Impact of faults and their mechanical properties on the regional stress field

Julie Maury, Theophile Guillon, Arnold Blaisonneau

Impact of faults and their mechanical properties on the regional stress field

J. Maury, T. Guillon & A. Blaisonneau
BRGM, Orléans, France

ABSTRACT: The impact of faults on the regional stress field is investigated. We show that if we consider all faults identified by geophysical studies in the Upper Rhine Graben stresses rotation appears. The stress magnitudes are also varying due to the presence of faults. When we assign different friction and stiffness properties to fault families based on their known characteristics the stress rotation pattern is quite different. Accordingly, the normal displacement of faults, parameter essential to determine the opening of faults is quite different between the two models. This implies it is very important to know active faults and closed faults. We argue for more studies on fault properties as it is quite essential to assign the right ones in order to identify stress redistribution. The model also shows that the sediment layer with its varying thickness also induces stress variations.

1 INTRODUCTION

Geothermal energy is a renewable resource still underutilized. To develop geothermal power plants we need a better knowledge of favorable areas. In non-volcanic contexts, the term favorable area indicates adapted conditions (high temperature, presence of fluid and permeability) at the lowest depth in order to decrease drilling costs. This means knowledge of fluid circulation at the regional scale is of utmost importance. Faults affect the stress field and change in the stress field will affect flow properties. Stresses can favor preferential flow paths through the rock mass (Swyer et al. 2016) by favoring circulation perpendicular to the shear direction (Auradou et al. 2006; Gentier et al. 1997) or enabling vertical up-flows circulations (Rowland & Sibson 2004; Swyer et al. 2016). Moreover, the stress field put constraints on the geometry of wells and their engineering characteristics.

To better define these fluid circulation and the impact of the stress field a regional Hydro Mechanical (HM) model was developed (Armandine Les Landes et al. in press). However, this model considers uniform properties for all faults considered. It is well known that, depending on their tectonic history (e.g. the amount they slipped), faults will have different properties (Ben-zion and Sammis 2003). We aim at investigating what impact varying mechanical fault properties have on the stress field. The active faults are the one that change the most the stress field. The amount of slip they accommodated change their equivalent mechanical properties. Finally, we are interested in the normal displacement of faults because it is a simple way to quantify their amount of opening.

The area of interest is the Rhine graben, France, because rifts are a good location for high temperature fluid at moderate depths. Indeed, in graben, the crust is thinner and is heated up by the nearby mantle. In addition, normal faults help to get fluid from deep reservoirs to shallower depths.

The model geometry is constrained by our geological knowledge of faults. However, we do not have any knowledge of faults mechanical properties, especially relative one to another. The aim of this work is to show such a knowledge is essential because faults can redistribute stresses under some conditions. We want to show the impact of including faults in a mechanical model and how their mechanical properties affect the stress field that, in turn, affect their hydraulic properties.

2 MECHANICAL MODEL

2.1 *General geometry*

The model is similar to the geometry used by Armandine Les Landes et al. (in press). It consists of a faulted block centered on the southern Upper Rhine Graben oriented N150° to apply tectonic stresses easily. The block is 180*180*10 km^3 (Fig. 1) (Lxlxdepth). The model consists of two layers, the basement and the sediments, the depth of the sediments varies from 2 km to 6 km and is taken from the report from Georg project (Georg team 2013). The thicker deposit basins are on the east border of the graben around Karlsruhe and Mannheim with an additional one west of Strasbourg. The geometry of the 351 faults in the model is the same as Armandine Les Landes et al. (in press) and is determined from published geophysical and geological work. For more information on the faults selection, the reader is referred to the aforementioned paper. The faults' geometry is constrained at the interface of sediment and basement. We prolonged these faults from the basement into the sediments without consideration of their age. This simplification will be discussed later on. In addition, we model the topography as a force on top of the model.

