European Geothermal Congress 2016

Strasbourg, France, 19-24 Sept 2016

Implication of petrography and structure of a rock mass for geomechanical processes associated with EGS projects

Carola Meller[1], David P. Sahara[1,2], Thomas Kohl[1]

[1] Karlsruhe Institute of Technology, Adenauerring 20b, 76131 Karlsruhe, Germany

[2]Institut Teknologi Bandung, Jalan Ganesha No. 10 Bandung, 40132 Indonesia

carola.meller@kit.edu

Keywords: EGS, hydrothermal alteration, geomechanics, induced seismicity, Soultz-sous-Forêts.

ABSTRACT

Effective and low-risk stimulation of geothermal reservoirs requires profound understanding of the lithology and structure of the target rock mass, which are key factors for the geomechanical response to high-pressure injection. The characterization of a rock volume is generally accomplished on the basis of geophysical borehole logging, hydraulic measurements, and cutting analysis. Very rarely, drill core material is available. Novel methods are required to retrieve a maximum amount of information from often limited data.

The Enhanced Geothermal System (EGS) in Soultz-sous-Forêts provides a large database of both, geophysical and hydraulic data, to develop and test new analysing techniques giving insight into processes during hydraulic stimulation. Recent studies [*Meller and Kohl*, 2014, 2015] already demonstrated a significant impact of hydrothermal alteration zones in granitic reservoir rock on the mechanical processes related to stimulation and deep water circulation.

This study aims at integrating various different datasets towards a petrophysical and structural description of the reservoir rock. We use borehole and hydraulic data of the Soultz-sous-Forêts EGS field to characterize the deep crystalline reservoir with respect to its role in affecting the failure processes during stimulation. Neural network analysis was applied to identify alteration zones and their related clay content. Combination of borehole data revealed the existence of mainly three geological units, which differ in lithology, alteration grade, and fracture content: the porphyritic granite, a transition zone, and a two-mica granite.

The occurrence of an abundance of fractures and breakouts in the two-mica granite indicate that this zone is weaker than the massive porphyritic granite. The interjacent transition zone is identified by its high clay content. A basically different response to fluid injection is observed for the three rock units. The study reveals an episodic fracture reactivation from two-mica to porphyritic granite, an anti-correlation between clay content and seismicity, and a significantly higher number of events in the two-mica granite. As the crystalline basement is the main target for EGS in the Upper Rhine Graben ab EGS projects world-wide, the understanding of the lithological key factors controlling seismicity in granitic rock is crucial for the future development of EGS.

1. INTRODUCTION

The response of a rock mass to massive fluid injections is to a large part determined by its mechanical heterogeneities originating from changes in lithology, fracture occurrence and hydrothermal alteration [*Zoback*, 2014]. Experimental studies revealed significant correlation between petrography and the frictional strength of granite (e.g. Collins and Young [2000] and Sajid et al. [2016]). Petrography changes induced by hydrothermal alteration therefore play an essential role for geothermal reservoirs. The dissolution of primary rock-forming minerals and the precipitation of secondary minerals, such as quartz, clay, or carbonates, change the in situ conditions on the mechanical strength of the rock [*Meller and Kohl*, 2014]. Jaeger et al [2007] showed that also pre-existing fractures in the reservoir have a significant effect on its weakening mechanism, especially if those fractures are oriented preferably to the maximum principal stress. For detailed characterization of a geothermal reservoir and to assess its mechanics, it is important to understand the significance lithology, fracture occurrence and hydrothermal alteration.

1.1 The Soultz-sous-Forêts project

The European geothermal project of Soultz-sous-Forêts targets a geothermal anomaly at the western border of the Upper Rhine Graben. Five wells have been drilled to a maximum depth of 5 km. The upper geothermal reservoir is hosted by a porphyritic monzogranite, which extends to a depth of ~4800 m forming the main granitic body of the Soultz geothermal system. It is characterized by large kalifeldspar crystals in a matrix of quartz, plagioclase, biotite, amphibole and accessories of magnetite, titanite, apatite, and allanite [*Hooijkaas et al.*, 2006]. The lower geothermal reservoir lies in fine-grained two-mica granite occurring at 4800 m depth with primary muscovite and biotite and only minor kalifeldspar.

