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Preparing for the First Basement Eavor-Loop™ Planned to be Drilled in Germany

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ABSTRACT

Energy providers in Germany count on Eavor-Loops™ for energy independence, to decarbonize their heat networks and/or replace their fossil fueled power plants. After the successful first power delivery by an Eavor-Loop 1.0™ in Geretsried, Eavor is progressing to install closed loop technology targeting the basement for commercial projects. Geoscience plays a vital role and hence derisking any of the potential geoscience hazards and uncertainties is subject to a lengthy process of data collection, acquisition, and evaluation. Funded by the client and supported by available state funding, a 2D seismic survey at the anticipated drill site and surrounding rural areas was conducted to enhance imaging and subsurface modeling. An extensive study of rock parameters was conducted for Eavor GmbH in collaboration with academic institutions, along with a geomechanics study carried out by Eavor. Based on the findings of these studies, the project site and the drilling process itself could be significantly de-risked.

1 INTRODUCTION

In collaboration with a local municipal heat network operator, Eavor is planning for the potential construction of a near-vertical Eavor-Loop 2.0™ into the basement of the southern German Molasse Basin. The single Eavor-Loop 2.0™ could consist of 2 vertical wells, each with 12 multi-laterals, which are connected at the toes to form 12 connected legs. The heat extracted from a section between 4000m to a maximum vertical depth of 7000m within the basement was estimated in a feasibility study. It could potentially serve up to 13500 households with baseload heat throughout the coming century. The feasibility study highlighted a lack of data regarding the integrity of the subsurface, which is necessary for planning any drilling operation, potentially marking the first commercial basement Eavor-Loop™. An illustration of the basement Eavor-Loop 2.0™ is provided for comparison with all other geothermal systems on the right of Figure 1.

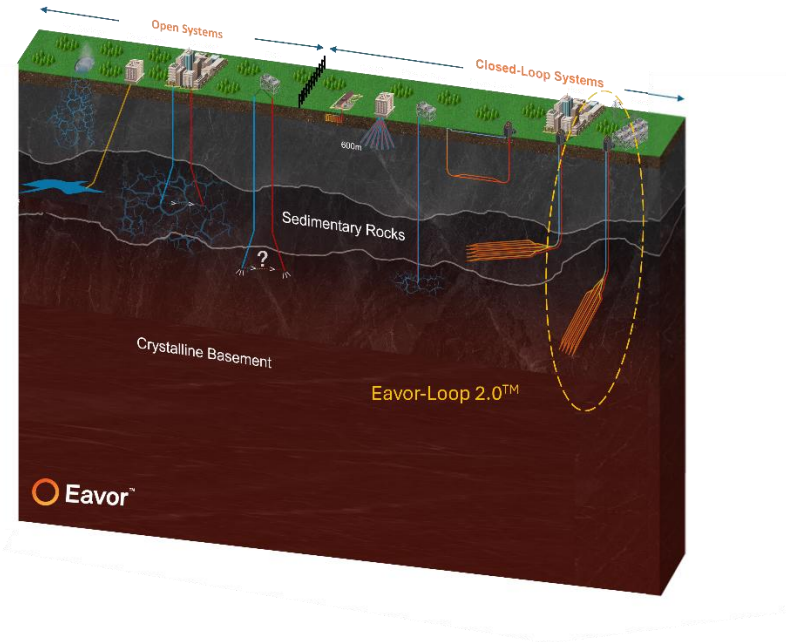


Figure 1: The two Eavor-Loop™ closed loop configurations to target the basement (far right) in comparison to all other geothermal systems.

While the vertical section is drilled and completed conventionally, the radiator section is drilled as open hole wellbores which are later sealed with proprietary Eavor Rock-Pipe™ sealing agent. For the sidetracking and steering of the open hole sections, conventional tools are used in tandem with the Eavor-Link™ active magnetic ranging system that helps to connect the laterals at the toes. Looking at the two basement layouts in Figure 1, it becomes obvious that Eavor-Loop 2.0™ systems target hotter sections of the crust, leading to a higher energy extraction. Drilling of the open borehole sections specifically requires good knowledge of the subsurface integrity and potential risks. The respective necessary data acquisition, methodology, and results are presented in this paper.

1.1 Geological Setting of the Study Area

Southern Germany consists of several tectonostratigraphic units (Figure 2). The Upper Rhine Graben forms the western tectonic boundary and is mainly characterized by Tertiary and Quaternary sediments. The eastern boundary is defined by the crystalline basement of the Bohemian Massif. The Molasse Trough in front of the Alps covers the area in a triangular shape. The basin developed from the late Eocene to early Miocene due to the flexural subsidence of the European plate. This flexure was induced by Alpine slab and topographic loading (Eskens et al, 2024).

