Proceedings World Geothermal Congress 2026
Calgary, Canada, June 8 – 11, 2026

Drill Deeper, Faster: Fluid-Driven High-ROP Drilling with Real-Time Seismic Insight for Deep Geothermal

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Keywords: Drilling, Seismic, ROP, Hammer, Performance

ABSTRACT

Geothermal energy is a leading candidate for providing clean, non-intermittent and renewable source of energy but its large-scale utilization is currently limited to thermal hotspots where higher than average geothermal gradient is present. For global scalability of this energy source, it is paramount to be able to drill deeper than the current average. However, two major bottlenecks currently limit this potential: low rates of penetration (ROP) during drilling and high uncertainties in subsurface structure.

Drilling for geothermal power requires expanding the exploration horizon beyond what is currently done in the traditional oil and gas sector. This includes drilling through the basement rock, typically hard granites, where traditional drilling bits are not well suited. Moreover, the sediment–basement interface acts like a seismic "mask": its strong reflectivity overwhelms deeper signals and prevents active seismic methods from imaging basement structures.

In this study, we develop a fully fluid driven system that delivers significantly higher ROP in hard granites compared to traditional polycrystalline diamond compact (PDC) bits, while simultaneously generating a controllable seismic source signal. Insights from previous projects like ORCHYD have shown that combining shearing and percussion actions enhances the rock cutting process far more effectively than the pure shearing action provided by PDC bits. By actively controlling the energy of the percussive impacts, the drill bit also functions as a controllable downhole seismic source, generating waves that can be recorded by surface geophones—effectively creating a reverse Vertical Seismic Profiling (VSP) configuration for illuminating the reservoir. The bit's performance is also assessed under laboratory conditions.

INTRODUCTION

Geothermal energy is a prime candidate for steady baseload, low-carbon power generation, yet large-scale deployment remains constrained by the ability to drill fast and reliably into crystalline basement at depth.

Beyond conventional sedimentary targets, deep geothermal developments must cross the sedimentary–basement interface and progress through hard, abrasive granites, where conventional drag-bit technologies suffer from low rate of penetration (ROP), excessive bit wear, and dynamic dysfunctions. In parallel, the sediment–basement interface forms a strong seismic reflector whose high contrast masks deeper arrivals and degrades seismic imaging, thereby increasing structural uncertainty during drilling. Addressing both bottlenecks—ROP and subsurface uncertainty—is essential to making geothermal broadly scalable.

At the scale of the bit-rock contact, two archetypal mechanisms govern fragmentation: shearing (drag cutting) and percussion/indentation. For PDC cutters, classical cutting models relate normal and tangential forces to depth of cut, cutter geometry, and kinematics, and express efficiency via Mechanical Specific Energy (MSE) (Gerbaud et al (2006), Detournay et al (2008), Teale (1965)). These models explain why PDC is highly effective when a stable depth of cut is maintained, yet becomes inefficient under low depth of cut, high friction, or dynamic instabilities. Conversely, indentation/percussion imposes impulsive normal loading that nucleates a crushed zone and drives radial/median/side cracking—an inherently favorable route for fragmenting hard, brittle rocks typical of basement formations. Decades of analytical, numerical, and experimental studies of wedge/conical indentation in rock have mapped the stress fields, damage zones, and scaling with confinement and indenter geometry (Xie et al, 2024).

These complementary strengths motivate hybrid strategies that couple percussion with shearing. Recent laboratory campaigns and modeling on axial–torsional/impact-assisted drilling show that superimposing controlled impacts onto a dragging cutter reduces cutting forces at a given depth of cut, promotes crack initiation ahead of the cutter, and lowers MSE (Xi et al, 2025).

In addition to improving penetration, these impact events constitute repeatable, energetic sources capable of generating a detectable downhole seismic signature. When combined with surface geophones or near-surface arrays, these signals can be exploited for Seismic-While-Drilling (SWD) or drill-bit geophysics, illuminating basement structure beyond the resolution of standard surface seismic under strong impedance contrasts. Thus, percussion-assisted shearing offers a unified pathway to drill faster and see farther.

