Thermo Drill

Fast track innovative drilling system for deep geothermal challenges in Europe

D8.3 General guidelines and recommendations in relation with deep geothermal drilling technologies

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Author(s) and company: Alfredo Ramos; Gabriela Reyes; José María Cascajo; Antonio Díaz (all INERCO); Dimitra Teza; Jörg Baumgaertner (both BESTEC), Karin Rehatschek, Tomas Stoxreiter (both MUL) Clément Baujard and Olivier Siebel (ESG)

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Abstract: Summary of the ThermoDrill project`s goals and achievements, and general guidelines and recommendations in relation with deep geothermal drilling technologies

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1. Executive Summary

Geothermal energy is a key component of Europe's energy strategy to significantly enhance the share of renewable and sustainable energy systems in Europe. In wide areas of Europe exists a geothermal potential as long as the wells are deep enough. To make geothermal energy more competitive, there is an urgent need to provide cost-efficient and novel deep drilling technologies. These technologies support in increasing the number of economically viable geothermal projects in Europe.

The main goal of ThermoDrill was the development of an innovative drilling system based on the combination of conventional rotary drilling with high pressure fluid jetting to allow at least **a 100% increase in the rate of penetration (ROP) in hard rock**, and an associated **cost reduction of more than 30%.**

The ThermoDrill consortium has impressively demonstrated its research and development capabilities within the past four years. The observed increase in drilling velocity of 75-140% will mainly result in a reduction of rig time, which has a significant impact on the cost of a well. In order to reach the full potential of the jet-assisted rotary drilling system, the technical maturity and durability of components exposed to high-pressure, such as the high-pressure nozzles needs to be further improved. If the number of round trips required to drill a well is reduced significantly, cost savings of up to 30% for the full wellbore construction are realistic, and even savings in the order of 40% become possible.

A highly relevant outcome of the project is that no conflicting interests have been identified between environmental and economic and technological goals. The Thermodrill system doesn't add any new hazards to a standard drilling operation. However, it also has a positive environmental effect, mainly due to the reduction of diesel consumption during the drilling phase. The main environmental benefit comes from the fact that the use of the new ThermoDrill drilling technology enables to drill more economically and cost-effectively, so that in the future geothermal energy can increasingly be used as an alternative energy source.

Additionally, a large amount of new theoretical and practical knowledge was generated during the project. Through the combination of conventional rotary drilling with high pressure fluid jetting the ThermoDrill system has the potential of being the game changing technology for the future hard rock deep drilling applications.

2. Introduction

2.1 Purpose of this document

The aim of this report is to give a general overview of the ThermoDrill project, and, based on its findings, to provide general guidelines and recommendations in relation with deep geothermal drilling technologies in order to support decision-makers to decide on the base of comprehensive information.

This document is oriented towards different target groups:

- Professionals working in the geothermal energy field or similar areas like oil/gas industry
- Geothermal energy end-users
- Research communities engaged for example in the fields of geothermal energy, underground construction, oil/gas drilling, simulation activities, etc.
- Policy decision makers at different levels of political activity
- General public for general awareness and acceptance of the technology

2.2 Scope of this document

This document provides an overview of the original objectives of the project along with the finally achieved results and their benefits. It also summarizes the lessons learned from the project, and identifies further developments required for commercial implementation. Last, but not least, remaining challenges and main recommendations are presented.

Considering the target groups mentioned above, this document focus on general notions, not delving into details on implementation.

2.3 Related Documents

This document is related to the already submitted deliverables. In particular, it is worth highlighting the following deliverables available at www.thermodrill-h2020.org:

- D9.3 Project Flyer and Project Video
- D6.1 Integration Plan
- D7.1 Test and Validation Plan

This report is also linked to deliverables not publicly available, such as:

- D2.2 Drilling/jetting fluid understanding and fluid/rock/material interaction review, weaknesses and strengths
- D3.3 Simulation is concluded and preferable drilling concept ready to review
- D4.2 An optimized working drilling/jetting fluid system is established
- D5.2 Optimised ThermoDrill bit prototype
- D6.2 Fully optimized ThermoDrill system
- D7.3 Testing & Validation Phase 2
- D8.2 Final report on HSE aspects, Risk management & Business process modelling
- D9.4 Final Dissemination and Exploitation Plan

3. Thermodrill at a glance

3.1 Brief project description

Europe is confronted with a number of significant challenges which are influenced by globalization trends and political changes. The use of geothermal energy as a renewable resource is a fundamental prerequisite for ensuring a secure and sustainable energy supply in Europe.

Heat from the Earth's interior has been used since ancient Roman times and continues to be a valuable and sustainable energy source to this day. The 24 MW geothermal plant in Rittershoffen in France, for example, supplies process heat to a nearby industrial site. But geothermal energy can also be used to generate electricity, as illustrated by the German geothermal power plant at Insheim, which supplies some 8,000 households with electrical power.

Enhanced Geothermal Systems (EGS) have the potential to become a cornerstone of Europe's future renewable energy strategy. EGS can provide baseload energy 24 hours a day, independent from daylight, season or windfall, with near zero carbon emissions and can be implemented almost anywhere in the world. Favourable locations normally lie at depths of between 3,000 and 5,000 meters below the surface, usually in hard rock formations such as granite. As drilling costs rise exponentially with increasing depth, they represent the main cost drivers of geothermal plants, typically accounting for more than half of the investment costs.

Although environmental impacts from geothermal power are subject to large variability due to the complex nature of geothermal reservoirs and corresponding technologies applied, it shows better environmental performance than fossil energy sources and most other renewable energy systems, being EGS using binary cycle technology the most promising geothermal technology.

The ThermoDrill consortium addressed the following research and development topics:

- ***Revolutionary and breakthrough drilling technology***

  Geothermal wells often have to be drilled through very hard rock formations. This normally takes state-of the-art drilling equipment to its limits, resulting in an urgent need for a faster and more durable technology. The combination of conventional rotary drilling with high pressure water jetting showed the potential to be the required game-changing technology. The high pressure jet cuts the rock surface in front of the drill bit, reducing the stress in the rock and thus significantly increasing the rate of penetration. The pressure is generated downhole, meaning that no additional surface infrastructure is required and high safety standards can be upheld.

- ***Unique drill bit prototype***

  The drill bit needs to withstand the enormous hydraulic pressure transferred through the bit to the jetting nozzles. For this reason, a novel high-pressure body was designed and integrated into the frame of a rollercone bit. The extended nozzles allow quick and easy maintenance and exchange of worn-out parts, while also keeping the distance between the borehole bottom and the nozzle to a minimum.

- ***Novel drilling fluid tailored to the new drilling technology***

  The main functions of a drilling fluid include removing the cuttings from the borehole bottom, ensuring wellbore stability and cooling the drill bit. The ThermoDrill project set out to find a fluid which acts not only as a drilling fluid but also supports the jetting process. The newly developed fluid combines these two functions and allows for increased drilling performance while meeting stringent environmental standards.

- ***Simulations and experiments***

  Assessing successful novel drilling approaches required detailed knowledge of the drilling process and the interaction between the high-pressure water jet and the rock. Simulation activities were therefore a central analytical element in the project. In addition, a large number of experiments were carried out to continuously optimise the current approach, as well as to make the ThermoDrill technology fit for future industrial use.