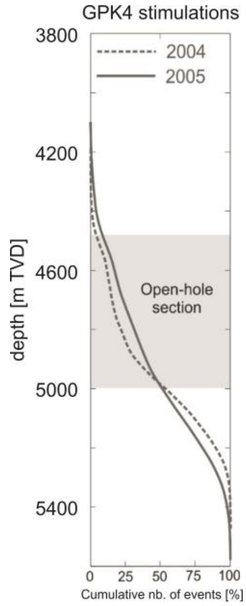
The pluton has been affected by the Upper Rhine Graben tectonics, which caused the formation of large sets of fracture zones, which are the main pathways for circulating fluids. Paleo-circulation of meteoric fluids from the Graben shoulders led to pronounced alteration of the Soultz granite. Alteration halos around the fractures are characterized by the transformation of mainly silicates and the precipitation of secondary clay minerals, quartz, carbonates, sulphates and iron oxides [*Genter and Traineau*, 1995].

The well GPK4 was stimulated twice. Details of the stimulation procedure will be given below. The cumulative number of events recorded during the 2004 and 2005 stimulations show, that the number of events is not very high (Fig.1) and the number of events varies with depth. 80% of located events occurred below 4800 m TVD. We assume that the different microseismic behaviour can be attributed to different structural and petrographical properties of the lithological units.

1.2 Results of preceding studies

The exceptionally large database of the Soultz-sous-Forêts EGS project including extensive logging and hydraulic, as well as seismic data, allows detailed analyses of the reservoir characteristics.

In a previous study, Sahara et al. [2014] showed the immediate effect of the fracture network on the heterogeneity of the stress field seen from stress indicators like borehole breakouts in the well GPK4. Magnetic susceptibilities of cuttings were used by Meller et al. [2014b] to estimate the lithology and the alteration grade of the Soultz granite. The clay content as an indicator of hydrothermal alteration has been estimated from fracture data and spectral gamma ray (SGR) logs by Meller et al. [2014a] using a neural-network analysis. In order to better explain the mechanical behavior of the reservoir, more detailed analysis of fractures and alteration in the Soultz-sous-Forêts reservoir and their impact on the mechanical properties is necessary.



	Duration (h)	Injected volume (m^3)	Number of located seismic events
GPK4 2004	83	9300	5753
GPK4 2005	95	12300	2968

Fig. 1 Cumulative number of microseismic events as a function of depth in GPK4. The open-hole section is marked in grey. The table shows duration, injected volume and the number of located events during the two stimulations.

1.3 Study goal

This study aims at developing a better understanding of the response of the Soultz reservoir to massive fluid injection on the basis of its petrographic and structural properties. It focuses on the open-hole section of GPK4 from 4480 to 4980 m depth TVD. A combination of magnetic susceptibility, fractures, alteration, and breakouts is used to identify different petrographical zones inside the reservoir. The seismic event catalogue recorded during hydraulic stimulation of GPK4 is subsequently used to identify patterns in the occurrence of microseismicity related to the petrographic zones. This study can provide key information for an improved planning and performance of reservoir stimulation.

2. METHODS

2.1 Database

The lithology of the rock was derived from cutting data analysis [Dezayes et al., 2005] combined with magnetic susceptibility measurements [Meller et al., 2014b]. A combination of bulk magnetic susceptibility and temperature-dependent susceptibility of drill cuttings was used to distinguish between porphyritic and two-mica granite and to determine the alteration grade of the rock.

Data of pre-existing fractures in the well GPK4 were obtained from image logs provided by the French Geological Survey (BRGM) [Dezayes et al., 2005]. Major fracture zones derived from geological analysis, induced microseismicity and vertical seismic profiles

[*Dezayes et al.*, 2010; *Sausse et al.*, 2010b] are also used in this analysis.

The alteration degree was estimated from a neural network based synthetic clay content analysis performed in the Soultz reservoir by Meller et al. [2014a].

Breakout data is used to infer the in-situ stress field and its heterogeneities in the reservoir [Sahara et al., 2014]. The orientation and width of borehole elongation trends on UBI images of the granite section of GPK4 were measured every 2 cm. A total of 472 borehole elongation pairs were identified in the open-hole section of GPK4. This detailed breakout data allowed for examination of the stress heterogeneity and its correlation with the mechanical properties of the crystalline rock.

