"Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in deep geothermal drilling"

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DELIVERABLE D2.1
"Project Specifications"

ABSTRACT

The main objective of the ORCHYD project is to improve drilling rate of penetration (ROP) in deep geothermal formations that are naturally exposed to extreme conditions of pressure and temperature. To achieve this, ORCHYD will implement an innovative technique combining slotting of peripheral grooves using a high-pressure water jet (HPWJ) and the destruction of the central rock core using a percussive drilling process. The jetting action causes stress relaxation of the rock in the immediate vicinity of the action of the drilling bit. In order to demonstrate the potential of the new drilling technique targeted by ORCHYD, it is essential to assess its performance in rock formations frequently encountered in deep geothermal projects, in particular, those exhibiting a very high resistance to the drilling process, thus inducing very low ROPs. Therefore, the objective of this report is to specify the most interesting drilling contexts and conditions to derive the maximum benefit from the technique devised within ORCHYD. This report allows the selection of conditions and materials for the experiments defined in the project, in terms of rocks and drilling conditions. This report is divided into the following parts: 1) a global presentation of the European geological context linked with geothermal energy; 2) presentation of relevant past, ongoing or future deep geothermal projects to make accurate selection of the types of rock for ORCHYD project investigations; 3) description of the selected rocks representative of such geological contexts and interesting difficult drilling conditions; 4) description of the drilling conditions in order to emulate them in the corresponding experimental setup to study the proposed drilling technique; and 5) presentation of a model for well drilling calculation costs, to assess the impact of the developed technology.

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1 European geological context for deep geothermal energy

In Europe, the different geological environment eligible for geothermal drilling, as (Ungemach et al., 2014) points out, can be gathered into 6 groups as the following and are mapped as presented in Figure 1. Ungemach et al., (2014) describes the reservoir engineering approach in term of low, medium and high enthalpy geothermal resources which correspond to geological settings.

A. Active subduction zones, volcanic island arcs, ocean ridge, recent or active extensional horst and graben settings hosting high-enthalpy volcano-tectonic structures (Central Tuscany, Iceland)
B. Recent "in plate" Pliocene/Quaternary volcanism (Catalunya, Chaine des Puys, …)
C. Large sedimentary units (Paris, Netherlands, North Germany, Denmark, Pannonia, …)
D. Tertiary-quaternary continental rifts (Rhine Graben, Limagne, …)
E. Orogenic fold-belts and foreland platforms often associated with deep faults
F. Crystalline massifs with hot springs and hydrothermal fault systems (Iberica Meseta, Central France, Sweden and Norway massif, …)

In the active subduction zones, volcanic island arcs (brown arc in Figure1), ocean ridge, recent or active extensional horst and graben (group A, in yellow in Figure 1), as in recent "in plate" Pliocene/Quaternary volcanism (group B not visible at the scale of this map), the geothermal gradient is high, so the geothermal reservoirs are often not very deep, requiring drilling of moderate length wells. Such geological settings represent a small fraction of the total viable settings since they are located only on limits of tectonic plates or in specific points.

Today, the sedimentary units (group C in purple and in pink in Figure 1) are quite well known to be made up of rocks of variable lithologies that are often not highly resistant to drilling operations, except when they are located at very great depths (because of high hydrostatic pressures and geostatic stresses that increase their strength and ductility).

In these geological settings, a large number of geothermal energy exploitation sites already exists. Often connected with a geothermal district heating, they are gathered and located on the GeoDH database and GIS tool with the help of European funds.

Thus, it is estimated that most interesting potential in Europe is located primarily in the geological settings of group D (dark grey), E (red) and especially F (light blue) that are composed of crystalline rocks. These low permeability rocks can only be exploited by EGS (Enhanced Geothermal System) technology, provided that the costs of drilling these rocks of very high resistance even at shallow depths are reduced.

These geological contexts are mainly in the metamorphic and crystalline rocks of the Variscan chain, which form a major part of the bedrock of Central and Southern Europe. (Variscan orogeny ended in Permian age: - 250 Million years before present.) These geological settings represent a large part of the European surface as potential geothermal reservoirs, as indicated by the conclusions of the European MEET (Multi-sites EGS Demonstration) project, whose ambition was to demonstrate that the production of electricity and heat from these different types of sites is technically feasible and economically viable. The European map shown in Figure 2 illustrates demonstration sites and potential transfer sites selected by MEET European projects to represent case study settings.

The MEET project presented a detailed classification of these Variscan geological contexts located in central Europe, but as this classification could not include northern Europe, we'd rather use the more extensive description of (Ungemach et al., 2014) presented above. Indeed, in northern Europe, similar crystalline rocks and geological settings are also encountered but their age is different because they belong to Caledonian orogeny which ended during Devonian: - 390 Million years ago. These crystalline formations of pre-Carboniferous age may be outcropping or buried under sediments of varying thickness, but most often of little thickness. Thus, in southern Sweden, the bedrock is only locally covered by a layer of a few meters' thick glacial deposits or soil (see Figure 3).

Due to the rock characteristics - very hard and or abrasive - these geological settings are the cause of the great difficulty of drilling and exploitation of geothermal reservoirs. Indeed, until now, the main disadvantages of EGS in these geological settings are related to the high costs of drilling and a relatively low experience due to the very limited number of power or thermal plants in operation.

In order to define the types of rocks and the drilling conditions of interest for the ORCHYD project, we give below a synthesis of some geothermal projects developed in these geological settings.

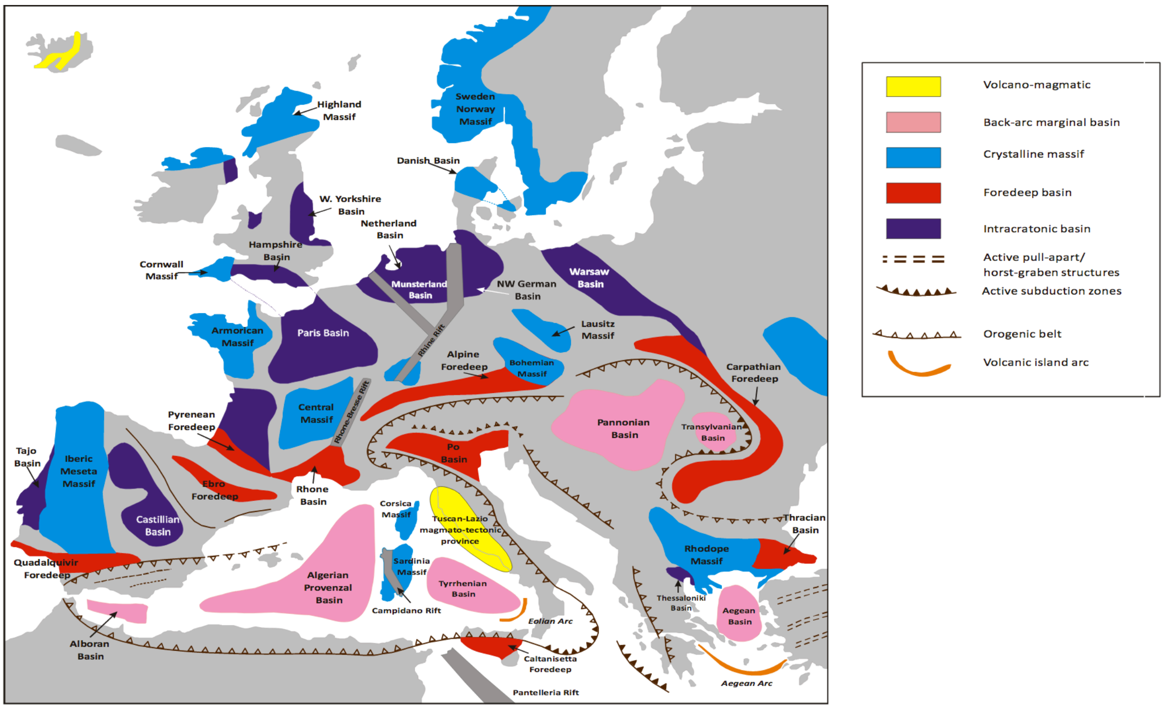

Figure 1. European geodynamic environments (PS. Danish basin should be colored in purple). (Ungemach et al. 2014).

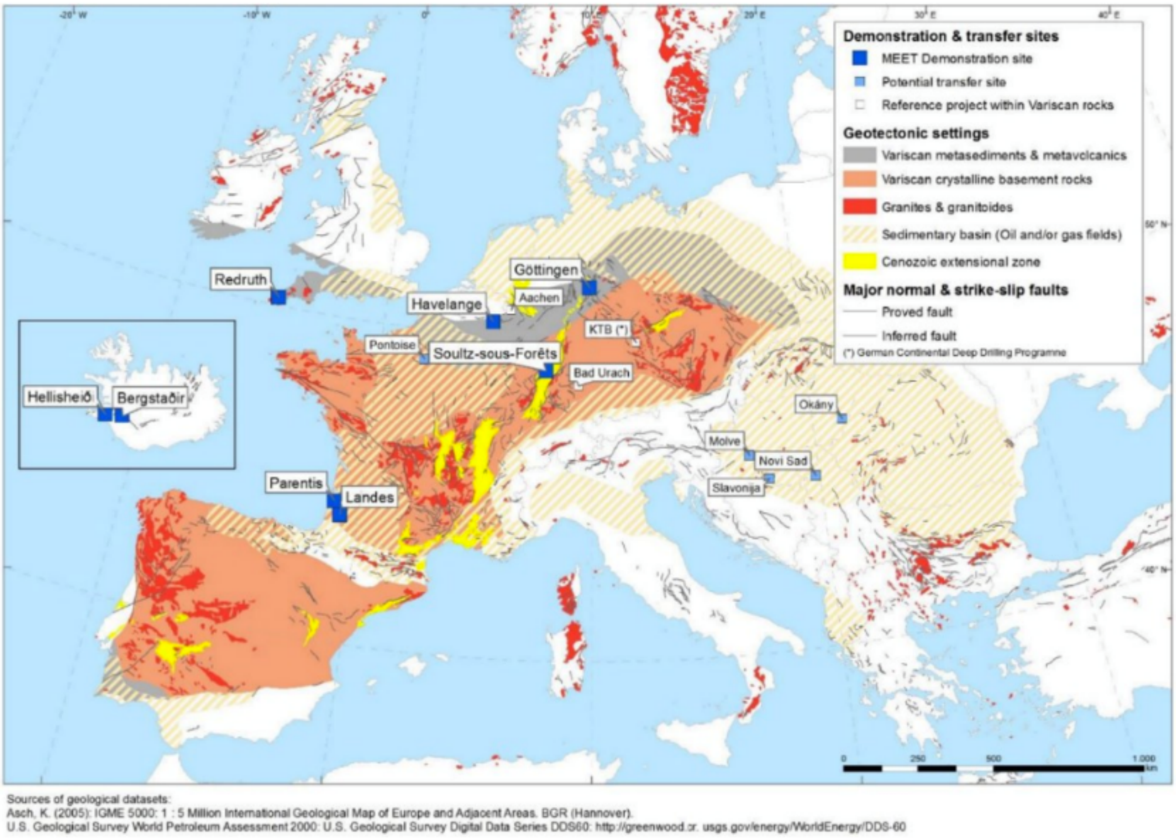

Figure 2. Illustration of the distribution of the Variscan basement in Europe, showing the vast extent of the crystalline massifs where granites predominate. (Trullenque et al. 2018)

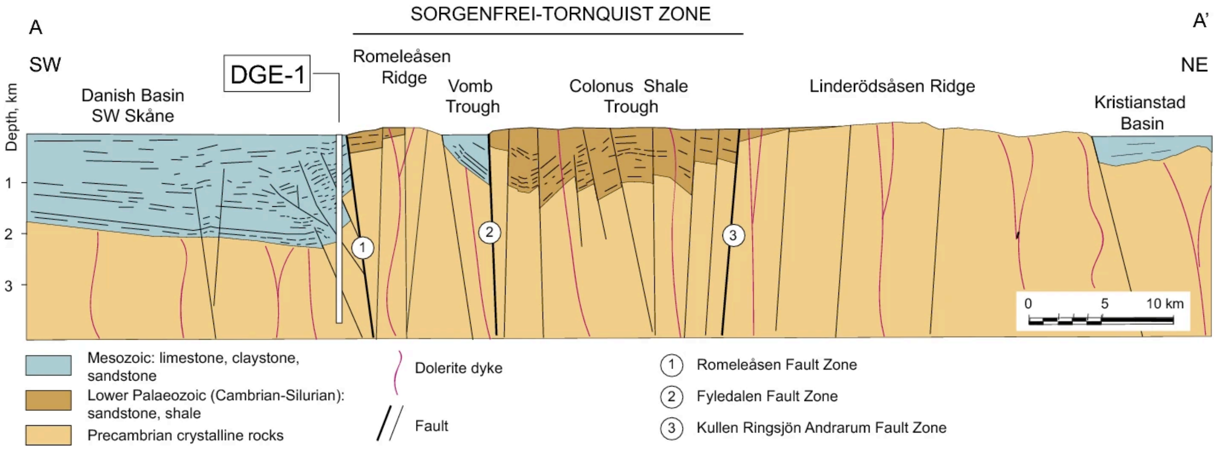

Figure 3. Geological sectioon of Skåne in the south of Sweden showing basement and outcrops of similar rocks. (Rosberg et Erlström 2019)

2 Analysis of the geological setting of major geothermal projects and their drilling performance

2.1 Soultz sous forêt

2.1.1 Location and geological setting (an example of Type D Tertiary-quaternary continental rifts)

The site of Soultz sous Forêts is probably one of the most studied sites worldwide for deep geothermal energy with an EGS technique. Several well-documented wells (BRGM, 2005) have been drilled there at depths of up to 5 km. The Soultz project site is located in the Upper Rhine Graben (western part for Soultz) as well as other geothermal projects such as Rittershoffen (France), Insheim (Germany) and Basel (Switzerland) (Ungemach et al., 2014) (Baujard et al., 2017).

