ORCHYD	
"Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in deep geothermal drilling"	This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006752

DELIVERABLE 5.3

"Report on jetting experiments performed"

ABSTRACT

The objective of the work defined in Task 5.3 is to conduct high pressure water jet (HPWJ) experiments under confining pressure to emulate grooving in downhole drilling conditions. In this work, we analyse the effect of essential design and operating parameters and other relevant drilling conditions in achieving the required groove depths. These experimental data also include provision of the benchmark tests used for numerical validation for both microscale and mesoscale models developed as part of Task 5.4.

A new experimental set up has been set up by modifying an existing one. It includes a high-pressure system incorporated into an existing experimental device allowing rock cutting under realistic drilling conditions and a choke system on the high pressure exit line to maintain constant back pressure. An experimental programme has been defined to analyse all the design parameters (nozzle type and diameter), operating parameters (standoff distance, rotation speed, injection pressure, number of rotations) and the in-situ drilling conditions (rock type, back pressure). These tests are performed to analyse the effects of the parameters on the groove depth that is crucial for the stress release process. A large effect of back pressure is observed. Another conclusion was on the large dispersion of the results due to rock heterogeneity and maybe experimental conditions.

DOCUMENT TYPE	R
DOCUMENT NAME:	D5.3.Report on jetting
VERSION:	vfinal
DATE:	07/02/2023
STATUS:	S0
DISSEMINATION LEVEL:	PU

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Review Approval:	Approved	Yes	Rejected (to be improved as indicated below)	
Remarks / Improvements:				

Version History			
Version:	Date:	Comments, changes, Status:	Person(s) / Organisation Short Name:
v0.1	20/01/23	First draft	Laurent (ARMINES)
v0.1	23/01/23	First round of comments	JP (ICL)
v1.1	03/02/23	Updated with comments	Laurent (ARMINES)
vfinal	07/02/23	Final version to submit	Naveen (ARMINES)

Version Numbering	
v0.x	draft before peer-review approval
v1.x	After the first review
v2.x	After the second review
vfinal	Deliverable ready to be submitted!

Status / Dissemination Level			
Status		Dissemination Level	
S0	Approved/Released/Ready to be submitted	**PU**	Public
S1	Reviewed	**CO**	Confidential, restricted under conditions set out in the Grant Agreement
S2	Pending for review		
S3	Draft for comments	**CI**	Classified, information as referred to in Commission Decision 2001/844/EC.
S4	Under preparation		

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1 Introduction

In the framework of the ORCHYD project, we investigate a drilling method that combines high pressure water jet (HPWJ) and percussion drilling to increase the rate of penetration (ROP) by a factor of 3 or 4. It is expected that the stress release effect of the proposed drilling method will assist in achieving this increased drilling performance. The rock state of released stresses is achieved by creating a peripheral groove on the rock surface using a HPWJ isolating the rock surface from the surrounding stress regime. This requires an optimal delivery of the HPWJ in the bottom hole conditions to create a peripheral groove of desired depth. While the theoretical results including the numerical modelling and simulation of HPWJ were already covered in the earlier deliverables of the project, this report covers the experimental efforts in studying the HPWJ. The report is divided into the following sections: preliminary theory of the stress release process and various influencing factors that affect the grooving ability; laboratory setup available in Pau and the modifications to accommodate the experimental routine for the ORCHYD project; different jetting experiments and the analyses of their outcomes, followed by a few concluding remarks.

2 Theory

2.1 Stress release

It is known that, in general, the confining stresses increase over depth due to the mere weight of the rock overlaying a given rock surface. It is also well known that rock resistance to cutting increase with confining stresses. Creating a borehole alters the stresses around the rock layer and influences the energy required to break the rock – more energy as the wellbore extends deeper. In ORCHYD project, we aim at exploiting the principle that creating a peripheral groove on the rock surface shall release it from the confining stresses emulating a near-surface condition. This effect is further influenced by the profile of the bottom hole indued by the bit profile. This principle is demonstrated in Figure 1 where a combination of concave drill bit profile and a peripheral groove creates the least radial stresses concentration (defined as the ratio between current and initial stresses) for the rock at greater depths (see further deliverable 4.1. and 4.2.).

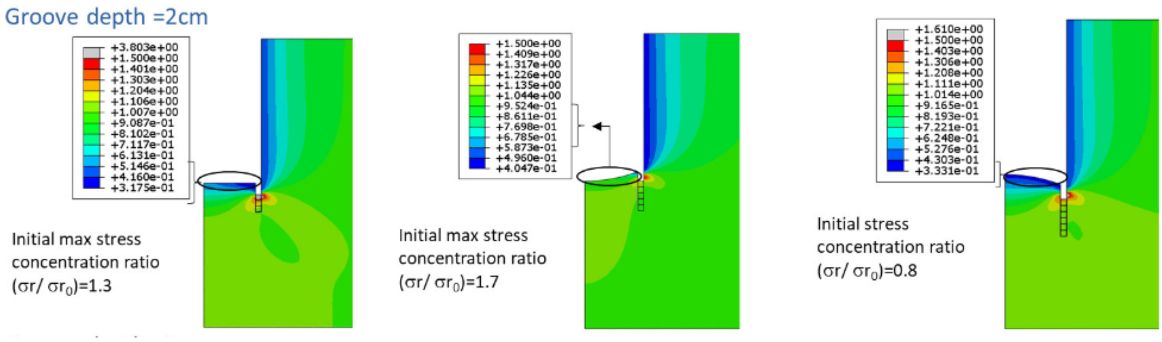

Figure 1: Mean Stress concentration factor distribution in the underground rock surface depending on the profile of the drill bit.

Another conclusion of the theoretical study conducted in WP4 is that stress release effect is enhanced with depth of the peripheral groove. The Figure 2 illustrates this with the evolution of the reduction of the mean stress concentration factor at the bit centre with the depth of the groove H expressed as a ratio of the diameter of the bit D. For the concave bit profile, the maximum stress release is obtained at a ratio of 0.4 i.e., more than 5 cm. But it can also be observed that the stress release is greater than 50% for a groove depth of 1.5 cm for a concave profile.