Building on lessons from recent projects such as ORCHYD, this paper investigates a fully fluid-driven hybrid system that couples-controlled percussion with shearing in hard granites. The system is designed to (i) deliver higher ROP; (ii) generate a controllable seismic source signal at the drill bit by actively modulating percussion energy. We first review the ORCHYD project results and then describe the drilling performance as well as the seismic signature in a controllable environment.

1 BACKGROUND

1.1 Highlights from ORCHYD

The ORCHYD project reports a systematic experimental and numerical investigation of a hybrid drilling concept coupling high-pressure water jetting (HPWJ) with down-the-hole (DTH) percussion for deep geothermal applications in hard crystalline rocks. The approach relies on the deliberate interaction between hydraulic slotting and dynamic mechanical impact to modify stress conditions and fracture mechanisms at the bit–rock interface under surrounding high confining geostatic stresses and hydraulic pressures in the borehole. Stress field analyses demonstrate that peripheral grooves generated by HPWJ induce a pronounced local stress-relief effect, partially counteracting the strengthening induced by lithostatic pressure at depths representative of several kilometers. This effect is shown to depend strongly on the drill bit profile and groove depth, with concave geometries providing the most efficient redistribution of radial stresses (Sellami et al., 2022). At the insert scale, combined numerical damage modeling and controlled impact experiments demonstrate that conical inserts with reduced tip radius enhance tip stress concentration and shear-dominated fragmentation, while an optimal center-to-center spacing of approximately 8 mm maximizes constructive overlap of damage zones. Full-scale laboratory drilling tests performed under 20 MPa mud pressure in Sidobre granite confirm the multiscale nature of the hybrid synergy, with rate of penetration and drillability increasing by factors of four and ten, respectively, as compared to a conventional tricone reference (Gerbaud et al., 2025). The results further identify a critical interaction distance between impact points and HPWJ grooves, within which rock removal is amplified by a factor of six due to crack deflection, shoulder collapse, and coalescence toward free surfaces. These findings demonstrate that the performance gains of the hybrid bit arise from percussion optimization with a genuine coupled hydro-mechanical fragmentation mechanism. Overall, the ORCHYD results establish HPWJ–percussion hybridization as a physically sound and technologically mature strategy for reducing mechanical specific energy, mitigating bit wear, and enhancing drilling efficiency in deep hard-rock geothermal environments, with direct implications for lowering well construction costs and improving economic viability.
However, the deployment of the hybrid HPWJ–percussion concept in deep geothermal environments inherently requires the generation of ultra-high fluid pressures directly at the bottom-hole assembly, which implies the integration of a downhole pressure intensifier capable of transforming conventional drilling fluid pressure into localized jet pressures exceeding 250 MPa. While this technological requirement represents a key engineering challenge for full-scale field implementation, the present results also demonstrate that substantial performance gains can already be achieved by focusing solely on the optimization of the percussive cutting system. Experimental observations and numerical analyses show that a careful joint optimization of cutter geometry, impact energy, insert orientation, and spatial interactions lead to a marked increase in drilling efficiency, even in the absence of active jet slotting. In particular, the combined effects of enhanced stress concentration at the insert tip, optimized insert spacing, and favorable interaction between successive impacts promote more efficient crack initiation and coalescence under high confinement. These findings indicate that the percussion optimization pathway constitutes a short-term, low-risk route for rapid industrial transfer, while the full hydro-mechanical hybridization enabled by downhole pressure intensification represents a medium-term breakthrough for further performance enhancement.