Although the concept of combining hydraulic and mechanical rock destruction methods was not completely new, novel techniques and methodologies were developed within the project. One major challenge was to ensure a sufficient jet cutting performance in crystalline rock under simulated wellbore conditions. As the few literature references consistently indicated termination of jet cutting above a critical ambient pressure level, a comprehensive experimental study was performed to identify boundary conditions which allowed for an adequate jet cutting performance. For that purpose, a novel testing device was designed and manufactured, capable of 450 bar ambient pressure, and jetting experiments with different nozzle size, stand-off distance, jet pressure but also different drilling fluids and rock types were performed. As a result, the critical parameters were defined and specifications for the jetting process in the borehole provided.

In order to prove the concept, full-scale drilling experiments were conducted at a drilling simulator. During the project, two novel drill bit prototypes (8 ½ in size) were developed and manufactured. The three-cone based design was distinctly different to earlier approaches and deviates significantly from traditional standard roller cone bit design. The drilling simulator experiments were again conducted with hard to drill crystalline rock. The test bench was adopted to allow for an external high pressure supply. In total, 17 rock samples were drilled and a maximum increase in ROP of more than 70 % was achieved. Three different drilling/jetting fluids were used, including a specially designed sepiolite based fluid and an established xanthan gum based fluid. Besides the very successful proof of concept, vital knowledge was created for the preparation of the field tests in a real wellbore.

The initial approach to provide ultra-high-pressure (UHP) fluid for the jetting action was based on an UHP pump on surface along with a dedicated high-pressure line inside the actual drill string to deliver the pressure to the drill bit. The major drawback of such an approach was the enormous pressure loss over the long distance of high-pressure pipe, and the expected increase in complexity, leading to disadvantages from various points of view (operational, cost investment, safety). The solution adopted consisted of a Downhole Pressure Intensifier (DPI), a technically challenging option due to space limitations in the drill string and the harsh working environment downhole (e.g. vibrations, high temperature).

The field test at a well in Austria, performed in May 2019, was the final step of the testing phase. The entire ThermoDrill system, with the novel drill bit and the DPI being the major additional components, was deployed in a real 1.3 km deep wellbore. The ThermoDrill technology was compared to conventional state-of-the-art roller cone technology. Although the drilled formation was not the optimum formation for roller cone bits, a very encouraging ROP increase was observed with the ThermoDrill system. The field test impressively verified the feasibility and efficiency of the novel drilling technology.

3.2 Assessment of project objectives

The overall project goal of developing an innovative cost-efficient drilling system was broken down into the following specific objectives:

- Be suitable for drilling hard and abrasive rock types.
- Withstand the extreme temperature and pressure conditions involved in geothermal drilling at depths below 3,000 m.

- At least a 100% increase in the rate of penetration in hard rock.
- An associated cost reduction of more than 30%.
- Meet the most stringent standards in terms of health, safety and environmental protection.

The original research objectives of ThermoDrill and corresponding achieved results can be summarized as follows:

- ***Phase 1 - Investigations and tests on laboratory scale***
  - Objective: investigate and understand the behaviour and impact of the water jet technology applied on hard and crystalline rocks to be expected in deep geothermal wells in Europe (rock mechanics).
    Result: linear cutting tests performed at the very beginning of the project found that the pressure, the jet nozzle diameter and the traverse velocity are the most important parameters for successful cutting of granite. High-pressure water jet cutting experiments were performed under atmospheric conditions on selected hard rock samples. The depth of the kerf created in sedimentary rock type was about twice as deep as the kerfs created in crystalline rock types, although the sedimentary rock showed smaller removed volume than granite, due to its irregular large breakouts.
  - Objective: investigate and understand the influence of high pressure and high temperature on the efficiency of the water jet technology.
    Result: high-pressure water jetting experiments were performed on granite under simulated downhole conditions (up to 450 bar back pressure) in a specially designed and built pressure vessel. These experiments showed that the stand-off distance, the hydraulic power of the jet, the magnitude of ambient pressure and the internal flow path of the nozzle control the cutting performance. It was possible to ascertain jetting parameters which enable a sufficient cutting performance in hard rocks even under deep wellbore conditions.
  - Objective: investigate pressure loss in coil/tubing at 3,000 meters or more.
    Result: after first investigations the decision was taken to create the high-pressure for jetting downhole by designing a downhole pressure intensifier (prototype). This has the advantage that no additional mud string has to be installed, leading to easier handling and low impact on standard tripping procedures, and no additional high-pressure equipment has to be installed and handled at surface (safety).
  - Objective: investigate abrasion and wear in the content of fluid circulation, cleaning, filtering, recycling.
    Result: cleaning of the ThermoDrill fluid was especially investigated, as drilling of granite creates abrasive fines that cause wear on all drilling components. Standard hardened steel nozzles and special ceramic nozzles did not prove to have a sufficient durability for the ThermoDrill application. Only hard metal nozzles showed adequate lifetime and performance and were successfully used in the lab and field tests.
  - Objective: investigate potential borehole fluids to be applied with HT/HP water jet technology to reduce friction and abrasion.
    Result: several fluids were evaluated and the sepiolite system was selected as the prime candidate for combined drilling/jetting fluid. It fulfilled the challenging requirements: a high carrying capacity, high salt tolerance, thermal stability to 150 °C, allow for efficient solids control and be environmentally friendly.

- ***Phase 2 - Conception and design***
  - Objective: formulate/synthesize appropriate drilling fluid/jet fluids considering HSE.
    Result: there are no HSE concerns if safeguards related to the drilling fluid were introduced (origin of sepiolite and corresponding fibres length in order to avoid potential health effects).

