Geomechanical Investigation of High Priority Geothermal Strata in the Molasse Basin, Bavaria, Germany

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Abstract

Due to the increasing use of geothermal energy in Bavaria, Germany, over the last years, the practical experience in geothermal plant operation for heat and power generation has shown an evident need for research. Especially questions related to deep geothermal energy need to be answered, and the risk of geothermal exploration in the Molasse Basin and the crystalline rocks in the northern part of Bavaria should be reduced to optimize reservoir engineering. The Molasse Basin, extending along the northern flank of the Alps, represents an alpine foreland basin. Situated south of Munich, the basin offers ideal conditions for the use of hydrothermal geothermal energy. The petrothermal potential in crystalline rock is focused in the northern part of Bavaria. The development and use of this future technology initially requires extensive research but has outstanding future potential. In this context, the determination of rock mechanical parameters is indispensable for the subsequent modelling of hydrothermal and petrothermal reservoirs. For this purpose, laboratory tests were conducted using drilling samples as well as analogue samples from quarries. Based on the results of these experiments a database has been created. This database improves the knowledge of the mechanical properties of representative rock types. Furthermore, the database improves the knowledge about detection of a local stress field, which has major impact on the hydraulic system of the geothermal reservoir. The outcome of this research should increase profitability and minimize risk of geothermal projects.

Keywords

Geomechanic • Molasse basin • Geothermal research

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1 Deep Geothermal Energy in Bavaria

1.1 Research Gap: Geomechanical Parameter Characterization

The local stress field has a major impact on the hydraulic system of a geothermal reservoir. An extensive and precise knowledge of the reservoir properties is necessary to complete a geothermal project successfully. Understanding the local stress field and the fractures around the bore hole is the key to an improving inflow from the reservoir into the exploration well. Since Barton et al. (1995) found that critical fractures are more often hydraulically active than uncritically stressed fractures, the geomechanical reservoir parameters describing the field of tension are important for the exploration of geothermal projects. The quality of these parameters depends on the identification of the deposit properties of the period and cost-intensive exploratory drillings. Due to the high costs, there are not enough. Deep core holes typically reach depths of several thousand meters. Because it is very expensive to drill them. The existing deep core holes were created during the course of the hydrocarbon exploration. Most of the data pool is limited to rock formations that were relevant for the oil industry. The database for geothermal host rock formations is very small.

In order to complete this database, various studies by Clauser and Huenges (1995), Clauser et al. (2002), Koch et al. (2007, 2009) have provided characteristic rock parameters. However, the geomechanical parameters describing the local stress field around the borehole, were not covered sufficiently. Homuth (2014) first published geomechanical rock mass parameters on analogue samples from different outcrops. Due to the small number of available samples, his general statement about the geomechanical reservoir characteristics was not useful.

The aim of this work is to fill the database with geomechanical parameters of analogue and drilled core samples. The parameters will therefore improve the understanding of

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the hydraulic inflow to the reservoir. This work will reduce the geothermal exploration risk in the north Alpine foreland basin (so-called Molasse Basin) and will optimize the reservoir engineering in the northern part of Bavaria in crystalline rock.

2 High Priority Geothermal Strata

2.1 Molasse Basin: Upper Jurassic Carbonates

The target formations of the geothermal reservoirs in the Molasse Basins are the Upper Jurassic carbonates (Malm) (Fig. 1). These rocks are underlaid by Permo-Carboniferous troughs and Variscan crystalline complex (Lemcke 1988). The basin is filled with Cenozoic sedimentary rocks, which are alternating sequences of sandstone with claystone (Meyer and Schmidt-Kaler 1989). Due to alpine tectonics and the formation of the Molasse Basin as a typical wedge-shaped foreland basin, synsedimentary fracture and fault zones influenced the Upper Jurassic carbonates (Büchi et al. 1965).

