

In-Situ Stress State of the Ruhr Region (Germany) and Its Implications for Geothermal Energy Utilization

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ABSTRACT

In this study, we carry out a reactivation potential analysis of discontinuities revealed from heavily faulted and folded Upper Carboniferous rock strata of the Ruhr region. We based this study on the notion that slip is controlled by the ratio of shear to normal effective stresses acting on a pre-existing plane of weakness in the prevailing stress field configuration. The results of this analysis were supported by indicators of localized fluid flow, both on micro and macro scales, which confirm the relationship between secondary permeability and in-situ stress state in the Ruhr region. Findings from this study, in conjunction with results of destructive laboratory testing, indicate that the steep NW-SE- and NNE-SSW-striking planar discontinuities are likely to be either close to the critical state or critically stressed in the in-situ stress configuration in the Ruhr region. These planar structures, as evidenced by indicators of localised permeability, are the main fluid pathways in the studied region. The NE-SW-striking discontinuities, on the other hand, are most likely to be closed and hydraulically inactive. Based on results gained from this study, implications for the utilization of deep geothermal energy in the region were discussed.

1. INTRODUCTION

It is generally accepted that fractures and faults are the main fluid conduits in the Earth's crust (Hickman et al., 1995). The in-situ stress tensor is one of the major controls on the reservoir permeability anisotropy, where fractures and faults with high shear to normal stress ratios are considered as primary fluid pathways in both crystalline and sedimentary formations (e.g.,

Barton et al., 1995). The presence of these, so-called, critically stressed planes make the permeability of crust about four times larger than for a case of an intact rock subjected to appropriate confining pressures (Townend and Zoback, 2000). An understanding of reactivation potential of fractures and faults is a critical issue in the development of man-made, and especially conduction-dominated, geothermal systems. Firstly, the success of such a system relies on the number of intersected permeable fractures and/or faults oriented favourably to the in-situ stress tensor. Secondly, if a fault cutting a reservoir has high effective normal stresses acting on its plane (i.e., sealing fault), it can isolate fluid flow and compartmentalize a reservoir. Thirdly, knowledge about reactivation potential of fractures and faults is important in cases where rock matrix permeability is low and stimulation treatments are necessary to enhance it. Fracture initiation, in case of hydro-fracturing, or reactivation, in case of hydro-shearing, may be needed to generate flow paths and enhance reservoir productivity. Significant pore pressure disturbances during fluid injections, not adjusted to the prevailing in-situ stress tensor and rock frictional properties, may reduce the frictional strength of faults, and induce their either aseismic or, if the stress conditions will be sufficiently altered over a large area, coseismic shear slip. As a result, before an establishment of any deep geothermal system and carrying out subsequent stimulation efforts, in-situ stress tensor and its effect on the fracture and fault network shall be well understood.

The Ruhr region is located in the heart of the North-Rhine Westphalia state in western Germany. It is one of the largest metropolitan areas of Europe with more than 5 million inhabitants covering an area between the valleys of the Ruhr, Emscher, Lippe, and Rhine rivers. The Ruhr district heating network supplies 6500 GWh per year with an installed thermal capacity of 2310 MW_{th} (Bartelt et al., 2013). The wider metropolitan