- Objective: investigate and design potential directional control for vertical water jet drilling.
  Result: in the current configuration the jet nozzle holder(s) is (are) mechanically connected to the high-pressure body of the ThermoBit prototype(s) allowing for vertical water jet drilling (parallel to the bit body centre axis). For vertical drilling a stabilized assembly can be used. Any directional drilling system required would have to be positioned above the DPI. Hence, directional drilling is possible with the shortest version of the DPI but has to be further investigated
- Objective: develop water jet and mechanical drilling combination for rapid hard rock drilling.
  Result: two innovative prototype bits were developed in 8 ½" size consisting of three legs, a high-pressure conduit/plenum system integrated into the bit body and a high-pressure tube. The development was supported by simulations. Depending on the prototype used, either one or two high-pressure jet nozzles are installed in the nozzle holder(s), that is/are threaded into the high-pressure body.
- Objective: redesign the drilling process and define the necessary research and development measures.
  Result: beside the designs of the ThermoDrill Bits and the new jetting and drilling fluid, the necessity to develop a Downhole Pressure Intensifier (DPI) prototype that can handle rock particles and harsh geothermal downhole conditions became obvious early in the project. The DPI prototype developed is based on principle of a pressure intensifier. Furthermore, a special connection between the single DPI units and the bit was developed.
- Objective: reconsider the casing and cementing issues for wells in hard stable rocks.
  Result: faster drilling can lead to less borehole stability issues, that may result in a different selection of the casing setting depth, and therefore less materials required. This can lead to additional savings and the reduction of environmental impacts coming from the life-cycle of the reinforcing steel.
- Objective: reconsider the overall drilling process in terms of necessities and saving potentials (risk).
  Result: a hazard identification (HAZID) study and environmental study by applying a life-cycle thinking approach (LCA) were performed. This was first done for standard rotary drilling and then for the ThermoDrill system with the conclusion that ThermoDrill in its current configuration, does not add any new hazards to the standard drilling operation, and will have savings in the energy consumption
- Objective: investigate HSE issues drilling (radioactivity, gas, fracture fluid losses, contaminations, seismicity...)
  Result: HSE aspects were studied intensively. A conceptual HAZID study to identify the measures that must be adopted to reduce or eliminate all unacceptable risks, was carried out. A risk matrix to classify the risks for every hazard scenario from the HAZID study was developed and applied. Environmental impacts were studied by a Life Cycle Assessment approach. From the environmental perspective, no relevant conflicting interests have been identified between environmental and economic and technological goals, having the ThermoDrill system an overall positive effect, mainly due to the reduction of diesel consumption during the drilling phase. All impact categories are expected to improve or remain unchanged. However, the main environmental benefit is based on the distinctly increased drilling performance and associated, the possibility to drill more economically and cost-effective. Thus, utilizing geothermal energy is getting much more attractive and will increasingly be considered as an alternative energy source.
- Objective: evolve criteria for planning and development of a prototype
  Result: the main system specifications were established for each prototype component of the system, based on data from the ThermoDrill drilling data base and considering aspects from conventional rotary drilling. Further technical specifications and details were established after laboratory jet testing.

- ***Phase 3 - Prototyping and testing***
    - Objective: set-up test facility and prototypes
    Result: full-scale drilling experiments were performed with a high-pressure fluid jet assisted rotary drilling system at an existing drilling simulator test bench. A mobile pump provided the required hydraulic power for jetting. The pumpability of sepiolite based mud was ensured prior to this test.
    Before running the Downhole Pressure Intensifier and the ThermoDrill bit prototype in the well, the system was tested under surface conditions (DPI Surface Acceptance Test). Additional jetting experiments were performed with hard metal nozzles to ensure sufficient lifetime during the first field test.
    - Objective: test prototype driller and prototype fluids in crystalline rock at HP/HT
    Result: the novel ThermoDrill bit designs (8 ½", 1-nozzle and 2-nozzle vs. baseline bit) were successfully tested along with the ThermoDrill Fluid (sepiolite vs. water and xanthan gum) in a large-scale drilling simulator. Compared to the performance of the standard drill bit, the rate of penetration (ROP) in granite was significantly increased by the ThermoDrill system. In this simulation experiments the fluid types used had no significant influence on the drilling performance of the high-pressure jet assisted drill bits. An increase in the erosion rate was observed with particle containing fluids. Intense research activities on nozzles with increased lifetime were subsequently performed, as sufficient solution was found.
    Within a field experiment the full ThermoDrill system consisting of the ThermoDrill bit equipped with the hard metal high-pressurenozzle (increased lifetime) and the Downhole Pressure Intensifiers (DPIs) installed inside a drill collar were tested in an approx. 1,3 km deep well in Austria. The observed parameters and the drilling performance validated the ThermoDrill approach impressively.
    - Objective: analyse the process and results
    Result: all testing activities ware performed stepwise and the most important parameters were continuously recorded and analysed. The tests were accompanied by HSE measures. The main outcomes/results of each test led to further optimizations in the prototypes (e.g. nozzle holder shape, nozzle material, design details in the DPI…).

3.3 Benefits and strengths of the ThermoDrill drilling system

The table below lists the most important benefits and strengths of the ThermoDrill drilling system.

Table 1: Benefits and Strengths of the ThermoDrill system

Benefits and Strengths
Innovative Technology Drill hard and hot rocks faster: - Reduction of rig time - Reduction of acoustic emissions - Reduction of carbon emissions - Reduction of technical and financial risks Increase of drill bit lifespan: - Less trips - Savings - Less wear Conventional drilling is still possible without the jetting system Better filtration system Better hole cleaning due to more efficient mud system Less wear on entire drill string Additional savings (fuel, power, water, mud material…) Upscaling is possible (larger diameters) Easy handling of the technology on the rig (no additional tools are required) No additional risks compared to conventional drilling technology (HSE)

3.4 Lessons learned from the Thermodrill project

3.4.1 Technology development

The main technical outcomes are summarized below:

- ***Jetting system including ThermoFluid***
  - The average grain size and the permeability seem to be relevant rock properties for the high pressure fluid jet cutting performance.
  - The experiments under downhole conditions showed that the standoff distance, the hydraulic power of the jet and the magnitude of the ambient pressure conditions control the cutting performance.
  - The tests with low hydraulic power jets (small nozzle diameter) showed similar results as observed by previous researchers but it was possible to ascertain jetting parameters which enable a sufficient cutting performance even under wellbore conditions.
  - The experiments, conducted with two different types of mud, did not show a significant negative influence on the cutting performance compared to pure water, which is crucial for the later application in geothermal wells.
  - Standard hardened steel nozzles and special ceramic nozzles did not prove to have a sufficient durability. Only hard metal nozzles showed adequate lifetime and performance and were successfully used in the laboratory and field tests.
  - The composition of the new drilling fluid and the appropriate dispersant, which allows controlling the viscosity with the temperature increase.
- ***ThermoBit***
  - The distinct ROP increase during the large-scale tests proves that the jetting parameters such as the stand-off distance were chosen adequately.
  - Selected HP nozzle diameter performed excellent with the applied total flow rate and the applied HP from the DPI.
  - Thread of nozzle holder and standard nozzle needs to be cleaned after usage to avoid unexpected NPT during B/U.
  - Simulation upfront drilling unknown formation gives useful information related to ROP, WOB and RPM.
- ***Large scale laboratory tests and field tests***
  - Under laboratory conditions and in hard crystalline rock, a linear relationship of the ROP and the applied weight on bit was verified with excellent coefficients of determination.
  - During the experiments, the significant influence of the total hydraulic power at the bit on the ROP increase was observed.
  - The favorable and most effective operational conditions of each novel bit type (1-nozzle bit and 2-nozzle bit) were found to lie in different ranges of WOB while the rate of penetration was increased by a factor of more than 1.7 at a maximum, compared with the standard roller cone bit for both bit types.
  - It was found that the type of fluid used had no significant influence on the drilling performance of the high-pressure jet assisted drill bits, whereas a distinct increase in the erosion rate was observed with the particle containing fluid.
  - Increasing the WOB in the laboratory experiments resulted in a decreasing total specific energy, indicating a better efficiency of the entire rock destruction process. This effect occurred because the jetted kerfs enabled the inserts to remove a distinctly larger volume compared to ordinary drilling, resulting in particles of larger size and reduced friction losses in the sphere of the kerfs.
- ***Drilling Procedures during Field Test***
  - Improve make-up torque of DPI connections to match drill-string make-up torque for easier handling and make-up of connections on site.
  - No abrasion damage seen on DPI units (neither low pressure nor high pressure side).

