Adding value to routinely obtained geothermal well data

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Executive summary

The number of geothermal wells is growing steadily in the Netherlands. However, the amount of data generated in the drilling phase of the wells is generally low. Therefore, the limited amount of data that is obtained, should be used to its full extent. The need was identified to check if more information could be distilled from the data that is routinely obtained during the drilling and testing phases of a well. The scope of this study was to see which techniques or methods can be applied on the data that is regularly gathered during drilling and testing, in order to get more information on the characteristics and parameters of the overburden and/or reservoir rock. This information can be of use for future exploration purposes or existing wells and doublets.

The scope of the study was set during the kick-off meeting with the steering committee. The study was conducted by first identifying routinely obtained data during the drilling phase and subsequently by using literature and specialists to identify methods and techniques that are available to obtain extra information from this data.

The data that is routinely obtained during drilling are cuttings, drilling parameters and logs. The most promising data are the cuttings that come to surface while drilling. Ten different analyses that can be performed on cuttings are discussed in detail. Each of those analysis the technical details, benefits, costs and limitations are summarised on one page. The information gathered by using these analyses cover reservoir quality, dating, stratigraphy and diagenesis. The drilling parameters are useful to review when new wells are being drilled, but clear methods to derive important additional information for exploration or reservoir quality have not been identified. Within the logs, the cement bond log (CBL) is an option for correlation and picking the tops of stratigraphic horizons when the gamma ray logs is not reliable or absent and a good bond is present. However, most geothermal wells have at least a logging while drilling (LWD) GR. Additional purposes for the well tests, if properly designed, are fault identification and drainage area.

The main conclusion of this report is that cuttings could be a valuable source of information for exploration or existing doublets. This report provides a concise summary of the methods available for cutting analysis that can be consulted by geothermal operators for problem-solving or exploration.

Nederlandse Samenvatting

Er is sprake van een gestage stijging van het aantal aardwarmteputten in Nederland. De uit de boringen verkregen geologische data wordt, in vergelijking met gasputten, relatief weinig benut. Bovendien is de datacollectie niet zeer uitgebreid. Het is daarom van groot belang om uit de aanwezige data zoveel mogelijk informatie/kennis over het reservoir te halen.

Het rapport heeft ten doel om aan te geven hoe er meer informatie te halen is uit de data die op dit moment routinematig wordt geproduceerd gedurende het boren en testen van een put.
Welke technieken en methodes zijn toe te passen op deze data om meer informatie te verkrijgen over het reservoirgesteente en/of de deklagen boven het reservoir?

De uitvoering is besproken in de kick-off vergadering met PanTerra Geoconsultants en de Begeleidingsgroep namens Kas als Energiebron. Dit rapport is primair bedoeld voor de aardwarmte-operators.
De eerste fase van deze studie bestond uit het identificeren van de beschikbare data verkregen gedurende het boren en testen van bestaande aardwarmteputten in Nederland , gebruik makend van de zogenaamde End-Of-Well rapporten.
In de tweede fase zijn, met behulp van literatuur en vakspecialisten, methodes en technieken beschreven die toepasbaar zijn op deze bestaande data om de gewenste extra informatie te verkrijgen.

De conclusies zijn als volgt aan te geven. De verkregen data gedurende het boren van een put komen van 1) cuttings, 2) boorparameters en 3) logs:

1. Aangezien cuttings standaard naar het oppervlak komen, bieden deze de meest veelbelovende mogelijkheden voor extra informatie. Ook bieden cuttings de enige directe informatie over de ondergrond. Tien verschillende cutting-analyses zijn in detail besproken. De technische details, voordelen, kosten en beperking voor elke analytische methode zijn beschreven. De informatie uit deze analyses betreffen de reservoirkwaliteit, de ouderdom, stratigrafie (afzettingsmilieu) en diagenese (verandering van de gesteente na afzetting).
2. De boorparameters zijn belangrijk gedurende het boren en afwerking van een nieuwe put, maar extra methodes om hieruit extra informatie te winnen voor exploratie zijn niet gevonden.
3. De logs bevatten mogelijk extra informatie in het geval dat de Gamma Ray (GR) log afwezig is of niet betrouwbaar is. De meeste geothermie putten hebben echter standaard minimaal een "Logging While Drilling (LWD)" GR log. Extra toepassingen voor de puttesten zijn (in combinatie met cuttings en logs) het identificeren van breuken en afwateringsgebieden in een put. Dit stelt evenwel extra eisen aan de puttesten.

De hoofdconclusie is dat met name de analyse van de cuttings waardevolle extra informatie kan leveren voor zowel de exploratie van nieuwe putten alsmede voor de bedrijfsvoering.

In het rapport is tevens een samenvatting opgenomen met de methodes die beschikbaar zijn om cuttings te analyseren, die de operators kunnen raadplegen om de kennis van de ondergrond rondom hun doublet te vergroten.

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1 Introduction

The number of geothermal wells in The Netherlands is growing. New geothermal wells provide valuable information for further growth of the sector. However, the amount of data gathered from the wells in the drilling phase is low as only limited open hole wireline logs and coring is done.

The data that is gathered in wells contains valuable information for the project at hand, but potentially also for other (future) projects.

Here we investigate which data is routinely collected during the drilling phase of a geothermal well and how to increase the value of this data by additional analyses which are not routinely performed. We focus on the rock information, whether it is reservoir rock or overlying rocks. The study's objective is to inform and advise operators about the available analytical techniques, their costs, benefits and limitations, so that an operator (or group of operators in the same area) can make informed decisions about the value of additional analyses for the purpose of further exploration and production of the reservoir, investigation of operational problems, etc.. Figure 1 shows a graphic representation of the scope of this project as agreed with the project's Steering Committee.

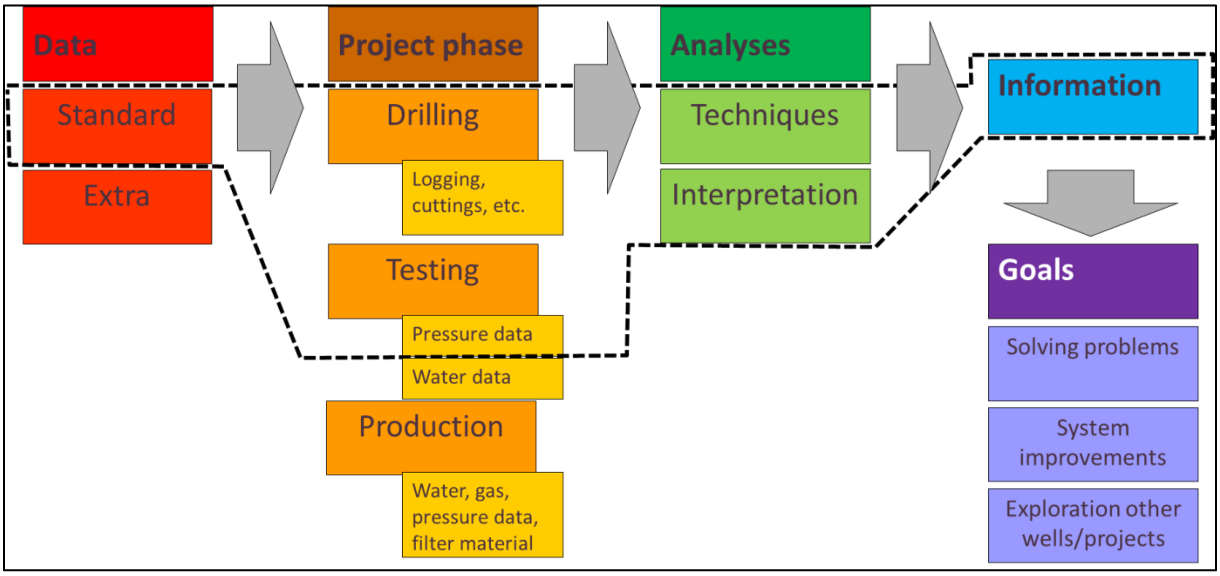


Figure 1: The project scope is highlighted with the dashed black line. Included is the regularly obtained data during the drilling and well testing phase.

This project was roughly subdivided in three phases, the review phase, the identification phase and the compilation phase:

1. The first phase was the review of geothermal End of Well (EOW) reports present at TNO-AGE to identify what data is regularly obtained in geothermal wells.
2. The second phase was to identify potential opportunities to obtain valuable information from additional analyses techniques. This is done by interviewing internal specialists combined with a literature research on the available techniques.
3. The third phase of this project was to compile and integrate the results into a comprehensible manner, and to summarize which analyses can be used to address typical geothermal project issues. This includes a summary of the analyses that can best be combined to get an optimal result.

2 Phase 1: Data gathering

A total of 27 End of Well (EOW) reports of Dutch geothermal wells present at TNO in January 2017 were reviewed during a data room session in order to summarize the data gathered during drilling of a well. An overview of the (anonymized) data available in these wells is presented in Table 1.

EOW reports are compiled for all wells during and after drilling. All the data gathered during drilling is included in these reports. Typical content of an EOW report comprises general information on drilling (schematics, depths, deviations etc.), drilling operations (mud data, casing and cementing performance etc.), information on the companies involved, rig info, etc. We found that not all EOW reports were 100% complete because the cement bond log (CBL) is compulsory for every well section but was not present in all reports.

The available data for each analysed well is grouped in Table 1 by (potential) purpose. The following groups were used:

- Rock Type
- Rock Strength / Fractures
- Hydrocarbons
- Mud
- Well cementation
- Drilling

Parameters such as type/change of drill bits (affecting drill cuttings quality and some drilling properties) as well as drilling problems encountered during drilling (affecting the economics and drilling efficiency) are commonly noted in the reports but are not included in Table 1. Note that in this table, the wells are anonymized for confidentially reasons.

Well tests are not reported in the EOW reports but well test data is routinely obtained in geothermal wells after the reservoir is completed, therefore well tests are included in this study.