Hydraulic stimulation data from GPK4 were recorded during two stimulations in September 2004 and February 2005. Both injections lasted about four days, whereas the total injected volume was 9300 m3 and 12300 m3, respectively. The injection of the 2004 stimulation was conducted at a constant injection rate of 30 L/s. At the end of the third day the injection rate was increased to 45 L/s for a few hours. Approximately 560 m^3 of NaCl heavy brine with a density of ~ 20% higher than fresh water were injected in the first six hours. In the 2005 stimulation, the injection was performed using fresh water only and was divided into three phases: 30 L/s for 24 hours, 45 L/s for 48 hours and 25 L/s for 24 hours. The bottom hole pressure (BHP) is determined using an in-house numerical borehole simulator [Nusiaputra et al., 2015], which using flow rate, pressure, equivalent NaCl-molality and fluid temperature.

The microseismic catalogue is taken from Dyer [2005] obtained. Recording of the seismic events was accomplished by three 4-component accelerometers and two 3-component geophones deployed at a various depth ranging from 1500 m to 4500 m. 5753 and 3817 microseismic events were localized by the down-hole network during the 2004 and 2005 stimulations, respectively. The location uncertainty is 50 – 80 m.

2.3 Rock mechanics

Mechanical properties of the Soultz granite are taken from previous laboratory studies. Petrophysical analysis of the samples taken from the roller reamer after drilling revealed a lower density for the two-mica granite (2.52 kg m^{-3}), compared to the porphyritic granite (2.62 kg m^{-3}) [*Baillieux et al.*, 2012]. Brocher [2005] showed empirically that rock with lower density tends to have lower elastic moduli. Hence, lower elastic moduli are expected for two-mica granite.

2.5 Induced seismicity

Due to the relatively low number of seismic events produced by the stimulations of GPK4 makes the determination of the detailed reservoir geometry difficult. 80% of recorded microseismic events were located deeper than 4800 m (Fig. 1). A flow test recorded during the GPK4 stimulation [*Nami et al.*, 2008] indicated a linear leakage of flow from 4500 m to the bottom-hole. Multidisciplinary studies [e.g. *Sausse*, 2002; *Kohl and Mégel*, 2007a; *Baujard and Bruel*, 2006; *Evans*, 2005] suggest that the characteristics of fractures in the crystalline rock play a fundamental role in governing the response of the reservoir to fluid injection. Knowledge of the mechanical properties of the fractured granite relies much on the very limited laboratory measurements performed on core samples [*Valley and Evans*, 2003; *Baillieux et al.*, 2012].

3. RESULTS AND DISCUSSION

3.1 Identified litho-structural units

On the basis of the different aforementioned data, we defined mainly three units in the Soultz reservoir, which differ in petrography and structure. We therefore call them litho-structural units (Fig. 2).

1. 4400 to 4630 m TVD
Relatively low density of fractures and low clay content. Porphyritic granite is only slightly affected by hydrothermal alteration. Two major fracture zones intersect the well in this zone.

2. 4630 to 4780 m TVD
Transition from porphyritic to two-mica granite. It has low to medium density of fractures and breakouts, and a medium to high clay content. The width of breakouts is found to be very narrow. The fracture zone GPK4-FZ4910 is intersecting the well in this interval.

3. 4780 to 4980 m TVD
Younger two-mica granite intruding the porphyritic granite. This zone has a medium to high fracture density and moderate clay content. The density and width of breakouts are found to be highest.

The boundaries of those lithologies are also found at similar depth in wells GPK2 and GPK3 [*Dezayes et al.*, 2003; *Genter*, 1999], which indicates sub-horizontal boundaries of the lithological layers in the deep reservoir.