   - Chemical reaction of drilling fluid in contact with DPI materials has to be investigated in more detail.

3.3.2 HSE issues

As the Thermobit and the DPI are purely mechanical driven , this means that for drilling activities that:

- No special supplies such as energy power, instrumentation air or hydraulic fluids are requested for the initiation and performance of the system.
- No special activities or tasks must be performed while drilling a well due to the handling and preparation of the BHA with the system. The procedures that a drilling company must use for drilling a well site, are the same they used up to now.

So, from HSE point of view there will be NO additional risks by applying the ThermoDrill drilling system instead of a standard drilling system.

As conclusion, the **ThermoDrill system doesn't add new hazards to a standard drilling operation**. No new chemicals, no need for other supplies (energy, air, etc), no different procedures for storage, handling, operation and maintenance of the Thermobit or the DPI. So, by using the ThermoDrill system the risks are the same risks that could appear in any well during a standard drilling operation.

The environmental analysis has been based on the Life Cycle Assessment (LCA) approach, considering as functional unit 1 m of well with a depth of 5000 m drilled in hard rock, including casing and cementing.

The LCA carried out focused on the differences between ThermoDrill and the base case, which was based on data from the project at Soultz-sous-Forêts in eastern France, where three deep wells to over 5000 m depth were drilled. The ThermoDrill case represented the drilling of a well with 5000 m depth using the ThermoDrill technology, which main characteristic is a 100% increase in ROP.

Main conclusions from LCA assessment are:

- ThermoDrill has an overall positive effect, mainly due to the reduction of diesel consumption during the drilling phase. But the main environmental benefit comes from the fact that the use of the new ThermoDrill drilling technology makes it possible to drill more economically and cost-effectively, so that in the future geothermal energy can increasingly be used as an alternative energy source.
- Because the drilling phase has a significant contribution to environmental impacts from deep geothermal energy, the ThermoDrill technology has clear potential to reduce overall negative impacts and thus to improve environmental performance of deep geothermal power and/or heat generation.
- No major conflicting interests have been identified between environmental and economic and technological goals. In this sense, most notably is that reduction of energy consumption and duration of drilling phase leads both to environmental and economic benefits.
- Energy and casing are the inputs responsible for most relevant environmental impacts related to the drilling of a deep geothermal well. Energy consumption is expected to be improved by the ThermoDrill technology.

3.3.3 Business model

The main conclusions of the business modelling are the followings:

- The ThermoDrill development aimed at improving the drilling performance on hard rocks like granite for deep geothermal projects. Considering only the well section drilled in 8.5” in these hard rocks and the associated required budget, the ThermoDrill technology shows an impressive performance. Cost savings in the order of 40% become possible.

- The technology also shows an overall strong cost saving potential in the range of 20% if the whole drilling budget including all fixed costs. Although this percentage of savings may perhaps still appear moderate on a first glance, the effective saving is impressive, summing up to 3 Million € per well and more.
- Various sensitivity analyses performed show that savings achieved in percentage are rather stable, obviously depending daily rig cost, but the rig costs as largest single cost item are not the all-decisive factor.
- The cost modelling demonstrates clearly that applying the ThermoDrill technology also **in the sedimentary well sections makes a lot of economical sense strongly reducing the** drilling costs further.
- The first field tests with the ThermoDrill technology indicated a highly encouraging increase in drilling progress. The modelling presented here is conservatively based only on a doubling of the drilling progress (100 % increase of drilling speed) once the ThermoDrill technology is used. Nevertheless, there appears to be still room for further improvement.

3.3.4 Excellent collaboration within the ThermoDrill consortium

The great (technical) success of the ThermoDrill project was only possible because of the excellent collaboration within the ThermoDrill consortium. All project team members exchanged freely and extensively their existing knowledge/experience in order to tackle the very challenging ThermoDrill tasks. This means that the fruitful collaboration was not only the key for the success, but also a chance for cross fertilization of existing know how and experience.

4. Identification of further developments

In order to reach the full potential of the jet-assisted rotary drilling system, the lifespan of the downhole pressure intensifier and all other components like the high-pressure nozzle has to be further investigated by research and development. If the number of trips required to drill a well can also be reduced significantly, cost savings of up to 30% for the full wellbore construction become realistic.

New technologies in the drilling process are allowing that old unviable wells, becomes into viable. Continued investment in drilling and completions technologies becomes more and more critical as wells become deeper, longer and more geologically complex. So, working on further developments for improving the technology is vital to introduce the ThermoDrill system to the deep geothermal drilling market.

5. Main challenges

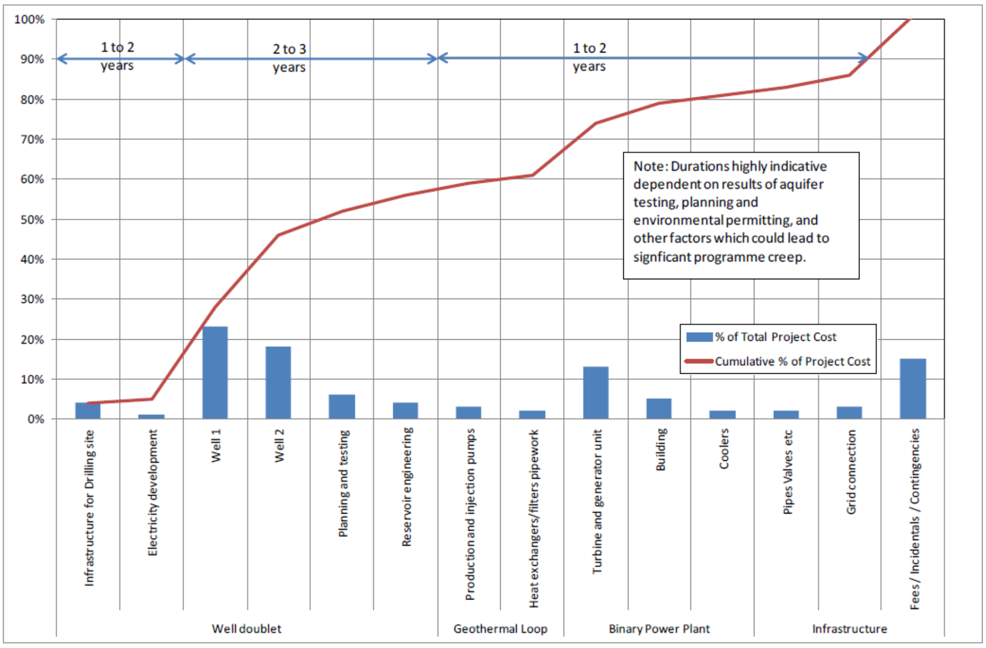
The challenge is to overcome both technical and non-technical barriers of a new geothermal project, being both factors intrinsically dependent. Indeed, financing costs are high due to high risks associated with costly drilling during early-stage exploration, and market financers generally are unwilling to take up these early stage risks and costs, which represents one of the major barriers for geothermal project developers

Deep geothermal wells require depths of 4,000 to 6,000 meters, having to penetrate sediments as well as crystalline rocks at various depths causing several related problems (e.g. drill string failures, low rate of penetration, borehole instability, insufficient borehole cleaning, loss of drill fluid circulation, etc). Drilling deep geothermal wells is therefore rather costly and risky, with a significant amount of start-up capital and some government assistance during the earliest phases of exploration commonly being required.

