PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 24-26, 2014
SGP-TR-202

Fracture Permeability Assessment in Deeply Buried Carbonates and Implications for Enhanced Geothermal Systems: Inferences from a Detailed Well Study at Luttelgeest-01, The Netherlands

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Keywords: fracture permeability, convection, carbonates, hydraulic fracturing, The Netherlands

ABSTRACT

This paper demonstrates that analysis of thermal convection and fracture flow properties from oil and gas wells can be used for the assessment of natural fracture permeability and its volumetric up scaling. We applied this approach to a Dinantian carbonate platform encountered at the Luttelgeest-01 Well (LTG-01) in the Netherlands and show that this location may have potential for an Enhanced Geothermal System.

1. INTRODUCTION

Naturally fractured reservoirs are considered a prime target for the development of geothermal power production in deep sediments and basement rock. For a subsurface heat exchanger to be successful, it is important to assess if the injection and production wells can be connected to a natural fracture network interconnecting the wells and whether the fracture network provides sufficient transmissivity. In addition, tensile fracturing of the reservoir is assumed to result in significant flow rates, as the fractures can well connect to the inferred natural fractures. This study demonstrates that analysis of thermal convection and fracture flow properties from oil and gas wells can be used for the assessment of natural fracture permeability and its volumetric up scaling[1]. We applied this approach to a Dinantian carbonate platform encountered at the Luttelgeest-01 Well (LTG-01) in the Netherlands.

Geothermal energy in The Netherlands is becoming increasingly widespread. Shallow applications such as Ground Source Heat Pumps (GSHPs) are already extensively used and over the last decade the use of direct heat from geothermal wells have seen a large increase in development, mainly in the horticultural sector. In 2012 a total of 9 deep projects had a cumulative production of 202 GWh_{th}/year, with projections doubling to 452 GWh_{th}/year towards 2015 (Heekeren and Bakema, 2013). However, so far no electricity has been generated from geothermal resources, as the average geothermal gradient of 31 °C/km sets the required high temperatures at great depths, resulting in high drilling costs and a generally assumed low permeability. The Dutch subsurface is relatively well understood due to its location in the major hydrocarbon province of the North Sea basin. Legislation prescribes the hydrocarbon industry to publish their data on the Dutch subsurface in a national database that comes publically available after 5 years, thereby greatly stimulating scientific research. However, information on temperature and permeability below 4 kilometres is scarce as it is below the most significant hydrocarbon reservoirs and therefore relatively unexplored. Over the last decade interest has increased due to newly developed hydrocarbon play concepts and several wells have been drilled into the deep formations. Analysis of the temperature data available from the oil and gas industry has greatly increased our knowledge of deep temperature patterns. Studies on temperature datasets identified temperature anomalies and recently several of those anomalies were interpreted to result from thermal convection (e.g. Garibaldi et al., 2010, Bonté et al., 2012, Pasquale et al., 2013 and Guillou-Frottier et al., 2013). Numerical analysis indicates that the thermal effect of natural fluid flow circulation in deep sediments and basement rocks is critically dependent on pre-existing thermal gradient, thickness and permeability (e.g. Pasquale et al., 2013).

The objective of this paper is to constrain the natural permeability of the Dinantian carbonate build-up encountered at LTG-01, to assess the possibility for thermal convection as suggested by thermal anomalies encountered in the well and to assess its impact on the prospective for Enhanced Geothermal System (EGS) development. First we introduce the geological setting of the Dinantian carbonate platform and the evidence for a thermal anomaly in LTG-01. Subsequently, we introduce the methodology for the assessment of permeability, followed by an analysis of LTG-01 data. Finally, we use the findings on natural permeability in the perspective of different stimulation strategies to enhance the performance of subsurface heat exchangers based on tensile fractures and discuss the implications for the potential of EGS in The Netherlands.

