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TNO report

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Rock evaluation and recommendation for radial jetting experiments in the framework of the planned Koekoekspolder GT-03 well

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1 Introduction

The main goal of the HIPE project (High Performance geothermal wells) is to demonstrate that radial jetting has the potential to increase the production of geothermal reservoirs in the Netherlands, at reduced costs. This will be done by enhancing the flow of a number of geothermal wells with radial jetting technology. One of the target reservoirs in the project is the Rotliegend in the Koekoekspolder (Figure 1). Here, a geothermal doublet was drilled in 2011. It consists of the wells KKP-GT-01 and KKP-GT-02 (Figure 2). The reservoir quality was less than expected. An additional well is planned to be added to the existing doublet. Reservoir stimulation by radial jetting is considered an option to improve the reservoir productivity. For an optimal planning of the radial jetting, a number of tests is planned. For these tests, rock samples are required. This report describes the reservoir rock that is present at the Koekoekspolder, and advises which outcrop analogues can be used for the jetting tests.



Figure 1 Location of the Koekoekspolder area in the Netherlands, indicated by the red dot.

2 The Rotliegend reservoir at the Koekoekspolder

The Rotliegend reservoir at the Koekoekspolder location is a Permian age sandstone of eolian origin. Therefore clay is sparse or absent. Cuttings of the KKP-GT-01 and KKP-GT-02 geothermal wells and a slabbed core of the nearby KAM-01 well (16m) reveal that part of the rock partly consists of detrital anhydrite and anhydrite cement. Anhydrite has a typical high density of 2.9-3.0 g/cc, compared to

2.6-2.7 for quartz, which enables its detection on density logs (marked RHOB in Figure 2). Density logs of the geothermal wells indicate that thick zones within the reservoir have been cemented by anhydrite (indicated in dark blue in Figure 2), thereby reducing the porosity and permeability to near zero. As can be seen from Figure 1, the zones can be up to 16 meters thick in the three wells that were reviewed. The zones can't be correlated across wells. This means that the cemented zones either have a limited lateral extent, or that the thickness variation is unpredictable. Figure 1 also shows that the porosity within the uncemented zones varies throughout the reservoir, from ~5% near the base of the reservoir in KKP-GT-01 (<10 mD), up to ~25% for the better parts (100s of mD). Note that in both the geothermal wells, the Carboniferous was not reached. It is therefore not known how far the Rotliegend extends downward from the TD-depth of both wells, but seismic evidence suggests that only a small part of the reservoir was not drilled.

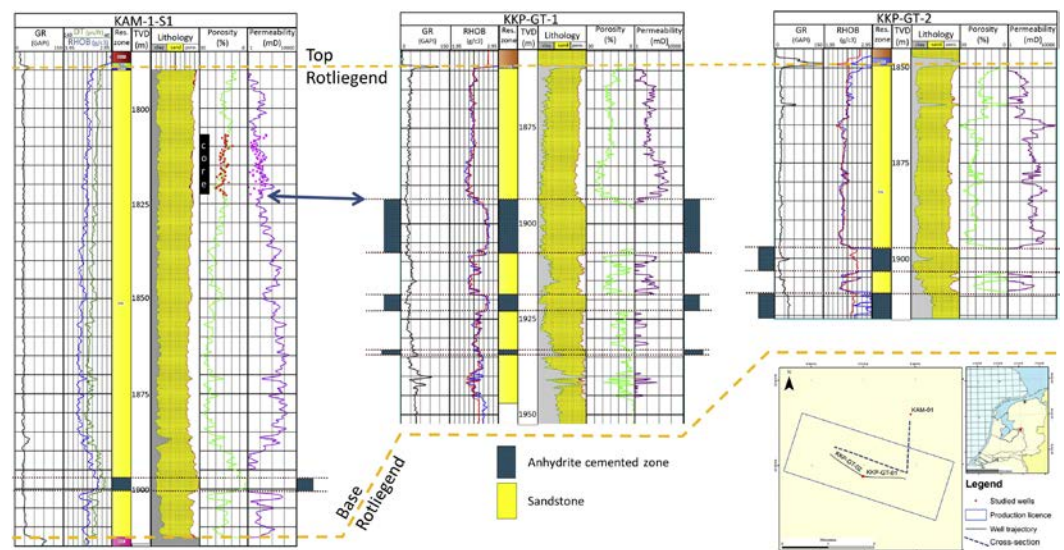


Figure 2 Well panel along the KAM-01, KKP-GT-01 and KKP-GT-02 wells. Source: Henares et al. 2014¹