The risk profile is still high, making investment unacceptable to investors owing to the high risks for limited return on investment. So, main challenge is the reduction of technical and financial risks along the implementation process of these projects, in order to make them possible to jump from the research stage towards development phase.

As shown in Figure 1, well construction currently accounts for a relevant percentage of total costs of a deep geothermal project, with the aggravating factor that spent is required at very early stage of the project, so that there is still an unassumable chance of scheme failure after spend of 60% of overall scheme budget

Figure 1: Approximate spend profile for phases of a Deep Geothermal project



Source: Atkins. Deep Geothermal Review Study. October 2013

So, most project failure risks concentrate on the initial phase (exploration) of a geothermal project, and currently the main challenges are:

- Risk mitigation:
    - Financial
    - Public awareness and social acceptance
- R&D:
    - Deployment of Enhanced Geothermal Systems
    - Exploration techniques (including resource prediction and exploratory drilling)
    - Advanced drilling/well completion techniques

The ThermoDrill project has proved that applying the ThermoDrill system is a proper countermeasure to risk mitigation due to:

- makes the goal of cost savings of up to 30% for the full wellbore construction become realistic. Therefore, helping to overcome part of current barriers, not only because of cost savings, but also due to corresponding reduction of financial risks associated to initial phase of geothermal projects
- no HSE issues appeared which allows a better acceptance from authorities and society.

6. Conclusions and recommendations

The ThermoDrill project has successfully achieved its primary goals, developing a fast and cost-efficient drilling system based on an innovative combination of conventional rotary drilling and fluid jetting, and meeting the following specific objectives:

- Be suitable for drilling hard and abrasive rock types, withstanding the extreme temperature and pressure conditions involved in geothermal drilling at depths below 3,000 m
- At least a 100% increase in the rate of penetration in hard rock.
- An associated cost reduction of more than 30%.
- Meet the most stringent standards in terms of health, safety and environmental protection

The observed increase in drilling velocity will mainly result in a reduction of rig time, which has a significant positive impact on the cost reduction of a well.

The very successful proof of concept of the ThermoDrill technology makes the goal of cost savings of up to 30% for the full wellbore construction become realistic, helping to overcome part of current barriers, not only because of cost savings, but also due to corresponding reduction of financial risks associated to initial phases of projects.

However, the ThermoDrill technology alone is not sufficient to ensure largescale implementation of deep geothermal energy, so that additional research activities must be performed. To improve the ThermoDrill technology on the one hand and to improve other accompanying activities/strategies on the other hand:

- ThermoDrill concept:
    - Optimization of the design of the devices in order to increase performance and lifespan of the downhole pressure intensifier and all other components
    - Continue the research activities in order to provide adequate directional drilling possible with this concept
    - Measurement While Drilling (MWD). Including within the DPI the capacity of measuring the most important parameters for further in line adjustment of the drilling process
- Accompanying activities/strategies:
    - Deployment of Enhanced Geothermal Systems
    - Exploration techniques (including resource prediction and exploratory drilling)
    - Advanced drilling/well completion techniques
    - Improvement of performance (conversion to electricity and direct use of heat)
    - Materials improvement (high temperatures, corrosion, scaling)

Last, but not least, abovementioned R&D activities should be complemented with actions focused on non-technical barriers, such as mitigation of both financial and social rejection risks.

Finally, for project developers planning in classical geothermal projects and specially those who wants to use the Thermodrill system, some general recommendations can be found below:

- Design in the well completion a main section in drilling diameter 8''1/2 in the reservoir hard rocks (which is generally the case as this section diameter is standard and allows to produce flowrates up to 100L/s in a classical geothermal reservoir)
- Design a straight 8''1/2 section in the well plan, it will be drilled with no directional Bottom Hole Assembly and no Measurement While Drilling elements in the BHA (which is also generally the case in order to reduce drilling risk). This will also ensure a longer lifetime of all downhole elements (bit, stabilisers, drill collars, strings, etc.)
- Ensure a good mud cleaning capacity on rig site, and drill the 8''1/2 reservoir section with fresh water if possible to maximize life duration of the high-pressure components (and of the BHA) and avoid any risk of damaging the reservoir.

7. References

[1] E. Commission, “EGS PILOT PLANT Publishable Final Activity Report,” 2009.

[2] C. Augustine, J. W. Tester, B. Anderson, and S. Petty, “A Comparison of Geothermal with Oil and Gas Well Drilling Costs,”, 2006.

[3] K. Evans, B. Valley, M. Häring, R. J. Hopkirk, C. Baujard, T. Kohl, T. Mégel, L. André, S. Portier, and F.-D. Vuataz, “Studies and support for the EGS reservoirs at Soultz-sous-Forêts \rFinal report April 2004 - May 2009 ,” no. EGS Pilot plant \r6th FP of the European Commission - EC Contract N°SES6-CT-2003–502706, 2009.

[4] Atkins. "Deep Geothermal Review Study. Final Report" Department of Energy & Climate Change, 2013.

[5] E. Commission. Strategic Energy Technology Plan. "Deep Geothermal Implementation Plan", 2018.

[6] M. Richter, “ESummary of Geothermal Drilling Technologies”. IEA Geothermal, 2017.

[7] T. S. Lowry, A. Foris, J. T. Finger, S. Pye, D. A. Blankenship. “Implications of Drilling Technology Improvements on the Availability of Exploitable EGS Resources”, 2017

[8] ESMAP (Energy Sector Management Assistance Program), “Geothermal Handbook: Planning and financing power generation”, 2012.

[9] Stoxreiter T., Martin A., Teza D., Galler R., Hard rock cutting with high-pressure jets 910 in various ambient pressure regimes. International Journal of Rock Mechanics and Mining 911 Sciences, 2018, Vol. 108

[10] Stoxreiter T., Portwood G., Gerbaud L., Seibel O., Essl S., Plang J., Hofstätter H., Full-920 scale experimental investigation of the performance of a jet-assisted rotary drilling system in 921 crystalline rock. International Journal of Rock Mechanics and Mining Sciences, 2019, Vol. 115

