Testing the applicability of radial jetting for Dutch geothermal projects

Extending the geothermal potential in the Netherlands with the help of radial jetting

For the Dutch Knowledge Agenda/ Kennisagenda Aardwarmte

Ministery of EA and Kas als Energiebron
(Ministery of EA, LTO Glaskracht Nederland)

Colophon

Date	12 June 2018
Verdion	V2
Author	Ronald den Boogert

Published Iiprojects b.v.
Westhaven 34
2801 PK Gouda, The Netherlands
Email ronald@inimpact.nl

Approved by:
Radboud Vorage
Bertran de Lange

Note

This report is different from a "standard" kennisagenda project. A large part of the work has been "blue collar work" such as sourcing samples in Germany and Belgium, transporting them from these places to Houston and testing the rocks. Another difference is the background of the involved people. They work for different institutes in different countries in even different continents.
We thank Radboud Vorage for reviewing the text but also his fotowork. We also thank Volker Wittig (Geozentrum Bochum), Hans Veltkamp (TNO), Resi Veeningen (Panterra), Ray Herbert (Radial Drilling Services Inc) for their pratical and theoreticall contribution.

We are now well prepared to make the next step which is a field test in the Netherlands where the promosing computer models and labtest must result in next step in developing cost efficient, high capacity geotermal fields.

Ronald den Boogert
Gouda 12th of june 2018

Table of content

1 Nederlandse Samenvatting

In dit project is gekeken naar de mogelijkheden om de kosten van geothermische installaties te verlagen door het gebruik van radial jetten. Nu komt het regelmatig voor dat een geothermisch systeem niet de gewenste hoeveelheid water levert of alleen deze hoeveelheid levert als er hoge drukken worden toegepast. Dit gaat ten kostte van het financieel rendement en maakt investeerders terughoudend.

Radial jetting is een techniek waarbij het contact oppervlak tussen de put en het waterhoudend reservoir aanzienlijk wordt vergroot door in een bestaande put een groot aantal kanalen met een lengte tot 100 meter en een diameter van 2 tot 5 cm te spuiten. De verwachting is dat door het vergrote contact oppervlak zowel het drukverlies fors daalt als de capaciteit belangrijk wordt vergroot.

De techniek is al meer dan 2000 keer succesvol toegepast in de olie- en gas industrie. De ervaring leert dat het jetten met een snelheid tussen de 50 cm tot 150 cm per minuut plaatsvindt. Een berekening van TNO laat zien dat de techniek ook voor de geothermie een aanzienlijke verbetering verwacht kan worden.

De praktijk is weerbarstiger. Het toepassen van deze techniek in de geothermie markt is zeer beperkt en het ontbreekt nog aan een succes. Omdat een geothermische installatie op een aantal belangrijke punten afwijkt van de olie- en gas systeem zijn deze verschillen geanalyseerd en in deze studie onder de loep genomen door het uitvoeren van een bovengrondse laboratorium test waarbij gekeken wordt of deze verschillen te overbruggen zijn.

De verschillen zitten met name in de reservoirs, de filters onder in de put en de ruimte tussen screen en reservoir. Het reservoir heeft vele variaties en maakt een studie lastig. Er is gekozen om niet alle combinaties te bekijken maar de aandacht te concentreren op juist die combinaties die nu kansen geven. Panterra geoconsults b.v. heeft op basis van een rekenmodel van TNO en algemeen beschikbare data de impact voor de Nederlandse ondergrond doorgerekend. In de Nederlandse context betekent dat voor drie van de vier lagen het verwachte debiet min of meer verdubbeld. Bijzonder is te zien dat vooral de Slochteren formatie zeer kansrijk is. Zeker de helft van Nederland heeft nu een interessant reservoir. In het onderstaande figuur blijkt dat lagen tussen 1500 en 3500 meter interessant zijn. Uit het onderste kaartje blijkt ook dat een flink deel van Nederland een goed reservoir heeft. Vooral de diepe delen geven kansen voor stadsverwarming. Op een diepte van 3000 meter heeft het water een verwachte temperatuur van rond de 105 graden Celcius.

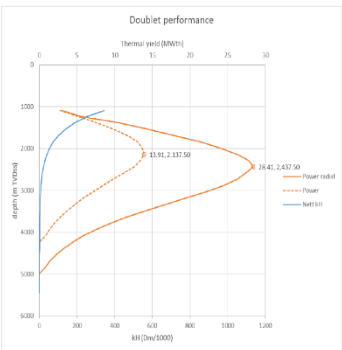


Figure 4-8: Doublet performance, in terms of thermal yield for the Slochteren Formation based on typical reservoir parameters corrected with respect to depth at a COP of 20. The thermal yield lines (orange) show that radial jetting (solid orange line) has the potential to significantly improve performance compared to the non-stimulated case (dotted orange line). Note that the optimum depth, signified by the annotated circle, increases when applying jetting. The nett transmissivity, kH, is represented by the blue line.