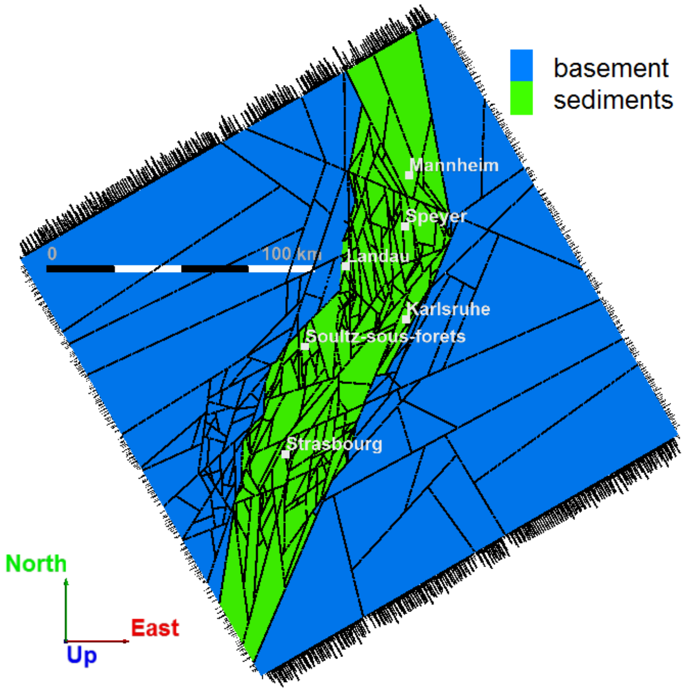

Figure 1. Model representation. The faults are in black. The green layer represent sediments. The outside arrows represent the horizontal load applied as boundary conditions. Main cities are indicated.

We do not use displacement boundaries as boundary conditions because it is difficult to constrain it from GPS observations. Indeed, the velocities observed are at the limit of the resolution level of the method (Nocquet 2012; Lehujeur 2011). It is under debate whether the actual state of stress of the alpine foreland is due to the convergence between Africa and Europa (Buchmann and Connolly 2007) or to gravity-driven mechanisms (Maury et al. 2014). To avoid this debate we use stress boundary conditions. We suppose that the vertical is a principal stress direction, which is reasonable at the depths considered. We know from focal mechanism inversion (Kastrup et al. 2004) and from some in situ observation (Cornet et al. 2007) that the regional maximum horizontal principal stress is close to the vertical stress. So we apply as boundary the weight of the overburden and an additional stress in the direction N150° that is such that SHmax=1.1*Svert. We have little constraint on the minimal horizontal stress. We apply the value estimated at Soultz-sous-Forêts (Cornet et al. 2007), even if it is a local value and could be partly due to local structures.

We suppose the matrix behavior is elastic and that all plastic deformation occur within the faults. The rock mechanical parameters used, shown in Table 1, are typical values for granite (main material of the basement) and sediments rocks. The plastic behavior of faults is modeled with a Coulomb yield criterion.

Table 1. Mechanical parameters for the matrix.

Material	Young modulus [GPa]	Poisson ratio []	density [kg.m^{-3}]
Basement	57	0.28	2680.
Sediments	20	0.3	2400.

We realize three different models to compare the impact of the different geological structures:

- model 1 that includes lithology and faults with uniform mechanical properties
- model 2 that includes lithology and faults with varying mechanical properties
- model 3 that includes only lithology

2.2 *Selecting faults properties*

Fault properties are difficult to determine. Some laboratory studies and compilations of them give estimates of elastic shear and normal stiffness (Kulhawy 1975; Bandis et al. 1983; Rosso 1976) or friction coefficient (Byerlee 1978; Jaeger and Cook 1984) on fractures. However, if the friction value is not very dependent on lithology or stress level (Byerlee 1978) it is not the case of the stiffness that presents a non-linear behavior. Moreover, there is the question of whether these laboratory data can be applied directly at the fault level or how to translate them at this scale. That is why we are focused here not on the absolute values of mechanical properties of which we have little knowledge but on the variation between models of these properties. Table 2 presents the properties used.

Table 2. Mechanical parameters for faults.

Fault material number	kn* [GPa.m^{-1}]	ks* [GPa.m^{-1}]	friction [°]	cohesion [Mpa]
1**	7	3	20	0
2	3.5	1.5	10	0
3	14	6	45	1

* kn: normal stiffness; ks:shear stiffness; **Reference fault parameters.

The area we model is slightly bigger than the zone where faults are identified. This is because in order to apply boundary stress conditions we rotate the model and enlarge it slightly to include all the graben. The faults defined in the inner model are continued into the outer area. This is reasonable because this concerns mostly faults on the shoulder of the graben where only large structures are included. However, to account for their ending we assign properties more rigid to the faults in this outer model (material number 3 parameters in Table 2).