DATA TYPE → / WELL ↓	ROCK TYPE				ROCK STRENGTH / FRACTURES					HYDROCARBONS		MUD		WELL CEMENTATION		DRILLING			DATA TYPE ← / WELL ↓
	Cuttings: Lithology	Cuttings: Lithological Accessories	Cuttings: Calcimetry and Dolometry	Log: GR (Gamma Ray)	LOT (Leak-off Test)	FIT/FST (Formation Integrity/ Strength Test)	Log: Caliper	ROP (Rate of Penetration)	Mud Loss / Lost Circulation	Log: HC Gas	Water/Gas analysis	Mud Weight	Mud type	CBL (Cement Bond Log)	Cement pump rate vs Pressure (CJR - Cement Job Report)	String Weight (WOB & Hookload)	RPM	Torque	
1	X	X		X, Partly		X	X, Partly	X		X		X	X	X	X	X	X	X	**1**
2	X	X		X, Partly		X	X, Partly	X		X		X	X	X	X	X			**2**
3	X	X		X, Partly		X	X, Partly	X		X		X	X	X		X			**3**
4	X	X		X, Partly		X	X, Partly	X		X		X	X	X	X	X			**4**
5	X	X		X, Partly			X, Partly	X		X	X		X		X	X			**5**
6	X	X		X, Partly				X		X			X		X	X			**6**
7	X (Described, litholog not at TNO)												X		X				**7**
8	X	X	X, Partly	X				X		X			X						**8**
9	X	X		X				X		X			X						**9**
10	X	X		X				X		X		X	X			X			**10**
11	X	X		X				X		X, Partly			X			X			**11**
12	X		X	X				X		X, Partly			X						**12**
13	X		X	X				X		X, Partly			X						**13**
14	X (In technical log, litholog not at TNO)							X (In technical log, litholog not at TNO)					X			X	X	X	**14**
15	X	X		X				X		X, Partly			X			X			**15**
16	X			X, Partly				X, Partly		X		X	X			X, Partly, only WOB			**16**
17	X			X, Partly				X		X		X	X			X, only WOB			**17**
18	X	X - paleontology	X, Partly	X, Partly	X	X		X		X, Partly		X	X	X	X	X			**18**
19	X	X - paleontology	X, Partly	X, Partly	X	X		X, Partly		X, Partly		X	X	X	X	X, Partly			**19**
20	X	X						X, Partly		X, Partly		X	X	X		X, only Hookload			**20**
21	X	X						X	X	X		X	X	X		X			**21**
22	X	X						X, Partly		X, Partly		X	X	X, Not at TNO		X, Partly			**22**
23	X	X		X, Partly				X, Partly		X, Partly		X	X	X, Not at TNO		X, Partly			**23**
24	X	X		X			X, Partly	X		X, >60m		X	X			X			**24**
25	X	X		X, Partly			X, Partly	X		X		X	X	X		X			**25**
26	X	X		X			X, Partly	X	X	X		X	X	X		X			**26**
27	X	X		X			X, Partly	X		X, Partly		X	X	X		X			**27**
Total	27	21	5	22	2	6	9	26	2	25	1	17	27	13	8	22	2	2	**Total**

Table 1: Overview table showing the available data gathered from end-of-well (EOW) reports of 27 geothermal wells from 10 areas in The Netherlands.

3 Phase 2: Additional information from regularly obtained well data

The data listed in Table 1 and the well test were reviewed and the datatypes that are of potential interest for further discussion were selected. Literature was also reviewed to see if additional uses for the same data could be found.

The data from Table 1 can be grouped into the information that can be gathered from drill cuttings (covered in section 3.1), drilling parameters (covered in section 3.2) and logs (covered in section 3.3). The information derived from well tests is briefly covered in section 3.4.

Attached to this report are also two appendices. Appendix 1 describes the various analyses that can be performed on cuttings. Appendix 2 discusses potential questions encountered during drilling or production, and the suggested analytical solution to this question.

3.1 Cuttings

Cuttings are fragments of rock derived from the penetrated formation. These cuttings are removed from the borehole and come to surface together with drilling fluids during drilling and provide the only direct information on the lithology.

Drill cuttings are described onsite and are reported for all studied geothermal wells. The information available is limited to the lithology (rock type) and lithological accessories (presence of glauconite, fossils etc.). Additionally, detailed analyses on cuttings focus on the bulk rock properties, microscale properties, and/or if the cuttings quality allows, more directly the reservoir quality of the rock. Bulk rock properties are all the properties (e.g. chemical, structural) of the entire rock sample, not focussing on specific minerals or grains (see section 3.1.1). Microscale properties are those properties not visible by eye and studied therefore under the microscope (see section 3.1.2).

Table 2 describes analyses for cuttings that provide extra information on stratigraphy, reservoir quality and dating/correlation purposes, including their potential benefits. For each analysis, a separate datasheet is prepared (Appendix 1). Appendix 1A is an overview sheet of what cuttings are, the risks, and the analyses that can be performed. Appendix 1B-K provides more detail on the analyses summarised in Table 2. In datasheet B-K, five columns are shown, describing:

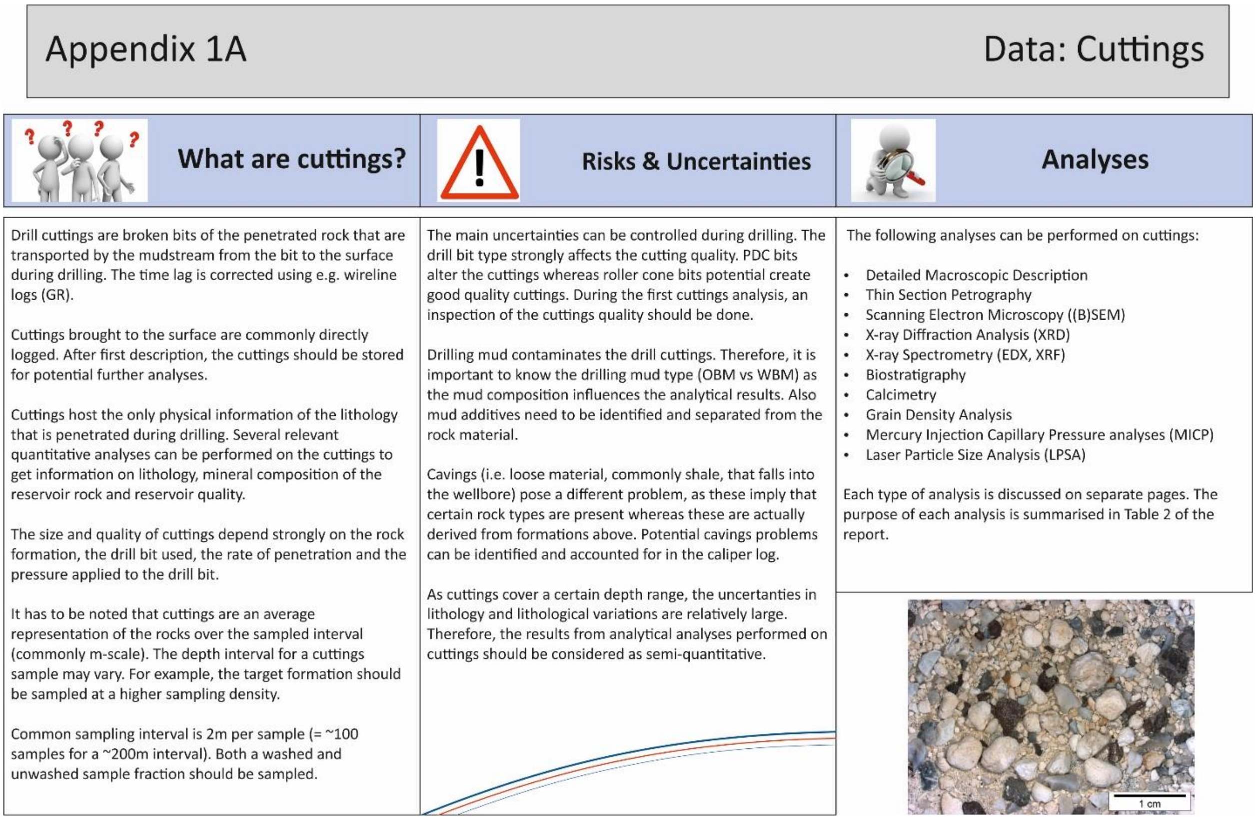
- A summary of the technical details of the analysis.
- Why this analysis could be performed, and what the benefits are.
- The limitations of the analysis and the analytical procedures.
- A cost estimate, mostly per sample.
- A list showing with which analysis this could be combined with.

Important for all these analyses is that the cuttings are properly cleaned. This cleaning should be done without damaging the cuttings themselves, including the minerals, grains, cement and pores that make up the cuttings. E.g. halite if present as a cement should not be dissolved and swelling clays should not be disturbed. It is also important to know the mud type used during drilling for drill cuttings cleaning purposes, as these might contaminate the cuttings and alter the results of certain analyses, such as XRD. The cleaning method applied to the cuttings is depending on whether the mud is oil-based (OBM) or water-based (WBM; fresh or saline water).