region of Rhine-Ruhr is one of the largest district heating networks in the world, fed primarily by fossil fuels, i.e., coal and natural gas. To meet national and international climate protection targets, this network is to be converted into a CO₂-free energy network in the forthcoming decades. The Ruhr region is defined by the rich coal-bearing layers of the Upper Carboniferous period, belonging to the sub-Variscan Trough, with hard coal extraction starting in the 13th century. In 2018, after more than 700 years of extensive hard coal mining activities, the last mine was decommissioned in the region. The conversion of the district heating system in the Ruhr region could rely on the use of its vast geothermal potential. Favourable conditions for establishing deep geothermal reservoirs may exist in the fractured sandstones of the Carboniferous age and karstified and/or dolomitized carbonate rocks of the Devonian age. Devonian carbonates were intersected at depths between 4500 and 6000 m in several deep exploration boreholes, north from the Ruhr region and are outcropping south of the Ruhr region in the vicinity of Wuppertal, Schwelm, Hagen, and Iserlohn (Figure 1). Based on the temperature profiles from exploration boreholes in the northern part of the Ruhr region, results from the deepest borehole in the region, and temperature measurements from local coal mines, the average geothermal gradient amounted to around 36°C/km. Therefore, temperatures of 170 to 230°C can be expected at the reservoir depths. Such thermal conditions may enable not only heat but also electricity production if sufficient permeability exists in-situ. Due to the well-developed industrial and private infrastructure in the Ruhr region, there is a great interest in utilizing geothermal energy sources, being it either mine energy storage or deep geothermal systems, and simultaneously a strong necessity for understanding and monitoring the possible movements on major discontinuities and related seismic risks.

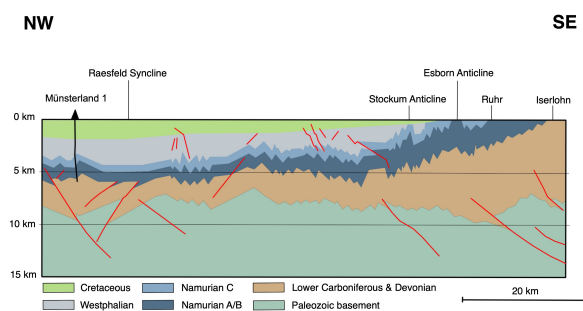


Figure 1: A simplified geological interpretation of the northern part of the DEKORP 2-N seismic line with major faults marked in red and the Münsterland 1 well intersecting the top of Devonian layers (Drozdowski, 1988).

The main aim of this study is to investigate the fracture behaviour under present-day stress tensor of the Upper Carboniferous rock strata of the Ruhr region and assess its effect on fluid flow. To do this, we use the slip tendency analysis, where we resolve shear and dilatational stresses along localised pre-existing planar

features and evaluate their slip and dilation potentials. Results of this analysis were compared with indicators of localised fluid flow based on observations of fluid loss during drilling operations, high quality temperature log, and macro-scale observations of fault leakage.

Within this study, we re-evaluated available in-situ stress data, coming mainly from the coal mining industry, across the Ruhr region and derived linearized pore pressure and in-situ stress gradients. We used results from destructive laboratory testing and field measurements to constrain the frictional properties of fractured rocks within the Ruhr region. Using the slip tendency analysis, the potential for shear slip along pre-existing discontinuities, revealed from exploration boreholes, with respect to the in-situ stress tensor was investigated and reactivation potential of the planar features assessed. Based on results gained from this study, implications for utilization of deep geothermal energy in the region were discussed.

2. GEOLOGICAL SETTING

The coal-bearing strata of the Ruhr region belong to the external fold and thrust belt of the latest stage of the Variscan orogen, located east of the Wales-Brabant Massif (Brix et al., 1988). The Variscan orogenic belt was formed during the Late Paleozoic convergence of the Euramerican and Gondwanaland continental masses (Ziegler, 1990). The collision and convergence took place during the Devonian and Carboniferous geologic periods.

