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The Deep Hydrogeothermal Project in Holzkirchen, Molasse Basin, Germany

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ABSTRACT

In Holzkirchen, a market town in the south of Germany close to the Alps, the currently deepest producing hydrothermal doublet in central Europe can be found. The Upper Jurassic carbonate reservoir in this region (Malm-Aquifer) is located between 4600 m and 5200 m depth and is known to have good transmissivity and a geothermal fluid with low salinity suitable for geothermal production (StMWIVT 2004). All in all, the project took 13 years to complete - from early conception in 2006 to the commencement of power production in 2019. Drilling of the two deviated wells in the deep sedimentary (Molasse) basin close to the Alps was a big challenge. The first well was spudded in January 2016. Following an intense gas kick while drilling the third section (of five in total) in the Lower Rupelian (Tertiary), the complete third section (1600 m) had to be abandoned and a sidetrack was drilled following a new well path to avoid the potential gas-bearing high-pressure zone. The final depth of 5600 m MD (5079 m TVD) was reached in May. After testing of the first well, the second well commenced in June. This well also proved problematic in the third section, where parts of the 9.7/8” liner as well as a drilling BHA were lost in two separate incidences due to differential sticking. Two sidetracks were drilled and after a total drilling period of about eight months, the final depth of 6084m MD was reached and followed by a circulation test of both wells which verified the required productivity and temperature. The most significant drilling challenge was the extremely high variance in pore pressures and the difficulty in foreseeing these pressures within the Oligocene and Cretaceous (approx. 3000 - 4500 m TVD), despite data from hydrocarbon offset wells. In spite of those drilling challenges, the success of the doublet in Holzkirchen represents the current peak of reservoir exploration in the southern part of the German Molasse Basin. Permeability is much lower compared to shallower wells that exploit the Malm-reservoir further north. The productivity of the Holzkirchen wells is strongly associated with a fault system. Nevertheless, the productivity (55 l/s) in combination with temperatures of more than 150°C is ample and sufficient to supply the district heating network of Holzkirchen with geothermal energy and to operate a small 3.4 MW ORC power plant.

1. INTRODUCTION

1.1 Geothermal Energy in Holzkirchen

The Holzkirchen geothermal project comprised the first deep geothermal wells to be drilled in the southern extents of the German Molasse Basin (Figure 1). The operator Geothermie Holzkirchen GmbH (GHG) pushed the project to assure that renewable geothermal energy can be provided to its customers in the form of direct use for district heating and power generation.

Figure 1: Location of Holzkirchen in the Southern German Molasse Basin.

Situated approximately 30 km to the south of Munich (South Germany), the market town of Holzkirchen benefits from a strong local economy and the ideal geological conditions for direct use and power generation from a deep geothermal aquifer in its subsurface. The Upper Jurassic carbonate reservoir (Malm), in this region found between 4600 m and 5200 m depth, is known to have appropriate natural permeability and its geothermal fluid to be of low salinity. This, together with its expected naturally sufficient yield, makes the Malm the ideal source for a combined direct use for district heating and power generation with a binary Organic Rankine Cycle (ORC) power plant.

Due to the great depth in which the reservoir is found, the financial and technical effort to make geothermal energy usable in Holzkirchen is relatively high compared to classical “high enthalpy” geothermal regions worldwide. On the other hand, the thermal resource is located directly below the final consumer, making costly and long transport routes as well as unfavorable impacts on the environment dispensable. It is also important to acknowledge that a value chain is created locally and that citizens benefit directly from the use of geothermal energy locally, since less capital flows out of the region in the long term, as would be the case e.g. for the purchase of fossil energy sources. The surplus flows into the local community works, which are 100% owned by the community of Holzkirchen. By the combined use of district heating (mainly during the cold winter months) and electricity generation, the geothermal plant can be optimally used throughout the year. With an actual feed-in tariff of 25.2 Cent/kWh guaranteed for 20 years, power generation plays a key role in financing the project.

1.2 Project History

The exploration work of the geothermal project began after the granting of the corresponding permit in 2006. As a first step, a geological feasibility study for the use of thermal water for electricity generation and for district heating was prepared. In this study, the geological framework conditions in the permit field and possible drilling sites were identified. In conclusion, it was established that for electricity generation sufficiently high temperatures were to be expected. Additionally, the structural geological situation of the geothermal reservoir (Malm) was classified as favorable. However, the project sites considered at that time were comparatively far away from the Holzkirchen area since the permit area at that time didn’t cover the community itself.

Due to the favorable preliminary evaluations, existing 2D seismic data from the 1970s and 1980s were reprocessed and evaluated for the Holzkirchen site in two processing steps and a preliminary development concept based on the 2D profiles was developed. To place the community of Holzkirchen within the exploration area, the permit field was extended.

In view of the great development depths of the Malm, the proximity to the geological-tectonic Alpine margin and the associated high drilling requirements at the Holzkirchen site, it was decided to carry out a risk-minimized geothermal exploration including a 3D seismic campaign targeting the reservoir. Based on the standards of the hydrocarbon industry, a survey design was developed for the project specifically. In Holzkirchen, a new 3D seismic measurement campaign was carried out in February and March 2011, for the first time in Germany on behalf of a municipality. The area covered by geophones was approx. 66 km². On the basis of the seismic data and the drilling data from former oil wells in the Darching/Holzkirchen area, a detailed reservoir model was created, providing the basis for the determination of the conceptual drilling paths and possible locations.

Initially, the geothermal reservoir was to be exploited using two deviated boreholes, each with large bore diameters and starting from separate drilling sites. The separate drilling sites were necessary to minimize the risk of a thermal breakthrough (cooled water from the injection well reaches the production well) by a sufficient horizontal distance, while simultaneously keeping the drilling risk as low as possible with moderate deviation of the boreholes at high pouring rates (approx. 150 l/s). For this development concept, detailed planning for the boreholes was then pushed ahead in the years 2011 to 2012. Meanwhile, exploration of the subsoil, landscape ecological assessments, explosive ordnance investigations and surveying work were carried out at the future drilling site locations. Starting in mid-2012, services for the drilling work and associated services were announced, tendered, negotiated and evaluated EU-wide (16 individual trades). At the beginning of 2013, the mining law operating plan procedure for the drilling sites was initiated. At the same time, talks and negotiations took place regarding project financing and discovery insurance.

In the context of the discussion on the amendment of the Renewable Energy Sources Act (EEG) in spring 2013, uncertainties arose regarding the continued availability and level of the feed-in tariff for geothermally generated power, causing discussions about the financing and thus the progress of the project. In addition, two other geothermal projects in the Molasse Basin asserted insurance claims due to insufficient discharge rates or temperature. Consequently, the insurer, with whom protracted and intensive negotiations took place in Holzkirchen on finding insurance, withdrew. Similarly, other insurers from across Europe were no longer available for exploration risk insurance. The market for exploration risk insurance for new geothermal projects in Germany had de facto come to a standstill, affecting all attempts to obtain insurance for the Holzkirchen project.