8. Glossary and acronyms

acidizing	The pumping of acid into the wellbore to remove near-well formation damage and other damaging substances. This procedure commonly enhances production by increasing the effective well radius. When performed at pressures above the pressure required to fracture the formation, the procedure is often referred to as acid fracturing.[1]
air drilling	A drilling technique whereby gases (typically compressed air or nitrogen) are used to cool the drill bit and lift cuttings out of the wellbore, instead of the more conventional use of liquids.[1]
annulus	The space around a pipe in a wellbore.
API	American Petroleum Institute. A trade association and standards organization that represents the interests of the oil and gas industry. It offers publications regarding standards, recommended practices, and other industry related information.[2]
BHA	Bottom-Hole Assembly. An assembly composed of the bit, stabilizers, reamers, drill collars, various types of subs, etc., that is connected to the bottom of a string of drillpipe.
BHT	Bottom-Hole Temperature. The temperature measured in the borehole at total depth.
BHCT	The temperature of the circulating fluid (air, mud, cement or water) at the bottom of the wellbore after several hours of circulation.[1]
BHST	Bottom hole static temperature. The temperature of the undisturbed formation at the final depth in a well. The formation cools during drilling and most of the cooling dissipates after about 24 hours of static conditions, although it is theoretically impossible for the temperature to return to undisturbed conditions. This temperature is measured under static conditions after sufficient time has elapsed to negate any effects from circulating fluids.[1]
BHT	Bottom hole temperature. The temperature measured in the borehole at total depth.
bit	The tool used to crush or cut rock. Everything on a drilling rig directly or indirectly assists the bit in crushing or cutting the rock. The bit is on the bottom of the drill string and must be changed when it becomes excessively dull or stops making progress. Most bits work by scraping or crushing the rock, or both, usually as part of a rotational motion. Some bits, known as hammer bits, pound the rock vertically in much the same fashion as a construction site air hammer.[1]
bit record	A report that lists each bit used during a drilling operation.[2]
BOP	Blowout preventer. A large valve at the top of a well that may be closed if the drilling crew loses control of formation fluids.[1]
brine	A geothermal solution containing appreciable amounts of sodium chloride or other salts.[3]
BSCW	Basic support for cooperate work. The shared-workspace-system used in ThermoDrill.
casing	Steel pipe placed in an well to prevent the wall of the hole from caving in, to prevent movement of fluids from one formation to another and to aid in well control.[2]
casing shoe	A short, heavy, cylindrical section of steel filled with concrete and rounded at the bottom, which is placed at the end of the casing string. It prevents the casing from snagging on irregularities in the borehole as it is lowered.[2]
CBL	Cement Bond Log. An acoustic survey or sonic-logging method that records the quality or hardness of cement used in the annulus to bond the casing and the

[1] Schlumberger Oilfield Glossary. URL: http://www.glossary.oilfield.slb.com. 19.10.2015.
[2] Oil and Gas Well Drilling and Servicing eTool. URL: https://www.osha.gov/SLTC/etools/oilandgas/glossary_of_terms/glossary_of_terms_a.html
[3] DOE Geothermal Glossary. URL: http://energy.gov/eere/geothermal/geothermal-glossary

	formation. Casing that is well bonded to the formation transmits an acoustic signal quickly; poorly bonded casing transmits a signal slowly.[2]
CET	Cement Evaluation Tools. Cement evaluation tools measure the bond between the casing and the cement placed in the wellbore annulus between the casing and wellbore. This real-time measurement is made with acoustic sonic or ultrasonic tools. Hydraulic isolation between reservoir layers is essential to avoid potential reservoir problems such as crossflow between reservoir zones behind the casing. The detection of poor cement, or the absence of cement, makes it possible to conduct remedial action before the well is completed to avoid potential production problems and their associated costs.[4]
circulation loss	The loss of drilling fluid to a formation, usually caused when the hydrostatic head pressure of the column of drilling fluid exceeds the formation pressure. This loss of fluid may be loosely classified as seepage losses, partial losses or catastrophic losses, each of which is handled differently depending on the risk to the rig and personnel and the economics of the drilling fluid and each possible solution.[1]
CT	Coiled Tubing. A long, continuous length of pipe wound on a spool. The pipe is straightened prior to pushing into a wellbore and rewound to coil the pipe back onto the transport and storage spool. Depending on the pipe diameter (1 in. to 4 1/2 in.) and the spool size, coiled tubing can range from 610 to 4,570 m or greater length.[1]
CTU	Coiled Tubing Unit.
coring	The process of cutting a vertical, cylindrical sample of the formations encountered as a well is drilled.[2]
cuttings	The fragments of rock dislodged by the bit and brought to the surface in the drilling mud. Washed and dried cuttings samples are analyzed by geologists to obtain information about the formations drilled.[2]
D&C	Drilling and Completions.
DC	Drill Collar. Thick walled pipe or tube designed to provide stiffness and concentration of weight at the bit.[5]
DD	Directional Drilling. The intentional deviation of a wellbore from the path it would naturally take. This is accomplished through the use of whipstocks, bottomhole assembly (BHA) configurations, instruments to measure the path of the wellbore in three-dimensional space, data links to communicate measurements taken downhole to the surface, mud motors and special BHA components and drill bits, including rotary steerable systems, and drill bits. The directional driller also exploits drilling parameters such as weight on bit and rotary speed to deflect the bit away from the axis of the existing wellbore.[1]
DDR	Daily Drilling Report. A record made each day of the operations on a working drilling rig and, traditionally, phoned, faxed, emailed, or radioed into the office of the drilling company and possibly the operator every morning.[2]
dogleg	The abrupt change in direction in the wellbore, frequently resulting in the formation of a keyseat.
DP	Drillpipe. The heavy seamless tubing used to rotate the bit and circulate the drilling fluid. Joints of pipe are generally approximately 9 m (30 feet) long are coupled together by means of tool joints.[2]
DPI	Downhole Pressure Intensifier
drilling mud	Drilling Fluids. Any of a number of liquid and gaseous fluids and mixtures of fluids and solids (as solid suspensions, mixtures and emulsions of liquids, gases and solids) used in operations to drill boreholes into the earth. One classification scheme is based only on the mud composition by singling out the component that clearly defines the

[4] Schlumberger, URL: hht://www.slb.com/services/drilling/cementing/cement_evaluation.aspx
[5] IADC Drilling Lexicon. URL: http://www.iadclexicon.org

	function and performance of the fluid: (1) water-base, (2) non-water-base and (3) gaseous (pneumatic).[1]
drilling rig	Equipment and machinery assembled primarily for the purpose of drilling or boring a hole in the ground.[5]
drillstring	The drillstring is the mechanical assemblage connecting the rotary drive system of the drilling rig on the surface to the drilling bit. It includes drill pipe and drill collars as well as ancillary equipment like stabilizers, shock absorbers and crossover subs.[6]
EGS	Rock fracturing, water injection, and water circulation technologies to sweep heat from the unproductive areas of existing geothermal fields or new fields lacking sufficient production capacity.[3]
elastic deformation	A temporary change in shape caused by applied stress. The change in shape is not permanent and the initial shape is completely recovered once the stress is removed.
ESP	Electric Submersible Pump.
filter cake	The residue deposited on a permeable medium when a slurry, such as a drilling fluid, is forced against the medium under a pressure. Filtrate is the liquid that passes through the medium, leaving the cake on the medium. Drilling muds are tested to determine filtration rate and filter-cake properties.[1]
fish	Anything left in a wellbore. It does not matter whether the fish consists of junk metal, a hand tool, a length of drillpipe or drill collars, or an expensive MWD and directional drilling package. Once the component is lost, it is properly referred to as simply "the fish." Typically, anything put into the hole is accurately measured and sketched, so that appropriate fishing tools can be selected if the item must be fished out of the hole.[1]
FIT	Formation Integrity or Formation Competency Test. Application of pressure by superimposing a surface pressure on a fluid column in order to determine ability of a subsurface zone to withstand a certain hydrostatic pressure.[5]
fluid loss	The leakage of the liquid phase of drilling fluid, slurry or treatment fluid containing solid particles into the formation matrix.[1]
formation pressure	The force exerted by fluids or gas in a formation, recorded in the hole at the level of the formation with the well shut in. Also called reservoir pressure or shut-in bottomhole pressure.[1]
fracturing	A method of breaking down the formation by pumping fluid at very high pressures.[5]
geothermal gradient	The rate of increase in temperature per unit depth in the Earth. Although the geothermal gradient varies from place to place, it averages 25 to 30 °C/km. Temperature gradients sometimes increase dramatically around volcanic areas. It is particularly important for drilling fluids engineers to know the geothermal gradient in an area when they are designing a deep well. The downhole temperature can be calculated by adding the surface temperature to the product of the depth and the geothermal gradient.[1]
GL	Ground Level
G&G	Geology and Geophysics.
GR	Gamma-Ray. High-energy, short wavelength, electromagnetic radiation emitted by a nucleus, which is penetrating and is best attenuated by dense material like lead or tungsten. The energy of gamma-rays is usually between 0,010 MeV and 10 MeV.[5]
HDR	The so-called Hot Dry Rock research aimed ultimately at extracting useful heat from rock formations which possess insufficient natural permeability to allow extraction of heated natural groundwater at the required rate.[7]
hook load	The weight of the drill stem and associated components that are suspended from the

