Petrophysical Report of the Dinantian Carbonates in the Dutch Subsurface

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Summary and conclusions

Well	Core	Logs	Well test	WFT
53/12-02		x		
BHG-01	x	x	x	
CAL-GT-01-S1		x	x	
CAL-GT-02		x	x	
GVK-01	x	x		
KTG-01	x	x	x	x
LTG-01	x	x	x	x
MOL-GT-01		x		
O18-01	x	x	x	x
S02-02	x	x		x
S05-01	x	x	x	x
UHM-02	x	x		x
WSK-01	x	x	x	

Figure 1. Overview of the wells and available data included in this study

A petrophysical study has been performed including eleven Dinantian well penetrations in the Netherlands, one in Belgium and one in the British sector of the Southern North Sea. Additional wells exist in the Maastricht area but only a few of these have log data allowing evaluation and these were not available in time for this evaluation. The wells evaluated are mostly in the South of the Netherlands, in Belgium and in the British North Sea sector (ten), two in the middle, WSK-01 and LTG-01 and one in the North, UHM-02.

The focus of the evaluation is determination of porosity and mineral composition. Due to the very low porosity and the heterogenous rock, it is not possible to determine any permeability. There are very few core permeability measurements and, mostly below detection limit. Instead, data available from well tests, wireline formation tests and losses has been added to the evaluation to provide indications of permeability.

For each well logged a formation temperature has been estimated, based on the maximum temperature measurements made during logging. Horner extrapolation of the measured temperatures provided good estimates of formation temperature at total depth (TD) of the wells and in some wells also the formation temperature at the top of Dinantian.

The conclusions from the study are as follows (for details please see the individual well reports):

- The limited number of wells penetrating the Dinantian, does not allow to draw any general conclusions about the geothermal potential of the Dinantian carbonates in the study area.
- Porosity is mostly below 2 % and over long intervals below 1 %.
- All wells have at least some short intervals with porosity exceeding 2 %, mostly in the range 2-6 %. In a few wells, porosity up to 25-32 % exist in very short intervals, less than 1-2 m.
- An exception is the South-Eastern wells, CAL-GT-01(S1), CAL-GT-02 and to some degree GVK-01, where porosity is higher over longer intervals. However, the clay content is also higher and it is likely that most of the matrix is tight in spite of the higher porosity.
- Porosity zones are associated with karst and dolomitization.
- There is a clear pattern of Limestone in the upper part of the Dinantian and more Dolomite towards the base.
- The Californie wells, CAL-GT-01(S1) and CAL-GT-02, have properties allowing geothermal extraction, probably due to (karstified) fracture/fault zones.
- 8 out of 11 wells were tested (production test / injection test or DST) and some had additional pressure tests, 2 out of 11 wells were only pressure tested (FMT / MDT / RFT) and 1 well did not have a record of any test;
    - Only three of the other wells, KTG-01, BHG-01 and S05-01 have had flow to surface, KTG-01 without lift and BHG-01 and S05-01 with N_2 lift.
    - Both KTG-01 and BHG-01 had H_2S recorded during well tests. KTG-01; 50ppm and BHG-01; 60-80 ppm. LTG-01 recorded signs of H_2S in the gasline during drilling. S05-01 had no H_2S recorded during testing. The absence of H_2S during a well test is not proof of no H_2S in the reservoir.
    - All other wells tested, WSK-01, LTG-01, O18-01 have no flow reported. However, two of the wells, LTG-01 and O18-1 have pressure records indicating some inflow.

    - Outside the Californie project, three wells have properties that have a good likelihood to allow circulation between wells, KTG-01 and BHG-01, both in Zeeland and probably also UHM-02 in the north.
- The temperature gradients are relatively high, varying from 32-38 deg °C/km to TD for the majority of the wells. The exception is the SE wells (Californie and GVK-01) where the gradient is 26-30 deg °C/km. A normal gradient is considered to be approximately 30 deg °C/km.
- In the few wells where a formation temperature could be estimated at top Dinantian, the temperature gradient was higher than the gradient to TD, above 41 deg °C/km and then significantly lower through the Dinantian section, 19-28 deg °C/km.
- Two wells, LTG-01 and UHM-02 are overpressured, LTG-01; 69-140 bar, UHM-02; 103-178 bar depending on the fluid density/gradient used.
- The porous intervals in well LTG-01 are poorly connected to an overall pressure system based on the pressure interpretation. Only one interval appears to be connected, with good pressure repeats after pumping out, while the other pressures that appear to be of acceptable quality are severely supercharged by invading mud filtrate and losses, indicating poor connectivity.
- UHM-02 has two sections with high porosity and probably good permeability. A water sample from one of these sections show very high concentrations of metals, particularly Zink and Lead. Cadmium, Silver and a few other metals were also anomalously high.

Recommendations

Based on the findings of the petrophysical study of the Dinantian, a number of issues need to be clarified further and the following recommendations result:

- Gather as much data as possible from the Dinantian well tests and evaluate them to provide a better assessment on the reservoir quality.
- Perform wireline logging in at least one of the Californie geothermal wells such that a more comprehensive and integrated evaluation of these key wells can be made.
- Have the water analysis and gas analysis in well UHM-02 assessed by a geochemical specialist and a production chemist. The aim should be to 1) understand the source of the water and 2) the possible complications of producing this formation water in geothermal projects.

Recommendations for future wells drilled for assessing the potential of extracting geothermal energy from Dinantian Carbonates.

- An evaluation program for any future Dinantian wells have been provided as part of the petrophysical work. This program should be used as a guide and developed further when more wells have been drilled.
- Due to the presence of Uranium in many of the Dinantian wells, it is essential to record spectral GR logs to separate Uranium anomalies from clay.
- Due to the heterogenous nature of the Dinantian it is essential that as much as possible is cored. Preferentially the entire Dinantian should be cored in the first well in any new area to be assessed for geothermal extraction.
- For any future wells, standard core analysis should be done on whole core and only in exceptional cases on plugs.
- Testing of the first well drilled in any new area for extraction of geothermal energy is essential. Geological and petrophysical evaluation methods will not be sufficient to answer the basic question if the formation is sufficiently permeable and can be stimulated such that the viability of geothermal extraction can be assessed.
- Pressure and fluid sampling of the first well drilled in any new area for extraction of geothermal energy is essential (either wireline or during testing).

Introduction

Geothermal energy systems have been considered as a potential alternative for the fossil fuel heating. Currently, there are geothermal projects already functioning in the Netherlands. However, the application of geothermal energy in existing projects is not adequate for the provision of high-temperature heat for, as an example, the process industry. It is anticipated that Ultra Deep Geothermal (UDG) energy could potentially make a substantial contribution to the transition towards a sustainable heat supply. To reach sufficiently high temperatures in the Netherlands, geothermal reservoirs at depths over 4 km are required. The Dutch subsurface at these depths has not been explored extensively until now and is therefore relatively unknown. Based on the limited amount of subsurface data, the Lower Carboniferous Dinantian Carbonates were identified by Boxem et al., 2016 as the most promising target matching the initial requirements for UDG.

The petrophysical study reported in this document is a result of SCAN, a government funded, program to scope out the potential of geothermal energy, including from the Dinantian Carbonates. This program includes a range of subsurface studies of the Dinantian Carbonates. The results of the SCAN studies will be released and become available via www.nlog.nl.

The purpose of this study was to determine the petrophysical properties of the Dinantian carbonate section in the wells with a comprehensive set of logs in the Netherlands (and immediate surrounding areas) penetrating this horizon. In the Netherlands, 26 wells penetrate the Dinantian horizon, however, 11 wells include a comprehensive set of logs. These are included in this petrophysical study. Additionally, one offshore UK well and one Belgian well were included.

