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Mud Hammer Drilling in Deep Hard Geothermal formation, from the single impact to the directional and vibration characterization

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ABSTRACT

A new 8 ½" mud hammer prototype and its associated innovative drill bits have been developed and tested to increase drilling performances in hard formations. This system is based on a high-power down-the-hole hammer, capable of delivering high-energy impacts at high frequency.

The different aspects of this innovative development, from the mud hammer and drill bit design to the full scale laboratory tests in a controlled environment are described here. The adaptation of the hammer to the constraints of deep geothermal drilling was an important part of the work, where the wear and impact resistance of the internal parts of the hammer was studied to propose new improvements. The design of the drilling bits, based on the modeling of the stresses at the bottom hole, the modeling of the insert-rock interaction and an extensive experimental campaign of impact tests, have made it possible to produce a new generation of innovative, high-performance drilling bits adapted to deep geothermal drilling conditions. The tests results on laboratory in different types of rock and confining pressure conditions representative of deep drilling indicated and confirmed the high potential of percussion drilling with a ROP increase of 300% compared to roller cone drilling performance.

Finally, the control of the drillstring vibrations and the directional behavior of the drilling system are very important in the success of deep geothermal drilling. The hammer and bit were coupled to a Positive Displacement Motor (PDM) and tested on a horizontal drill rig with different bent angles. The tests showed that the hammer had a directional behavior equivalent to that obtained with a roller cone bit in rotary drilling and that the majority of the axial vibrations induced by the percussion were absorbed by the PDM.

1. INTRODUCTION

Drilling represents from 30% to 50% of the cost of a hydrothermal geothermal electricity project and more than half of the total cost of Enhanced Geothermal Systems (EGS)" (Dumas, 2013). The high cost of drilling remains one of the major obstacles to the development of deep geothermal energy due to the low drilling speeds in the hard and abrasive granitic formations found in drilling the basement. Today the traditional rotary drilling technique with roller cone bits is not efficient in such a formation and leads to low drilling speeds and high bit wear (Cardoe, 2021). On the other hand, percussive drilling is a mature and efficient solution for drilling hard and brittle rocks to depths of 1000-2000 meters and uses two well-tested techniques: the air hammer or the clear water hammer. However, for deep geothermal drilling, the use of air hammers is limited (well stability issues and delivery of air pressure to the hammer) and that of water hammers requires the use of clean water, which requires either to drill with total loss or expensive treatment of the drilling fluid on the surface before pumping it into the circuit. As granite or basement formation remains brittle even in deep drilling conditions, percussive drilling is a good candidate to significantly increase the drilling speed in these deep formations where hard and abrasive rocks are present and subjected to high geostatic and hydrostatic pressures. These conditions increase their resistance (Hokka et al. 2016) and complicate the drilling process, which leads to substantial drops in the rate of penetration (Gnirk and Cheatham 1965; Cunningham and Eenink 1959; Han et al. 2006). Thus, the drilling techniques must be adapted and optimized for these extreme conditions. Down-the-hole (DTH) percussive drilling is a technology that consists in applying a series of impacts via an oscillatory movement of a piston which impacts a drill bit at a frequency of 20–30 Hz with a velocity of 1–10 m/s (Haimson 1966), leading to rock fragmentation by compressive and tensile forces under the drill bit (Hartman 1959; Lindqvist et al. 1984; Hustrulid and Fairhurst 1972;

Mishnaevsky 1995). This mechanism is ensured by the drill bit buttons, also called inserts, which are in contact with the rock surface. At each impact, compressive waves travel through the drill bit down to the rock material, which enables the bit penetration by indentation of the inserts into the rock (Hartman 1959).

In order to make the percussive drilling efficient for deep geothermal drilling conditions, improvement should be done on the drilling bit and also on the mud hammer itself. To achieve this objectives, the work has been divided as follows:

1- Study the stress regime in large diameter deep drilling. The aim here is to understand the effect of stress concentrations at the face generated by the excavation of a large volume of rock. This definition of the stress regime will be necessary to optimize the cutting elements and their positions on the tool.

2- Optimize the work of the elements in contact with the rock and their interactions. The type, position, orientation, composition and shape of these elements must be adapted to the drilling conditions.