1.2 Experimental setup

The horizontal drilling test bench recently developed by Mines Paris–PSL in Pau, as schematically shown in Figure 1, constitutes a complementary experimental facility to the existing drilling platforms, specifically designed for controlled investigations of directional and dynamic drilling processes. The setup enables the drilling of boreholes up to 7 m in length in a wide range of lithologies and allows the introduction of artificial faults to reproduce structural heterogeneities. It supports both rotary drilling modes, with full rotation of the drill string, and sliding modes, with rotation applied only downstream of a positive displacement motor (PDM), thereby reproducing realistic directional drilling configurations. A major asset of the facility is the possibility to deploy a fully instrumented drill string of up to 15 m, into which downhole components such as stabilizers, mud hammer, PDMs, and rotary steerable systems can be integrated. The bench further allows rapid reconfiguration of the experimental setup and instrumentation at multiple locations along the string, while operating in a fully controlled environment in terms of rock properties and drilling parameters. The combination of flexibility, representativeness, and instrumentation makes the Pau horizontal bench a powerful tool for the experimental investigation of drillstring dynamics, bit–rock interaction, and directional drilling performance. For this specific investigation, a Recon® vibration sensor was incorporated into the bit shank and a Recovib accelerometer from Micromega was added on the back side of the rock sample to record the dynamic drilling signal transfer to the rock.

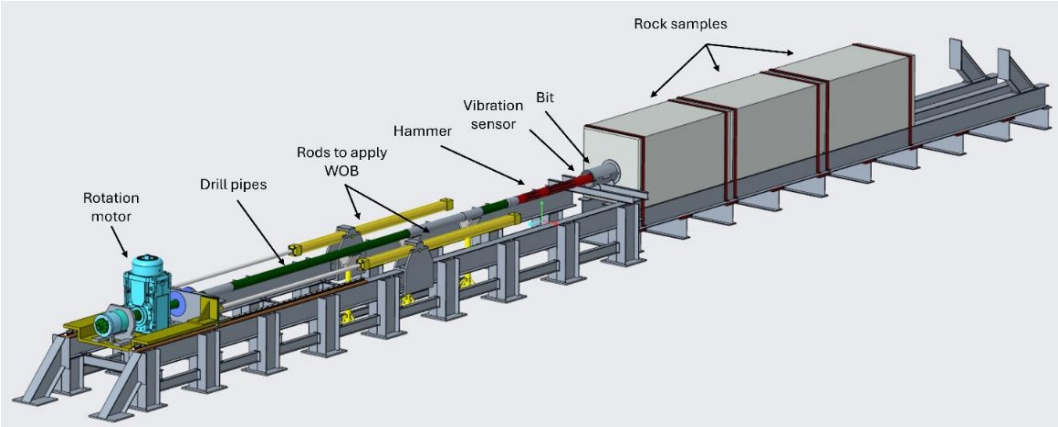


Figure 1: Schematic representation of the drilling experimental platform to investigate dynamic drilling processes with variety of rocks and interbedding features

2 ROP IMPROVEMENT

To assess the relevance of coupling shearing and percussive mechanisms for the efficient breakage of hard rocks representative of deep geothermal drilling conditions, a series of comparative drilling experiments was conducted on the horizontal test bench under strictly controlled and identical operating parameters. A mud hammer developed within the framework of previous project was employed, and four dedicated 6-inch drilling bits (Figure 2) were tested to quantitatively compare the drilling performance and evaluate the contribution of percussion within a shear-dominated cutting process. Bit A corresponds to a conventional hammer bit equipped with semi-spherical inserts specifically designed to withstand the high-impact loads transmitted by the mud hammer. Bit B is a tricone bit commonly used for drilling hard formations in geothermal applications. Bit C is a standard PDC bit designed for hard-rock drilling under purely rotary conditions. Finally, Bit D is a bit specifically designed and developed within this project, featuring an aggressive cutting structure combined with enhanced impact resistance, enabling simultaneous rock destruction by both percussion and shearing mechanisms. This experimental campaign provides a direct and quantitative basis for evaluating the mechanical synergy between impact loading and shear cutting in hard-rock drilling. Tests were performed with water at atmospheric pressure on Sidobre Granite, a coarse-grained Variscan granodiorite (304 Ma) quarried near Saint-Salvy-de-la-Balme (France). Its density (≈ 2629 kg/m^3) and high P-wave velocity (~ 5900 m/s) indicate negligible open porosity (< 0.5 %). Uniaxial compressive strength is 150–170 MPa (quasistatic), indirect tensile strength ≈ 10 MPa, and triaxial strength rises from ~ 380 MPa at 20 MPa confinement to ~ 800 MPa at 100 MPa, with failure evolving from axial splitting to single shear planes under high confinement (Dumoulin et al., 2024)).