[6] Nguyen, Jean-Paul (1996): Drilling. Oilfield and Gas Field Development Techniques. Paris (Editions Technip).

[7] Garnish, John D. (1991): Research and development on geothermal energy in Europe. Proceedings of the Ussher Society, 7, 309-315.

	hook.[1]
HTHP	High temperature and high pressure.
HWDP	Heavy-Weight Drill Pipe. Pipe with thick wall used in transition zone to minimize fatigue and as bit weight in directional wells.[5]
hydrostatic pressure	The normal, predicted pressure for a given depth, or the pressure exerted per unit area by a column of freshwater from sea level to a given depth.[1]
IADC	International Association of Drilling Contractors. A trade association that represents the interests of members of the drilling segment of the oil and gas industry. It offers publications regarding recommended industry practices and training materials.[1]
induced seismicity	Induced seismicity is earthquake activity resulting from human activity that causes a rate of energy release, or seismicity, which would be expected beyond the normal level of historical seismic activity. In addition to the subsurface stresses, fluid pressures play a key role in causing seismicity.[8]
injection	The process of returning spent geothermal fluids to the subsurface. Sometimes referred to as reinjection.[3]
jet nozzle	The passageway through jet bits that causes the drilling fluid to be ejected from the bit at high velocity. [1] The purpose of fluid streams is to keep the bit cones clean, cool down the bearings and to sweep formation cuttings towards the annulus.
kelly	The square or hexagonal shaped steel pipe connecting the swivel to the drill string. The kelly moves through the rotary table and transmits torque to the drill string.[5]
keyseat	A small-diameter channel worn into the side of a larger diameter wellbore. This can be the result of a sharp change in direction of the wellbore (a dogleg), or if a hard formation ledge is left between softer formations that enlarge over time. In either case, the diameter of the channel is typically similar to the diameter of the drillpipe. When larger diameter drilling tools such as tool joints, drill collars, stabilizers, and bits are pulled into the channel, their larger diameters will not pass and the larger diameter tools may become stuck in the keyseat.[1]
LCA	Life cycle analysis is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service throughout its life cycle. This goal is accomplished by taking the following steps: compiling an inventory of relevant inputs and outputs of a system, evaluating the potential impacts associated with those inputs and outputs and interpreting the results of the inventory and impact phases in relation to the objectives of the study.[9]
LCM	Lost Circulation Material. Solid material intentionally introduced into a mud system to reduce and eventually prevent the flow of drilling fluid into a weak, fractured or vugular formation. This material is generally fibrous or plate-like in nature, as suppliers attempt to design slurries that will efficiently bridge over and seal loss zones. In addition, popular lost circulation materials are low-cost waste products from the food processing or chemical manufacturing industries. Examples of lost circulation material include ground peanut shells, mica, cellophane, walnut shells, calcium carbonate, plant fibers, cottonseed hulls, ground rubber, and polymeric materials.[1]
LOT	Leakoff Test. A test to determine the strength or fracture pressure of the open formation, usually conducted immediately after drilling below a new casing shoe. During the test, the well is shut in and fluid is pumped into the wellbore to gradually increase the pressure that the formation experiences. At some pressure, fluid will enter the formation, or leak off, either moving through permeable paths in the rock or by creating a space by fracturing the rock. The results of the leakoff test dictate the maximum pressure or mud weight that may be applied to the well during drilling operations. To maintain a small safety factor to permit safe well control operations, the maximum operating pressure is usually slightly below the leakoff test result.[1]

[8] Lawrence Berkeley National Library. Induced Seismicity. URL: http://esd1.lbl.gov/research/projects/induced_seismicity/

[9] Madu, Christian (2001): Handbook of environmentally conscious manufacturing. Springer Science-Business Media, New York.

lubricant	A mud additive for lowering torque (rotary friction) and drag (axial friction) in the wellbore and to lubricate bit bearings if not sealed. Lubricants may be solids, such as plastic beads, glass beads, nut hulls and graphite, or liquids, such as oils, synthetic fluids, glycols, modified vegetable oils, fatty-acid soaps and surfactants.[1]
LWD	Logging While Drilling. The measurement of formation properties during the excavation of the hole, or shortly thereafter, through the use of tools integrated into the bottomhole assembly.[1]
MD	Measured Depth. The length of the wellbore, as if determined by a measuring stick. This measurement differs from the true vertical depth of the well in all but vertical wells. Since the wellbore cannot be physically measured from end to end, the lengths of individual joints of drillpipe, drill collars and other drillstring elements are measured with a steel tape measure and added together. Importantly, the pipe is measured while in the derrick or lying on a pipe rack, in an untensioned, unstressed state. When the pipe is screwed together and put into the wellbore, it stretches under its own weight and that of the bottomhole assembly. Although this fact is well established, it is not taken into account when reporting the well depth. Hence, in virtually all cases, the actual wellbore is slightly deeper than the reported depth.[1]
mud additive	A material added to a drilling fluid to perform one or more specific functions, such as a weighting agent, viscosifier or lubricant.[1]
mud circulation	The movement of drilling fluid out of the mud pits, down the drill stem, up the annulus, and back to the mud pits.[1]
mud weight	A measure of the density of a drilling fluid expressed as pounds per gallon, pounds per cubic foot, or kilograms per cubic meter. Mud weight is directly related to the amount of pressure the column of drilling mud exerts at the bottom of the hole.[1]
MUL	Montanuniversitaet Leoben.
multilateral	Pertaining to a well that has more than one branch radiating from the main borehole.[1]
NDT	Non-Destructive Test. Test used to detect internal, surface and concealed defects or imperfections in materials, using techniques that do not damage or destroy the items being tested.[5]
O&M	Operations and Maintenance.
PAC	Polyanionic cellulose. A cellulose derivative similar in structure, properties and usage in drilling fluids to carboxymethylcellulose. PAC is considered to be a premium product because it typically has a higher degree of carboxymethyl substitution and contains less residual NaCl than technical grade carboxymethylcellulose, although some PACs contain considerable NaCl.[1]
PDC bit	A drilling tool that uses polycrystalline diamond compact (PDC) cutters to shear rock with a continuous scraping motion. These cutters are synthetic diamond disks about 1/8 inch thick and about 1/2 to 1 inch in diameter.[1]
permeability	The capacity of a substance (such as rock) to transmit a fluid. The degree of permeability depends on the number, size, and shape of the pores and/or fractures in the rock and their interconnections. It is measured by the time it takes a fluid of standard viscosity to move a given distance. The unit of permeability is the Darcy.[3]
porosity	The ratio of the aggregate volume of pore spaces in rock or soil to its total volume, usually stated as a percent.[3]
reamer	A tool used in drilling to smooth the wall of a well, enlarge the hole to the specified size, help stabilize the bit, straighten the wellbore if kinks or doglegs are encountered, and drill directionally.[1]
reservoir	A naturally occurring underground body of liquids, such as water or steam.
RKB	Rotary Kelly Bushing. Bushing that sits on top of the rotary table. It transmits torque from the rotary table to the kelly and is commonly used as a reference for vertical measurements from the drill-floor.[5]
roller cone bit	A tool designed to crush rock efficiently while incurring a minimal amount of wear on the cutting surfaces. The roller-cone bit has conical cutters or cones that have spiked