In addition to determining the petrophysical properties of the Dinantian the work aimed at creating a set of edited and spliced curves for future work on these wells. A petrophysical database in the program Interactive Petrophysics (IP) was created. An evaluation program for future Dinantian wells has been provided.

The aim of this report is to summarize the evaluation and the results of the evaluation of the Dinantian wells. For most wells, a separate and more detailed petrophysical evaluation report is available.

The geology of the Dinantian carbonates and of the overburden are described in detail in the SCAN report on Facies Distribution and Diagenesis of the Dinantian Carbonates. This report will be published in Q2 2019.

Petrophysical Evaluation of the Dinantian.

Study preparations

Prior to starting the evaluation of the Dinantian section, all data available were retrieved from the NLOG. In the course of the project, additional data and reports from some Dutch wells were requested from and made available by Nederlandse Aardolie Maatschappij (NAM), these have been made available to NLOG as well. Data from the Belgian well Mol-01 was made available by Vlaamse Instelling voor Technologisch Onderzoek (VITO), for analysis within the UDG Exploration Work Program.

The data was uploaded to IP, both composite logs and raw logs. The composite logs are the logs supplied by the operator to the authorities. These files tend to only contain the following basic log curves: GR, density, neutron and sonic. This is not sufficient for a comprehensive petrophysical evaluation. Therefore, additional log data had to be added to the data used for the evaluation. Of particular importance were the caliper of the density, spectral GR curves (Uranium, Thorium and Potassium (Kalium)) and resistivity curves. For some wells, the density correction and the PEF were also added. The composite curves were not always suitable and had to be replaced in a number of wells.

For many of the wells, the curves had to be spliced, depth matched and for the density and sonic edited prior to the evaluation. The main reason for editing the sonic and density curves, was to obtain reliable curves for the geophysicists. Most of the edits of these curves were in the sections above the Dinantian. Only in a few wells have the density and sonic been edited in the Dinantian and then only when it is obvious that these logs are wrong. In such cases, primarily neutron and resistivity have been a guide in the editing process.

Methodology: Porosity and lithology evaluation

For most wells, the porosity is calculated from the sonic-neutron x-plot, sometimes combined with a porosity calculated from the density-neutron x-plot. In addition, porosity has been calculated from all porosity measurements, density, sonic and neutron, applying a Limestone matrix in most cases, as a check on the porosity derived from the x-plot(s). For well KTG-01, the matrix density was determined from the PEF, assuming Limestone-Dolomite mix. The porosity was calculated from the density measurement applying the matrix density determined from the PEF.

In a number of wells, there are sections with very poor borehole conditions, affecting the measurements made by the different porosity tools. Consequently, the resulting porosity is often too high. For these wells, a resistivity porosity has been calculated and applied to limit the final porosity. This allows a more realistic porosity to be calculated in washed out sections with rugose borehole. The formation water resistivity (Rw) has been derived using Picket plots in most of the wells.

However, in a few wells where the Picket plot have a too scattered appearance, not allowing a conclusive derivation of the Rw, a set of resistivity porosity curves were calculated from the deep resistivity curve (laterolog) applying several different Rw values. The resistivity porosity that best matched the x-plot porosity, in sections with good borehole, determined the Rw value to use.

The evaluation of the two wells in Californie, CAL-GT-01(S1) and CAL-GT-02 are much more uncertain than the rest of the wells and only the upper part of the -01 well have a good porosity determination thanks to both sonic and NMR porosity. The lithology cannot be determined from logs in any of these wells due to the lack of density and neutron logs and it is assumed that both wells have a Limestone matrix in the evaluation. For CAL-GT-01(S1), the porosity below the open karst is calculated from the sonic with the assumption of Limestone matrix. In CAL-GT-02, the porosity is entirely determined from the resistivity using a Rw determined from a Picket plot in CAL-GT-01.

High Uranium concentrations are common in the Dinantian. In most wells there are sections with high GR to very high GR that are caused by Uranium. For most wells there is a spectral GR that distinguishes the different elements that are the source of gamma rays, Uranium, Thorium and Potassium (Kalium). The two latter elements are associated with clay, while Uranium is not. Consequently, the Potassium (Kalium) concentration is used as the clay indicator for wells with spectral GR. In one of the wells, S02-02, the spectral GR is erroneous and a clay indicator has therefore not been calculated. In the well BHG-01 no spectral GR exist. However, it is almost certain that all the high GR in these wells are due to Uranium and not due to clay.

In a few wells, WSK-01, CAL-GT-01(S1) and CAL-GT-02 the clay indicator has been calculated from the GR. The reason is that there is no spectral GR in these wells except in the top part of Dinantian in CAL-GT-01 and there is a relatively good relationship between GR and calculated porosity, something that is to be expected in a carbonate with varying clay content, where the clay increases the porosity. However, the intervals with a higher porosity and higher clay content have no reservoir qualities and are almost always tight. There is a risk that the clay content calculated in these wells is partially too high due to the presence of Uranium causing the elevated GR. However, it is unlikely to cause large errors in the evaluation of these wells.

For the majority of wells a clay indicator cut-off of 0.1 has been applied. The exceptions are S02-02, BHG-01 where no reliable clay indicator could be calculated and KTG-01. In KTG-01, a reliable clay indicator could be calculated. However, the issue was that no reliable cut off could be established due to the infill in the karst containing clay and at the same time having reservoir quality rock. The core showed that the karsted sections KTG-01 had partial infill of soil/fine sand and that there did not appear to be any voids. The logs do also indicate that there is some clay or Feldspatic material with slightly elevated Potassium content in KTG-01. In none of these wells is it believed that the lack of a clay cut-off would have a significant impact on the evaluation and assessment of the reservoir quality.

For the majority of the wells, the Limestone-Dolomite proportion, has been calculated using either the apparent matrix slowness ($Dtma_{app}$) from the sonic-neutron x-plot or the apparent matrix density ($Rhoma_{app}$) from the density-neutron x-plot. One exception is the well KTG-01 where the matrix density was based on the PEF and the proportion of Limestone and Dolomite was calculated from this. The calculated Limestone and Dolomite proportions have been corrected for the clay indicator in the wells with a clay indicator.

In the BHG-01 well, Pyrite content has been calculated due to very high Pyrite concentration in a few intervals. In KTG-01 Baryte content has been determined. However, in other wells where high densities (>3000 kg/m^3) are present, this is mentioned in the discussion in the individual well report and no separate calculations to determine the proportions of heavy minerals has been attempted. The most likely minerals causing the elevated density values are Baryte, Pyrite and Sphalerite. However, as the proportion of these minerals, even in the high density intervals is low, it does not have a significant impact on the evaluation and porosity is unlikely to be erroneous due to this.

Result: Porosity and lithology evaluation

The detailed evaluation results for the wells are found in the evaluation reports for each individual well. The Dinantian varies in its development across the country with the wells in the South-East of the country having higher porosity, but also having higher clay/organic content. Most wells are dominated by low porosity values below 2 % and when the dominant porosity is higher, only in the Californie wells, the higher porosity is mostly associated with higher clay content and then the matrix is unlikely to be productive.

All wells have some intervals with porosity above 2 % and the two types of porosity development are karst and dolomitization. Based on the cored sections with karst, the karst is mostly filled in by detrital material and carbonate rubble and is not open. Due to the few intervals of karst cored, no definite conclusion on the openness of the karst can be deducted. However, the logs support that most karsted sections penetrated have infill. An exception is the cavernous section in CAL-GT-01(S1).

In the following graphs, a comparison of the derived petrophysical properties of the different wells are displayed.