3- Qualify a hydraulic hammer adapted to large diameter drilling. This step will involve using the principle of the hydraulic hammer already used for the 6" borehole and applying it for an 8 1/2" borehole.

4- Design a drilling tool suitable for large diameter deep drilling. The aim here is to organize the placement of the cutting elements on the tool to optimize their work and their efficiency.

5- Test on site. The aim here is to show both the drilling performance in terms of life time or penetration speed, to measure the impact of percussion on the entire drill string system and to assess the directional behavior.

2. STRESSES AT THE BOTTOM HOLE

The drilling of the hole disturbs the initial stress state and redistributes the stresses at the bottom of the hole. The stress state of the rock at the bottom of the well plays a dominant role in the rock cutting process (Maurer 1962, Bingham 1965, Murray & Cunningham 1955). This is influenced by the hydrostatic pressure applied by the mud column, the horizontal geostatic stresses, the vertical stresses related to the weight of the soil and the pore stresses (pore pressure) within the formation to be drilled.

Numerical simulations using the commercial software COMSOL Multiphysics® were made to determine the distribution of stresses around a wellbore taking into account the geostatic stresses, the hydraulics of the mud column and the characteristics of the formations to be drilled with two objectives:

- To know the constraints that will be applied to the inserts for the optimization of their implantation on the bit face

- To find the best bit profile for deep percussive drilling by limiting the impact of geostatic constraints.

Numerical simulations were performed axisymmetrically with a 10-meter high and 1 meter wide geometric model, an 8 1/2" diameter hole 5 meters deep. We have chosen to simulate a granitic rock, non-porous and non-permeable. Given the characteristics of granite and that the phenomenon of redistribution of stresses under the effect of excavation is a rapid phenomenon, we have used a purely elastic model to characterize the drilled formation. Since the objective of these simulations is to find the most suitable profile for percussive drilling, we analyzed the effect of the position of the nose and its radius of curvature on the stress distribution. Fig.1 shows the effect of the inner cone on the first main stress distribution. An increase in the stress concentration at the nose of the bit can be seen at the periphery (this is in line with observations on site where a privileged damage zone of the cutting edges is observed at this location). We also observe a decrease of the main stress in the nose of the bit, which is even more important with a negative cone angle. This allows us to estimate that the destruction of the rock will be easier in the center of the bit with a concave profile. We also note a decrease in stress along the borehole wall. On the other hand, the rock will be more resistant at the nose of the bit. It will therefore probably be necessary to increase the density of inserts at the bit nose to limit the loading on each insert.

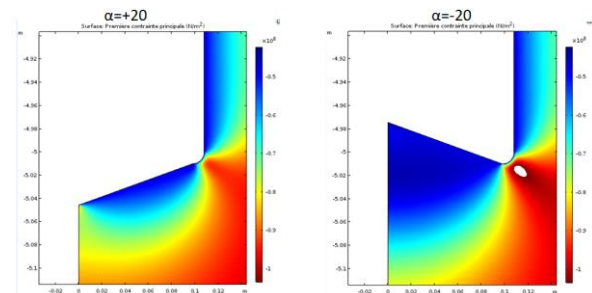


Figure 1: Effect of the cone angle on the first principal stress

We varied the shoulder radius of the bit profile from a value of 10 mm to a value of 120 mm by steps of 10 mm. We present here the result of the two extremes, 10 and 120 mm radius (Fig.2). We can observe that the stress concentration at the nose of the bit is lower with a high radius of curvature. However, we can also see that the stresses at the center of the bit are higher with a high radius of curvature. It is highly likely that a combination of an inner taper with a medium radius of curvature will be required to limit the stress concentration at the nose of the tool and optimize the rock cutting process at the center of the tool.