Model 1 includes two sets of parameters for the fault zones: the reference one (number 1) for all inner fault zones, and a more rigid one (number 3) to account for their progressive clamping in the outer area.

Most of the Rhine graben’s structures that moved during the rifting process were reactivated Hercynian structures. This generates a complex fault history with fault parameters that must reflect this fact. Armandine Les Landes et al (in press) identified five different fault sets based on their orientation and origin. From this first characterization, we extract two fault sets that will have different parameters than the base set.

Sanjuan et al. (2016) identifies the direction NE-SW as a direction where fluid circulate. On the contrary, the N-S ones are “dry” faults. Moreover, fault mechanism of earthquakes (Edel et al. 2007; Ustaszewski and Schmid 2007) suggest that this NNE-SSW to NE-SW direction has been recently reactivated. To account for this observation we assign lower friction coefficient to these faults (material number 2).

On the other hand, structures oriented E-W are older structures that play little part in the last tectonic stage so we assign very rigid properties to these faults (material number 3).

To sum up, model 2 exhibits three sets of parameters for the fault zones: the reference one (number 1) for inner fault zones, a less frictional one (number 2) for NE-SW fault, and a more rigid one (number 3) for the E-W oriented fault zones. Again, fault are affected material number 3 in the outer area.

3 RESULTS

Figure 2 shows the horizontal over vertical stress ratio magnitude at 5 km depth for models 1 and 2. The mean stress ratio is 1.1 that corresponds to the ratio applied. Some variations are observed in the most faulted part for both models.

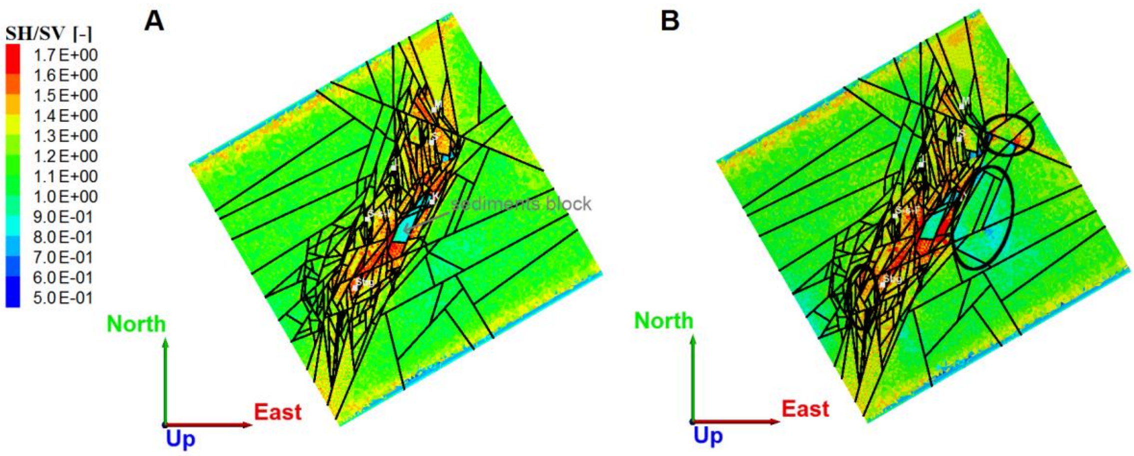

Figure 2. Ratio of maximum horizontal stress over vertical stress. A. Model 1. A grey arrow indicates the block of sediments. B. Model 2. Black ellipses indicate areas presenting variations from model 1. Faults are in black. Main cities plotted in Figure 1 are plotted here in blue with one letter for label.

Selecting faults based on their properties modifies the stress field. Figure 2B shows the impact of changing this at a regional scale. We observe that the stress ratio is little impacted by fault properties. Nevertheless, some differences are observed between model 1 and 2 (circled areas in Figure 2). Around the intersection of faults with different mechanic properties the stress ratio varies positively (increase to 1.6) or negatively (decrease to 0.7). These variations are localized but have a non-negligible magnitude.

The mean maximum horizontal stress orientation also corresponds to the applied stress direction of N150° (Fig. 3). However, some rotations occur near faults up to 15°. These are less localized effects than the variation in stress ratio and show a clear impact of faults on the stress field. What is notable is that these variations in stress orientations are limited to some faults while other do not affect it at all.