Anhydrite is a mineral which consists of calcium sulphate (CaSO_4). It is common in the Dutch subsurface, dominantly in the Zechstein, which overlies the Rotliegend in a large part of the Netherlands. In the Zechstein the anhydrite occurs as thick layers that were formed as evaporites. Here, anhydrite is the dominant (or only) mineral in the rock. When exposed to fresh water, anhydrite can transform into gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) by adopting water in its crystal structure. The mineral expands when doing so. This chemical reaction occurred in the German town of Staufen, where a well was drilled in an overpressured reservoir. Reservoir fluids were then expelled from the reservoir and flowed into an overlying anhydrite layer, where the conversion into gypsum caused severe damage to the buildings of the town. Pure anhydrite rock samples were tested extensively by the University of Utrecht for a project which investigated the possibility of storing radioactive waste material in the subsurface. Pure anhydrite however will respond differently to radial jetting than anhydrite-cemented sandstone. This latter type of sandstone was however not

¹ Henares, Bloemsma, Donselaar, Mijnlief, Redjosentono, Veldkamp and Weltje (2014). The role of detrital anhydrite in diagenesis of aeolian sandstones (Upper Rotliegend, The Netherlands): Implications for reservoir-quality prediction. *Sedimentary Geology* 314. DOI: 10.1016/j.sedgeo.2014.10.001

tested. Pure anhydrite formed as evaporite is however completely different from the Koekoekspolder reservoir, where quartz is still the dominant lithology (Henares et al.: 'detrital anhydrite grains are also present as framework components (5 to 10%) [...] Anhydrite pore-filling cement [...] is concentrated in the coarse-grained laminae, where it completely occludes primary pores'). It should also be noted that in the Koekoekspolder reservoir, the anhydrite has been stable in its current form (i.e., in a saline fluid) for a long time, without converting into gypsum.

3 Relevant properties

It is not known yet how anhydrite-cemented sandstone, containing abundant anhydrite grains in addition to the common quartz grains, reacts to radial jetting. In order to find a suitable rock analog of the Koekoekspolder reservoir, it is important to know what the determining rock properties are. Age is in principle irrelevant – a Triassic eolian sandstone could in theory be just as relevant as one from the Permian.

Until now it has not been possible to find an exact outcrop equivalent. A complicating factor is that anhydrite rapidly converts to gypsum, when exposed to fresh water in outcrop. This is the main reason that anhydrite cemented sandstones are not well known from outcrops.

Within the framework of the SURE-project², various sandstones were tested for radial jetting. One of the findings of SURE is a relation between jettability and porosity, tensile strength (TS) and grain size, for which experiments were conducted on the Gildehaus, Dortmund (also known as Ruhrsandstein) and Bad Dürkheim sandstones (SURE confidential MSc thesis). However, numerical analysis of the rock destruction process showed that not only tensile failure of the rock due to the 'water hammer' effect plays a role³. Also shear failure and 'pore breakthrough', caused by a highly increased pore pressure where the water jet hits the rock, facilitate breakout of grains. Hahn et al.⁴ considered porosity, permeability, uniaxial compressive strength (UCS) and tensile strength for determining the jettability. Table 1 shows that, of the tested sandstone samples, the Gildehaus sandstone has the best jettability index, closely followed by the Bad Dürkheim sandstone. The jettability factor of the Dortmund sandstone is almost a factor of 10 lower. The conclusion of Hahn et al. is that 'the combination of high porosity and permeability with low values of mechanical strength enhances the erosion'. However, it should be noted that the Gildehaus sandstone has an uniaxial compressive strength that does not differ considerably from the Dortmund sandstone, but the tensile strength is about half.