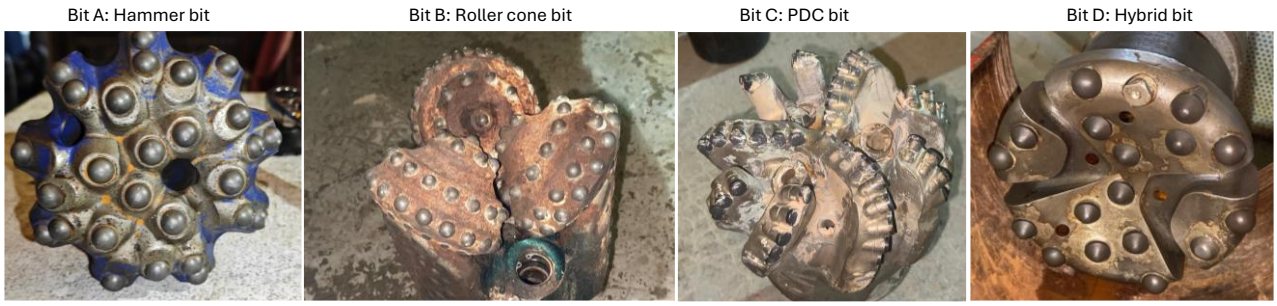


Figure 2: Different types of drill bits used to showcase their relative performance, to highlight the efficiency of the hybrid bit design (bit D).

Figure 3 illustrates the evolution of the rate of penetration (ROP), expressed in $m \cdot h^{-1}$, as a function of the weight on bit (WOB). The results show that the standard PDC bit, which primarily removes rock through shearing, outperforms both the tricone bit and the conventional hammer bit over the investigated loading range. In contrast, the hybrid bit, which combines percussive and shearing mechanisms within the cutting process, exhibits a marked and systematic enhancement of drilling performance. Unlike the conventional hammer bit, the hybrid bit displays a clear positive sensitivity of ROP to increasing WOB, highlighting the shearing action, while maintaining performance levels that are consistently higher than those of the PDC bit. Moreover, at low WOB, the hybrid bit demonstrates ROP values that exceed those of the other bits by a factor of three to four. This behavior is of particular interest for long horizontal drain sections, where the available WOB is often strongly limited by friction and wellbore geometry, and where maintaining high penetration rates under reduced axial load represents a critical operational challenge.

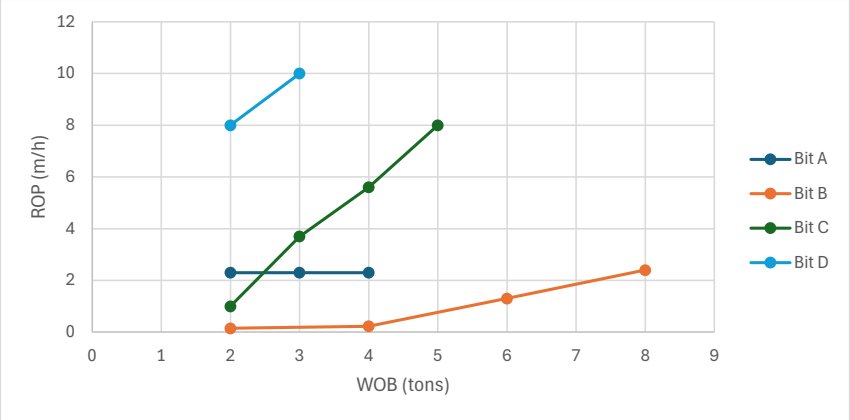


Figure 3: A chart plotting the trend of ROP vs. WOB for different type of drill bits tested. Bit D showcases improved performance as compared to the others.