The mean maximum horizontal stress direction stay N150° whatever the faults properties. However, there are some local variations that can be observed. The variations from the mean direction observed in model 1 are accented in model 2. In addition, some new areas present variations. Comparing model 1 and 2 shows that variations in stress orientations are a lot more important for model 2. The more important variations (+15° on one side of a fault and -15° on the other side) concern faults oriented NE-SW with material number 2. Some of these faults slip in model 2 but not in model 1.

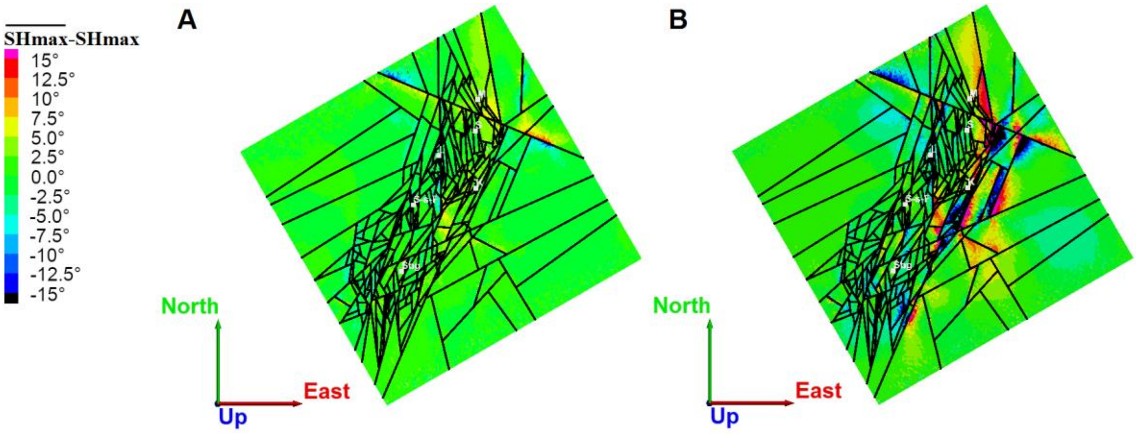

Figure 3. Difference in degree from the applied direction of maximum horizontal stress, N150°. A. Model 1. B. Model 2.

Figure 4 shows the normal displacement of faults in model 1 and model 2. We can see the important impact the fault material has on displacement. In model 2, the amount of closing is reduced as a whole compared to model 1 but some opening appears. This opening of faults is localized at the intersections between faults where the variations of parameters would be more important (mostly intersections of faults having material numbers 2 and 3).

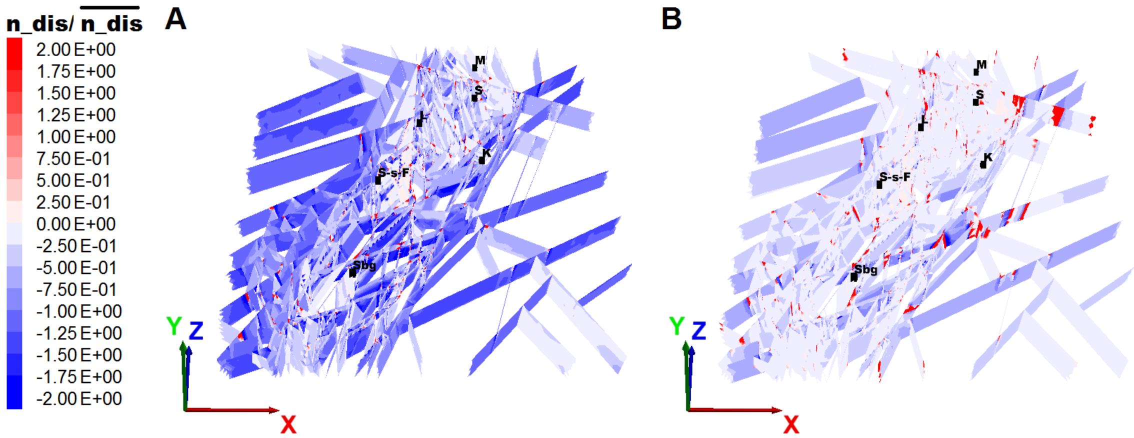

Figure 4. Normal displacement relative to the mean normal displacement on all faults. A. Results for model 1. B. Results for model 2. Blue means closure of faults and red mean opening of faults.

In addition, the faults outside the graben are closing more (they are more blue) than the faults inside the graben for both models. This suggest either the presence of sediments or the interaction between faults impact the amount of closing on any given fault.