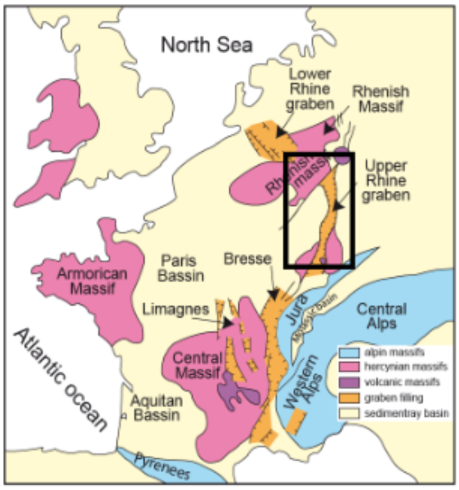

Figure 5. Upper Rhine garben location.

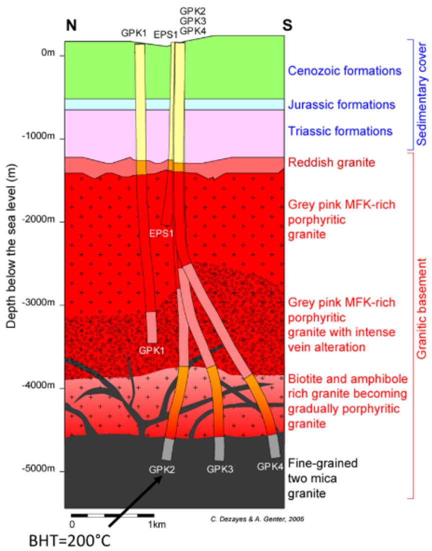

Figure 4. Geological section

The geothermal reservoir of Soultz is located in a low permeable naturally fractured and hydrothermalized granite primarily related to major faults and fracture zones which, in turn, are connected to dense networks of small-scale structures (Dezayes et al., 2010). Figure 5 shows a view of the geology at Soultz. After a sedimentary cover of about 1500 m, the wells were drilled in hard granite formations to a final depth of 5,000 meters. The basement is composed mainly of porphyritic granites while the reservoir is composed of fine grained two mica granite.

2.1.2 Drilling performance

In the framework of the European funding project THERMODRILL, (Baujard et al., 2017) studied the different deep boreholes drilled in the Upper Rhine Graben and presented the ROP measurements obtained in the different wells (Figure 6) with roller cone rotary drilling. Low ROP, below 5 m/h, can be seen in most cases, mainly in deep fine granite in Soultz project.

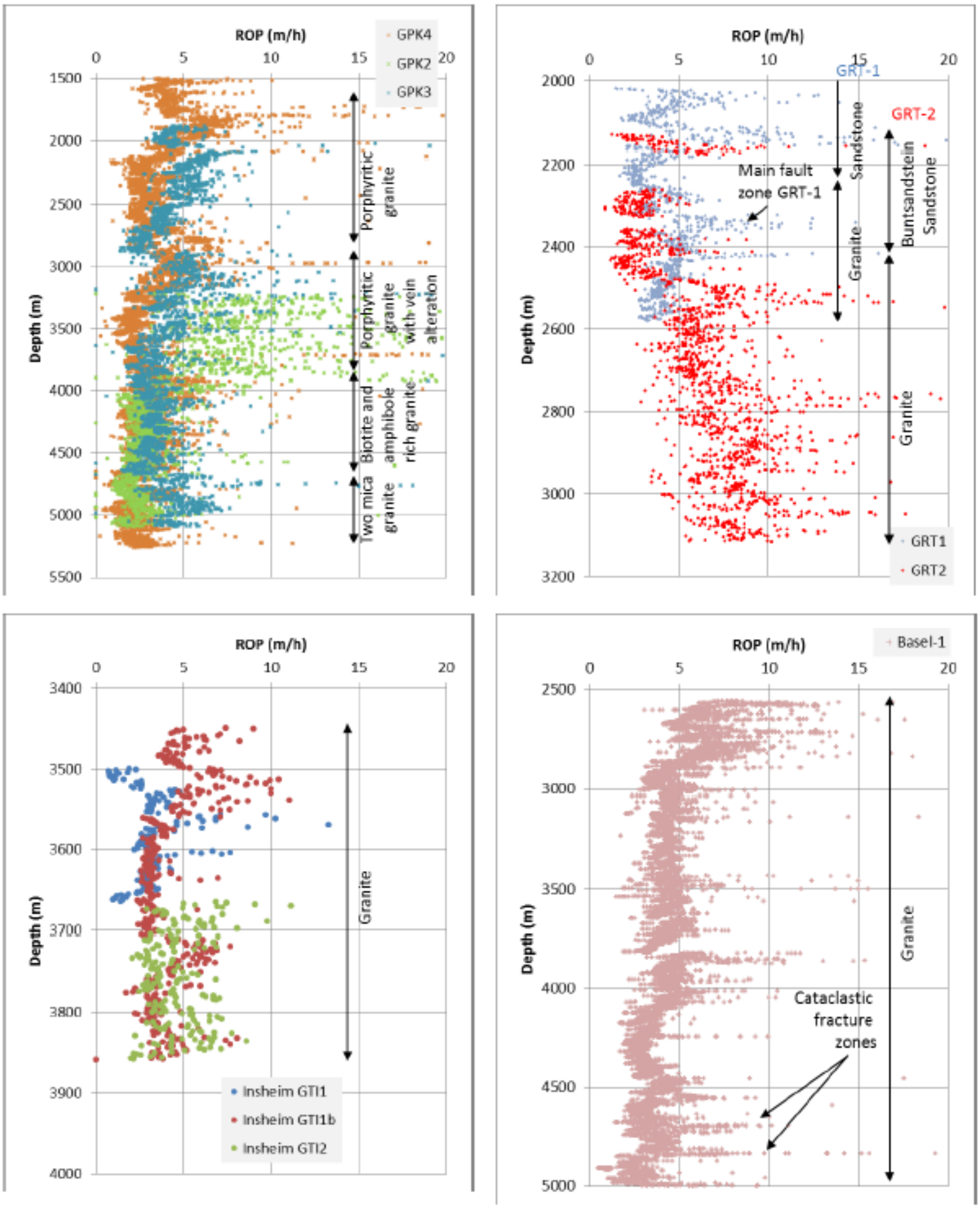

Figure 6. ROP values of the drillsite in the Rhine graben: Soutlz-sous-Forêts (upper left); Rittershoffen (upper right); Insheim (lower left) and Basel (lower right). (Baujard et al., 2017)

A decrease of the ROP with depth can be observed as well as an average value less than 3m/h above 3,500 m drilling depth. Baujard et al., (2017) also points out that the high ROP values were obtained in altered granite zones. It can be also observed in Rittershoffen drilling operation that the cover rock, sandstone, is difficult to drill and exhibit low ROP to about 3 m/h.

Note: After each example, our analyses are provided in italics font format.

In such geological setting, the basement may be composed of granites with various grain size, and varying degrees of weathering and fracturing. Apart from some drilling sections in altered rocks, the ROPs remain low, especially at great depth in fine-grained granites, as well as in deep sandstone formations.

2.2 Espoo, Finland

2.2.1 Location and geological setting (an example of type F Crystalline massifs)

The company St1 is constructing the first industrial-scale geothermal heat plant in Finland, in the region of Espoo, with the capacity of up to 40 MW. The most important goal of this pilot project is to develop and test technically and financially profitable solutions for all work phases of the geothermal business concept so that it can be commercialized. One of the challenges was to drill two wells:

- ❖ Two simulation wells reach the depths of about 6,4 km making them the deepest geothermal wells in the world.
- ❖ One observation well OTN-2

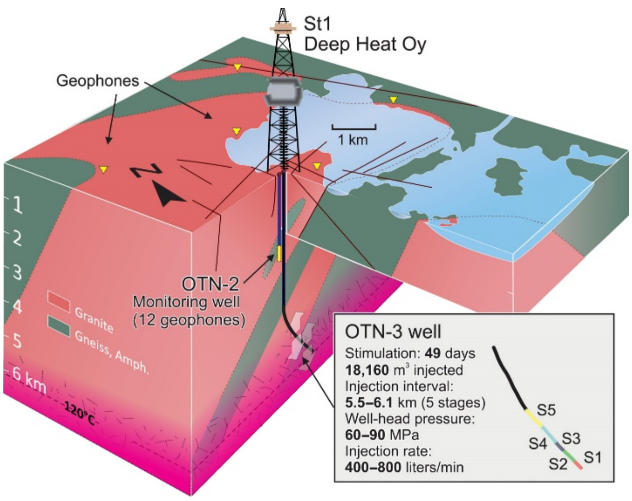

Figure 7. Schematic view of the St1 Otaniemi project.

Both wells were drilled in crystalline Precambrian Svecofennian basement rocks consisting of granites, pegmatites, gneisses, and amphibolites with an indicated measurement of uniaxial compressive strength (UCS, a measure of rock strength) value of up to 560 MPa (typical UCS in Helsinki region varies between 250 – 400 MPa).

2.2.2 Drilling performance

The drilling of the production wells first utilized air hammer drilling technology (often referred to as DTH drilling) to reach a depth of 4.5 km. Then, drilling into the hard bedrock was continued using both water hydraulic hammer and conventional rotary roller cone bits. The first well took 24 drilling days and 44 BHAs (Bottom Hole Assemblies) to reach the targeted depth with an average ROP of 2m/h. In addition, abrasive wear was also identified as the primary break down mode (Cardoe et al. 2021).

Figure 8. Roller cone bits completely destroyed after drilling the St1 well (Cardoe et al. 2021).

This is an example of drilling into very aggressive rock formations combining high hardness and abrasiveness. This last characteristic is related not only to the quartz content of the rocks but also to their size and angularity. The granitic rocks encountered have various textures, considering that pegmatites are encountered and have grains of centimetre size. The gneisses (resulting from the metamorphism of an initial granite), were also part of the crystalline rocks encountered while drilling. These crystalline rocks combining high hardness, high quartz content and a wide range of grain sizes, were very difficult to drill with existing drilling techniques. This resulted in excessive wear and frequent failure of the drilling bits, very low ROP, and therefore the need to frequently pull up the drill string to replace the drilling bits. These difficult drilling conditions lead obviously to long drilling times and excessive costs.

2.3 Iceland Deep Drilling Project (IDDP) at Reykjanes

As discussed in (Friðleifsson, Elders, and Albertsson 2014), the aim of the Iceland Deep Drilling Project was to drill into supercritical geothermal systems and examine their economic potential (>374 ◦C and >221 bars of hydrostatic pressure, increasing with increased salinity). The IDDP was established in the year 2000 by a consortium of three Icelandic energy companies, HitaveitaSuðurnesja (now HS Orka hf), Landsvirkjun and Orkuveita Reykjavíkur, and Orkustofnun (OS) (the National Energy Authority of Iceland). In December 2015, the plans for the IDDP-2 had been accepted as a part of the EU H2020 program DEEPEGS, with an international oil and gas company, Statoil, (now known as Equinor) to participate in the IDDP consortium until 2020.

2.3.1 Location and geological setting (an example of type A ocean ridge)

In 2016 and 2017 the geothermal well RN-15/IDDP-2 was drilled in the Reykjanes geothermal field, in southwest Iceland (Figure 9). With a total measured depth of 4650 m the well RN-15/IDDP-2 marks the deepest well drilled in Iceland to date and the hottest geothermal well (more than 426°C) reaching supercritical fluid conditions. Drilling was completed in 168 days by deepening the pre-existing production well drilled in 2004 to a depth of 2507 m.

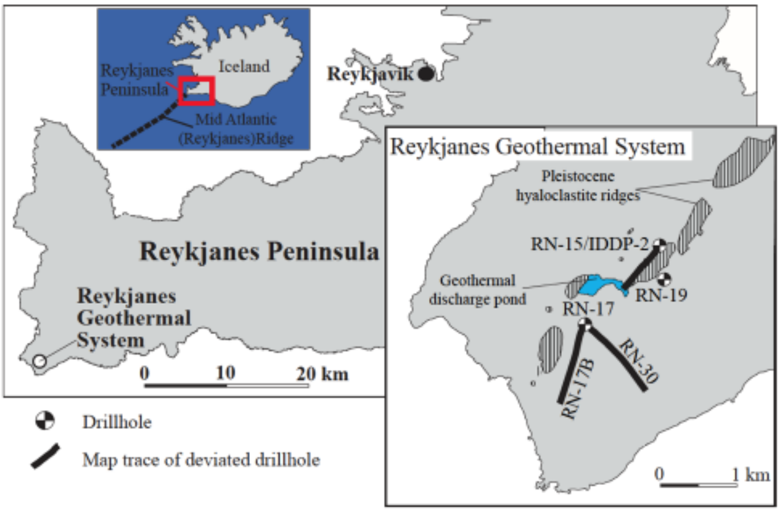

Figure 9. Location map of the Reykjanes geothermal system and location of IDDP drilling activities (Zierenberg et al., 2017).