In autumn 2014, consideration was given to possible alternatives to an exploration risk insurance policy. One of the examined options was the overcoming (drilling and re-utilisation) and deepening of former oil wells in the Holzkirchen area. The examination of the documents on the dismantling revealed that the use of an oil well that had been drilled and deepened further into the Malm is associated with very severe restrictions (can only be used as a reinjection well and with very low flow rates). Moreover, there were also residual risks regarding the condition of the installed steel pipes (casings) that are technically difficult to calculate. The option was therefore not pursued.

As a second option, the realization of a project variant with the focus primarily on district heating was under discussion, going hand in hand with lower minimum requirements for the pouring rate and thus with smaller necessary drill diameters (starting from a multipad well site (Alte Au)). Lower pouring rates also reduce the exploration risk as well as the necessary investment sums for the boreholes. On April 2015, the regional council of Holzkirchen initiated the realization of such a smaller project variant.

The well site was built in late autumn 2015 and was completed before the Christmas holidays. Assembly of the drilling rig began between Christmas and New Year, so that the spud in of the first well started on 27.01.2016.

Drilling operations on Th1 proceeded smoothly until March 2016, when an unexpected gas kick in the layer of the Rupelian “Bändermergel" stopped the progress abruptly at a depth of 4200 m. To continue drilling, a sidetrack (Th1a) and a new target in the reservoir were required. The sidetrack was successfully drilled until the mid of May 2016 and reached a final depth of 5600 m MD. Pumping tests proving the success of the drilling operation were carried out in June 2016.

The drilling operations of well Th2 began trouble-free as well, however in the third section casings became stuck during the installation of the liner. As a result, costly fishing and milling operations were necessary to remove the casings, prolonging over the course of several months and to the detriment of the project schedule. Further problems caused by pipe sticking during a check-trip through the sidetrack of the third section were encountered, requiring a further sidetrack and lead to more delay. In the beginning of March 2017, the well in Holzkirchen reached its final depth of 6084 m MD as the longest and deepest well in the Southern Molasse Basin and probably the deepest hydrothermal producing well in central Europe so far. .

The first delivery of district heating took place in December 2018, while the power plant for power generation commenced operation in July 2019.

2. GEOLOGY AND HYDROGEOLOGY

2.1 Overview

The geothermal reservoir of Holzkirchen is part of supra-regional Malm aquifer. It is a carbonate reservoir of Upper Jurassic age at the base of the asymmetric Molasse Basin. The Molasse Basin is filled with sediments (mainly clays, marls and sandstones) of Eocene-Miocene age (Lemcke, 1988). Holzkirchen is located close to the Alps where the Molasse Basin has its greatest depth of around 5000 m. Therefore, the thermal water in the underlying Malm aquifer reaches temperatures of 150-160°C, the hottest in the whole Molasse Basin.

2.2 Structural Geology

In the Malm at the basis of the Molasse Basin, the structural geology is dominated by syn- and antithetical faults, respectively, of ± W - E and WSW - ENE. A garland-shaped course, caused by so-called accommodation zones (ramps) with feathering in several fault branches, is also frequently observed in the structural geology of the Molasse Basin base in the Alpine foothills.

The tectonic structures, where some were already established at the end of the Jurassic as weak zones, run predominantly parallel to the basin axis in the W-E and WSW-ENE direction in the entire Molasse Basin. In the course of the strong lowering of the northern alpine predepth, the weak zones developed into elongation structures (normal faults) up to the end of the Upper Oligocene (Bay. GLA, 1996), which are characterized by predominantly antithetic fractures (here: dipping to the north). Towards the south, the age of the normal faults characteristically increases (Bachmann & Müller, 1992). The vertical offset of these faults reaches from a few meters up to more than 200 metres. The horizontal extension of some of these fault-systems can be as wide as several tens of kilometres.

In Holzkirchen the existence of a big antithetic fault system (so called “Holzkirchner-Darchinger Bruch”) was known from 2D seismic surveys mainly measured in the 1970s - 1980s and from nearby oil exploration wells, drilled in the 1960s - 1980s. To get a better picture of this fault system in detail, a new 3D seismic survey was launched by the community of Holzkirchen in 2011, putting the main focus on exploring the geothermal reservoir.

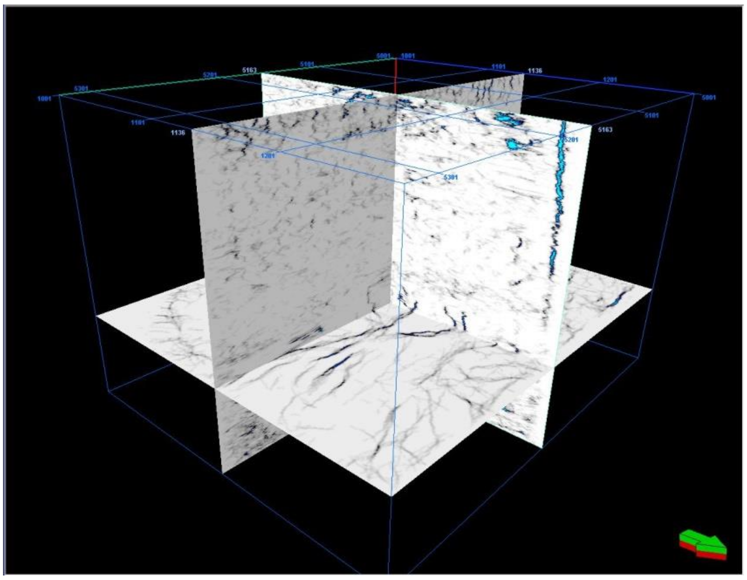

Figure 2: Ant tracking cube (time cube) of the 3D seismic survey in Holzkirchen, shows in several slices the direction of the faults. The z-slice (time-slice) is at 2250 ms.

After acquiring the seismic data, several methods, such as seismic attributes and ant tracking (Figure 2), were used to interpret the data. As a result a detailed model of the structural geology was established. Apart from the fundamental structural geological interpretation, the reservoir itself was also further subdivided. The interpretation regarding the facies, specifically of mass (reef) facies versus thin layered (basin) facies, was of particular importance (Figure 3).