2. GEOLOGICAL SETTING

During the Carboniferous, the northern part of The Netherlands was part of the North West European Carboniferous Basin (NWECB). This east-to-west striking basin extended from present day Poland into large parts of Great Britain (Kombrink et al., 2008) (Figure 1). The basin originated at the end of the Caledonian orogeny, during the Devonian and Early Carboniferous, when

[1] The SI unit of permeability is m^2 however here we use the more common industrial unit Darcy, 1 Darcy is equivalent to approximately $10^{-12}\,m^2$.

extension caused the formation of WNW-ESE trending, fault bounded half graben. While the cause of these extensional stresses is still debated (van Hulten, 2012), there is consensus that these graben structures formed an important control on Carboniferous sedimentation. During the Dinantian period, carbonate platforms developed on the structural heights, while shales filled the deeper basins (Geluk et al., 2007) (Figure 2). It is possible that transient sub aerial exposure of the platforms may have led to karstification (Van Hulten and Poty, 2009).

The carbonate platforms are currently found at great depth in the Northern part of The Netherlands and therefore our knowledge of the platforms is relatively limited. Recent hydrocarbon exploration projects resulted in new publically available data, and based on new seismics and well data, several paleogeographical interpretations have been made. Several 10 km long reef trends extended over large parts of the northern provinces. The dimensions of the reefs can be compared to other well-known examples from the Mississippian in the Caspian region, where they form a major petroleum play. However, no hydrocarbons have been encountered so far in the Dutch Carboniferous (Van Hulten, 2012).

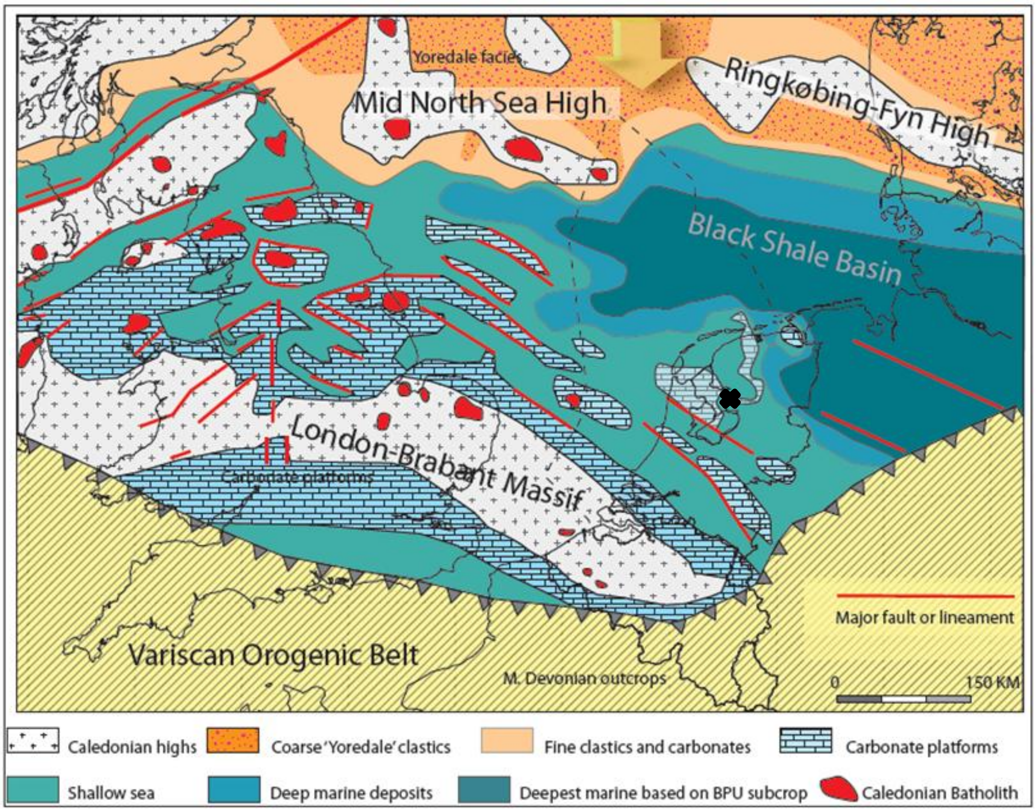

Figure 1: Paleogeography of the Mississippian (corresponding to the Dinantian period of the Western European time scale) according to Van Hulten (2012). The location of the LTG-01 Well is indicated by the black cross.