An epicontinental sea, connected to the northern part of the Tethys, was the deposit environment of the Upper Jurassic carbonates. The Upper Jurassic is composed of alternating sequences of limestone, marl and dolomites (Meyer and Schmidt-Kaler 1989).

In southern Germany, the Upper Jurassic is separated in a massive and bedded facies. The massive facies, also called reef facies, is built by reef and reef-like organisms. This facies, can be dolomitized influencing the behavior of the carbonate rocks. The limestones were partially carstified by the uncovering and eroding of the Upper Jurassic limestones during the Cretaceous period (Koschel 1991).

Situated south of Munich, the basin offers ideal conditions for the use of hydrothermal geothermal energy. The requirement for the hydrothermal geothermal energy is the presence of a water-bearing formation, the Upper Jurassic carbonates. In a hydrothermal circuit, the hot water is pumped to the surface where the essential part of its heat energy is available via a heat exchanger to a secondary power plant circuit. The cooled thermal water is then traced back into the subsoil via a second borehole (injection borehole).

These carbonates exist there at depths between 3500 and 6000 m b.l.s. with host fluid temperatures between 65 and 120 °C. The thickness of the Upper Jurassic reservoirs can reach up to 400 m (Pomoni-Papaioannou et al. 1989). The Molasse Basin has a typical dip of 5° (Clauser et al. 2002) in the south-east direction, which results in an outcrop area north of the Basin (Fig. 2). The outcrops of this area (Swabian and Franconian Alb) reflect the properties of the geothermal reservoirs.

2.2 Northern Part of Bavaria: Crystalline Rock

The target formation of the northern part of Bavaria consist of different granite types of the Variscan basement. These rocks build the basement of the Franconian Basin,