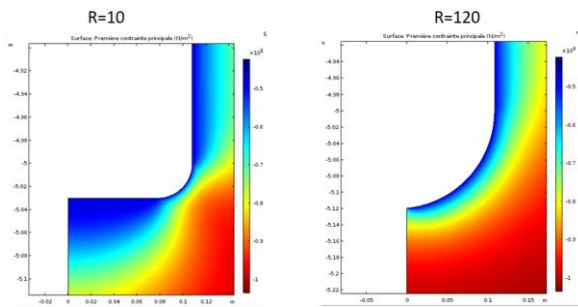


Figure 2: Effect of the shoulder radius on the first principal stress

These simulations allowed defining behaviors related to the drilling process at great depth and to the bit profile. The main conclusions of these simulations are:

- There is a high stresses concentration at the bit nose
- The increase in stresses at the bit nose is more important as the radius of curvature is smaller
- The presence of an inner cone allows the stresses at the bit center to be slightly released
- Geostatic stresses increase the stress concentration at the bit nose

3. OPTIMIZATION OF THE CUTTER-ROCK INTERACTION

Percussive drilling is a dynamic process. The rock removal following this process is influenced by many factors such as:

- Confining pressure which increases the rock resistance (Hokka et al., 2016),
- Loading speed: Percussive drilling has a localized strain rate in the [1:10s-1] rank (Liu et al., 2018, Haimson, 1966, Hartman, 1959) considered as an intermediate strain rate rank where the dynamic aspect can be considered for rock fragmentation.
- Mechanical properties of the rock such as rock strength, rock abrasivity, plasticity, ...
- Rock heterogeneity: The size of the insert-rock contact surface (1 to 4 mm) is of the same order of magnitude as the heterogeneities of the rock. Consequently, punching during percussive drilling presents a local impact that may strike one of the different minerals constituting the rock.
- The form of insert: At the elemental scale, the insert shape dictates different locations of cracks following an impact. These can have several shapes. If an insert is more effective on a type of rock, then it is likely that the hammer will be more effective in a massif of the same type. With regard to the effect of insert shape, the flatter the insert (larger insert-rock contact area), the more plasticization the rock undergoes and the more ductile its behavior (Nguyen, 1978, Reichmuth, 1963, Lindqvist, 1984). On the other hand, a sharp insert penetrates rocks more easily (Gnirk, 1965).

In order to increase the cutting efficiency, both numerical simulations and experimental works of the insert-rock interaction have been performed to optimise the inserts set-up on the bit face. This work has been detailed in Aldannawy & al, 2022 and is summarized here.

3.1 Numerical simulation

In order to estimate the fracturing induced by the rapid impacts, a velocity-dependent coupled elastoviscoplastic damage model was used (Aldannawy et al 2022). The viscoplastic model is a derivative of a quasi-fragile material plasticity model following a generalization of the Duvaut-Lions regularization (Duvaut G, 1972). The plastic damage model is implemented in the finite element software Abaqus.

- Effect of the form of the insert

Fig.3 shows the distribution of the tensile damage variable. In this figure, it can be seen that the damage is located on the surface, in the form of spalling. It can be seen that the larger the radius of the insert, the greater the damage. Therefore, for a large contact surface between the insert and the rock, larger spalls can be generated. Fig.4 shows the distribution of the compressive strain hardening variable ζ_c which reports on the damage caused by the impact. In this figure, it can be seen that for an insert with a smaller radius, the damage under the insert is more important

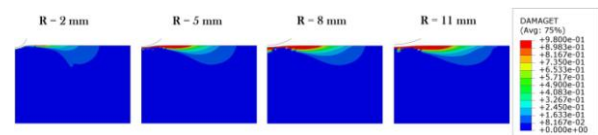


Figure 3: Distribution of the tensile damage variable $d(\xi_t)$

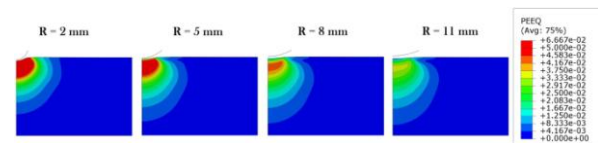


Figure 4: Distribution of the compressive strain hardening variable ζ_c

- Confining pressure effect

Fig.5 shows the distribution of the tensile damage variable for different confining pressures. We notice the important effect of this pressure which prevents the propagation of damage on the surface and therefore the spalling is very small for a high pressure. The same is true for the compression effect. The damage under the insert is strongly weakened (Fig.6).

