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Investigation on thermal spallation drilling and on the applicability of a combined thermo-mechanical drilling system for deep geo-energy resources

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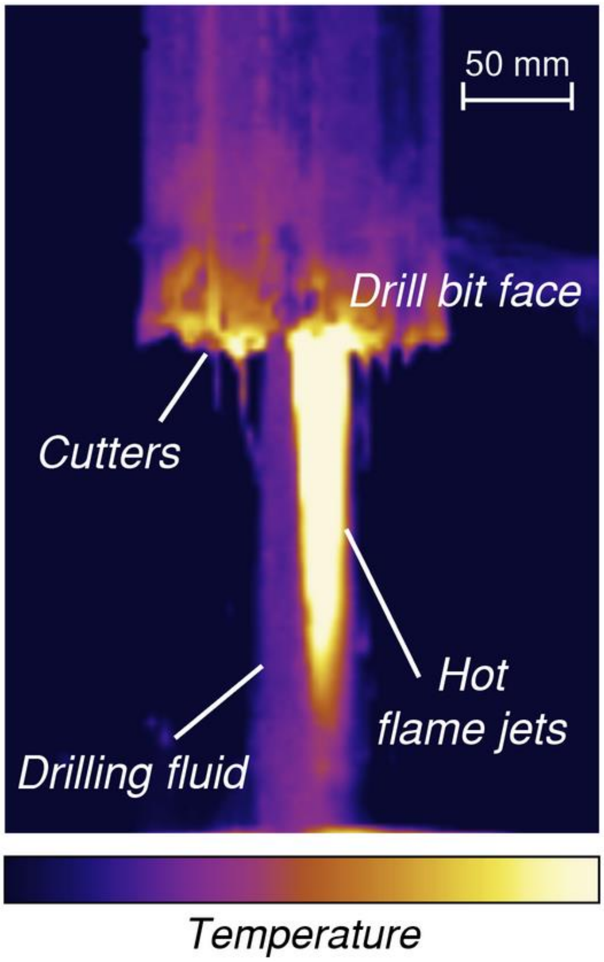

Figure 1: Infrared (IR) image of CTMD drill head.

Source: Rossi, E., et al., (2020c). A combined thermo-mechanical drilling technology for deep geothermal and hard rock reservoirs. Geothermics, 85C, 1–11. https://doi.org/10.1016/j.geothermics.2019.101771

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Zusammenfassung

Tiefe geothermische Ressourcen können eine Schlüsselrolle im zukünftigen Energieversorgungssystem spielen. Die Bohrung von Tiefbohrungen zur Erschließung dieser tiefen Georessourcen in hartem kristallinen Gestein ist jedoch mit großen Herausforderungen für konventionelle Bohrtechnologien (z. B. Rotary Drilling) verbunden. Die schlechten Leistungen konventioneller Bohrmethoden in hartem Gestein, in Bezug auf den Verschleiß der Bohrkronen und niedrige Penetrationsraten, führen zu bedeutenden unproduktiven Zeiten, häufigem Austausch der Bohrkronen und geringer Prozesseffizienz, was wiederum die wirtschaftliche Realisierbarkeit von tiefen Geothermieprojekten behindert.

Daher wurde in dieser Arbeit mit dem Ziel, die Wirtschaftlichkeit des Bohrprozesses zur Erschließung tiefer geothermischer Ressourcen zu verbessern, eine neuartige Bohrtechnologie vorgeschlagen, die als Combined Thermo-Mechanical Drilling (CTMD) bezeichnet wird. Diese Technologie basiert auf dem Konzept der thermischen Unterstützung (durch Flammenstrahlen) des konventionellen mechanischen Bohrverfahrens. Auf diese Weise kann der Flammenstrahl induzieren: (a) das Auslösen der thermischen Spallation, wenn das Gestein die erforderlichen Eigenschaften für das thermische Abbrechen des Gesteins hat, oder (b) die thermische Schwächung des Gesteinsmaterials (flamenunterstütztes Rotary Drilling), die sich durch einen effizienteren Abtragsprozess auszeichnet, der von den Bohrfräsern durchgeführt wird. In dieser Arbeit untersuchten wir die Realisierbarkeit des Konzepts zuerst durch Laborexperimente, dann implementierten wir auch den Technologieprototyp in ein Bohrgerät im realen Maßstab und testeten die Technologie im Feld. Schließlich wurden numerische Simulationen durchgeführt, um den thermischen Spallationsmechanismus des Gesteins weiter zu untersuchen.