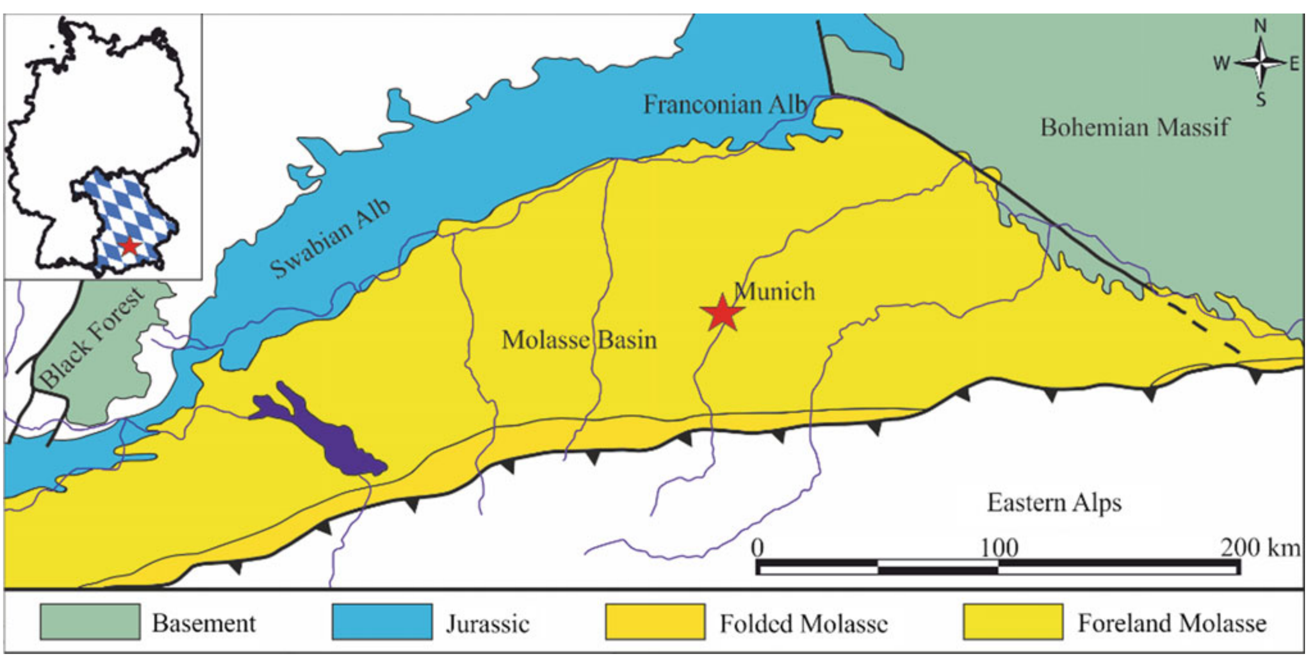

Fig. 1 Geological overview map of the Molasse. According to Walter (2007)

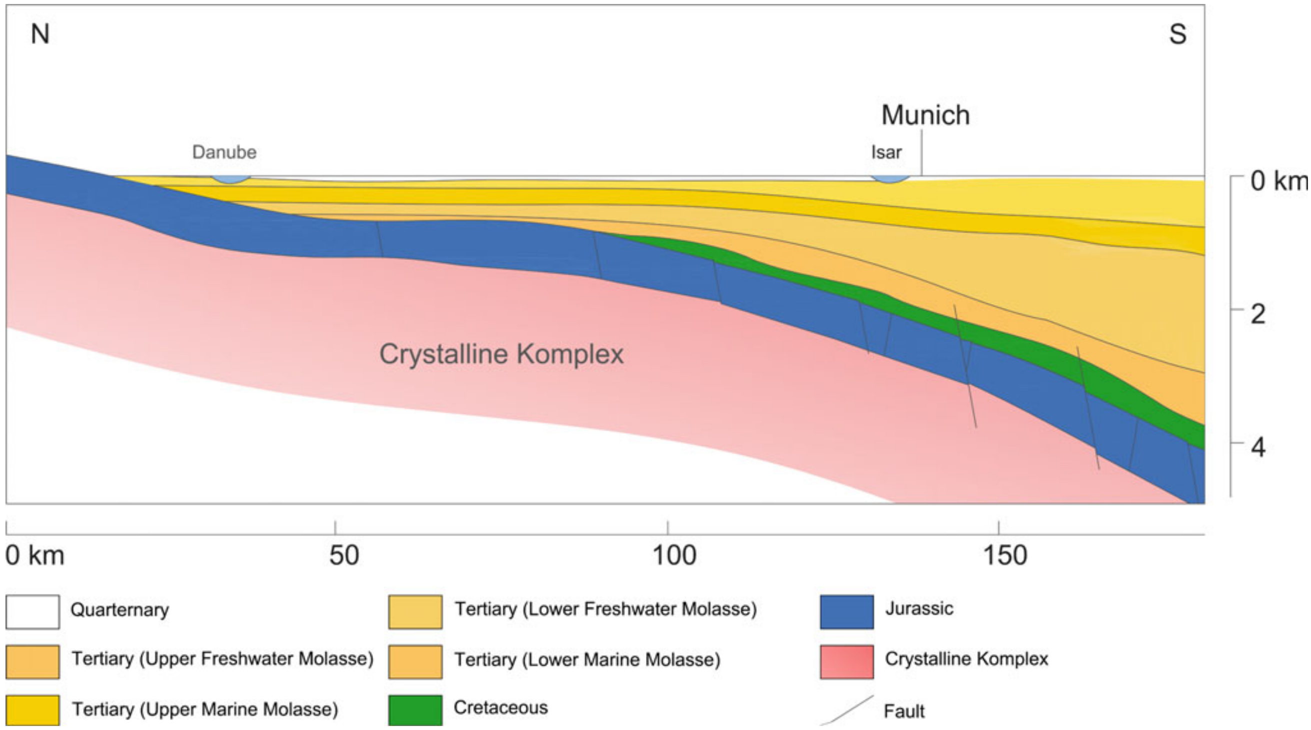

Fig. 2 Geological cross-section of the Molasse Basin. Modified after Lemcke (1988)

a Permo-Mesozoic sedimentary platform. The sediments consist of sandstones, pelites, limestone and marls (Scharfenberg et al. 2016).