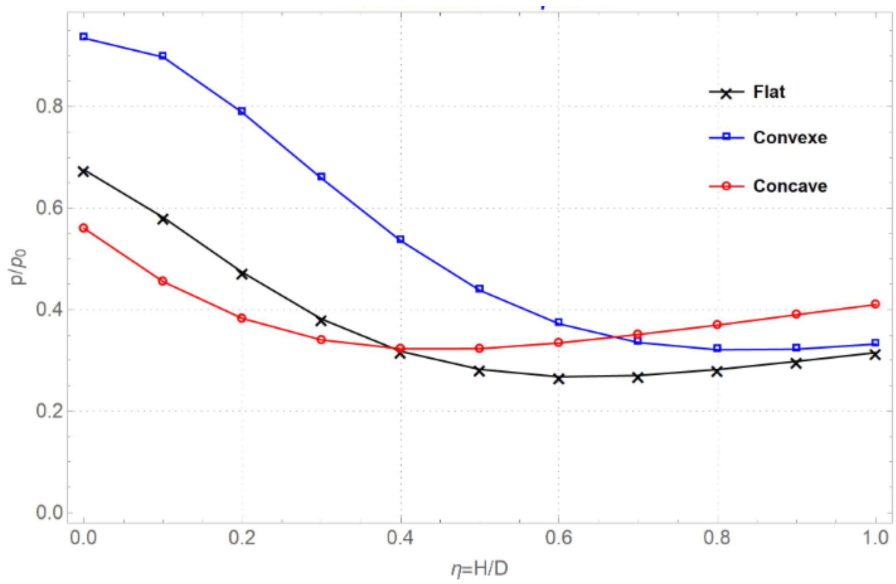

Figure 2: Stress release using mean stress concentration factor

Creating a deep groove is crucial to optimise the stress release and increase the bit ROP but it is also challenging to create such deep peripheral grooves in the downhole conditions – several phenomena including high hydraulic pressure (due to the fluid circulation in the annular column of the wellbore) and stand-off distance (the distance between the exit of the HPWJ and the rock surface) are in play. Thus, it is necessary to study the influencing parameters and study them at the laboratory scale to design the prototype to deliver this effect during percussion drilling.

2.2 Influencing factors of HPWJ

There are many studies in the literature on the experimental study of the effect of high pressure water jetting and the parameters influencing the destruction of rock at atmospheric pressure. Stoxreiter et al (2018) performs circular cuts with pure water on 6 rocks with jet pressures of 4000 bar. Harris and Mellor made linear cutting tests on 3 different rocks with a pure water jet. Karakurt et al (2012) performed cutting tests with an abrasive water jet. There are also many experimental results for the analysis of the cutting performance of high-pressure water jets in submerged environments with low confining pressures where the focus is on the generation of cavitation at the nozzle outlet to improve cutting performance (Hualin et al (2017)). However, only few experimental studies are available under high confinement up to 45 MPa back pressure (e.g., Reichman (1980), Kolle (1987) or Stoxreiter (2019)).

Based on the numerical and the laboratory studies, influence of several factors have been observed. For the stress release effect to play a role, the drill bit profile and the depth of the peripheral groove are two major influencing factors. For obtaining the required groove depth, factors that affect the HPWJ like the nozzle type and diameter; stand-off distance: the distance between the nozzle outlet and the rock surface; the inlet pressure to the jet nozzle; hydrodynamic pressure on the rock surface due to the drilling mud (water in this study) circulation and the exposure time of the rock to the HPWJ due to drill bit rotation play critical roles in realising deep grooves to optimise the stress release effect.

It must be noted that these parameters are function of the candidate rock. Based on the study in Deliverable D2.1. Project Specifications, the Sidobre granite has been chosen as the candidate rock for the sensitivity analyses of the influencing parameters. The optimal parameters studied from the Sidobre granite were used to understand their effect on other rock types such as the Red Bohus and Kuru Grey granites. Table 1 summarizes the rock characteristics of Sidobre, Red Bohus and Kuru Grey granites.

Tableau 1: Characteristics of the rock drilled

Name of Rock	**Type of Rock**	**UCS (MPa)**	**UTS (MPa)**	**Grain size min-max (mm)**	**Density (gr/cm^3)**	**Sound velocity (m/s)**	**Porosity (%)**
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

3 Experimental study

The aim of the ORCHYD project is to demonstrate at laboratory scale the influence of HPWJ in improving the percussion drilling performance using the DTH (down the hole) mud hammer. Studying such a phenomenon is complex involving both hydraulic and mechanical dynamics that are coupled, usually in a non-linear manner. According to small gain theory in control systems engineering, an interlinked system of two stable systems is stable provided the small gain condition is satisfied. Similarly, we aim to optimize the rock breakage through the hydraulic and the mechanical effects separately, expecting the combined system to thereby be optimized. Experimentally studying the rock breakage under the influence of the hydraulic energy produced by the HPWJ is further detailed in this report. This study is conducted to validate the numerical simulations to be reported through other deliverables of this work package.

3.1 Laboratory setup

The experimental set up was initially used to study the rock breakage caused by the impact of a single insert to optimize the percussion drilling process. The piston that impacts the rock with a hammer insert is submerged in a cell that can be pressurized up to 500 bars (description of the test is done in Al Dannawy et al (2022)). This allows us to study the rock breakage process in the downhole conditions.

The platform hosting the block of rock inside the pressure cell can rotate and is controlled separately by a hydraulic motor. Due to this degree of freedom, the rock breakage due to shearing action of a single cutter of the drill bit can be studied – allowing the bit design to be optimized. With these functionalities available, further modifications were necessary to accommodate the HPWJ system, to monitor and control the influencing parameters. The modifications carried out are specified in the following sections.

3.2 Modifications for ORCHYD

High pressure cell: The system to maintain the cutter was removed and changed to allow the high pressure to be brought close to the rock. The new system (Figure 3) is composed of a high-pressure tube with a nozzle fixed at the extremity inside the cell (1) with two sealing systems at the top and bottom. The rock (2) is fixed to a rotating plate. The cell (3) is filled with water and is pressurized with the choke restriction at the flow outlet.