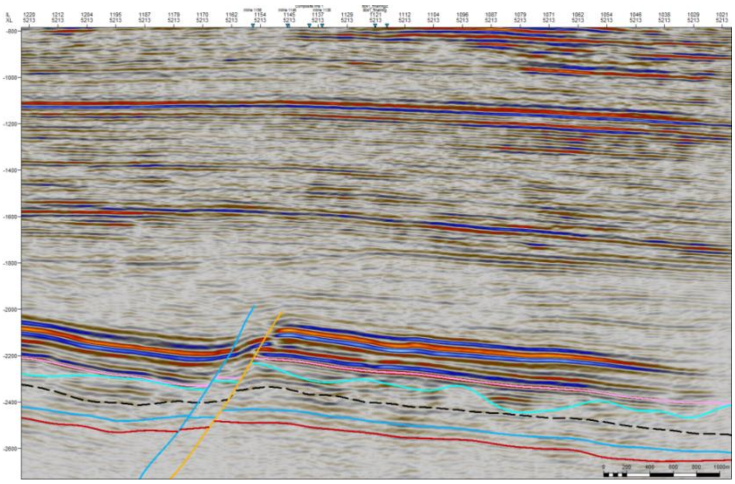

Figure 3: Assignment of the horizons in the reservoir model Holzkirchen exemplary for the seismic X-line 5213 (north: left – south: right; in two way travel time with 2-x excessive scale). The main antithetic fault (Holzkirchner-Dachinger Bruch) is marked orange. To the reservoir related horizons from stratigraphically younger to older: Top Purbeck facies (pink), Top of mass carbonate (light blue), Intra Malm 1 (black dashed), Basis of mass carbonate (dark blue), Top Dogger / Middle Jurassic (dark red).

The sketch in Figure 4 shows the main faults at the Top of the Malm reservoir in the Holzkirchen area. General strike direction of the main fault system is WSW-ENE / W-E. Additionally several associated faults were observed in detail. Directly north of the well site, an area where several fault directions intersect can be found. This area appeared to be the most promising for reservoir exploration due to its favorable tectonic and lithologic (facies) setting and was selected as drilling target. However, shortly before the target could be reached, it had to be abandoned due to a gas kick when drilling a lens of sand in the Rupelian Bändermergel subformation. The following days, completely new targets for the doublet had to be chosen. The new targets had to meet several requirements: 1) it had to be outside of the high pressure, gas bearing area, 2) it had to be in a distance from the multi drilling pad site were the drilling risks with increasing inclination of the well paths to reach the top of the reservoir were still acceptable, 3) the horizontal distance of the two wells in the reservoir had to be large enough to avoid a direct thermal breakthrough, and 4) the seismic information had to point to good hydraulic conditions in the reservoir (faults and facies). These requirements limited the options for new targets severely. Figure 4 shows the location of the abandoned first target and the new targets on the faults directly to the east (Th1a) and to the west (Th2b) of the well site Holzkirchen.

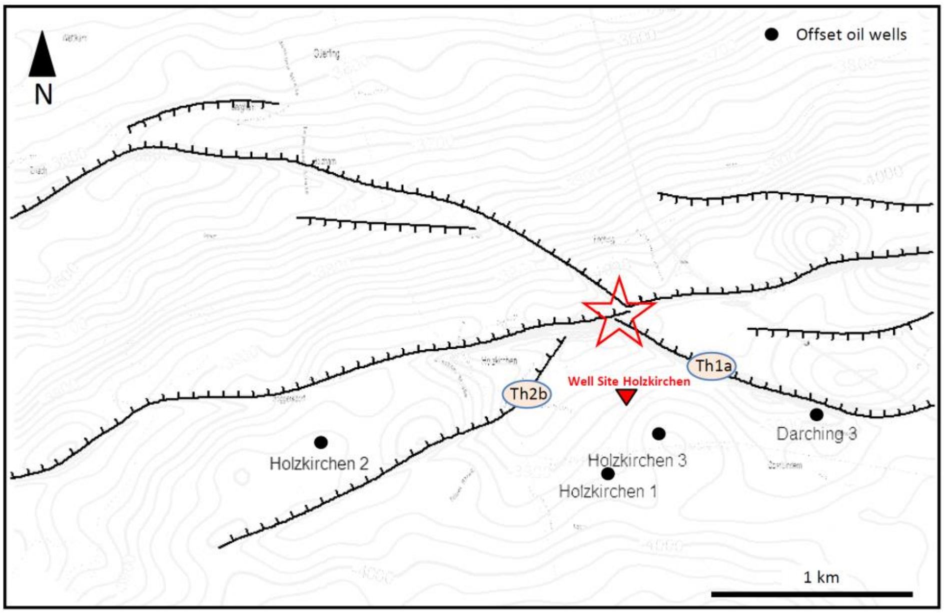

Figure 4: Sketch of the main faults direction in the Malm reservoir of the Holzkirchen area. The red star shows the original preferred target in the reservoir that had to be abandoned because of a gas kick during drilling.

2.3 Stratigraphic sequence of the Holzkirchen wells

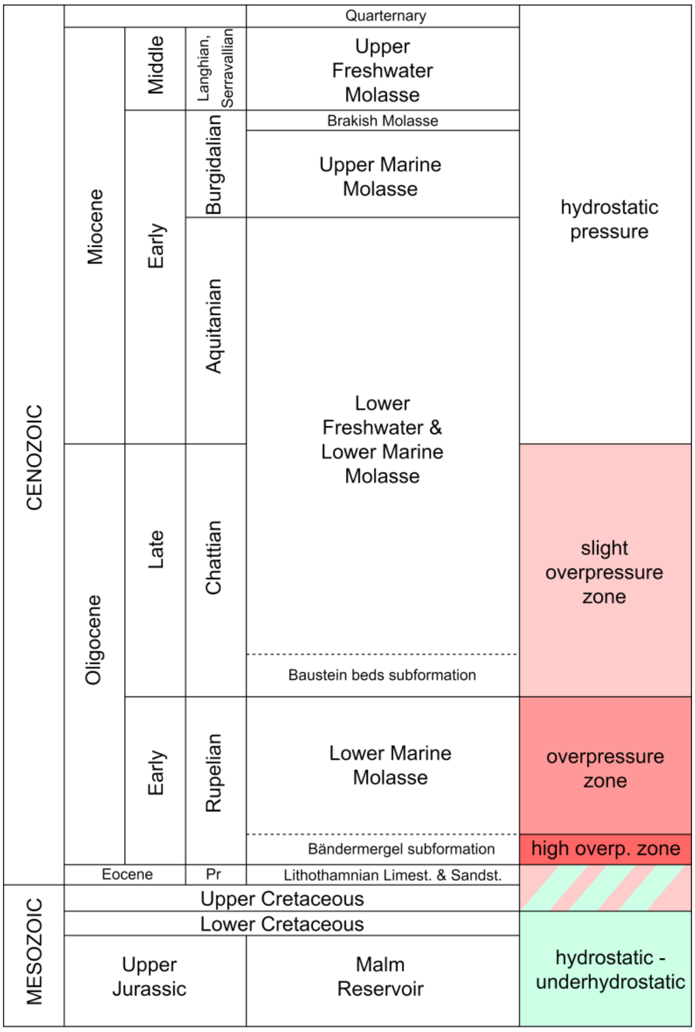

Figure 5: Stratigraphy of the geothermal wells of Holzirchen and pressure regime.