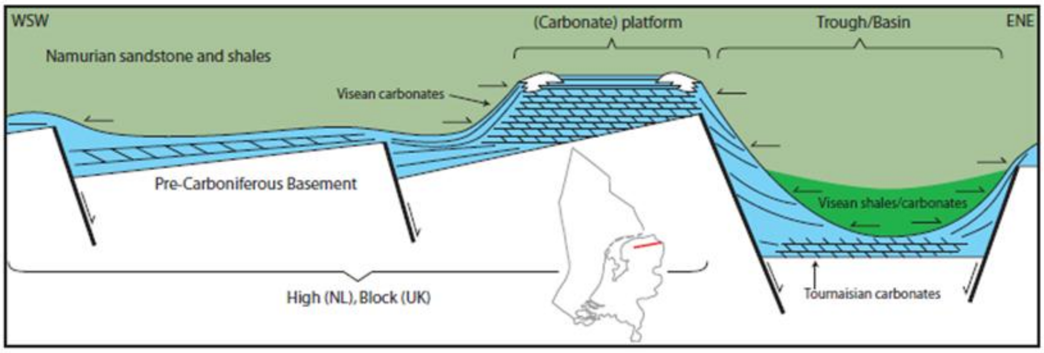

Figure 2: Schematic cross section along a Dinantian carbonate build-up in the Dutch onshore (Kombrink, 2007).

3. THERMAL ANOMALY

Previous work on the temperature distribution of the Dutch subsurface was done by Bonté et al. (2012). They analysed 1293 subsurface temperature measurements in 454 wells and found an average thermal gradient of 31°C/km with a surface temperature of 10°C. In their model they accounted for both the effect of variations in petrophysical parameters (thermal conductivity and radiogenic heat production) and the transient effect of vertical tectonic motions. Two layers in the Dutch onshore subsurface were identified that create remarkable variations in temperature. The first, is the Zechstein salt layer, causes strong spatial thermal variations due to its irregular distribution and high conductivity. The second, the Silesian (Upper Carboniferous) also has a major impact on the temperature. The effect of this layer is strongly insulating due to its low conductivity, which results in an increase in the thermal gradient below this layer.

Bonté et al. (2012) identified a thermal anomaly at the Luttelgeest-01 well, where temperatures at depths greater than 4000m are higher than expected. To get a clear idea of the thermal anomaly at Well LTG-01 we applied a Horner temperature correction to the available well data (Dowdle and Cobb, 1975 and Rider, 2000). Results of the temperature values against depth are shown in figure 3 (red line). For comparison, the average geothermal gradient for The Netherlands (black line) is also plotted. The Horner corrected temperatures from LTG-01 show a positive anomaly in the thermal gradient of up to 45 °C /km above the Dinantian interval. The temperature gradient within the Dinantian reservoir is approximately 10°C/km lower than the average for the Netherlands, while the temperature gradient above the Dinantian is about 20°C/km higher than the average.

The anomaly could not be reproduced within the 3D thermal model of the onshore Netherlands. Bonté et al. (2012) suggested that additional heat is being generated by a magmatic intrusion formed during the collapse of the Variscan Orogen. An alternative explanation is the occurrence of hydrothermal convection. Thermal convection can explain small-scale thermal anomalies, provided permeability is sufficiently high. It is generally assumed that permeability at great depth is very low as a result of compaction due to the overburden pressure. There are, however, several processes that can counteract this, such as fracturing and dissolution. This paper will focus on the feasibility of the hypothesis that the anomaly is caused by convection, and its implications for the development of EGS.

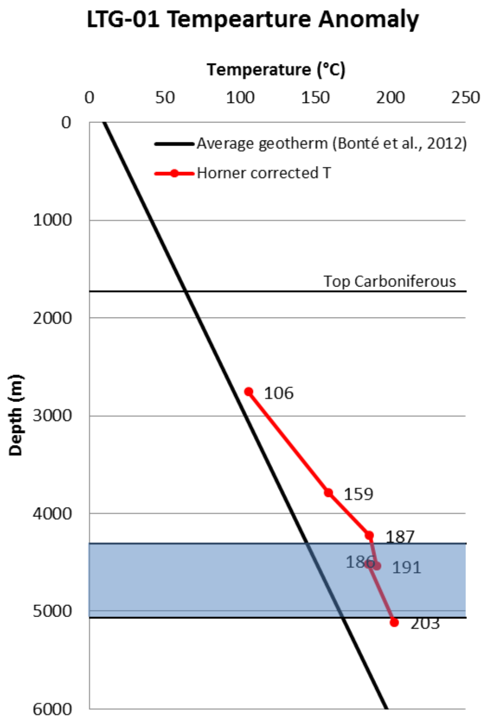

Figure 3: Temperature versus depth plot showing the Horner corrected temperatures for LTG-01 (red line) and the average geothermal gradient for The Netherlands (black line). The shaded blue area indicates the depth interval in which Dinantian carbonates occur.

