Technology Roadmap for Geothermal Hard Rock Drilling

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Keywords: Geothermal drilling, hard rock

ABSTRACT

The development of more efficient hard rock drilling technologies will be valuable for the geothermal, oil and gas and mining industries. Low penetration rates, equipment wear and damage are challenges often associated with the destruction of hard rock. This paper investigates the hard rock drilling process and includes a state of the art review of the drilling technologies that attempt to address the challenges.

Drilling can be broken down into three fundamental processes that need to be addressed to achieve efficient hard rock penetration:

1) Transfer of mechanical energy to the rock, thereby breaking or fracturing it
2) Keeping secondary effects of the impact within tolerable limits (e.g. bit wear, detrimental drill-string dynamics)
3) Sufficient removal of cuttings from the bit/rock interface

Deep drilling poses a particular challenge for the control of the rock breaking process in view of the great distances involved coupled with geological uncertainty and harsh environments (e.g. high temperature). Effective management of the drilling operation is complicated by the lack of real-time information at a sufficiently high bandwidth, meaning that precise process control is difficult. A number of surveillance systems and models are used to attempt to mitigate the lack of down-hole information. The current best practice regarding rock breaking and the avoidance of dysfunctional behaviour is presented.

Drilling tools must be constructed to achieve optimal rock breaking performance. However, tools also need to resist excessive wear and failure, and broken rock must be effectively removed from the bit/rock interface. A discussion is given of recent downhole tool developments and aspects of the drilling fluid and circulation systems.

Hard rock drilling improvements are discussed in terms of three technology areas:

1) Improved process control
2) Better tools and solutions
3) New drilling systems

In accordance with this approach, a roadmap is suggested for technologies that seem to have the greatest potential.

1 INTRODUCTION

There is a need for new knowledge and solutions for deep drilling in hard rock. A number of applications and industries face challenges when such wells are to be constructed with today's solutions and technologies. Drilling of deep wells (several km deep) in soft formations is a relatively mature technology. The same can be said for shallow drilling in hard rock. However, the combination of deep and hard rock drilling is challenging. High cost, equipment wear and failure, and low penetration rates are common issues.

Geothermal drilling frequently faces both challenges above, as typical geological formations are hard and the heat source reservoir is deep below the surface. High temperature, fractured rock, high pressure and large well diameters are additional challenges. In a geothermal energy roadmap, developed by the International Energy Agency (2011), the key research and development priority is more cost-effective drilling technology.

This paper is focused on progress on (subsurface) technology development for deep and hard rock drilling, with a particular focus on rock breaking. It is believed that this part of the drilling is the key to cost and efficiency improvements. However, a number of other issues need to be considered for a given rock breaking method to be viable.

The work is based on literature studies, results from the NEXT-Drill project[1] and expert opinions provided by the involved partners.

1 https://nextdrill.wordpress.com/

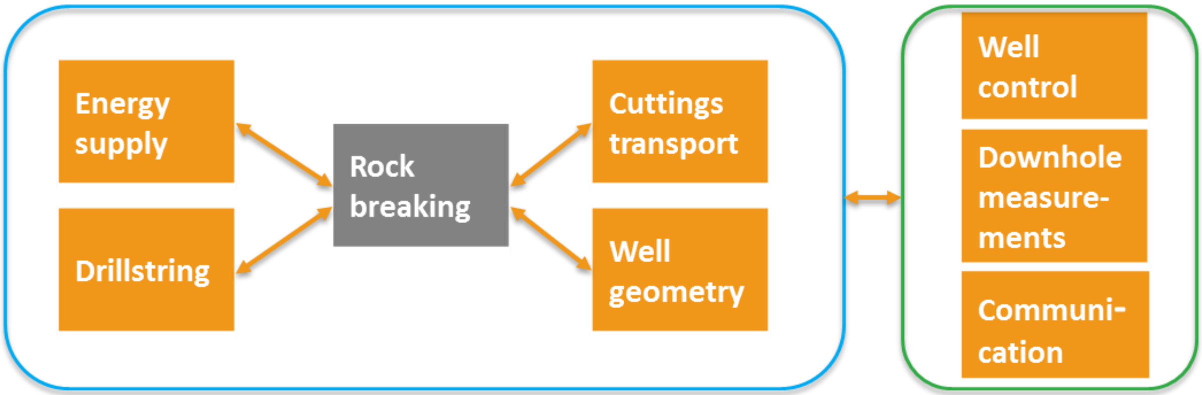

Figure 1: Rock breaking as part of the "drilling process chain", illustrating the relationship between rock breaking and other aspect to be taken care of when drilling.

1.1 Geothermal drilling and cost

The cost of drilling for geothermal resources is a major challenge in many cases. The fraction of the investment spent on wells varies from case to case. Literature indicates a range from 30 to 75 %, and even beyond (Finger & Blankenship, 2010), (MIT, 2006), (Hirschberg *et al*., 2015), (Dumas *et al*., 2014). The low end is representative of high grade hydrothermal systems while the high range is more representative of lower grade enhanced geothermal systems.