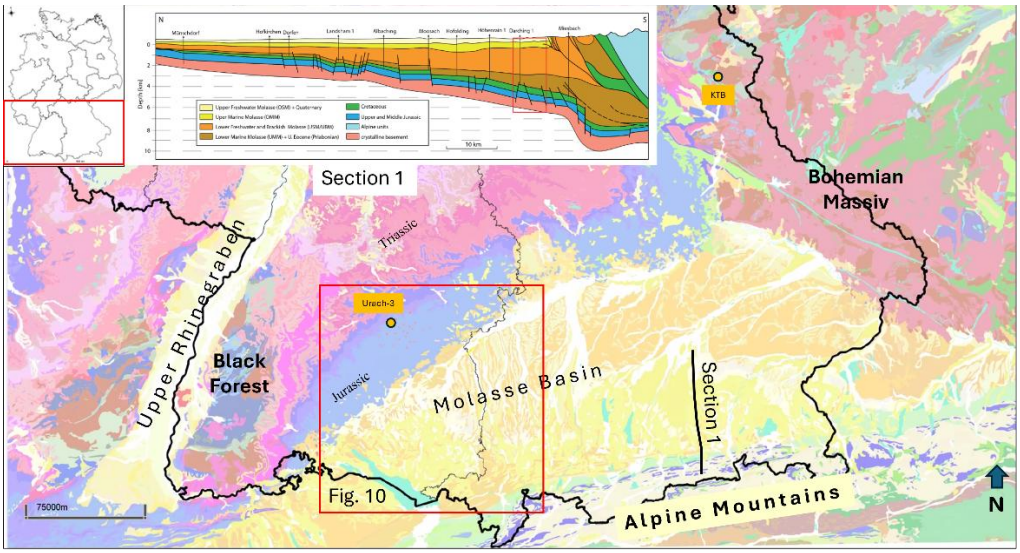


Figure 2: Regional Context using the 1:1 Mio Geological Map of Germany (BGR -GK1000) and a section based on the interpreted TRANSALP seismic survey (Shiplin et al, 2020; Lüschen et al, 2006). Also shown are the two scientific basement wells: Urach-3 and KTB.

Mesozoic rocks (Triassic to Jurassic) directly overlie the crystalline basement. These rocks dip towards the south and outcrop along the northern edge of the Molasse Basin, while the Tertiary Basin holds the erosional debris of the rising Alps. These Tertiary sediments increase in thickness towards the Alps (Figure 2, Section 1) and reach thicknesses of up to 5000 m. Due to their low thermal conductivity, these sediments create a thermal blanketing effect across southern Germany which leads to relatively higher geothermal gradients. In combination with the presence of excellent Upper Jurassic carbonate karst aquifers, the region hosts several classic hydrothermal facilities. However, in the areas where those aquifers are missing or are at too shallow depths, the Eavor-Loop™ system could still utilize the higher temperatures present in the basement.

1.2 Missing Data and Existing Data

While the southernmost part of the Molasse Basin is well understood due to oil and gas exploration activity throughout the last century and until today, some areas still lack vital information about the subsurface.

In rural areas, regulations have prevented the easy acquisition of seismic data and gaps are present. These gaps should be filled as this is primarily where heat-offtake takes place or where old fossil fuel-fired power plants need to be replaced. For this study new data was acquired and other publicly available data was used to gain knowledge in respect to the basement underneath southern Germany. Key reference wells are the deep boreholes of the Urach and KTB scientific drilling campaigns, that reached depth of 4445 m (Urach-3) to 9101 m (KTB-HB) each in primarily metamorphic basement. Existing vintage 2D data and other offset well data were acquired from the authorities or their original owners. Direct measurements on borehole samples with respect

to thermal conductivity and geomechanical parameters were also missing to best characterize the target basement rocks, and so a respective parameter study was planned for and conducted between 2022 and 2025.

2 STUDIES FOR SUBSURFACE DESCRIPTION AND RISK ASSESSMENT

Former modelling studies in relation to seismic resolution in basement (Schuck et al, 2012) concluded that only single low angle faults can be resolved by seismic, while steeper dips and presence of noise impair resolution. Still, large fault-offsets of basement and Mesozoic sections can be seen, and hence new seismic was planned for. A rock parameter study, geomechanical modelling, and new findings based on the new integrated 3D Geologic Model are presented below.

2.1 2D Seismic Acquisition

The acquisition of the 2D seismic lines was planned throughout 2024 and took place in February and March of 2025 and proceeded on schedule without incident. The four lines totaling 53.2 km were planned to cross a potential drilling site close to an existing heat network and hence had to cover urban areas. 2500+ vibrator points were made, and over 10,000 geophone locations granting receiver spacing of 5 m and a maximum fold of 240. Parameter tests were carried out prior to acquisition to ensure that all objectives will be met (reaching into the basement & resolving the sedimentary section as best as possible). Several events were held and public notices made to inform the public regarding the acquisition program. Through collaboration with industry and local governments, the program was executed with diligent care to the residence and the environment. All source points were made in locations already accessible to Vibroseis trucks (Figure 3); and when approaching infrastructure, the source strength was decreased to maintain the integrity of nearby buildings following the limits defined in the DIN 4150-3 standard.