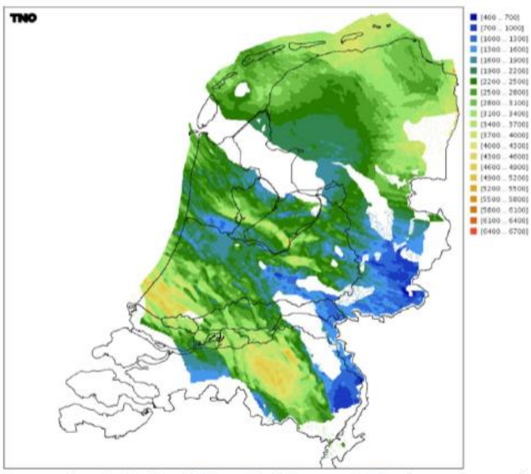


Figure 4-9: Depth map (and lateral extend) of the top of the Slochteren Formation (from ThermoGIS, www.NLOG.nl)

Ondergronds kan er volgens de leverancier een jetsnelheid van 50 tot 100 meter bereikt worden. Een dergelijke snelheid is niet geconstateerd tijdens de labtesten voor drie van de vier samples. Volgens de leverancier komt dat doordat de stenen uit de groeven verweerd, uitgedroogd en niet onder druk staan. Ook de onafhankelijke deskundige van GZB ziet een verschil in de jetbaarheid boven- en ondergronds. De beide andere verschillen zijn prima te hanteren met het bestaande concept. Zo werd de ruimte tussen screen en steen prima overbrugt met de jetslang. Ook het frezen van de wirewrap filter leverde geen problemen op.

De centrale vraag van deze studie is; *"Is radial jetting een aanvulling voor de Nederlandse Geothermie systemen"*. Uit de labtest komt naar voren dat de geothermie specifieke afwijkingen geen probleem zijn voor de invoering van deze techniek. Het reservoir blijft wel een zorg. Een mogelijke verklaring voor het verschil in succesratio tussen geothermie en olie- en gas is dat indien een laag niet geschikt is, er maar een enkele put wordt gejet. Als de laag wel succes oplevert worden er tientallen zo niet honderden putten in dit reservoir gejet. Het lijkt verstandig om juist in de gesteentes met een hogere porositeit te starten. In Nederland is dit gezien het marktpotentieel de Slochteren of de Nieuwerkerk formatie (waarvan de Delft en Rijswijk zandsteen een member zijn). De ervaring leert dat het erosieproces makkelijker gaat in een hoog poreus materiaal dan een minder poreus materiaal. Hierbij lijkt een poreuze dunne laag meer geschikt dan een dikke minder poreuze laag.
De Engelsen zeggen "the proof of the pudding is in the eating". Gelukkig heeft dit project een vervolg gekregen in het High Performance Geothermal Wells (HIPE) project waarin putten in drie van de vier type reservoirs meedoen. Mocht blijken dat een reservoir geschikt is voor de jet techniek dan zullen er zeker veel putten volgen aangezien er voor een relatief kleine investering vele tientallen % meer debiet te halen zou kunnen zijn.

2 Description of the project

2.1 Problem definition

The economic prospects of deep geothermal systems will be significantly improved if the flow rate can be enhanced to the maximum of the casing system. This favourable economic perspective is needed to accelerate a further roll-out of wells between 2,000 and 5,000 meters. In a recent TNO report jetting technology[1] is expected to deliver the required benefits at lower costs, without damage to the environment or installation and with a non-controversial way of working. This study aims to investigate with a lab-test if (and how) radial jetting can be applied in Dutch geothermal projects.

2.2 Aims of the project

Technological goals

There are many factors that contribute to a successful radial jetting job. The quality of the service provider is the most important factor, along with the formation, tools, pressure set, flow rate, chemicals used and last but not least the well completion play a role. Many issues are vendor dependent and can be solved by those companies. The reservoir specifications play a role for all providers. Unfortunately, reservoir characteristics vary from one well to another making lab testing expensive (every well must be tested separately) or even impossible (if the well data is not yet available). This program has two technology goals. The first goal is to deliver four samples which are representative of Dutch geothermal wells for jetting technology. The process will be well documented so other service providers can harvest their own samples in the future. The second goal is to test if radial jetting can work on a successfully penetration of one or all four samples.

Energy- goals

The results of the project will facilitate future energy goals by paving the way for a field tests. This project will give a good indication of the jettability of the combination of the reservoir and the well completion. With this information it will be easier for operators to decide to participate in a field-test.

The results of the project will also contribute to the energy goals by facilitating future goals; More than 10 projects are now in an evaluating phase. Two of the planned projects require a stimulating technology to provide a positive economic perspective in order to receive approval for financial funding. Another eight projects are requiring a much higher temperature than today systems can bring. Deeper wells can deliver the required higher temperature. However, flowrate may be even a bigger problem at these depths. radial jetting technology can help these project get the needed flow rate in an acceptable way.

2.3 Relation to other projects

The project works together with a partner, Geo Zentrum Bochum (GZB) in the radial jetting project from the EU (SURE). TNO has also contribute to this study. Results from the TNO report http://nlog.nl/cmis/browser?id=workspace%3A//SpacesStore/a14412a5-4b82-44ae-811a-89ca8d45a82f have been used.