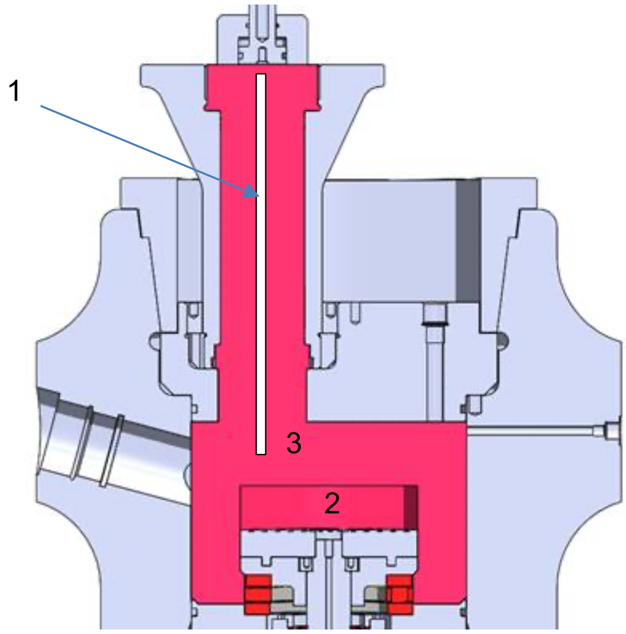

Figure 3: Drawing of the experimental device with its modifications

HPWJ system: In this project, to deliver the HPWJ in the downhole environment, a downhole intensifier will be used (refer to Deliverable D5.2). However, to study HPWJ system under laboratory conditions, a high-power diesel pump is used to create fluid pressures of up to 2500 bars. A high-pressure transmission line is used to channel the flow to the experimental setup. The transmission line is secured to a base plate hosting a rigid axial pressure line to which different nozzles can be attached. This pressure line has a degree of freedom to move axially thus controlling the stand-off distance. This is crucial as the hydraulic power of a jet drops drastically above a stand-off distance between 7 and 10 times the diameter of the nozzle (refer to Deliverable D5.1). The HP used is a WOMA type 250 M P18 with the following parameters: Pump power - 133 kW; Maximum pressure - 250 MPa; Maximum flow rate - 29.5 l/min; Motor type - TWD 710 V; Motor power - 168 kW; and Maximum nozzle diameter - 1.05 mm.

Figure 4: The high pressure impact cell modified to accommodate the high pressure water jetting experiments.

Back pressure choke: Though the cell can hold up to a pressure of 500 bars, it was in static conditions, i.e., the cell was pressurized using a hydraulic pump. However, it is necessary to have a choke to control the pressure during fluid flow. A spring type choke was used in this system. The torsional spring can be screwed a priori to maintain the required pressure inside the cell. A high-pressure transmission line connects the exit of the pressure cell to the choke. Choke plugging with the rock cuttings was common. Thus, a double sieve filter was fixed to hold back the rock particles from entering the high-pressure line leading to the choke.

Rotation control: First, the influence of the static parameters such as the stand-off distance, HPWJ pressure, etc. were studied to understand the grooving effect of different water jets. However, the HPWJ will be used with the DTH mud hammer that also rotates. Thus, it is also necessary to control the rotation speed of the platform to control the exposure of the rock to the HPWJ. To read the position of the rock with respect to the HPWJ and to calculate the rotation speed of the platform, a laser system reading distance was setup along the rotation gear – counting the gear teeth provides position and the rate of change provides speed.

Sensor integration: To monitor the influencing parameters, the experiments must be equipped with the right sensors. Two pressure sensors are placed in the system – one at the juncture of the high-pressure transmission line from the pump to the rigid transmission line leading to the nozzle; another that measures the pressure inside the cell.

The high-pressure pump is installed with its own monitor and control system that measures the flow rate and pressure at the outlet of the pump. The pump can be operated in two modes – automatic and manual – to reach a flow of required pressure. The data from all sensors are channelled through a data acquisition card to the Labview platform, both provided by National Instruments. Once the sensors are calibrated, they can be communicated using a custom Labview code.

To measure the impact pressure during the rock breakage of a given jet cone, a custom sensor was fabricated – 5 mm impact area with the rest covered by a strong steel plate. This setup was designed to rotate to capture the pressure distribution under the cone of HPWJ (for more details on the impinging pressure and its distribution, refer to Deliverable 5.1.).

3D crater scanning: A laser scanning system was setup to scan the craters created by the impact of HPWJ. The system is controlled by a Labview software routine and works on the principle of measuring the time for reflection of the laser beams. The setup has been modified to accommodate scanning in both transitional and rotational manner (see Figure 5). The processed data can then be used to graphically view the contours of the crater using software like CloudCompare and ParaView. An example of a crater is shown in Figure 6.

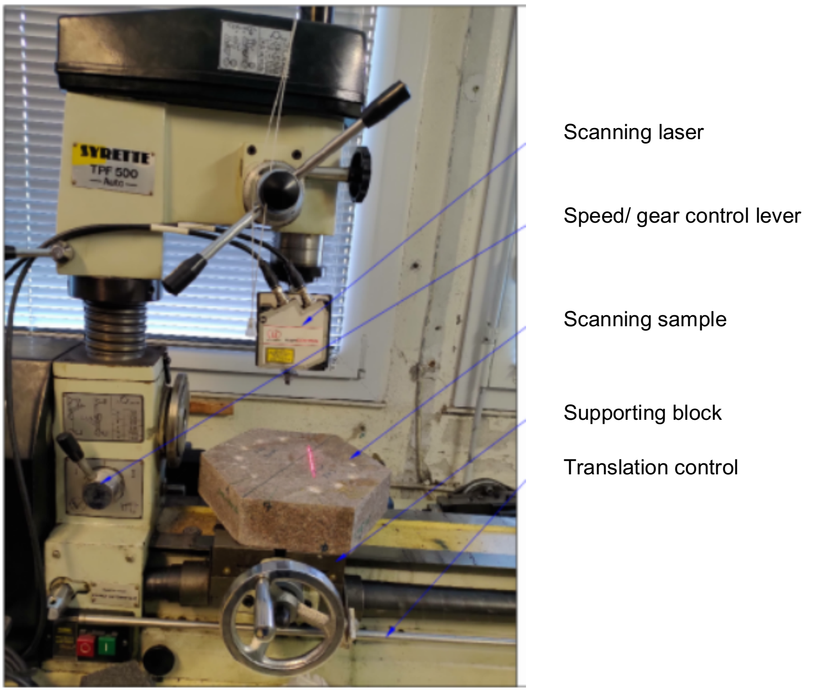

Figure 5: The laser scanning setup to create a 3D rendering of the impact crater of the HPWJ.