The development of the Franconian basin begins with the end of the Variscian orogenesis. The Variscian Orogen has been subjected to uplift and erosion since the lower Carboniferous (Welzel 1991). The post-variscan development, characterized by a crustal collapse and an extension of the lithosphere, led to the formation of half trenches and ditches in the Upper Carboniferous. These intramontane basins locally covered over 2500 m sediments of the variscian mountain range (Bauer 2000).

During the Upper Carboniferous period, magma penetrated overlapping rocks and formed extensive granite plutons. These granites built subsurface granite bodies, which provide potential heat sources for the petrothermal geothermal energy. In contrast to the hydrothermal systems, petrothermal systems use the heat energy of the crystalline rock. In petrothermal systems, crystalline rock with a low permeability are used as a heat source. It should be noted that “petrothermal systems” include all geothermal reservoirs that have been influenced by engineering measures, either chemical or hydraulic stimulation (Stober and Bucher 2014). This stimulation enhances the permeability in the borehole area.

In Germany, about 95% of the geothermal energy potential is attributable to this technology (VBI 2013). According to the zoning of the variscian orogen of Kossmat (1927), the field of interest (Franconian Basin) is situated within the saxothurian zone (Fig. 3; Riemer 2011). The first signals for increased underground temperatures were found during a drilling campaign in the 1970s and 1980s (Gudden 1981). In 2000 Bauer (2000) identified a regional geothermal anomaly. This local anomaly is located north of Bayreuth in the area of the Franconian Basin, in the spreading extension of the granite of the Fichtelgebirge. In this anomaly, the geothermal gradients reach up to 5 °C/100 m (Riemer 2011). In the Fichtelgebirge, the outcrops display properties of geothermal reservoirs. The Fichtelgebirge includes four different types of granite, which will be analyzed as analogue samples.

3 Materials and Methods

To carry out a geomechanical reservoir characterization of high priority geothermal strata, drill cores from Bavaria were already searched for in the existing database of the geothermal information system (GeotIS). The discovered wells, which were drilled in Bavaria, are compared with the Lower Saxony Soil Information System (NIBIS). This information system contains the cored boreholes (Müller and Waldeck 2011). The samples have been selected from different depths of the drillings in order to characterize the high