Y-axis title wrong, should be Net to Gross (fraction) → Torbjorn will send the excel file to change the plot

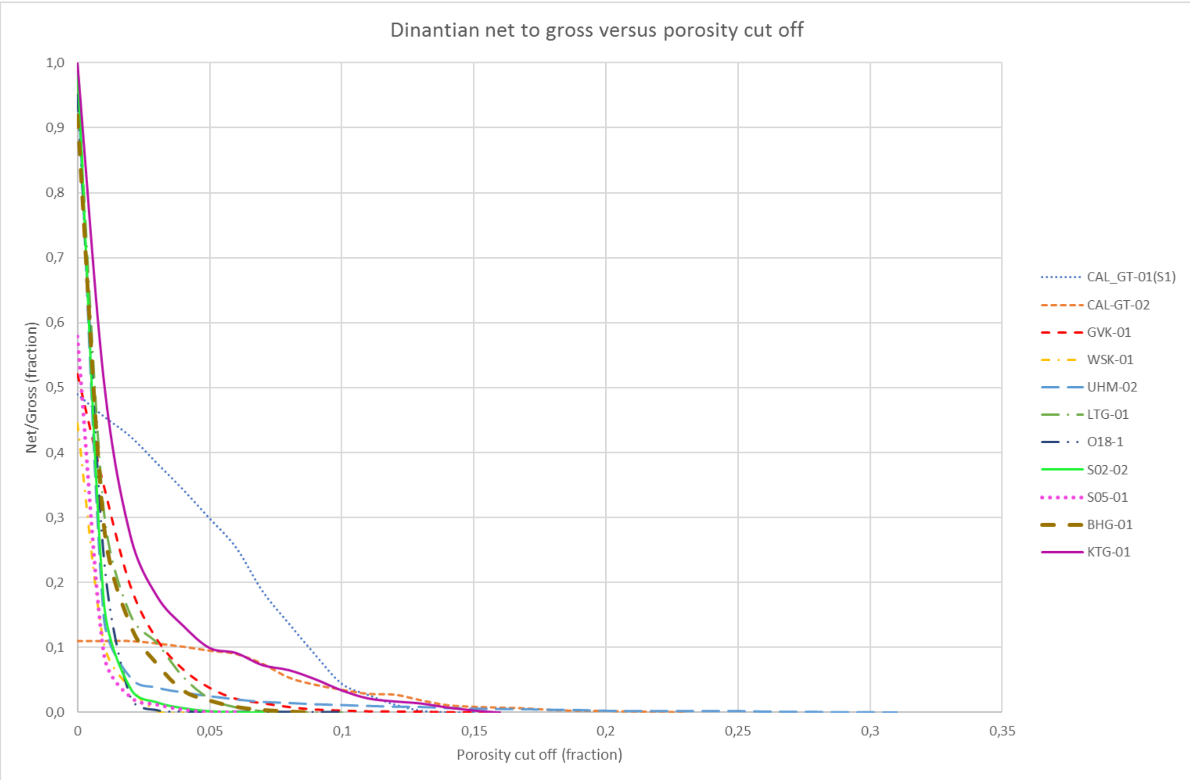

Figure 2. Net to gross for the Dinantian wells versus porosity cut off, vclay cut-off of 0.1

In figure 2 is the very fast drop off in net/gross demonstrated for all wells except the Californie wells CAL-GT-01(S1) and CAL-GT-02. These wells have a low net/gross at 0 porosity cut off due to the clay cut off of 0.1. The drop off in net/gross for them is however slow in comparison to all the other wells. The other well that deviates from the majority is KTG-01. This is due to KTG-01 only having the mostly Dolomitic base of the Dinantian with better porosity. The other wells have a more complete Dinantian section with more tight Limestone.

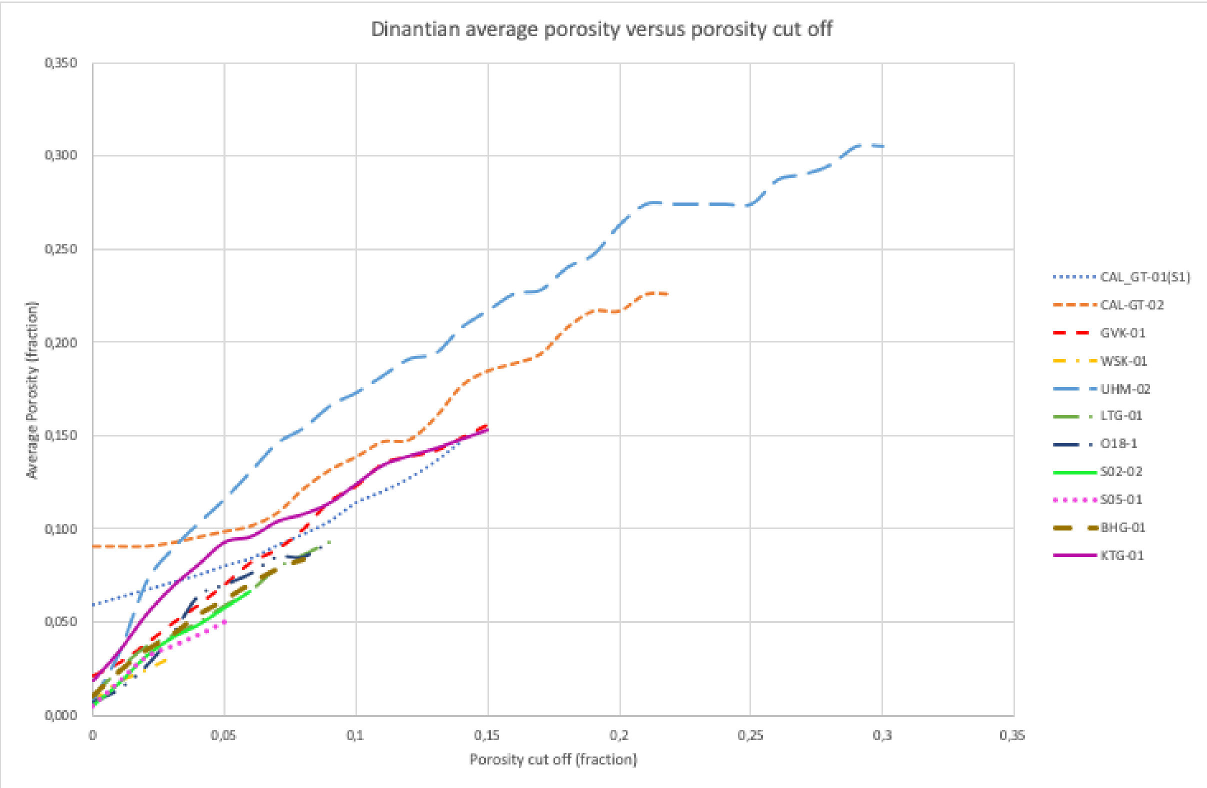

Figure 3. Average porosity for the Dinantian wells versus porosity cut off, vcl cut-off 0.1

In figure 3, the two Californie wells, CAL-GT-01(S1) and CAL-GT-02 are anomalous with much higher average porosity for the low porosity cut offs. UHM-02 and KTG-01 also deviates from the majority of wells. For UHM-02 this is caused by the very high porosity in two intervals towards the base of the Dinantian. In KTG-01 the deviation is due to the well only having the better Dolomite base of the Dinantian present.

The following graph, figure 4 , shows the normalized product of porosity and net thickness (pore volume) versus porosity cut-off, for a Clay Indicator cut-off equal to 0.1. The normalization is achieved by dividing the product of porosity and net thickness at the different porosity cut-offs by the same product at no porosity cut-off. The reason for using this display is that the gross interval of Dinantian varies by almost a factor of 10 and therefore a direct comparison of porosity*net thickness (pore volume) does not clearly illustrate the difference between wells in how the total pore volume declines with increasing porosity cut-off.