[1] http://www.nlog.nl/cmis/browser?id=workspace%3A//SpacesStore/3f222f34-7810-484d-a350-16bae4f12d0f

2.4 The Approach

2.4.1 Preparations

As said a successful well enhancement program depends on many factors. Since the jetting technology has been deployed over 2000 times successfully internationally in the oil- and gas industry the focus of this project is to study the differences between oil/gas- and a geothermal well for the Dutch situation. The mechanical part has been tested at the lab of Radial Drilling Services in Houston (USA) and the local reservoirs have been modelized by Panterra Geoconsultants b.v. with the help of the Doubletcalc model of TNO.

Reservoir selection
Many types of reservoirs are available in the Netherlands. For the four most used reservoirs a calculation is made to estimate the impact of a well enhancement with an objective to increase the skin factor from 0 to -6. The calculation is based on the TNO DoubletCalc model and the expertise of Panterra Geoconsults. For details see the report InImpact Kennisagenda Radial Jetting G1345 of Panterra Geoconsult which is also a part of this project.
The first selected reservoir is the **Nieuwerkerk Formation** where the Delft sandstone is a member off. The results are an more than doubling of the maximum capacity. Due to the better performance many new locations will get a positive economic outlook. Remarkable is the enormous range of the target area which stretches from 1600 meter to 3100 meter and covers a large part of the Northern and western part of the country.

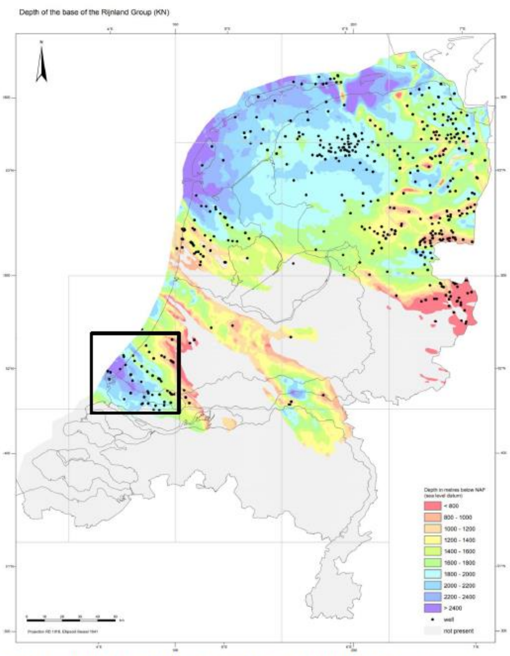


Figure 4-2: Depth map for the top of the Schieland Group which is close to the top of the Nieuwerkerk sandstones but extends further (from www.NLOG.nl). The extent according to TNO mapping of the major sandstone member in the formation, the Delft Sandstone, is presented in Figure 4-3. The black square outlines the map shown in Figure 4-3.

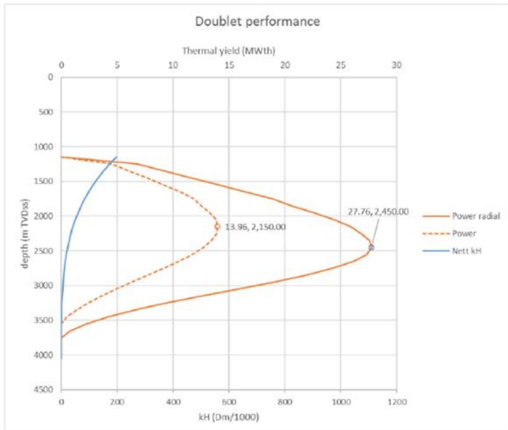


Figure 4-1: Doublet performance, in terms of thermal yield for the Nieuwerkerk Formation based on typical reservoir parameters corrected with respect to depth at a COP of 20. The thermal yield lines (orange) show that radial jetting (solid orange line) has the potential to significantly improve performance compared to the non-stimulated case (dotted orange line). Note that the optimum depth, signified by the annotated circle, increases when applying jetting. The nett transmissivity, kH, is represented by the blue line.

The second selected reservoir is the **Triasic Buntersandstone**. The expected performance increase is almost 100 %. The target range varies from 1500 meter to 2500 meter. If this range is plotted in the Dutch map the target reservoirs are limited.

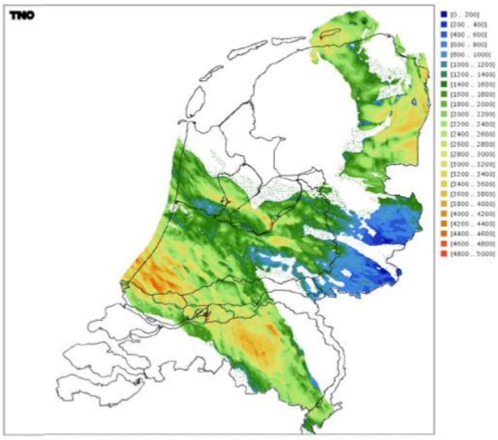


Figure 4-6: Depth map (and lateral extend) of the top of the stacked Triassic Bundsandstein (from ThermoGIS, www.NLOG.nl).