The Ruhr region is influenced by two main fault systems. The major faults strike in the NE-SW direction with dips ranging from steeply inclined to bed-parallel reaching lengths of up to 40 km. These reverse type faults have horizontal displacements in the order of tens to hundreds of meters with few reaching horizontal displacements of 2500 m. The reverse faults are dissected by multiple NW-SE oriented normal faults resulting in a horst-and-graben structure with few strike-slip faults of various orientations also being observed in the region (Brix et al., 1988). Folds, mainly NE-SW oriented, vary significantly in shape and dimension with wavelengths of up to 10 km, increasing towards the north, having amplitudes in the order of several hundred meters. Extensive hard coal mining activities exposed thick molasse-type clastic sediments of the Upper Carboniferous age ranging from shales, silt- to coarse-grained sandstones with 2 to 2.5 m thick coal seams of varied strength, all heavily deformed by thrusting and folding (Bachmann, 1971). North of the Ruhr region, thick, in places up to 1800 m, Cretaceous strata overlays the Upper Carboniferous sequences (Drozdowski, 1993). Four deep exploratory boreholes, located north of the Ruhr region i.e., Münsterland 1, Versold 1, Iselburg 3, and Vingerhoets 93 have all reached Devonian layers. Carbonates of the Middle and Upper Devonian age, being part of the Devonian Reef Complex, are outcropping south of the Ruhr region close to the city of Iserlohn (Figure 1).

Based on laboratory studies carried out on rock samples from the Ruhr region it can be concluded that low

matrix permeability of $< 10^{-18} \text{ m}^2$ characterizes sandstones of the Upper Carboniferous age (e.g., Stoeckert, 2015) and permeability of $< 10^{-15} \text{ m}^2$ characterizes Devonian limestones and dolostones (Balcewicz et al., 2021). Matrix porosity of both rock formations does not exceed, on average, 5 to 7 % (Thielemann et al., 2001). Due to the low matrix permeability of the host rocks in the Ruhr region, it is expected that the future geothermal systems will rely on the secondary permeability, being it either lithofacies of increased hydraulic properties, pre-existing fractures, bedding planes, and/or faults.

3. METHODOLOGY

3.1 In-situ stress state

The information about the magnitudes of the principal in-situ stresses and pore pressure in the Ruhr region, collected throughout this study, was based on re-evaluated data from Wedewardt (1995), Braunher (1976), Rummel (1993), Müller (1989), Müller (1991), Stelling (1992), internal reports by MeSy Solexperts GmbH as well as on the results from drilling operations and geophysical logging from 17 wells in the Ruhr, and adjacent, regions within the Carboniferous layers acquired in this study. The mentioned dataset included i) 115 measurements of minimum horizontal stress, S_{Hmin} , from which depth was known for 80 measurements, ii) 80 measurements of maximum horizontal stress, S_{Hmax} , from which depth was known for 49 measurements, iii) 17 measurements of vertical stress, S_v , based on geophysical logging, and iv) pore pressure, P_p , magnitudes acquired from 233 measurements of the density of water sampled from the local coal mines between 20 and 1470 m depth and fluid densities applied during drilling operations in the studied boreholes.

3.2 Slip and dilation tendency analysis

The fluid flow along any discontinuity depends primarily on the in-situ stress tensor and its positioning in the subsurface. Once the in-situ stress tensor is known, acting shear, τ , and effective normal, σ_n' , stresses along any arbitrarily oriented planar feature can be resolved (Jaeger, 2007). Subsequently, in accordance with the Amonton's law, slip tendency, T_s , defined as a ratio between τ and σ_n' , can be assessed (Morris et al., 1996):

$$T_s = \frac{\tau}{\sigma_n'} \quad [1]$$

Discontinuities with T_s approaching or exceeding frictional resistance for sliding, μ , are assumed to have increased likelihood for a shear movement:

$$T_s \leq \mu. \quad [2]$$

Frictional coefficients for both intact and fractured samples of the Ruhr sandstone, based on published laboratory studies, are presented in Figure 2. The average frictional coefficient obtained from these tests, was used to constrain the failure threshold in slip tendency analysis. Most of discontinuity surfaces are

not perfectly planar, but rather rough and undulating. In its undisturbed initial state, discontinuity surfaces mate to create the smallest possible apertures. However, once the in-situ stress state is such that a discontinuity undergoes a degree of non-gouge forming microshear movement, asperities will slide over each other, resulting in discontinuity's self-propping effect and permeability increase. As a result, discontinuities with increased likelihood for a shear movement can be simultaneously assumed to be hydraulically active. On the other hand, discontinuities with low T_s are considered to have low fluid flow potential and are expected to be "locked".