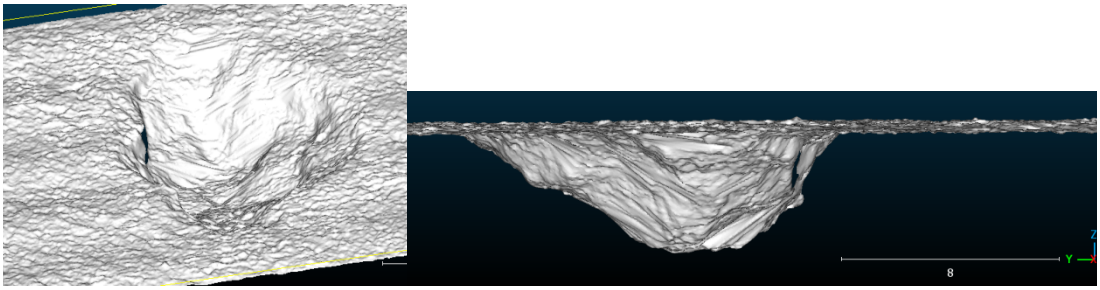

Figure 6: A graphical rendering of the crater scan data in CloudCompare.

4 Tests

4.1 Nozzle

Two types of nozzles were used in the experimental program (Figure 7): F1 and F21. The F1 nozzle has a conical shape and was used most often for conducting the tests and the F21 is ceramic nozzle with a slightly rounded transition section and radius shape.

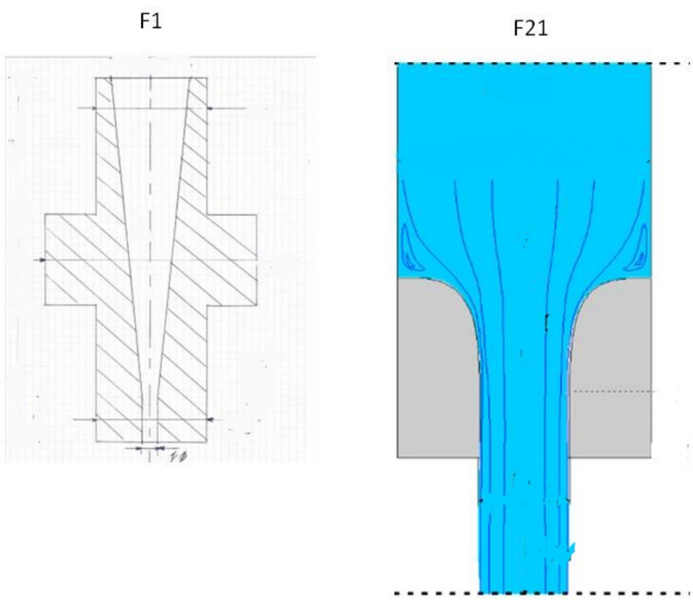

Figure 7: Drawing of the two types of nozzles tested in the experimental work.

4.2 Non-traversing tests

In the first phase of the experiments, the rock samples are held stationary under the impact of the HPWJ to study the effect of back pressure, injection pressure, standoff distance, and exposure time. As groove depth is the influencing parameter in the stress release process, it is chosen as the control variable to understand the influence of other parameters related to the HPWJ. Here, the groove depth is measured as the maximum depth of the crater created by the HPWJ impact. A rock sample of Sidobre granite was used in these tests.

In Figure 8, the maximum groove depth achievable under the influence of different back pressure is shown with a nozzle F1 of 1 mm diameter, a jet pressure of 240 MPa, a standoff distance of 5 mm and an exposure time of 20 s. This particular study is important as it directly translates to the depth of operation of the HPWJ, i.e., a back pressure of 40 MPa is equivalent to operating the HPWJ at a depth of 4 km. It can be noted that, when all other parameters are set constant, the grooves are shallower with the increase in depth of the drilling operation.

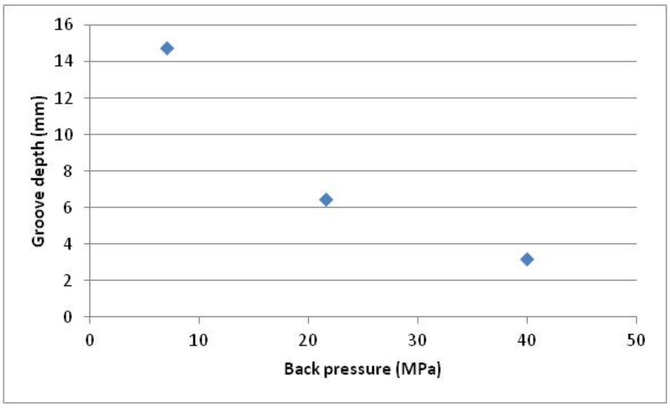

Figure 8: Effect of the back pressure on the groove depth

In Figure 9, the influence of the injection pressure on the groove depth is shown (nozzle F1 of 1 mm diameter, back pressure of 20 MPa, standoff distance of 5 mm and an exposure time of 20 s). The results are in line with as one may expect, i.e., the higher the injection pressure the higher is the energy available to break the rock and thus the creation of a deeper groove. It is important to note that 250 MPa is the highest operating pressure of the pump available at the laboratory facility in Pau. However, achieving such high pressure in the downhole environment only by using a downhole environment can be challenging (refer to Deliverable D5.2. to understand the performance of the downhole intensifiers).