Erstens wurde die Machbarkeit des Konzepts des flammenunterstützten Drehbohrens hinsichtlich der induzierten thermischen Schwächung des Gesteinsmaterials bewertet. In diesem Rahmen wurde eine Laborstudie zu den Auswirkungen von thermischen Flammstrahlbehandlungen mit hoher Heizrate und hoher Temperatur durchgeführt. Aus den Ergebnissen dieser Arbeit geht hervor, dass bei der Behandlung von Granit- und Sandsteingestein mit hohen Heizraten die Druckfestigkeitseigenschaft monoton mit der Behandlungstemperatur abnimmt, während die Behandlung des Gesteins mit niedrigeren Heizraten eine anfängliche Erhöhung der Gesteinsfestigkeit bei moderaten Temperaturen zeigt. Die Analyse der thermischen Rissbildung (thermal cracking) nach der Flammenerwärmung zeigt signifikante Unterschiede in der beobachteten bevorzugten Rissbildung im Vergleich zu langsamen Ofenbehandlungen. Diese Studie kommt zu dem Schluss, dass niedrige Heizraten für eine von thermischer Ausdehnung dominierte Rissbildung im Gestein verantwortlich sind. Andererseits wird die thermische Rissbildung bei der Flammenbehandlung mit hohen Heizraten durch die Stresskonzentrationen bestimmt, die durch hohe thermische Gradienten von der behandelten Oberfläche verursacht werden.

Als nächstes wurden Experimente zum Schneideverhalten von thermisch behandeltem Gestein durchgeführt, um die Abtragseigenschaften während des thermisch unterstützten Drehbohrkonzepts zu untersuchen. Diese Studie zeigt, dass sich das Schneiden von Granit- und Sandsteingestein in drei Regime bezüglich des Eindringens des Werkzeugs in das Gestein, der Kräfte auf die Schneide und des Verschleißzustands des Werkzeugs unterteilen lässt. Zuerst folgt das Werkzeugeindringen einer verschleißdominierten Phase, danach folgt eine Druckphase und schließlich ist das dritte Schneidregime durch die Rückfallphase des Werkzeugs auf niedrigere Eindringwerte gekennzeichnet. Weiterhin wurden in dieser Studie die wichtigsten Leistungsparameter des Gesteinsabtrags, wie Abtragsrate, Verschleißrate und spezifische Energie, ausgewertet. Daraus kann geschlossen werden, dass der durch thermische Rissbildung unterstützte Gesteinsabtrag beim flammgestützten

Drehbohren die Abtragsrate in hartem Granit erheblich steigern und die Verschleißrate der Schneidwerkzeuge im Sandsteingestein hauptsächlich reduzieren kann.