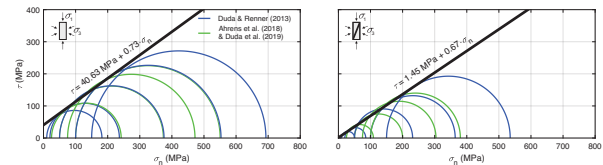


Figure 2: Mohr's diagrams for peak (left) and residual (right) stress of triaxially deformed Ruhr sandstone samples at different confining pressures (based on Duda (2012), Duda (2019), and Ahrens (2018)). The given equations describe linear envelopes in the Mohr diagrams, that is, Mohr-Coulomb failure and friction criteria for intact (left) and fractured (right) rock, respectively.

Based on Gudmundsson (2002) it is known that extensional fractures also act as fluid-conducting features. To investigate the tendency of a discontinuity to dilate in an acting stress state, dilation tendency, T_d , being described as a potential for a given discontinuity to dilate under a given 3D in-situ stress tensor was computed (Ferrill, 1999):

$$T_d = \frac{\sigma_1' - \sigma_n'}{\sigma_1' - \sigma_3'} \quad [3]$$

where, σ_1' and σ_3' are the maximum and minimum effective principal stresses, respectively. To assess how close a given cohesionless discontinuity is to the critical state (i.e., failure), Coulomb's failure function, CFF , was computed (Zoback, 2007):

$$CFF = \tau - \mu\sigma_n'. \quad [4]$$

Negative CFF values describe stable planar feature, as acting τ are insufficient to overcome its resistance to sliding. In the case of CFF approaching or being equal to zero, frictional sliding on a pre-existing discontinuity is likely to occur.

3.3 Discontinuity analysis and permeability verification

To evaluate the effect of the in-situ stress tensor on the reservoir permeability, geometry of discontinuities was acquired from dipmeter logs from old deep vertical coal exploration boreholes. Although results from dipmeter logs are used primarily to indicate bedding planes, it is widely known that such logs provide information on

faults, folds, disconformities, nonconformities, and pre-existing fractures. As slip tendency analysis is a method applicable for any planar structure or feature, we use it for all discontinuities registered with dipmeter logs. We do not distinguish between bedding planes, faults, or fractures, but rather analyse the dataset in a more statistical manner. In one shallow exploration well, we have used available results from an acoustical borehole imager tool, indicating pre-existing natural fractures. As no information from mud logging was available, we do not attempt to constrain lithological profiles from the studied wells. For investigation of the relationship between localized fluid flow and registered planar features, verification data is necessary. Most often, such data include results from high-quality temperature logs, electrical images, Stoneley wave logs, flow-meter logs, or injection tests. In our case, in one well only a high-quality temperature log, from a thermal response test, was accessible. In other wells, due to the lack of any verification data, we have used fluid loss information registered during drilling operations.

4. RESULTS

A compilation of in-situ stress measurements across the Ruhr region is presented in Figure 3. Acquired data resulted in an average linearized P_p gradient of 10.8 ± 1.0 MPa/km. An average linearized S_v gradient amounted to 23.1 ± 1.3 MPa/km. Acquired in-situ stress data resulted in an average linearized S_{hmin} gradient of 16.1 ± 4.3 MPa/km, whereas the average linearized S_{Hmax} gradient amounted to 33.6 ± 9.6 MPa/km. The S_{hmin}/S_v ratio for the Ruhr region amounted to 0.66 ± 0.18 and the S_{Hmax}/S_v ratio to 1.37 ± 0.39 . A considerable scatter of both S_{hmin} and S_{Hmax} values between around 600 and 1200 m depth was observed. Transpressional tectonics with regime stress ratio, RSR , amounting to around 2, was observed in the upper-most depths until approximately 600 m depth. Between depths of 600 and 1000 m, transition from transpression to a strike-slip regime was observed. Below that depth and until 2000 m, in-situ stress measurements indicate predominantly strike-slip stress regime. Both pure normal and reverse faulting regimes, can be considered as relatively unlikely in the Ruhr region.