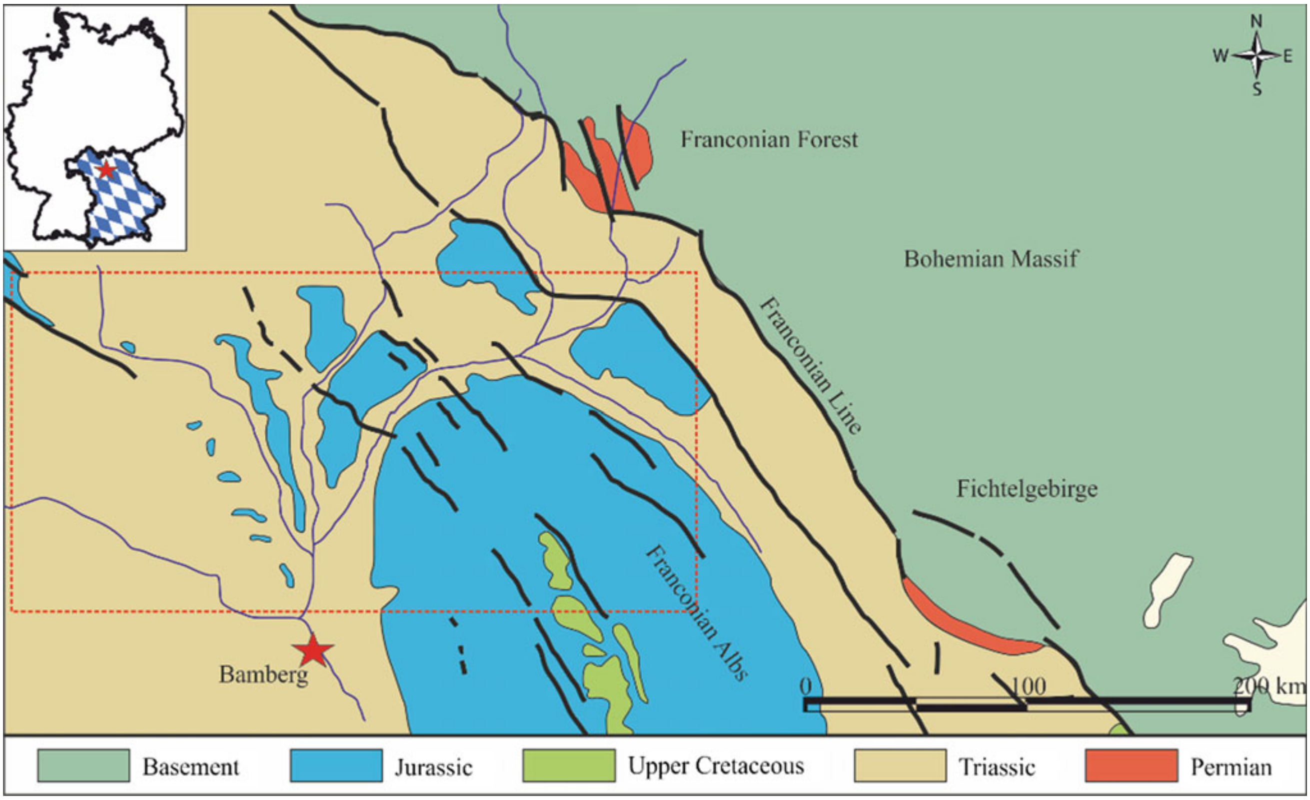

Fig. 3 Geological overview map of the target area (marked area) (Riemer 2011)

geothermal strata completely geomechanically. Historically not all companies release the cores for sampling, so analogue samples of outcrops from quarries are also taken (Alber and Backers 2015). The analogue samples have the advantage that they are available in large quantities and are therefore easy to sample. Together with the core samples of former oil drillings, they form the material for this research.

The analogue samples should originate from the same rock formations (stratigraphy, lithology, facies) as the samples of the drillings to characterize the respective reservoir aquifer (Philipp et al. 2007). The core drillings and quarries are present in all parts of Bavaria so that the aquifer can be studied throughout the region. In order to characterize the reservoir in a geomechanical manner, a large number of samples is required.

After the core samples from drillings and analogue samples from quarries have been collected, laboratory tests are carried out on these samples.

After the drilling cores have been overcored or the analogue samples have been drilled, they are cut to length and prepared with an end face grinder. To measure the geomechanical properties of the samples, and to create reproducible results, the samples are dried at 105 °C to mass constancy and then cooled to 20 °C in an exsiccator. For the statistical validation of the measured values, 5–10 individual measurements of the respective characteristic values are carried out.

The laboratory program includes the following tests:

(1) Ultrasonic tests (US)/non-destructive tests

The US tests are carried out according to DIN EN ISO 16810. The P-shaft serves as an indicator of porosity. The transversal shaft (S-shaft) combined with the P-shaft determine the dynamic modulus of elasticity (E_{dyn}) and the Poisson's ratio.

(2) Uniaxial Compressive Test

The UCT tests are carried out according to the test recommendation of the DGGT (2004) in order to determine the rock strength and to correlate the strength with its others properties. In addition, knowing determined strength, statements can be made about the depth of the loosening and thus the prevailing stress conditions (Hoek and Martin 2014). The deformation modulus, the Young's Modulus transverse expansion destruction work according to Thuro (1996) have been determined.