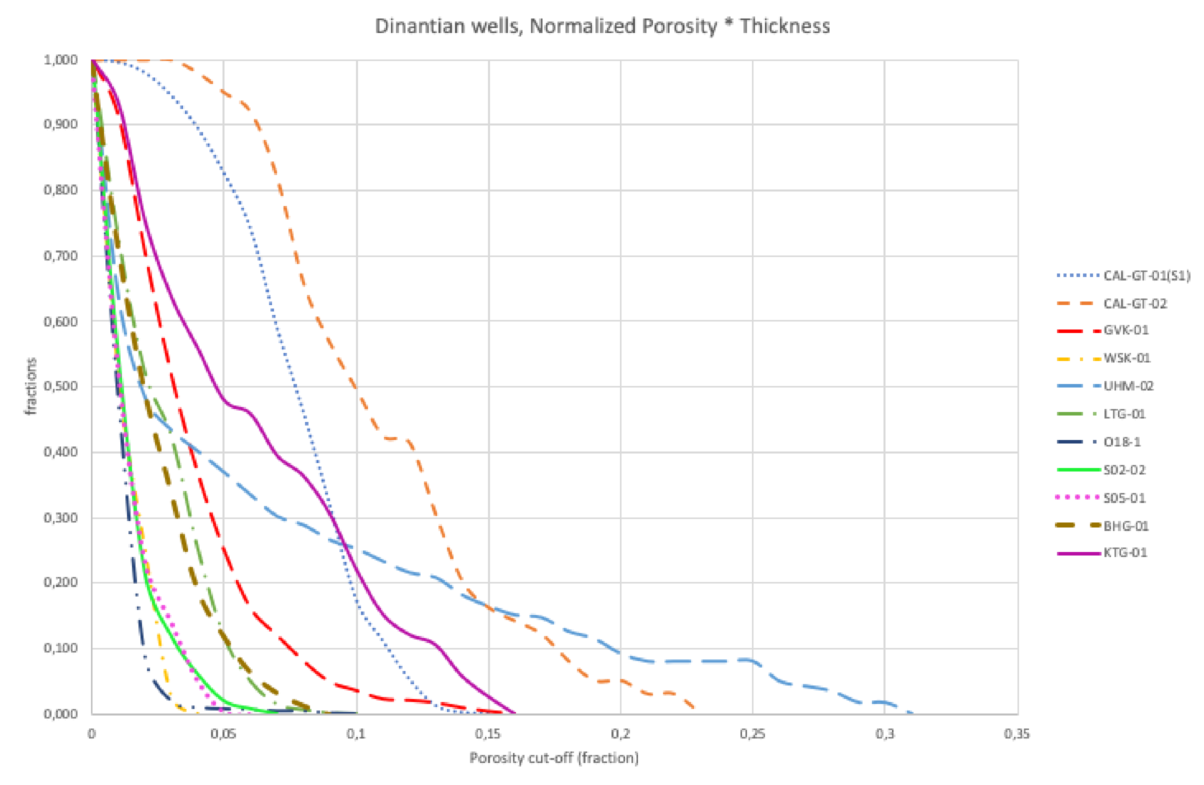

Figure 4. Normalized porosity*net versus porosity cut-off.

In figure 4, the majority of the wells have a very fast drop off in pore volume (porosity*net thickness) with increasing porosity cut-off and have little pore volume above 5 % cut-off and no pore volume above 10 % cut-off. Five wells have a proportion of the pore volume above the 10 % cut-off, of which GVK-01 has less than 4 % of the pore volume above this cut-off. The other wells are the two Californie wells, CAL-GT-01(S1) and CAL-GT-02, KTG-01 and UHM-02. (Note that BHG-01 has one very thin interval with calculated porosity above 10 %. However, this corresponds to a very sharp and probably deep washout with the result that the porosity calculation in this layer is so uncertain that for the comparison between wells, the layer is excluded).

The two Californie wells, CAL-GT-01(S1) and CAL-GT-02, are anomalous by having no or very little porosity below 2-3 % and therefore the porosity*net thickness remains relatively constant for the low porosity cut-offs. These wells have a higher normalized porosity*net thickness than any of the other wells up to 10 % porosity cut-off. It should be pointed out that the evaluation of the two wells in Californie, CAL-GT-01(S1) and CAL-GT-02 are much more uncertain than the rest of the wells and only the upper part of the -01 well have a good porosity determination thanks to both sonic and NMR porosity. The lithology cannot be determined from logs in any of these wells due to the lack of density and neutron logs.

Two other wells deviate from the majority of wells and have higher porosity. These wells are UHM-02 and KTG-01. For UHM-02, the difference is dictated by the high porosity layers (up to 32 %) towards the base of the Dinantian. Such high porosity layers do not exist in any of the other wells. The trend in normalized porosity*net thickness for UHM-02 is similar to the majority of wells up to a porosity cut-off of 2 %. However, above this cut-off the large difference is apparent. This is explained by UHM-02 having approximately 55 % of the product of porosity and net thickness in the low porosity interval, where the low porosity is compensated by great thickness. The higher porosity (above 2 %) constitutes approximately

45 % of the layers total pore volume (high porosity and some very high porosity but relatively thin).

The well KTG-01 has a relatively even drop in porosity*net thickness from no cut-off to 16 % cut-off. This well is probably the well with the best overall reservoir characteristics and it is the only well that had flow to surface without artificial lift.

Of the other wells there are some differences displayed in this graph and there appear to be three groups of two wells each that can be distinguished. BHG-01 and LTG-01 appear to be better than the other 4 wells and are following each other closely. The middle group consist of S05-01 and S02-02 where these two wells show a deviation from the two poorest wells, O18-01 and WSK-01 above approximately 2 % porosity cut-off. For a better comparison of these wells see fig 7 and 8.

The following two figures display the wells in the South West of the Netherlands. Figure 5 shows the normalized pore volume versus porosity cut-off, and figure 6, the total pore volume versus porosity cut-off.