Der Bereitschaftsgrad der vorgeschlagenen Technologie wurde durch einen Proof-of-Concept im Feld demonstriert. Dazu wurde die Technologie zur Integration in eine konventionelle Bohranlage hoch-skaliert und Tests an einer Gesteinsprobe aus Granit unter realistischen Bohrbedingungen durchgeführt. Bei diesen Tests wurde Wasser als Bohrspülung verwendet, um das Bohrgut zu transportieren und die benötigte Kühlung der Systemkomponenten zu ermöglichen. Die beiden Bohrungsmodi der Technologie, nämlich das thermische Spallationsbohren (Modus I) und das flamenunterstützte Rotary Drilling (Modus II), wurden separat untersucht und die resultierenden Leistungsparameter der Bohrung mit einem standalone-mechanischen Benchmark-Bohrtest verglichen. Bezüglich des thermischen Spallationsbohrens zeigt diese Arbeit, dass das Verfahren auch unter vollständig getauchten Wasserbedingungen durchführbar ist. Darüber hinaus liefert diese Studie den Nachweis, dass die mechanische Integrität des ausgebrochenen Gesteins durch das thermische Spallationsbohren nur geringfügig beeinflusst wird, was wahrscheinlich auf eine stabile Bohrlochwand hinweist, die mit dem thermischen Spallation-Bohrverfahren erzeugt wird. Das flammenunterstützte Rotary Drilling kann durch die Einstellung geeigneter Prozessparameter und die Rotation des Bohrgestänges in Betrieb genommen werden. Das gesammelte Bohrgut und die erzeugten akustischen Emissionen während des Bohrversuchs deuten darauf hin, dass der thermische spallation-unterstützte Abtrag des Gesteins einen effizienteren Fragmentierungsprozess des Hartgesteins im Vergleich zum standalone-mechanischen Bohren bewirkt. Aus den gemessenen Parametern geht hervor, dass das flammenunterstützte Rotary Drilling das konventionelle Bohren in Bezug auf die Eindringrate und die Gesamtlebensdauer des Bohrers übertrifft. Daraus schließen wir, dass die Kombination von thermischer Unterstützung von konventionellem Bohren den Bohrprozess effektiv intensivieren und damit die Erreichbarkeit von tiefen Georessourcen in hartem Gestein erhöhen kann.

Numerische Simulationen des thermischen Spallationsbohrens wurden durchgeführt, um die entscheidenden Faktoren des Bohrprozesses zu untersuchen. Um das Einsetzen der thermischen Spallation im Gestein zu erfassen, wurde deshalb ein "Spalling-Failure-Modell" in unsere thermomechanischen Simulationen integriert. Insbesondere betrachteten wir die Rolle von Materialheterogenitäten, maximaler Strahl-Flammen-Temperatur und maximaler Strahl-Flammen-Temperaturanstiegszeit auf das Einsetzen der inelastischen Verformung und der nachfolgenden Schädigung des Gesteins. Weiterhin untersuchten wir Unterschiede im Energieverbrauch für die untersuchten Systemkonfigurationen. In den Simulationen wird die Bedeutung der Materialzusammensetzung hervorgehoben, da die thermische Spallation in feinkörnigem Material mit starker Materialheterogenität favorisiert wird. Weiterhin wurde das Modell verwendet, um die Beziehung zwischen der Jet-Flame-Temperatur und dem Beginn der thermischen Spallation zu testen. Der vorgestellte Modellierungsrahmen erlaubt es, in Zukunft weitere Untersuchungen zu zusätzlichen Faktoren wie Bohrlochtiefe, Gesteinssättigung oder ähnlichen Eigenschaften durchzuführen.

Summary

Deep geothermal resources can play a key role in future energy supply systems. However, drilling of deep wells, to access these deep geo-resources in hard crystalline rocks, poses major challenges for conventional drilling technologies (e.g., rotary drilling). The poor performances of conventional drilling methods in hard rocks, in terms of wearing of the drill bits and low penetration rates, yield significant non-productive time, frequent drill bit replacements and low process efficiency, which in turn hinder the economic viability of accessing deep energy resources.