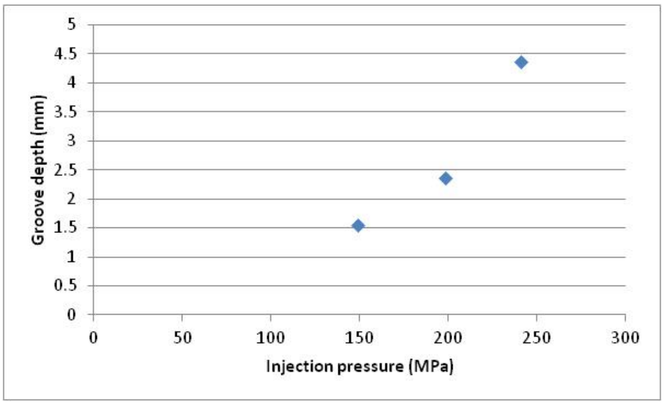

Figure 9: Effect of the injection pressure on the groove depth

In Figure 10, the effect of the standoff distance, i.e., the distance between the outlet of the jet and the rock surface on the groove depth is shown (nozzle F1 of 1 mm diameter, back pressure of 20 MPa, injection pressure of 240 MPa and an exposure time of 20 s). The lower the standoff distance, the closer is the jet to the rock and effectively less dissipation of energy during the jetting process. The results clearly show that a deeper groove is achieved when the standoff distance is lower. They are also consistent with the conclusion that the bottom of the hole eroded by the jet does not significantly exceed the distance from the nozzle over which the jet core is at full strength (i.e., 7-10 times the nozzle diameter). However, one of the limiting parameters in such implementation is the design requirements and the practicality of a drill bit that can accommodate it.

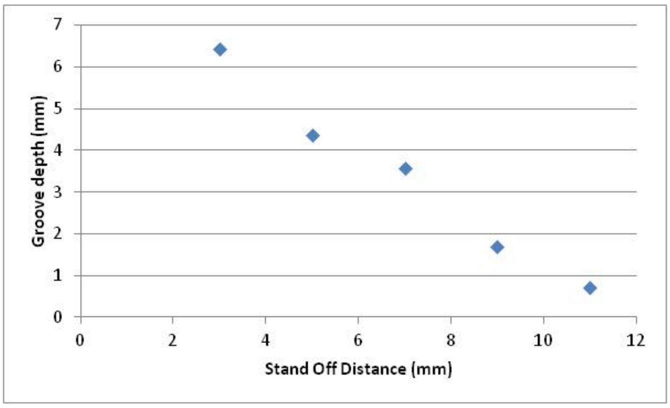

Figure 10: Effect of the standoff distance on the groove depth

The non-traversing tests were carried out to understand the influence of different factors individually and also to calibrate the rock models that are developed in parallel. The experimental data produced from these experiments are necessary to match the simulation parameters and optimize the influencing parameters. A setpoint for the back pressure of 20 MPa, injection pressure of 240 MPa, and standoff distance of 5 mm was taken and the exposure time to the HPWJ was varied. To obtain statistical accuracy, the test was repeated over a few times and are shown in Figure 11. The dispersion in the test results can be attributed mainly to the rock heterogeneity and also to the control system for the exposure time.

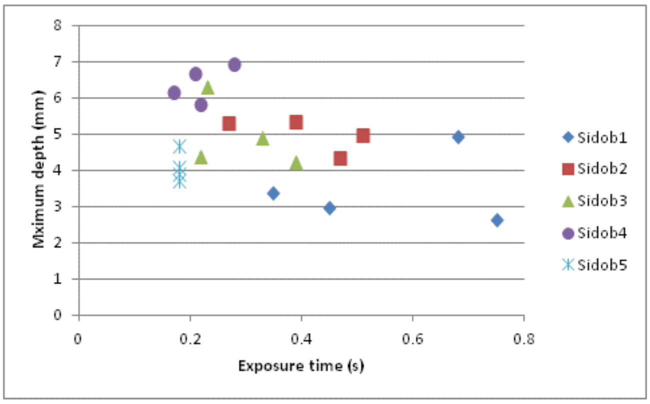

Figure 11: Effect of exposure time of the HPWJ on the groove depth

4.3 Traversing tests

In the next phase of the experiments, the influencing parameters were studied under the influence of the rotation of the rock sample. This step is necessary to understand the jetting action during the drilling process when the drill bit is in rotation. Again, the numerical model of such process must be calibrated to the experimental data. Thus, a particular test was carried out to isolate the impact location during the rotation of the rock. Tests were performed with nozzle F1 of diameter 1 mm with 250 MPa of injection pressure, 20 MPa of back pressure and 4 mm standoff distance. It can be seen from Figure 12 that a steel plate was fabricated to create slots of 1 cm which would isolate the crater zone to around that area under the impact of HPWJ while rotation. For each rock sample, we measured the depth of 5 craters created under the same operating conditions. Figure 13 shows the effect of the rotation speed on the groove depth achieved. It may be said that the higher the rotational speed, the lower is the depth of the groove achieved. A faster rotation was necessary in this study to facilitate the numerical simulation of the crater that is computational expensive. We can also note a strong dispersion in the results at each rotation speed mainly due to rock heterogeneity. Note that the high speed of 80 RPM can't be reached quickly and this explains why the first and last measurements have the lowest RPM (corresponding to the start and stop of the rotation).