(3) Tensile Test (Brazilian Test)

The tensile strength of the test specimen is determined indirectly by the tensile splitting strength. The relevant tests are carried out in accordance with the recommendation of DGGT (2008).

(4) Triaxial Compressive Test

The triaxial compression tests are carried out according to DIN 18137-2. To measure under simulated geothermal reservoir conditions a Thermo-Triax-Cell simulating have been used. The Mohrian voltage circuits determine the following parameters: Angle of internal friction and the Cohesion.

In order to get a prognosis of tool wear during drilling, two different abrasiveness tests are carried out. These results complete the geomechanical database.

(5) Cerchar Abrasivity Test

The Cerchar Abrasiveness Index (CAI) assesses the abrasive properties of the samples by scratching (Cerchar 1986, recommendation 23 according to DGGT 2016).

(6) LCPC Abrasivity Test

The LCPC abrasiveness test determines the abrasiveness of the rock, in the form of the LCPC abrasiveness coefficient LAK, by grinding (AFNOR 1990; Thuro et al. 2006; Thuro and Käsling 2009).

All results serve as input parameters for geomechanical reservoir simulations.

4 Objectives and Research Questions

Two areas in Bavaria are unique in terms of their geothermal potential, the Upper Jurassic carbonates in the South Molasse Basin and the crystalline rock in North East Bavaria. The geomechanical characterisation is an important criterion for the characterization of crystalline and sedimentary geothermal aquifers. However, there are still considerable uncertainties regarding the minimization of the exploration risk and the safe development of the geothermal potential.

In order to reduce these uncertainties, the following research questions will be addressed:

1. Which geomechanical parameters have
   (a) the project-relevant Upper Jurassic carbonates and
   (b) the project-specific granite of Northern Bavaria?
2. Which local stress situation exists around the borehole?
3. Which failure mechanisms can be deduced and which stress redistributions can be identified?

The intended research aims answer the posed questions and contribute to the geomechanical characterization of the rock of the geothermal drillings.

5 Summary

Analogue studies offer the possibility to generate a comprehensive data base of geothermal rock parameters in a cost-efficient way. This is also of particular interest if there is not a sufficient number of deep core drillings, which is currently the case in the Molasse Basin area. The results of the geomechanically investigations will present a data set of previously unachieved quality and quantity.

The suggested database will enable an improved prognosis with a quantification of the uncertainty of rock properties. A successful reservoir exploration, modelling and management directly depends on the quality of the input data and the general understanding of the system. The database obtained within the scope of this research will be applied in future projects to assure a sustainable data basis.

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References

Alber, M., Backers, T.: Erforschung der Mechanismen und Simulation hydraulisch induzierter Risse in geklüfteten Gesteinen für die Optimierung des Aufschlusses geothermischer Lagerstätten. In: Abschluss zum Verbundprojekt des BMWi mit dem Förderkennzeichen 0325279A & 0325279B, 136 p (2015)

Barton, C.A., Zoback, M.D., Moos, D.: Fluid-flow along potentially active faults in crystalline rock. Geology **23**, 683–686 (1995)

Bauer, W.: Geothermische Verhältnisse des Fränkischen Beckens (Nordbayern/Südthüringen). Lehr- und Forschungsbereich Hydrogeologie und Umwelt, Würzburg, 186 p (2000)

Büchi, U., Lemcke, K., Wiener, G., Zimdars, J.: Geologische Ergebnisse der Erdölexploration auf das Mesozoikum im Untergrund des schweizerischen Molassebeckens. Bulletin der Schweizerischen Vereinigung von Petroleum-Geologen und-Ingenieuren **15**, 7–38 (1965)