Datasheets overview as presented in Appendix 1

#	Analysis	Type of analysis	Information obtained	Why useful
A	Cuttings general: overview sheet			
B	Macroscopic Analysis	Macroscale analysis	Cuttings quality, lithology	Stratigraphy, reservoir quality
C	Thin Section Petrography	Microscale analysis	Cuttings qulaity, detailed lithology, porosity	Stratigraphy, reservoir quality
D	Scanning Electron Microscope (BSEM & SEM)	Microscale analysis	Detailed lithology, porosity, clay mineralogy	Detailed info on reservoir quality
E	Calcimetry	Bulk rock analysis	Carbonate cement quantification	Reservoir quality related to diagenesis
F	Mercury Injection Capillary Pressure (MICP)	Reservoir quality analysis	Pore throat size distribution	Direct measure of reservoir quality
G	Laser Particle Size Analysis (LPSA)	Bulk rock analysis	Grain size distribution, clay content	Indirect measure of reservoir quality
H	Grain Density Analysis	Bulk rock analysis	Identification of high density intervals	Indirect measure of reservoir quality
I	X-ray Diffraction (XRD)	Bulk rock analysis	Mineral composition, clay mineralogy	Indirect measure of reservoir quality
J	X-ray Spectometry (EDX, XRF)	Bulk rock analysis	Elemental composition to identify minerals	Indirect measure of reservoir quality
K	Biostratigraphy	Microscale analysis	Microfossil content and distribution	Dating, correlation

Table 2: Overview showing the analyses described in Appendix 1, the information obtained from these analyses and why it is potentially useful for well operators. The letters A-K refer to the information sheet of the analysis. The types of analyses are described in section 3.1.1 to 3.1.3.


Appendix 1A

Data: Cuttings

What are cuttings?

Drill cuttings are broken bits of the penetrated rock that are transported by the mudstream from the bit to the surface during drilling. The time lag is corrected using e.g. wireline logs (GR).

Cuttings brought to the surface are commonly directly logged. After first description, the cuttings should be stored for potential further analyses.

Cuttings host the only physical information of the lithology that is penetrated during drilling. Several relevant quantitative analyses can be performed on the cuttings to get information on lithology, mineral composition of the reservoir rock and reservoir quality.

The size and quality of cuttings depend strongly on the rock formation, the drill bit used, the rate of penetration and the pressure applied to the drill bit.

It has to be noted that cuttings are an average representation of the rocks over the sampled interval (commonly m-scale). The depth interval for a cuttings sample may vary. For example, the target formation should be sampled at a higher sampling density.

Common sampling interval is 2m per sample (= ~100 samples for a ~200m interval). Both a washed and unwashed sample fraction should be sampled.

Risks & Uncertainties

The main uncertainties can be controlled during drilling. The drill bit type strongly affects the cutting quality. PDC bits alter the cuttings whereas roller cone bits potential create good quality cuttings. During the first cuttings analysis, an inspection of the cuttings quality should be done.

Drilling mud contaminates the drill cuttings. Therefore, it is important to know the drilling mud type (OBM vs WBM) as the mud composition influences the analytical results. Also mud additives need to be identified and separated from the rock material.

Cavings (i.e. loose material, commonly shale, that falls into the wellbore) pose a different problem, as these imply that certain rock types are present whereas these are actually derived from formations above. Potential cavings problems can be identified and accounted for in the caliper log.

As cuttings cover a certain depth range, the uncertainties in lithology and lithological variations are relatively large. Therefore, the results from analytical analyses performed on cuttings should be considered as semi-quantitative.

Analyses

The following analyses can be performed on cuttings:

- Detailed Macroscopic Description
- Thin Section Petrography
- Scanning Electron Microscopy ((B)SEM)
- X-ray Diffraction Analysis (XRD)
- X-ray Spectrometry (EDX, XRF)
- Biostratigraphy
- Calcimetry
- Grain Density Analysis
- Mercury Injection Capillary Pressure analyses (MICP)
- Laser Particle Size Analysis (LPSA)

Each type of analysis is discussed on separate pages. The purpose of each analysis is summarised in Table 2 of the report.

1 cm

Figure 2: The main datasheet (Appendix 1A) with information on cuttings and what type of analyses can be performed on cuttings in order to obtain more knowledge on the type of lithology and reservoir quality. For each type of analysis, a separate data sheet (sheets B-K) is present Appendix 1.

3.1.1 Bulk rock analyses

Bulk rock analyses are those analyses that provide information on the entire (bulk) rock volume. Bulk rock analyses provide information on the mineralogical composition (i.e. XRD and calcimetry; Appendix 1I and 1E), the elemental composition (i.e. XRF and EDX; Appendix 1J), grain size (LPSA; Appendix 1G) and/or the bulk density (average density of the bulk rock; Appendix 1H). The main reasons for performing these tests is to understand what minerals and grains are present as the rock composition largely controls the reservoir quality. For example, if XRD shows that a significant amount of clay is present, the reservoir quality is most likely less good compared to a sample with less clay. If the sandstone is poorly sorted according to LPSA, the initial porosity (porosity during deposition) was lower, resulting in a poorer reservoir quality compared to a well sorted sandstone with a high initial porosity. If calcimetry and XRD shows that carbonates are common in the sandstone (and most likely occurring as cements), pores are likely partially filled, which also negatively influences the reservoir quality.

More information on the bulk rock analyses options is given in the datasheets E and G-J in Appendix 1.

3.1.2 Microscale analyses

With microscale analyses we refer to the analyses performed on microscale features of the rock sample. Microscale features are those features not visible by the eye or with a low magnification binocular microscope and therefore require special preparation and more advanced microscopes. Microscale analyses can be performed on sieved or handpicked samples (taking only the largest cuttings or the cuttings type of interest; with the potential problem of a biased selection), or the bulk cuttings (taking all cuttings material; with the potential problem of mud additives contamination and loose material). Once the sample is cleaned properly and drilling mud additives are removed, microscale analyses can be performed.

Petrography can be performed on both carbonate and siliciclastic rocks, and requires the preparation of a thin section (Appendix 1C). Petrography on siliciclastic cuttings provides and visualizes information on the detrital (particles derived from pre-existing rock) and authigenic (generated after deposition; e.g. carbonate cements) mineral composition, as well as the porosity. The reservoir quality is strongly dependent on the presence of clay minerals, the degree of compaction and the authigenic mineral components, which filled up the pores. Petrography on carbonate rocks provides useful information on the pore sizes, types and pore connectivity, on the diagenetic history and the presence of non-carbonate minerals that might affect the reservoir quality.

The pores, cements and clay minerals can be visualized using the scanning electron microscope. The SEM can be used in two modes, called BSE-mode (BSEM) and SE-mode (SEM), as discussed in Appendix 1D. BSEM (Backscattered Electron Microscopy) gives highly detailed images of the pores and mineral types in 2D whereas SEM (using the Secondary Electron Microscopy) gives images showing the 3D morphology of the minerals (including clay minerals) and pores. Advanced analyses such as Cathodoluminescence (CL) and Ultraviolet Light (UV) analyses focus on authigenic minerals (e.g. cements) or the presence of organic material, giving insights in the timing and distribution of cements and organic material deposition which have reduced the porosity and permeability. CL and UV analyses are not discussed separately in Appendix 1 as these are very specific and potentially complex analyses, only interesting for strongly cemented or organic-rich (oil containing) samples.

A completely different type of a microscale analysis is biostratigraphy (Appendix 1K). For biostratigraphy, microfossils are identified and counted in order to define the age of the sediment in which the microfossils occur. This technique is also useful for reservoir correlation, e.g. to determine whether the reservoir unit is the same for both the injection and production well.

More information on the microscale analyses is given in the datasheets C-D and K in Appendix 1.

3.1.3 Analysis of reservoir quality

In combination with the bulk rock and microscale analyses, the reservoir quality can be inferred from a selection of additional analyses. The most direct measurement of the reservoir quality can be done with Mercury Injection Capillary Pressure (MICP) tests, which measures the pore throat diameter distribution and the theoretical permeability (Appendix 1F). But also (B)SEM and point counting (discussed in section 3.1.2) potentially provide direct info on the reservoir quality in terms of 2D macro- and microporosity. Indirect information on the reservoir quality can be derived from Laser Particle Size Analysis (LPSA; reservoir quality is related to grain size and sorting) and potentially calcimetry/dolomitry (as carbonate cement reduces the reservoir quality).

3.1.4 Summary

It is always advised to perform a so-called macroscopical description (Appendix 1B) of the cuttings samples prior to other analyses, as this is a cost efficient, useful and fast analysis to identify the quality of the cuttings as well as the main lithologies. The macroscopical description can be compared with the results from the onsite cuttings description performed on the drill rig, which is standard practice for every well. The results are quality checked and can be used as a basis for a purposeful and efficient work plan for further (more in-depth) analyses. Figure 3 summarises the analysis options and their purpose.

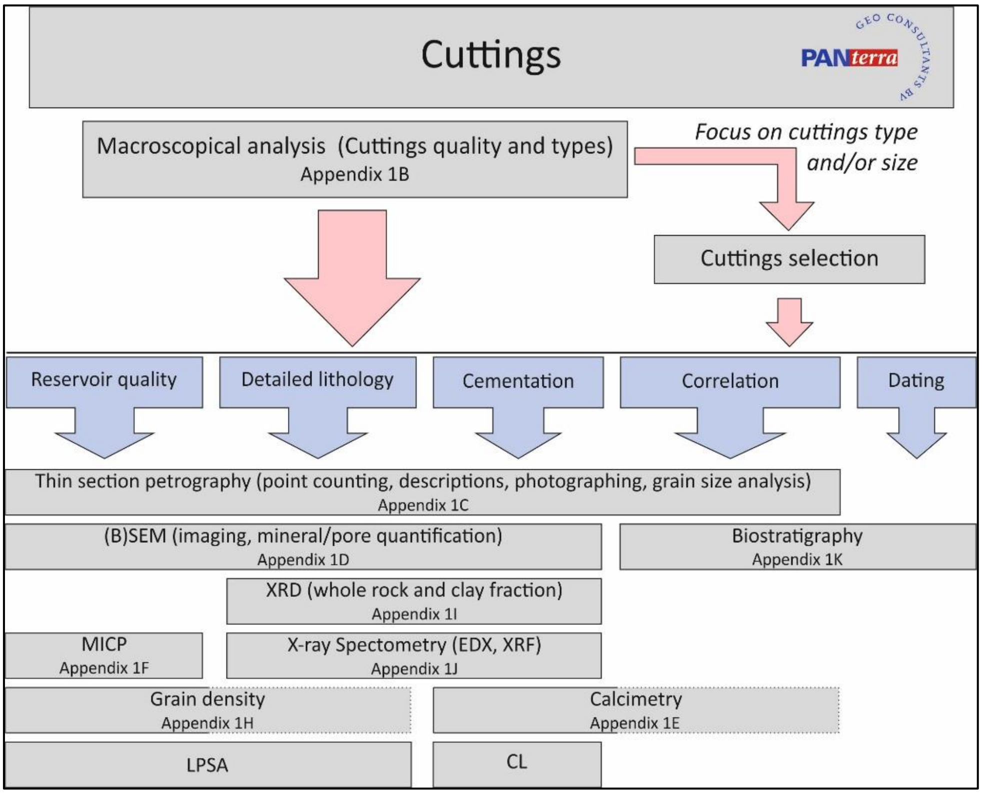


Figure 3: Flowchart diagram showing which analyses (grey boxes) can be performed for what purpose (blue boxes).