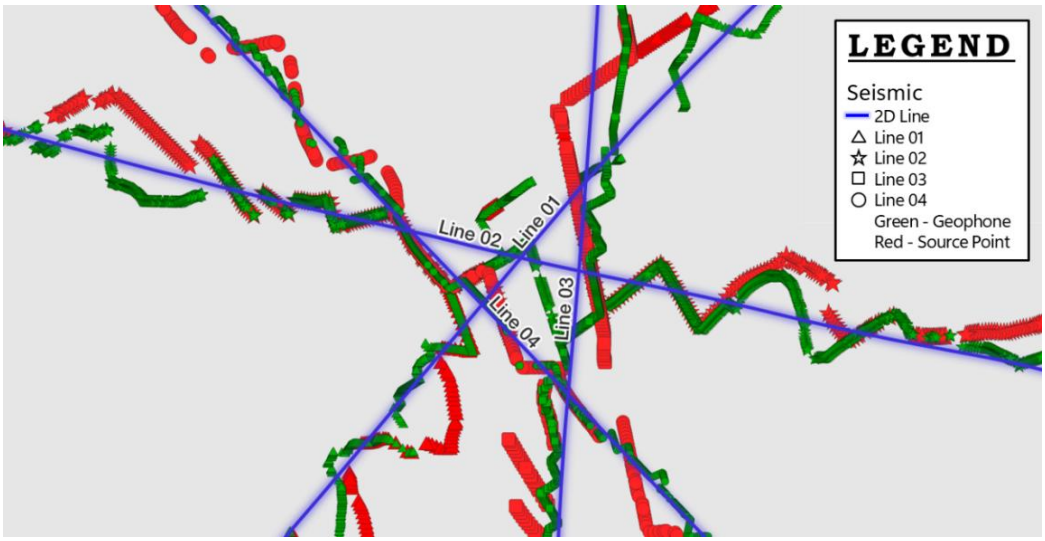


Figure 3: Map schematic of the intersection of the four seismic lines in area of interest.

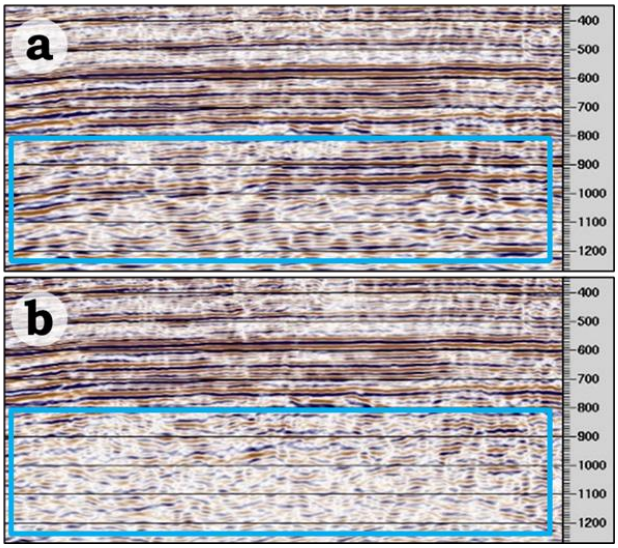


Figure 4: Representative cross-section of seismic data. Basement is around 750 ms. a) shows the multiples in the data imposing non-geologic features in the basement in the blue rectangle. b) shows the impact of suppressing the multiples and preserving the geologic signal.

The seismic was processed with a thorough PreSTM processing sequence. During processing there was strong evidence of multiples. Migration velocities and other processing parameters were reviewed to delicately remove the coherent noise from the data and preserve an accurate and representative geologic section. This preserved the image of the interface between the base of the sedimentary section and top of crystalline basement as shown in Figure 4. An existing well was tied to the new seismic and nearby wells were tied to vintage lines for a refined integration of the newly acquired seismic. With the help of this newly acquired data the area was interpreted down to Top Basement and connected to vintage lines showing a connection across the Bavarian to Baden-Wuerttemberg State borders. Here, the available 3D geological models historically stopped and showed broken and unconnected fault systems. Together with petrophysical and geomechanical studies, the overall understanding of the tectonic setting in the area can be built upon.

2.2 Petrophysical characterization of crystalline rocks in the Molasse Basin

The crystalline basement in the South German Molasse Basin is predominantly covered by younger deposits, and accessible outcrops are found only in a few places, such as the southern Black Forest or the Bavarian Forest. To provide representative rock property data for site exploration and reservoir simulations, eight different lithologies from the crystalline basement in the Molasse Basin were collected from quarries and available wellbore cores in Bavaria and Baden-Wuerttemberg. Their composition was granitic nature, as a predominantly granitic basement is anticipated at the project site. Cylindrical specimens were prepared from the collected rock samples and subsequently analyzed at the Technical University-Darmstadt laboratories to determine their mineralogical composition, petrophysical properties (e.g., density, porosity, thermal conductivity and diffusivity, and heat capacity), and rock mechanical properties (e.g., UCS, tensile strength, Young's Modulus) after Weydt et al. (2021, 2025).

Additionally, selected samples were examined at GFZ Potsdam to measure thermal conductivity and diffusivity under high-temperature conditions using a Hot Disk device (20 °C to 275 °C; Peksa and Fuchs, 2024). The collected rock samples (Figure 5) from Baden-Wuerttemberg comprise the Malsburg granite (a medium to coarse-grained biotite granite) and sample material from two boreholes: well A (alkali feldspar granite, ~990 m depth) and well B (biotite granite, ~1,164 m depth). Additional samples include the Hauzenberg granite (a light grey, medium to coarse-grained two-mica granite) from the southern Bavarian Forest, the Thanstein granite from the Upper Palatinate Forest (likewise a two-mica granite), as well as core samples from three wells: well C (biotite granite, ~1,586 m depth), well D (biotite granite, ~2,200 m depth), and well E (gneiss, ~2,390 m depth). While the samples obtained from the quarries represent fresh, unaltered material, the core samples retrieved from the wellbores exhibit weak to moderate alteration and/or fine fissures or fractures healed with secondary alteration minerals such as clays, chlorite, or calcite.