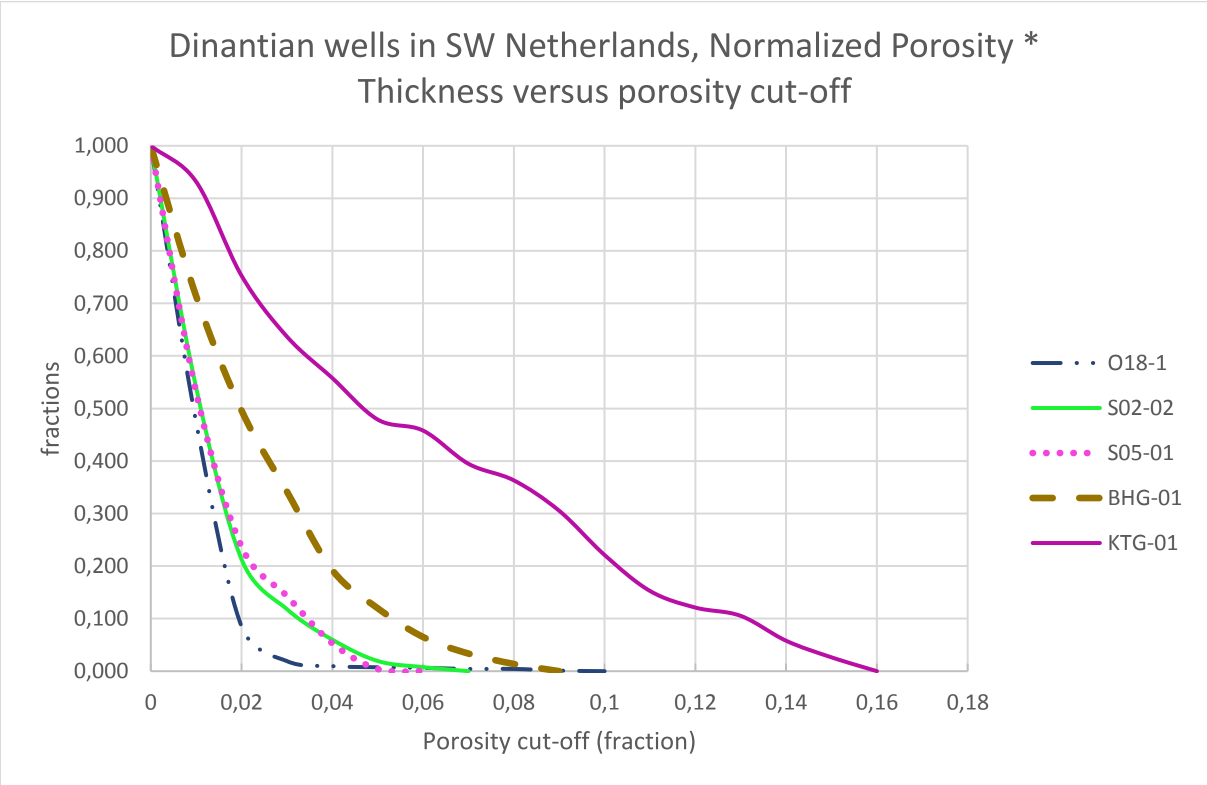

Figure 5. Normalized porosity*net for wells in the South-West of the Netherlands versus porosity cut-off, vcl cut-off 0.1.

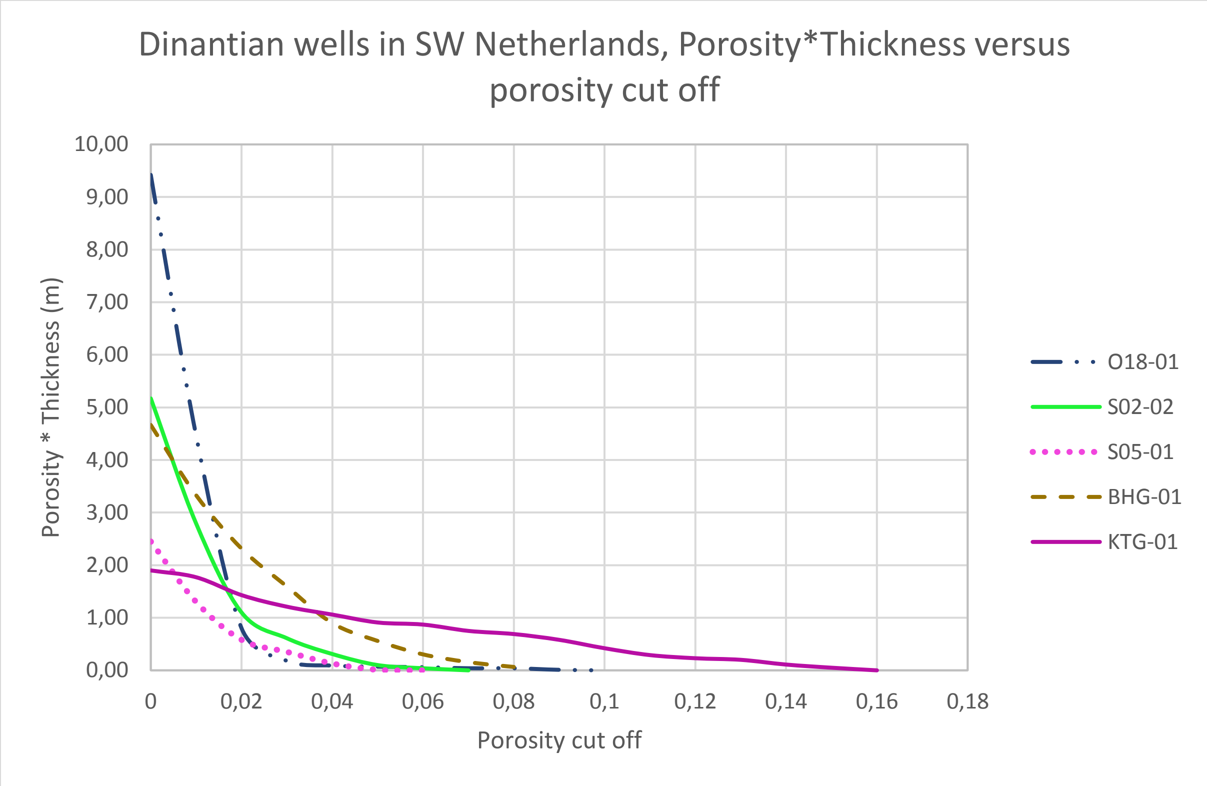

Figure 6. Pore volume (porosity*net) for wells in the South-West of the Netherlands versus porosity cut-off, vcl cut-off 0.1.

In the normalized plot, figure 5, the wells can be ranked on average properties where the tightest well is O18-01, followed by S02-02, S05-01, BHG-01 and KTG-01. Due to the large variation in gross thickness, the pore volume in the different wells differ by large numbers, figure 6. In O18-01, the gross thickness is 1329 m and in KTG-01 98 m, which is only 7 % of the thickness in O18-01 while the pore volume in KTG-01, without porosity cut-off, is 20 % of the pore volume in O18-01. This is due to the much higher porosity in KTG-01. For higher porosity cut-offs, KTG-01 surpasses O18-01 in total pore volume already at a porosity cut-off of 2 % where KTG-01 has a pore volume of 1.43 m and O18-01 0.8 m and the difference in pore volume increases rapidly for higher porosity cut-offs.

The two figures, 5 and 6, demonstrate that the two best wells are KTG-01 and BHG-01. The two wells S02-02 and S05-01 are relatively similar and the poorest well is O18-01. When comparing the wells, the well tests should be considered, and for the five wells in the South-West of the country, only four have been tested. Three of the wells, KTG-01, BHG-01 and S05-01 did all flow after acid stimulation and artificial lift. Well S02-02 was not tested but based on the similarity with S05-01, it is likely that this well also would flow after acid stimulation and with artificial lift. O18-01 was tested but not stimulated and it is likely that it would also flow with stimulation of the more porous layers combined with artificial lift, although due to the poorer signature this is not certain.

For the comparison of the Dinantian wells with no porosity exceeding 10 %, expanded porosity cut-off scales are required and these are displayed in the two following graphs.