A target of 25 % reduction of well construction cost within 2020/2025 is given by The European Geothermal Energy Council (Angelino *et al*., 2016). In less favourable areas where the wells required are deep and through hard rock, a larger cost reduction is likely needed to make geothermal based electricity viable.

Research efforts to implement new solutions to reduce the cost of geothermal well construction have been discussed e.g. by Blankenship *et al*. (2005), Vollmar *et al*. (2013), Nygaard *et al*. (2010) and Randeberg *et al*. (2012). Additionally, there are great opportunities for utilizing technologies and expertise from the petroleum drilling industry.

1.2 Aspects of deep drilling in hard rock

Deep and hard rock drilling can be regarded as the "double challenge of drilling" as two challenging tasks are addressed at the same time. Each challenge considered separately has relatively well-developed solutions. For deep drilling, rotary drilling with a suitable drill bit is a viable solution. For (shallow) hard rock drilling, percussion hammer drilling has a good track record. However, using percussion hammer drilling in deep wells is still considered to be a challenge.

The routes to improvement of established technologies can be along two main paths:

1) Enabling percussive drilling as a generally applicable technology for deeper wells
2) Improving the performance of rotary drilling in increasingly harder rocks

In addition, combined rotary and percussive action has some attractive features.

When pinpointing the issues and challenges associated with hard rock drilling, the drilling process can be described as a chain of technical issues that need to be resolved. The single most important aspect is probably the rock breaking process, yet there are several additional aspects that influence the drilling process chain, as illustrated in Figure 1.

2 ROCK BREAKING TECHNOLOGIES

A variety of methods and tools have been developed for breaking rock, however, at least below the limit of what is considered as hard rock (compressive strength about 200 MPa) conventional rotary drilling is still the most commonly used in the deep geothermal and oil and gas industry. In the mining industry, on the other hand, percussive drilling is typically the preferred choice when rock strength exceeds this limit.

Concurrently, there is a constant quest for better performance, either by improving the conventional methods, or by developing new ones. Already in 1960, a review was made of the development of alternative drilling tools (Ledgerwood, 1960). It was stated that many of the "new" systems that were explored at that time, in fact were not new (see Table 1). Today, development work is still being carried out on some of these same concepts, and they are still often described as "new".

Most of these drilling tools represent variations of or alternatives to the drill bit, though some belong to the group of tools that can be added to the bottomhole assembly (BHA) in order to enhance the rock breaking efficiency. The latter include tools that generate vibratory power to the rotating bit with the aim of increasing the drilling rate, and concepts where high velocity jets are applied to enhance mechanical rock breaking.

Table 1: "Many drilling concepts are old" (Ledgerwood, 1960).

Flame Drill	1853
Bottom Hole Rotary Hydraulic Motor	1873
Electric Arc (British Patent)	1874
Conventional Rotary	1884
Chemicals to Soften Rock	1887
Bottom Hole Electric Percussor	1890
Bottom Hole Electric Motor	1891
Bottom Hole Hydraulic Percussor	1900
Retractable Bit & Bottom Hole Motor	1902
Reelable Drill Pipe	1935
Abrasive Laden Jets	1941
Shaped Explosive Charge	1954
Pellet Impact Drill	1955

2.1 Non-mechanical rock breaking

Non-mechanical rock breaking methods may have some promising features when it comes to their potential for removing rock, compared to mechanical methods. A brief review of non-mechanical methods is given below.

2.1.1 Thermally induced rock breaking

A number of thermal based methods breaking rock have been suggested or investigated (e.g. Maurer, 1966). The common factor is that the formation is exposed to some sort of heat source, causing rock failure. The thermal energy destroys the rock via two primary mechanisms: Spalling and fusion/vaporization. Many rock types will spall or fracture when exposed to moderately high temperatures (370-760 °C). Even higher temperatures will generally result in fusion and vaporization of the rock, i.e. phase change to liquid or gas phase. The mechanism in which rock is broken may be relatively complex. For instance, electric discharge may be termed "thermally induced rock breaking", however, the rock breaking may involve pressure pulses that destroy the rock by compression.

A number of concepts for supplying heat to break rock in wells have been suggested. Hydrothermal flames, electric sparks and arcs may provide plasma, i.e. ionized gas, which is brought into contact with the formation. Electron beams supply heat directly to the rock. Electromagnetic energy in the form of laser light, microwaves etc. may also be utilized. The energy can alternatively be supplied (indirectly) in the form of some kind of hot fluid. On what is to be considered a purely conceptual level, the possibility of freezing the rock and causing fractures has also been suggested.

In view of drilling in hard rock, thermal based methods have some attractive properties compared to mechanical drilling. As the "hardness" of the rock is associated with its mechanical properties, thermal rock breaking methods utilize thermal properties, and may be relatively independent of rock type. Hard, brittle rocks could actually be especially suited for utilizing thermal rather than mechanical stresses to destroy them.

Thermally based methods are not yet demonstrated as viable for rock breaking in deep wells. Challenges with supplying sufficient energy downhole, difficulties of operating the system under pressure and in a liquid-filled well, excessive thermal wear on drilling tools, are typical obstacles to date.