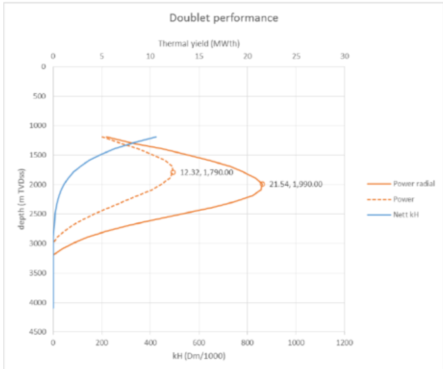


Figure 4-5: Doublet performance, in terms of thermal yield for the Triassic Bundsandstein based on typical reservoir parameters corrected with respect to depth at a COP of 20. The thermal yield lines (orange) show that radial jetting (solid orange line) has the potential to significantly improve performance compared to the non-stimulated case (dotted orange line). Note that the optimum depth, signified by the annotated circle, increases when applying jetting. The nett transmissivity, kH, is represented by the blue line.

The third reservoir is the Slochteren formation. In this case the expected performance is doubled. Remarkable is the combination of a wide target depth from 1500 meter to 3500 meter and the availability of enormous amount of potential locations at this target depth.

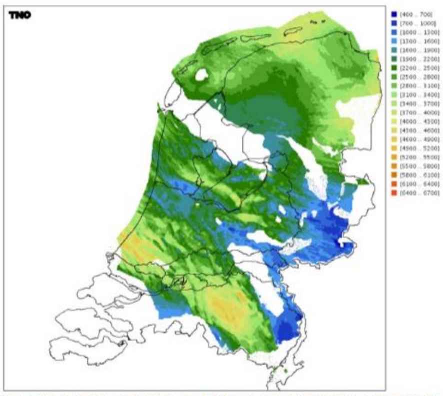


Figure 4-9: Depth map (and lateral extend) of the top of the Slochteren Formation (from ThermoGIS, www.NLOG.nl)

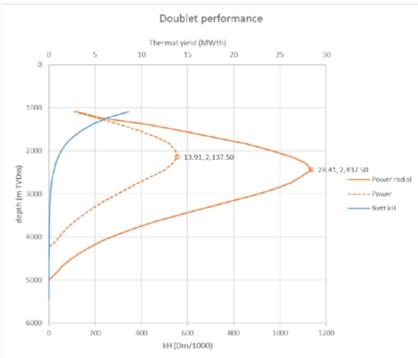


Figure 4-8: Doublet performance, in terms of thermal yield for the Slochteren Formation based on typical reservoir parameters corrected with respect to depth at a COP of 20. The thermal yield lines (orange) show that radial jetting (solid orange line) has the potential to significantly improve performance compared to the non-stimulated case (dotted orange line). Note that the optimum depth, signified by the annotated circle, increases when applying jetting. The nett transmissivity, kH, is represented by the blue line.

The last reservoir is the Carboniferous Kolenkalk. The calculations do show a target zone below 5000 meter. The radial jetting technology has a limitation to 5000 meters which means this reservoir is not suitable for this kind of stimulation. Although the calculations do not show a very good economic outlook it has been decided to test this reservoir as well. There are a number of doublets currently operating in this reservoir and they show a far better performance than what could be expected from this calculation due to the available fractures which give additional waterflow.

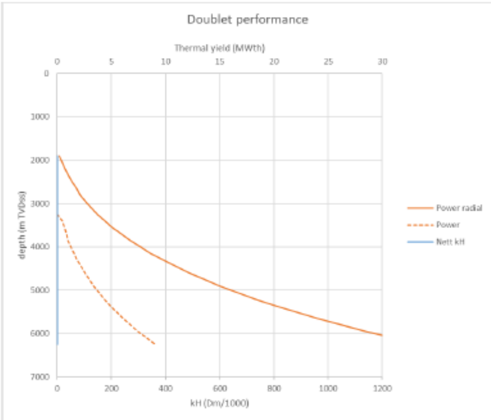


Figure 4-11: Doublet performance, in terms of thermal yield for the Carboniferous Kolenkalk based on typical reservoir parameters corrected with respect to depth at a COP of 20. The thermal yield lines (orange) show that radial jetting (solid orange line) has the potential to significantly improve performance compared to the non-stimulated case (dotted orange line). Note that the nett transmissivity (blue line), kH, is very small at all depths.

Based on the above mentioned calculations of Panterra Geoconsults the following reservoirs are selected,

- Nieuwerkerk Formation, Cretaceous sandstone (Delft and Rijswijk)
- Slochteren Sandstone, Permean Sandstone
- Triassic sandstone
- Dolomite (Kolenkalk)

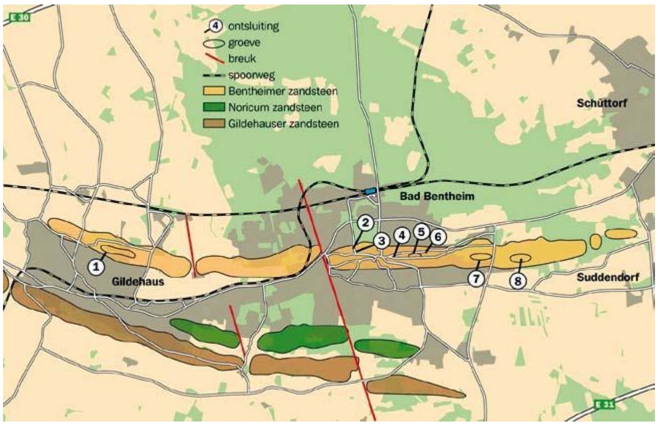
Sample specifications
For the labtest the samples should preferably have the following format, 10 cm x 10 cm x 30 cm. The porosity must preferably be above 6 %.