The stratigraphic sequence (Figure 5) begins at the surface in Holzkirchen with a quaternary layer of about forty meters thickness, which is composed of fluvio-glacial deposits (gravel, sand, conglomerate and marl).

The Neogene (Upper Tertiary) starts with the layers of the Upper Freshwater Molasse (OSM; Middle Miocene age). These sediments are predominantly composed of (sand and clay) marls with intermediate limestone and sand layers and an approx. 60 m thick conglomerate bank, and have a total thickness of approx. 430 m. They are followed by the approximately 40 m thick deposits of the Brackish water Molasse (Kirchberg strata) whose lithology is determined by clay marls with varying proportions of mostly fine sand and mollusk shells with low coal contents. Below the basis of the Kirchberg layers the sediments of the Upper Marine Molasse appear with glauconite sands and marls (in total approx. 110 m), the Neuhofen layers (210 m) (clay marl, fine sand marl and fine to medium sandstones) and the Eggenburg (Burdigalian) with a 160 m thick sand-marl alternation. At the Holzkirchen site the Upper Eger formation (Aquitanian) as well as the Lower Eger formation (Chattian) are characterized by the transition area between marine influence from the east and terrestrial influence from the west and south (numerous transgression horizons and partly also brackish milieu). The Upper Eger (total thickness approx. 1,060 m) is initially dominated by clay and marlstone sediments, and then turns increasingly into sandstone sequences (including the appearance of the marine Nantesbuch sandstone (approx. 60 m)). Thin coal seams are frequently interposed. In the foothill of the Upper Eger, clay marl stones follow, flowing smoothly over the clay marl stones of the Lower Eger (each approx. 70 m thick). Below the Aquitanian the Paleogene (Lower Tertiary) sequences occur. For the following Chattian Sand Series (Lower Eger, clay marl stones and interbedded layers of sandstones), a thickness of min. 1250 - 1280 m can be observed. The lower part of the Chattian formation is then dominated by thick banked sandstones (so called Baustein beds) (approx. 130 m). Coal layers appear as well.

The transition to the Lower Marine Molasse (Kiscell) is also fluent: Lower Chattian Marl and Rupelian Clay Marl together have a total thickness of approx. 730 - 780 m. This is followed by the Rupelian Bändermergel subformation (banded marls of approx. 70 m), partly with intermediate sandstone lenses of several meters thickness (here under high pressure and gas-bearing; cf. gas kick

Holzkirchen Th1); and in the deepest Kiscell approx. 5 m of bright marl limestone (Heller Mergelkalk) and dark fish shale (Fischschiefer) (approx. 10 m).

The molasse sediments are completed at the basis by the Lithothamnian limestone (approx. 60 m) of Eocene age and the Priabonian Basis Sandstone (coarse grained sandstone of approx. 20 m thickness; known as oil carrier in the Holzkirchen area).

To the basis the Upper Cretaceous follows with a glauconite sandstone and the clay marls of Turonian age (total thickness approx. 120 m). At the base of the Turonian at the transition to the Cenomanian is the approx. 60 m thick so called Seewen limestone. The Lower Cretaceous follows with approx. 20 - 40 m thick Gault sandstone (Albian/Aptian) and approx. 40 m thick limestone of Valanginian/Hauteriveian. The transition to the Malm (Upper Jurassic) in the form of the Purbeck facies (Berriasian) was drilled with a thickness of approx. 30 m. The Purbeck sediments consist of limestone and increasingly of dolomite to the basis.

2.4 Geology of the Malm reservoir in Holzkirchen

The Upper Jurassic carbonates (Malm) in Holzkirchen have a thickness of approximately 600 m. But not all of this Malm serves as reservoir. Porosity and permeability are strongly controlled by the facies of the carbonates. Dolomitized mass facies is considered to be particularly well permeable (cf. Boehm et al., 2013). Due to the diagenetic conversion of calcite to dolomite, an increase in porosity is achieved due to grain coarsening and thus more volume is generated for the thermal water circulation (secondary porosity). In addition, at the grain boundaries of the dolomites and dolomitic limestones, karstification is preferred (cf. Andres, 1985). On the other hand the layered, marly limestones react only to a small extent to the carbonate solution through CO_2-rich deep groundwater, which is according Stier & Prestel (1991) the driving force behind the karstification of carbonates in the deep underground. Stier and Prestel (1991) attribute far greater importance to the facial formation of carbonates for the ability to karstify and thus the hydraulic permeability than to an increasingly effective karstification in the vicinity of structural geological fracture zones. Recent findings, however, revise this general assumption and point to increased karstification in the area of fault zones.

In the wells Holzkirchen Th1a & Th2b the Upper Malm was found in predominantly calcareous facies. Dolomitic mass facies then appear in the Middle Malm, accompanied by mud losses during the drilling work (Figure 6), which increased to total losses by drilling through the fault. After the evaluation of the geology in the reservoir section the well Th1a was drilled in a transition milieu (slope of a reef and basin) while the well Th2b finally hit a basin in the Jurassic carbonate platform.

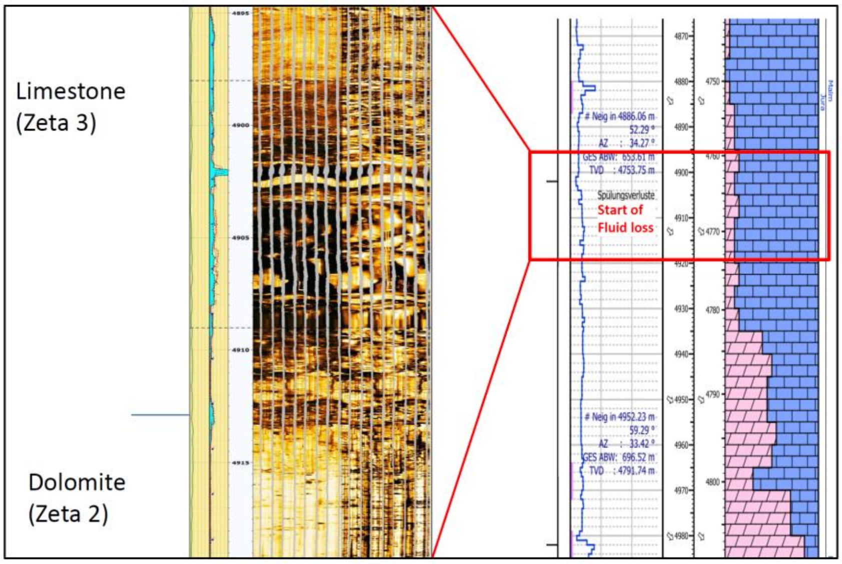

Figure 6: Extract from the reservoir section of the well Holzkirchen Th1a (left: caliper & imager-Log, right: geology with the first occurrence of fluid losses).