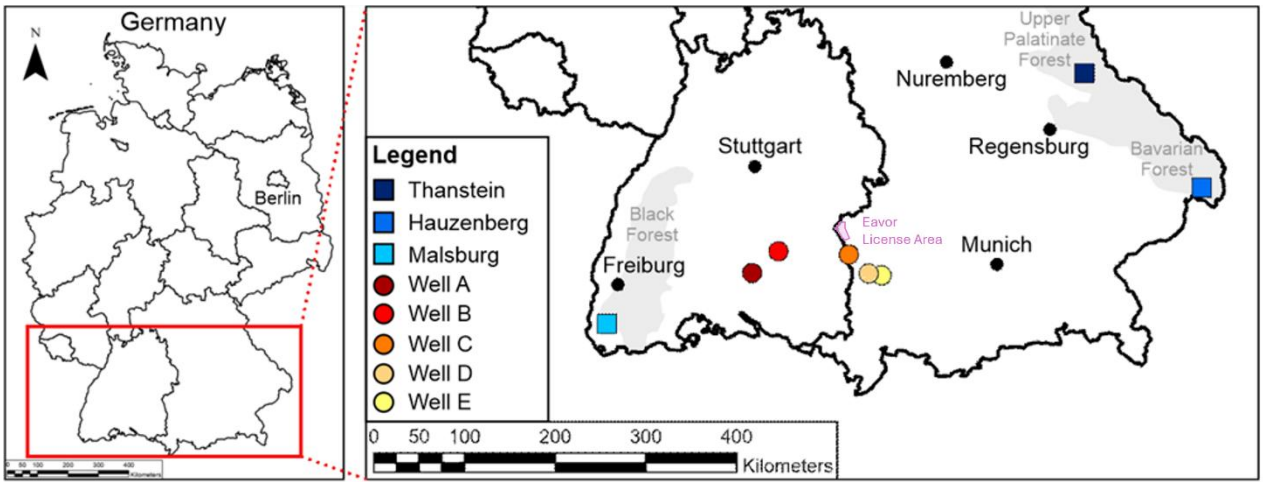


Figure 5: Sampling locations of the analyzed crystalline rocks. The grey shading represents the extent of the Black Forest and the Bavarian Forest basement areas. Rectangles represent quarry samples, whereas circles indicate wells.

Selected results of the petrophysical measurements are presented in Figure 6. With the exception of the core from well E (2.74 gcm^{-3}), the grain densities of the rock samples range between 2.62 and 2.65 gcm^{-3}. The bulk density is slightly lower, ranging from 2.59 to 2.63 gcm^{-3}. Effective matrix porosity generally falls below 2%, varying between 0.7% and 2%. Likewise, matrix permeability is generally lower than 10^{-18} m^2. In case of fine cracks and fissures, matrix permeability was one order of magnitude higher (10^{-17} m^2; well B and D). Magnetic susceptibility is relatively consistent across the dataset, ranging between 0.04 and 0.06 · 10^{-3} SI units. Exceptions are observed in the samples from wells A and E, which exhibit higher values of 0.11 and 0.18 · 10^{-3} SI units, respectively. Thermal conductivity and diffusivity measured under ambient conditions range between 2.52 (well A) and 2.83 $Wm^{-1}K^{-1}$ (Thanstein granite) and 1.3 (Malsburg) and 1.55 ·$10^{-6}m^2s^{-1}$ (well B), respectively. Between ambient temperature and the maximum temperature level of 275 °C, thermal conductivity decreases by an average of 20%. Over the same temperature range, thermal diffusivity decreases by as much as 45 to 50%. The specific heat capacity at ambient temperature ranges between 727 and 782 J $kg^{-1}K^{-1}$ and, in contrast to the previous parameters, increases with rising temperature. At 200 °C, specific heat capacity ranges between 940 and 990 J $kg^{-1}K^{-1}$.

a)