Geothermal completions
Completions in a geothermal doublet are different from the traditional oil- and gas well. From interviews with the supplier of the screens (HPWellscreen) it became clear that completions are carried out with either a 4,5 inch in the first projects and 7 inch in the later ones. The pipe is predrilled perforated. In some cases the predrilled perforated casing is wire wrapped. In this study a 7 inch pre perforated wire wrapped screen has been used which was provided by ECW. This type of screen was never been tested before at the lab of radial drilling services b.v.

Based on the report of Panterra, TNO was asked to deliver a list of potential quarries where samples could be found. The Bentheimer and Bebertal quarry and limestone quarries were visited. The proposed limestone quarry was closed. A nearby quarry, Aachener Blaustein Werk Gier at the Hahnerstrasse has been visited instead.

name (local name)	rock type	age	quarry location	quarry owner	address
(Bentheimer Sandstein)/Gildehaus Sandstein	sandstone	Cretaceous	Steinbruch am Romberg in Gildehaus	Natursteinwerk Monser GmbH	Almelostr. 3, D-48529 Nordhorn
Bebertal	sandstone	Permian	Bebertal (Sventesius quarry)	Naturstein Gerlinde Pöpl	Am Steinbruch 2, 39343 Bebertal
Roter Mainsandstein	sandstone	Triassic (Buntsandstein)	Miltenberg	Peter Wassum GmbH	Im Söhlig 20, 63897 Miltenberg (Nord)
~~Kohlenkalk~~; Dolomit	limestone		Aachen, Kornelimünster	Max Blees GmbH, Werk Kornelimünster?	Venwegenerstr. , D-52076 Aachen

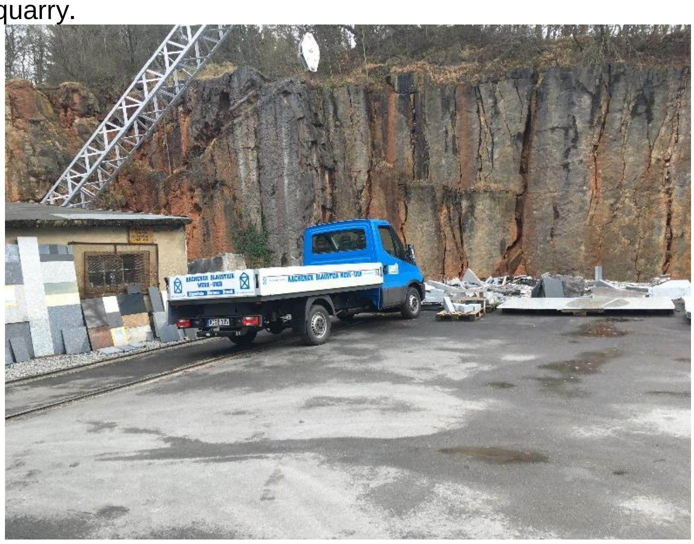
Gildehaus Sandstone
The Gildehaus Sandstone has a similar high permeable as the reservoirs in the western part of the Netherlands. The porosity has a value of approximately 22 % according an EAGE fieldtrip document (see attachment 1).



Bebertal Sandstone
TNO advised to visit the Sventevius quarry in Bebertal near Magdenburg. In a report of the German research institute LBEG the reservoir is mentioned as the stratigraphy is equivalent to the Dutch Slochteren formation (see attachment 2) The porosity of this formation is between 7 and 10 %.

Limestone Quarry Aachener Blaustein Werk Gier

This quarry is located in an area with a larger number of limestone quarries. The by TNO suggested quarry is located 4 km from this quarry.



Trias Quarry Peter Wassum in Miltenberg

The Miltenberg quarry was closed as well due to shortage of water. Samples were sourced from stock.

The samples have been tested at Panterra. The results are listed below.