Figure 3 also presents the lower hemisphere stereographic projection of T_s and T_d for the Ruhr region based on average linearized pore pressure and in-situ stress gradients from this study and average azimuth of S_{Hmax} for the Ruhr region (Kruszewski et al., 2021). It can be observed that discontinuities most favourably oriented for failure in the in-situ stress tensor, with a maximum T_s of 0.79, are vertically dipping with strike angle of 6 and 134°. The NE-SW striking fractures have a low T_s and are, thus, much less likely to experience frictional sliding. The dilatation tendency is the highest for fractures striking along the azimuth of S_{Hmax} and lowest for the ones striking perpendicular to it. It can be, therefore, said that the NW-SE and NNE-SSW striking discontinuities will be the preferential fluid flow pathways in the Ruhr region. The NE-SW striking fractures, with much higher normal effective stresses and low T_d , will be likely

closed in the present-day stress state configuration and hydraulically dead. We confirm these findings below.

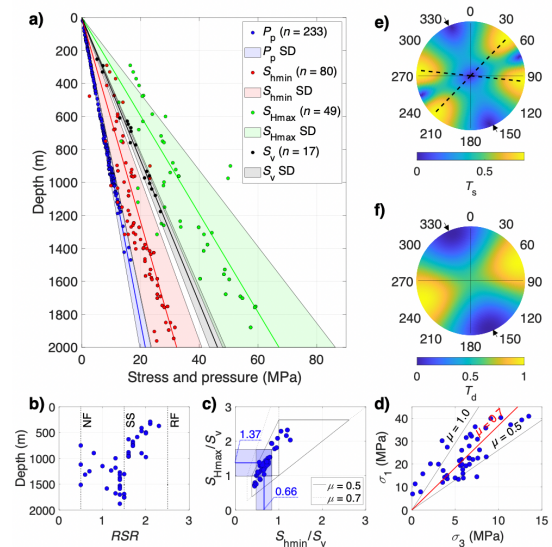


Figure 3: a) The state of stress of the Ruhr region; b) regime stress ratio, RSR , from re-evaluated in-situ stress measurements; c) in-situ measurements presented on a stress polygon plot with mean stress ratios; d) coefficient of friction based on re-evaluated in-situ measurements (line of best fit marked in red); e) slip and f) dilatation tendencies based on extrapolated stress and pore pressure gradients from this study (arrows point to the azimuth of S_{Hmax}).

The well A (Figure 4) is located in the vicinity of the former Victoria mine, north of General Blumenthal and Lohberg mines. In this borehole, breakout analysis indicated azimuth of S_{Hmax} of 127° . The orientations of discontinuities obtained from a dipmeter log revealed low dip angles ($< 20^\circ$) between depths of 660 and 980 m. Below that depth and until 1100 m moderate dip angles ($< 40^\circ$) were observed, whereas between 1100 and 1170 m again low ($< 20^\circ$) dip angles were revealed. The strike direction until 870 m depth does not have any major trend and is highly scattered. Below that depth and until the end of the log, discontinuities strike predominantly in the NW-SE direction. It was revealed that around 4 % of the registered discontinuities have $T_s > 0.5$, from which approximately 43 % experienced fluid loss (shaded or marked with red dashed lines in Figure 4). Critically stressed planes correlate well with bulk densities of 2500 kg/m^3 and gamma ray values below 100 gAPI, indicating confinement within sandstone layers. The rest of fluid loss zones correlate with coal-bearing formations, which can be observed by a sharp density decrease and a borehole diameter increase, both indicative of a penetration through the weaker coal layers.