4. METHODS

As mentioned above, a possible explanation for the increased temperature values found in the Dinantian carbonates is convective transport of heat. For this hypothesis to be possible, sufficient permeability is required over the thickness of the carbonates. To constrain the natural permeability of the Dinantian carbonates, the available data from the LTG-01 Well has been analysed. Subsequently we assessed the possibility of thermal convection by means of a Rayleigh number analysis. Finally we analysed the performance of two tensile fracturing hydraulic stimulation strategies to asses if fracturing of the Dinantian Carbonates may results in significant flow rates for geothermal electricity generation. All the data used is publically available from the NLOG database.

4.1 Permeability assessment from well data

To assess the natural permeability of the Dinantian carbonate build up we used well data from oil and gas wells that is publically available in The Netherlands. The lithological description, wireline logs, wireline pressure measurements and measurements on samples from LTG-01 were used. To compare the permeability values of these different sources all values were transferred into transmissivity values. Transmissivity is the mathematical product of aquifer thickness and permeability:

$$T = \sum_1^N k_i \cdot H_i \tag{1}$$

where T is the transmissivity, k_i the permeability and H_i the thickness of the layer. N is the number of layers and index i refers to the individual layers. The unit of transmissivity is m^3 or its industrial equivalent Darcymeter (Darcym).

Information on the circulation of the drilling mud provided additional information on the presumed fractures within the carbonates. A Coriolis sensor had been used by the operator at LTG-01 to measure drilling fluid density and flow-rate parameters. By spotting major mud losses or micro losses various fractured zones had been detected in the carbonates from 4540 m to 5162 m measured depth (MD). Huang et al. (2011) proposed a simple and direct method to estimate the hydraulic fracture width from mud losses. The model was based on the radial flow of a non-Newtonian Bingham plastic fluid into an unlimited extensional fracture. The geometry of the model is shown in figure 4. It assumes that the mud spreads out radial into a horizontal fracture. The mud flow is driven by the overpressure Δp between the wellbore and the formation and will eventually stop because the overpressure reaches the yield stress τ_y of the drilling fluid.

$$w = \left[\frac{9(V_m)_{max}/\pi}{(\Delta p/\tau_y)^2}\right]^{1/3} \tag{2}$$

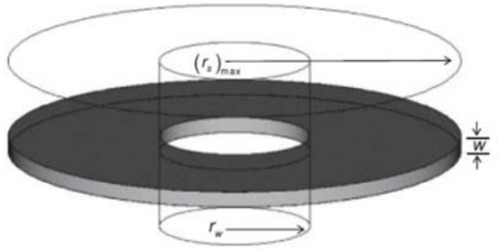

Figure 4: Mud loss problem geometry. Mud spreads out radially from the wellbore into the formation.

4.2 Convection and Rayleigh number analysis

Assuming that thermal convection is able to explain the abnormal low thermal gradient from LTG-01, we followed the rationale of Horton and Rogers (1945) and Pasquale et al. (2013) to find a minimum required permeability value to allow for thermal convection. Rayleigh (1916) first described the breakdown of stability in a layer of viscous fluid heated from below. He assessed the relation between the buoyant forces that drive convection and the viscous forces inhibiting it, and expressed this in the dimensionless Rayleigh number (Ra). If the Rayleigh number is equal to or greater than the critical Rayleigh number (Ra*), convection will occur. This critical value for Ra* is $4\pi^2$ (Horton and Rogers, 1945).