3.2 Drilling Parameters

During drilling and cementing, various drilling parameters are measured and documented. These drilling parameters include ROP, mud losses, but also data on the mud type and borehole cementation. Also strength tests such as FIT, FST and LOT tests are commonly conducted. The main question is: what additional information on the reservoir can be gathered from these drilling parameters?

Overall drilling parameters can be reviewed to optimise these parameters for future drilling operations. This is probably done within the drilling of doublets when one drilling company drills multiple wells. We found one company (the company does not exist anymore) that in cooperation with the University of Aberdeen claimed that it could predict reservoir characteristics with drilling parameters and the hydrocarbon gas log as input using advanced computational mathematics[1]. The method does not use empirical formulae but offset wells are used to train the algorithm. The paper does not present the full method but shows case studies with promising results comparing normal well logging results and the results from the algorithm using only the drilling parameters. These case studies should be regarded with caution but this approach could be of interest for the Dutch reservoirs as well since we have a lot of oil and gas wells to train an algorithm with.

Below, the drilling parameters derived from geothermal wells are listed, summarizing the meaning, and the (potential) use of these parameters.

3.2.1 FIT / FST / LOT

FIT/FST (Formation Integrity Test/Formation Strength Test) and LOT (Leak-Off Test) are strength tests that are carried out during the drilling phase of the well, in order to confirm (as the name suggests) the strength of the formation at the casing shoe. The difference between a FIT and LOT is the pressure exerted on the formation. A LOT is a pressure test until the formation breaks (leaks), whereas a FIT is a pressure test until the designed pressure (i.e. no intention to fracture of the formation). The main use of these strength tests is to validate a well engineering plan and reduce risks. It (and especially LOT's) also provides info on the minimum horizontal stress and formation strength (directly read from the LOT). These strength tests alone however do not contribute significantly to the knowledge of individual lithologies and the reservoir quality. The LOT is however important for a geothermal project because the maximum injection pressure can be calculated with the results from this test.

3.2.2 ROP

The rate of penetration (ROP) is an important parameter, showing speed at which the drill bit cuts through the rock. The ROP is depending on the mud density, the bit type, weight on bit (WOB), etc. Rock-related parameters that affect the ROP are the lithology (rock type, rock strength etc.) and porosity. Since the ROP identifies distinct transition in lithologies, it can potentially be used as a parameter to correct depth shifts and to correlate with nearby wells. This can be an addition to the information obtained from GR logs and cuttings data. In the case of carbonates or strongly fractured rocks, it can also be used to identify faults and fault zones, as well as karsts. Additionally, the ROP also determines how much cuttings will be produced during drilling and to some extent the quality of the cuttings.

3.2.3 Mud Losses

Mud losses, also known as (partial) loss of circulation, is a situation where the amount of mud returned to the surface is lower than the amount pumped into the well. Mud losses indicate permeability and at a certain depth are an indication for a natural fracture (zone) or karsts in carbonates. Such features can be confirmed with other datatypes, such as caliper logs, borehole breakouts and GR.

3.3 Logs

3.3.1 Gamma Ray log

Gamma rays (GR; natural radioactive radiation) are emitted by minerals that contain naturally occurring radioactive elements (K, U and Th). Compared to sandstones, shales generally contain significantly more minerals with those radioactive elements and therefore emit more gamma rays. Therefore, gamma rays are used to determine the lithology and to distinguish between reservoir (e.g. sandstone) and non-reservoir (e.g. shale) rock.

Routinely, the GR log is used to determine the lithology and the inferred reservoir quality. Additionally, the GR log is also used to calibrate the cuttings depth to the wireline logging depth.

A novel goal of the GR log is to gain a first indication of the porosity as TNO has done for the Delft sandstone. TNO made a cross correlation between GR and porosity in offset wells, and applied this correlation to wells without logs that are usually used for porosity determination.

3.3.2 Calcimetry / Dolomitry Log

Calcimetry / Dolomitry is a special test (only seen in one geothermal well; see Table 1) that can be done both on the rig site as well as in the lab. The results can be presented as log. It quantitatively measures the carbonate content by dissolving the carbonate in acid (see Appendix 1).

Calcimetry / Dolomitry can be applied on both carbonate rocks and siliciclastic rocks, although the purpose is different. By logging the carbonate content in siliciclastic rocks, problematic zones with carbonate cement might be identified. This data can be compared with the gamma ray log and with other analyses performed on the cuttings (e.g. petrography). The presence of carbonate cement might be related to local changes in sedimentology, but also potentially to an increase in fluid flow due to e.g. a nearby fracture. Once carbonate cement streaks are identified, these might potentially be correlated to similar streaks in nearby wells.

By performing calcimetry / dolomitry on carbonate rocks, the total calcite / dolomite content can be determined. These minerals have different physical properties and cause different responses in wireline logs. The presence of dolomite or calcite can be related to the depositional setting or to diagenesis, which helps correlation between wells.

3.3.3 CBL

A cement bond log (CBL) is an acoustic log for evaluating the quality of the cement bond. Both the bond between the cement and the casing, as well as the bond between the cement and formation are evaluated. There are two scenarios from which additional information on the lithology can potentially be gathered from a CBL. The first scenario is when a bond between the cement and the formation is poor. This could represents problematic intervals with dehydrated swelling clays, cavings or washouts, indicating that the formation is potentially poorly consolidated or strongly fractured. Such poorly bonded areas can be compared with the GR log or cuttings data in order to identify or verify the reason for the poor bonding. The second scenario is when a bond between the cement and the formation is good. With a good cement bond, the acoustic signal penetrates through the cement into the formation, giving some information on the formation itself. In case a GR log is lacking at a certain interval, the CBL might act as a log that can be used for formation top picking. Theoretically, when the acoustic signal through the cement is strong enough and the bond is perfect, additional information (e.g. on the porosity) might be gathered from a CBL.

3.3.4 Gas Log

A gas log is present for nearly all geothermal end-of-well reports. The gas log presents the presence of natural hydrocarbon gas detected in the mud, using gas chromatographs and is depending on e.g. the mud weight and ROP. Both light gas (C1; methane) and heavier hydrocarbon gases (C2; ethane, C3; propane, etc.) are recorded. Gas shows can be seen in non-reservoir organic-rich siltstones/shales. The main purpose is however to identify hydrocarbon bearing reservoirs. Even though hydrocarbon bearing reservoirs are not of direct interest for geothermal wells, gas shows may indicate zones with potential risks during drilling. Additionally, in the reservoir section, a gas log does give an indication of the quality and to some extent the connectivity of the reservoir, which can be compared the GR log and cuttings data.

3.3.5 Caliper Log

A caliper log is measured with a mechanical (hydraulic) tool with multiple (>4) arms that stand out. This tool measures the size and shape of the borehole. The main use of the caliper log is to determine the amount of cement necessary for casing the well. It however also provides indirect information on the lithology. Washouts are easily identified and indicate unconsolidated material. Irregular shapes commonly indicate a shale interval, whereas a straight shape commonly indicate a consolidated shale-poor formation (e.g. sandstone). Additionally, borehole breakouts and presence of fractures, which can be identified in a caliper log as well, give an indication of the local stress field.

3.4 Well tests

Build up and interference well tests are regularly performed for geothermal wells in Netherlands. The main information well tests provide is the transmissibility (permeability x thickness) and skin value. The transmissibility can be translated to permeability if the net reservoir thickness is known. The skin of the well is a dimensionless factor that is the production efficiency when comparing the actual performance with the theoretical performance of the well. A positive skin indicates a lesser productivity and a negative skin indicates a better then theoretically possible.

Well tests can, in theory, provide detailed information the structure of the subsurface and the reservoir quality. The design and possible test/hardware errors during testing are important to the extent and detail to which the well test can be interpreted. A concise summary of the well test applications is listed in the poster "Well Testing

Applications" by HIS Markit[2]. Here are the most important uses of a well test for geothermal operators beside the usually obtained knowledge:

- Distance to reservoir barriers, e.g. drainage area and drainage shape.

A well test can provide an indication of the closest distance to a flow barrier, this for instance be a fault or change in lithology. The shape of the drained area can be also be inferred from a well test. This information on the structure or reservoir extend can be very useful for planning future wells.

- The degree of fault sealing

The degree of fault sealing is a parameter which can be determined by a well test. This is useful if a fault is observed but it is not certain whether the fault is permeable or to which degree the fault is permeable.

- Multi-layered reservoirs

Whenever several reservoirs have been drilled the well test can provide permeability estimations for the individual reservoirs. This is important if it is unknown if all reservoirs contribute to the flow.

- Fractured reservoir parameters

In reservoirs which rely on fractures to produce a well test can indicate different permeability estimations for the fractures and for the matrix permeability (dual porosity system). This is useful for doublets in Kolenkalk in the south of the Netherlands where the permeability of the fractures is different from the matrix permeability.