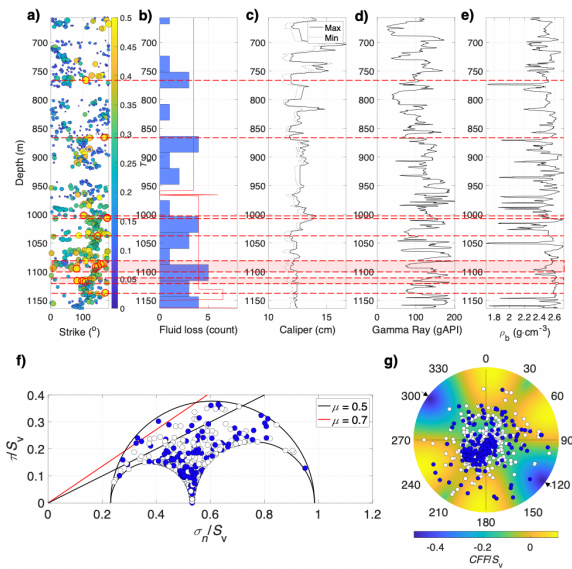


Figure 4: Results of the slip tendency analysis in the well A.

The well B (Figure 5) is located in the most western part of the Ruhr region, close to the former Friedrich-Heinrich and Lohberg mines. The azimuth of S_{Hmax} of 135° was assumed for the well B based on results from hydrofracturing tests carried out in the Friedrich-Heinrich mine. Based on the results from a dipmeter from this well, it was revealed that discontinuities located between depth of 620 and 650 m, have highly varied dip angles, proving no major trend. Below that depth and until 825 m, low dip angles ($< 10^\circ$) were registered. Between 825 and 875 m depth, dip angle increased to 20° . Registered discontinuities strike predominantly in the N-S direction. In the well B, only around 3 % of registered discontinuities have $T_s > 0.5$. Three major fluid losses were localized in the analyzed interval i.e., between 625 and 650 m, 740 and 775 m, and between 830 and 875 m depth, with all being correlated to the planes with high T_s values. Six planar features have $T_s > 0.5$ and fluid loss was observed in three of them. These three planar features correspond to the main fluid loss zones in the well (marked with red dashed lines in Figure 5). No geophysical logging was made available from the well B to make a comparison with lithology.

The well C (Figure 5) is located in the southern part of the Ruhr region within the city of Bochum. The azimuth of S_{Hmax} amounting to 124° was assumed based on the drilling-induced fracture analysis performed in this well. Based on the acoustical borehole imager tool results, it was discovered that registered discontinuities have a highly varied dip angles ranging between 30 and 90° until approximately 300 m depth. Below that depth they become more consistent and amount to approximately 60° . The registered discontinuities strike predominantly in NW-SE direction. A small group of discontinuities, striking perpendicularly to the NW-SE direction was registered between depth of 150 and 300 m. In the well C, around 50 % of registered discontinuities have $T_s > 0.5$ from which approximately

61 % have thermal anomaly of more than 0.5°C . Based on the analysis of the high-quality temperature log for indication of permeable discontinuities, it was discovered that fractures striking between 140 and 160° direction with high dip angles between 50 and 70° are the most likely to be permeable i.e., are related to the highest thermal anomalies in the well.

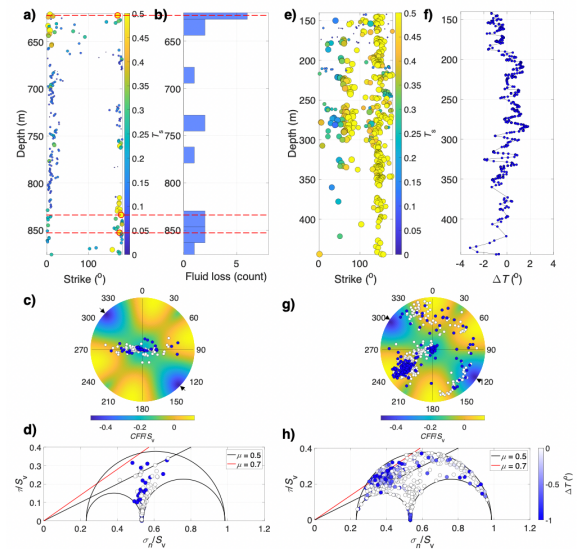


Figure 5: Results of the slip tendency analysis in well B (a, b, c, d) and C (e, f, g, h).