As cementing was not successful, drilling had to continue without any return of drill cuttings to the surface from a depth greater than 3200 m, except for drill cuttings that were intermittently sampled between 3000 and 3200 m depth. Consequently, the drill cores (Figure 10) are the only deep rock samples recovered from the well. Friðleifsson et al. (2017) give a description of the IDDP-2 well: analysis of drill cuttings indicates that the uppermost section of RN-15 down to about 1400m is dominantly volcanic rock with interbedded zones of basalt flows, basalt breccia, pillow lavas, and hyaloclastite. The zone from 1400 to 3500m depth is, therefore, interpreted as the transition zone between overlying volcanic rocks and an underlying sheeted dike complex. And finally, the zone below 3500 m is basalt sheeted dike complex.

2.3.2 Drilling performance

There is very little information on drilling performance through basalt as the greatest difficulties encountered during drilling were the loss of mud and sticking of the drill pipes. However, in the final report of WP 6.8 of the DEEPEGS project, ROP less than 5 m/h can be noted above 3500 m. Another important point concerns the difficulty and the low ROP obtained during these coring operations (Table 1).

This is an example of a project in volcanic rocks exploring very hot zones, with major problems linked above all to the very high temperatures which poses exceptional challenges in terms of cementing, drilling fluid circulation, well stability, equipment, etc. This particular geological context located on an oceanic ridge obviously presents a magnificent geothermal potential and often requires wells to be drilled at a depth of less than 1 km to reach temperatures of 200°C. Naturally, it is expected that the technology targeted by the ORCHYD project will contribute to improve the ROP in this type of site, however, the limited extent of this type of resource and the shallow depth of the reservoirs, make these contexts not the first priority for ORCHYD whose primary ambition is to contribute to extend the potential of geothermal resources by reducing the costs of very deep drilling.

Table 1. Overview of the 13 core runs attempted in well RN-15/IDDP-2 at Reykjanes (after DEEPEGS, 2020)

Core run	Start	Coring interval	Cored length [m]	Drilling time [h]	ROP [m/h]	Core recoverd [m]
1	18.9.2016	3068,7-3074,1	5,4	7,12	0,8	0
2	4.10.2016	3177,6-3179,0	1,4	2	0,7	0
3	30.10.2016	3648,0-3648,9	0,9	5	0,2	0,52
4	2.11.2016	3648,9-3650,7	1,8	10,25	0,2	0
5	11.11.2016	3865,5-3869,8	4,3	8,5	0,6	3,85
6	12.11.2016	3869,8-3870,2	0,4	2,5	0,2	0,15
7	22.11.2016	4089,5-4090,6	1,1	2,25	0,5	0,13
8	28.11.2016	4254,6-4255,3	0,7	5,5	0,1	0,28
9	6.12.2016	4308,7-4309,9	1,2	3	0,4	0
10	7.12.2016	4309,9-4311,2	1,3	8,25	0,2	0,22
11	16.1.2017	4634,2-4642,8	8,6	1,25	6,9	7,58
12	17.1.2017	4642,8-4652,0	9,2	1	9,2	9
13	19.1.2017	4652,0-4659,0	7	0,75	9,3	5,58
Total			43,3			27,31
				Core recovery about 63 %		

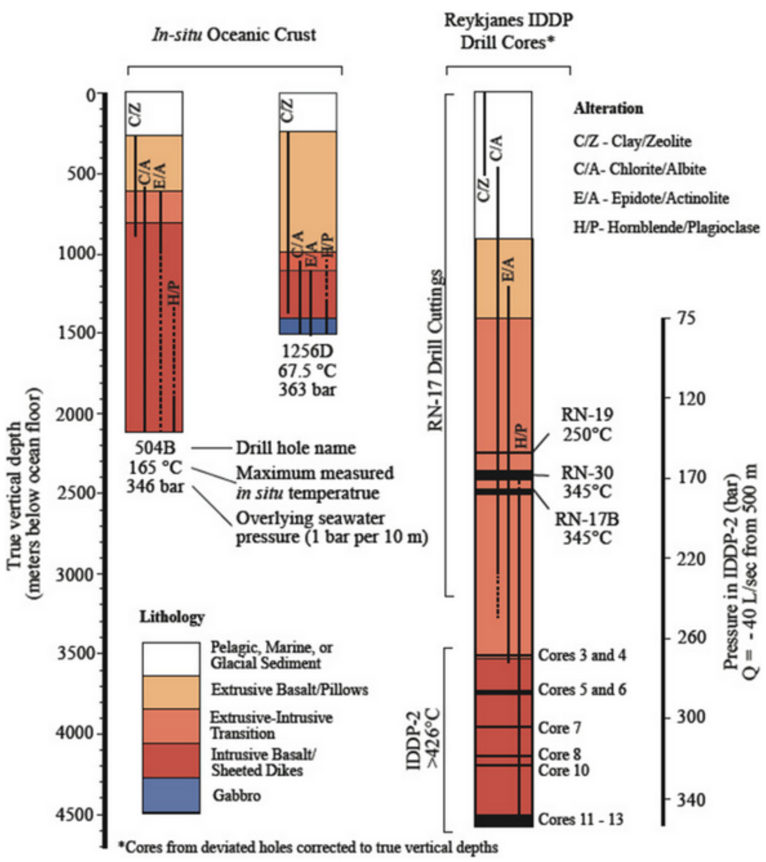

Figure 10. Comparison of alteration and rock types observed in IDDP cores from the seawater-recharged Reykjanes geothermal system to the two deepest holes drilled into in-situ oceanic crust (Friðleifsson et al., 2017).

2.4 Sweden

In Malmö, Sweden, E.ON plans to build a geothermal deep-heat power plant. The boreholes will be drilled five to seven kilometers deep into the ground. The expected maximum temperature of 160 °C will be sufficient to feed the heat directly into Malmö's district heating network. The pilot project is one of Europe's first geothermal power plants to extract geothermal energy from depths of several kilometers on an industrial scale.

On another hand, the bedrock of Skåne, the southernmost province of Sweden, has been targeted for geothermal feasibility studies since the late 1970s (Rosberg and Erlström 2019) and a deep exploration well, DGE-1, was drilled in 2001 at 3701 m after entering the fractured crystalline basement at 1946 m.

2.4.1 Location and geological setting (an example of type F Crystalline massifs)

The Swedish geology is mainly characterized by the massive Baltic shield with its crystalline bedrock with overlying sedimentary rock formations of significant thickness found in the southern part of the country, including the Malmö region. These formations contain porous sandstones at considerable depth with very good hydraulic properties, what is quite rare in northern Europe.

The crystalline basement of the DGE-1 well is dominated by various gneisses, granites, metabasites and dolerites and the repeated tectonic events in the Romeleasen Fault Zone have resulted in a severely fractured crystalline basement (Rosberg and Erlström 2019).

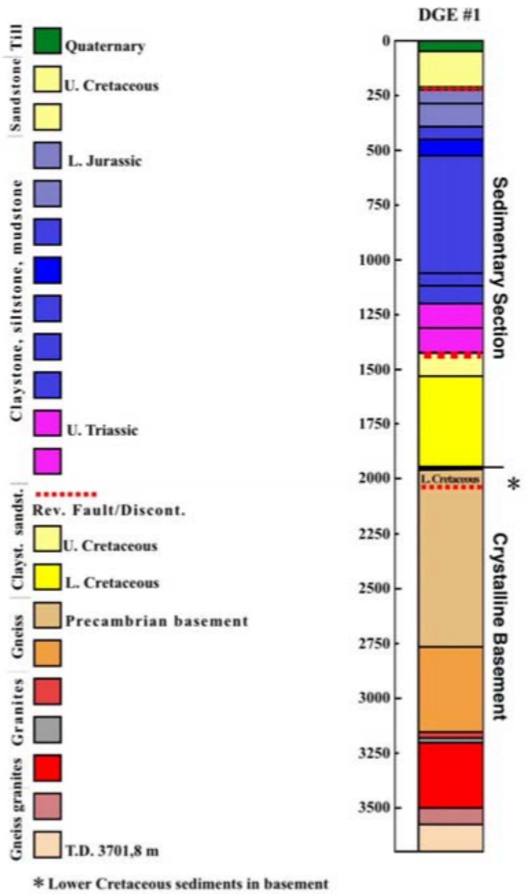

Figure 11. Lithology of well DGE-1.

2.4.2 Drilling performance

Only drilling information can be obtained from DGE-1 well (Bjelm 2006) where four different drilling method were used: conventional mud rotary drilling, air rotary drilling, percussion drilling with air hammer and percussive drilling with mud hammer. Drilling experiences were promising with both hammer methods but stopped rapidly due to a valve issue. In all, when drilling the crystalline basement, ROP was very low between 0.6 m/h and 2 to 4 m/h.

Air rotary drilling showed low ROP between 0.6 m/h and 2 m/h. Percussion drilling test was carried out between 2878 and 2972 m with higher ROP occasionally around 5 m/h and commonly around 4 m/h (Figure 12).

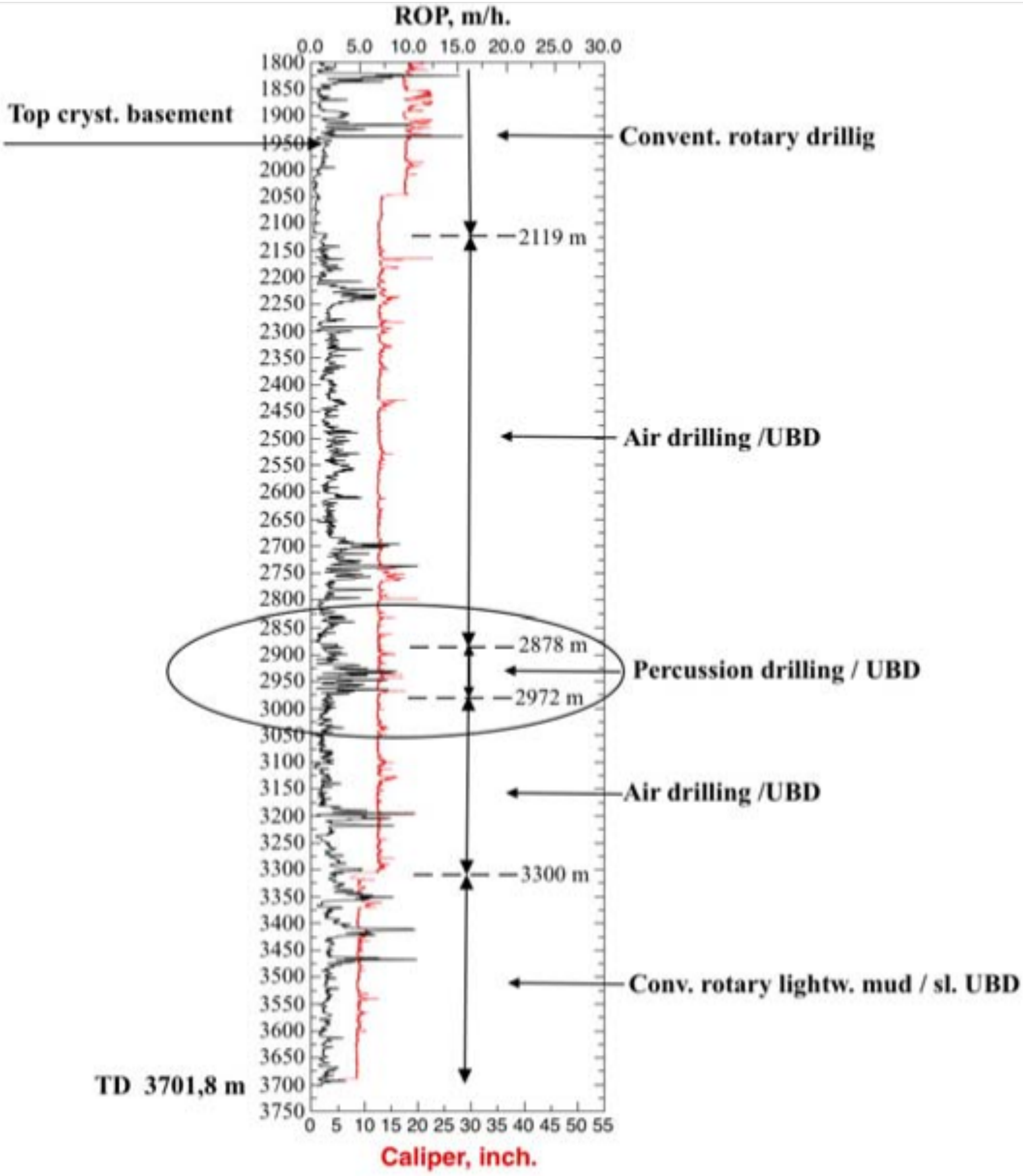

Figure 12. Drilling methods and respective rate of penetration.