Unit	Area	ρ_P [g cm^{-3}]	ρ_B [g cm^{-3}]	ϕ [%]	K [m^2]	X [10^{-3} SI]	λ [W m^{-1} K^{-1}]
Thanstein	Upper Palatinate Forest	2.66 (6) ±0.003	2.63 (3) ±0.007	1.2 (3) ±0.2	3.7E-19 (3) ±5.4E-19	0.04 (15) ±0.009	2.83 (17) ±0.15
Hauzenberg	Bavarian Forest	2.65 (6) ±0.014	2.60 (3) ±0.012	2.0 (3) ±0.3	2.1E-18 (3) ±1.4E-18	0.04 (8) ±0.003	2.60 (17) ±0.21
Malsburg	Black Forest	2.63 (37) ±0.008	2.61 (34) ±0.024	1.4 (22) ±0.4	3.1E-19 (4) ±4.5E-19	0.04 (70) ±0.020	2.60 (49) ±0.16
Well A	BW	2.65 (7) ±0.017	2.63 (2) ±0.002	1.2 (2) ±0.4	3.3E-18 (2) ±5.9E-19	0.11 (7) ±0.009	2.52 (7) ±0.09
Well B	BW	2.62 (14) ±0.020	2.62 (6) ±0.018	0.7 (6) ±0.4	1.5E-17 (6) ±3.2E-17	0.06 (14) ±0.025	2.80 (14) ±0.14
Well C	B	2.64 (3) ±0.007	2.62 (2) ±0.004	0.8 (2) ±0.6	4.2E-20 (2) ±2.0E-20	0.04 (3) ±0.026	2.67 (3) ±0.23
Well D	B	2.63 (11) ±0.019	2.62 (6) ±0.007	0.7 (6) ±0.3	9.3E-17 (6) ±1.6E-16	0.06 (11) ±0.005	2.63 (11) ±0.06
Well E	B	2.74 (1) ±0.003	-	-	-	0.18 (1) ±0.026	2.79 (1) ±0.11

Arithmetic mean, ± = Standard deviation, () = number of measured samples, B = Bavaria, BW = Baden-Wuerttemberg
ρ_P = Particle density, ρ_B = Bulk density, ϕ = Porosity, K = Permeability, X = Magnetic susceptibility, λ = Thermal conductivity

b)

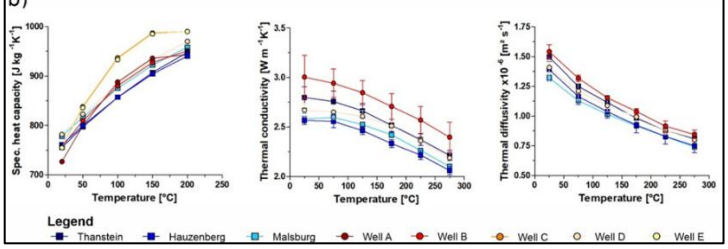


Figure 6: a) Summary of the measured petrophysical properties under ambient conditions of surface and wellbore core samples of the crystalline basement in the Molasse Basin. b) Changes in the specific heat capacity, thermal conductivity and thermal diffusivity of selected samples at increasing temperatures.

The thermal rock-properties were used to model the temperature using an in-house modelling software. The temperatures reached by the toes of the planned Eavor-Loop™ at a maximum depth of 7000 m could vary

between 213 – 258 °C. The respective temperature profiles were used to model the heat-output and were used as a variable for the geomechanics analysis.

2.3 Geomechanical Analysis

Geomechanical analysis plays a crucial role in Eavor-Loop™ well design as it can anticipate wellbore stability issues during drilling. The geomechanical analysis results are used to define an optimal well trajectory design and operational strategies to minimize or mitigate drilling events that can result in severe drilling disruption and consequently project delays and higher costs.

Wellbore stability modelling aims to predict the geomechanical behaviour of the subsurface and evaluate possible risks during the drilling of the Eavor-Loop™ wells. This analysis is based on analytical solutions derived from Kirsch's equations, which describe the stress distribution around the wellbore wall under certain in-situ stress, pressure, and thermal conditions. By comparing these stress distributions with the rock strength parameters, the model can anticipate the occurrence of compressive or tensile failures, as presented in Figure 7. Such failures, characterized as borehole breakouts or tensile fractures, may result in serious operational issues.

The geomechanical model for the basement Eavor-Loop™ was developed using multiple data sources, including offset wells, laboratory measurements, regional tectonic studies, and published literature on rock mechanical properties. However, the availability of offset well data in the area is limited, particularly at the depth of interest, since most wells in the region penetrate only the sedimentary package and do not reach the crystalline basement. To supplement these data gaps, Eavor has collected geomechanical information for basement rock from outcrops and a few wells in the vicinity, as summarized in Table 1. In addition, in-situ measurements from the deep boreholes Urach 3 and KTB were used to calibrate in-situ stresses and pore pressure predictions.

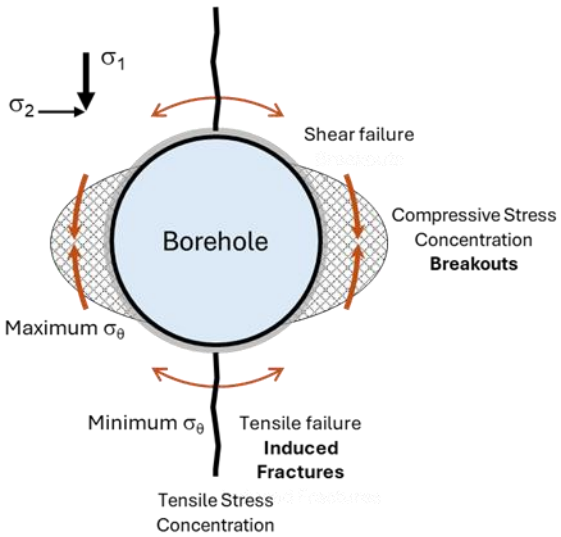


Figure 7: Wellbore stability schematic, showing tangential stress in orange along with the location of breakouts and induced fractures.