Figure 12: The steel plate fabricated to isolate the impact zone to 1 cm width and the resulting craters created localized around the 1 cm slots

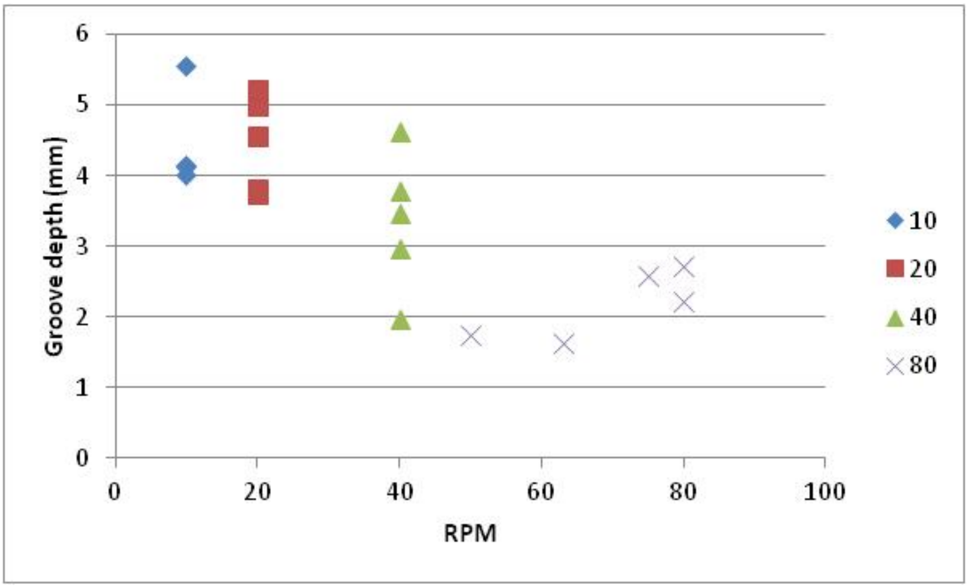

Figure 13: Effect of rotational speed on the groove depth

In the second part of the experimental study in the traversing phase, a full rotation of the HPWJ was conducted to understand the grooving process during the drilling action. Similar to the non-traversing experiments, the influence of different parameters was studied while the rock was rotating. Figure 14 shows a Sidobre rock sample that was placed under the impact of the HPWJ during rotation. This rock was scanned using the laser setup and then graphically viewed using ParaView to calculate the groove characteristics (depth, width and cross area) along the circumference of the rock. We observed a large fluctuation of the groove depth between 0 to 6 mm (the peak depth at 8 mm is the starting point and is obtained before rotation when the cell is pressurised at the beginning of the jetting). This large fluctuation can be explained by the heterogeneity of the rock (the impact zone of the jet is about 1 mm in diameter while the grain size is 4 to 10 mm) and by the turbulence inside the cell (the jet is used to pressurise the cell with a small volume of water and the choke opens and closes to maintain a constant back pressure). We also observed a high groove width between 5 and 20 mm, much greater than the impact area of the jet (1 mm diameter) (**Error! Reference source not found.**). This large groove width without any rock will reduce a lot the rock in contact with the drill bit cutters and will aid improvement in the ROP.

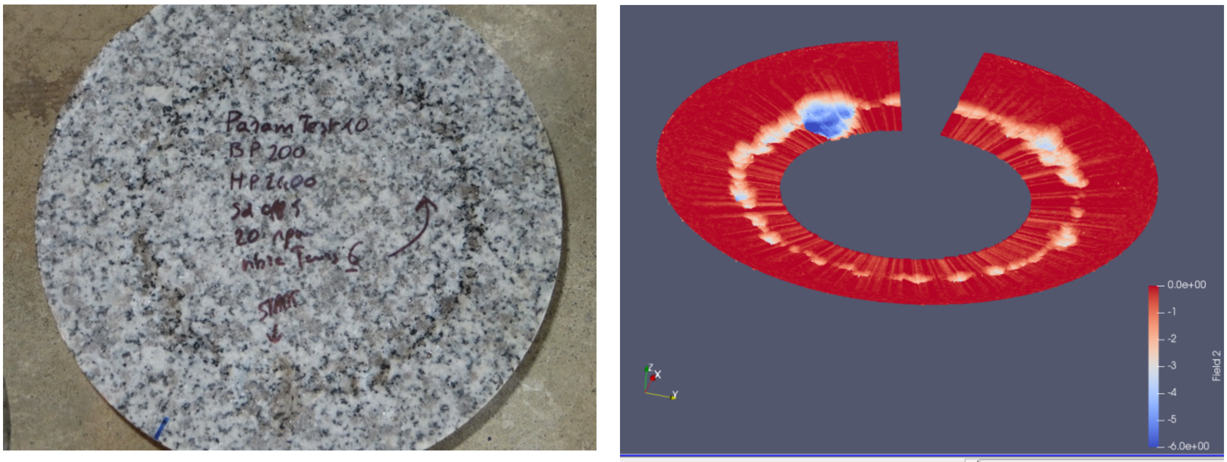

Figure 14: The rock under the influence of HPWJ while rotating and the graphical view of the crater data scanned using the laser setup

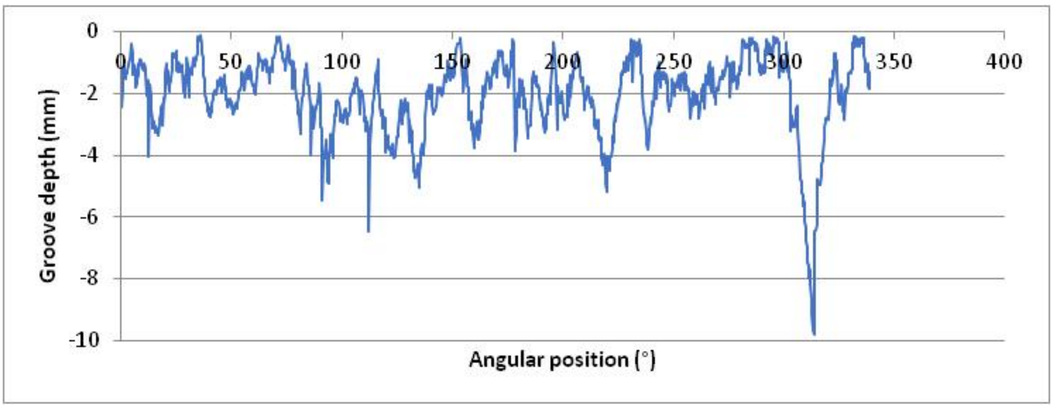

Figure 15: Groove depth with respect to the angular position of the rock subjected to HPWJ during rotation

Similar to the non-traversing test, the following Figure to 19 show how the groove depths are affected due to the standoff distance, the rotation speed, the number of rotations the rock is exposed to the HPWJ and the back pressure. It can be noted that a range of maximum and minimum depth is shown here due to the heterogeneity of the rock sample and its exposure to the HPWJ during jetting process. Since the stress release effect is linked to the groove depth, the distribution in the plots helps us understand the level of stress release. We observe the same type of result in the decrease of groove depth with the increase of the standoff distance, of the rotation speed or of the back pressure. It can also be noted (Figure 18) that the number of rotations does not increase the depth of grooving. It seems therefore that there is no damage under the kerf during the first pass which could have been accentuated during the following passes. This is atleast the case for Sidobre and the effect on other types of granites needs further investigation.