2.5 Hydraulic Characteristic

Holzkirchen Th1a:

The well Th1a well was tested in three short-term pumping tests using the airlift method after completion of the drilling work:

- Cleaning lift with Airlift
- Short-term test with Airlift
- Performance test with Airlift

Between the pump tests, two 4-stage acid stimulations were carried out, each with 100 m³ of 15% hydrochloric acid incl. inhibitor.

The hydraulic evaluations of the short-time pumping tests showed transmissivities of $1.61 \cdot 10^{-5}$ m²/s to $1.63 \cdot 10^{-5}$ m²/s m²/s and a productivity index (PI) of 1.1 l/s/bar.

Holzkirchen Th2b:

In Holzkirchen, (short-term) pump tests were initially planned as airlift tests following the respective borehole. The aim was to obtain the hydraulic data at the lowest possible cost with the best possible borehole cleaning and a wide range of production rates.

The experience gained during the first pumping tests at the well Th1a with regard to reservoir hydraulics and the unexpectedly low position of the cold resting water level (due to the comparatively high topographical position and the fact that the water in the borehole had cooled down considerably at the beginning due to the supply of cold service water to combat fluid loss) led to a fundamental rescheduling of the pumping test after completion of the drilling work on Th2b. Therefore the well was tested in two short-term pump tests with an electric submersible pump (ESP):

- Short-term test with an ESP
- Short-term performance circulation test Th2b into Th1a using an ESP

Before the first short-term test and before the performance circulation test, two 4-stage acid stimulations were carried out, each with a total of 100 m³ 15% hydrochloric acid incl. inhibitor.

The hydraulic evaluations of the short-time pumping tests showed transmissivities of $2.18 \cdot 10^{-5}$ m²/s to $2.30 \cdot 10^{-5}$ m²/s and a productivity index (PI) of 0.99 l/s/bar.

Both wells show a connection to the reservoir via hydraulically active faults. No skin effects could be identified, which can be connected to successful acid stimulation measures of the borehole in the carbonatic reservoir.

The pore pressure of the Malm aquifer is under hydrostatic. In Holzkirchen the static water level in the well Th2b is typically between 250 - 280 m below surface.

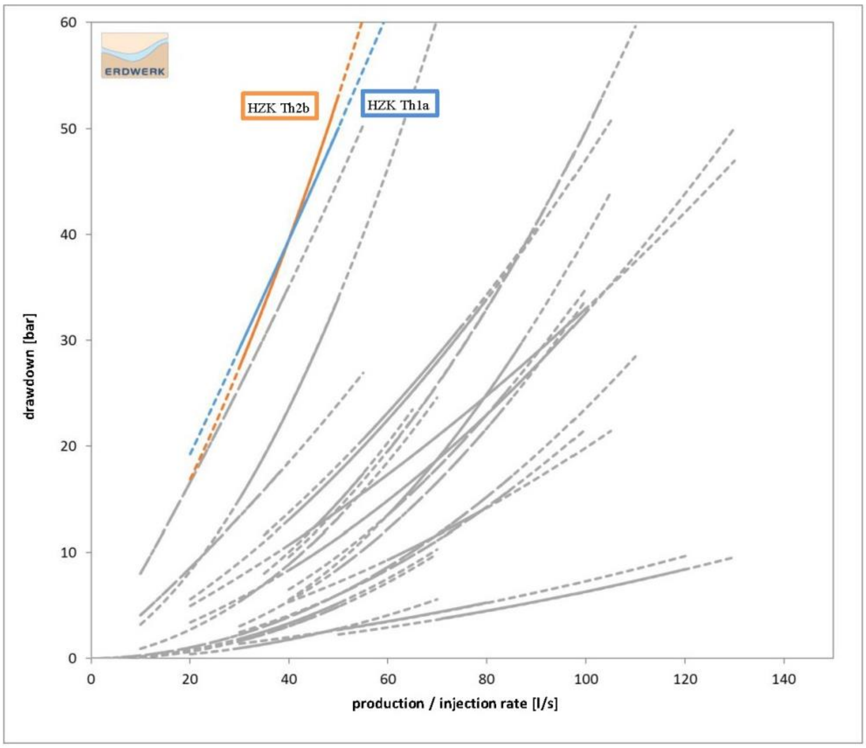

Figure 7: Comparison of the productivity curve of the Holzkirchen Th2b (orange curve) and the injection curve of the Holzkirchen Th1a (blue curve) after power circulation test with productivity and injection curves respectively from geothermal boreholes in the Greater Munich area (grey curves).

In comparison to other geothermal wells in the Greater Munich area, the two wells of Holzkirchen are rather worse from a hydraulic point of view (Figure 7). On the other hand, the high temperatures compensate for the poor hydraulic properties. The maximum temperature of the thermal water in the course of the short-term pumping tests in the Holzkirchen Th2b was measured with a value of 157.1 °C during the pumping during the short-term test (1st short-term pumping test). This corresponds to a temperature gradient of 2.94 to 3.21 °C/100 m calculated at the final depth (5070.1 m TVD) or at Top Malm (4653.3 m TVD) with an assumed mean annual temperature at the surface of 8 °C.

Additionally in the course of the temperature log measurement during the clearing run, a maximum rock temperature of 160.14 °C in the Malm bedrock could be measured in the Th2b.

2.6 Hydrochemistry

At approx. 600 mg/l, the total mineralisation of the thermal water from the production well in Holzkirchen (Th2b) is relatively low. Among the constituents, sodium with 100 mg/l (50 %) and calcium with 50 mg/l (30 %) dominate the cations. The anions were dominated by chloride with 170 mg/l (60 %) and bicarbonate with 190 mg/l (37 %). The analysed thermal is to be described as a fluoride-containing thermal spring containing sulphide sulphur. The water presents an organic odor and sometimes a thin film of oil can be observed on the probe water surface. Measuring of gas quantity shows a value of 100.0 ml/l. The main volumetric components were CH_4 (approx. 44 vol%), N_2 (approx. 27 vol%) and CO_2 (approx. 28 vol%). The H_2S content of 8.19 mg/l (0.24 vol%) should also be mentioned as a relevant secondary component. The hydrochemistry of the water sample from Th1a (now used as injection well) showed the influence from the acid stimulation of the carbonates (higher chloride and higher calcium / magnesium content compared to the water sample from the well Th2b, that was taken after a longer period of testing).