Table 1: Geomechanical laboratory parameters for basement rocks collected for the project

Sample location	UCS (MPa)	Tensile Strength (MPa)	Internal Friction Angle (Degree)	Poisson's ratio	Young's Modulus (GPa)	Density (g/cm^3)
Malsburg	192.00	20.00	57.10	0.18	32.50	2.59
Thanstein	145.00	19.80	49.00	0.26	26.80	2.63
Hauzenberg	187.00	21.50	56.20	0.19	27.00	2.60
Well A	97.00	9.70		0.18	34.90	2.63
Well B	140.00	21.30		0.17	33.50	2.62
Well C	213.60	19.60				2.62
Well D	200.00	20.80		0.14	33.40	2.62
Mean	**167.80**	**18.96**	**54.10**	**0.19**	**31.35**	**2.62**

Figure 8 displays the wellbore stability analysis for the most likely scenario, based on mean rock and stress properties. This case incorporates the stress state derived from logs, literature, and in-situ stress measurements in the area, indicating a strike-slip regime where S_{Hmax} slightly exceeds S_v (Seithel et al, 2015; Ziegler & Heidbach, 2020). It also includes the most likely pore pressure conditions. The results suggest that the well can be safely drilled with a mud weight ranging from 0.99 to 1.42 SG along most of its length. These limits correspond to pore pressure as the lower bound and minimum stress as the upper boundary. Furthermore, several sensitivity analyses have been performed to identify potential risks during drilling to plan mitigation strategies. Based on the sensitivity analysis, the project appears to have favourable geomechanical conditions for drilling, as the basement rock exhibits high mechanical strength in laboratory assessments. Additionally, pore pressure is anticipated to be at or below hydrostatic levels, thereby ensuring a consistent mud window throughout the borehole. The sedimentary sequence is also expected to be competent, lithified formations, which reduces the risk of borehole breakouts or the initiation of induced tensile fractures. However, the occurrences of karst features within the shallow overburden Upper Jurassic could lead to fluid losses and this needs to be accounted for.