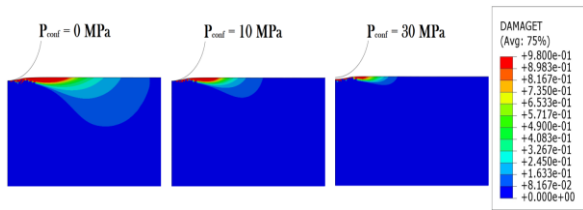


Figure 5: Distribution of the damage variable $d(\xi t)$ – confining pressure

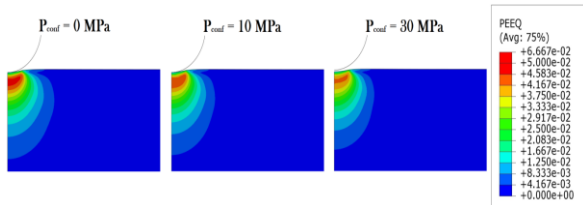


Figure 6: Distribution of the compressive strain hardening variable ξc - confining pressure

3.2 Experimental validation

Numerous single insert-rock impact tests have been performed using the specific experimental device described in Aldannawy & al, 2021 and shown in Fig.7.

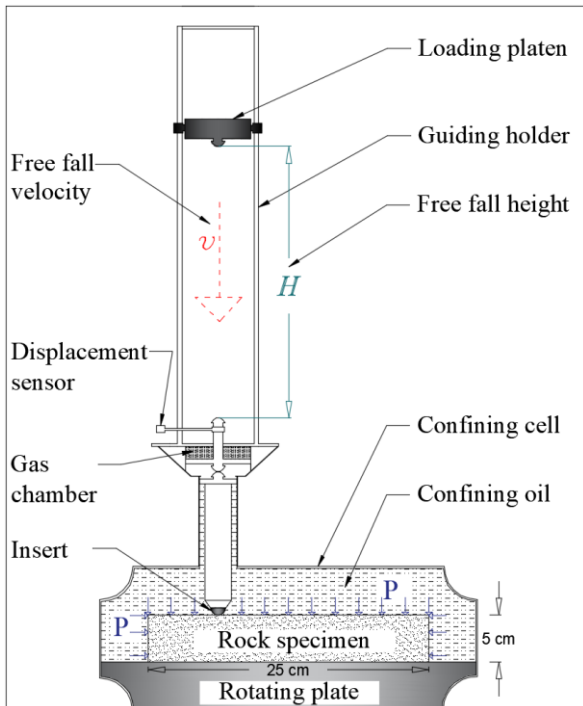


Figure 7: Simplified schematic representation of the drop test after Aldannawy and al, 2021

The rock sample is placed in a cell where a pressurized liquid (mineral oil in our case) can be put. After having fixed the height of the initial position of the mass, this mass is released in free fall to reach the insert with an impact speed and energy.

Tests were done with two rocks (Red Bohus granite, UCS=196.4 MPa and Nero Impala Gabbro, UCS=285 MPa), two confining pressure (10 MPa and 30 MPa) and 4 inserts (Chisel, Cone, Semi-spherical of 13 and 16 mm diameter respectively S13 and S16– Fig.8)



Figure 8: Inserts tested

Impact results are shown in Fig.9 that presents a histogram showing the average values of volume drilled. The inserts are ordered on the x-axis according to their radii of curvature from largest to smallest (except for the Chisel). On this figure, we notice the similarities in performance and ranking of the different inserts on each of the two rocks studied. Let's consider the particular case of the conical insert with its two different angles (60° for "Cone" and 90° for "Cone4"), we can observe that the conical insert with the smaller angle has been better in terms of volume removed (4% in the case of RB and 10% in the case of NI compared to "Cone4"). If we consider that the removed volume is the indicator of the efficiency of the drilling, we can say that the conical insert is the most efficient insert, especially if the cone angle is 60°.

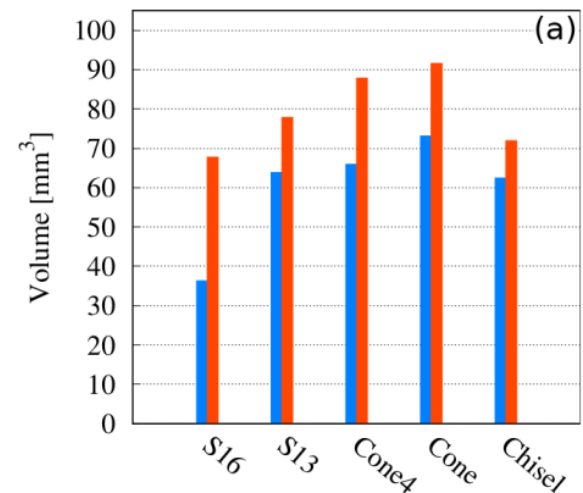


Figure 9: Histograms representing the resulting volume drilled crater (after Aldannawy 2021)