As in the ST1 project in Finland, this example of geological setting is of great importance to ORCHYD, since it involves very deep drilling in various sedimentary and crystalline rocks with *very high resistance to drilling, resulting in very low ROP, making the economics of these deep projects questionable.*

2.5 Other planed deep geothermal projects

We have presented the main deep geothermal projects achieved or in progress. Other projects planned or under exploration may be interesting as application sites for the ORCHYD technology. It is therefore important to analyze the geological contexts of these new projects, particularly with a view to selecting for the ORCHYD program the rocks and experimental conditions representative of these sites.

Among the future projects, we can mention the Lavey-les-Bains project in Switzerland, where it is planned to drill a geothermal well to a depth of 3,000 m in gneiss over almost the entire borehole (Figure 13). Also, in Switzerland, the Haute-Sorne project (drilling of a doublet at a depth of 5,000 meters) where, after crossing the 1,500 m cover, 95% of which is made up of limestone and marl, the borehole will be drilled into the bedrock made up of gneiss and granite. Italy and Turkey are also main regions in Europe for deep geothermal activity.

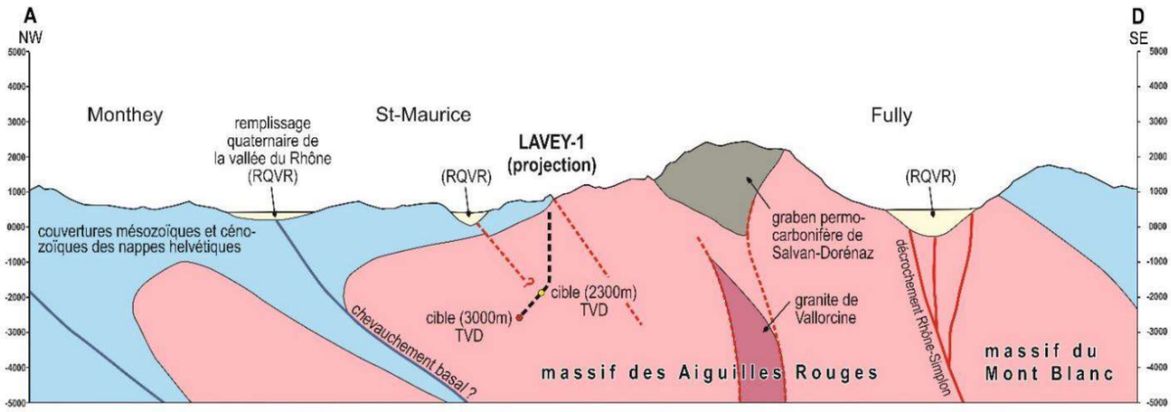

Figure 13. Geological section of Lavey-les-bains site.

In Italy, and especially in the highly depleted Toscane-Larderello area, the deep exploration and reinjection program showed the presence of permeable layers within the Metamorphic Basement, up to 3,000 – 4,000 m depth, with reservoir pressure and temperature increasing with depth up to 7 MPa and 350°C, respectively (Manzella et al. 2019). Recently, DESCRAMBLE project (Novel drilling technology and investigation of supercritical condition in continental Europe) funded by Europe through H2020 drilled at 2900 meters depth in extreme conditions (temperature of 500°C and 300 bars pressure).

In Turkey, deep reservoir explorations are going on for electricity production purposes. For this reason, deep drilling targets have reached up to 4500 m. The successful results have been obtained and deep marble reservoirs discovered (about 240°C) at Kizildere and Tekkehamam geothermal fields (Mertoglu, Şimşek, and Basarir 2016).

Moreover, it should be noted that the geothermal target for the Variscan metamorphic successions overprinted by younger extensional tectonics is partly composed of quartzites in which very low penetration rates of less than 1 m/h were achieved during the drilling of the Havelange well in 1981-1985 (Graulich, Leclercq, and Hance 1989).

In these last geological contexts metasediment = metamorphic rocks (originally sedimentary) are present as marble and quartzite.

3 Rock Selection for ORCHYD investigations

There are many examples of deep geothermal wells in Europe where developers of the EGS technique are seeking different geological settings to examine its efficacy. From the above review, it appears that igneous and metamorphic rocks are the most present and the most difficult to drill. Indeed, they generally combine the two main characteristics making very difficult their mechanical drillability, namely hardness and abrasiveness. The effects of these two characteristics of the rock matrix are even more detrimental to drilling performance, especially in low fractured rock. In these rocks, it appears that the ROP is still in the range of 0,5 to 5 m/h, with a short lifetime of drilling bits, often rendering the performances unacceptable. As ORCHYD's objective is to increase ROP in such formations, it appears that the main target for ORCHYD technology is **plutonic or igneous rocks**, mainly **granites which can be homogeneous or not, of fine, medium or coarse** grains.

For granite rocks, the average grain size determines the three types: fine (<1mm), medium (1-5mm) and coarse (>5mm).

Regarding the granularity of granite, there are three main factors at the time of crystallization that determine this. The density of the seeds which appear at the time of crystallization, the chemical composition of the magma and the rate of cooling.

An example is given in Figure 14 with the outcropping pluton or batholith of rapakivi granite dated at -1650 Million Years in which coarse and fine Balmoral Red granites are extracted. The granite termed 'fine-grained' also named 'even-grained' granite exists only in the small "bubble" of the extreme eastern part of the batholith. Typically, medium and coarse granites are located in the internal part of the batholith where the cooling rates were smaller during crystallization. (At that time, a thick cover of rocks, protected both granites from fresh air. Of course, with time, erosion, removed this cover.)

As future deep geothermal boreholes could be located in any particular part of a batholith, investigations of ORCHYD project must check efficiency of our tools in various grain sized granites.

Volcanic rocks and primarily **basaltic** rocks are also encountered in some geothermal drilling. Such materials are extremely fine grained or even glassy. The corresponding geological contexts, apart from Iceland are not widely encountered in Europe. The high thermal gradient of such sites complicates drilling operations but could reduce depth/length of wells, often less than 1 km. Such drilling conditions which must be studied carefully can greatly benefit from ORCHYD technology.

However, the limited extent of this type of exceptional resource and the shallow depth of the reservoirs, make these contexts not a first priority for ORCHYD whose primary ambition is to contribute to extend the potential of geothermal resources by reducing the costs of very deep drilling.

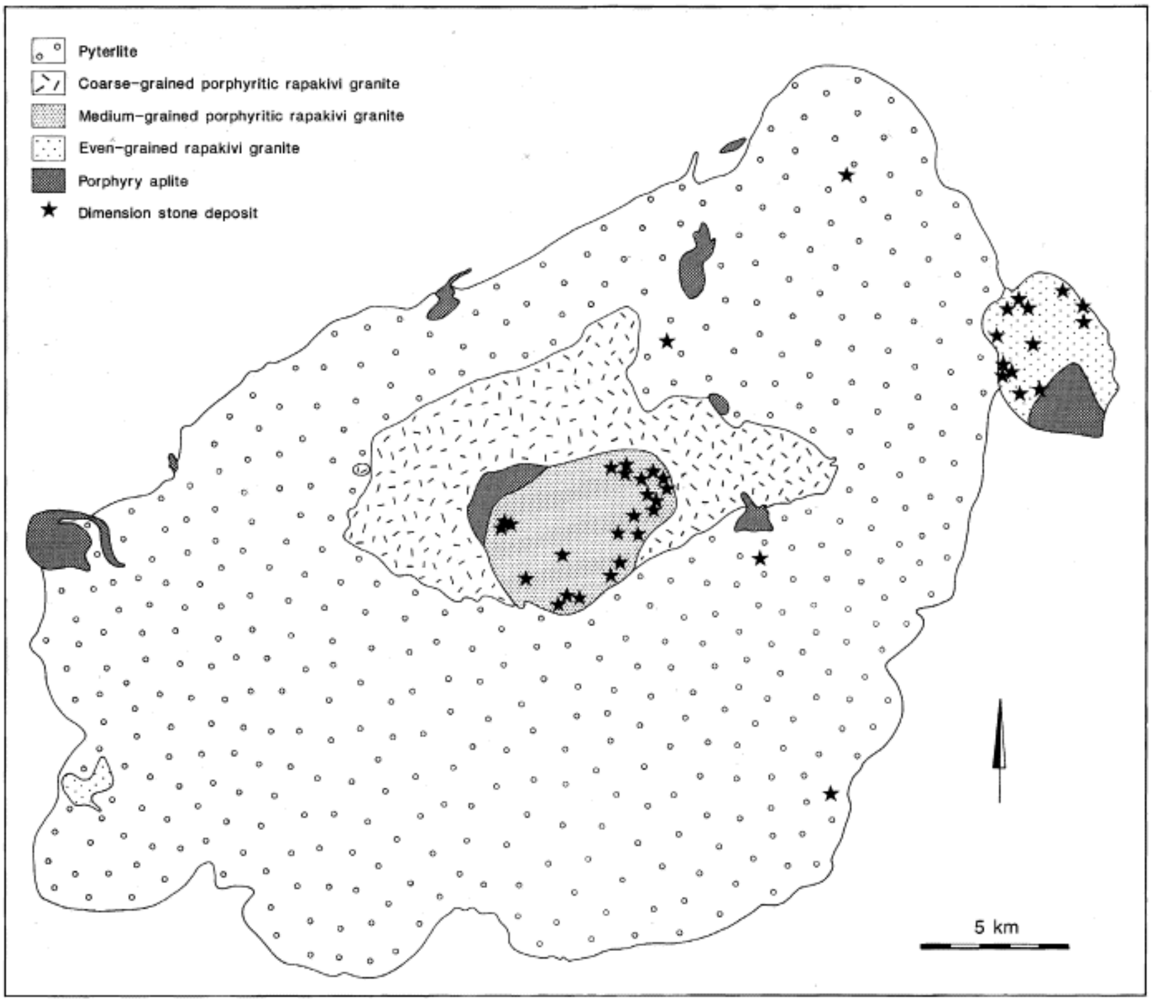

Figure 14. Geological map of the Vehmaa rapakivi granite batholith in Finland. The dimension stone deposits are marked by stars (Selonen, Luodes, et Ehlers 2000).

We have seen from the various examples presented above that **metamorphic rocks** are also encountered in European deep geothermal boreholes and that they cause low ROP. They can result from metamorphism of plutonic rocks as ortho**gneiss** with high content of very hard quartz. When they result from metamorphism of sedimentary rocks such as sandstone or limestone, the resulting **quartzite** and **marble** could be very hard and the ROP traversing such metasediment rock masses in the overburden or in the geothermal reservoir could be low. It is therefore wise to study such metamorphic rocks and optimize the response of the ORCHYD technology i.e. the coupling of HPWJ and percussive drilling in a drilling configuration allowing stress relaxation to occur to counter the increased in situ mean stress associated with deeper drilling.

The above analysis allows the selection, for the laboratory pilot drilling tests defined in the project, the group of rocks in which the effort to improve drilling speeds should be concentrated. We decided to consider in each type of rock formation, the most difficult rocks to drill, i.e. the most resistant intact rock, , presenting no or very few discontinuities or detectable defects, and preferably, very abrasive.

The literature cites fairly wide ranges of physical characteristics of such hard rocks frequently encountered in deep geothermal drilling. We can give the ranges indicated in the Table 2.

Table 2. Overview of physical characteristics of rocks.

Rock	Density	Porosity (%)	UCS (MPa)
Granite	2.4 to 2.8	0.5	100 to 280
Gneiss	2.6 to 2.8	1	120 to 300
Quartzite	2.5 to 2.7		70 to 230
Marble	2.6 to 2.8	0.5	100 to 150
Sandstones	1.8 to 2.8	10-30	3-160

Following, the analysis of the European geological context presented above and the associated geothermal potential, the drilling performance in geothermal sites in production and exploration, it was decided to retain a set of six rocks which will be presented below. Naturally, this choice is also conditioned by the possibilities offered to obtain a sufficient volume of rocks for the investigations planned within the framework of the ORCHYD project. However, if a supply failure is anticipated before the start of the tests, the selection of another available rock of the same type and with equivalent characteristics would be made.

3.1 Characteristics of selected rocks

Table 3 summarizes the principal physical characteristics of the 6 selected rocks. This choice is also guided by scientific reasons. In order to compare effect of rocks, it will be good to have rocks of the same hardness: same UCS. For example, to visualize the effect of UTS or the effect of grain size, the other parameters must be close or equal.