Convection of pore fluid in a porous medium as a result of a vertical temperature gradient was first treated analytically by Horton and Rogers (1945) and Lapwood (1948) and is therefore often referred to as the Horton-Rogers-Lapwood problem. Zhao et al. (2008) give a comprehensive review on this problem and provide the following expression for the Rayleigh number in a porous medium:

$$Ra = \frac{(\rho_{f0} C_p)\rho_{f0} g \beta_T k \Delta T H}{\mu \lambda_e} \tag{3}$$

where ρ_{f0} is the reference density of the pore fluid, C_p is the specific heat of the pore fluid, g gravitational acceleration, β_T is the coefficient of thermal expansion of the pore fluid, k is the permeability, ΔT is the temperature difference between the top and bottom of the medium, H is the thickness of the layer, μ is the viscosity of the fluid and λ_e the effective thermal conductivity of the rock mass and the pore fluid: $\lambda_e = \phi\lambda_f + (1 - \square)\lambda_s$. With ϕ being the porosity, λ_f the conductivity of the pore fluid and λ_s the conductivity of the rock mass. It assumes that the upper and lower boundaries are impermeable and that there is no internal heat generation within both the porous medium and the fluid.

Using the minimum Rayleigh number required for the onset of convection (Ra*), equation (3) can be rewritten to constrain the minimum required permeability (k_{min}):

$$k_{min} = \frac{Ra^* \mu \lambda_e}{(\rho_{f0} C_p)\rho_{f0} g \beta_T \Delta T H} \tag{4}$$

For the parameter values we used site specific values of LTG-01 for the temperature difference and the height of the convective layer. Furthermore we assessed the effect of the temperature, pressure and salinity dependence of the water properties ($\rho_{f0}, C_p, \mu, \lambda_e, \beta_T$) on the results for the minimum Rayleigh permeability. Holzbecher (1998) provided relations for the temperature dependence of density, specific heat, dynamic viscosity, thermal expansion and thermal conductivity. The pressure and temperature effect on pure water can also be found in the "RefProp" database, based on the "International Association for the Properties of Water and Steam" Formulation (IAPWS) (Wagner and Pruβ, 2002). Relations for pressure and salinity are harder to find. Batzle and Wang (1992) provide relations for temperature, pressure and salinity dependence of density and viscosity. Temperature and salinity dependence of specific heat capacity was provided by Grunberg (1970). The combined effect has been incorporated (cf. Van Wees et al., 2012). To test the effect of salinity we used values for fresh, brackish, salt and brine from Holzbecher (1998). The salinity at LTG-01 was obtained from the well log data. At the depths relevant for our problem an average Chloride (Cl^-) content of 5.6 g/l was recorded.

4.3 Tensile fracturing strategies

The final part of this work investigated the effect of tensile hydraulic stimulation. If permeability is defined by a natural fracture network, as inferred for the Dinantian carbonate platform at LTG-01, hydraulic fracturing can be used to increase the connectivity between fractures within the fractured reservoir itself as well as the connectivity of the fractured reservoir with injection and production wells. Tensile fracturing in non-critically stressed tectonic environments, such as occur in large parts of the Netherlands, allows to perform hydraulic stimulation most likely marked by a relatively low level of induced seismicity (Pluymaekers et al., 2013). Here we used the Dinantian carbonate platform as an example reservoir to test a tensile hydraulic stimulation strategy. Based on the well log analysis in the previous section we estimated the reservoir depth, thickness, default permeability and the temperature and salinity of the brine. The thermal and flow properties of the reservoir fluid were taken temperature, pressure and salinity dependent as described in the previous section.

For the development of the subsurface reservoir we adopted a target flow rate of 100 l/s. This was achieved through a horizontal well layout with a significant horizontal section ranging from 1000 to 2000 m, and the criterion of multiple fractures in the well layout as shown in figure 5. The commercially available software package MFRAC was used as an hydraulic fracture simulator to model the fracture propagation, fracture flow behaviour and proppant transport (Pluymaekers et al., 2013). In the well layout the fractures were oriented parallel to the wellbore to increase the contact surface between the well and the low permeable formation.

Electricity production is accomplished with a binary power plant marked by a reinjection temperature of 80 ^{0}C. The levelised cost of energy (LCOE) will be calculated based on the techno-economic performance assessment by Van Wees et al. (2012).