Hence, with the aim of improving the economics of the drilling process to access deep energy resources, in this work we investigated novel drilling technologies, namely thermal spallation drilling and Combined Thermo-Mechanical Drilling (CTMD). The latter technology is based on the concept of providing thermal assistance to conventional mechanical drilling. In this way, the flame jet can induce: (a) the thermal spallation onset, when the rock exhibits the required properties for thermal spallation of the rock; or (b) the thermal weakening of the rock material (flame-assisted rotary drilling), which is characterized by a more efficient removal process, performed by the drilling cutters. In this work, we investigated the viability of the concept, first through laboratory experiments, then by implementing the technology prototype into a real-scale drill rig and testing the technology in the field. Lastly, numerical simulations were performed to investigate further the thermal spallation mechanism of the rock.

Firstly, to evaluate the feasibility of the flame-assisted rotary drilling concept concerning the induced thermal weakening of the rock material, a laboratory study on the effects of high heating rate, high temperature flame-jet thermal treatments was performed. From the findings of this work, it appears that, when the granite and sandstone rocks are treated at high heating rates, the compressive strength property monotonously decreases with the treatment temperature, whereas treating the rock at lower heating rates shows an initial increase of rock strength for moderate temperatures. Analysis of the thermal cracking characteristics after flame heating highlights significant differences in the observed preferential crack occurrence, compared to slow oven treatments. This study concluded that low heating rates are responsible for a thermal-expansion-dominated cracking of the rock, whereas, during flame treating at high heating rates, thermal cracking is governed by stress concentrations caused by high thermal gradients from the treated surface.

Building on this, experiments on the cutting behavior of thermally treated rocks were performed to shed light on the removal characteristics during the thermally-assisted rotary drilling concept. This study showed that the cutting of granite and sandstone rocks can be divided into three regimes concerning tool penetration into the rock, forces on the cutter and wear state of the cutting tool. Initially, the tool penetration follows a wear-dominated phase. This cutting regime is followed by a compressive stage. Finally, the third cutting regime is characterized by a tool fall-back phase that lowers penetration values. Further, this study evaluated principal rock removal performance parameters, such as rock removal rate, drill bit wear rate and specific energy required during the rock-cutting process. From this, it can be concluded that thermal-cracking-enhanced rock removal, during flame-assisted rotary drilling, can considerably enhance the removal rate into hard granite and mainly reduce the wear rate of the cutters in sandstone rock.

In order to demonstrate the readiness level of the proposed technology, a proof-of-concept of the CTMD technology in the field was performed. To this end, the technology was scaled up and integrated into a conventional drilling rig to perform tests on a sample of granite under realistic drilling conditions, using water as the drilling fluid to transport the cuttings and provide the required cooling of the system components. The two drilling modes of the technology, namely, thermal spallation drilling (Mode I) and flame-assisted rotary drilling (Mode II) were separately investigated and the resulting drilling performance parameters were compared to a standalone-mechanical benchmark drill test. Concerning the thermal spallation drilling mode, this work showed that the process is feasible also under fully submerged water conditions. Moreover, this study provided evidence that the mechanical integrity of the excavated rock is only marginally influenced by thermal spallation drilling, which is likely an indication of the stability of the borehole wall, created employing the thermal spallation drilling

mode. Flame-assisted rotary drilling can be switched into operation by setting appropriate process parameters and by rotating the drill string assembly. The collected cuttings and the generated acoustic emissions during the drill test suggest that thermal-cracking-enhanced removal of the rock yields a more efficient fragmentation process of the hard rock, compared to standalone-mechanical drilling. From the measured parameters, the flame-assisted rotary drilling mode is found to outperform conventional drilling concerning penetration rate and overall drill bit lifetime. Hence, we conclude that combining thermal assistance with conventional drilling can effectively intensify the drilling process and thereby increase the viability of economically accessing deep energy resources in hard rocks.