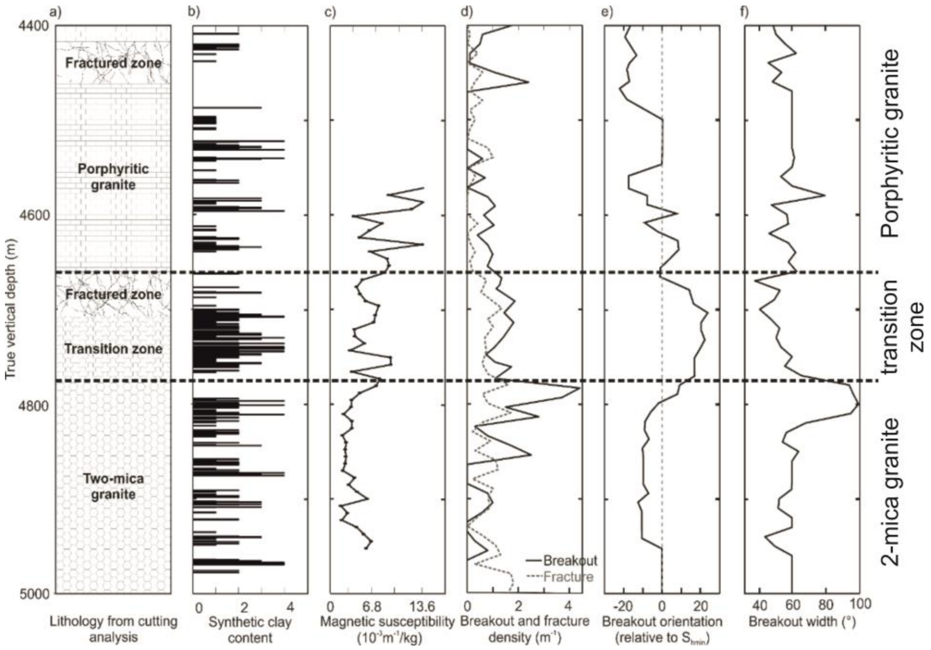


Fig. 2: Geophysical and geological data of the open-hole section of GPK4. a) Lithology log from the interpretation of cutting data, b) synthetic clay content log derived from spectral gamma ray and natural fracture data [*Meller et al.*, 2014b], c) magnetic susceptibility measured from cutting data, d) breakout and fracture density [*Sahara et al.*, 2014], e) breakout orientation, f) breakout width.

3.2 Induced seismicity

Hydrothermal alteration zones, characterized by an enrichment of clay minerals might act as a zone of weakness [*Sausse et al.*, 1998]. Altered samples in Soultz are characterized by smoother surfaces of fractures [*Sausse*, 2002] and fracture surfaces covered with weak clay minerals, suggesting a lower frictional strength of altered rock. Valley and Evans [2003] showed with laboratory tests that the Young's modulus of massive porphyritic Soultz granite is around 54 GPa, and significantly reduced for altered granite. Uniaxial compressive strength is found to decrease with increasing fracture density [*Alm et al.*, 1985]. On the basis of these results, we conclude that that the two-mica granite, which has a lower density, higher alteration grade, and higher fracture density, is less stiff than the porphyritic granite.

The higher number of borehole breakouts in the two-mica granite compared to the porphyritic granite section (Fig. 2d) is also consistent with a reduction of the compressional rock strength as suggested by Haimson and Chang [2005]. The larger asymmetry of breakouts formed in the two-mica granite (identified by Sahara et al. [2014]) might be associated to higher mechanical heterogeneity of the two-mica granite. The transition from porphyritic to two-mica granite was identified at similar depths for all Soultz wells [*Hooijkaas et al.*, 2006].

Fig. 3 shows cross sections of the microseismic event density of the GPK4 stimulation as a function of time. Two major fracture zones (GPK4-FZ4970, and GPK4-FZ4620) are plotted as grey lines. During the initial stage of the 2004 heavy brine injection, microseismic events first occur in the lower part of the reservoir, where the two-mica granite is encountered. The microseismic events at this stage are scattered in a radius of ~170 m around the bottom-hole. At t = 20 h, most of the microseismic events occur near the fracture zone GPK4-FZ4970. A cluster of microseismic events in the porphyritic zone begins to develop after the hydraulic injection is increased to 45 L/s for a couple of hours at the end of the 2004 stimulation. At shut in (t = 75 h), two distinct microseismic clusters occur in the porphyritic and in the two-mica granite. A similar pattern of microseismic density is also observed during the 2005 stimulation. This episodic pattern of fracture reactivation, from porphyritic to two-mica granite, is consistent with the variation of the frictional strength of those granites proposed by the borehole data analysis.