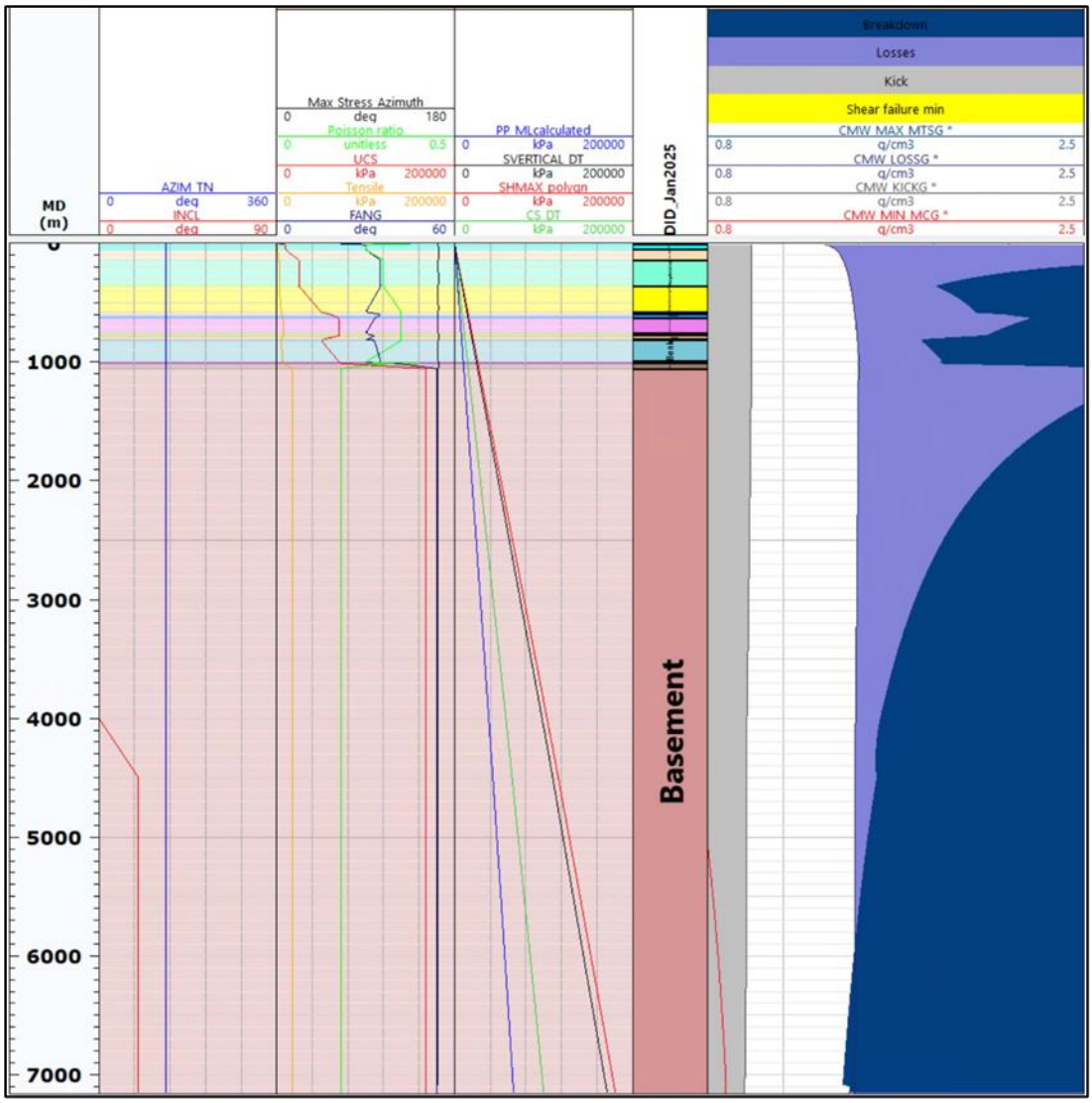


Figure 8: Wellbore stability analysis for the most likely scenario in the Molasse Basin. The first track presents the wellbore azimuth and inclination. The second track shows the mechanical properties of the expected lithology. The third track displays the stress state and pore pressure. Finally, the last track illustrates the safe mud window, with mud weight limits highlighted.

2.4 Structural Setting

Based on the newly acquired seismic data and the geomechanical analysis, the structural model for the region covering the Neu-Ulm area can be newly described and potentially linked to identified structures in the wider area. Various structural styles are known to exist in the southern German Molasse Basin reaching from normal extensional faults (sometimes conjugate faults forming x-type faults), to reverse faults (re-activated normal faults) and thrusts usually limited to the area close to main alpine thrust front (Shiplin et al, 2020).

The two subregional seismic lines composed from new and/or vintage lines show the general structural dip towards the south (A-B) with thickening of Tertiary section and thinning of the Mesozoic section towards the alpine front in the south (Figure 9). The east-west section (C-D) shows a very subtle thinning of the Mesozoic section (Triassic to Jurassic) towards the east.

The expected normal to strike-slip faulting regime was confirmed by the geomechanical study and is based on the prevailing near N-S direction of S_{Hmax} (Reinecker et al, 2010; Heidbach et al, 2025). Normal faulting could be identified on the existing seismic as a E-W striking fault displaying substantial dip (Figure 9). A single fault with the highest offset is marked as a blue fault together with the blue circle on the line A-B. Numerous other dip-slip faults dipping towards the south plus splays and minor reverse components could be identified on that section. The blue dip-slip fault is trending like many of the other identified faults parallel to the alpine front and is related to the normal faulting that occurred during crustal loading while the alpine nappes and folds were advancing.

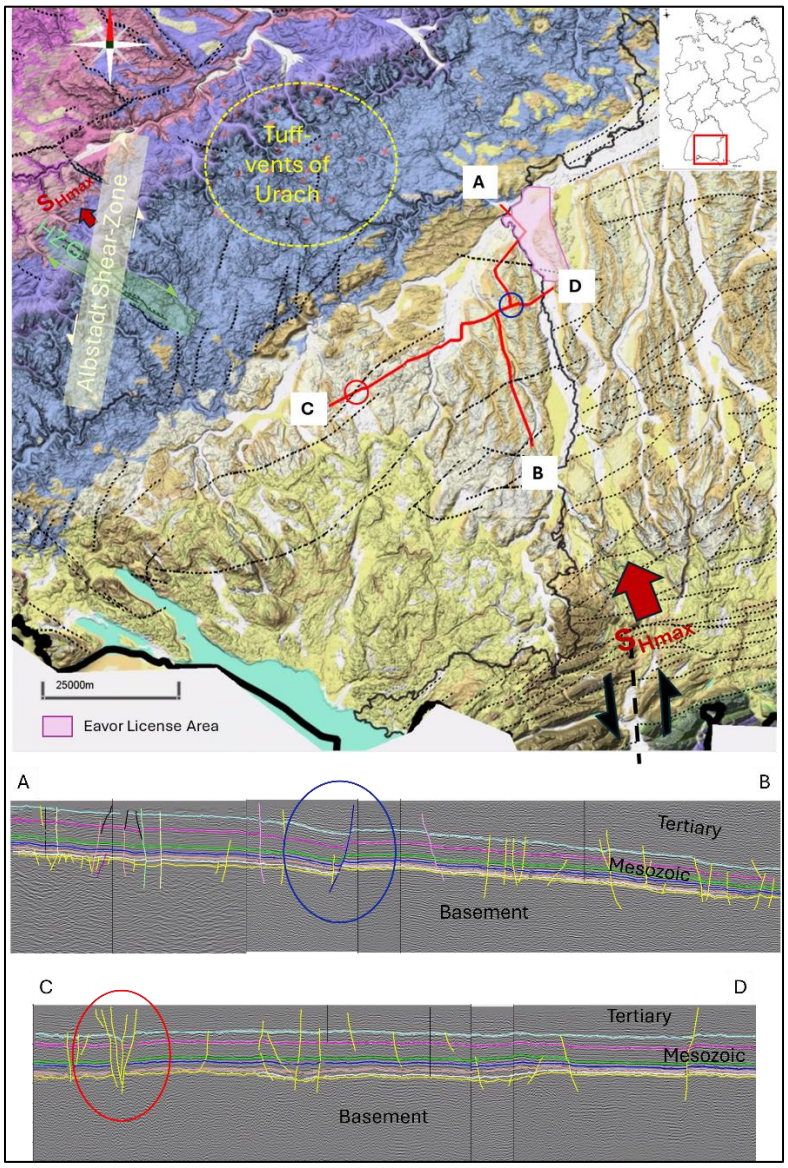


Figure 9: Major faults near the license area had to be identified and ruled out as a risk for the site. The colour of the circles on the map corresponds with the ovals on the cross-sections. Further descriptions can be found in the text (adjusted after Mader et al 2024 & Berge & Veal 2005, Surface Map: DEM Copernicus plus GK 1000, BGR).