² SURE: <https://www.sure-h2020.eu/>

³ Water hammer or hydraulic shock is a pressure wave which occurs when a moving fluid is forced to a sudden stop.

⁴ Hahn, S., Wittig, V. and Bracke, R. (2019). Extended Horizontal Jet Drilling for EGS applications in petrothermal Environments. European Geothermal Congress, the Hague, 2019. (based on SURE deliverable D5.1)

The experimental setup also plays a role. SURE deliverable 5.1⁵ shows that, for a different experiment, the jettability of the Gildehaus is much larger than for the Bad Dürkheim sandstone, despite its higher uniaxial compressive and tensile strength.

Table 1 Jettability indices for three sandstones as derived by Hahn et al. (2019).

rock	jettability [m ³ /J]	porosity [%]	permeability [mD]	UCS [MPa]	TS [MPa]
Gildehaus	0.0029	23.7	630	53	3.5
Dortmund Ruhrsandstein	0.0007	8.7	0.002	68	7.2
Bad Dürkheim	0.0027	19.5	46	30	2.9

Table 2 Rate of penetration (ROP) in various sandstones. Source: Hahn and Wittig (2019)

rock	flow rate [l/min]	pressure at bit [bar]	ROP [m/h]	nozzle type
Rüthener	20	230	0.14	rotating
Gildehaus	20	230	4.28	rotating
Friedewald	20	230	0.46	rotating
Bad Dürkheim	20	230	0.25	rotating

A cautious and somewhat preliminary conclusion may be that porosity is most important, then mechanical strength, then permeability. Referring to Figure 2, it becomes obvious from the strong vertical variation in porosity and permeability that multiple tests are then required to obtain a balanced impression of the jettability of the Rotliegend reservoir at the Koekoekspolder site.

4 Rock property databases

Various databases containing rock property information are known to exist.

The NLOG database contains porosity and permeability measurements of large core plugs, but usually the size of the actual samples stored in the core shed (the width of the core) is too small for performing a jetting experiment, especially if multiple experiments are required.

Many sandstone quarries have internet sites with brief description of the mined rock, but relevant rock properties are rarely mentioned. The online German Natursteine Databank (www.isa-org.de) contains information about a very large number of rocks used for construction, but is not searchable in a useful way (i.e., using petrophysical or mechanical properties).

⁵ Hahn, S., Wittig, V.; The Horizon 2020 Project SURE: Deliverable 5.1 - Report on Jet Drilling at Ambient Conditions 2019, Potsdam: GFZ German Research Centre for Geosciences, DOI: 10.2312/gfz.4.8.2019.006

A petrophysical properties database⁶ that was generated for the IMAGE project⁷ contains samples having porosity measurements on sandstones, but none of them also reports permeability.

5 Rock sampling options

Given the difficulty of finding a perfect analog, TNO has considered various alternatives:

1. The 16-meter core of the KAM-01 well is the most representative piece of rock. Only slabs 0.5 cm thick are present in the TNO core shed. This is not enough for executing a radial jetting experiment. Alternatively, the rest of the core is considered to be available in the NAM core shed. The diameter of this core is probably around 10 cm. In order to execute multiple experiments, a large part of the core material should be made available. It is not known yet if NAM is willing to make multiple pieces of the core available for testing.
2. For the SURE-project, radial jetting tests were conducted on various sandstones. All those rocks were also described in terms of porosity and permeability, and mechanical parameters⁸. As can be seen from Table 3, most tested sandstones had very low permeability, except for the Gildehaus and Rùthener sandstones.