*Table 3. Physical characteristics of selected rocks (data provided by Geosciences Centre database except for *).*

Name of Rock	Type of Rock	UCS MPa	UTS MPa	Grain size min-max mm	Density	Sound velocity m/s	Porosity %
La Clarté*	Gneiss	164.0		< 0.2 mm	2.65		0.5
Saint Anne	Marbled limestone	176.8	7.0	< 0.4 mm	2.72	6425	0.7
Red Bohus	Granite	196.0	7.0	0.5 - 3 mm	2.62	5200	
Kuru Grey	Granite	201.5	12.5	0.3 - 1.5 mm	2.62	4210	0.33
Sidobre*	Granodiorite	221		2 – 10 mm	2.65	3960	0.5
Condroz	Quartzite	215.0	17.8	< 0.25 mm	2.63	5351	1.64

(UCS obtained on tests in which sample size is 50 or 70 mm and with length to diameter or width ratio equal to 1 in accordance with NF EN 1926 for which specimens could be cubic or cylindrical. In Geosciences databases, all tests are performed with cylindrical samples of 50 mm or 65 mm diameter and with length to diameter ratio equal to 2. Although strictly a granodiorite, for convenience in this work, it is grouped with and referred to as one of the three granites.)*

A granodiorite is an igneous rock belonging to the granite family in which Plagioclase feldspar is more abundant than Orthoclase or Potash feldspar.

Some triaxial tests have already been performed on many of these rocks in the Geosciences Center and other mechanical characteristics are available such as Young's modulus and Poisson's ratio.

3.2 Granites Red Bohus, Kuru grey, Sidobre Silverstar

Red Bohus granite (medium grained, UCS=196 MPa), is extracted in the south western part of Sweden near the cities of Brastad and Lysekil. The batholith dates from 922 million years, is 100 km long and 22 km wide (Andersson, Lie, et Husebye 1996)

Kuru grey granite (fine grained, UCS= 201 MPa), is outcropping in the central part of Finland between cities of Kuru and Kapee (Selonen, Luodes, et Ehlers 2000). The grey granite covers an area of 20 km^2 (central part of a larger batholith of 100 km^2). The batholith age is 1875 million years.

Sidobre Silverstar (coarse grained) is extracted near Saint-Salvy-la-Balme (Center of France) in the Plo quarry. The Sidobre batholith covers a surface of 200 km^2 and is dated from 304 million years (Le Mailloux, 2018).

Red Bohus granite is a light reddish rock, with clearly visible interlocking crystal grains, composed of feldspar (in white and pink, Fld) of the order of 60%, quartz (in grey) of the order of 35% and biotite (black) of the order of 5%. Feldspars have sizes that can be larger than a millimeter. Iron oxides coloured feldspar minerals in orange. No anisotropy is observable.

Kuru grey granite is a light grey rock with clearly visible interlocking crystal grains, , composed of feldspars (in white, Fld) of the order of 62%, [K feldspar 31.5 % - Plagioclase 30.4 %] quartz (in grey) 31.7 % and biotite (black,) of the order of 4 %, Muscovite 1%. These crystals are relatively close in size, on the order of a millimeter. No anisotropy is observable.

The granodiorite of the Sidobre Silverstar is mainly composed of:

- Quartz 20-35 %
- Feldspar microcline 15-20 %
- Feldspar plagioclase 35-45 %
- Biotite 5-10%
- Other minerals <3%

Quartz often appears in clusters of 5 mm connected in centimetre long chains. Microcline often appears in crystals of about a centimeter in size. Plagioclase are often between 2 and 3 mm and less than 1 cm. Grains of Biotite are typically 3 mm long. No anisotropy is observable.

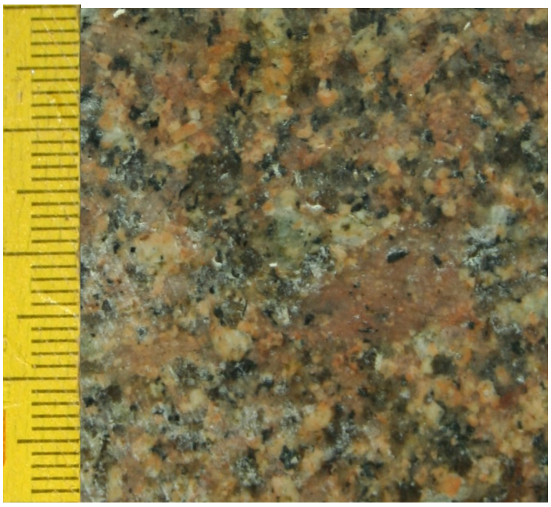

Figure 15. Red Bohus granite (picture under nature light).

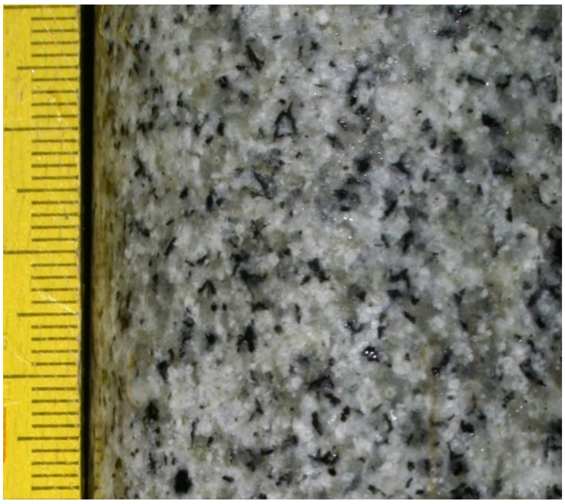

Figure 16. Kuru grey granite (picture under natural light).

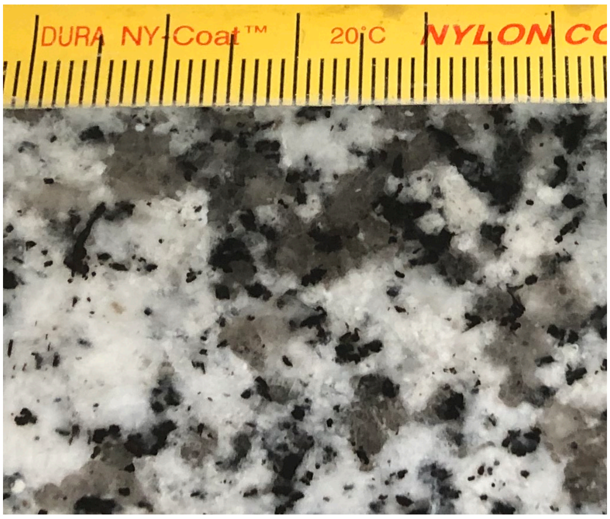

Figure 17. Sidobre Silverstar granodiorite (picture under natural light).

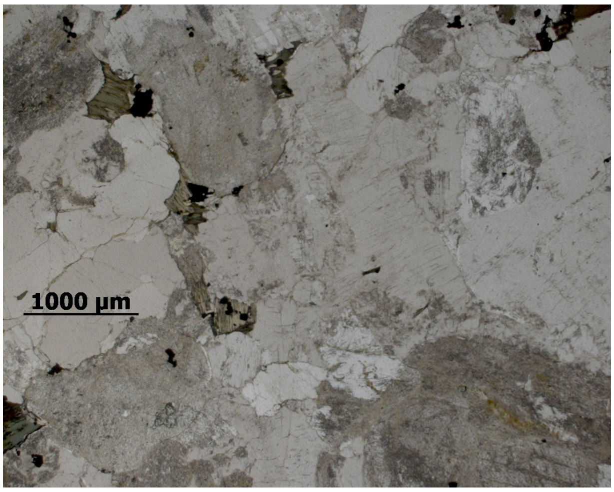

Figure 18. Red Bohus granite - grain size between 0.5mm and 3mm. It contains mainly quartz, feldspar and biotite (picture under cross polarized light).

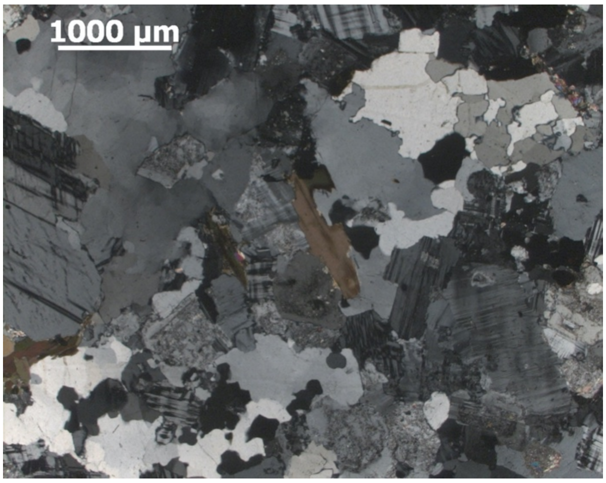

Figure 19. Kuru grey granite - grain size between 0.3mm and 1.5mm. It contains mainly quartz, feldspar and biotite (picture under cross polarized light).

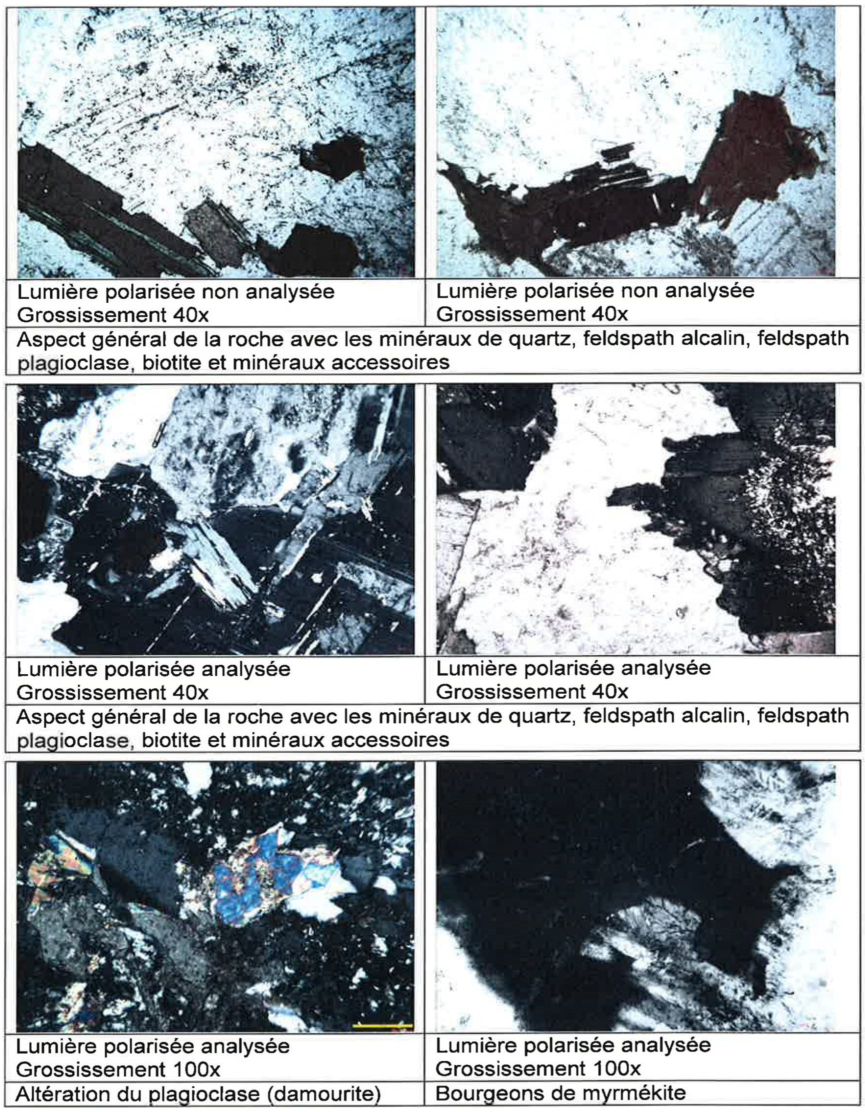

Figure 20. Silverstar grandodiorite of Sidobre (pictures under cross polarized light). Scale is written below each picture, size remains constant and with text in French, as requested by the Plo company).

The main mechanical difference between the Red Bohus and Kuru grey granites (which have similar UCS values) is the tensile strength: for Red Bohus it is 7 MPa, for Kuru grey 12.5 MPa. This difference is probably linked with the interlocking of the grains: the grains of Kuru grey granite have the shape of puzzle pieces, those of Red Bohus are more rounded (compare Figures 18 and 19).

Sidobre Silverstar is very hard, UCS in the same range of Red Bohus and Kuru grey though at present, no tensile strength data is readily available. The important point is that it has significantly larger grains than the two other granites with approximately the same laboratory scale strength so the effect of grain size can therefore be assessed. This source of rock is also readily available and completes the selected igneous isotropic rocks.

The three other rocks are metamorphic and for this reason they could have anisotropy. At the scale of laboratory, sample size is always quite small. To avoid a large impact of anisotropy and heterogeneity on consistency of test results, we selected metamorphic rocks with very fine grain size.

Figure 21. Puzzle pieces interlocked.

3.3 Orthogneiss La Clarte

This rock is extracted by Charier Company to produce gravels or blocs near the city of Herbignac in Brittany in the Variscan chain (France). This part of the chain is Hercynian and dates from 360 million years. The geological setting is close to the geological setting of the geothermal project of Lavey-les-Bains in the Alps (Switzerland).