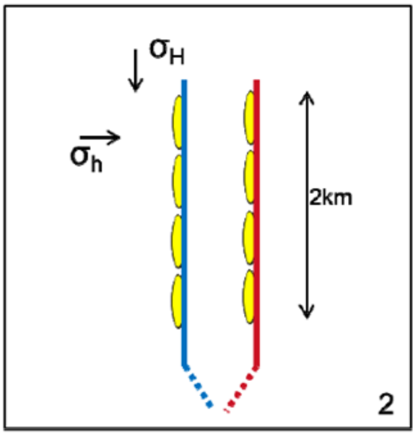

Figure 5: Schematic layout of the sub vertical fractures (top view), relative to the wells (after Pluymaekers et al., 2013; their scenario 2). The modelled scenario is marked by fractures oriented parallel to the fracture well.

5. RESULTS

5.1 Permeability assessment

The available well data on the Dinantian of the LTG-01 were analysed in order to find indications for increased fracture permeability. The matrix porosity of the limestones is very low, as expected from the large depth of the reservoir and corresponding to the permeability as obtained from the samples. However, there were several indications for higher effective permeability related to fractured zones:

- Observations of faults, fractures and fissures had been reported in the lithological description of the composite well log. Other indications were given by the presence of fracture fillings, calcite and dolomite intervals. The presence of micro-pyrite indicated that hydrothermal fluids have been present in the past and may still be present.

- Wireline logs of LTG-01 showed intervals with high gamma ray (GR) and neutron density separation which might be indicative for increased permeability.

- Wireline pressure measurements indicated a large range of permeability values for a 100 m thick interval. An estimate of the transmissivity of this interval is 2 Darcym or 2 10^{-12} m^3.

- Two core samples provided horizontal permeability values ranging from 0.2 to 9.60 mDarcy or 0.20 10^{-15} to 9.60 10^{-15} m^2. For the 100 m interval between the two cores this results in a transmissivity value of 0.5 Darcym or 5 10^{-13} m^3.

- The analysis of the mud losses that occurred during drilling at LTG-01 resulted in a permeability value of around 60 mDarcy or 6 10^{-14} m^2 for the complete reservoir thickness of 600m. This corresponds to a transmissivity of 36 Darcym or 3.6 10^{-11} m^3.

The intervals showing signs of fracture permeability range from 4550 to 5150 m measured depth. This interval corresponds to the occurrence of the Dinantian carbonates, from 4355 to 5124 m measured depth.

5.2 Rayleigh number analysis

Using the Rayleigh number analysis for the temperature range of the Dinantian carbonates [144-167°C] we found values of the minimum permeability around 3 10^{-14} m^2 or 30 mDarcy. Multiplied with reservoir thickness, the resulting transmissivity is in the order of 1.8 10^{-11} m^3 or 18 Darcym. This number, however, depends on the input parameters. An analysis of the effect of pressure and temperature dependence of the involved water properties, based on an average geothermal gradient of 31 C/km, showed that the derived permeability strongly decreased with depth. At greater depth, smaller permeability values are required for the onset of thermal convection (figure 6). We found that the pressure and temperature dependence of the coefficient of thermal expansion had the largest impact. The effect on salinity on these values is rather small.