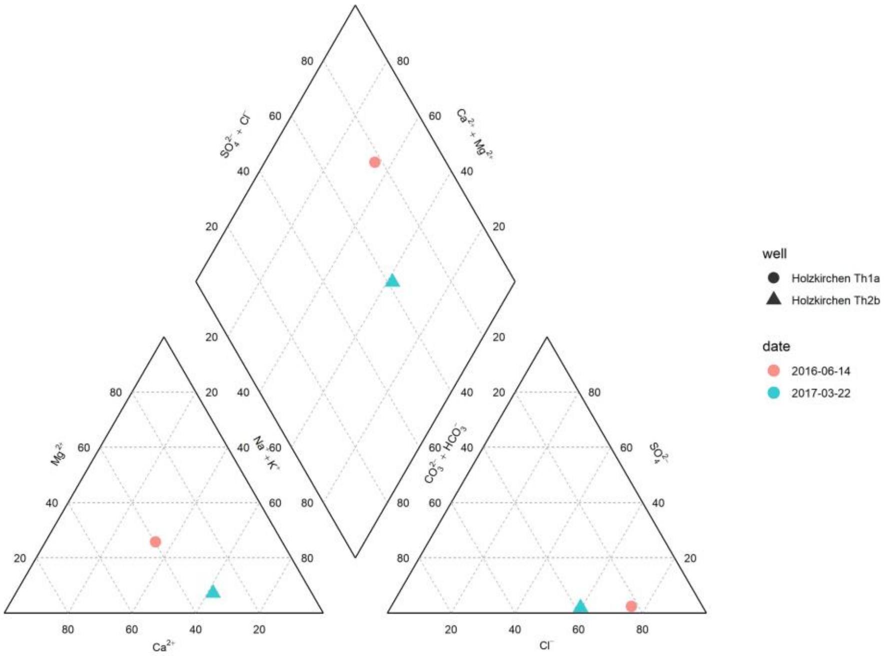

Figure 8: Piper diagram of the thermal waters from the Holzkirchen wells. The water sample of the Th1a (circle) was still influenced by the acid stimulation.

The isotope signatures of $\delta^{18}O$ and $\delta^{2}H$ of the production well is on the Meteoric Water Line for atmospheric waters (Figure 9) and is significantly depleted compared to recent waters. The stable isotopes thus indicate meteoric waters formed at cooler temperatures. The water sample of the Th1a was still influenced by the acid stimulation (red spot in Figure 9).

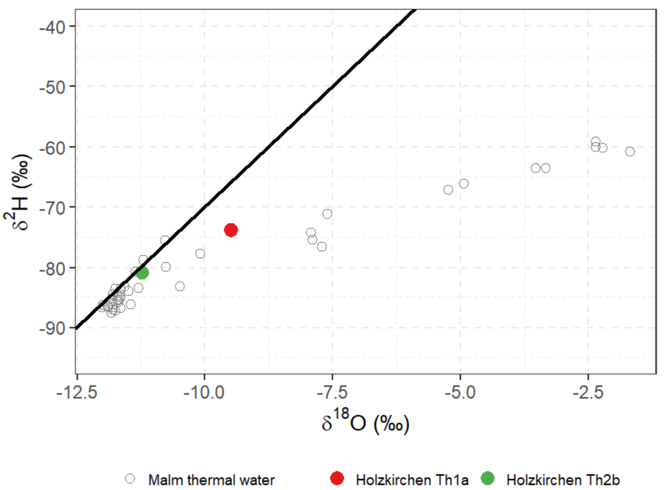

Figure 9: Isotope signatures $\delta^{18}O/\delta^{2}H$ of the thermal waters produced from the Holzkirchen boreholes compared with Malm waters from other Bavarian geothermal wells in the South German Molasse Basin (white circles). The water sample from Th1a was still influenced by acid stimulation.

3. WELL DESIGN

The wells were designed with 5 sections starting with a 23” (18.5/8”) surface section followed with 16” (13.3/8”), 12.1/4” (9.5/8” - 9.7/8”), 8.5” (7”) and 6.1/8” (5”) bit and casing diameter. The first two sections should reach a depth of about 2500 m TVD. Below this depth first over pressured and gas bearing formations were assumed. The third section was planned to the base of the Tertiary at a depth of about 4300 m TVD. Finally, the fourth section should be drilled through the Cretaceous to reach the top of the Malm-reservoir at a depth of about 4600 m TVD.

3.1 Special Design Considerations in the Oligocene and the Cretaceous

The pressure regime at the base of the Oligocene (Rupelian) and the Cretaceous varies largely according to data from offset wells. The pore pressure gradient in the Oligocene tends to be overpressured. Within the Cretaceous some offset wells showed under-hydrostatic conditions; others showed slightly over-pressured formations (cf. Figure 5). To separate these zones, the setting depth of the third liner was planned at the base of the Oligocene and a fourth section was planned to drill through the Cretaceous.

3.2 Special Design Considerations Regarding Well Integrity

The well was designed to produce 65 l/s with a temperature of max. 160 °C at a max. dynamic fluid level of 900 m below surface. The upper part of the 13.3/8” production casing overlapping the 18.5/8” surface casing was installed as an uncemented tieback. This enables a controlled annulus between the surface casing and the production casing. The resulting advantage in the production well is the eliminated risk of annular pressure build-up (APB). In the injection well, the risk of an undetected injection in shallow formations is eliminated. To reduce the risk of annular pressure buildup in the cemented overlap between the 13.3/8” liner and 18.5/8” surface casing and the 9.5/8”-9.7/8” liner and 13.3/8” liner the collapse rating of the inner casing along the overlap was increased by using pipe with high collapse rating. For the casing design, higher safety factors than required by German standards were used to decrease the risk of failure. Therefore, the New Zealand standard for geothermal wells (NZS 2403, 2015) was applied as an additional guideline. Non-rotating protectors were used successfully to prevent casing wear, which would immediately reduce casing strength. In addition, build-up sections were realized as smooth as possible to prevent high side forces between the drill string and casing to minimize wear. Finally, there was a high focus on cementing following best practices in all sections.

3.3 Drilling Progress and Challenges

3.3.1 Holzkirchen Th1/Th1a

The first well (Holzkirchen Th1) was spudded in January 2016. The first two sections went according to plan. However, in the lower tertiary (Rupelian Bändermergel subformation) an intense gas kick with a gradient of 1.85 SG occurred.