Sample 1
Cretaceous SST (Delft and Rijswijk) – Gildehaus

Diameter plugs: ~3.8cm

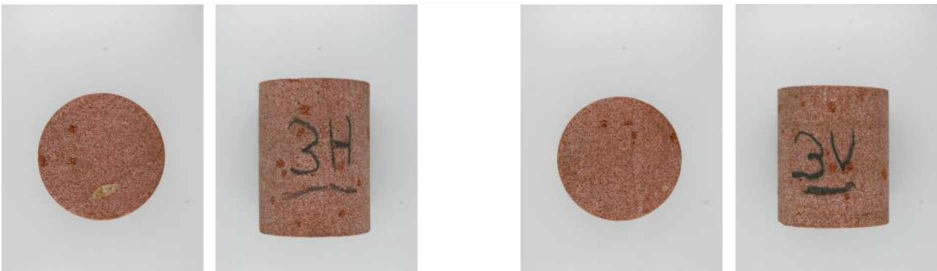
Sample Number	Core Depth (m)	Ambient He Porosity (% of Vb)	Gas Permeability (mD)	Emp. Klink. Perm. (mD)	Grain Density (g/ml)	Remarks
1H	-	23.3	2625	2528	2.64	
1V	-	23.5	3155	3047	2.64	

Sample 2
Permian SST (Rotliegend) – Bebertal

Diameter plugs: ~3.8cm

Sample Number	Core Depth (m)	Ambient He Porosity (% of Vb)	Gas Permeability (mD)	Emp. Klink. Perm. (mD)	Grain Density (g/ml)	Remarks
2H	-	8.0	0.38	0.25	2.65	
2V	-	6.4	0.04	0.02	2.66	

Sample 3
Triassic SST - Miltenberg



Diameter plugs: ~3.8cm

Sample Number	Core Depth (m)	Ambient He Porosity (% of Vb)	Gas Permeability (mD)	Emp. Klink. Perm. (mD)	Grain Density (g/ml)	Remarks
3H	-	15.5	15.8	12.8	2.63	Vug
3V	-	15.0	3.70	2.75	2.63	

Sample 4
Dolomite

Diameter plugs: ~3.8cm

Sample Number	Core Depth (m)	Ambient He Porosity (% of Vb)	Gas Permeability (mD)	Emp. Klink. Perm. (mD)	Grain Density (g/ml)	Remarks
4H	-	0.4	0.0	0.0	[illegible]	
4V	-	0.5	0.0	0.0	[illegible]	Chipped

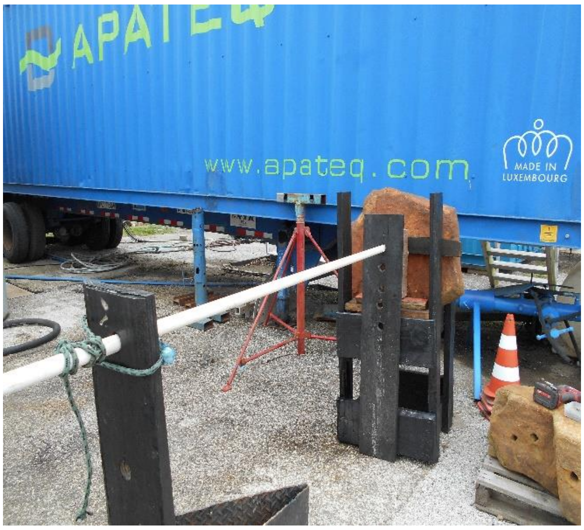
At 5th of February all samples were shipped to Houston. Unfortunately all parcels arrived but the Gildehaus sample was missed. The material has been tested in combination with their completion by RDS. The jettebility and the jetspeed (meters penetration /hour) have been determined.

Test set up Jetting operations

On a water bay a resin housing was installed. The resin housing contains a sample holder and a hose guiding tube.

Figure 1 resin housing on top of the water bay

Figure 2 Sample holder and hose supporting tube



Figuur 3 testsite for larger stones

The selected stones where before testing put into a basket of water for at least one hour to absorb as much water as possible. Two type of nozzles are available, a static and a rotating dynamic one. A rotating nozzle has more jetting power and a static nozzle creates more contact surface. The test started with a static one but due to disappointing results the dynamic was selected. All tests are run at 4000 to 6000 psi. Acids helps to improve the jetting speed in with limestones. The limestone sample was jetted with 15 % acid.

Figuur 4 Results Trias sandstone with static nozzle

Figuur 5 results Trias sandstone with dynamic nozzle

Figuur 7 checking the nozzle before testing

Figuur 6 Pressure between 4000 and 6000 psi (275 and 413 bar)

2.4.2 Results

The following four differences between oil / gas and geothermal plants have been identified.

- The reservoir might be different
- The completion has a gap between the casing and reservoir
- The completion has a wirewrapp screen which might be a challenge for the milling process.

In a lab test all three differences have been tested.

The labtest details

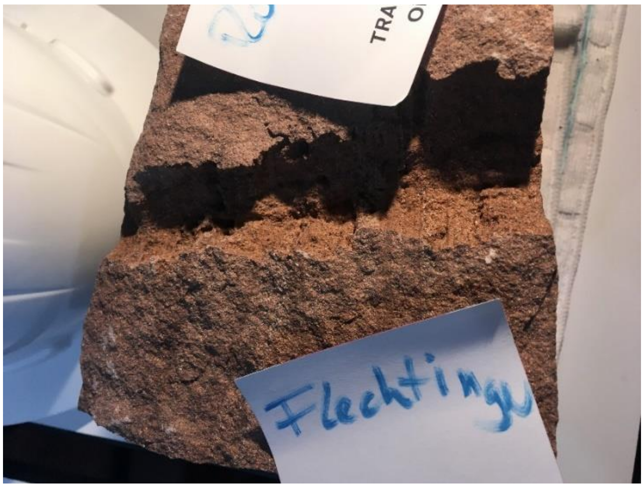
Date	12 and 13th of February
Temperature	Between 3 and 6 degrees C.
Weather	Wet humidity above 90 %
Witness kennisagenda	Radboud Vorage
Witness specialist	Volker Wittig Geozentrum Bochum
Operator	Ray Herber (RDS Inc)

The gildehaus sample has been tested without witness one week later.