3 BIT SEISMIC SOURCE AND SEISMIC WHILE DRILLING

For Seismic While Drilling (SWD) applications, a key requirement is the precise characterization of the seismic source generated at the bit and of the elastic waves effectively transmitted into the surrounding rock mass, so that they can be reliably detected by surface or near-surface geophones. Figure 4 presents the axial acceleration recorded during drilling with the hybrid bit (Bit D), as well as the corresponding frequency-domain analysis performed both on the bit and on the rock. The time-domain signal (Figure 4a) reveals a sequence of highly repeatable and well-defined impact events generated by the mud hammer, indicating a stable and controlled percussive excitation. The associated Fourier spectra (Figure 4b) demonstrates that the dominant emission frequency measured around 28 Hz on the bit is clearly preserved in the signal transmitted into the rock, with consistent spectral peaks observed in both datasets. This direct coherence between the source signal and the propagated wavefield confirms that the hybrid bit acts as an efficient and controllable seismic source during drilling. In contrast with conventional rotary bits, where vibrations are often broadband and poorly correlated with rock response, the hybrid percussive–shearing mechanism generates a structured, energetic, and spectrally identifiable signal that is particularly well suited for SWD applications.

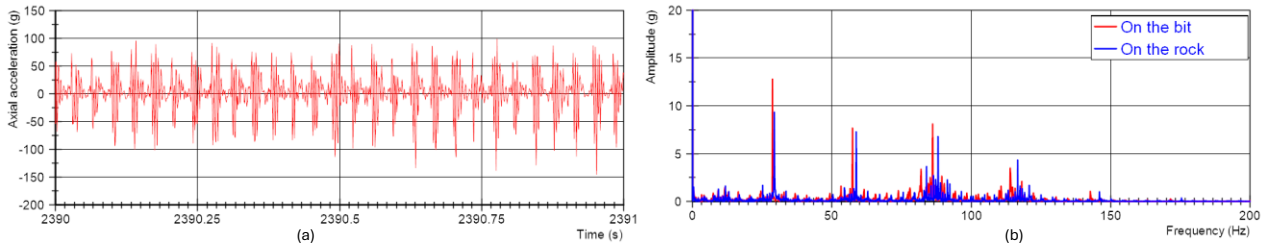


Figure 4: Acceleration recorded on the rock during drilling with the hybrid bit, (b): Amplitude spectrum of the acceleration recorded on the bit and on the rock with the hybrid bit

4 CONCLUSIONS

This study demonstrates that the coupling of controlled percussion with shearing within a hybrid drilling system provides a robust and efficient solution to enhance both drilling performance and enable Seismic While Drilling (SWD) capability in hard-rock geothermal environments. Comparative laboratory tests show that the hybrid bit significantly outperforms conventional hammer, tricone, and standard PDC bits. Beyond mechanical performance, the hybrid bit provides a dual functionality as both a drilling device and a downhole seismic source, enabling simultaneous reservoir characterization and drilling optimization in hard crystalline formations.

From a technology readiness perspective, the results indicate that rapid industrial deployment is already feasible through the optimization of the percussive shearing cutting structure alone. The improvements obtained by jointly tuning cutter geometry, impact energy, insert orientation, and their spatial interactions correspond to a TRL 5–6 level, based on full-scale laboratory validation under representative drilling conditions. In the mid-term, further system-level integration and long-duration field testing are expected to raise the technology to TRL 7–8. Overall, the proposed hybrid approach offers a scalable, low-risk, and industrially realistic pathway to address the key bottlenecks of deep geothermal drilling, namely rate of penetration and subsurface uncertainty.

Acknowledgements

These results were obtained thanks to the European Union's Horizon 2020 research and innovation programme funding under grant agreement no. 101006752 (project ORCHYD) and by the ADEME French research funding under grant agreement no. 23ESD0101-A (project GEOSIS).

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