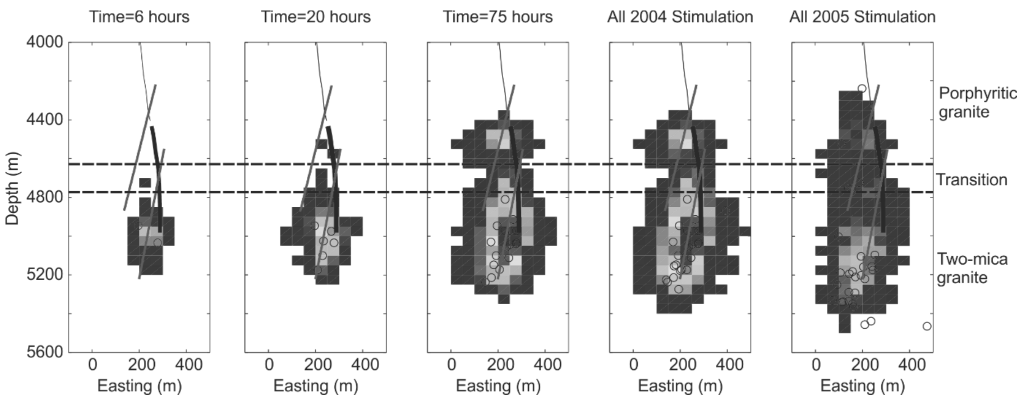


Fig. 3: Microseismic event distribution for different stimulation stages of the 2004 stimulation of GPK4 and BHP level in N280°E cross sections. Major fractures GPK4-FZ4620, and GPK4-FZ4910 are plotted as grey lines.

From Fig. 3, we can see that in the transition zone between porphyritic and two-mica granite, the number of seismic events is reduced. According to the synthetic clay log (Fig. 2b), this zone is characterized by rather high clay contents. Meller and Kohl [2014] found that the magnitude of induced seismic events is inversely correlated to the clay content of the fracture, on which the event is induced (Fig. 4).

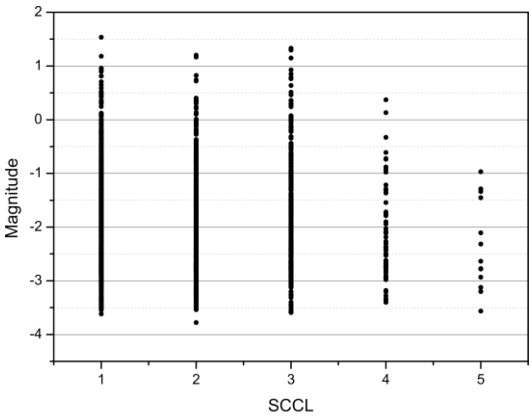


Fig. 4: Magnitude of seismic events of the GPK1 and GPK3 stimulations plotted versus the clay content of the fracture zone, where the event was located. Increasing clay content goes ahead with a decrease of maximum magnitude [*Meller and Kohl*, 2014].

Furthermore, they showed that high clay contents favour aseismic movements on fractures. Therefore, low seismicity and low magnitude of seismic events might be related to the high clay content in the transition zone. This low magnitude events pattern in high clay content intervals was also observed during the GPK1 and GPK3 stimulations [*Meller and Kohl*, 2014]. Aseismic creep during stimulation of the Soultz-sous-Forêts geothermal field was already suggested Cornet et al. [1997], Bourouis and Bernard [2007] and Schoenball et al. [2014] and is supposed to play a significant, but not measurable, role during hydraulic stimulation at Soultz.

From the beginning of the injection, the BHP of GPK4 was already 16 – 17 MPa higher than at the GPK3 and GPK2 stimulation. *Hasan and Kabir* [2010] mathematically explain the BHP as a function of the injection rate and the injectivity (or permeability) of the rock. The small permeability of the fracture zones intersecting GPK4 [*Sausse et al.*, 2010a] might cause this high borehole pressure. Numerical studies show that BHP might only represent near wellbore conditions, and the pressure might decline very fast with distance from the well [*Kohl and Mégel*, 2007b]. These might explain the limitation of the fracture reactivations in the two-mica granite, and the small number of microseismic events in the GPK4 stimulations, although those stimulations produced the highest BHP.

The results of this study indicate that the occurrence and character of microseismicity occurring during the GPK4 stimulation correlate with the variation of lithology and structure of the rock observed from borehole data of GPK4. Microseismic events first develop in the two-mica granite and then move upwards, whereas the event density remains comparatively low in the transition zone between porphyritic and two-mica granite (Fig. 5).