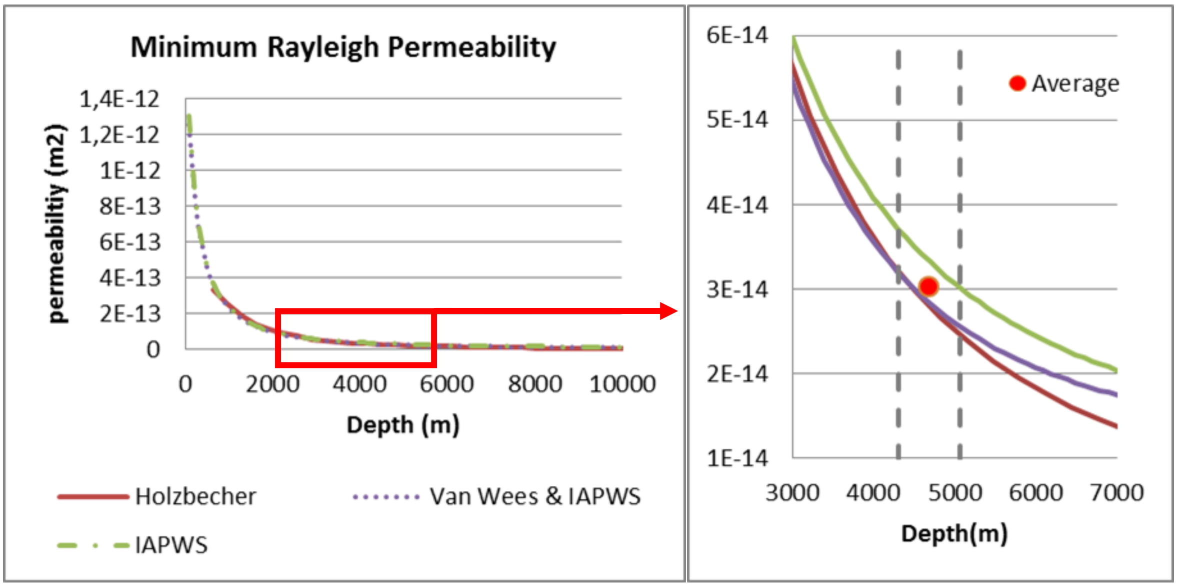

Figure 6: The dependency of the minimum Rayleigh permeability on different models for water properties with depth. Left for the [0-10000m] interval, right a close-up for the [3000-7000m] interval. The red dot indicates the average value of the permeability for the three models at the mean reservoir depth.

5.3 Tensile fracturing strategies

Based on the well log analysis we found that the interval, in which signs of fracture permeability were found, ranged from 4550 to 5150 m measured depth. Fracturing analysis showed that the expected vertical interval of the fractures would be confined to ca 200m because of stress heterogeneities predicted from stratigraphic layering, as identified from well logging (Pluymaekers et al., 2013). For the modelling we adopted conservative upscaled permeability values of 4mD, approximately one order of magnitude lower than the values inferred from the Rayleigh instability analysis and mud losses, but in agreement with the transmissivity from the rock samples. The results show that the required pressure drive for the parallel fractures is 95 bar and the LCOE for the reservoir simulation is 17 eurocents/kWh.

Parameter	LTG-01 value
Reservoir depth	4550 to 5150 m measured depth.
Fractured reservoir thickness	200 m
Default reservoir permeability	4 mD
Brine temperature	185-200 ^{0}C
Brine salinity	5000 ppm

Table 1: Parameter values for the tensile fracturing model based on the LTG-01 data

6. SYTHESIS AND DISCUSSION

We have analysed the available well data for the LTG-01 Well and provided a Rayleigh number analysis on the minimum permeability required for the onset of thermal convection in the Dinantian carbonates. Here we will compare the results and assess whether the Carboniferous carbonates at LTG-01 have geothermal reservoir potential.

Table 2 provides an overview of permeability results of the Dinantian carbonates at LTG-01. All values in table 2 are accompanied with uncertainties as many assumptions and simplifications were made in order to obtain them. For this reason all values should be appreciated as a first order magnitude approximation.

No visible porosity had been reported on the lithological description from the composite well log. This is consistent with the low porosity and permeability found in the rock samples. Based on this we conclude that the matrix permeability of Dinantian carbonates is poor. However, the wireline pressure measurements and the mud loss calculations provide higher permeability values. The resulting transmissivity values are in the range of 2-6 Darcym or 2-6 10^{-12} m^3. The signs of fractures that were found in the composite well log suggested that the intervals of increased permeability may be related to fractures. In the literature we found that an active extensional tectonic setting is in favour of high permeability values (Cloetingh et al., 2010, Faulds et al., 2010 and Faulkner and Armitage, 2013). Permeability related to the graben structure found at depths below the Dinantian carbonates may have been lost due to time dependent dissolution processes.

By performing a Rayleigh number analysis we constrained the minimal permeability required for the onset of convection to be 30 mDarcy or 3 10^{-14} m^2 and the associated transmissivity values for a 600m thick reservoir are 18 Darcym or 2 10^{-11} m^3. This value is rather high compared to the values that Pasquale et al. (2013) found for a deep carbonate aquifer of the eastern sector of the Po Plain. This difference can mainly be attributed to large difference in reservoir thickness between the two locations. The reservoir studied by Pasquale et al. (2013) about 5000m thick while the Dinantian reservoir studied here only has a thickness of about 600m. In addition to this Pasquale et al. (2013) used the actually measured low thermal gradient of 13.5 °C/km. We used the relatively high average temperature gradient for The Netherlands (Bonté et al., 2012), because the Rayleigh number analysis addresses the onset of thermal convection and should therefore be applied to the original temperature difference before the onset of convection. Furthermore, we introduced more accurate relationships for the temperature and pressure dependence of the involved water properties. We showed that the minimum required permeability value strongly decreases with increasing depth as a result of the pressure and temperature effect.