Fig.10 presents the confining pressure effect on the volume drilled. It can be seen that the drilled volume decreases with increasing confining pressure. In addition, the decrease rate is higher for lower values

of pressure, where the volumes decrease rapidly between 0 and 10 MPa, and then decrease slowly for higher confining pressures. This development appears to be in agreement with other studies [Han et al., 2005a, Saksala, 2016].

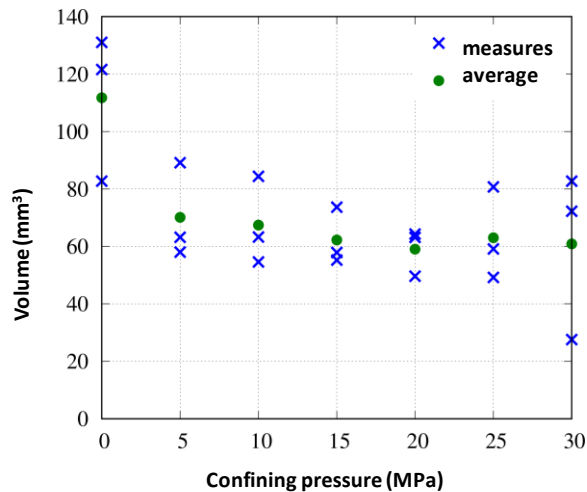


Figure 10: Resulting volume drilled crater as a function of the confining pressure

The study of the elementary interaction of an insert with the rock to be cut alone does not allow for the optimization of the performance of percussive drilling. Indeed, even if it is necessary to size the insert according to the rock to be cut, the distribution of the inserts on the bit will play a major role. The breakage of the rock under the impact of the insert occurs both in the direction of the impact and perpendicular to it with the development of radial cracks. To optimize the performance of percussive drilling, the inserts should be placed on the tool in such a way that two neighboring impacts are close enough to allow the junction of radial cracks and thus significantly increase the volume of rock cut by these two impacts.

Fig.11 shows the evolution of the volume of rock removed as a function of the interaction distance between impacts for an S13 insert in Red Bohus with 10 MPa of fluid pressure. It can be seen that this has a significant importance on the performance and that there is an optimal interaction distance.

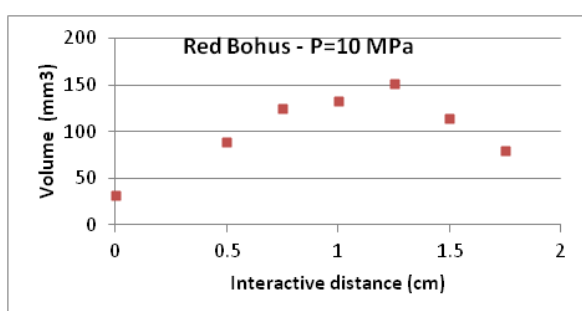


Figure 11: Resulting volume drilled crater as a function of the interactive distance between two impacts

More results can be found in Aldannawy et al (2022).

4. DRILL BIT DESIGN

Drill bit design was based on the previous results, namely

- The results of the simulation of the stresses at the bottom hole which will guide the definition of the profile of the most adapted bit
- The results of the numerical simulations and the elementary or interaction tests which will allow to guide the choice of the best adapted inserts according to the formations to be drilled.

We therefore opted for two bits: a classical bit with semi-spherical inserts (Fig.12) and a hybrid bit with dome and cone inserts shape. For both bits, a positioning of the inserts was done to generate the most interaction between the impacts, a maximum number of inserts and an optimum bit profile.



Figure 12: Drill bit designed for the test trial

5. TEST TRIALS

5.1 Experimental set-up

The experiments were conducted on a new Horizontal Drilling Test Bench that can handle the experiments related to drilling a fully horizontal wellbore (Fig13 & 14). This setup can drill through 7m of different rock types and can include different elements in the BHA such as stabilizer, mud motor, MWD, and so on. WOB is controlled by two hydraulic pistons and rotation can be provided by the drillstring up to 100 RPM and/or by the mud motor up to 175 RPM.