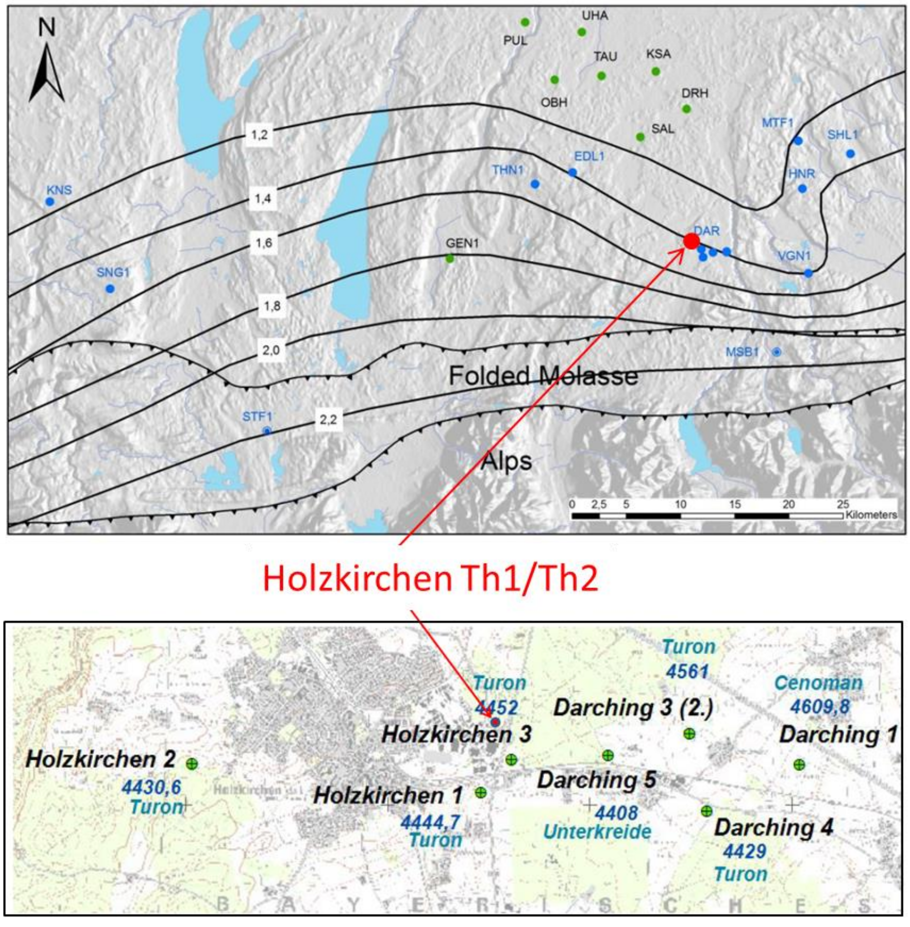

Figure 10: Pressure gradient for the Lower Tertiary according to Müller et al., 1988 (map on the top); offset wells in the close vicinity of Holzkirchen Th1/Th2 (map on the bottom).

Although the Rupelian formation is known to be overpressured, a gradient of this magnitude was not expected. Based on nearby offset wells, the formation pressure was estimated to be hydrostatic to max. 1.27 SG. Figure 10 (map on the bottom) shows the offset wells (abandoned and cemented oil wells) in close vicinity. The closest well is Holzkirchen 3 with a surface distance to the geothermal well of about 500 m. According to drilling reports, the Oligocene was drilled with a mud weight of 1.13 SG from about 1900 m TVD to 4200 m TVD indicating that no high-pressure zones have been encountered. The well Darching 3a showed the highest pressure encountered in the offset wells. A drill stem test was performed on a sandstone layer in the Rupelian formation, resulting in a recorded pressure gradient of 1.27 SG. As an additional source used for the well design, a pressure gradient map published by Müller et al. in 1988 based on oil and gas wells in the region was used (Figure 10, map on the top). According to Müller et al., the expected pressure gradient at the location is 1.4 SG.

The kick was observed quickly, and the well was shut in immediately. The gas was circulated out and the mud weight was increased to 1.90 SG. The well was under control but the kick tolerance at the 13.3/8” casing shoe was on its limit, making further drilling operations risky. A second kick with higher pressure or volume would possibly not have been controllable. Therefore, the section was abandoned and cemented back up to the liner shoe of the previous section. A sidetrack (Th1a) was drilled along a redesigned well path to avoid the previously encountered potential high-pressure gas-bearing zone which was now identified by seismic attribute analysis. The Rupelian formation was drilled with 1.80 SG mud weight without any signs of overpressure (kicks or borehole instabilities). After the last two sections were drilled according to plan, the final depth of 5,600 m MD / 5,079 m TVD was reached.

3.3.2 Holzkirchen Th2/Th2a/Th2b

The second well Holzkirchen Th2 started in June 2016, using the same well site. The first three sections went according to plan. The mud weight in the third section was increased based on the experiences from the first well and no overpressure was encountered. However, the 9.7/8” - 9.5/8” liner got stuck halfway along the section length while running in hole. Extensive fishing and milling operations followed, where part of the liner was lost. The section was abandoned by cementing back up to the liner shoe of the second section.

The reason for the stuck liner is not clear. As the mud weight was highly elevated (1.80 SG), differential sticking in one of the normal pressured sandstone formations or sandstone layers within the marls is probable. The last trip out of the hole was performed dry without any overpulls and shakers after bottom ups have been dry. Therefore, hole cleaning as the main issue was ruled out. Formation instabilities in the lower Rupelian are known from offset wells but have not been encountered during drilling and the open hole time was minimal. Moreover, the liner got stuck in the upper half of the section, while stability problems were expected in the lower part. To reduce open hole time, a wireline log was not run. Therefore, additional information from e.g. a caliper log is not available and the cause for the stuck liner remains unclear.

After abandonment of the section, a sidetrack Th2a was drilled to section depth but during a check trip and before running the casing, the drill string got stuck. Fishing was not successful; parts of the drill string were lost in hole. The drill string got stuck while making connection, the stuck point was at a normally pressured sandstone formation between accelerator and jar without offset and the mud weight was 1.80 SG. Therefore, the reason for the stuck drill string most probably was differential sticking.

Consequently, a second sidetrack (Th2b) was drilled. As differential sticking was assumed as the probable reason of the stuck drill string and the possible reason for the stuck casing, the section depth was changed to the top of the Rupelian Bändermergel (high pressure zone) instead of the base of this formation. This enabled drilling and casing running with lower mud weight resulting in a reduction of differential sticking risk. Finally, the section was drilled successfully, and the liner was run and cemented.

Drilling the high-pressure zone in the fourth section together with the Cretaceous to the top of the reservoir beard the risk of having fluid losses in the potential higher permeable sandstone formations in the Cretaceous. Simultaneously, the mud weight had to be kept high enough to stabilize the high-pressure formation in the Rupelian Bändermergel. Therefore, the mud weight was kept to a minimum to reach sufficient kick tolerance and to reduce the risk of losses. As the 9.5/8” casing shoe was close to the potential overpressure zone in the Bändermergel, sufficient kick tolerance was achieved with a mud weight of 1.40 SG. During drilling the Bändermergel, no overpressure was encountered. However, in the Cretaceous some minor losses occurred as expected. Therefore, the mud weight was decreases to 1.37 SG, but now instabilities occurred in the Bändermergel formation above. After losses were cured by pumping lost circulation material (LCM) the mud weight was increased again to 1.50 SG which finally successfully stabilized the borehole wall. It was a balancing act to adjust the mud weight on the one hand to stabilize the Bändermergel and on the other hand to avoid losses in the Cretaceous.