Tab. 1 Hydraulic injection data and maximum pressure increase of the GPK4 stimulations in Soultz-sous-Forêts

	Total injected volume (m^3)		**Max pressure increase (MPa)**	
	GPK4a	GPK4b	GPK4a	GPK4b
1st quarter	3045	2770	17.3	16.8
2nd quarter	5185	6445	17.3	18
3rd quarter	7365	10055	17.5	18.6
4th quarter	9145	12175	17.5	18.6

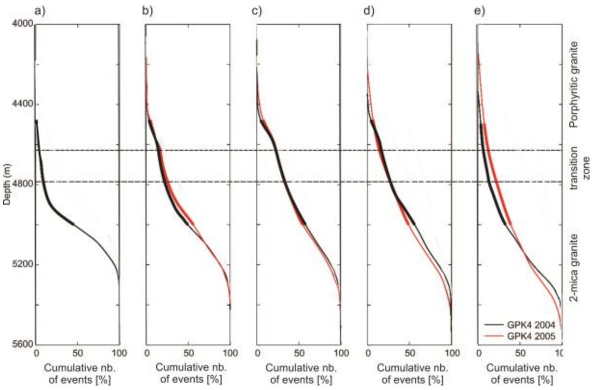


Fig. 5: Evolution of microseismicity in the four quarters of the GPK4 stimulations (a-d) and total cumulative number of microseismic events (e).

This information is of crucial importance for the planning of hydraulic stimulations or injection of fluids and gases into the underground. The existence of hydrothermal alteration zones can promote aseismic movements, which could contribute to a significant but not measurable part to the effectiveness of hydraulic stimulation. In a previous study by Evans [2005] it was already demonstrated that hydrothermally altered zones are best stimulated during massive injection. Therefore, focusing on hydrothermally altered fracture zones could increase the effectiveness of hydraulic stimulation while keeping the seismic hazard low. Yet, aseismic movements also represent a risk, as large movements can occur, which are not measurable. This can be a danger for borehole stability or for seal integrity of e.g. CO_2 storage sites.

The concentration of microseismic events in the two-mica granite at the low injection rate of the GPK4 stimulation suggests that the damaged area can be limited by appropriately adjusting the stimulation strategy according to the geomechanical model of the reservoir. This will be particularly importance for deep CO2 storage and tight oil and gas reservoir fracturing, in which the stimulation shall target a specific formation and not creating new fractures in the seal layer of the reservoir.

5. CONCLUSIONS

This study addresses the question of how petrographic and structural parameters of the reservoir rock affect the mechanical response to massive fluid injection. Integrated analysis of borehole data suggest a structural and petrographic and, hence, a mechanical zonation of the reservoir.

Three zones in the reservoir are identified based on various geophysical logs of GPK4. The interpreted variation of the mechanical properties of the porphyritic and two-mica granite is reflected by the evolution of microseismicity in the reservoir during GPK4 stimulation. Furthermore, the clay content provides key information about the area in which creeping mechanism might occur during stimulation. Hence, the combination of those rock characteristics needs to be considered to improve the geomechanical modelling of fractured granite.

Careful analysis of log data provides key information about the mechanical properties of the fractured granite. The impact of the fracture network on mechanical heterogeneities is very pronounced in crystalline rock, which is otherwise mechanically isotropic. For an economic and safe development of future EGS projects targeting crystalline rock, the key factors controlling the response of the rock mass to massive fluid injection have to be carefully identified and analysed with novel methods.

The results of this study provide a better understanding of the significance of the mechanical properties characterization in fractured rocks. The detailed study presented in this paper will be published in a forthcoming paper by Sahara et al. in Geophysical Journal International.

REFERENCES

Alm, O., L.-L. Jaktlund, and K. Shaoquan (1985), The influence of microcrack density on the elastic and fracture mechanical properties of Stripa granite, *Physics of The Earth and Planetary Interiors*, *40*(3), 161–179, doi:10.1016/0031-9201(85)90127-X.

Baillieux, P., E. Schill, L. Moresi, Y. Abdelfettah, and C. Dezayes (2012), Investigation of Natural Permeability in Graben Systems: Soultz EGS Site (France), in *Thirty-Seventh Workshop on Geothermal Reservoir Engineering*, p. 12.

Baujard, C., and D. Bruel (2006), Numerical study of the impact of fluid density on the pressure distribution and stimulated volume in the Soultz HDR reservoir, *Geothermics*, *35*(5-6), 607–621, doi:10.1016/j.geothermics.2006.10.004.