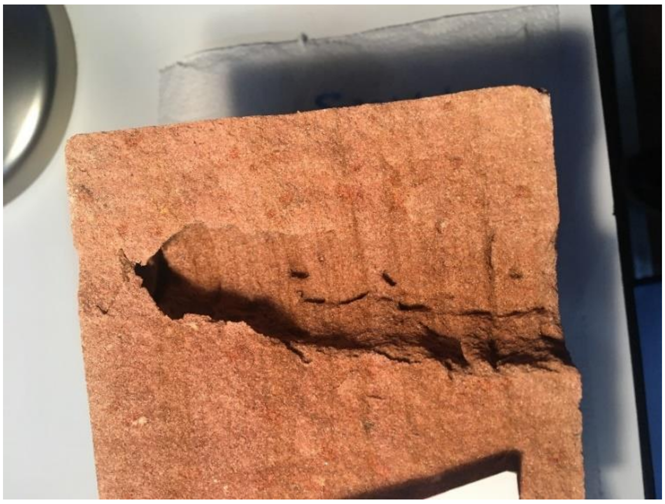
2.4.2.1 Results of jetting the potential reservoirs

The good news is that all samples were jettable. The bad news is that the progress was sometimes very slow. A few centimetres in a half an hour. Only the Gildehaus sample showed an easy process.

Figuur 1 Results static nozzle in Rotliegend



Figuur 8 Result dynamic nozzle Rotliegend



Figuur 9 Result Trias dynamic nozzle

Figuur 10 Result Limestone Dynamic Nozzle

Sample	Fluid	Result	Time
Nieuwerkerk Formation	100 % water	Hole	5 minutes
Trias	100 % water	Hole	30 minutes
Rotliegend	100 % water	Hole	30 minutes
Limestone	15 % HCL	Cm hole	30 minutes

2.4.2.2 Results of the "gap test"

In a standard oil and gas completion the space between screen and reservoir is filled with cement. The cement supports the jethose. In a geothermal completion the cement and support is missing. For this reason a test has been carried out to overcome the space of approximately 2 cm between shoe and rock. As can be seen in the pictures below the test was succesfull.

2.4.2.3 Results milling process of the wirewrap screen

On the pictures below the wire wrap screen can be seen. Also the mill just came through the wirewrapp and the supporting pre-drilled perforated 7 “pipe. It took about half an hour to get through the pipe and screen which is a normal time.

Figuur 11 Result milling through wirewrapp screen ECW

3 Attachments

3.1 Attachment 1 Information Gildehaus Sandstone quarry

The Sandstone reservoir is described in the following document

Excursion guide EAGE 2014 Fieldtrip 1
Analogues for the Schoonebeek oil reservoir: present-day, sub-recent and Lower Cretaceous shallow marine sediments

Petrography Extensive petrographic work was done by Mansurberg (2001). He states ..”The Lower Cretaceous Bentheim Sandstones of the Lower Saxony Basin in Northwest Germany are mature quartz arenites in terms of texture and mineralogy. This study shows that the mineralogical maturity to a large degree is the result of diagenetic processes. The Sandstones are highly porous and permeable and show presence of quartz cement as overgrowths which cement the sandstone, partly dissolved detrital feldspar grains oversized pores caused by complete feldspar dissolution and authigenic kaolinite-dickite booklets” From abstract Mansurbeg 2001).. “Although the sandstones are at present mainly quartz arenites (Figure 35), originally they were arkosic wackes and subarkosic arenites according to the classification scheme of Folk 1968)” (caption fig 16 of Mansurbeg 2001)…

Petrographically, the Bentheimer Sandstone (Figure 36) is a well sorted fine to medium grained quartz arenite (Figure 35). Quartz grains constitute more than 95% of the framework grains:• (diameter); •Grain size: 100-300 µm (rounded and well sorted); • Pore throats: 10-30 µm (unimodally at 10 µm); •Pore size: ~100 µm; •Low Iron content.

Figure 35: Left grain size distribution of the Bentheimer Sandstone From Kemper 1976); right Triangular diagram showing the present-day mineralogical composition of the Bentheimer Sandstone. Mansurbeg (2001)

The sandstone has excellent reservoir quality with porosity in the order of 22% and permeability in excess of 1 Darcy.

3.2 Attachment 2 Information of the Bebertall quarry

Field Guide to the Rotliegend in the vicinity of Magdeburg and the Harz, North Germany

Robert Schöner & Roberto Pierau

Landesamt für Bergbau, Energie und Geologie

with contributions from Michiel Harings, EBN B.V.