Further, the energy efficiency of breaking rock is probably significantly lower for many thermally based methods (especially for fusion/vaporization) than for mechanical. Therefore, the challenge of supplying sufficient power would be even greater for thermal methods.

A number of companies and research groups are working on different technologies for thermally assisted mechanical drilling – see e.g. Ezzedine *et al.* (2015). The common challenge with such concepts is that they require a system for transferring the needed power to the downhole tool. This is a challenge shared with electrically powered mechanical drilling (see also section 4.4). The complexity of operating both the mechanical drillbit and the thermal system also suggest that the technology needs significant development before being available for deep drilling applications.

2.1.2 Fluid based rock breaking

Fluid flow in the wellbore is necessary for drilling, as cuttings need to be transported from downhole to surface. However, utilization of fluid flow may not just be auxiliary, but could act as a rock breaking method in itself (e.g. Dickinson & Dickinson, 1985).

Fluid-assisted drilling involves weakening the rock by fluid flow in addition to the mechanical impact. Application of jetting, erosion or cavitation effects (or combinations of these) are under development in order to support deep drilling. An advantage of such a combined drilling method is that it could be implemented without an additional system for transferring the hydraulic power needed. If significant changes to the drillstring are needed (e.g. drillpipes with extreme pressure rating), the technologies are less attractive from an operational point of view.

In this area, the ThermoDrill[2] project could be mentioned. It is a recently launched EU project (Horizon 2020) with the aim of implementing conventional rotary drilling in combination with fluid jetting. The target is to achieve a doubling of ROP (rate

2 https://thermodrill.unileoben.ac.at/en/project/

of penetration) in hard rock and reduce well construction costs by 30 %.

Another recently granted EU project is SURE[3] (Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource), investigating radial jet drilling technology as a method to increase the efficiency of geothermal drilling.

2.1.3 Chemical rock weakening

Highly reactive chemicals, such as fluorine and strong acids, will weaken the rock, depending on rock type, concentration of chemicals etc. So-called acid drilling has been suggested for the creation of holes in acid-soluble rock (e.g. carbonates).

Explosives are used extensively to break rock in excavation, mining, tunnelling etc. Use of explosives to break rock in deep wells has only been described at a conceptual level to date.

The use of chemicals for deep drilling in general poses a number of unresolved challenges, e.g. handling of aggressive and dangerous chemicals, and difficulties of controlling the process.

2.2 Mechanical drilling and energy efficiency

The energy efficiency of drilling is often associated with the mechanical specific energy (MSE), first introduced by Teale (1965) as the energy that is required to excavate one unit volume of rock. It is a concept that can be used to quantify the mechanical power delivered to the bit, which is the power that defines the capacity of the system, directly affecting efficiencies, operating practices and performance (Pessier *et al*., 2012).

The energy efficiencies of most drilling methods can be assessed by comparing the specific energy to the compressive strength of the rock. Typically, the drilling efficiency is highest when the specific energy is roughly equal to the compressive strength. However, it is not always possible to obtain accurate measurements of how much energy that is spent on actually breaking the rock and how much that is lost elsewhere in the system.

It is useful to take a step back and consider the total energy balance of the drilling system, including all the energy that is transferred in and out of the well, but excluding auxiliary (topside) components at the drilling rig. This is illustrated in Figure 2.

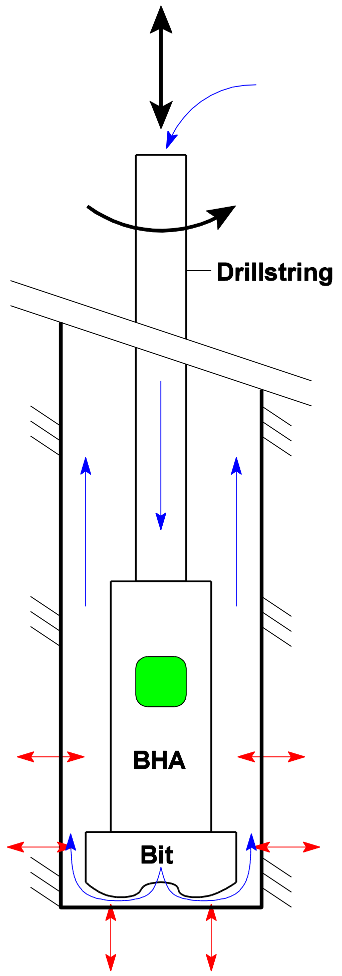

Figure 2: Energy balance for the drillstring system. The black arrows correspond to mechanical energy, i.e. due to hoisting and rotation of the drillstring. Hydraulic energy is provided by the fluid flow, which is shown as blue arrows, heat transfer is illustrated with red arrows, and finally, electrical energy may be available from battery packs (green) in the BHA.