4 Phase 3: Data integration

Most of the data that is acquired during drilling or from cuttings can be combined together in order to get better insights in the lithologies and reservoir qualities. Variations in reservoir quality within and between wells is one of the main reasons for drilling, injection and production problems. Therefore, gaining a good understanding of the reservoir lithology and quality is of key importance. Some data types discussed in chapter 3 are meaningless when evaluated alone. An example is the HC gas log, which does not tell you whether you are in a reservoir or in a source rock interval. Together with a GR log and cuttings data however, the HC gas log could confirm or even invalidate observations.

In order to answer questions to certain problems, it is important to characterise the lithology, the reservoir quality and the rock strength of the interval of interest. Small variations in lithology, such as the presence of pore-filling clay minerals, might cause major problems during injection or production. This does not necessarily mean the porosity of such an interval is poor, as the presence of pore-filling clay does not necessarily reduce the porosity significantly, but it may reduce the permeability significantly.

How to characterise the lithology, reservoir quality and rock strength of a certain interval most efficiently, and what combinations of analyses and parameters can be used, is discussed below.

4.1 Lithological and sedimentological characterisation

The most direct method to obtain information on the lithology is from cuttings. To get better insights in the lithological characteristics, it is best to combine a macroscopic description with thin section petrography and chemical analyses such as XRD, grain density analyses or calcimetry. This can be compared with the GR log to identify lithological zones. More detailed analyses on the lithology comprises the combination of (B)SEM, MICP and LPSA. When specific problems arise regarding organic material or cementation, CL and UV can be performed. In case the lithology is known, but the age is uncertain, the cuttings can be used for biostratigraphy. Drilling parameters such as strength tests, caliper and the CBL can be checked in order to identify certain problem zones or zones of interest.

4.2 Reservoir quality characterisation

Analysing cuttings is also the best method to focus on the porosity and permeability of a certain interval. This can best be done by combining thin section petrography with (B)SEM analyses, MICP, grain density analyses and LPSA.

Direct data on the reservoir quality is obtained with MICP, but the details on the pore shape and size can only be obtained with thin section petrography and (B)SEM. Indirect indications of the reservoir quality can be obtained with grain density analysis, calcimetry, LPSA and XRD. This is because the grain size, carbonate cement and clay content are important parameters that commonly affect the reservoir quality significantly. Drilling parameters, apart from GR logs, are mostly valueless for reservoir characterisation.

4.3 Rock strength characterisation

The rock strength is more difficult to determine with cuttings. Stronger rocks might result in larger cuttings (and vice versa), but other parameters such as drill bit type and ROP are parameters that affect the cuttings size and quality more significantly. A direct measure of the (minimum) rock strength are the FIT/FST and LOT, which are commonly performed at certain points in a well. In case such strength tests are unavailable, the combination of cuttings data (by defining the rock type), caliper data, the ROP and mud losses might give an indication of the rock strength. FIT/FST/LOT results can potentially also be combined with the detailed lithological and reservoir quality analyses in order to be able to extrapolate these results over a certain interval.

5 Conclusions and recommendations

The assessment of the End of Well (EOW) reports of 27 geothermal wells showed that the amount of routinely obtained data in wells during drilling is limited to cuttings, drilling parameters and logs as the main data groups.

The main conclusion is that cuttings are the main source of additional information for current or future geothermal projects in the Netherlands. Several techniques are available which can give information on the detailed lithology, cementation (consequently giving clues on the reservoir quality) and correlation. These techniques can help to address production and injection problems, and improve pre-drill reservoir quality prediction. Both the quality of the cuttings, as well as the purpose (i.e. to gain additional information on lithology, reservoir quality and age) for additional analyses determines which technique or what combination of techniques can best be used.

Even though most information on the lithology can most reliably be obtained with cuttings, drilling parameters and logs provide some additional information on the rock type and/or rock strength. This is most commonly useful for correlation (with nearby wells) and depth shifts, as well as for the identification of potential problematic intervals. The method that uses the drilling parameters to describe the reservoir quality could be investigated further to see if this can be applied to the Dutch geothermal reservoirs.

Since cuttings are the most direct and reliable data obtained from a well, it is important for future geothermal projects that the cuttings are sampled and registered at a regular and relatively dense interval (e.g. every 1 or 2 meter in the interval of interest, and every 5 meter in the overburden). Before drilling, it can be considered to select a rollercone bit rather than a PDC bit for the interval of interest in order to ensure a good cuttings quality.

6 References

1 Hurst, A., Tischler, G. and Arkalgud, R. (2009). Predicting Reservoir Characteristics From Drilling and Hydrocarbon-Gas Data Using Advanced Computational Mathematics. SPE number 123785. Paper prepared for SPE Offshore Europe Oil & Gas Conference & Exhibition, Aberdeen UK, 8-11 September 2009.

2 Well Testing Applications poster by IHS Markit. 3925-JH-0117. Retrieved from cdn.ihs.com/www/pdf/Well-Test-Applications-Poster.pdf.

Appendix 1: Cuttings Analyses

Appendix 1A — Data: Cuttings

What are cuttings?

Drill cuttings are broken bits of the penetrated rock that are transported by the mudstream from the bit to the surface during drilling. The difference between the depth the cuttings are assumed to originate from, and the wireline depth, is corrected with the GR log.

Cuttings brought to the surface are commonly directly described. After first description, the cuttings (both a washed and unwashed fraction) should be stored for potential future analyses.

Cuttings provide the only physical information of the lithology that is penetrated during drilling. Several relevant quantitative analyses can be performed on the cuttings to get information on lithology, mineral composition of the reservoir rock and reservoir quality.

The size and quality of cuttings depend strongly on the rock formation, the drill bit used, the rate of penetration and the pressure applied to the drill bit.

It has to be noted that cuttings are an average representation of the rocks over the sampled interval (commonly m-scale). These intervals commonly vary along the well.

Common sampling interval is 2m per sample (= ~100 samples for a ~200m interval).

Risks & Uncertainties

The drill bit type strongly affects the cutting quality. PDC bits alter the cuttings whereas roller cone bits potential create good quality cuttings. During the first cuttings analysis, an inspection of the cuttings quality should be done.

Drilling mud contaminates the drill cuttings. Therefore, it is important to know the drilling mud type (OBM vs WBM) as the mud composition influences the analytical results. Also mud additives need to be identified and separated from the rock material.

Cavings (i.e. loose material, commonly shale, that falls into the wellbore) pose a different problem, as these imply that certain rock types are present whereas these are actually derived from formations above. Potential cavings problems can be identified and accounted for in the caliper log.

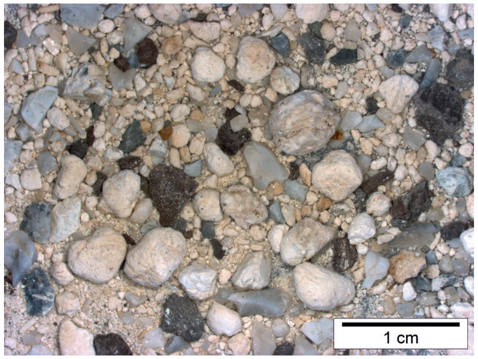
As cuttings cover a certain depth range, the uncertanties in lithology and lithological variations are relatively large. Therefore, the results from analytical analyses performed on cuttings should be considered as semi-quantitative.

Analyses

The following analyses can be performed on cuttings:

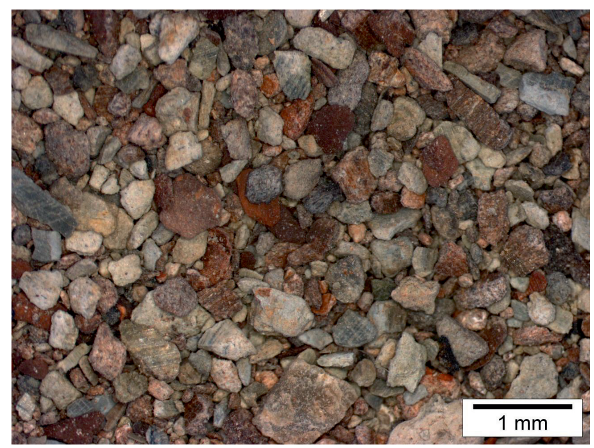
- Detailed Macroscopic Description
- Thin Section Petrography
- Scanning Electron Microscopy ((B)SEM)
- X-ray Diffraction Analysis (XRD)
- X-ray Spectrometry (EDX, XRF)
- Biostratigraphy
- Calcimetry
- Grain Density Analysis
- Mercury Injection Capillary Pressure analyses (MICP)
- Laser Particle Size Analysis (LPSA)

Each type of analysis is discussed on separate pages. The purpose of each analysis is summarised in Table 2 of the report.



Appendix 1B — Type of Analysis: Macroscopical Analysis

 How? Technical details	 Why? Benefits	 Limitations	 Price estimate	 To combine with...
A so-called macroscopic analysis is performed on the cleaned and dried cuttings, using a low magnification binocular microscope fitted with a camera. Overview photos and a short description of the selected cuttings provide a good overview of the lithologies and changes with depth. Main purpose is to determine which lithologies are present, and the cuttings quality. This acts as a basis for further analyses. If required, handpicking of cuttings for further analysis (e.g. BSEM) can be done at this stage. A bias in handpicking stage. A bias in handpicking should be avoided.	A macroscopic analysis of the cuttings is a cost efficient and fast method to get a direct overview of what intervals might be important for further analyses. It is a direct quality control of the mudlog or litholog created shortly after drilling. After the macroscopic analaysis, a cost efficient project plan can be developed and relevant analyses can be selected. Cavings, mud additives and other artificial components can be identified. Log data can support the presence of cavings.	A macroscopic analysis does only provide qualitative information. Quantitative data is not produced at this stage of the cuttings study. Depending on the cuttings quality, a relative large uncertainty can remain on discriminating true lithology from cavings or drill mud additives. When cleaned properly, artificial non-sediment/rock components (metals, nut shells, rubber, etc.) are relatively easily identified.	Per sample: • Description+ overview photo ~€100 • If required, handpicking or sieving for further analysis ~€100	A macroscopical analysis should always be performed prior to further analysis. This is to test the quality of the cuttings and to select (i.e. hand pick or sieve) sample material if required.