Clauser, C., Deetjen, H., Höhne, F., Rühaak, W., Hartmann, A., Schellschmidt, R., Rath, V., Zschocke, A.: Erkennen und Quantifizieren von Strömung: Eine geothermische Rasteranalyse zur Klassifizierung des tiefen Untergrundes in Deutschland hinsichtlich seiner Eignung zur Endlagerung radioaktiver Stoffe. In: Endbericht zum Auftrag 9X0009-8390-0 des Bundesamtes für Strahlenschutz (BfS), Applied Geophysics and Geothermal Energy E.ON Energy Research Center, 159 p, Aachen (2002)

Clauser, C., Huenges, E.: Thermal conductivity of rocks and minerals. In: Ahrens, T.J. (ed.) Rock Physics and Phase Relations: A

Handbook of Physical Constants, AGU Reference Shelf, 3, pp. 105–126. American Geophysical Union, Washington (1995)
DGGT: Empfehlung Nr. 10 des Arbeitskreises 3.3 “Versuchstechnik Fels” der Deutschen Gesellschaft für Geotechnik e. V.: Indirekter Zugversuch an Gesteinsproben – Spaltzugversuch. Bautechnik **85** (9), 623–627, Ernst & Sohn, Berlin (2008)
DIN 18137-2: Baugrund, Untersuchung von Bodenproben - Bestimmung der Scherfestigkeit - Teil 2: Triaxialversuch, Beuth Verlag, Berlin (2011)
DIN EN ISO 16810: Zerstörungsfreie Prüfung – Ultraschallprüfung – Allgemeine Grundsätze (ISO 16810:2012), Beuth Verlag, Berlin (2014)
Gudden, H.: Über Thermal-Mineralwasser-Bohrungen im Coburger Umland. Jahresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins **63**, 229–252 (1981)
Hoek, E., Martin, C.D.: Fracture initiation and propagation in intact rock—a review. J. Rock Mech. Geotech. Eng. **6**, 287–300 (2014)
Homuth, S.: Aufschlussanalogstudie zur Charakterisierung oberjurassischer geothermischer Karbonatreservoire im Molassebecken. Dissertation Technische Universität Darmstadt, Darmstadt, 314 p (2014)
Käsling, H. & Plinninger, R.: Empfehlung Nr. 23 des Arbeitskreises 3.3 “Versuchstechnik Fels” der Deutschen Gesellschaft für Geotechnik e. V.: Bestimmung der Abrasivität von Gesteinen mit dem CERCHAR-Versuch. Bautechnik **93**(6), 409–415, Ernst & Sohn, Berlin (2016)
Koch, A., Hartmann, A., Jorand, R., Mottaghy, D., Pechnig, R., Rath, V. Wolf, A., Clauser, C.: Erstellung statistisch abgesicherter thermischer und hydraulischer Gesteinseigenschaften für den flachen und tiefen Untergrund in Deutschland (Phase 1 – Westliche Molasse und nördlich angrenzendes Süddeutsches Schichtstufenland). In: Schlussbericht zum BMU-Projekt FKZ 0329985, Aachen, 220 p (2007)
Koch, A., Jorand, R., Arnold, J., Pechnig, R., Mottaghy, D., Vogt, C., Clauser, C.: Erstellung statistisch abgesicherter thermischer und hydraulischer Gesteinseigenschaften für den flachen und tiefen Untergrund in Deutschland (Phase 2 – Westliches Nordrhein-Westfalen und bayerisches Molassebecken). In: Abschlussbericht zum BMU-Projekt FKZ 0329985, Aachen, 174 p (2009)
Koschel, G.: Geologischer Überblick–Hydrogeologische Randbedingungen, München, Freiburg i. Br (1991)
Kossmat, F.: Gliederung des varistischen Gebirgsbaues. Abhandlungen der sächsischen geologischen Landesanstalt. 1, 1–39, Leipzig (1927)