Numerical simulations of thermal spallation drilling were performed to investigate the crucial parameters of the drilling process. To capture the thermal spallation onset of rock, a spalling failure model was integrated into our thermomechanical simulations. In particular, we considered the role of material heterogeneities, maximum jet-flame temperature and maximum jet-flame temperature rise time on the onset of inelastic deformation and subsequent damage. We further investigated differences in the energy consumption for the studied system configurations. The simulations highlight the importance of material composition, as thermal spallation is favored in fine-grained material with strong material heterogeneity. Further, the model was used to test the relationship between the jet-flame temperature and the onset of thermal spallation. The presented modeling framework allows, in the future, to conduct further investigations of additional factors, such as borehole depth (i.e. pressure) and fluid saturation of rock pores.

Main findings

- Under high-heating-rate flame-jet heating of the rock, the compressive strength is continuously decreased for the entire treatment temperature range.
- Two preferential cracking regimes are found: at low heating rates, thermal cracking is governed by the rock thermal expansion; at high heating rates, the stress concentrations, induced by the thermal gradients in the rock material, are responsible for the observed cracking phenomena.
- Thermal-cracking-enhanced rock removal, found during the flame-assisted rotary drilling mode of CTMD, results in improved penetration of the cutting tool both in sandstone and in granite rocks. This is also evidenced by the investigated drilling performance parameters.
- In granite rock, we found that, after thermally treating the rock, the removal rate is greatly improved. On the other hand, in sandstone rocks, we show that the main result of thermally-assisted drilling is a reduction in the cutting tool's wear rate.
- Field testing of the CTMD technology showed that thermal spallation drilling (Mode I of the technology) could be a feasible process even under realistic (water-submerged) conditions, as long as specific precautions are implemented to protect the flame-jets. Rock damage by thermal spallation is found to be limited to shallow depths into the rock from the borehole wall. From this, we infer that the thermal spallation process should contribute only marginally to the overall wellbore instability.
- Field tests of the flame-assisted rotary drilling mode (Mode II of the CTMD technology) showed that this approach is an efficient process to remove/drill hard rocks. Under the conditions of this test, the drilling process was found to be significantly intensified (increased rate of penetration and decreased specific wear of the drill bits) when thermally-assisted by flame-jets, compared to standalone-mechanical rotary drilling.
- The CTMD technology can also profit from the established know-how and infrastructure of the conventional drilling industry, which could enhance the implementation of thermal-based assistance approaches in the field and facilitate accessing deep geo-resources in hard basement rocks.
- To enable the application of the CTMD concept to be further used in deep wells, additional research questions need to be addressed concerning the feasibility of the proposed rock-breaking concept under in-situ conditions (e.g., in-situ stresses and temperatures). Also, further technical developments are required such as enabling down-hole combustion under great drilling depths.
- Our numerical simulations highlight the importance of material heterogeneities with varying thermo-mechanical properties for thermal spallation.
- Our simulations further indicate that smaller grains lead to more rapid failure progress during thermal spallation drilling, as smaller grains lead to more abundant distributions of temperature and stress gradients.
- Finally, we also showed that high maximum jet flame temperatures are energetically most efficient.

Contents

1 Introduction

1.1 Background and Motivation

(Please refer to the attached Ph.D. thesis (link) in Appendix).

In order to meet our ever-increasing energy demand, deep geo-resources will be key for the development of sustainable solutions for our future energy supply system. Nonetheless, providing access to these underground resources represents, to this date, one major challenge hindering their successful exploitation.

Indeed, tapping deep (> 3 km) energy sources (hydrocarbon or heat) requires drilling deep boreholes which are often found in hard, crystalline formations. Here, conventional drilling methods perform poorly, both in terms of penetration rate and wear rate of the drill bits, and they are responsible for very high costs, which also increase exponentially with well depth. To increase the economic viability of drilling, favoring access to resources from the deep subsurface, improvements in the drilling process efficiency in hard, crystalline rocks are to be attained. One promising approach to effectively excavate hard rocks is by thermal spallation. Despite the good performance found in hard rocks, the thermal spallation process is impeded in softer rocks or in the presence of stress-relieving cracks. Thus, to enhance the implementation of a thermal-based drilling concept and increase the overall drilling performance, this work has investigated combining thermal spallation with conventional rotary drilling. This technology, termed combined thermo-mechanical drilling (CTMD), is based on providing thermal assistance, e.g., by flame jets, to conventional mechanical drilling. It is expected to reduce drilling efforts by improving the removal performance and the overall bit lifetime, especially in hard rocks.