Appendix 1C

Type of Analysis: Thin Section Petrography

How? Technical details

Thin sections (TS; ~30µm thick slides of the cuttings) from unwashed or cleaned samples are prepared. Blue epoxy dye and various types of staining aid in the identification of pores and minerals.

Depending on the requirements, the TS can be photographed and described in detail.

Cuttings components (rock fragments, minerals) and macropores can be point counted to quantitatively determine the contents of the rock fragments, minerals and (potentially artificial) pores.

The grain size, along the long axis and in 2D can be measured and the grain size distribution (i.e. sorting parameters) can be determined.

The rock types and abundancies can be recorded.

Why? Benefits

TS petrography is performed to get a good understanding of the rock composition and the type and size of macropores.

The spatial relationship between detrital components, diagenetic components and pores can be determined.

Combining the above gives good indications of the reservoir quality and heterogeneity of the sampled interval.

TS petrography also gives good insights in what might be problem areas (with reduced macroporosity), and what causes potential injection or production problems (e.g. clay minerals, mica or cements).

Commonly, drilling mud additives can be distinguised from true rock material in the thin section.

Limitations

The cuttings quality is the main limitation. The quality is strongly dependent on the bit type used and the rate of penetration. Cuttings might be sheared and/or completely broken up. This destructs minerals and pores.

A disadvantage is the small amount of cuttings that can be fitted on a thin section, and whether these are representative of the rock. This should be considered in the TS preparation. Optional, larger thin sections can be prepared, which would fit more fragments.

Price estimate

The costs depend strongly on the analyses performed on the thin section.

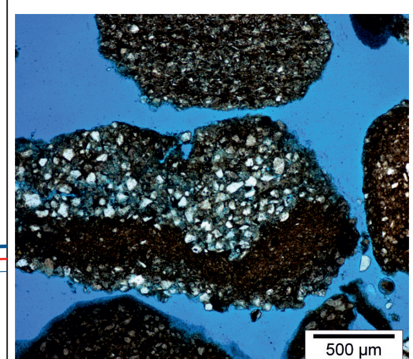
Per Sample:

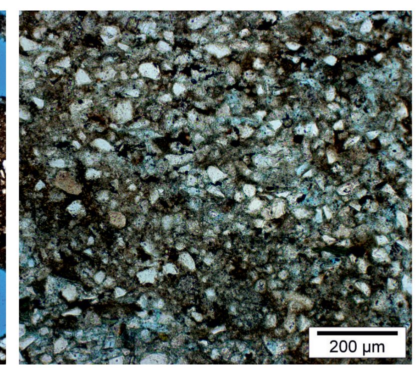
- Conventional Thin Section ~€75
- Point Counting+Description ~€275
- Detailed Photographs ~€100
- Grain Size Analysis ~€100

To combine with...

TS Petrography can best be combined with:

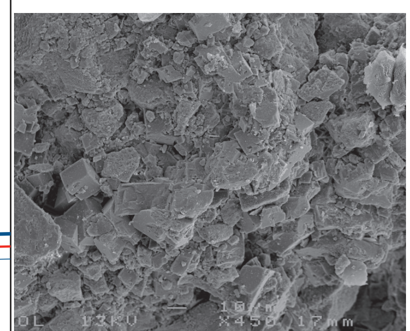
- XRD analyses to check the bulk mineralogical composition and clay types.
- SEM and BSEM analyses to focus more in detail on minerals and pores.
- EDX analyses to confirm presence of minerals that could not be identified with TS peterography.

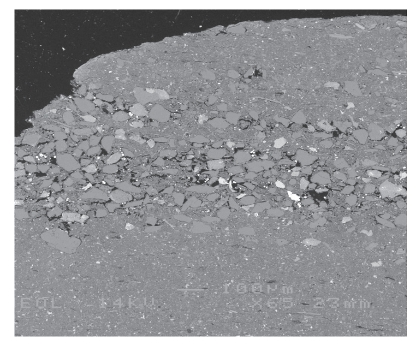




Appendix 1D Type of Analysis: Scanning Electron Microscopy

 How? Technical details	 Why? Benefits	 Limitations	 Price estimate	 To combine with...
The scanning electron microscope (SEM) bombards focussed electrons to a point on the sample. The resulting emitted electrons are detected, such that a scan is made. From this, a greyscale image is created. There are two scanning modes: Secondary Electron mode (SE-mode) and Backscattered Electron mode (BSE-mode). SEM images are 3D appearances of the rough cuttings surface, allowing to visualise the shape of crystals and pores. BSEM images are taken from polished surfaces (i.e. a polished thin section or a polished impregnated block) and are dependent on the atomic numbers of the minerals. Therefore, minerals can be distinguished from each other and from the pores in high detail.	Both SEM and BSEM allow for detailed analyses of the small cuttings, showing the pore distribution, pore geometries and the presence of clay minerals or cements within the pores. Such highly detailed information can be necessary to explain production problems or variations in reservoir quality. Microporosity cannot be identified and quantified other than in the electron microscope. Also complex or small (e.g. clay) minerals which can not be identified under the conventional microscope can more easily identified in the scanning electron microscope.	Main limitation is related to the small volume that is analysed, and whether this is representative for the various cuttings. The cuttings quality is a major limitation for the analysis of porosity. Commonly, artificial structures are relatively easy identified in BSEM. In SEM, the limitations regarding sample quality are more significant. For BSEM, an impregnated sample with a polished surface is necessary. This should be taken into account when preparing e.g. thin sections.	The combined SEM+BSEM costs are relatively high, but the analyses can be done separate depending on the purpose of the analysis. Per sample (including preparation): • SEM ~€450 • BSEM ~€550 • Image analysis BSEM ~€150	SEM and BSEM can best be combined with: • TS Petrography to compare structures and minerals • EDX to identify unknown minerals

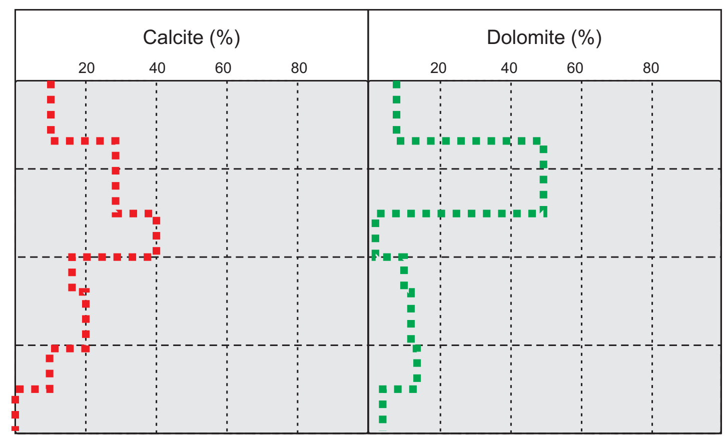




Appendix 1E

Type of Analysis: Calcimetry

 **How? Technical details**	 **Why? Benefits**	 **Limitations**	 **Price estimate**	 **To combine with...**
Calcimetry, also known as the acid solubility test, determines the amount of acid soluble components (i.e. calcite and dolomite). Calcite dissolves in acid (e.g. HCl) at room temperature conditions, dolomite at elevated conditions. The calcite / dolomite content is calculated from the residues after treating the sample material with the acids. This type of analyses can be done on-site, or after cuttings collection in the laboratory.	Calcimetry is a quick, efficient and low-cost method to get a better understanding of the total carbonate content. With enough samples, a log can be created, which identifies critical carbonate cement intervals. The log can be compared or potentially correlated with wells that have already calcimetry data and other logs. With knowledge on thepresence and type of carbonate cement intervals in siliciclastics, an acidization strategy can be applied. Also for carbonate reservoirs, calcimetry can help for a potential acidization strategy.	Calcimetry is a bulk rock analysis. A discrimination between carbonate grains or carbonate cement cannot be made. Calcimetry is a destructive test that requires at least 3 grams of sample material. This material can not be used for other analyses. Siderite is (at high temperature) also soluble in HCl. If the presence is unknown, dissolved siderite might be interpreted as dolomite, overestimating the dolomite content. To create a representative log-like dataset, a large amount of samples need to be analysed.	Calcimetry is a relatively low-cost analysis and can be focussed on intervals where cementation might be important, hence limited samples are necessary: Per sample: • ~€150,-	Since calcimetry is a bulk-rock analyses, the calcite and dolomite source can best be identified together with: • TS Petrography • (B)SEM



Appendix 1F

Type of Analysis: MICP analysis

How? Technical details

Mercury Injection Capillary Presure (MICP), also known as High Perssure Mercury Injection (HPMI) is a method to measure pore volume by forcing mercury through the pore throats into the pore spaces.

The necessary pressure applied (for mercury to enter the pores) is related to the pore throat size; with increasing pressure, pores with smaller pore throats will be saturated.

Assuming cuttings are of good size and quality, the final results are the pore throat size distribution, a (mercury) porosity and a theoretical permeability.

Why? Benefits

MICP provides the only quantitative measurement to directly assess the reservoir quality of cuttings in terms of pore throat size and (theoretical) permeability.

The permeability of a rock is most strongly dependent on the pore throats, as these are the bottlenecks in a reservoir. Knowing the size and distribution of this provides a good estimate of the reservoir quality.

Once a sample selection per lithology is made, a comparison between the lithologies can be easily done.

Limitations

The major limitation is the quality of the cutting. If the cuttings (hence the pores) are deformed, the pore throats and permeability are strongly affected.

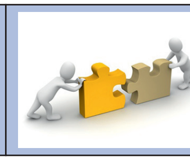
Therefore, the general cuttings quality should be inspected prior to MICP analysis with e.g. BSEM or TS petrography. Note that after inspection, the same cuttings can not be used for MICP as these are resinated.