Lemcke, K.: Das Bayerische Alpenvorland vor der Eiszeit: Erdgeschichte, Bau. Bodenschätze. Geologie von Bayern I. Schweizerbart, Stuttgart (1988)
Meyer, R.K.F. & Schmidt-Kaler, H.: Paläogeographischer Atlas des süddeutschen Oberjura (Malm). Bundesanstalt für Geowissenschaften und Rohstoffe und den Geologischen Landesämtern in der Bundesrepublik Deutschland, Hannover, 77 p (1989)
Mutschler, T.: Neufassung der Empfehlung Nr. 1 des Arbeitskreises “Versuchstechnik Fels” der Deutschen Gesellschaft für Geotechnik e. V.: Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern. Bautechnik **81**(10), 825–834, Ernst & Sohn, Berlin (2004)
Müller, U. & Waldeck, A.: Auswertungsmethoden im Bodenschutz: Dokumentation zur Methodenbank des Niedersächsischen Bodeninformationssystems (NIBIS®). In: GeoBerichte 19, Landesamt für Berbau, Energie und Geologie (LBEG), 416 p, Hannover (2011)
N F (NORMALISATION FRANÇAISE) P18-579 (AFNOR): Granulats - Détermination des coefficients d’abrasivité et de broyabilité. Paris: AFNOR Association francaise de normalisation, AFNOR (1990)
Philipp S.L., Gudmundson A., Oelrich A.R.I.: How structural geology can contribute to make geothermal projects successful. In: European Geothermal Congress 2007, Unterhaching, 10 p (2007)
Pomoni-Papaioannou, F., Flügel, E., Koch, R.: Depositional environments and diagenesis of Upper Jurassic subsurface sponge- and tubiphytes reef limestones: Altensteig 1 well, western Molasse Basin, Southern Germany. Facies **21**, 263–283 (1989)
Riemer, A.: Kluft- und Störungssysteme im westlichen Oberfranken und Eigenschaften des Temperaturfeldes mit Fokus auf die Mürsbacher Temperaturanomalie. Unveröffentlichte Diplomarbeit, Geozentrum Nordbayern, 86 p (2011)
Scharfenberg, L., de Wall, H., Bauer, W.: In situ gamma radiation measurements on Variscan granites and inferred radiogenic heat production, Fichtelgebirge, Germany. Zeitschrift der Deutschen Gesellschaft für Geowissenschaften **167**(1), 19–32 (2016)
Stober, I., Bucher, K.: Geothermie, 2nd edn. Springer, Heidelberg, 306 p (2014)
Thuro, K.: Bohrbarkeit beim konventionellen Sprengvortrieb - Geologisch-felsmechanische Untersuchungen anhand sieben ausgewählter Tunnelprojekte. Münchner Geologische Hefte **1**, 149 (1996)
Thuro, K., Singer, J., Käsling, H., Bauer, M.: Abrasivitätsuntersuchungen an Lockergesteinen im Hinblick auf die Gebirgslösung. In: Deutsche Gesellschaft für Geotechnik: Beiträge zur 29. Baugrundtagung 27. - 29. Sept. 2006, Bremen, pp. 283–290 (2006)
Thuro, K., Käsling, H.: Classification of the abrasiveness of soil and rock. Geomechanik und Tunnelbau, **2**(2), 179–188 (2009)
VBI (Verband Beratender Ingenieure): VBI-Leitfaden Tiefe Geothermie. Schriftenreihe der VBI **21**, 108 (2013)
Walter, R.: Geologie von Mitteleuropa. 7 edn. Schweizerbart, Stuttgart, 511 p (2007)
Welzel, B.: Die Bedeutung von K/Ar-Abküfflaltem an detritischen Muskoviten für die Rekonstruktion tektonometamorpher Einheiten im orogenen Liefergebiet - ein Beitrag zur Frage der varistischen Krustenentwicklung in der Böhmischen Masse. Göttinger Arbeiten zur Geologie und Paläontologie **49**, 61 (1991)