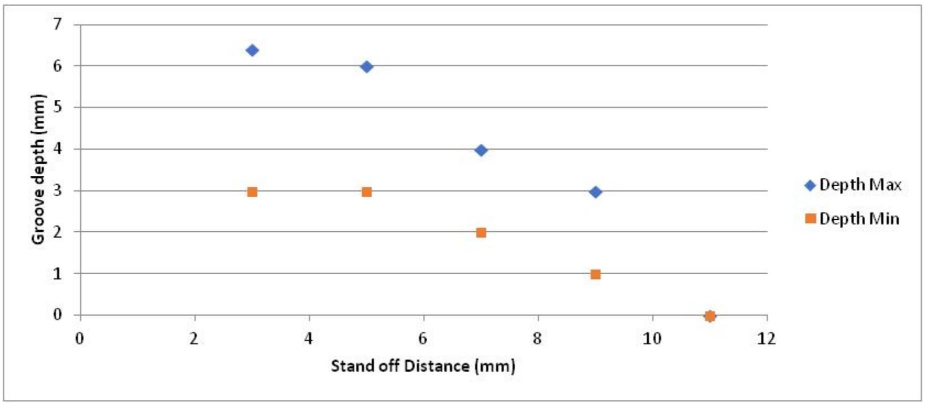

Figure 16: Influence of standoff distance on the groove depth while rotation (Injection Pressure = 240 MPa, Back Pressure = 20 MPa, Nozzle F1, Diameter 1 mm, Rotation speed = 20 RPM)

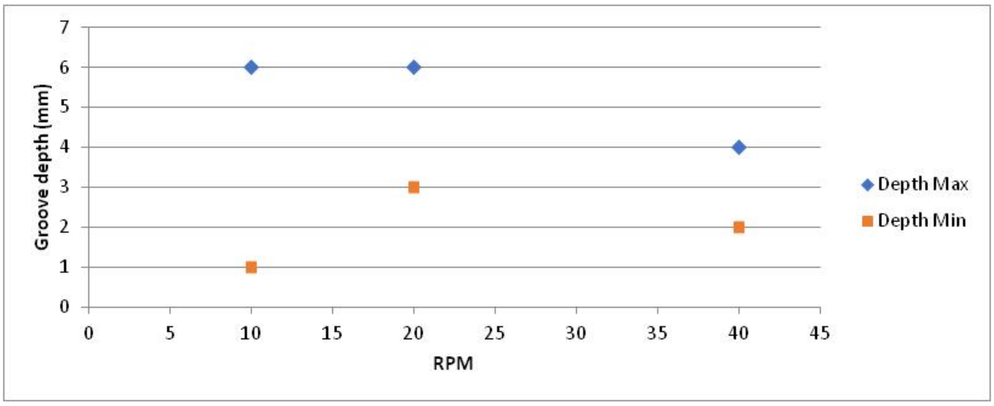

Figure 17: Influence of rotation speed on the groove depth (Injection Pressure = 240 MPa, Back Pressure = 20 MPa, Nozzle F1, Diameter 1 mm, Stand Off Distance = 5 mm)

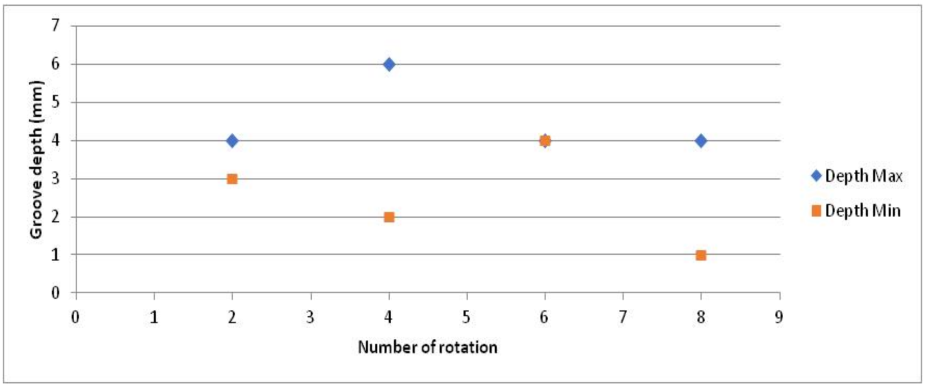

Figure 18: Influence of number of rotations on the groove depth (Injection Pressure = 240 MPa, Back Pressure = 20 MPa, Nozzle F1, Diameter 1 mm, Rotation speed = 20 RPM, SD = 5 mm).

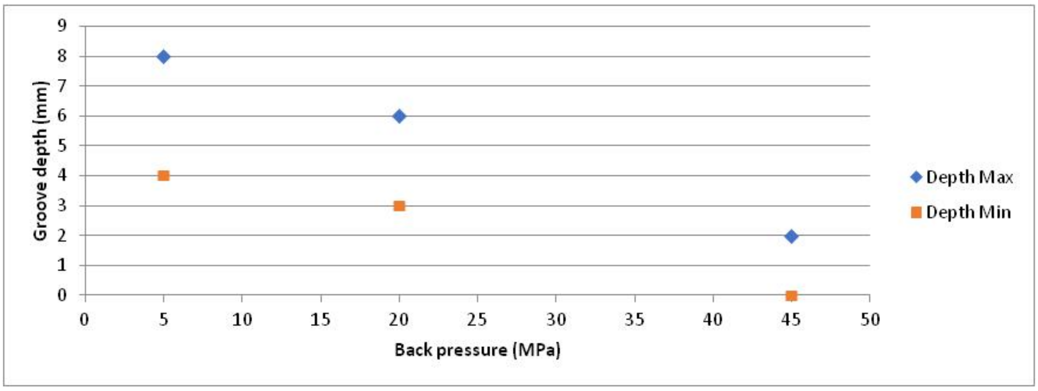

Figure 19: Influence of back pressure on the groove depth while rotation (Injection Pressure = 240 MPa, Nozzle F1, Diameter 1 mm, Rotation speed = 20 RPM, SD = 5 mm).