Table 3 Properties of the rocks tested in the SURE project. Source: SURE deliverables D4.1, D5.1

rock	age	porosity [%]	permeability (xy) [mD]	UCS [MPa]	TS [MPa]
Rùthener Grùnsandstein	Cretaceous	25.0	405		
Gildehaus Sandstein	Cretaceous	24.0	233	53	3.5
Bad Dùrkheim Sandstein	Triassic	19.0	3	30	2.9
Friedewalder Sandstein	Triassic	18.6		42	3.7
Obernkirchener Sandstein	Cretaceous	17.0	2	63	
Roter Mainsandstein	Triassic	14.0	3	51	2.9
Ruhrsandstein	Carboniferous	9.0		68	7.2
Bebertal / Flechtingen Sandstein	Rotliegend	8.5	0.2	56	3.8

3. Rotliegend sandstone outcrops can be found around Bretzenheim in the Saarland-Nahe area. This area was also the target of a PhD dissertation⁹ for which a large number of outcrop samples was tested for porosity and permeability. For the eolian facies, comparable to Koekoekspolder, the porosity

⁶ Bär, Kristian; Reinsch, Thomas; Bott, Judith (2019): P³ - PetroPhysical Property Database. V. 1.0. GFZ Data Services. Potsdam. <http://doi.org/10.5880/GFZ.4.8.2019.P3>

⁷ www.imageh2020.eu

⁸ Bakker, R. R., Kluge, C., Blöcher, G., Reinsch, T., Bruhn, D. F., Medetbekova, M., Christensen, H. F., Nick, H. M., and Barnhoorn, A. (2019): The Horizon 2020 SURE Project: Deliverable 4.1 - Report on rock properties. Potsdam: GFZ German Research Centre for Geosciences, DOI: 10.2312/gfz.4.8.2019.004.

⁹ Aretz (2016). Aufschlussanalogstudie zur geothermischen Reservoircharakterisierung des Permokarbons im nördlichen Oberrheingraben. TU Darmstadt.

and permeability ranges are 13-18% and 0.1-10 mD (Figure 2). Hence, the maximum permeabilities are considerably lower than those found in the Koekoekspolder.

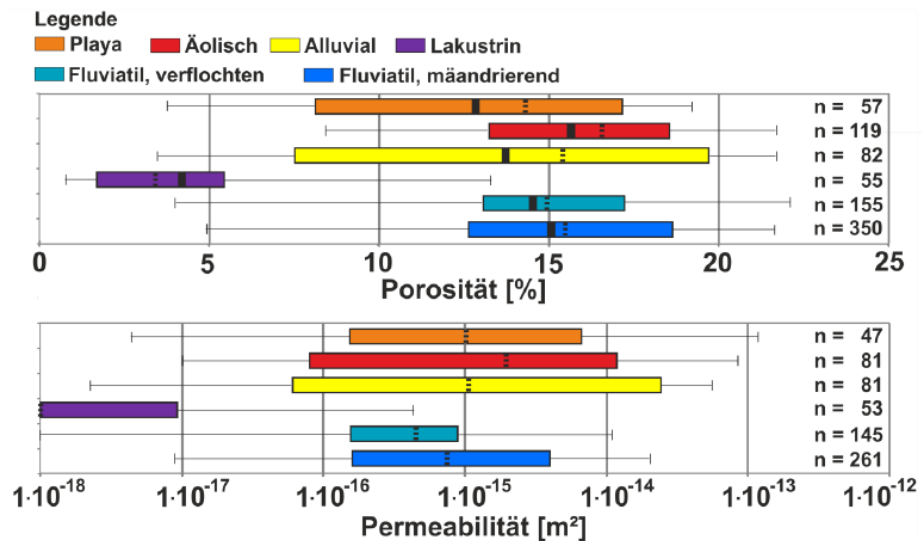


Figure 3 Porosity and permeability values obtained from outcrop samples in the Saarland-Nahe area (source: Aretz 2016). A value of $1 \cdot 10^{-12}$ corresponds to 1000 mD, $1 \cdot 10^{-15}$ equals 1 mD.