4 DISCUSSION

We observe some variation in the magnitude of the principal stresses. Since these variations occur mainly within the graben, we can reasonably assume that they are influenced not only by the faults but also by the sediment layer. Figure 5 confirms this with a plot of the stress ratio for model 3 that has no faults. The stress variations are very similar to what is observed within the faulted model 1. The stress ratio vary from a maximum value of 1.7 under the area where sediments are thickest to 0.8 in the sediments themselves (grey arrow in Figure 2). The variation in thickness of the sediment layer impact the stress ratio. In addition, the topography more important on the shoulders of the graben than within it increases the difference between the two areas. On first order stress magnitude are impacted by the variation in density between the sediments and the basement and the geometry of the basement. However, depending on the mechanical parameters of the faults some local variations are clearly due to faults (circled area in Figure 2). Furthermore, horizontal stress orientations variations are due mainly to faults. Figure 5B shows some very limited variations in stress orientations (<6°) for the continuous model while both faulted model present variation of 10 to 15°. Once again, the fault mechanical parameters play a preponderant role in these variations since the stress variations of model 1 and 2 are very different.

From our results, the length of the faults affects the size of the area impacted by the stress redistribution but not the amplitude of the redistribution. Figure 3 shows that a small fault can have as much impact as a large one locally. This suggests that from a prospective point of view, to locate favorable geothermal area a description of the complete fault system is necessary. Moreover, the connections between faults of different mechanical properties is very important since it is at these locations that main normal displacement occur (Fig. 4 B).

Some open questions remain concerning faults. In this model, fault zones are modeled as planes whereas we know that in reality they are curved surfaces at different scales. For example, in the Rhine graben some faults become inclined with depth. This variation of geometry would have an impact on the stress field and should be considered. Another assumption we made is that the faults are continuous at the basement-sediments interface. This is a strong assumption that is probably not true for all faults. We have some evidences of the normal faults cutting both the basement and the sediments (shift in the interface sediment-basement depth) so we can model these faults in both layers. However, for other type of faults, we have knowledge of them mostly in the sediments and this becomes a problem when looking at stress results deeper into the basement. Future work should include a more detailed description of faults to be able to model a more precise stress field.

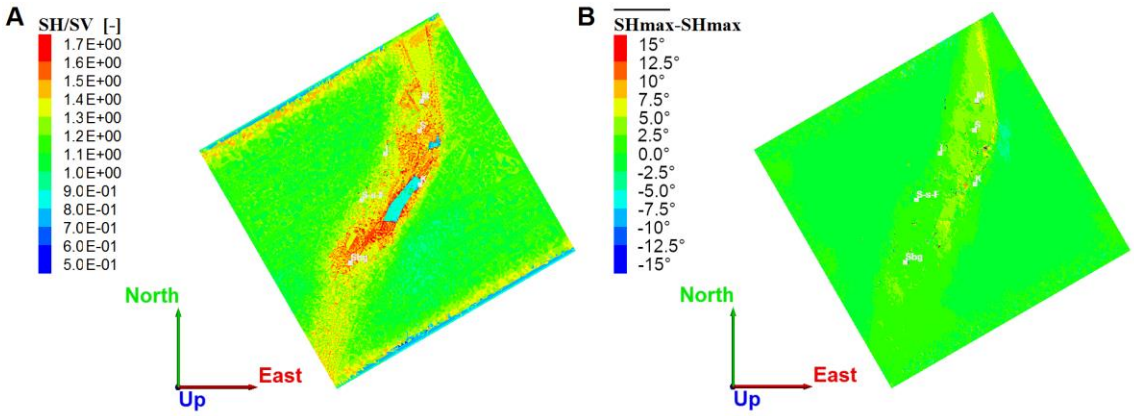

Figure 5. Stress results at 5000 m depth for the continuous model. A. Ratio of maximum horizontal stress over vertical stress. B. Difference in degree from the applied direction of maximum horizontal stress, N150°.

We tried to assign different fault properties based on history criteria. Nevertheless, those are generic criteria and some more knowledge of fault behavior is needed. In particular, looking at seismicity could bring information on the state of specific faults. Furthermore, we do not have exact knowledge of fault properties and so we only consider variation from reference material properties. This is a good first approximation to understand what parameters are important. However, we can only show tendencies until we get mechanical properties backed by some observation. The rock behavior is better constrained by laboratory experiment (even if their extrapolation to large-scale can be questioned) and have less impact since the deformation is localized within faults. The variations induced by the sediment is more due to the geometry of the interface that is relatively well constrained by geophysical studies, than to material properties.

