stanford, California, February 13–15. 2017.

Willis-Richards J, Watanabe K, Takahashi H. Progress toward a stochastic rock mechanics model of engineered geothermal systems. J Geophys Res. 1996; 101:17481–96.

Zaytsev ID, Aseyev GG. Properties of aqueous solutions of electrolytes. Boca Raton: CRC Press; 1992.