Comparing the transmissivity values obtained from the wireline pressure measurements and the mud losses to the value from the Rayleigh number analysis shows a factor 3 to 9 difference. This means that 3-9 fractured intervals may be able to accommodate thermal convection, provided that they are sufficiently connected.

Injection of fluids at high pressure reduces the effective normal stress and may result in tensile fracturing of the reservoir rock, thereby creating pathways for fluid flow. Fracturing of a reference reservoir with a default permeability of 4 mDarcy and a thickness of 200 meter – which is in line with conservative estimates for transmissivity values from the different analysis approaches – produces very high flow rates, suitable for the production of electricity. Our findings demonstrate that the Dinantian carbonate platform at LTG-01 may have physical potential for the development of an enhanced geothermal system.

This paper provides a first order assessment of the geothermal reservoir potential of Carboniferous carbonates in the Dutch subsurface. Future work will use thermal 3D numerical models to establish a more detailed understanding of implications arising from the interaction between geothermal anomalies and natural fracture permeability (cf Guillou-Frottier et al., 2013)

Source/method	**Depth interval**	**Permeability**	**Transmissivity**
Composite well log		Several intervals within the Dinantian show signs of increased permeability	
Wireline pressures	4535-4647 m ~100 m	19-598 mDarcy $1.9\ 10^{-14}$ - $5.99\ 10^{-13}$ m^2	2 Darcym $2\ 10^{-12}$ m^3
Rock samples	4378-4473 m ~100 m	0.2-9.6 mDarcy $0.20\ 10^{-15}$ - $9.60\ 10^{-15}$ m^2	0.5 Darcym $5\ 10^{-13}$ m^3
Mud loss calculations	~600m	1-2 10^4 Darcy 1-2 10^{-8} m^2	4-6 Darcym 4-6 10^{-12} m^3
Rayleigh number analysis	~600 m	30 mDarcy $3\ 10^{-14}$ m^2	18 Darcym $2\ 10^{-11}$ m^3

Table 2: overview of the results

7. CONCLUSIONS

Based on publicly available data for the LTG-01 Well we made an estimate of the fracture permeability of the Dinantian carbonates at Well Luttelgeest-01, The Netherlands. Well logs, wireline measurements, measurements on samples and mud loss analysis were examined. Subsequently, the minimum required permeability was obtained from a Rayleigh number analysis, consistent with thermal convection inferred from the conspicuously low temperature gradient observed in the well at the fractured reservoir depth level. Subsequently the observed and estimated permeabilities were compared and the effect of the inferred permeability on reservoir performance was evaluated.

The results show that the fracture permeability found at the LTG-01 Well is limited to no more than 3 to 9 transmissive zones over a depth interval of 600m. Individual fracture transmissivities range from 5 to 10 Darcymeter. It follows from the Rayleigh number analysis that the minimum required cumulative transmissivity of the depth section is approximately 20 Darcymeter. Comparing these results shows that several fractures are sufficient to explain the thermal anomaly by means of thermal convection, provided that the fractures have a good volumetric connectivity. Tensile fracturing of the reservoir, parallel to the horizontal injection and production well can result in significant flow rates as the fractures can well connect to the inferred natural fractures. The flow performance for a reference case with a reservoir temperature of 190°C, at 5 km depth and with a default permeability of 4 mDarcy can range up to 100 l/s. The Levelised Cost of Energy (LCOE) is estimated to be 17 €ct/kWh, depending on subsurface conditions and cost for hydraulic stimulation. We showed that thermal convection and fracture flow properties from oil and gas wells can be jointly used for the assessment of natural fracture permeability, its volumetric up scaling and its implications for an EGS system.

8. ACKNOWLEDGEMENTS

This study has been partially funded by the European Union Seventh Framework Programme Integrated Methods for Advanced Geothermal Exploration (IMAGE) under grant agreement n° 608553.

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