We choose to assign stress boundary conditions because we do not have enough knowledge to use displacement boundary conditions. However, we also do not have a real idea of the value of the minimum horizontal stress and it could affect the stress field. Further work should include sensitivity analysis of this parameter for more objectivity in model interpretation. Finally, the initial state is only due to gravity. We know the Rhine graben has a complex tectonic history and it affects the stress field. There are probably remnant stress concentration that we did not consider. Boundary conditions of passed tectonic events are badly constrained – especially regarding magnitudes – and we consider that accounting for a more detailed initial state would introduce more uncertainties. To confirm or infirm this, we should develop multi-staged models in the future.

5 CONCLUSIONS

We modeled stress field of the Upper Rhine graben using discrete fracture network. The sediment layer is also taken into account as well as topography. As we do not have a precise idea of the actual velocity field, we use stress boundary conditions.

The faults yield a variation of the stress field, mostly in direction. These variations, up to 15°, are concentrated around faults that are ideally oriented, relative to the current stress field, to slip. Some local variations in stress ratio are also observed near faults.

When we assign different fault properties based on their history, we can observe that the stress field is changed. Some faults slip more and the rotation of the maximum horizontal stress is increased. In addition, the interaction of faults with different properties generate stress redistribution.

If we look at the normal displacement on faults, we can observe, as expected, variations depending on the fault properties assigned. These variations are important because they will affect the hydraulic aperture, which is a key property to model fluid circulation.

Comparing these results to a continuous model, we show that the global variation in stress ratio inside the graben is due to the contrast of lithology but local variations are due to faults.

The main points this study shows are: 1) slip on a fault will modify the horizontal stresses orientations at a kilometric scale; 2) the length of the fault moving affect the radius of the area affected but not the magnitude of the stress rotation; 3) the larger opening of faults occur at the intersection of faults with different mechanical properties.

This work underlines the importance of assigning different mechanical properties not only on varying layer but also on faults at the regional scale. It is a first step to evaluate the influence of stress on hydraulic properties of faults.

6 ACKNOWLEDGEMENTS

This work was conducted in the framework of the TEMPERER project (French National Research Agency grant agreement No. ANR-10-IEED-0801-02) which is supported by the French Government through the Investments for the Future programs.

7 REFERENCES

Armandine Les Landes, A., T. Guillon, M. Peter-Borie, A. Blaisonneau, X. Rachez, and S. Gentier. in press. "Locating Geothermal Resources: Insights from 3D Stress and Flow Models at the Upper Rhine Graben Scale." *Geofluids*.

Auradou, H., G. Drazer, A. Boschan, J.-P. Hulin, and J. Koplik. 2006. "Flow Channeling in a Single Fracture Induced by Shear Displacement." *Geothermics* 35 (5–6): 576–88. https://doi.org/10.1016/j.geothermics.2006.11.004.

Bandis, S.C., A.C. Lumsden, and N.R. Barton. 1983. "Fundamentals of Rock Joint Deformation." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 20 (6): 249–68. https://doi.org/10.1016/0148-9062(83)90595-8.

Ben-zion, Y., and C. G. Sammis. 2003. "Characterization of Fault Zones." In *Seismic Motion, Lithospheric Structures, Earthquake and Volcanic Sources: The Keiiti Aki Volume*, edited by Y. Ben-Zion, 677–715. Basel: Birkhäuser Basel. https://doi.org/10.1007/978-3-0348-8010-7_11.

Buchmann, T. J., and P. T. Connolly. 2007. “Contemporary Kinematics of the Upper Rhine Graben: A 3D Finite Element Approach.” *Global and Planetary Change* 58 (1–4): 287–309. https://doi.org/10.1016/j.gloplacha.2007.02.012.

Byerlee, J. 1978. “Friction of Rocks.” In *Rock Friction and Earthquake Prediction*, edited by J. D. Byerlee and M. Wyss, 615–26. Basel: Birkhäuser Basel. https://doi.org/10.1007/978-3-0348-7182-2_4.