Mechanical power is provided as axial (hoisting) by the drawworks and rotational power from the topdrive or rotary table, or converted from hydraulic power through the use of downhole motors (positive displacement motors or turbines). The hydraulic power is provided by mud pumps. Furthermore, electrical power may be available from battery packs in the BHA, from generators in connection with the aforementioned hydraulic systems, or in unconventional systems through cables from the surface. In the latter case, electrical motors may be used to provide mechanical power downhole, but otherwise the electrical power is generally only sufficient for instrumentation and similar purposes. Finally, thermal power should be

3 http://www.gfz-potsdam.de/en/section/geothermal-energy-systems/projects/sure/

mentioned in the energy balance, both related to heat exchange between the formation, drilling fluid and equipment, and to heat generation (transformed from mechanical and hydraulic energy) due to friction and dissipation.

Each power source has its explicit capacity limit, and in addition, there are implicit limitations in the power transmission lines, e.g. piping capacity with respect to both mechanical load and pressure tolerance. The limits are largely dependent on the design of each specific well and on the equipment chosen during the planning phase of a drilling campaign.

2.3 The "process chain" of mechanical rock breaking

A "process chain" can be made for rock breaking, illustrating what concerns and considerations need to be taken into account when drilling.

Principally speaking, three primary concerns should be taken care of in a rock breaking process suitable for drilling:

1) Mechanical energy should be transferred from the bit to the rock, generating fractures and crushing the rock to pieces small enough to enable hole cleaning.
2) Secondary effects of the impact between bit and rock – e.g. bit wear, and tool and drillstring dynamics – should be within tolerable limits.
3) Cuttings should be removed from borehole, i.e. broken rock must be transported effectively away from the bit-rock interface to promote penetration rates and prevent clogging etc.

In the following, the different techniques for mechanical rock breaking relevant for deep drilling are treated with special emphasis on the three concerns listed above. The matter of cuttings transport is usually not the most challenging when ROP is low, however, the shape and size of the cuttings particles could be a concern even in hard rock drilling.

2.4 Percussive drilling

In many cases, and even at substantial well depths, air/gas hammers have been efficiently deployed to construct wells. However, in order to be a viable technology when there is a risk of influx to the well or hole collapse, percussive drilling needs to be done with a liquid drilling fluid. Therefore, developments within air/gas hammer drilling will not be treated in any detail here, as it is not considered generally applicable to hard rock drilling for the variety of different formations that may be encountered e.g. in geothermal drilling.

2.4.1 <u>The physics of percussive drilling</u>

Percussion drilling can be described as four fundamental processes (Han *et al*., 2009): 1) The drillbit penetrates the rock with axial compression and vibration; 2) The rock receives repetitive impacts, stress propagates, and damage accumulates; 3) Rock fails and disaggregates; and 4) Cuttings are transported away from the bit and up the well. These processes are coupled and difficult to model in a complete framework (Depouhon *et al*., 2015). The physics of this relates to the bit (including cutters or buttons) mechanics, rock mechanics, bit-rock interaction, fluid flow (cuttings transport), temperature dependencies, etc.

Literature and experience show that percussive drilling in hard formations could result in higher rates of penetration than rotary drilling technologies. However, with greater depth, i.e. increasingly higher pressure, percussive drilling is commonly considered being less effective. Reasons for this are not fully understood, but there are several effects that may influence the ROP reduction with higher pressure.

Higher confining pressure acting on the rock results in higher compressive strength. In tests on Kuru granite under confinement, the main failure mechanism by compressive impact is shear failure (Hokka *et al*., 2016). This could explain why the efficiency of percussive drilling is more affected by bottomhole pressure than for rotary drilling (see section 2.5.1).

The performance of percussive drilling may also be reduced due to a so-called chip hold down effect caused by the bottomhole pressure (e.g. Garnier & van Lingen, 1959). The hydrostatic pressure exerted on the formation may reduce the generation of rock chips that can be removed from the bottom of the well, and thus reduce the ROP. High-pressure jets and additional rotary action could possibly counter this effect.

Establishing underbalanced conditions could be a way forward to improve the performance of percussive drilling at greater well depth. In underbalanced drilling, a light fluid constitutes the fluid column, and the pressure on the bottom of the well is designed intentionally to be lower than the pressure in the formation. Technologies for underbalanced rotary drilling are commercially available.

2.4.2 <u>Percussive drilling operation</u>

From an industrial perspective, percussive drilling of deep wells is a relatively unproven technology, with little field evidence of reliable and continuous operation of hammers and drillbits. There are few deep wells drilled with percussive drilling technologies. As a result of this, the optimal drilling parameters and tool selection is challenging for a given well construction case.

A number of critical issues need to be resolved for deep percussive drilling. Examples of these are hardware selection, such as hammer types, drillbit design etc. Optimal drilling parameters are also not sufficiently known in many instances. Hammer frequency, optimal energy per blow (again related to hammer properties), and wellbore stability issues associated with the percussive drilling are some of the factors that imply a need for additional investigation.

Results from experimental work in the NEXT-Drill project, such as sequential drop tests and percussive drilling tests in laboratory, indicate that rotational speed plays a significant role in determining ROP. The influence of indexation (the ratio of the bit angular velocity divided by hammer frequency) and impact energy on the ROP has been investigated and reported by Fourmeau *et al*. (2015).