Bourouis, S., and P. Bernard (2007), Evidence for coupled seismic and aseismic fault slip during water injection in the geothermal site of Soultz (France), and implications for seismogenic transients, *Geophys J Int*, *169*(2), 723–732, doi:10.1111/j.1365-246X.2006.03325.x.

Brocher, T. M. (2005), Empirical Relations between Elastic Wavespeeds and Density in the Earth's Crust, *Bulletin of the Seismological Society of America*, *95*(6), 2081–2092, doi:10.1785/0120050077.

Collins, D. S. (2000), Lithological Controls on Seismicity in Granitic Rocks, *Bulletin of the Seismological Society of America*, *90*(3), 709–723, doi:10.1785/0119990142.

Cornet, F. H., J. Helm, H. Pointrenaud, and A. Etchecopar (1997), Seismic and Aseismic Slips Induced by Large-scale Fluid Injections, *Pure Appl. Geophys.*, *150*(3), 563–583, doi:10.1007/s000240050093.

Dezayes, C., P. Chèvremont, B. Tourlière, G. Homeier, and A. Genter (2005), Geological study of the GPK4 HFR borehole and correlation with the GPK3 borehole (Soultz-sous-Forêts, France), *Open File Report RP-53697-FR*, 94 pp., BRGM, Orleans.

Dezayes, C., A. Genter, G. Homeier, M. Degouy, and G. Stein (2003), Geological study of GPK3 HFR borehole (Soultz-sous-Forêts, France), *Open File Report*, 128 pp., BRGM, Orleans.

Dezayes, C., A. Genter, and B. Valley (2010), Structure of the low permeable naturally fractured geothermal reservoir at Soultz, *Cr Geosci*, *342*(7-8), 517–530, doi:10.1016/j.crte.2009.10.002.

Dyer, B. C. (2005), Soultz GPK4 Stimulation September 2004 to April 2005. Seismic Monitoring Report *BP38*, GEIE "Exploitation Minière de la Chaleur", Kutzenhausen.

Evans, K. F. (2005), Permeability creation and damage due to massive fluid injections into granite at 3.5 km at Soultz: 2. Critical stress and fracture strength, *J. Geophys. Res.*, *110*(B4), B04204, doi:10.1029/2004jb003169.

Genter, A. (1999), Geological and well-logging data collected from 1987 to 1989 at the HDR site Soultz-sous-Forêts, *Open file report BGRM*, *R40795*.

Genter, A., and H. Traineau (1995), Fracture analysis in Granite in the HDR Geothermal EPS-1 Well, Soultz-Sous-Forets, France, *BRGM Rapport*(R-38598), 53.

Haimson, B., and C. Chang (2005), Brittle fracture in two crystalline rocks under true triaxial compressive stresses, *BRUHN, D. & BURLINI, L. (eds) 2005. High-Strain Zones: Structure and Physical Properties.*, *240*(1), 47–59, doi:10.1144/gsl.sp.2005.240.01.05.

Hasan, A. R., and C. S. Kabir (2010), Modeling two-phase fluid and heat flows in geothermal wells, *Journal of Petroleum Science and Engineering*, *71*(1–2), 77–86, doi:10.1016/j.petrol.2010.01.008.

Hooijkaas, G. R., A. Genter, and C. Dezayes (2006), Deep-seated geology of the granite intrusions at the Soultz EGS site based on data from 5 km-deep boreholes, *Geothermics*, *35*(5-6), 484–506, doi:10.1016/j.geothermics.2006.03.003.

Jaeger, J. C., N. G. Cook, and R. W. Zimmermann (2007), *Fundamentals of Rock Mechanics*, 4th ed., 475 pp., Blackwell Publishing, Malden, USA.

Kohl, T., and T. Mégel (2007a), Predictive modeling of reservoir response to hydraulic stimulations at the European EGS site Soultz-sous-Forêts, *Int. J. Rock Mech. Min. Sci.*, *44*(8), 1118–1131, doi:10.1016/j.ijrmms.2007.07.022.

Kohl, T., and T. Mégel (2007b), Predictive modeling of reservoir response to hydraulic stimulations at the European EGS site Soultz-sous-Forêts, *International Journal of Rock Mechanics and Mining Sciences*, *44*(8), 1118–1131, doi:10.1016/j.ijrmms.2007.07.022.