5.2 Certification of a hydraulic hammer for Geothermal Drilling

The major problem of the water hammer is the wear of the internal parts of the hammer when using water that is not perfectly clear. One then needs either to work with lost water which is not very economical nor very ecological, or to recycle and treat the drilling water to remove the impurities to a level exceeding the capabilities of most commercially available mud treatment systems (very expensive operations). The

interest of the technology developed in this project is to design a mud hammer, able to work with a mud loaded with solids. For this, the internal parts of the hammer in movement and/or in contact with high fluid speeds are made, for the most part, of hard material. This results in a hammer that is much more resistant to abrasive wear.

Temps : 0.0

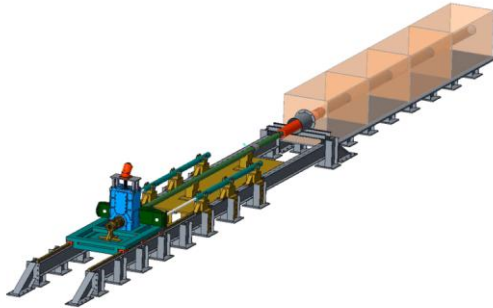


Figure 13: Schematic of the Horizontal Drilling Set Up



Figure 14: Horizontal Drilling Set Up

The certification of the hydraulic hammer consists in carrying out a drilling of several hours in a controlled environment while measuring the evolution of the performances with time. In order to be representative, the drilling was carried out with a bentonitic mud loaded with very fine sand.

Wear evolution was controlled in real time by measuring the injection pressure and the impact frequency during drilling. Indeed, the wear of the parts results in a decrease of efficiency and thus a decrease of the performances. A continuous control of these parameters will indirectly allow to know the evolution of the wear. At a constant injection rate, the loss of

performance will be reflected by a drop in injection pressure (which may also depend on other pressure drops in the circuit) and the frequency of pulsations in the injection pressure (frequency depending on the impact frequencies of the hammer).

No wear development was observed during 10 hours of hard drilling conditions. That was confirmed by the inspection of the moving parts inside the hammer which presented no damage.

5.3 Dynamic and Directional behaviors

Drilling tests were carried out on the Horizontal Drilling Set Up with two mains objectives:

- Characterization of the vibration behavior of the mud hammer. The tests performed revealed high vibration levels, and a vibratory behavior that is very different from conventional rotary drilling. This behavior can be both beneficial (e.g. improved transmission of weight in deviated wells) but also destructive (damage to the electronics of downhole instruments: MWD, LWD...). The Horizontal drilling rig allows high frequency vibration measurements. Coupled with measurements directly on the BHA and the Bit, they will make it possible to analyze the vibratory behavior of the hammer and to issue recommendations to the operators in the development of their BHA.

- Evaluation of directional behavior in rotary percussive drilling: this aspect is a recurring request from drilling operators, as the vast majority of deep geothermal wells are nowadays drilled using directional drilling. As for PDC Bit steerability in rotary drilling, the directional behavior of the roto-percussive system has an important influence on the overall directional response of the entire string. Once the directional behavior has been evaluated on a horizontal drill rig, a roto-percussive directional drilling method can be developed with recommendations to operators for the construction of their BHA.

Sliding and rotating tests have been carried out at 3 bent sub angles (0, 1 and 2°) and the accelerations in the X, Y and Z directions were measured at the bit or above the mud motor.

The illustration below (Fig.15) shows the interior of the well during these tests. One can clearly see a lip in the middle of the well which marks the transition between a double rotation drilling phase (the eccentricity of the tool movement causing a widening of the well) and the single rotation drilling phase (simple helical movement)



Figure 15: downhole Rotating/Sliding transition with 1° bent angle

Fig.16 shows the axial acceleration at the bit (a) and above the mud motor (b) as a function of times. We can observe 3 test phases that highlight the fact that:

- The percussion of the down-the-hole hammer is well observed at the bit (acceleration intensity along the main axis HGZ-RMS of the order of 1.5g) when it drills.
- The percussive effect is strongly attenuated above the engine as evidenced by the low levels of main axis acceleration above the engine (HGZ-top-RMS) compared to those measured below (HGZ-bottom-RMS)
- Note that the intensity of the HGZ signal is limited because the pressure drop in the hammer had been reduced for the conduct of these tests

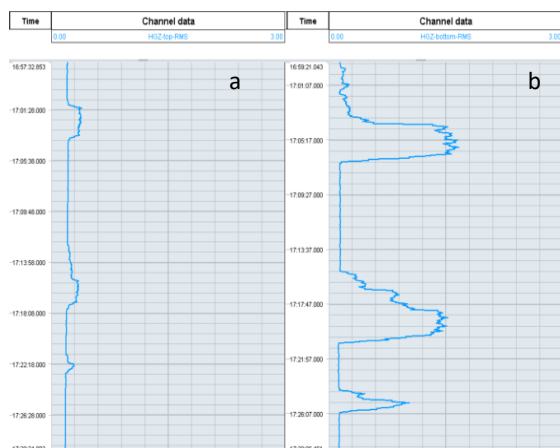


Figure 16: Acceleration along the drilling axis at the bit (b) and above the mud motor (a)

The directional tests were performed in two stages. The first step consisted of drilling in double rotation (motor and drill string rotation) and, in the second step, drilling in single rotation (only motor rotation) with two different bent orientations. The Fig.17 shows an example of directional result with the evolution of the well inclination with the drilled depth for a bent angle of 2°. We find the changes in bent orientation at 32 cm (first dotted vertical line with a bent oriented for a lateral deviation) and at 70 cm (second dotted vertical line with a bent oriented for a falling inclination). We thus find that the hammer does not present major difficulties for well deflection with a mud motor. However, a more thorough study of its steerability should be carried out given the long lever arm between the bit and the bent due to the presence of the 1.5 m long hammer between the two.

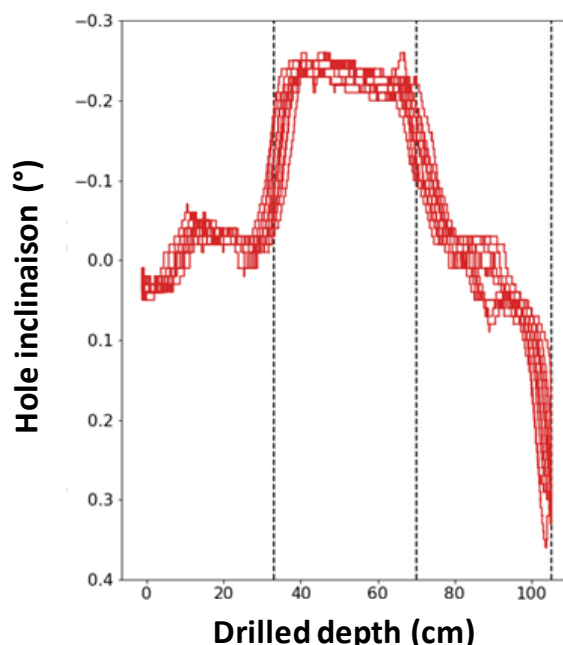


Figure 17: Hole inclination during directional drilling with 2° bent angle.

3. CONCLUSIONS

The objective of the project was to develop the hammer technology for 8 ½" diameter geothermal drilling. The work was done in different steps to take into account most of the impacting parameters on the performance:

- The definition of the in-situ downhole stresses at the bottom hole allows to adapt the bit profile accordingly
- The development of a numerical model of the insert-rock interaction during percussion to analyse insert design parameters effect on the performance
- Carrying out an extensive experimental campaign to study the effect of rock hardness, mud pressure, impact energy, insert shape and interaction between inserts on cutting performance (see Aldannawy et al 2022)
- Defining design criteria for 8 ½" bits suitable for percussive drilling
- Carrying out qualification tests of the hammer developed in the framework of the project

In addition, additional tests have demonstrated the directional capability of the hammer associated with a mud motor.

The final result is the development of a large diameter hammer-drilling tool assembly with :

- A hammer that does not lose efficiency after 10 hours of operation.
- Drilling bits adapted to large diameter drilling, including innovative hybrid bit capable of reaching high penetration rates.

Acknowledgements (optional)

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