5. DISCUSSION

Based on the investigation performed in this study, the most hydraulically conductive are found to be the steeply dipping NNE-SSW and NW-SE striking discontinuities. The direction of these discontinuities, as confirmed with the permeability indicators on borehole scale, is also the preferential direction of the fluid flow in the Ruhr region.

Fluid flow and discontinuity analysis indicates that in the analysed wells there are i) relatively few discontinuities that dominate the flow and ii) relatively low number of planar features that are critically stressed. Nonetheless, the results of this analysis prove that the intersected critically stressed pre-existing planar features are hydraulically conductive and a match between critically stressed planes and permeability indicators can be considered as very good. This was indicated by fluid losses at depths corresponding to the critically stressed planes and is especially visible in the depth-related plots in Figure 4 and 5. There intervals with planes having higher T_s values represent intervals where fluid losses were registered as well as in the three-dimensional Mohr plots. Although fluid loss data cannot be used to give accurate estimates on reservoir permeability, it is still useful in a qualitative sense for indicating fluid-conducting features. The increased resolution of the verification data, i.e., more sophisticated drilling fluid loss data, would additionally reduce the uncertainty during critically stressed plane evaluation. However, even without detailed information on individual pre-

existing planar features and limitations of the verification data set, a correlation between the in-situ stress state and preferential direction of fluid flow was found for the rock mass of the Ruhr region in wells A, B, and C. Especially good correlation is seen in the well C, where great majority of critically stressed planes are related to the high thermal anomalies, proving their increased permeability. In cases where a fluid loss was not related to a critically stressed planes, it may have been instead related to a permeable coal-bearing layers, drilling-induced fracture, or extensive borehole deformations (i.e., wash-outs or wide breakouts) developed during drilling operations.

Results from this study agree with conclusions made by Rudolph et al., (2010) who, based on 3D numerical modelling efforts and results from geophysical logging from exploration boreholes across the Ruhr region, observed that in the vicinity of the NW-SE striking faults within Carboniferous sandstone formations increased permeability exists. The hypothesis of the NW-SE and NNE-SSW direction of permeability could be also confirmed by surface methane emissions study by Thielemann (1999), who concluded that most of the emitted gas at the surface, in the vicinity of the city of Bochum, is emitted alongside an NNW-SSE direction. Thielemann (2001) observed that NW-SE striking Sachsen and Munster faults, located in the vicinity of the city of Hamm, were responsible for a few-meter-wide methane emission zones, along longitudinal fault axes, sourced at around 800 m depth. Such an observation confirms the interconnectivity of the permeable faults from the coal layers up to the surface. Reinewardt (2009) showed that during the penetration of the NW-SE striking Krudenburg fault, which dips around 80° to the west and has a thickness of around 80 m, within the Prosper-Haniel mine in 1982, major water and mud inflows were observed at all fault sections causing major disruptions during mining operations. Attempts of sealing the highly permeable fault with grout were made using relief boreholes and grout being injected into the fault via injection boreholes. High permeability was also observed during drilling through the NW-SE striking Blumenthal fault close to city of Recklinghausen (Pilger, 1960). Fault penetration during coal mining activities created there a water ingress and strong methane outgassing. The studies described above, although being on a much bigger scale, confirm the hypothesis of the preferential direction of permeability within the Ruhr region, as confirmed on a borehole scale and, thus, confirm the strong co-dependency of the present-day in-situ stress tensor and fluid flow.