Compared to rotary drilling, percussive drilling might be more challenging in terms of steerability and ability to maintain a predetermined well path. Again, this could be both a fundamental technical issue and a matter of maturity of the drilling technology.

Experience and literature suggest that hammer life should not be disregarded as an important element of the achievable lifetime of the drilling equipment. The first generation of liquid hammers require water with very low particle content or contaminating chemicals (e.g. Wittig *et al*., 2015). This is in many cases a challenge, as availability of pure water at relatively large quantities is a limited resource. Using pure water as drilling fluid also implies that the specification of the drilling fluid is very limited compared to what is needed in the field. Modification of density, viscosity and gel properties are generally required in order to achieve sufficient cuttings transport and use the drilling fluid as a well control element. Therefore, liquid hammers should tolerate particles in the drilling fluid without compromising lifetime of the tool. The technological developments are aiming to improve the tolerance of the hammer to abrasive wear.

Even though liquid hammers are still quite unconventional technologies when deep wells are being drilled, there are some examples where this solution has been deployed. For instance, water hammer drilling has been done in South Korea down to 5000 m depth in granite. An ROP above 10 m/hr even at great depths has been reported in this case. However, the drilling was underbalanced, as a light drilling fluid with a certain fraction of air was used (Wittig *et al*., 2015).

New wells to be drilled with liquid hammers are also planned in the near future. A relevant case is a planned 7 km deep well in Finland, managed by St1[4]. The drilling contractor Strada Energy[5] will be using a fluid hammer operating system for this very deep geothermal well. Strada Energy claims that the technology is proven to a depth of more than 5 km, and that it can be used even at overbalanced conditions. The company has developed a drill rig especially suited for deep percussive drilling. Achieved ROP is reported to be 25 m/hr in 200 MPa granite, however, no third-party information is available.

It is not clear whether this type of liquid hammer can be used for the wide range of formations that can be encountered in deep drilling. However, percussive drilling performed at balanced or overbalanced conditions, i.e. when there is a risk of influx from the formation to the wellbore, must be considered to be immature. Deep percussive drilling is not yet available for wells where heavy drilling fluids are needed.

2.5 Rotary drilling

Despite developments within percussive drilling, the conventional method of constructing deep wells is still by means of rotary drilling technology. PDC (polycrystalline diamond compact) bit technology works by shearing the rock, being an effective rock breaking method. It is traditionally not used for hard rock, but has become the preferred technology for ever harder formations as cutters are made harder and more impact resistant.

Currently, PDC bit technology is typically suitable for formations with compressive strength up to about 200 MPa. For harder formations, roller-cone and impregnated diamond bits can be used, but the disadvantage of these technologies is significantly lower rock breaking efficiency. As pinpointed by Pessier *et al*. (2012), the introduction of PDC bits significantly improved the ROP of rotary drilling. Because of the much more efficient rock breaking mechanism, PDC technology can be considered a step change in rotary drilling. Therefore, developments within rotary shearing of rock is the path believed to offer the greatest improvements for deep drilling.

2.5.1 The physics of rotary drilling

As described e.g. by Han *et al*. (2009), the requirements for breaking the rock by rotary action is sufficient weight and torque exerted by the drillbit on the formation. The WOB (weight on bit) must be high enough (and cutters hard enough) to press the cutters into the rock, and secondly, the cutters must generate and localize enough shear stress through bit rotation to break the rock. This mechanism of shearing of the rock (utilized most clearly for PDC bits) seems to be increasingly favourable with depth as the rock becomes more plastic and less susceptible to breaking by axial impact (i.e. percussive drilling).

As for percussive drilling, rotary drilling is challenged by increasing depth (as the rock strength increases due to confinement of the formation), and favoured by underbalanced conditions. However, as described in section 2.4.1, the negative effect of borehole pressure is less pronounced for rotary drilling than for percussive. Therefore, it seems that rotary drilling should be the (mechanical) drilling technology selected once exceeding a certain well depth. Precisely at what depth

4 http://www.st1.eu/news/st1-has-made-an-investment-decision-to-construct-a-geothermal-heat-pilot-plant

5 http://www.stradaenergy.com/technology/world-leading-technology

this limit is met is not a trivial question and depends on available operational parameters and drilling tools.

2.5.2 Rotary drilling operation

Rotary drilling is the commonly preferred technology when drilling deep wells. Because of the technology development driven by the oil and gas industry, expertise and experience within rotary drilling are readily available and can be built on for further improvements.

The greatest operational challenge of deep drilling is to ensure that optimal weight, torque, rotary speed and drilling fluid flow rate are applied downhole. This is a general problem associated with the lack of information about the bit-rock interaction and conditions at and ahead of the drillbit. The problem is especially pronounced when the formation has stochastic properties (heterogeneous formations).

In hard rock, dysfunctional vibrations can lead to excessive tool wear and damage that must be mitigated (section 3).

2.6 Rotary-percussive drilling

Both literature (e.g. Han *et al*., 2009, and Fernandez & Pixton, 2005) and experience from the NEXT-Drill project indicate that rock breaking (and consequently ROP) could be improved when combining percussive and rotating action (section 2.4.2).