The 7” liner was run as a tapered string with high collapse pipes for the over-pressured zone. Therefore, the casing inner diameter and consequently the drilling diameter in the reservoir was reduced from 6.1/8” to 6”. After a total drilling period of about eight months, the final depth of Th2b 6084 m MD / 5050 m TVD was reached in March 2017.

3.4 Final Well Design Specifications

The final well design specifications are given in Table 1 (Holzkirchen Th1a) and Table 2 (Holzkirchen Th2b).

Table 1: Final casing schematic of Holzkirchen Th1a

Surface Casing			Production Liner/Tieback			Production Liner			Production Liner			Pre-drilled Liner			Open Hole	
from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	OD
m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	inch
0 797.7	136.0 P-110	437.87 18.5/8	0 654.3 Tieback	72.0 VM-95 HCS	313.61 13.3/8	2316.7 2571.2	62.8 VM-95 HCS	219.08 9.7/8	4251.5 4658.0	29.0 VM-95 S	157.80 7	4625.8 5293.1	18.0 L-80	108.62 5	5593.0 5600.0	6.1/8
			654.3 812.7 Liner	72.0 VM-95 HCS	313.61 13.3/8	2571.2 3319.3	53.5 L-80	216.79 9.5/8				5293.1 5593.0	15.0 K-55	111.96 5		
			812.7 2412.5 Liner	72.0 L-80	313.61 13.3/8	3319.3 4310.0	62.8 VM-95 HCS	219.08 9.7/8								

Table 2: Final casing schematic of Holzkirchen Th2b

Surface Casing			Production Liner/Tieback			Production Liner			Production Liner			Pre-drilled Liner			Open Hole	
from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	Wt Grade	ID OD	from to	OD
m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	ppf -	mm inch	m MD m MD	inch
0 930	136.0 P-110	437.87 18.5/8	0 827.3 Tieback	72.0 VM-95 HCS	313.61 13.3/8	2507.1 2705.1	62.8 VM-95 HCS	219.08 9.7/8	4245.6 4452.0	29.0 VM-95 S	157.08 7	4918.6 4977.3	18.0 L-80	108.62 5	6067.0 6084.0	6
			827.3 959.3 Liner	72.0 VM-95 HCS	313.61 13.3/8	2705.1 3467.4	53.5 L-80	216.79 9.5/8	4452.0 4600.9	32.0 VM- 110 HC	154.78 7	4977.3 6067.0	18.0 L-80	108.62 5		
			959.3 2615.4 Liner	72.0 L-80	313.61 13.3/8	3467.4 4452.0	66.9 P-110	216.89 9.7/8	4600.9 4945.9	29.0 VM-95 S	157.08 7					

3.5 Technical Conclusions for Further Wells

Based on the experience made in Holzkirchen, the assumptions regarding the pressure gradient in the Oligocene should not only focus on drilling reports from offset wells. The major cause for elevated pore pressure gradients in the Oligocene is disequilibrium compaction overpressure (Drews 2018). Drilling in undercompacted shales with mud weights lower than the pore pressure will typically lead to borehole instabilities (cf. Bowes and Procter, 1997). This can be recognized by cavings on the shakers during drilling, or by overpulls during tripping. Additionally, the caliper log will show an enlarged hole. However, the pore pressure gradient cannot be determined by shutting the well in, as there is no significant fluid influx into the well. Thus, even if the drilling report of an offset well shows a higher mud weight used to stabilize the borehole wall, it might be below the formations pore pressure. Therefore, this information cannot be used to determine the exact pore pressure.

In conclusion, offset well data will not always provide exact information regarding the pore pressure for the Oligocene in this region. Consequently, using conservative pore pressure assumptions based on a larger regional scale is recommended. This should not only include wells in the vicinity to the drill site, but also wells of similar depth in further distance, weighing them equally.

Further, an additional sixth casing string should be incorporated into the design for future wells of similar depth and pressure regime in the Molasse Basin, allowing for shorter sections and the use of proper mud weight to achieve sufficient kick tolerance in over-pressured zones without increasing the risk of differential sticking in normal pressured zones. (cf. Lackner et al., 2018)

4. POWER PLANT AND DISTRICT HEATING

4.1 District Heating Network

Already in the early nineties of the past century, the community Holzkirchen started with the installation of a district heating network to supply its citizens with heat. Key elements of the network were the cogeneration units integrated in municipal buildings. Over the years, three central heating stations were built: “Heizzentrale I (Hallenbad)”, “Heizzentrale II (Krankenhausstraße)”, as well as “Heizzentrale III (Rosenheimer Straße)”. Each of them was equipped with gas-powered cogeneration units and gas- and oil-powered peak load boilers. Building on these central elements, the district heating network was expanded, now spanning over several kilometres in supply lines. Today, the thermal maximum load of the district heating network amounts to approximately 10 MW at an outside temperature of -16°C.

Keeping performance-based networking in mind, all three heating stations were laid out for inflow at 70°C during summer and 80°C during winter, and return flow at 55°C. The goal was to optimize the workload and the economic efficiency of the network and to include small contributions through renewable energies. Due to Holzkirchen's geographical location in the forested Prealps, the focus was put on biomass use as a viable option. However, the emissions connected to the combustion of biomass and their immissions into the local centre of town were always considered problematic.

The production of geothermal energy in considerable quantities opened the possibility to supply the existing district heating network to a large extend regeneratively. Since the technical attributes of the subnetworks are similar, geothermal energy could be merged into the grid without the necessity for alterations on the customer’s heating systems.

4.2 ORC Power Plant

Delivered by Turboden S.p.A. (based in Brescia, Italy), the ORC power plant was realized in direct proximity to the drilling site at the outskirts of the town. Through the short distance to the well, temperature losses are minimized. During the planning of the power station, focus was put on the compatibility between power plant and heating network to use the thermal energy ideally. For the economic efficiency of the overall project, the optimal operation of the power plant is a mandatory prerequisite.

With these basic specifications, the power plant was separated into a high temperature and a low temperature section. This division is intended to ensure the optimum use of available geothermal energy in terms of efficiency. Depending on the seasonal demand, the district heating can be decoupled at different points of the plant.

Having a comparably low GWP factor of 3, isobutane was chosen as the working fluid used in the ORC power plant. However, its high flammability and the therefore necessary safety measures regarding explosion and fire protection pose difficulties in the handling of the working fluid.

Early July 2019, test operations to produce electrical energy commenced in Holzkirchen (Figure 11). Since then, technical parameters regarding performance increase and reliable operation of the plant are adapted regularly.

Beginning fall 2019, electrical energy is to be fed permanently into the public supply grid with an average electrical output of 3.4 MW. While being independent of the availability of wind or solar radiation, a substantial share of the municipality’s energy demand, electrical as well as thermal, can be met at high output rates using renewable energy.

Figure 11: Heating station and ORC Power Plant in Holzkirchen at the beginning of power generation on 4th July 2019.

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