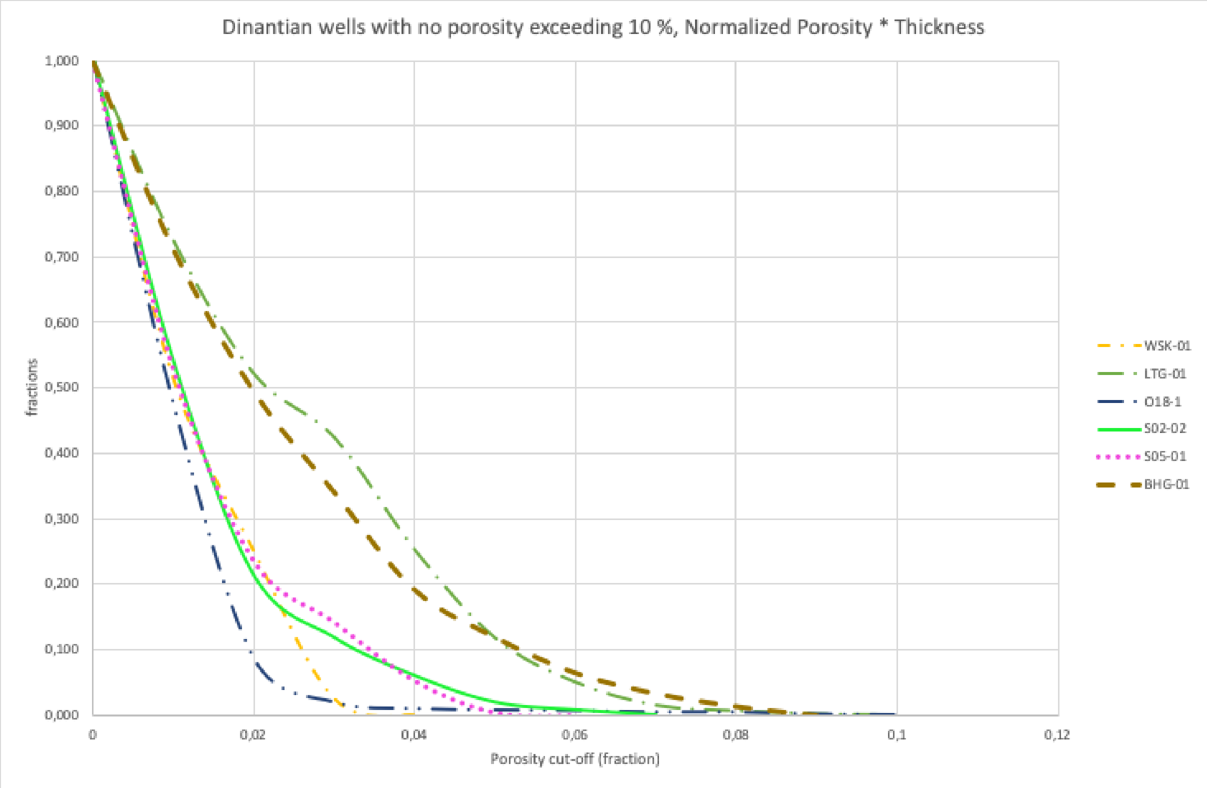

Figure 7. Normalized porosity*net for wells with no porosity exceeding 10 % in the Dinantian versus porosity cut-off, vcl cut-off 0.1.

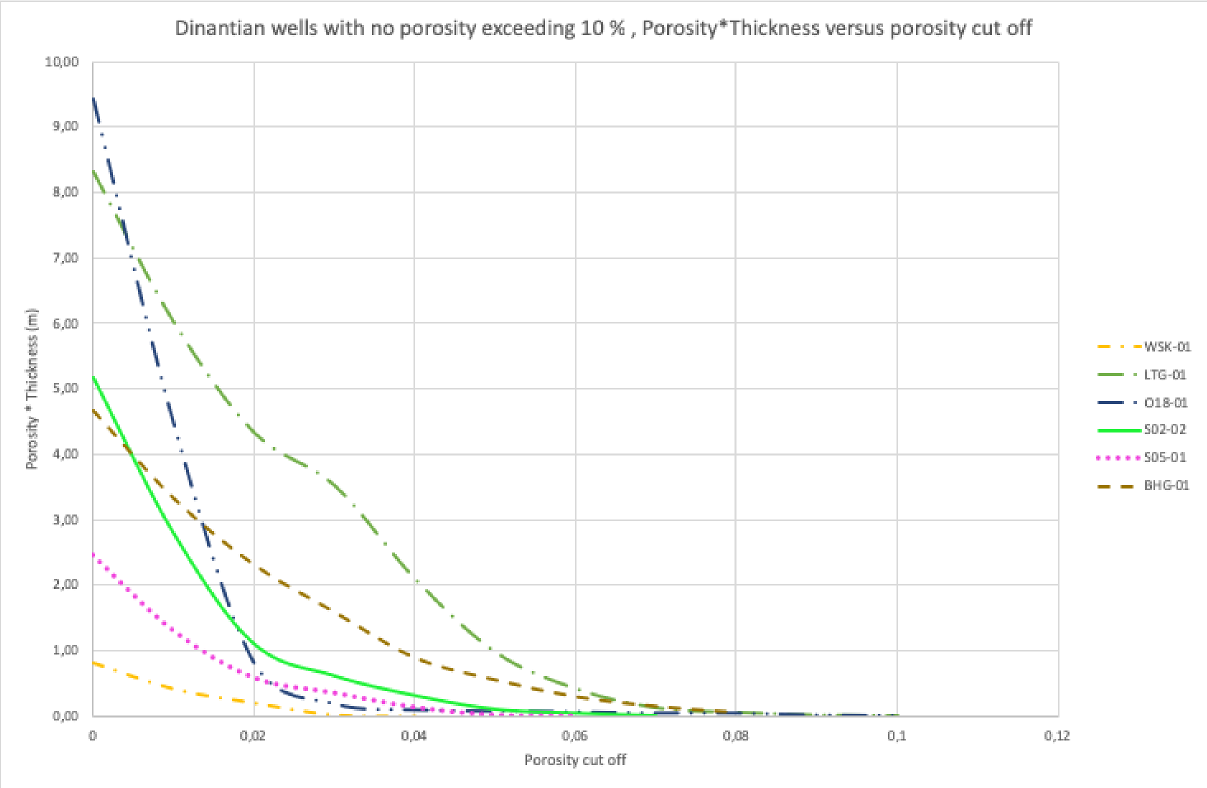

Figure 8. Pore volume (porosity*net) for wells with no porosity exceeding 10 % in the Dinantian versus porosity cut-off, vcl cut-off 0.1.

Based on the graphs above, figure 7 and 8, the two wells BHG-01 and LTG-01 appear to have the best properties and it can be argued that LTG-01 is the best of the two. However, the tests in the two wells point to that BHG-01 is the better well when it comes to productivity. LTG-01 did not flow to surface but had probably some inflow based on the down hole pressure. The wireline pressure tests in LTG-01 were indicating that the well had poor vertical communication and the only zone providing a reasonable pressure was the interval tested. No pressure tests were performed in BHG-01.

The two wells S05-01 and S02-02 are overall similar. In S05-01 three tests were performed. All were acid stimulated and flowed to surface with reasonable rates applying Nitrogen lift. S02-02 was not tested but based on the similarity to S05-01, it is likely that also S02-02 would have flowed with acid stimulation and Nitrogen lift.

The two wells O18-01 and WSK-01 appear to be similar based on figure 7. However, figure 8 demonstrates that there is a large difference between these two wells with WSK-01 having much less overall porosity and this also applies to the more important porosity exceeding 2 %. Both these wells were tested with no stimulation and both tests were negative with no flow registered. O18-01 did however have some inflow based on the pressure recordings in the well.

The conclusion of the result of the petrophysical evaluation is that the low porosity below 2 % dominates. However, most wells do have some higher porosity and the majority of the wells tested did have some inflow and the wells that were acid stimulated could flow to surface using artificial lift.

Permeability evaluation

There exists a large amount of core from the Dinantian and porosity and grain density has been measured on a large number of core plugs. However, only a small proportion of these plugs have permeability measurements performed. One likely reason that permeability measurements have not been performed on the plugs is that it has been judged that the plugs were likely to have very low permeability due to their low porosity. Other reasons could have been quality of plugs or that the plugs had permeability measurements attempted but these were never reported. It is therefore not possible to determine any relationships between core porosity and permeability.

Even if there was a large amount of permeability measurements on the cores, it is not probable that a permeability-porosity relationship could be established for the matrix of the Dinantian formation. The reason is that a good permeability-porosity relationship for higher porosity in the heterogenous parts of the Dinantian is highly unlikely to exist. It may be possible to find permeability-porosity relationship for the more homogenous low porosity sections (<2 %), dominating the Dinantian. However, the permeability in these sections is very low, probably in the micro-Darcy range and potentially less. In the karsted, maybe fractured sections, the permeability could vary by several orders of magnitude for a given porosity. The reason is, among others that the infill in these sections have very varied composition. Consequently, interval characterized by fractures and karst, can have a very low and very high permeability, independent of the measured porosity.

To assess the permeability, the data from well tests, wireline formation tests and to some degree losses have been gathered and incorporated in the evaluations. This data is in most cases not conclusive. However, it does give an indication if it is probable that the formation is permeable or not.