Observation with a polarizing optical microscope (Figures 22 and 23) shows the presence of quartz, feldspars and phyllosilicates. The porphyroblastic texture of the sample (bigger feldspar crystals than quartz crystals) shows shear schistosity markers with sigmoidal shapes (rotating porphyroblasts). The material can be classified as an augen-gneiss. The petrographic compositional analysis indicates:

- 62.6% sensitive minerals in alkaline medium (microcrystalline quartz, flint, etc.)
- 3.4% plagioclase feldspar
- 20.5% alkali feldspar
- 0.4% micaceous minerals of black mica type (biotite) in the process of chloritization
- 11.7% phyllosilicate minerals (e.g. illites)
- 1.4% opaque minerals and metal oxy-hydroxides.

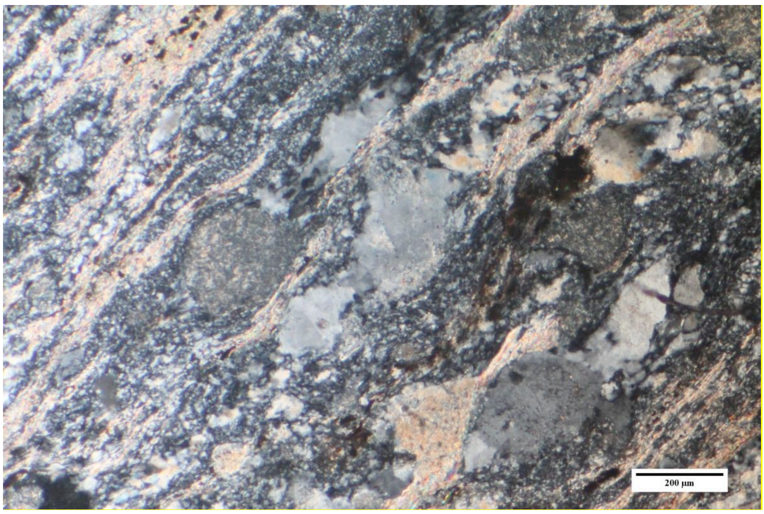

Figure 22. Orthogneiss of La Clarte - grain size less than 0.2mm. It contains mainly quartz, feldspar and biotite (picture under cross polarized light).

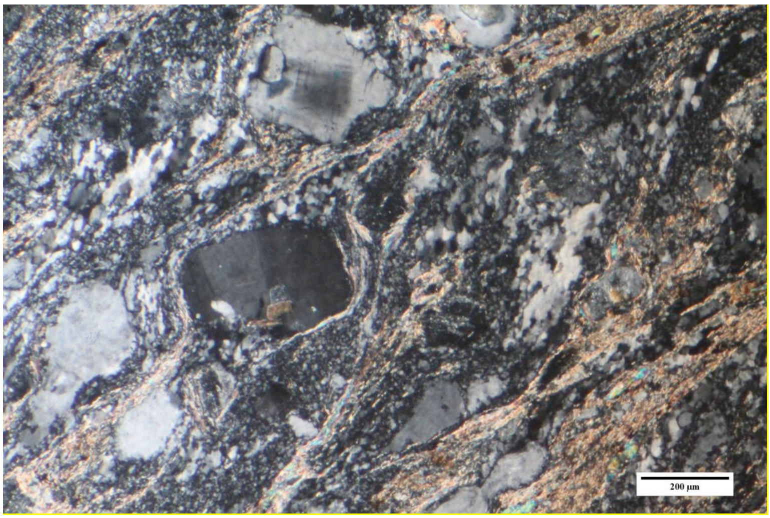

Figure 23. Orthogneiss of La Clarte. During metamorphism, minerals transform, and a new organization of the texture is visible (picture under cross polarized light).

3.4 Quartzite of Condroz

This rock belongs to upper Famennien age (360 million years – in upper part of Devonian period). Greyish to greenish, the fine-grained rock is composed mainly of quartz and feldspars of more or less equi-granular size and of detrital origin. The quartz grains of relatively narrow size range are interlocked. The high UCS is comparable to the strongest granite however the tensile strength is much higher (UCS 215 MPa and UTS 17.8 MPa), the high quartz content and tensile strength suggest this will be the most problematic rock to drill through. However, a distinct but not strong foliation is observable in thin sections (see Figure 25) underlined by the streaks of white micas (muscovite, Mus). Any mechanical anisotropy effects are considered likely to be relatively insignificant but can be taken into account in the initial characterization research of the samples to be used in ORCHYD. At normal scale (Figure 23), the rock appears isotropic and the grain size is not detectable. With a microscope (Figure 25), a texture with preferred orientation can be picked out by the alignment of mica crystals. Minerals have size smaller than 0.25 mm.

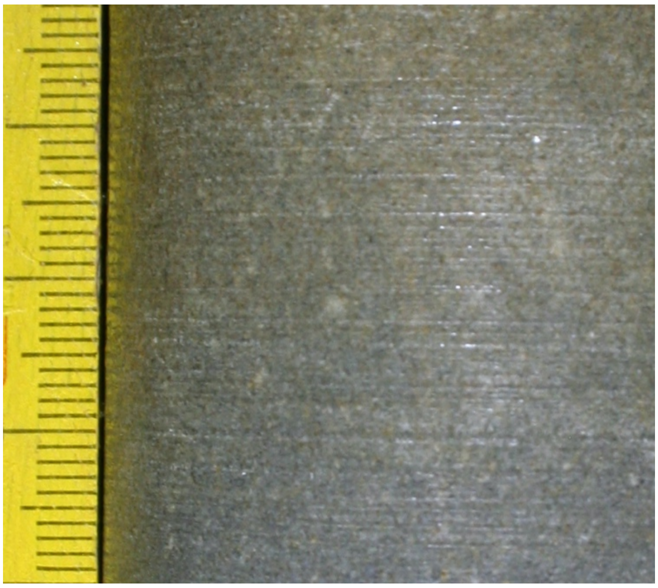

Figure 24. Condroz quartzite (picture under natural light).

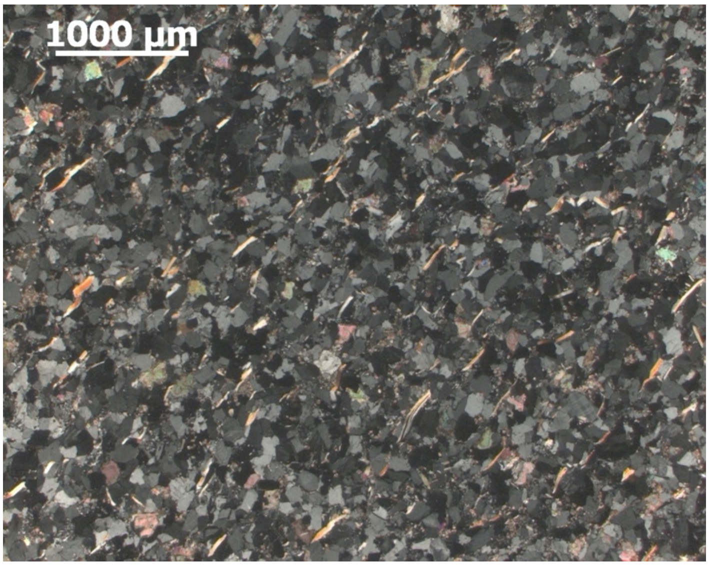

Figure 25. Condroz quartzite - grain size inferior to 0.25mm. It contains quartz, feldspar and elongated white mica (picture under cross polarized light).

3.5 Marbled limestone of Saint-Anne

The rock belongs to Barremien Age (125-130 million years) in Lower Cretaceous period. This marbled limestone (Figures. 26 and 27) is a massive rock of light grey to bluish grey, containing numerous calcareous bioclastic debris (shells, corals ...) of variable size (in white) embedded in a very fine calcareous matrix (also called micrite, in grey). Stylolites (due to the pressure - dissolution deformation mechanism) are dispersed in the rock block. It is typical of brecciated rock and such networks of stylolites are a tectonic marker indicating often crenulated sites where insoluble components are left behind after the carbonate has gone into solution under the tectonic pressures. They extend roughly normal to the former maximum stress direction, but the crenulate form tends to prevent them from acting as flaws and sites of weakness. At the scale of the laboratory sample, they form a random network. The largest bioclasts are millimetric but the calcareous cement between them is very fine, with grain size lower or around 0.01 mm. At this laboratory scale, the rock could be considered as isotropic and is very hard with UCS reported as 177 MPa. This rock presents a relatively low ratio (UTS/UCS) compared to that of the selected Condroz quartzite, which may be an indicator of its greater brittleness, a favorable characteristic for rock failure under dynamic loading such as that applied by percussive tools. It would also be interesting to compare this rock with granites with similar mechanical characteristics.

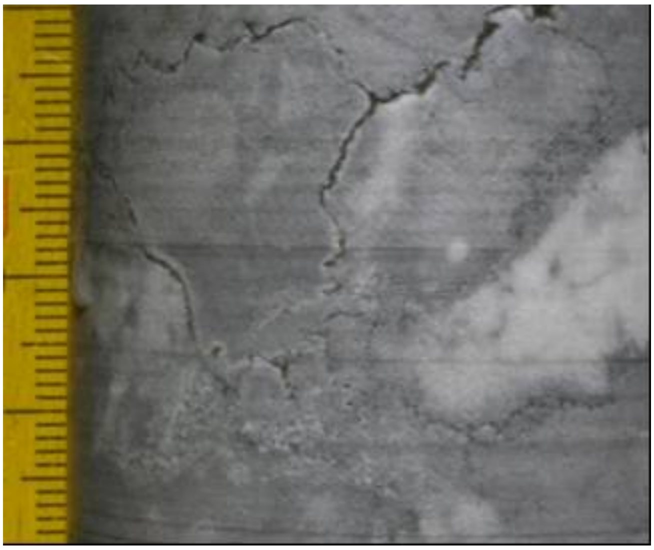

Figure 26. Marbled limestone of Saint-Anne (picture under natural light) with some stylolites (see arrows) and bioclasts.

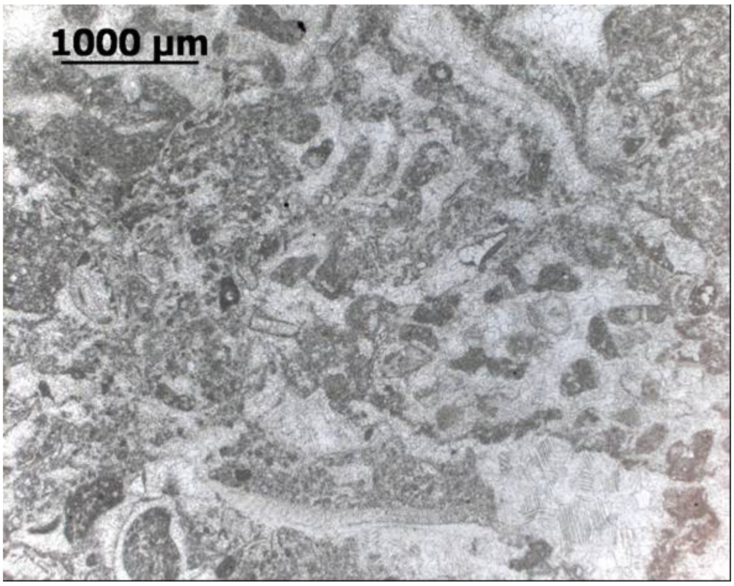

Figure 27. Marbled limestone of Saint-Anne Micrite, Bioclastic - grain size is from 0.02 to 0.4 mm. It contains mainly Calcite: $CaCO_3$ either in bioclasts or in the micritic cement (picture under polarized light).

4 Drilling conditions for ORCHYD investigations

In order to assess and optimize the performance of the ORCHYD system, a large drilling test program in the selected rocks is planned, covering all the technical Work Packages, from WP4 to WP8. A detailed plan of tests specific to each WP will be elaborated. The aim here is to define the general conditions of the drilling tests so as to allow them to reproduce as closely as possible the real downhole conditions for which the ORCHYD system is intended.

This involves specifying the conditions under which the rocks will be drilled. This concerns the drilling fluids to be used and the pressure and temperature regimes designed to reproduce the conditions of deep drilling operations.

The drilling tools that will be used as well as the operating parameters and the physical quantities to be measured, to assess the drilling performance, will be presented in the specific test programs for each WP.

4.1 Drilling Fluids

The drilling fluid has several roles in the drilling process: transport to the surface the rock chips created by the drilling tool at the bottom-hole, cooling of the bit, stabilization of the well being drilled, control of pressures in the well, transmission of measured data to the surface, activation of certain drilling equipment such as downhole PDM motors, percussive hammer, steering systems, etc.

In geothermal drilling practice, the most commonly used fluids are water (alone, aerated, with or without foam) and Water-Based Mud (WBM). To reduce problems due to mud losses, chemical additives of various types are most often added to the mud, which extends and improves the performance of these WBM. In the ORCHYD project, it is planned to experiment with three fluids to keep the experimental variables to a manageable number and to include one based on graphene based additives. These present a good alternative to chemical additives for fluid loss control in deep boreholes, as they can produce a strong mudcake to prevent fluid losses into the formation rock. Moreover, a range of graphene based fluids may be studied in WP 6.3 as part of the testing and characterization programme. However, the impacts of using these fluids with new solid additives compared with using clean water or WBM fluids when drilling still need to be evaluated in terms of processes and mechanisms: rock drillability mechanisms, downhole bit cleaning, creation of high-pressure water jets, etc. Similarly, it must be verified that the use of these additives does not lead to problems of plugging of any components of the drilling systems (hammer, HPWJ nozzles, intensifier).