Figure shows the groove depth with the type of nozzle. It can be observed that the nozzle F21 is much more destructive giving greater groove depths in this configuration. More comparative tests should be performed to conclude on the best nozzle shape.

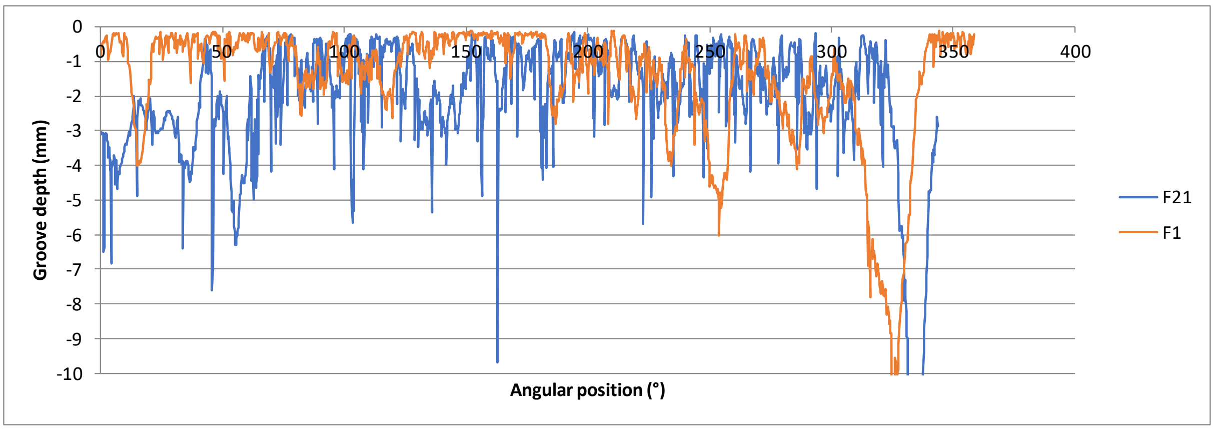

Figure 20: Influence of nozzle type on the groove depth while rotation (Injection Pressure = 200 MPa, Back pressure = 20 MPa, Diameter 1 mm, Rotation speed = 20 RPM, SD=5 mm)

Figure shows the maximum and minimum groove depth for different rock types and the UCS of the rocks. A great difference in performance can be seen between the different types of rock. Indeed, if we consider the three granites (Sidobre, Red Bohus and Kuru Grey) which all have UCS around 210 MPa, we note a groove depth which can vary by a factor of three (2 mm max for Kuru Grey against 6 mm for Sidobre). It is interesting to note here that Kuru Grey is the granite with the smallest grain size and Sidobre is the one with the coarsest grain size. There is also a difference in performance with sandstone or limestone.

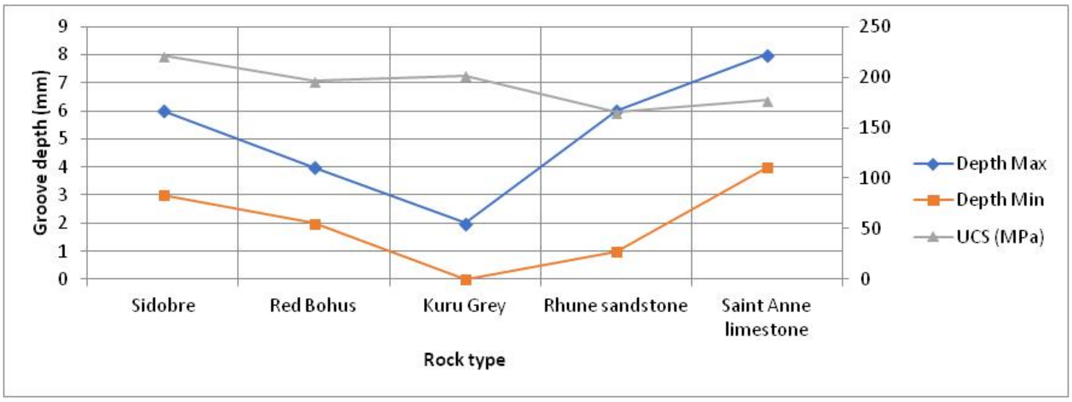

Figure 21: Effect of rock type on the groove depth (Injection Pressure = 240 MPa, Back Pressure = 20 MPa, Nozzle F1, Diameter 1 mm, Stand Off Distance = 5 mm, Rotation speed 20 RPM)

5 Conclusion

The objective of this task was to carry out an experimental study of rock cutting by high-pressure water jetting by studying the effect of operating and design parameters (type of nozzle, nozzle diameter, injection pressure, rotation speed) and of the in-situ environment (type of rock, back pressure). The various tests carried out showed that the depth of the groove hardly reached a depth greater than 10 mm and that the back pressure had a significant negative effect on the depth. It was also possible to observe that the groove cut could lead to an improvement in performance with a groove width well beyond the impact zone. Due to the heterogeneity of the rocks, the groove depths varied while rotating the jet, giving a minimum and maximum value – likely to provide a distribution in the level of stress release. Finally, we can also consider that the results obtained correspond to the minimum value that can be obtained in real conditions. Indeed, it is very likely that the jet is disturbed in the experimental device where we inject at a flow rate of 30 l/min in a volume with a control of the pressure of the cell by opening/closing a choke actuated by a spring. Future tests on the drill rig should clarify this hypothesis as the confining pressure will be controlled with a fluid flowing at a rate of 600 l/min.

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