The best data for this purpose is the well tests as they test a larger interval, which is essential in a heterogeneous rock. If the well flows at reasonable rates, even without a closer evaluation of the pressures and flow rates, it can generally be concluded that the well is productive. On the other hand, if the well shows no inflow or very poor inflow, this is most likely due to a poor formation that is unlikely to produce. A caveat to this conclusion is that the formation may be damaged by the drilling fluids and that any permeable zones are damaged so severely that this masks the permeability. This is particularly the case when the test is terminated early.

In this report, only the written conclusions of the test and a quick check on the pressure record for the tests, where this exist, are included and a likely conclusion is drawn. However, due to the potential of formation damage it is recommended that a closer look at the pressure data is made in the wells where data is available.

In the following table the tests of the different wells are listed with conclusions:

Well	Interval (m)	Type test	Acid stim.	Flow	Lift	Conclusion
CAL-GT-01	Dinantian	Pump test	No	Yes	Pump	Decreasing PI with increased pump rate
CAL-GT-02	Dinantian (Devonian)	Injection test	No	Yes	Injection	Decreasing PI with increased injection rate
KTG-01	Dinantian	Open hole DST	Yes	Yes	Nitrogen/ no lift	After initial N_2 lift the well flowed to surface with no lift. 50 ppm H_2S.
BHG-01 (test 1)	2407-18	DST after perfor.	Yes	Yes	Nitrogen	Flowed water to surface with N_2 lift.
BHG-01 (test 2)	2165-85	DST after perfor.	Yes	Yes	Nitrogen	Flowed water to surface with N_2 lift. 60-80 ppm H_2S.
S05-01 (test 1)	1911-43	DST after perf.	Yes	Yes	Nitrogen	Produced water with N_2 lift. No H_2S recorded.
S05-01 (test 2)	1430-91	DST after perf.	Yes (frac.)	Yes	Nitrogen	Produced water with N_2 lift. No H_2S recorded.
S05-01 (test 3)	1189-1236	DST after perf.	Yes	Yes	Nitrogen	Produced water with N_2 lift. No H_2S recorded.
O18-01	Dinantian	Open hole DST	No	No	Nitrogen	No flow to surface recorded. Some inflow indicated by down hole pressure gauges
WSK-01	4299-4322	DST after perf.	No	No	?	No flow recorded.
LTG-01	4580-4620	Test after perf.	?	No	Nitrogen	Probably some inflow, downhole pressure indicate this.

All tests were performed in the Dinantian. In some wells with open hole it is possible that other sections than the Dinantian contributed to flow. This is particularly likely in CAL-GT-02.

Two conclusions can be drawn from the well tests. It appears that with acid stimulation, reasonable flow rates can be achieved, at least for a short-term test, in wells with quite poor porosity development. Particularly, the three tests in S05-01 do support this conclusion. Another conclusion is that there is a risk for H_2S in the Dinantian wells.

The wireline pressure measurements and sampling attempts have been included in the reports for the individual wells, both to determine the pressure in the Dinantian, but also to provide an assessment of the permeability. The wireline formation testing tools do not actually provide a permeability measurement directly but a mobility, mD/cP (permeability/viscosity) based on a simple draw down equation, specific for the packer and tool used. As the fluid in the Dinantian wells is water, except maybe in UHM-02 (oil-based mud filtrate), the viscosity is close to 1 and therefore the mobility value provided is close to the actual permeability.

All the pressure measurements have been made with a probe and this has a very small testing area, only a few square cm. This, in combination with the very heterogeneous formation, result in many tight or completely no flow measurements in zones that are evaluated to have good porosity and is likely to have at least some permeability.

Another, often more important, issue is that many of the better intervals have poor hole conditions or the formation is not suitable to get a good seal to the hydrostatic pressure and therefore the pressure test attempt result in a seal failure. Open fractures will almost always result in a seal failure because the wellbore pressure will bypass the packer seal against the borehole wall via the fracture.

The result of most of the pressure test attempts are therefore seal failures or tight. The number of successful tests is low, in some wells not a single point resulted in a reservoir pressure being recorded and therefore not in any mobility/permeability measurement. The tight tests do indicate that the formation at the point tested has no or at least very low permeability <<1 mD. These do therefore indicate that the formation has low permeability but due to the very small area tested it is not a very reliable indication at a particular depth. However, with many tight tests in a well it still provides an indication that the well is likely to have low permeability in most intervals.

In the table below are a summary of the wireline formation tests performed in the Dinantian:

Well	No. test providing valid pressure	No. dry/tight tests	No. seal failures	Comment
KTG-01	None	13	3	
S02-02	1	3	13	1 valid pressure in Dinantian. Gradient approx. 0.1033 bar/m (1053 kg/m^3), possibly supercharged. Pressure just above Dinantian have same gradient. This does possible indicate a slight overpressure.
S05-01	1	28	6	1 valid pressure with sample taken. Gradient approx. 0.1010 bar/m corresponding to a density of 1030 kg/m^3 (sea water)
O18-01	None	9	4	
LTG-01	7(10)	39	77	7 tests at 4604-4605 m gives a formation pressure of approx. 602 bar (overpressure 69-140 bar). It is possible that this pressure is supercharged. 3 more pressures appear acceptable but are clearly supercharged.
UHM-02	1	10	11	1 valid pressure after fluid sampling. Pressure was 706.9 bar at 5154.5 m. Overpressure is 103-178 bar depending on gradient applied.

From the above it can be concluded that the formation tests provide the best information on the permeability of the formation. This is also likely to be the case for any future well targeting the Dinantian.

The wireline formation tester (MDT) formation water sample taken at 5154.5 m in the Dinantian in the well UHM-02 has been extensively analyzed. The table below provides the result of the formation water analysis and the associated gas.

Analysis of the water.

Density	1.197	kg/l	at 22.6 °C
pH	6.4		
Resistivity	4.86	Ohm*cm	at 21.8 °C

Cl	176000	mg/l	W721
SO_4	<25	mg/l	W721
HCO_3	462	mg/l	W371
CO_3	0	mg/l	W371
OH	0	mg/l	W371
PO_4	<7.5	mg/l	W721
BO_3	290	mg/l	HASKONING
Br	900	mg/l	W721
Na	69000	mg/l	W331
K	6500	mg/l	W331
Ca	31000	mg/l	W231
Mg	600	mg/l	W231
Sr	2100	mg/l	W231
Ba	2300	mg/l	W231
Fet	25	mg/l	V081
Mn	164	mg/l	W168
Pb	222	mg/l	W174
Dissolved Si	12	mg/l	HASKONING
As	100	µg/l	HASKONING
Cd	1400	µg/l	HASKONING
Cu	1300	µg/l	HASKONING
Ni	370	µg/l	HASKONING
Zn	832	mg/l	W180
Hg	<5	µg/l	W361
Ag	1300	µg/l	HASKONING
Co	<10	µg/l	HASKONING
Cr	5	µg/l	HASKONING

Formic acid	13	mg/l *	W651
Acetic acid	64	mg/l *	
Propionic acid	13	mg/l *	
Butyric acid	<5	mg/l	
Valeric acid	<5	mg/l	

Analysis of the gas phase

Helium	1.5	mol%
Hydrogen	2.5	mol%
Nitrogen	84.5	mol% (*)
Methane	4.3	mol%
Ethane	0.02	mol%
Carbon dioxide	6.9	mol%
Carbon monoxide	0.08	mol%
C6 components	0.01	mol%
C7 components	0.03	mol%
C8 components	0.07	mol%
C9 components	0.05	mol%
C10 components	0.03	mol%
C11 components	0.01	mol%
C12 components	< 0.01	mol% (**)
C13 components	< 0.01	mol% (**)
C14 components	< 0.01	mol% (**)

The result of the water analysis is a salt saturated brine with a very high metal content. Of particular interest are Zink (832 g/m^3), Lead (222 g/m^3), Silver (1.3 g/m^3), Cadmium (1.4 g/m^3). Concentrations of other metals are also anomalous. Calcium, Strontium and Barium are other elements in high concentrations and tend to cause issues with scaling. The concentrations of some of the valuable metals are probably sufficiently high to be of interest for extraction.