Other factors contributing to the discontinuity bulk permeability including discontinuity cohesion, filling material, aperture, roughness, or the degree of remineralization were not investigated in this study. These factors may create exceptions to the overall correlation between in-situ stress tensor, discontinuities, and permeability. Ismail et al. (2016) proved that in clay-rich reservoirs, no direct relation between clay content and magnitude of permeability

exists, with high permeabilities existing for both clay- and calcite-rich rocks. They indicated that as clay content increases, higher permeability reduction at increasing effective stress, in comparison with calcite-rich samples, exists. The permeability of clay-rich rocks is, thus, much more sensitive to effective stress, which emphasizes the importance of forecasting geothermal fluid production based on stress-dependent permeability in clay-rich reservoirs. Only comprehensive data analysis including geophysical and temperature logging, wellbore imaging, in-situ flow testing, and core studies would fully evaluate the importance of all aforementioned factors on the fluid flow across pre-existing discontinuities in the Ruhr region.

Due to the scarce intrinsic matrix porosity and permeability of the formation rocks in the Ruhr region, it is expected that the future geothermal systems will rely primarily on either fracture network systems, faults, or carbonate rocks with a high degree of dolomitization or karstification. To take the most benefit of the hydraulically active discontinuities, during the development of a deep geothermal system, drilling a geothermal borehole in a potential reservoir layer in NE-SW or WNW-ESE direction will be the most advantageous in terms of reservoir secondary permeability. If drilling in this direction will be connected to the penetration of the major NW-SE or NNE-SSW striking normal fault, seismic activity can be considered as likely. This is especially expected in case of hydraulic stimulation efforts in any of these structures. Once penetration of the major NW-SE striking fault will be necessary, fault segments with lower slip tendency should be targeted. It is expected that the NE-SW reverse faults are hydraulically dead and could act as a seal within a reservoir. To establish the best hydraulic connection between a geothermal doublet, wells could be drilled in either NW-SE or NNE-SSW direction to one another. Due to the potentially likely occurrence of critically stressed fractures and faults in the Ruhr region, it is advised to perform comprehensive 3D geomechanical modelling and implement real-time seismic monitoring using traffic light systems or seismogenic index models to minimize seismic risks related to the exploration of deep geothermal resources. Additionally, more comprehensive laboratory studies on the frictional properties under reservoir-specific conditions are sought.

6. CONCLUSIONS

In this study, we investigated the relationship between the in-situ stress state and reservoir permeability in a heavily faulted and folded Upper Carboniferous rock mass of the Ruhr region. Based on the collected in-situ stress data, the stress state of the Ruhr region remains relatively homogeneous and can be described predominantly by a strike-slip regime with pure normal and reverse regimes being considered as unlikely. In-situ stress measurements below 2000 m depth are advised to better constrain the in-situ stress tensor at greater depths in the Ruhr region. The slip tendency

analysis of planar features located in exploration boreholes suggests that only a small percentage of discontinuities registered by the dipmeter are critically stressed, whereas around half of all discontinuities registered by borehole imager tool are considered critically stressed. To establish relationships between orientations of planar features and fluid flow, we used data on both micro and macro scale including i) fluid loss data, ii) high-quality temperature log, and iii) indications of fault permeability from coal mining operations. These data presented evidence that formation permeability is enhanced at depth intervals with brittle lithologies and critically stressed pre-existing discontinuities that are favourably oriented for failure within the current stress field. It was revealed that the steeply dipping NW-SE and NNE-SSW oriented discontinuities penetrated by the analysed wells play an important role in providing fluid migration pathways in the low-permeability rocks of the Ruhr region. The critically stressed discontinuities are found to be better hydraulic conduits than discontinuities unfavourably oriented for failure (i.e., structures striking in the NE-SW direction) in the prevailing in-situ stress tensor, which are closed and hydraulically dead. As it is expected that future geothermal systems in the Ruhr region will rely primarily on secondary permeability, drilling new geothermal boreholes in the NE-SW or WNW-ESE within a potential target layer will be the most beneficial in terms of reservoir bulk permeability.

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