To sum up, the motivation of this work is to find an effective drilling solution to improve the drilling performance and facilitate accessing deep geo-resources in hard rocks. This work investigates the fundamentals behind both stand-alone thermal spallation drilling and the proposed CTMD method and, from this, the readiness of the CTMD technology is demonstrated in the field to evaluate the technical feasibility and the potential performance improvements of combining a thermal assistance to conventional drilling.

1.2 Objectives

(Please also refer to the attached Ph.D. thesis (link) in the Appendix and the attached paper).

The goals of the project were to investigate, through laboratory and field testing, the viability and performance of thermal spallation drilling and, in particular, combining thermal assistance (by e.g., flame jets) with conventional drilling, i.e. the combined thermo-mechanical drilling (CTMD) method, reducing the effort and costs of drilling deep wells in hard rocks to access deep geo-resources.

To investigate the feasibility of the combined thermo-mechanical drilling (CTMD) method, several research questions had to be answered prior to demonstrating the technology under field conditions. Firstly, it was crucial to understand the thermal weakening of the rock material under the conditions of flame-jet heating. This study included evaluating the principal contributions to rock strength reduction from high temperature and high heating rate thermal treatments, with a focus on induced thermal cracking of rock. After the thermal weakening mechanism, the process needed to be optimized concerning treatment speed and the sought rock weakening. Thereafter, laboratory experiments permitted quantifying potential improvements of the CTMD method in terms of rock removal and drill bit wear performance. Furthermore, the removal mechanism during the interaction of the thermally treated rock and a cutter needed to be investigated. Having answered these fundamental questions, an implementation of the CTMD method was carried out and served as a proof-of-concept. The goals of this field implementation were to show the feasibility and integration potential of the CTMD method into conventional drilling systems and demonstrate the performance of the CTMD technology, regarding rock removal and drill bit wear rates, compared to the state-of-the-art, i.e., conventional rotary drilling.

Furthermore, in order to provide a better understanding of the thermal spallation drilling process, a numerical modeling framework was developed. In this way, the key parameters that yield drilling success were identified, while also providing insights into the processes occurring during the thermal spallation of the rock.

Thus, the objectives of the conducted project can be formulated as follows:

- Investigate the thermal effects on rocks:
  a) Rock weakening - High heating rates and temperatures
  b) Induced thermal cracking
- Investigate the interactions between rock and cutter:
  a) Rock cutting mechanisms
  b) Rock removal and drill bit wear performance
- Develop and field test of the CTMD technology:
  a) Integration solution
  b) Evaluate field feasibility
  c) Demonstrate readiness and performance under realistic conditions
- Numerical modeling of thermal spallation drilling:
  a) Identify key parameters and improve the understanding of thermal spallation processes

2 Flame-heating effects on rock strength

(A complete description of this work can be found in Chapter 2 in the attached Ph.D. thesis (link) in the Appendix and in the published journal paper (Rossi et al., 2018)).

This work provided insights into the effects of thermally treating rocks. Thermal treatments of rocks, performed by a flame jet, and therefore characterized by fast heating to high temperatures, constitute a fundamental aspect of the proposed CTMD technology. We thus analyzed how thermal treatments affect the mechanical strength of the rock and we studied the rock microstructure after the thermal treatments.