The solution gas is anomalous with very high Nitrogen concentration, high Helium and Hydrogen concentrations. The C6 to C14 components are almost certainly caused by the oil-based mud and did not exist in the solution gas.

It is recommended that the water composition is assessed by a geochemical specialist and a production chemist. The aim should be 1) to understand the source of the water and 2) the possible complications of producing this formation water in geothermal projects.

Formation Temperature evaluation

Where possible, an attempt to determine the formation temperature has been made utilizing the log header information. This is to assist in the actual petrophysical evaluation when utilizing the resistivity log to determine the porosity. The formation temperature is also essential for the geothermal project as it is the main parameter that determines the geothermal power of the doublet. Therefore, an accurate estimation is essential.

The best formation temperature measurements are normally made during production tests. However, there are no temperature measurements made/found in the records of the formation tests and the only reliable temperature measurements are the maximum temperatures measured during logging. These maximum thermometers are Mercury thermometers that record the maximum temperature encountered during the logging run. Due to the cooling effect of the mud, circulated in the well during drilling, the maximum temperature is not a formation temperature but a lower temperature (exceptions to this are at shallow depths were the mud and drilling action may heat up the formation). If there are two runs or more with maximum temperature measurements made, the temperature will normally increase for each logging run and this can be used in a Horner extrapolation to determine the formation temperature. The exact depth of the temperature measurements is not known and in reality, it is in most cases a bit above the bottom of the log due to the longer circulation time close to the bottom of the borehole, prior to pulling out of the hole. The distance above the bottom is typically 50-150 m but can be outside this range. In this report the depth of the temperature measurement is assumed to be some 10-20 m above the deepest point of the top of the log string where the maximum thermometers are located.

For most wells, a formation temperature estimate using the Horner extrapolation method can only be made at the bottom of the well due to insufficient data for log suites at shallower depths. In a few wells the formation temperature can also be determined at shallower depths. This is the case in LTG-01, O18-01 and in S05-01.

In figure 9 below are all the wells with Horner extrapolated formation temperatures shown except GVK-01. The reason GVK-01 is not shown is that it is anomalous compared to the other wells with a gradient of 26 °C/km compared to the other well's gradient of 32-38 °C/km.

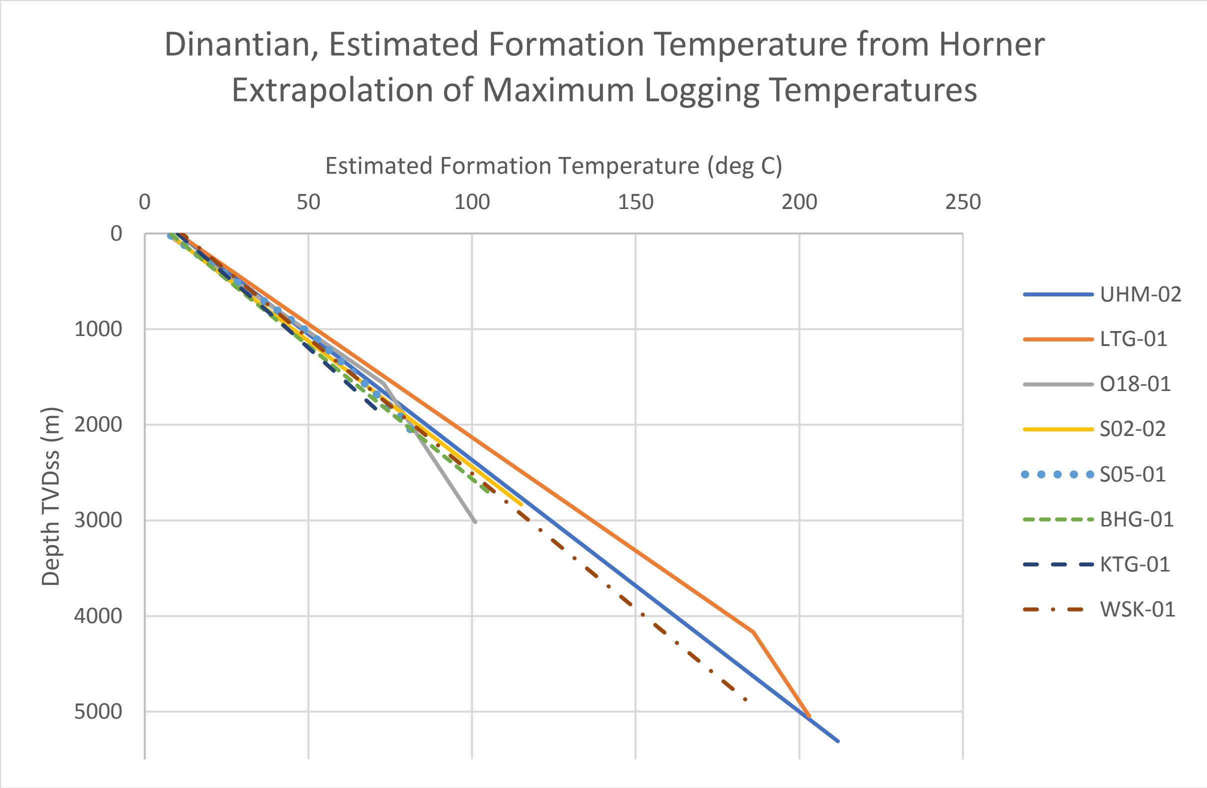

Figure 9: Estimated formation temperatures for the Dinantian wells applying the Horner extrapolation technique.

In the few wells where a formation temperature could be estimated at top Dinantian, the temperature gradient was higher, above 41 deg °C/km and then significantly lower through the Dinantian, 19-28 deg °C/km. This applies to both LTG-01 and O18-01 (42 °C/km down to top Dinantian and then 19 °C/km through the Dinantian) and to S05-01 (41.6 °C/km down to top Dinantian and then 28 °C/km through the Dinantian).

There is a high probability that the formation temperature gradient would have a similar trend in a number of the other wells with a much higher temperature gradient down to top Dinantian followed by a significantly lower temperature gradient through the Dinantian. The most likely explanation to this is a higher thermal conductivity of the Dinantian compared to the overburden. The overall very tight nature of the Dinantian is highly unlikely to permit convection, something that in a highly permeably rock can explain low temperature gradients.

The well GVK-01 is considerably cooler compared to the other wells with a gradient of 26 °C/km. The little data that is available for the Californie well from logs indicate a gradient around 30 °C/km, lower compared to the other Dinantian wells but not anomalous.

References and input data

NLOG: Most log data and well reports used for the evaluation and preparation of the petrophysical report were downloaded from the NLOG website (www.nlog.nl).

Individual Petrophysical reports for the following wells:

1. Brouwershavensegat-01 (BHG-01)
2. Californie-GT-01 and Sidetrack (CAL-GT-01(S1))
3. Californie-GT-02 (CAL-GT-02)
4. Geverik-01 (GVK-01)
5. Kortgene-01 (KTG-01)
6. Luttelgeest-01 (LTG-01)
7. O18-01
8. SO2-02
9. SO5-01
10. Uithuizermeeden-02 (UHM-02)
11. Winterswijk-01 (WSK-01)

Other references used are:

- Composite logs for the individual wells
- Biweekly drilling reports
- Testing reports
- End of well reports

For the MDT sample in well Uithuizermeeden-02:

Chemistry Laboratory Report – GasWater Analysis (04 June 2002) numbers 2 and 4 (both Word documents). Request number LR2002050035.