	teeth around them. As the drillstring is rotated, the bit cones roll along the bottom of the hole in a circle. As they roll, new teeth come in contact with the bottom of the hole, crushing the rock immediately below and around the bit tooth. As the cone rolls, the tooth then lifts off the bottom of the hole and a high-velocity fluid jet strikes the crushed rock chips to remove them from the bottom of the hole and up the annulus. As this occurs, another tooth makes contact with the bottom of the hole and creates new rock chips. Thus, the process of chipping the rock and removing the small rock chips with the fluid jets is continuous. The teeth intermesh on the cones, which helps clean the cones and enables larger teeth to be used. There are two main types of roller-cone bits, steel milled-tooth bits and carbide insert bits.[1]
ROP	Rate of Penetration. A measure of the speed at which the bit drills into formations, usually expressed in feet (meters) per hour or minutes per foot (meter).[1]
rotary drilling	A drilling method in which a hole is drilled by a rotating bit to which a downward force is applied. The bit is fastened to and rotated by the drill stem, which also provides a passageway through which the drilling fluid is circulated. Additional joints of drill pipe are added as drilling progresses. [1]
rotary table	Device used to apply torque to the drill string during drilling and normally located in the centre of the drill floor.[5]
RPM	Revolutions per minute.
RSS	Rotary Steerable System. A tool designed to drill directionally with continuous rotation from the surface, eliminating the need to slide a steerable motor. Rotary steerable systems typically are deployed when drilling directional, horizontal, or extended-reach wells. State-of-the-art rotary steerable systems have minimal interaction with the borehole, thereby preserving borehole quality.[1]
shut-in	To close the valves on a well so that it stops producing. To close in a well in which a kick has occurred.[1]
sidetrack	A secondary wellbore drilled away from the original hole. It is possible to have multiple sidetracks, each of which might be drilled for a different reason (multilateral).
SL	Sea level.
stabilizers	They are included in the drill string, more precisely at drill collar level, to control the bit and keep it on the right trajectory, whether vertical or deviated. The shapes and makes vary depending on the formation, the abrasiveness and the service required.[6]
stress	The force applied to a body that can result in deformation, or strain, usually described in terms of magnitude per unit of area, or intensity.[1]
sub	A short, threaded piece of pipe used to adapt parts of the drilling string that cannot otherwise be screwed together because of differences in thread size or design. A sub (a substitute) may also perform a special function. Lifting subs are used with drill collars to provide a shoulder to fit the drill pipe elevators; a kelly saver sub is placed between the drill pipe and the kelly to prevent excessive thread wear of the kelly and drill pipe threads; a bent sub is used when drilling a directional hole.[1]
TCI bit	Tungsten Carbide Insert bit.
TD	Total Depth.
THP	Tubing Hanger Pressure. The pressure in the production tubing.
top drive	A top drive (frequently also referred to as a power swivel) is a piece of equipment that serves the following functions: rotating the drill string (formerly undertaken by the rotary table); providing a conduit for drilling mud (formerly undertaken by the rotary swivel); disconnecting/connecting pipe (formerly undertaken by the iron roughneck); closing in the drill pipe by an integrated kelly valve (formerly undertaken by the kelly valve in connection with the rotary table); lifting/lowering drill string by use of standard elevator (formerly undertaken by the hook by using same kind of elevator). Top drives may be either electrically or hydraulically driven. If they are hydraulically driven, several hydraulic motors are normally used. Elevator links and elevators are not regarded as a part of the top drive (standard drilling equipment).[5]

torque The turning force that is applied to a shaft or other rotary mechanism to cause it to rotate or tend to do so. Torque is measured in foot-pounds, joules, newton-meters, and so forth.[1]

Tubing Hanger Component used to support the downhole completion tubing string. It is also typically used to seal and contain the completion annulus from the environment.[5]

TUM Technische Universitaet München.

TVD True Vertical Depth. The vertical distance from a point in the well (usually the current or final depth) to a point at the surface, usually the elevation of the rotary kelly bushing (RKB). This is one of two primary depth measurements used by the drillers, the other being measured depth.[1]

UBI Ultrasonic Borehole Imager. See ultrasonic measurements.

UCS Unconfined compressive strength, uniaxial compressive strength. A measure of a material's strength. The unconfined compressive strength (UCS) is the maximum axial compressive stress that a right-cylindrical sample of material can withstand under unconfined conditions, the confining stress is zero.[1]

UHP Ultra high pressure

ultrasonic measurements In the context of borehole logging, measurements of acoustic signals that are in the hundreds of kilohertz to the low-megahertz range. Such ultrasonic instruments are mostly of the pulse-echo type, and are used in the borehole televiewer, and in various cased-hole devices to determine corrosion and cement-bond quality.[1]

USIT Ultrasonic Imaging Tool. See ultrasonic measurements.

VES Vertical Electrical Sounding.

VSP Vertical Seismic Profile. A class of borehole seismic measurements used for correlation with surface seismic data, for obtaining images of higher resolution than surface seismic images and for looking ahead of the drill bit.[1]

WOB Weight on bit. The amount of downward force placed on the bit.

well logging Assessing the geologic, engineering, and physical properties and characteristics of geothermal reservoirs with instruments placed in the wellbore.[3]

well stimulation A treatment performed to restore or enhance the productivity of a well. Stimulation treatments fall into two main groups, hydraulic fracturing treatments and matrix treatments. Fracturing treatments are performed above the fracture pressure of the reservoir formation and create a highly conductive flow path between the reservoir and the wellbore. Matrix treatments are performed below the reservoir fracture pressure and generally are designed to restore the natural permeability of the reservoir following damage to the near-wellbore area.[1]

WL Water level.