A number of research groups and drilling tool developers have suggested and tested different types of rotary-percussive drilling tools. In some cases the working principle of the tool is considered to be mainly percussive, and in others mainly rotary.

As mentioned in section 2.4.1, the rock breaking effect caused by axial impacts utilized in percussive drilling is reduced with bottomhole pressure (and even more so than for rotary drilling). Therefore, a combined rock breaking mechanism could extend the pressure level (and well depth) at which percussive drilling can be utilized.

Such a combined rock breaking method could also be favourable in formations with heterogeneity, i.e. with both hard and soft rock formations present.

Compared to “pure” percussive drilling, the cuttings removal from the bit/rock interface may be more efficient because of bit rotation, which results in a fresh rock surface consistently. In addition, the chip hold down effect considered to reduce the rock breaking effect of percussive drilling may be counter-acted by adding a rotary rock breaking component.

An operational advantage of implementing a combined rotary-percussive drilling solution is that rotary drilling can continue in case of hammer malfunction or failure. This is most relevant if the primary rock breaking method is by rotary action. One can also envisage using a system for turning the hammer on and off depending on what kind of formation that is encountered, e.g. rotary drilling through soft rock sections and rotary-percussive for harder rock.

3 DRILLING PROCESS CONTROL DEVELOPMENT

Deep drilling involves great distances, harsh environments, high temperature and need for robust and reliable equipment. Sensitive measurement equipment and high-speed communication systems are generally not available and drilling operations are typically challenged by lack of real-time information at high bandwidth.

In this section, development of measures for improved drilling process control is discussed.

3.1 Complementary drilling tools

Modern drilling and especially drilling in hard rock is associated with challenges such as dysfunctional dynamics, excessive bit wear and sub-optimal rock breaking efficiency. High levels of vibration can damage tools and equipment and lower operational performance. Dynamic dysfunctions are experienced more frequently due to the increased use of PDC bits. Such bits are more aggressive than roller cone bits and have increased the rate of penetration at the price of requiring more power and higher torque, which in turn can generate larger variance in torsional oscillations (Pessier *et al*., 2012).

A number of non-bit tools can be added to the BHA to address these challenges. Their purpose are either to mitigate dysfunctions or directly to improve rock breaking performance. The latter is achieved e.g. by deliberately generating vibrations that are said to enhance the drill bit's ability to fracture and remove the rock, or by weakening the rock through the use of fluid jets, thermal methods etc. Examples of the dysfunction mitigating tools are stabilizers, shock absorbers, vibration dampers, and anti-stall tools.

A non-exhaustive list of commercial tools is given in Table 2. The primary purpose of the majority of these is to mitigate dysfunctional behaviour during drilling, which in effect improves drilling efficiency. Additionally, some of the tools are claimed to contribute directly to the rock breaking process through improved crushing efficiency such as by vibrations, hydraulic or thermal effects.

Table 2: Examples of tools that can be added to the bottomhole assembly in order to mitigate dysfunctions or to improve drilling efficiency.

Tool	Main function	Working principle	Area of application	Power balance	Notes
Tomax: AST	Anti stick-slip tool	Retract bit during excessive torque	Stringers, enlargement	Loading and unloading spring	
NOV: Drilling Agitator Tool (DAT)	Improve weight transfer	Oscillate BHA in axial direction		PDM provides power to the tool	Lower effective friction and reducing stick-slip
NOV: Anti-stall tool	Anti-stall tool	Relieve excessive differential pressure across PDM		Pressure loss reduced (or prevented from increasing) when activated	Does not prevent stalling completely but limits pressure spikes
Ulterra Drilling Technologies: TorkBuster Anti Stick-Slip	Torsional impact hammer			Use hydraulic power, adds to pressure loss	Reducing stick-slip *and allow more aggressive bit → ROP enhancement*
APS Technology: AVD	Active vibration damping			Turbine generated electrical power, and dissipating vibration energy (mechanical energy)	Using magneto-rheological fluid, adjusting viscosity to change damping
Frank's International: HI-tool	Harmonic Isolation tool			Absorbing (dissipating) vibration energy	
Adjustable Gauge Stabilizer	Supporting and centralizing bit	Cam mechanism extending stabilizer blades	Holding angle in tangent sections	Activated by differential pressure	Several vendors
Halliburton	Anti-stick device				"Turbopower turbine with Anti Stick Device"
Cougar DS: ST5	Shock tool				
General Downhole: DE-VIBEorientsub	Protects MWD string from vibration and shock	Dampening			
H.P.H.T. Drilling Tools: The Fluid Tremor	Reduce stick-slip and friction	Controlled axial oscillations and torsional loading	Hard rock drilling with roller cone and PDC bits		Claimed to assist drill bit action

When evaluating whether complementary tools should be employed in a given drilling operation, there are several aspects that need to be considered. Among these are the various risks, e.g. will the tool introduce any non-intended functionality to the system leading to negative side effects or destructive behaviour, and will the tool contribute to increased or decreased energy efficiency? In general, the more pieces that are added to the system, the harder it is to isolate the effect of each component.