4.2 Simulated depths and associated pressures and temperatures

The project targets deep drilling of 4 to 6 km. The Armines test benches have the versatility of being able to simulate such conditions by reproducing several types of pressure regimes.

The bottom-hole pore fluid pressures at these depths will be about 40-70 MPa. Experimental rigs that can apply a cell pressure up to these values to confine the fluid and rock under jetting conditions are available at Armines. Moreover, the mean stress at such depths is typically up to 100-150 MPa. The Armines Vertical Drilling Bench –VDB- (using full-scale drilling bit) and the Single Cutters Tester –SCT- (using single cutting tooth) can apply independently a confining stress and an axial stress on the specimen being drilled of up to 100 MPa for the SCT (70 MPa for the VDB), while also delivering the necessary high drill fluid pressures. This allows to get an accurate approximation of the pressure conditions encountered during drilling at the targeted depths.

All the selected rocks are of very low permeability. To help simulate their behaviour under saturated conditions, the option of applying vacuum conditions to aid pre-saturation will be considered.

In addition, deep geothermal formations can reach temperatures, above 200°C. Under these conditions, exchanges between the drilling mud and the formation leads to an increase in the temperature of the circulating mud, which is continuously monitored in order to control and design the drilling fluids, cement, and all drilling and completion equipment. An important question for ORCHYD is whether such temperature within the rock affects the process of HPWJ slotting and the hybrid hammer system's drillability of the selected rocks. Thus, an advantage of the laboratory facilities at Armines is that rock samples can be heated up to 250°C when simultaneously subjected to high confining stress and fluid pressure regimes. It would therefore be ideal to accommodate in the research testing programme a series to simulate in-situ conditions combining high temperature, overburden pressure and hydrostatic mud pressure while drilling with the proposed new hybrid drilling system.

5 Model of well construction costs

In order to be able to assess the impact of the project results on the well construction costs specific to deep geothermal projects, a model is required. The influence of saving drilling time, the tools and drilling bits consumption and the associated costs will be taken into account in the model and compared to previous projects conducted using traditional rotary drilling. A sensitivity analysis is then conducted to identify the critical variables.

5.1 Structure of the model

The cost model is built in an Excel sheet and decomposed into multiple tables starting from the general information and then focusing on the details. For ergonomic purpose, the inputs and outputs of the model are classified in different tables of different colours.

Estimating the total cost of a geothermal plant project is a complex task. Extensive work has been done in that way by Idaho National Laboratory and summarised in the Geothermal Electricity Technology Evaluation Model (GETEM) (Mines, 2016). It includes obviously the drilling of the geothermal well, the investment cost of the power plant with operating and maintenance but also less direct cost such as exploration, permitting, taxes, etc. Two types of power plants can be studied, either binary or flash-steam based on the resource.

Our model is focussing on the direct economic impact of the ORCHYD project, that is the construction of the well(s). It is a major part of a geothermal project in terms of time, cost and risk. For high temperature geothermal projects, the well building cost is often estimated to be above 40% (Thorhallsson et al., 2012) or even 50% (Yost et al.,2015) of the total investment. Of course, this percentage is very variable from one project to another as it increases exponentially with the well depth (Lukawski et al., 2016). In any event, a change of the drilling performances and thus of drilling operation cost will have a significant impact on the whole project. The first table of the model is dedicated to this matter. The estimated cost of the geothermal project is assumed to be known and used as an input to study the impact of ORCHYD's results. It is then compared to the total well building cost calculated further in the model, to deduce the percentage of the well construction cost on the total.

The inputs include data on the well structure, the depth of geothermal wells (usually ranging between 3,000 and 7,000m deep) and the length to drill in hard rock sections which is an important input as it is the area of interest for the drilling tools developed in ORCHYD's framework. The wells are composed of drilling sections with various diameters starting wide (26" for example) down to narrower holes. The number of sections is specified here, as a drilling cost per section is further defined.

The cost of constructing a well can be decomposed into three main components (Kipsang, 2015):

- Pre-drilling operations: this includes site preparation, rig mobilisation, rig move and rig-up;
- Drilling costs, that will be detailed further;
- Casing and completion costs.

Pre-drilling operations costs as well as casing and completion costs are fixed inputs to the model, as they do not depend on the drilling technology used. The drilling costs are divided in a daily rig rate, the cost of the drilling equipment and the cost of services. We assume the project may influence only the drilling time and the used drilling equipment. Therefore, a daily rig spread rate is used in the model. It includes the rig rental with crew, rental tools, consumables supply (water, diesel, lubricating oil, drilling mud, …) and various services (drilling supervision, civil, reservoir and geological engineering, logistics and logging).

Casing and completion costs are also out of scope for this model. Nevertheless, they can be easily estimated based on unit costs available in the literature. For example, the cost of cement is then calculated based on the volume needed, and the casing cost depends on the length and diameter of the section (Kipsang, 2015).

5.2 Drilling cost model

As previously mentioned, the drilling cost is divided into a number of sections of various diameters. The drilled well may include sections in different rock formations with different hardnesses. The drilling cost for the sections drilling in soft rocks are inputs for the model. The sections costs in hard rocks are calculated based on the following inputs:

- The daily rig spread rate;
- A unit mean tripping time (in and out, given in hours);
- The rate of penetration (ROP);
- The bit unit cost and its lifetime;
- The cost of the innovative tools introduced in the bottom hole assembly (BHA), in our case the hammer and intensifier, and their respective lifetime;
- A daily supervisor rate required to use these specific tools. This cost is therefore not included in the daily rig spread rate.

The first output of the model is the number of main drilling equipment components used, such as bits (B), hammers (H) and intensifiers (I). They are cal culated following:

i = B,H,I
$$number\ of\ i\ used = \frac{length\ to\ drill\ in\ hardrock}{i\ life * ROP} \quad (1)$$

The result is rounded up to the upper whole number. Tripping operations are required every time an equipment needs to be replaced. Nevertheless, only the tool that needs to be replaced the most will trigger a tripping operation: the other tools can be replaced alongside. For example, if the drilling bits dulls twice as fast as the intensifier, the intensifier will be replaced every two tripping operations, along with the bit. There will then be as many trips as bits used. Tripping time (in days) is therefore calculated as:

$$tripping\ time = \frac{\max\,(i = B, H, I\ ;number\ of\ i\ used) * unit\ tripping\ time}{24} \quad (2)$$

Drilling time in days for the section is given as a function of ROP by:

$$drilling\ time = \frac{length\ to\ drill\ in\ hard\ rock}{ROP * 24} \quad (3)$$

Total time is simply the sum of tripping and drilling time. Based on these outputs, the costs can be calculated. The cost of drilling equipment is given by:

$$drilling\ equipment\ cost = \sum_{i=B,H,I} i\ unit\ cost * number\ of\ i\ used \quad (4)$$

The overall supervising rate is equal to the supervisor rate multiplied by the total time for the section drilled in hard rock. The total rig spread cost is calculated as follows:

$$rig\ cost = (drilling\ time + tripping\ time) * rig\ spread\ rate \quad (5)$$

The total drilling cost for the section is finally given by:

$$total\ section\ drilling\ cost = drilling\ equipment\ cost + overall\ supervising\ cost + rig\ cost \quad (6)$$

This result is then used to calculate the total drilling costs (sum of all sections) and finally the total well building cost.

5.3 Case study

The main objective of the cost model is to be able to evaluate the budgetary impact of introducing the new drilling system including hammer and intensifier in the BHA, by comparison with traditional rotary drilling. A precise evaluation will only be possible at the end of the project, knowing the actual properties of the developed tools (lifetime, cost, reached ROP, …). At this early stage, a preliminary study can be conducted, based on an evaluation of the expected results. A sensitivity analysis can then be made as included below, to assess the influence of variations of the relevant parameters.

5.3.1 Deep geothermal Soultz-sous-Forêts project: well GPK-3

This preliminary study is made based on the rather well documented example of the well GPK-3, drilled in 2003 at Soultz-sous-Forêts in the Rhine Graben in France. It was drilled alongside other wells in the framework of a European EGS project, which aimed to exploit the heat contained in deep fractured granite. The well was drilled down to 5 km depth and reached a rock temperature of 200 °C (Cuenot et al., 2008). It is divided in four sections. The first and second ones, down to 574 m and 1447 m are drilled in sedimentary rock at diameters of 24" and $17^{1/2}$" respectively. From that point, granite is reached and the hole is drilled at $8^{1/2}$" down to 5101 m and reopened to $12^{1/4}$" down to 4580 m (Baumgärtner et al., 2000). Between 2681 and 3180 m, directional drilling was done using a downhole mudmotor. A total of 33 tricone bits have been used, working an average of 40 hours each and reaching an average ROP of 3.5 meters per hour (Baumgärtner et al., 2000). Seven bits have been used to drill the two first sections, leaving 26 bits for the hard rock section. Two bits have been rerun, so a total of 35 tripping operations have been conducted. The total well building cost was 5 815 000 € (Augustine et al., 2006).

Some data are outputs from the model in the case of a projected drilling operation. The information that has been gathered about the drilling of GPK-3 now becomes an input to the model, for example the number of bits used or the total well building cost. The model is adapted accordingly to determine missing data.

The reaming of the hole to $12^{1/4}$" has been done while drilling the $8^{1/2}$" section. This case being studied only for comparison purposes with the percussive and HPWJ combined technology, the reaming is not taken into account as it would probably be the same in both cases. Therefore, a unique section from 1447 m to total depth is considered.

A rig spread rate of 55 000 € per day is considered and the unit tripping time is averaged to nine hours. The first section of the well has been drilled in 100 h, using two drill bits in 24". Taking also into account tripping time, the calculated cost is 310 417 €, considering a bit unit cost of 20 000 €. Similarly, the cost of the second section is 737 500 €. It was drilled in 255 h using 5 bits in $17^{1/2}$" estimated to cost 10 000 € each.

An estimation of the cost of pre-drilling operations for a 3000 m geothermal well is given by Kipsang (2015). 70 000 $ are attributed to drill site preparation and 420 000 $ to rig mobilisation, demobilisation and transport. Following this, converting dollars to euros, a total of 410 000 € is associated to pre-drilling operations. Casing and completion costs are more difficult to evaluate. Knowing the actual total well building cost, it can be deduced from all the other values. The resulting value of 1 092 083 € seems consistent with the 720 000 $ given by Kipsang (2015) for a shallower well.

5.3.2 Percussive & HPWJ drilling projection

The real costs building the GPK-3 well, conducted with rotary drilling, will be compared to projected costs of what could have been done with the combined technology of percussive drilling and high-pressure water jetting. As mentioned above, a supervising rate associated to the use of these specific tools is introduced. It is estimated at 500 € per drilling day.

Based on previous studies on the separate technologies, the unit cost of the tools and their expected lifetime can be estimated as in Table 4. A specifically designed drill bit will also be designed during the project.

Table 4. Projected cost for BHA tools with Percussive & HPWJ drilling.

Hammer unit cost	50 000 €
Hammer life	100 h
Intensifier unit cost	90 000 €
Intensifier life	120 h
Bit unit cost	20 000 €
Bit life	30 h

These values enable the calculation of the number of each key equipment component required to drill the hard rock section and therefore the total equipment cost and the tripping time. A projected ROP of ten meters per hour is used. This assumption and those in Table 4 are addressed later in the sensitivity study.

5.3.3 Comparison

To evaluate the impact of the introduction of the combined technology in the BHA, a comparison is made over the various outputs of the model, not only in terms of costs, but also of drilling time and equipment used. The actually rotary drilling case history data is used as the reference. Table 5 summarises the main parameters relevant for the comparison.

Table 5. Comparison of Rotary drilling vs Percussive & HPWJ projected drilling – GPK-3.

	Rotary drilling	**New technology**	**Variation**
Number of bits used	26	13	-50 %
Tripping time (day)	13	5	-63 %
Drilling time (day)	44	15	-63 %
Drilling equipment cost (€)	130 000	820 000	+531 %
Rig cost (€)	3 135 000	1 155 000	-63 %
Total section drilling cost (€)	3 265 000	1 985 500	-39 %
Total drilling cost (€)	4 312 917	3 033 417	-30 %

Even though the bit used with rotary drilling has a longer projected lifetime (40h compared to 30h), the number of bits used to drill the hard rock section with the combined technology is 50

% lower, due to the higher ROP. Drilling and tripping time are divided by more than two, hence the rig cost is also reduced by 63 % compared to the amount spent with rotary drilling. On the other hand, the cost of the used drilling equipment is significantly increased (more than five times). Fewer drilling bits are required but the unit cost of the specific drill bit, designed for percussive operation with high pressure nozzles, is necessarily higher. On top of that, the cost of the integration of the Mudhammer and the intensifier in the BHA is significant. Nevertheless, regardless of this equipment cost increase, the total cost of the section **drilling is reduced by 39 %**, leading to a saving of 1.3 million euros on the total drilling cost.