4. Gypsum quarries can for instance be found near Harztor, Niedersachswerfen and Ellrich in the Harz/Thüringen. Reportedly, anhydrite also occurs in these quarries. However, it must be mentioned again that pure anhydrite is a poor analogue to the Koekoekspolder anhydrite-sandstone. Also, rocks sampled from these quarries are generally weathered (bulk density ~ 2.0 in contrast to ~ 2.9 for pure anhydrite).
5. Anhydrite can potentially be created from gypsum by heating a gypsum solution to temperatures above 100 °C. In the pores of an ordinary quartz sandstone, submerged in a gypsum solution, gypsum cement will therefore be formed when the water evaporates. If the resulting gypsum bearing sandstone is heated to a temperature above 100 °C, anhydrite will be formed. This process, however, is poorly controllable and it is unknown what the resulting rock will be like. For instance, it is not known whether anhydrite will form within the pores throughout the entire rock, or only superficially. Also, the porosity, permeability and strength of the resulting rock cannot be predicted beforehand.

At this moment in time, only option 2 seems feasible. Option 1 is considered to potentially give valuable extra information but the feasibility is doubtful. Therefore, therefore the recommendations in the next chapter are based on option 2.

6 Quarry sample recommendation

In the absence of a rock sample that is an acceptable analogue for all rock characteristics relevant for jetting, the following priorities are identified to facilitate selection of an acceptable rock sample: porosity is considered the most important

factor, followed by compressive or tensile strength and finally permeability. Presence of anhydrite is also considered important, but no quarry analogue was identified. It should be noted that, although the recommendations given here are the best analogues we could find, they are still not a good analogue for the rocks expected in Koekoekspolder.

In the Kampen and Koekoekspolder wells, a rough subdivision can be made on the basis of the porosity and permeability: good, medium and poor reservoir quality. Cemented zones are not considered as they are considered to be un-jettable. Unfortunately, no rock strength measurements are available for the Koekoekspolder reservoir. A back-of-the-envelope calculation for the order of magnitude of tensile strength is ~42 MPa @13% porosity, and ~18 MPa @26% porosity (lower porosity yields higher strength). These values are however only indicative and should be used with extreme caution.

Table 4 Koekoekspolder rough division in porosity / permeability zones.

quality	porosity [%]	permeability [mD]	KKP-GT-01 depth [mTVD]	KKP-GT-02 depth [mTVD]
high	20-25	100-200	1883-1893	1863-1897
medium	15	10	1863-1883 1908-1918	1850-1863
low	10	3	1923-1947	-

The high porosity zones are best approached by the Bad Dürkheim, Friedewalder, Gildehaus, Obernkirchener and Rùthener sandstones. Of those, only the Gildehaus and Rùthener sandstones have higher permeabilities, but both are soft (low UCS / TS). Because a higher strength rock is considered to better represent the Rotliegend reservoir at Koekoekspolder, the Triassic Friedewalder sandstone is advised although the porosity is slightly lower, and no permeability measurement is available. Also, small amounts of clay occur in the Friedewalder, but this is considered to be a minor problem.

For the medium porosity zones, the Bebertal / Flechtingen, Roter and Dortmund sandstones apply. Both the Bebertal / Flechtingen and Roter sandstones have however very low permeability, lower than the medium porosity Koekoekspolder reservoir zone. The Dortmund sandstone is very tight. The Triassic Roter is favoured on the basis of the slightly lower UCS, the Bebertal being very solid.

For the lowest porosity zones, no representative recommendation can be made on the basis of any tested samples but is doubtful if stimulation of those poor-quality zones will yield a much better productivity.

It should be noted that information about the grain size and mineralogical composition of the advised rocks is only marginally available, and that relevant differences with the Koekoekspolder reservoir rock are likely to occur.

In order to be able to better interpret the results of the jetting experiments, and to relate them to the results obtained in the SURE project, it is strongly advisable to obtain multiple samples from a single quarry, because differences in reservoir properties are likely to exist, and to drill core plugs from the samples (at least 2 per

specimen) for testing porosity, permeability and strength of the samples. Also, it is important that the orientation of the obtained samples be registered (top / bottom, bearing).

Finally, it must be stressed that the recommended rock sample options are considered the best possible at this stage, but that many uncertainties exist regarding the actual applicability in the light of differences in porosity, permeability, rock strength and lithological composition with the Koekoekspolder reservoir.

7 Quarry addresses

Friedewalder:
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