Furthermore, aside from the direct cost of the component, as the system complexity increases, so does the cost and potentially the need for extra personnel and expertise. Likewise, there may be limitations to the system, either in the form of positional restrictions (increased distance from the bit to steering and measurement systems) or weight restrictions. The importance of hydraulic power at the bit in order to obtain efficient hole cleaning of the borehole bottom and annulus should also be emphasized (Pessier *et al*., 2012). This is crucial for long wells, where large cuttings bed heights may significantly decrease performance because the amount of power available at the bit is reduced. If too many tools that require hydraulic power is added to the BHA, the mud pump capacity may be exceeded. In long wells, the piping may be a limiting factor with respect to pressure capability.

To summarize, the need for including a particular non-bit tool to the BHA should be assessed by clearly identifying the issue that is addressed by the tool. The resulting improvement should then be evaluated at a system level in order to ensure that the effective performance is improved without undesirable side effects.

3.2 Wired pipe technology

There are significant system-related limitations for present hard rock drilling technologies. These are primarily associated with 1) lack of information about the interaction between bit and formation, and 2) lack of precise and real-time control of the process.

Today's deep drilling is done by powering the rock breaking process from surface by adding weight and rotation to the drillstring, as well as circulating a drilling fluid. Communication with the BHA is done via mud-pulse telemetry at low bandwidth and low update frequency.

Wired pipe technology for communication is still relatively expensive, immature and non-standard, and raises some challenges regarding robustness and signal attenuation along the drillpipe (see e.g. Lawrence *et al*., 2009). The attractiveness of such a system is the possibility of controlling the drilling process.

Many of the present drilling challenges are associated with the fact that downhole drilling parameters (WOB, TOB, RPM and hammer frequency) are sub-optimal for the conditions encountered. There could be major improvements both for percussive and rotary drilling efficiency when introducing wired pipe. This would enable more accurate control of the rock breaking process than with the present situation of relatively little information of what is actually happening at the bit-rock interface.

Further, additional well data could be gathered real-time with sensors placed along the drillstring. Near-bit sensors, giving information about what is ahead of the bit could also be utilized when such technologies are available.

4 PERSPECTIVES AND TECHNOLOGY ROADMAP

In the present setting "technology roadmap" is to be understood as an overview of challenges and areas of improvement for mechanical rock breaking technologies. Improvements are considered in view of what may be ready for field application in the near future (5-10 years).

Non-mechanical drilling needs significant development before being mature enough for field application and is therefore not discussed in the following.

4.1 Percussive drilling development

Percussive drilling is generally not the technology of choice for drilling engineers aiming for deep wells. This may be attributed to both convention and technological reasons. Within the technological domain, several factors should be improved.

Extending the well depth for which percussive drilling is the technology of choice would require developments within a number of areas. First, a deeper understanding of the rock breaking mechanisms (percussive drilling physics) is required to decide the "optimal" drilling parameters (amplitude, frequency, RPM and hydraulics) for a given configuration. Both laboratory work and field trials are necessary to achieve improvements for deep percussive drilling.

Second, there is a need for more accurate control of the rock breaking process, by means of real-time time communication with the downhole tool. An electrically powered percussive hammer could be an option in this regard (section 4.4). Electrical hammers could also offer a wider range of frequencies than fluid-based hammers, with potentially higher ROP levels.

The "hardware" used for percussive drilling should also be improved. This includes both the drillbit, hammer and other equipment in the BHA. The focus of the modelling and experimental work regarding tool life in the NEXT-Drill project has been on materials for drillbits, and the results demonstrate that there is a potential for gradual improvement by optimizing material composition and manufacturing process (Saai *et al*., 2014, and Tkalich *et al*., 2016).

Developments of liquid hammers should aim for a wider applicability in terms of various drilling fluids. This implies incorporation of more abrasion-resistant materials used in the hammer, particularly for components prone to high shear forces and subsequent material wear and damage. The main challenge seems to be developing liquid hammers with tolerance to high levels of particles in the drilling fluids, through both new designs and material improvements. Development of liquid hammers for a wide range of drilling fluids is presently an area of research and development for the tool manufacturers.

Deep percussive drilling is still an immature technology, and one should expect significant development as experience is gained in the industry and new technologies are developed.

4.2 Rotary drilling development

A key challenge for rotary drilling technology, especially for shearing bits, is the onset of dysfunctional vibrations that can occur when drilling in hard formations. PDC cutters are harder than any rock encountered, but impacts due to dysfunctional dynamics can lead to accelerated wear and damage to the bit. The force levels experienced by cutters when torsional vibrations ("stick-slip") occur may well exceed the levels seen in percussive drilling. Material technology improvements must therefore be supplemented by improvements within control of the drilling process, i.e. reductions in vibrations and optimization of drilling parameters.

As described in section 2.5, accurate control of the bit-rock interaction is critical to avoid damage to the drilling tool with a subsequent need for tripping out of the hole. One measure to mitigate this is the introduction of tools in the BHA to complement the drillbit. When evaluating different tools available in the market (or under development), it is a challenge that third-party evaluations of the tool performance are lacking. Studies are made by the tool manufacturers, and there is a lack of comparative lab and field tests to identify pros and cons with different tools.