This analysis is conducted with estimated values of the equipment cost, lifetime and resulting ROP. The impact of variations on these parameters is conducted in the next part.

5.4 Sensitivity analysis

The project results may have an impact on some parameters used in the previous case study. The hammers, intensifiers and bits unit cost will be determined by the chosen design. Their respective lifetime may be optimised, along with the rate of penetration. In order to determine the critical parameters and the effect of a variation, a sensitivity analysis is conducted.

5.4.1 Influence of the ROP

The first analysis is conducted over the ROP value. The ROP targeted by ORCHYD is in the range 4-10 m/h, with the new hybrid technology, in hard rock. For this case study, we analyse a variation of ROP between 2 and 15 m/h, around the value of 10 m/h considered as a first assumption in the case study above. The impact on the cost is illustrated in Figure 28.

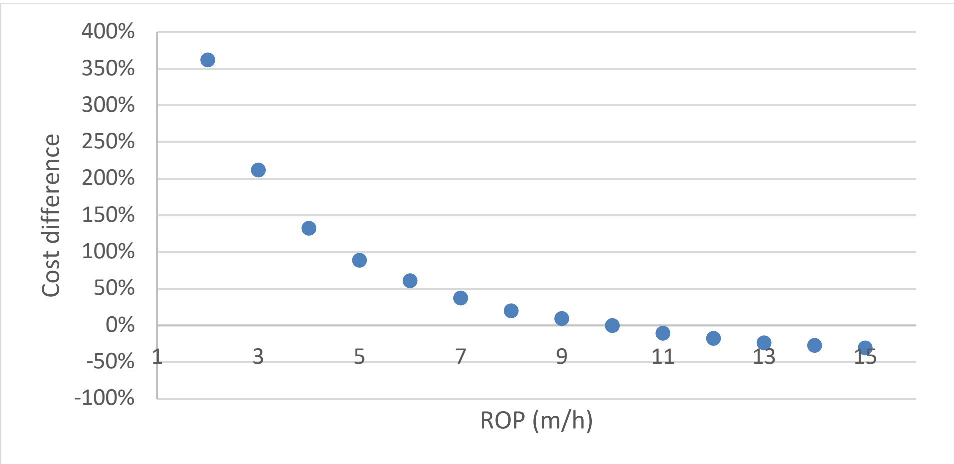

Figure 28. Variation of the total section drilling cost with respect to ROP.

It can be noticed that a change from 4 to 5 m/h leads to a cost decrease of more than 20%, whereas only 7 % when going from 9 to 10 m/h. Nevertheless, to compensate for the increase in drilling equipment cost with the new technology, the bottom line or minimum value of 5.8 m/h of ROP needs to be reached in order to start to show a cost benefit over the slower 3.5 m/h achieved with rotary drilling. Indeed, with a ROP value lower than 5.8 m/h, the total drilling cost for the section in hard rock becomes higher than the actual cost with the rotary technique. This result would be different when compared with wells drilled in very hard lithologies where rotary mud drilling speeds remain in the range of 1 to 2 m/h. For GPK-3, the average ROP of

3.5 m/h used in this calibration exercise is already quite high for rotary drilling and might be due to a pre-fractured granite basement, easier to drill. In such fractured rock conditions, reaching 10 m/h with the tools developed in ORCHYD's framework might be a quite conservative assumption.

5.4.2 Variation of the equipment unit cost

The cost of the hammers, intensifiers and bits will be directly influenced by the building constraints imposed by the coupling of these technologies. Even though an estimation was made, the actual cost may vary according to the project orientation. A fluctuation of the cost, in the range -30 % / +30 % around the estimated value has been investigated and is illustrated in Figure 29.

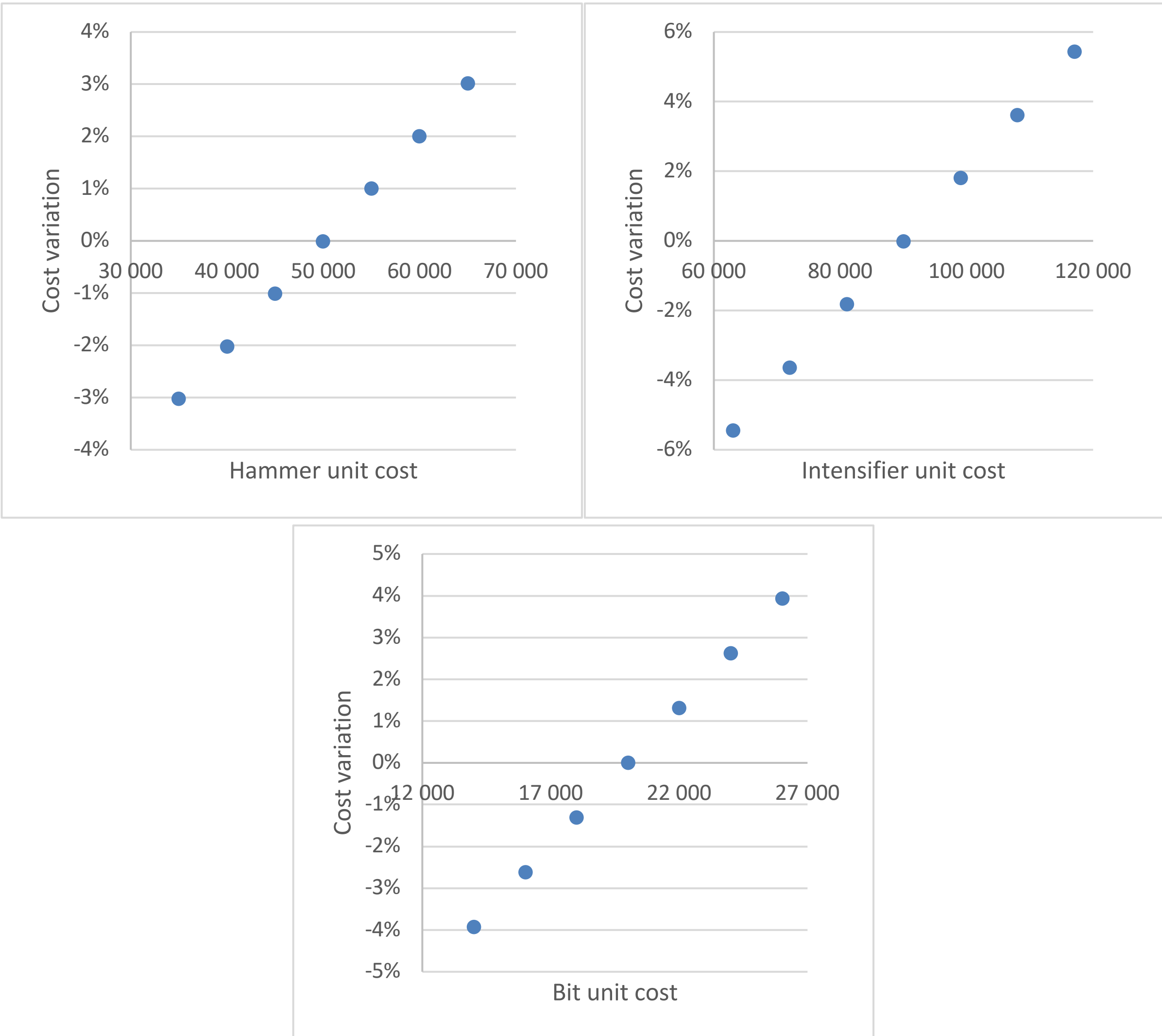

Figure 29. Variation of the total section drilling cost with respect to the equipment cost (hammer, intensifier and drill bit).

The variation of the total drilling cost of the section is evolving linearly with the unit cost of the drilling equipment. For a 30 % change from the estimated cost, the total section drilling cost is modified by 3 %, 5.4 % and 3.9 % for the hammers, intensifiers and bits respectively. Comparing these results with the fact that a ROP increase from 7 to 10 m/h leads to 27 %

reduction in costs, we can conclude that ROP has a significantly larger impact than a decrease in equipment cost.

5.4.3 Impact of the equipment lifetime

The lifetime of the tools is a critical aspect of the study as it determines the number of equipment components required to drill to a certain depth and thus the tripping time. Similarly to the equipment cost, we study a variation of 30 % around the estimated value of the lifetime of each tool. In this case, the evolution is non-linear, as the calculated number of tools used is rounded up to the upper whole number. The obtained results for the Mudhammer and the intensifier are presented in Figure 30. Increasing the lifetime of the hammer up to 20 % has no impact on the cost. It needs to be increased by 30 % to get 2.5 % reduction on the total cost. On the intensifier, a lifetime increase of 10 to 30 % leads to the same variation in cost: around 4.5 %.

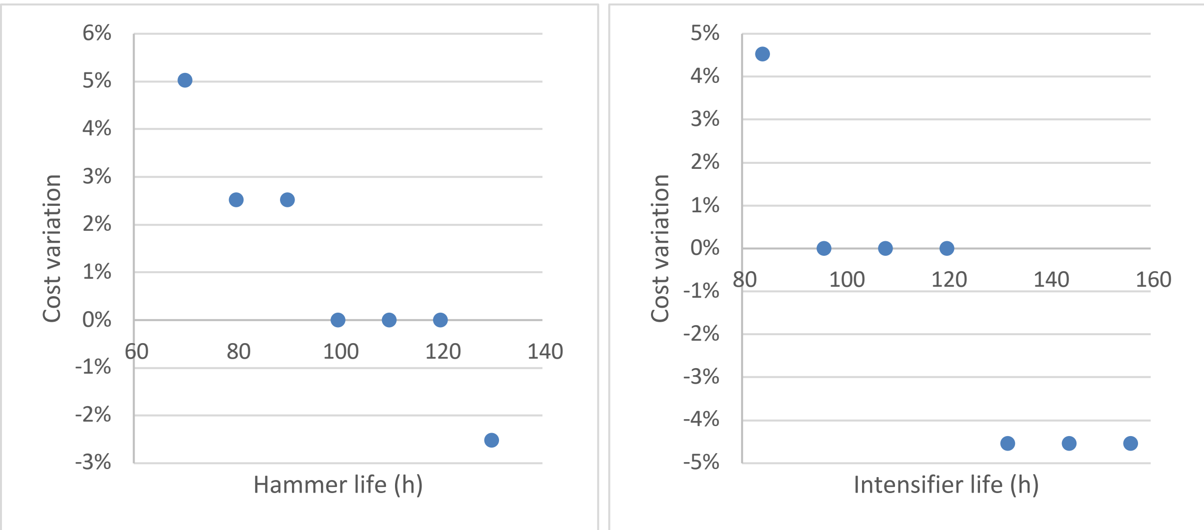

Figure 30. Variation of the total section drilling cost with respect to mudhammer (left) and intensifier (right) lifetime.

The drill bits lifetime is more critical, as a dull bit necessarily leads to a tripping operation. Hammers and intensifiers, having longer lifetimes, can be replaced alongside with a bit. Therefore, as it can be seen in Figure 31, a nine hours reduction of bit lifetime leads to more than an 8 % cost increase. Indeed, in our case study, 18 bits would be used instead of 13, leading to 5 additional tripping operations.

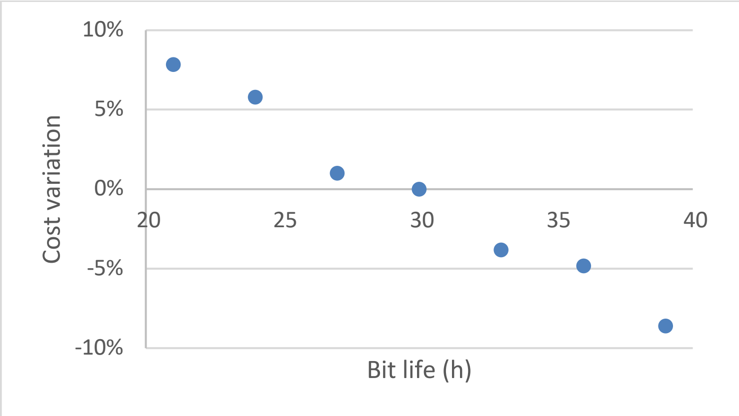

Figure 31. Variation of the total section drilling cost with respect to drill bit lifetime.

From the sensitivity analysis, two critical aspects have been identified. The ROP is the main parameter influencing the drilling cost: it will be the main target of the project. Nevertheless, the ROP increase must not be achieved regardless of the drill bit lifetime, as we can see that its value has a potentially great impact on the total costs, though secondary compared to ROP. The cost of the drilling tools and the hammer and intensifier lifetimes must be looked at as secondary impacts, but they will have a lower influence on the total costs.

6 Conclusion

This report will be used as a reference throughout the project to develop and test the new drilling technique. Based on the analysis of the geological settings of previous or future deep geothermal projects, a selection of representative drilling conditions is presented. The main rock types to be targeted in the scope of the project have been identified, along with drilling conditions such as drilling fluids, depth, pressure regime etc., that will be reproduced during the experimental evaluation of the developed prototypes. The range in drilling performance achieved will be able to be analyzed in terms of cost savings, using the cost model. Finally, the sensitivity analysis conducted on a case study led to the identification of the main cost influencing parameters that will be studied during the project, namely the ROP and the drilling bit lifetime.

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