Cornet, F.H., Th. Bérard, and S. Bourouis. 2007. “How Close to Failure Is a Granite Rock Mass at a 5km Depth?” *International Journal of Rock Mechanics and Mining Sciences* 44 (1): 47–66. https://doi.org/10.1016/j.ijrmms.2006.04.008.

Edel, J.-B., K. Schulmann, and Y. Rotstein. 2007. “The Variscan Tectonic Inheritance of the Upper Rhine Graben: Evidence of Reactivations in the Lias, Late Eocene–Oligocene up to the Recent.” *International Journal of Earth Sciences* 96 (2): 305–25. https://doi.org/10.1007/s00531-006-0092-8.

Gentier, S., E. Lamontagne, G. Archambault, and J. Riss. 1997. “Anisotropy of Flow in a Fracture Undergoing Shear and Its Relationship to the Direction of Shearing and Injection Pressure.” *International Journal of Rock Mechanics and Mining Sciences* 34 (3–4): 94.e1-94.e12. https://doi.org/10.1016/S1365-1609(97)00085-3.

Georg team. 2013. “Geopotentials of the Deep Upper Rhine Graben.” BRGM/RP-61945-FR. http://www.geopotenziale.org/home?lang=2.

Jaeger, J. C., and N. G. Cook. 1984. *Fundamentals of Rock Mechanics*. 3. ed., repr. Science Paperbacks 18. London: Chapman and Hall.

Kastrup, U., M. L. Zoback, N. Deichmann, K. F. Evans, D. Giardini, and A. J. Michael. 2004. “Stress Field Variations in the Swiss Alps and the Northern Alpine Foreland Derived from Inversion of Fault Plane Solutions: STRESS FIELD IN SWITZERLAND.” *Journal of Geophysical Research: Solid Earth* 109 (B1). https://doi.org/10.1029/2003JB002550.

Kulhawy, F. H. 1975. “Stress Deformation Properties of Rock and Rock Discontinuities.” *Engineering Geology* 9 (4): 327–50. https://doi.org/10.1016/0013-7952(75)90014-9.

Lehujeur, M. 2011. “Etude Cinématique Des Déformations Crustales (Géodésie Gps) Dans La Région Du Graben Du Rhin - Comparaison à La Sismicité Instrumentale.” Master report. EOST.

Maury, J., F. H. Cornet, and M. Cara. 2014. “Influence of the Lithosphere–Asthenosphere Boundary on the Stress Field Northwest of the Alps.” *Geophysical Journal International* 199 (2): 1006–17. https://doi.org/10.1093/gji/ggu289.

Nocquet, J.-M. 2012. “Present-Day Kinematics of the Mediterranean: A Comprehensive Overview of GPS Results.” *Tectonophysics* 579 (December): 220–42. https://doi.org/10.1016/j.tecto.2012.03.037.

Rosso, R.S. 1976. “A Comparison of Joint Stiffness Measurements in Direct Shear, Triaxial Compression, and In Situ.” *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 13 (6): 167–72. https://doi.org/10.1016/0148-9062(76)91282-1.

Rowland, J. V., and R. H. Sibson. 2004. “Structural Controls on Hydrothermal Flow in a Segmented Rift System, Taupo Volcanic Zone, New Zealand.” *Geofluids* 4 (4): 259–83. https://doi.org/10.1111/j.1468-8123.2004.00091.x.

Sanjuan, B., R. Millot, Ch. Innocent, Ch. Dezayes, J. Scheiber, and M. Brach. 2016. “Major Geochemical Characteristics of Geothermal Brines from the Upper Rhine Graben Granitic Basement with Constraints on Temperature and Circulation.” *Chemical Geology* 428 (June): 27–47. https://doi.org/10.1016/j.chemgeo.2016.02.021.

Swyer, M.W., T.T. Cladouhos, C. Forson, J.L. Czajkowski, N.C. Davatzes, and G.M. Schmalzle. 2016. “Permeability Potential Modeling of Geothermal Prospects Combining Regional Crustal Strain Rates with Geomechanical Simulation of Fault Slip and Volcanic Center Deformation: A Case Study for Washington State Geothermal Play Fairways.” In . American Rock Mechanics Association.

Ustaszewski, K., and S. M. Schmid. 2007. “Latest Pliocene to Recent Thick-Skinned Tectonics at the Upper Rhine Graben – Jura Mountains Junction.” *Swiss Journal of Geosciences* 100 (2): 293–312. https://doi.org/10.1007/s00015-007-1226-0.