Drillbit improvements to extend lifetime and improve rock-breaking performance is another important "hardware" area. Drillbit manufacturers perform extensive investigations of the influence of cutter size, angle, cutter grain size, number and placement of cutters, hydraulics etc. It is unclear to what extent step-change improvements can be expected.

4.3 Rotary-percussive drilling development

In order to exploit both the rotary (shearing) and percussive (impact) components of the applied load, drill bits should be specifically designed to provide optimal performance. However, as the physics of "pure" rotary and percussive drilling is challenging enough to identify and describe, combined rotary-percussive drilling is poorly understood on a detailed level. A full description would include a number of coupled physical processes.

4.4 Electrical drilling development

If electrical power is supplied from surface, it is assumed that real-time communication (i.e. wired pipe, section 3.2) will also be available. There are several advantages to this solution.

Electrical motors for downhole use have superior durability compared to hydraulically powered motors. Potentially the lifetime of an electrical motor will be several orders of magnitude higher than a hydraulic positive displacement motor (PDM). Electrical motors are robust, compact and can withstand relatively high temperatures.

There are additional attractive features of electrical drilling (Lurie *et al*., 2003). The use of an electrical downhole tractor system could provide a more accurately controlled WOB, as well as decouple the drillstring and the BHA to reduce dysfunctional bit dynamics. Well trajectory can also be more accurate with an electric BHA, with e.g. orientation and thruster capabilities.

Electrical drilling has been used to construct deep wells, primarily in Russia (Abyzbayev *et al*., 1997). The main challenge of the technology is to supply power downhole in a reliable way. Make and break of drill pipe connections means that power transmission can be unreliable. Coiled tubing technology could be a solution to this.

Electrical power downhole offers the application of downhole traction systems that reduces the need for adding WOB through the length of the drillstring, thus reducing the risk of buckling and other problems seen frequently in long reach drilling. An example of such new drilling concepts is given by Stokka *et al*. (2016). This drilling concept offers possibilities of simultaneous drilling and completion, suitable e.g. in areas with complex pressure regimes. However, the most relevant aspects for hard rock drilling could be the possibility to control weight and torque on the bit very accurately, as well as practically eliminating destructive drillstring vibrations.

In percussive drilling, implementation of an electrical hammer could also offer improvements compared to hydraulically powering the hammer. Resonator's solution is one example of such technology. The improvement potential is associated with the possibility of accurately controlling an electrical tool, thus "tuning" hammer frequency, amplitude and indexation/rotary speed for a given configuration of drillbit, formation and downhole parameters.

Liquid hammers often suffer from limited lifetime due to abrasive wear, especially when introducing particles (e.g. bentonite) in the drilling fluids. Electrical hammers do not require flow through the hammer to provide power, thus making them potentially more suitable for "difficult" drilling fluids.

The deployment of electrical hammers can extend the applicability of percussive drilling, regarding both drilling efficiency (MSE) and drilling fluids that can be used. In this perspective, the often experienced limitations of percussive drilling in deep wells could be addressed.

The major challenge associated with employing electrical rotary and percussive drilling in deep wells is supplying electrical power downhole. Significant technology development is required in order to develop a drillstring that can transfer electrical power from the rig to the BHA in a reliable, safe and cost-effective manner.

5 CONCLUSIONS

Deep drilling in hard rock is associated with a number of challenges in order to achieve sufficiently low cost of well construction for geothermal plants. The cost of deep geothermal well construction should be reduced in the order of 25-50 %. There are possibilities for improvement in all areas of well construction, however, the focus of this paper is subsurface technology development.

The main improvements are restricted according to a timeline of 5-10 years into the future, excluding many of the technologies needing substantial development to be implemented in the field. In this short-term period, further development of the most mature drilling methods is clearly needed.

Challenges and areas of improvement for mechanical rock breaking technologies are mainly along three paths:

1) Extend the applicability of percussive drilling by enabling deeper wells to be constructed
2) Enable rotary drilling to manage even harder formations
3) Develop technology for combined rotary-percussive drilling

The need for more accurate control of the downhole process should be met by development of real-time downhole communication systems and comparative lab and field tests to identify pros and cons with different downhole tools.

In the longer run, deployment of electrically powered percussive hammers and drilling motors seems attractive. If technology for transmitting electrical power through the drillstring becomes sufficiently reliable, real-time control and durable drilling motors could open great opportunities for efficient drilling.

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Acknowledgements

The authors would like to acknowledge the support from research partners, the Research Council of Norway and industry partners Sandvik Mining, LKAB Wassara; H.C Starck, BP, Statoil, Resonator, Norhard and Rock Energy in the knowledge building project KPN 216436 NEXT-Drill (Numerical-experimental technology platforms for cost-effective deep hard rock drilling).

Abbreviations

BHA	Bottomhole assembly
MSE	Mechanical specific energy
PDC	Polycrystalline diamond compact
PDM	Positive displacement motor (mud motor)
ROP	Rate of penetration
RPM	Revolutions per minute
TOB	Torque on bit
WOB	Weight on bit