Field trip during the TNO-AGE, EBN and LBEG meeting:
Rotliegend reservoir and acquifer properties in a geothermal and E&P context

19.-20. September 2013

INTRODUCTION

Objectives

The key Permian outcrops selected for this trip are located west of Magdeburg, and east and south of the Harz Mountains, Germany. The outcrops display typical lithological characteristics of the Rotliegend comparable to those observed in the subsurface of the Central European Basin System (Southern Permian Basin), both in northern Germany and the Netherlands. The field trip focuses on aspects of Rotliegend sedimentology and the controls of reservoir/aquifer properties, which are relevant in a geothermal and E&P context. The outcrops allow studying the interaction of typical Rotliegend fluvial and aeolian facies types, the base Permian unconformity and the underlying Upper Carboniferous deposits, and the Rotliegend-Zechstein transition with the *Kupferschiefer* (Copper Shale), which is known as an important marker in well logs.

The clastic Rotliegend aeolian-fluvial facies of the Eisleben Formation in the selected outcrops are in many aspects comparable to those observed in time equivalent formations such as the Slochteren Sandstone in the Netherlands. The Slochteren Formation and their lateral equivalents in Germany are the most prolific gas reservoirs in western Europe. These mainly Upper Permian coarse clastics straddle the entire length of the southern edge of the Southern Permian Basin, as indicated in fig. 8 of this guide. Particularly the well sorted aeolian sandstones intrinsically bear excellent reservoir properties, which also qualifies these formations as potential targets for geothermal exploitation. These sandstones were sourced from the Variscan mountain belt, located immediately south of the basin, and typically shale out towards the basin axis further to the north, were the Rotliegend reaches is maximum thickness, mainly consisting of shales and occasionally evaporites (Fig.6-8). A typical S-N section is indicated in fig. 1 as a result of the fluvial-aeolian interactions, combined with regional differences in topography and basin development. The lower parts of the Upper Rotliegend are still displaying a wide variety of facies, from alluvial/fluvial conglomerates to aeolian dune deposits. Fig. 11 displays an E-W cross-section through the southern edge of the Southern Permian Basin and gives a good indication of this variation. The Lower Rotliegend Volcanic Subgroup is mostly absent in the Netherlands, but quite common in Central Germany.

Stop 1 Sventesius Quarry at Bebertal

Location: South of the Flechtingen hills, 6 km north of motorway A2 exit no. 65 or 66, 1 km west of the village Bebertal

Coordinates: 11°18.4'E, 52°14.3'N

Subject: Aeolian-fluvial clastic Rotliegend succession - analogue for deeply buried Rotliegend reservoir sandstones in the Southern Permian Basin

Stratigraphy: Erxleben Fm. (Upper Rotliegend, probably equivalent to Dethlingen Fm. in northern Germany and Lower Slochteren Mb. in the Netherlands)

Objectives of outcrop visit:

- Aeolian-fluvial interaction and architecture
- Sedimentary features of aeolian deposits
- Bounding surfaces of aeolian deposits

Outcrop description:

The "Sventesius" outcrop is an active quarry in Upper Rotliegend fluvial-aeolian sandstones. These local sandstones (*Flechtingen Bausandstein,* "building stone") were quarried since the beginning of the last century. They are a building stone of good quality with a pressure resistance of about 3770 kp/cm². The *Flechtingen Bausandstein* is part of the 120-160 m thick Erxleben Formation, which is probably time-equivalent to the Dethlingen Formation (lower Elbe Subgroup) in the North German Basin, and the Lower Slochteren Sandstone Member in the Netherlands.

The dominant lithology consists of large-scale cross-bedded medium-grained aeolian sandstones. Characteristic features include gradual build-up of dunal foresets (max. 35°). These are truncated by sigmoidal discontinuity surfaces. The aeolian system was periodically influenced by fluvial events. Fluvial lithofacies comprise pelitic and gravelly sheet-flood deposits, conglomerates and gravelly sandstones as well as well-sorted sandstones (reworked aeolian deposits). Thin fluvial deposits are interbedded with aeolian sandstones in the quarry. Fluvial lithofacies are dominant in the underlying stratigraphic interval, as evident from drill cores.

Reservoir geology:

Most Rotliegend gas reservoirs are dominated by sandstones of aeolian origin. Heterogeneities in a sandstone succession, which are important in upscaling from outcrop to reservoir scale, are often controlled by the arrangement of hierarchies of sedimentary facies and their bounding surfaces. The outcrop exposes in a unique manner 3-D geometry and internal characteristics of aeolian dune bed forms, aeolian-fluvial interaction and the spatial configuration of sedimentary bounding surfaces.

In spite of the different geological history of the Flechtingen hills, which were uplifted in the Upper Cretaceous and Tertiary, the reservoir quality of the *Flechtingen Bausandstein* is still comparable to Rotliegend dune sandstones in the German gas fields buried to a depth of 3000-5000 m:

- dune deposits: Φ = 10.7%, K = 3.44 mD, rock density = 2.65 g/m³
- interdune sand sheets: Φ = 7.3%, K = 0.55 mD