In addition, a fault system showing large offsets (marked with the red oval on line C-D) could be identified on vintage data. The potential major strike-slip fault-system was historically interpreted to be a normal fault that is changing its strike direction at this location from NE-SW to NNE-SSW. This, however, seems unlikely as the faults are near vertical and converge to a narrow zone within the basement, which would be more akin to a transfer system. This setting could potentially be similar to the well-known Albstadt Shear-Zone (ABZ marked in yellow, Figure 9 map inlet). The ABZ (Mader & Ritter 2024) is related to the most seismically active German graben system (Hohenzollern graben HZG, marked in green). This graben developed as shallow reaction to the NNE-SSW left-lateral strike-slip motion of the ABZ fault deeply rooted in the basement. An additional NW-SE dextral fault zone parallel to the HZG is getting re-activated by alpine tectonic processes. The identified transfer-fault system on section C-D could display a similar yet older setting. The Tertiary tuff-vents of Urach displaying a positive geothermal anomaly, confirmed by a scientific well, are located directly to the north of the identified fault-system. A relation between those features could be assumed, but this would require further studies. Strike slip faults were also identified at the alpine thrust front (Berge 2005) and are marked with black arrows together with the identified maximum stress direction (marked for each investigated area as dark red arrow). This illustrates the potential occurrence of strike-slip faults at small angles in relation to this stress direction. Further studies could uncover strike-slip faults inside or below this above illustrated part of the Molasse Basin.

Both identified major fault types could be ruled out with the newly acquired 2D seismic for the project location (Figure 10). A minor transfer-fault system could be seen parallel to the Iller river that can be avoided using the currently planned drill site. Smaller dip-slip faults were identified close to the project site, that will not cause any major drilling hazards.

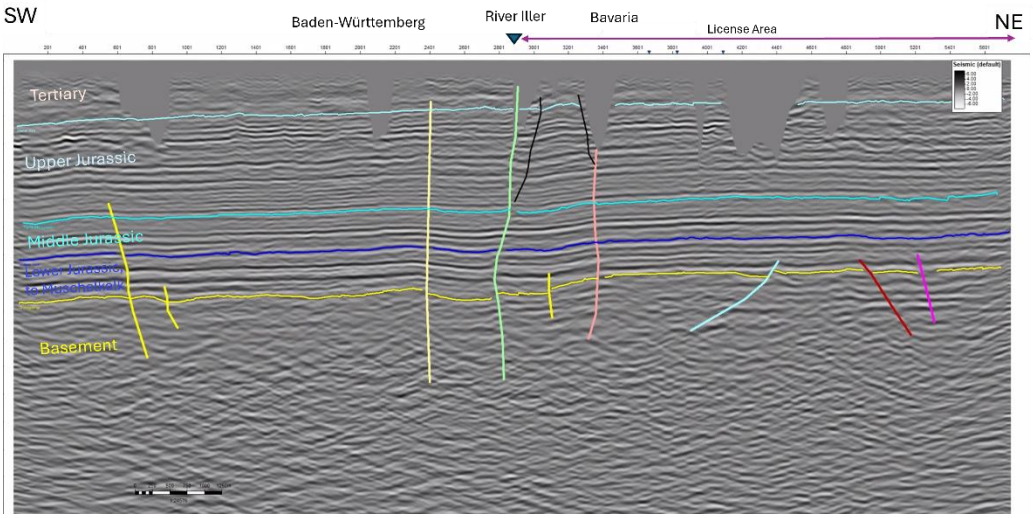


Figure 10: Seismic section crossing the border between Bavaria and Baden-Württemberg showing indications of a transfer system parallel to the Iller river.

CONCLUSIONS

A normal to strike-slip (transtensional) tectonic regime was expected and could be confirmed for the project site, which like observed in more distal areas could lead to normal or strike slip faults with substantial offsets. A newly acquired set of 2D seismic lines processed to best resolve the deeper basement and sedimentary cover confirmed weaker realizations of those fault regimes close by, but not at the project site, substantially de-risking it. Together with newly established rock properties of the expected primarily granitic basement, a detailed geomechanical study concluded that the basement can safely be drilled with a mud weight ranging between 0.99 to 1.42 SG. A flexible adjustment may be required along the open, slightly inclined borehole. Modelling of the temperature with newly established thermal rock properties point to temperatures potentially as high as 258 °C at depths of 7000 m below surface. The subsurface could support the building of an Eavor-Loop 2.0™ in case the decision will be taken to further progress with the project.

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