Meller, C., A. Genter, and T. Kohl (2014a), The application of a neural network to map clay zones in crystalline rock, *Geophys J Int*, *196*(2), 837–849, doi:10.1093/gji/ggt423.

Meller, C., and T. Kohl (2014), The significance of hydrothermal alteration zones for the mechanical behavior of a geothermal reservoir, *Geotherm Energy*, *2*(12), 21, doi:10.1186/s40517-014-0012-2.

Meller, C., and T. Kohl (2015), How Synthetic Clay Content Logs Can Help to Assess the Behaviour of a Geothermal Reservoir Upon Hydraulic Stimulation: Proceedings World Geothermal Congress, in *Proceedings World Geothermal Congress*, Melbourne.

Meller, C., A. Kontny, and T. Kohl (2014b), Identification and characterization of hydrothermally altered zones in granite by combining synthetic clay content logs with magnetic mineralogical investigations of drilled rock cuttings, *Geophys J Int*, *199*(1), 465–479, doi:10.1093/gji/ggu278.

Nami, P., R. Schellschmidt, M. Schindler, and T. Tischner (2008), Chemical Stimulation Operations for Reservoir Development of the Deep Crystalline HDR/EGS System at Soultz-sous-Forêts (France), in *Thirty-Third Workshop on Geothermal Reservoir Engineering*, p. 11.

Nusiaputra, Y. Y., F. Qadri, D. Kuhn, and H. Abdurrachim (2015), Empirical Correlation for Optimal Turbine Inlet Temperature and Pressure for Geothermal Sub- and Supercritical Organic Rankine Cycles (ORC), in *Proceedings World Geothermal Congress*, Melbourne.

Sahara, D., M. Schoenball, T. Kohl, and B. Mueller (2014), Impact of fracture networks on borehole breakout heterogeneities in crystalline rock, *Int. J. Rock Mech. Min. Sci.*, *71*, 301–309, doi:10.1016/j.ijrmms.2014.07.001.

Sajid, M., J. Coggan, M. Arif, J. Andersen, and G. Rollinson (2016), Petrographic features as an effective indicator for the variation in strength of granites, *Engineering Geology*, *202*, 44–54, doi:10.1016/j.enggeo.2016.01.001.

Sausse, J. (2002), Hydromechanical properties and alteration of natural fracture surfaces in the Soultz granite (Bas-Rhin, France), *Tectonophysics*, *348*(1–3), 169–185, doi:10.1016/s0040-1951(01)00255-4.

Sausse, J., C. Dezayes, L. Dorbath, A. Genter, and J. Place (2010a), 3D model of fracture zones at Soultz-sous-Forets based on geological data, image logs, induced microseismicity and vertical profiles, *Comptes Rendus Geoscience*, *342*, 531–545, doi:10.1016/j.crte.2010.01.011.

Sausse, J., C. Dezayes, L. Dorbath, A. Genter, and J. Place (2010b), 3D model of fracture zones at Soultz-sous-Forets based on geological data, image logs, induced microseismicity and vertical seismic profiles, *Cr Geosci*, *342*(7-8), 531–545, doi:10.1016/j.crte.2010.01.011.

Sausse, J., A. Genter, J. L. Leroy, and M. Lespinasse (1998), Description and quantification of vein alterations: palaeopermeabilities in the Soultz-sous-Forets granite (Bas-Rhin, France), *B Soc Geol Fr*, *169*(5), 655–664.

Schoenball, M., L. Dorbath, E. Gaucher, J. F. Wellmann, and T. Kohl (2014), Change of stress regime during geothermal reservoir stimulation, *Geophys. Res. Lett.*, *41*(4), 1163–1170, doi:10.1002/2013gl058514.

Valley, B., and K. Evans (2003), Strength and Elastic Properties of the Soultz Granite, *Synthetic 2nd year report EC Contract SES6-CT-2003-502706*, 6 pp., E. T. Zürich, Zürich, Switzerland.

Zoback, M. D. (2014), *Reservoir geomechanics*, 12th ed., xiv, 449, Cambridge University Press, Cambridge.

ACKNOWLEDGEMENTS

The Soultz borehole data and the seismic catalogue are courtesy of GEIE Deep Heat Mining. This research was conducted within the portfolio topic GEOENERGIE of the Helmholtz Association of German Research Centres and was funded by Energie Baden-Wuerttemberg (EnBW), Germany.