The size of the cuttings should be large enough to obtain reliable MICP results. Too small cuttings are commonly damaged and yield too little pores to give a reliable result.

Price estimate

MICP is a very useful but relatively costly analytical procedure.

The price per sample is:
Handpicking: ~€100
MICP analysis: ~€450



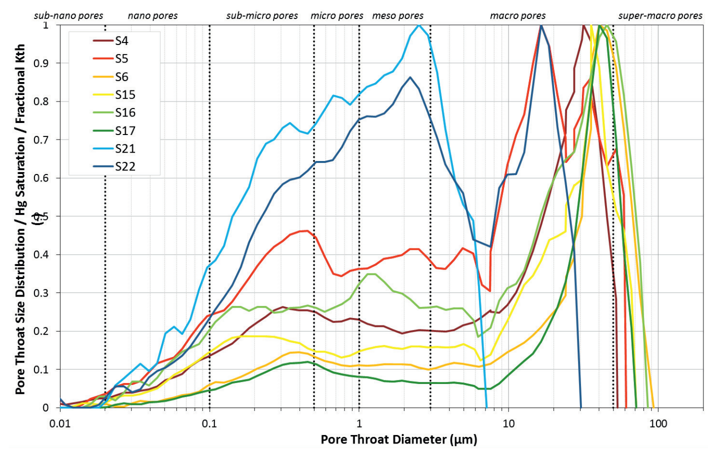
To combine with...

To check the quality of the cuttings:

- TS petrography
- (B)SEM

The check the relation between pore throat size and grain size:

- LPSA
- Grain size point counting



Appendix 1G — Type of Analysis: LPSA

 How? Technical details

Laser Particle Size Analysis (LPSA) is a diffraction technology where a laser beam is passed through a sample that is suspended in water.

The sample will be carefully disaggregated, carbonate cement is dissolved, and the loose particles are placed in the analyzer.

The intensity and angle of a scattered laser beam, is directly related to the particle size through which the laser passes. This is measured and the results are converted to a grain size histogram.

 Why? Benefits

LPSA is a fast and repeatable method to get quantitative results of grain size and grain size distribution in 3D.

Not only the grain size, but also the grain size distribution (including clay minerals) are provided.

Relative little sample material is required.

The grain size, including clay, is commonly directly related to the reservoir quality and can be compared with or plotted against e.g. MICP.

The procedure shows a good repeatability. Therefore, the results can reliably be compared with other samples and wells.

 Limitations

The main limitations are related to sample preparation and sample quality.

Only siliciclastic samples can be used.

Clustering of grains, or the incomplete disaggregation of the sample result in an overestimation of the grain size. This is commonly the case for cemented rock (which normally yields better cuttings) and for clay-rich samples.

Grains with cement overgrowths or angular grains also yield an overestimation or error due to the fact that during calculations, round grains are assumed.

 Price estimate

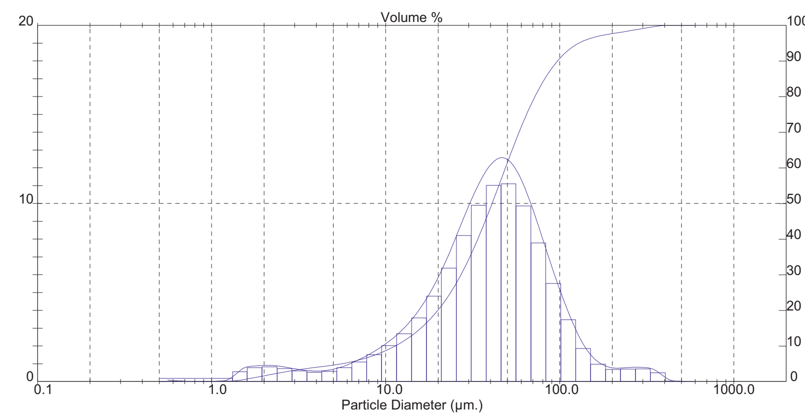
LPSA analysis requires some sample preparation (disggradation of grains).

Per sample:
Sample prep: ~€50
LPSA analysis: ~€200

 To combine with...

LPSA results can best be combined with:

- TS Petrography
- (B)SEM
- MICP
- XRD



Appendix 1H

Type of Analysis: Grain Density Analysis

How? Technical details

Grain density refers to the density of all solid material in the rock (i.e. the bulk rock) or cuttings.

Grain density analysis measures the density of the bulk rock. This can be performed per cuttings type (when cuttings are preselected per rock type/facies) or the total amount of cuttings.

The grain density is measured in a so-called gas pycnometer which determines the volume of the sample material. This is the volume within the sample chamber that is inaccessible for the gas).

Using the mass of the material, a grain density is calculated.

Why? Benefits

Grain density analysis provides a quick method to identify heavy cement streaks such as dolomite, siderite and anhydrite, which can be destructive for the reservoir quality or form barriers to flow.

The grain density provides an alternative to the density derived from a density log, which is generally not available for geothermal wells. Density analyses can also be used to calibrate (if present) density logs.

Very important is that from the grain density analysis, the porosity of the cuttings can be estimated (using the bulk and grain volume), given the cuttings are of good quality.

Porosity is a sensitive input parameter for well test interpretations.

Limitations

A relatively large amount (approximately the volume of a plug) of cuttings material is required in order to get good results.

The cuttings need to be cleaned properly. If drilling mud remains around the cuttings, the grain density will be unreliable. Especially barite (common drilling mud additive) will have a significant influence on the grain density.

It only gives bulk rock results of the sampled interval, and no further details.

Price estimate

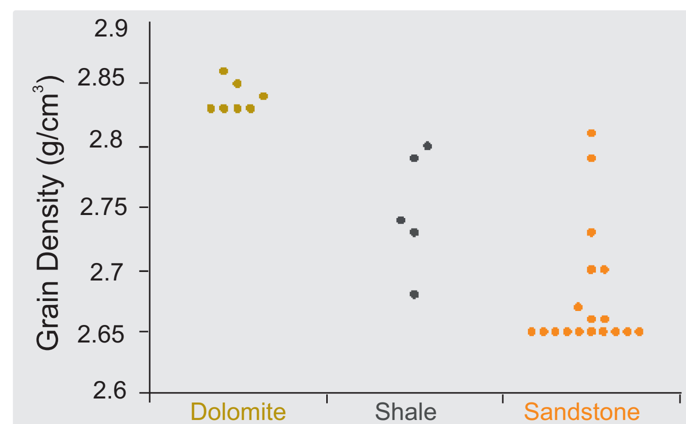
Measuring the grain density of a sample is a relatively low-cost analytical procedure.

Per sample, including cleaning and drying: ~€35

To combine with...

Grain density analysis is an easy to apply method. It is best combined and compared with:

- Log data (e.g. Gamma Ray)
- TS petrography
- XRD



Appendix 1I

Type of Analysis: X-ray Diffraction (XRD)

How? Technical details

Whole Rock and Clay Fraction X-ray diffraction (XRD) analysis can be done on rock samples.

Whole Rock (WR) measures the bulk rock composition. Clay Fraction (CF) measures the clay-sized particle composition (<2µm).

In an XRD-instrument, X-rays are bombarding the sample. Each mineral in the sample diffracts the X-rays differently.

The resulting diffractograms allows for identification of the crystalline phases.

A semiquantitative calculation of the composition can be done based on the relative heigth and width of the mineral specific peaks.

Why? Benefits

WR XRD analysis is done to determine mineralogy in order to identify the composition (presence of stable minerals) of the siliciclastic or carbonate rock. Also the presence of potentially porosity reducing cements can be identified.

CF XRD analyses is done to determine the clay mineralogy, including the swelling clays. Clay minerals generally affect the reservoir quality significantly, also in small quantities.

A combination of WR and CF analyses gives the full-range (from clay, to cements to quartz grains etc.) insights in the mineralogy.

Limitations

Limitations are mostly related to mud additives and drill mud composition, which influence the results. The sample must therefore be cleaned properly prior to analysis, with understanding of the drilling mud used.

No information on the non-crystalline material can be obtained. If non-crystalline material is present (e.g. organics, mud additives), the noise/background data will increase.

Price estimate

Per sample:

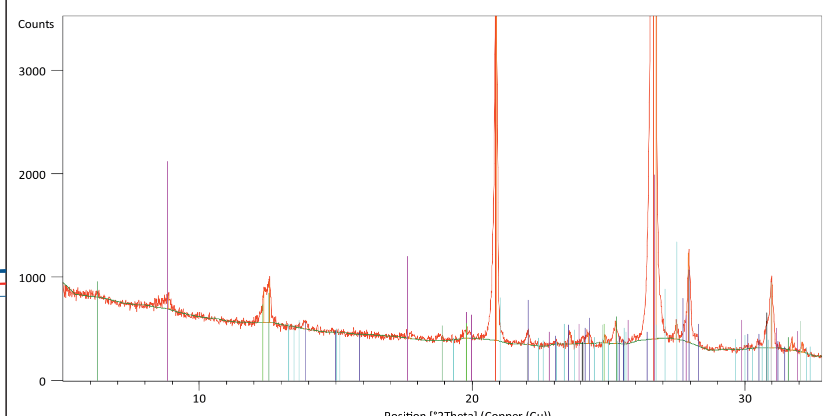
- WR analysis, ~200€
- WR+CF analysis, ~425€

Per interval:
Depends on the sampling interval and frequency from the formation of interest as well as the sample quality (does it requires additional sample preparation /cleaning?).

To combine with...

XRD can best be combined with:

- TS petrography to check the spatial distribution of cements and clay minerals.
- XRF and EDX to check with the elemental composition, confirming mineral composition and/or non-crystalline material occurrence.



Appendix 1J — Type of Analysis: X-ray Spectrometry

How? Technical details

X-ray spectrometry is a non destructive method to analyse the chemical (i.e. elemental) composition of a representative (mostly homogenized) sample.

Two types of X-ray spectrometry exist; Energy-dispersive (EDX) and Wavelength-dispersive (WDS and XRF).

Electrons, X-rays or gamma rays are bombared on the sample which excites primary (EDX, WDS) or secondary (XRF) X-rays with various energies.

Also elements of non-crystalline materials are detected.

Both bulk analysis (when homogenized) as spot analyses can be done on the sample.

Why? Benefits

X-ray spectrometry provides a fast way to gain (additional) info on the single mineral, single cutting or the bulk rock composition of the sample.

Both information on the major element composition (main building blocks of minerals) as well as on the trace element composition can be gathered.

Knowing the elemental composition helps in the analysis of e.g. XRD and (B)SEM analysis, as chemical variations in certain types of minerals (e.g. carbontes) might affect e.g. wireline logs and the interpretation of the reservoir quality.

Limitations

Selecting an appropriate elemental analysis method is a tradeoff between price, accuracy and the duration of an analysis.

EDX analyses are less accurate but faster and more cost efficient compared to XRF.

Minerals cannot be directly analysed, only their elements.

Price estimate

The cost varies slightly per analytical procedure and the accuracy wished.

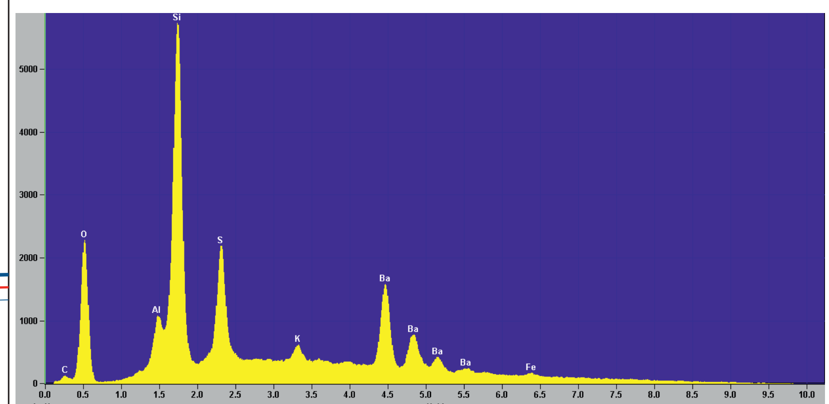
Per sample:

- EDX: ~€100
- XRF: ~€150

To combine with...

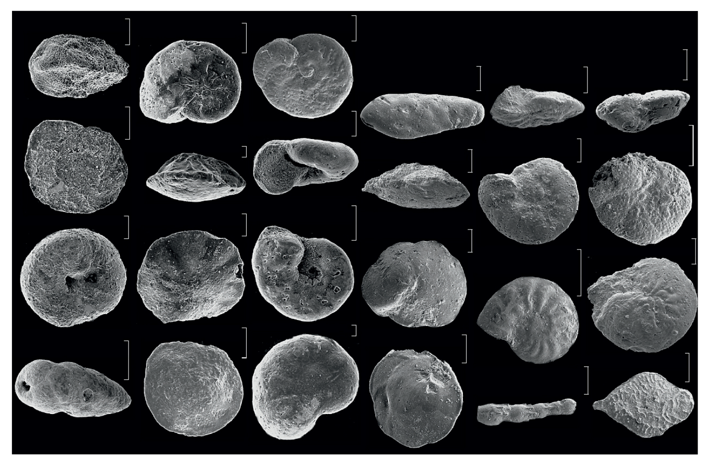
X-ray spectrometry can best be combined with:

- XRD to know the mineral composition.
- (B)SEM to identify mineral phases.



Appendix 1K — Type of Analysis: Biostratigraphy

How? Technical details	Why? Benefits	Limitations	Price estimate	To combine with...
Biostratigraphy is a way to define the age of a certain formation with help of the microfossil (e.g. plankton, pollen and foraminifera) assemblage. Organisms that changed their appearance relatively quickly in earth history can be used as stratigraphic markers to (roughly) determine the age and depositional environment of the interval. By identifying and counting the amount of each microfossil species present, an abundancy log can be created and compared with the lithology. This can be correlated with nearby wells, e.g. the other well of the geothermal doublet.	Biostratigraphy provides a direct measure of the relative age of the sediments, which can be verified with the lithostratigraphy and wireline data. This provides a direct proof whether the target is reached or not. Biostratigraphic samples do not require a very good cuttings quality. It can potentially be performed on PDC-bit cuttings, which can not be used reliably in e.g. thin section petrography. The age can be compared with the available data and correlated with other wells for exploration. This gives insights in the stratigraphy and thus the distribution of reservoir sands.	Self-evident is that microfossils need to be present in the studied interval. The presence of cavings should be double checked, as microfossils might have been derived from formations above, giving erroneous results. Biostratigraphy is a specialised and complex study and is not only focussing on the age of the fossils, but also the environmental range, spatial occurrence and the degree of preservation. It does not provide a direct measure of the reservoir quality of the sample.	Biostratigraphy analyses are relatively expensive, but only required in intervals of interest. Per sample: • Biostratigraphy: ~€450	Biostratigraphy can be performed individually. To get a correlation between sedimentary age and reservoir quality, it can best be combined with e.g.: • TS Petrography • MICP



Appendix 2: Potential questions and suggested solutions

In this Appendix typical questions are posed that often arise during drilling and production of geothermal wells. Suggested analytical procedures on cuttings and/or other obtained data are provided to help getting to the answer on the question. This may aid in the solution or prevention of technical complications during drilling or production, also for future projects in a region.

Question?	Solution	Suggested analyses
1: How do I determine whether swelling clays are present?	Swelling clays are directly identified by clay fraction XRD analysis on cuttings. SEM analysis on clays can also identify potential swelling clays from non-swelling clays. During drilling, the mud composition can be adapted to inhibit swelling (e.g. by increasing salinity). To check the effects of salinity on the clays, a swelling test can be done.	• Hot-shot Clay Fraction XRD analysis (i.e. analysis can be done during or directly after drilling to remedy drilling problems) • SEM analysis • Cuttings swelling test
2: How do I determine the reason for drilling problems?	Some of the most common drilling problems are pipe sticking, lost circulation and borehole instability. These problems can be very complex and related to (a combination of) e.g. hole deviation, the mud, cuttings accumulation in the annular space. This in turn could be related to the rock lithology, variations in lithology, rock strength etc. In case a lithologic problem is expected cuttings analysis may help in the understanding of the problem. For example, are drilling problems likely to be due to shaly intervals, swelling clays, salt intervals, carbonate-rich intervals or fractured intervals?	• Shales: WR & CF XRD, SEM • Carbonates: WR XRD, SEM, TS Petrography, Calcimetry • Salt: GR log, WR XRD, SEM • Fractures: See question 5.
3: How do I analyse (unexpected) cementation streaks?	Cementation streaks are intervals of varying thickness (few cm to a few m) enriched in e.g. carbonate, anhydrite or salt cement where the permeability is (strongly) reduced. The presence of cemented layers can sometimes be related to the original depositional environment of the sediment, although often it has a post-depositional origin. Cement streaks can be identified by analysing the GR log in combination with thin section petrography, SEM, EDX/XRF and XRD on cuttings which allows for identifying the cementing mineral as well as the structure/pervasiveness of the cement. In the case of carbonate cement, the cement content and type can also be analysed with an acid solubility test.	• GR log • Thin section petrography on cuttings • BSEM analyses • EDX • XRD/XRF • Acid solubility test / Calcimetry

4: How do I determine the porosity and permeability of the rock?	In the absence of a full logging suite, the most quantitative method to gain information on porosity and permeability from cuttings is by performing MICP which gives a theoretical permeability of the tested reservoir material. Porosity of cuttings can be measured in the laboratory as well by using an automated pycnometer. The cuttings however need to be of a good quality (i.e. rock texture should be unaltered) to get a reliable indication. Cuttings description inclusive thin section petrography and SEM analysis is recommended to assess the reservoir quality.	• MICP • BSEM analyses • Thin section petrography on cuttings
5: How do I identify natural fractures?	Natural fractures cannot be identified by cuttings. An interval with extremely fine cuttings might be an indication of a fault zone, but can also have numerous other reasons (WOB, bit-type, lithology, etc. Natural fractures may be identified with a caliper log (if acquired), and from mud losses.	• (Macroscopic) Cuttings analysis • Caliper log • Mud losses / Loss of circulation
6: Is the reservoir I inject in, the same reservoir as I produce from?	Whether the composition and texture of the reservoir at the production and injection side of a doublet are the same, can be determined by comparing the GR logs and the cuttings from both the producer and injector wells. The cuttings can be analysed by performing thin section petrography and XRD. Biostratigraphy can also help to identify whether certain intervals of the wells are from the same formations.	• GR log • Thin section petrography on cuttings • XRD • Biostratigraphy
7: How do I identify the fines present in e.g. a filter?	Fines in the borehole might result in major production problems. To identify the source of the fines, the fines need to be identified and characterized. This can be done by combining LPSA, XRD and EDX. This provides information on the grain size (useful for determining the filter mesh size) as well as confirmation on the source of the material, e.g. whether it may have been derived from the formation or not. In case palynomorphs are present in the fines, biostratigraphy can be performed to determine the source interval of the fines.	• LPSA • WR XRD • XRD • Biostratigraphy
8: How do I identify scaling and corrosion products?	Scaling and corrosion material detached from the casing and collected after e.g. a scraper run can be analysed by XRD and by performing SEM/EDX analysis. The material retrieved from downhole samples are first to be analysed for bulk composition since scale products are likely to be mixed with other particles such as e.g. formation material, drilling mud additive and artefacts. It is best to compare downhole samples against data of the actual reservoir rock (e.g. cuttings) to distinguish between reservoir and non-reservoir material, including potential scale products.	• XRD (for crystalline minerals) • EDX (for amorphous material)