Laboratory experiments on sandstone and granite were carried out to analyze the effects of high-heating-rate, high-temperature flame treatment on the compressive strength property of the rock. This parameter is indicative of the weakening of the rock structure and was therefore used to understand the relevance of flame-treating the material, mimicking flame assistance during the drilling mode II of the CTMD technology. In order to perform flame thermal treatment experiments in granite and sandstone rock samples, a specific experimental setup was developed for this work. The rock treatments were performed using a flame-jet, which treats the rock sample surface under different conditions (temperatures of up to 650°C and heating rates of up to 20°C/s).

The results showed that high temperatures are responsible for significant decreases in rock compressive strength. Further, heating the rock at high heating rates enables suppressing the material hardening (strength increase at moderate treatment temperatures). Thereby, the compressive strength of the rock, treated at high heating rates, monotonically decreases over the whole treatment temperature range. Besides the compressive strength of the material, this study also evaluated thermal cracking in the rock microstructure, induced by the thermal treatment, enabling comparing slow oven heating and fast flame heating. This comparison allowed the conclusion that thermal-expansion-dominated thermal cracking occurs at low heating rates, whereas at higher heating rates, thermal cracking is likely caused by the high thermal gradients generated in the near-surface rock.

3 Investigation of rock-bit interaction during CTMD

(A complete description of this work can be found in Chapter 3 in the attached Ph.D. thesis (link) in the Appendix and in the published journal paper (Rossi et al., 2020d)).

As the next step within the laboratory analysis of the investigated CTMD technology, the removal characteristics of thermally treated rocks were investigated. Specifically, this chapter focused on the interaction between a scratching tool and the rock during cutting tests on granite and sandstone, comparing untreated (i.e. without heating) and post-treatment (i.e. with heating) conditions. In this manner, this work provided insights into the effectiveness of the CTMD technology also concerning the removal performance of the drilling tool.

Using a novel experiment setup, several cutting process parameters were investigated during the scratch testing of the rock. This allowed characterizing the rock removal regimes, as the cutting tool removed the rock, and also the quantitative evaluation of common process performance indicators (rock removal rate and drill bit (cutter) wear rate).

This study provided evidence of three main rock removal regimes during the rock cutting process: first, a wear-dominated regime, followed by a compression-based progression of the tool at large penetrations, and a final tool fall-back regime for increasing scratch distances. Furthermore, the rock cutting performance under untreated conditions were compared with the post-treatment case. This analysis showed that a particular thermal-cracking-based rock removal mechanism, found during the testing of the thermally treated rock, can greatly enhance the penetration performance, especially in granite, and significantly reduce the wear rate of the cutting tool in sandstone.

4 Field demonstration of CTMD technology

(A complete description of this work can be found under Chapter 4 in the attached Ph.D. thesis (link) in the Appendix and in the published journal papers (Rossi et al., 2020a; Rossi et al., 2020b; Rossi et al., 2020c; Rossi et al., 2020e)).

Building on the findings of the laboratory investigations in Chapters 2 and 3, we describe here the field implementation of the CTMD technology. This work demonstrated the novel drilling technology under realistic process conditions. It focused, at first, on the thermal spallation drilling mode (Mode I) and then proceeded with the implementation and testing of the flame-assisted rotary drilling mode (Mode II).

The results of the thermal spallation drilling mode showed that the flame jet is effective in inducing the thermal spallation onset in the granite rock, even when water is used as the drilling fluid to transport the excavated particles. To monitor the rock removal process, during the field test (both during Mode I and Mode II), the acoustic emissions in the rock were monitored. Furthermore, in the context of thermal spallation drilling, this work investigated the effects of thermal spallation on the overall mechanical integrity of the surrounding rock. The analysis was performed by modeling the stability of the thermally induced cracks from the spalled surface into the granite rock. The relatively thin damage layer, generated into the rock by the thermal spallation process, is expected to contribute marginally to the instability of the surrounding rock, confirming that thermal spallation does not considerably affect the integrity of the created borehole.

As the second mode of the CTMD technology, flame-assisted rotary drilling was tested and compared to conventional mechanical drilling. During the testing of this second drilling mode, the acoustic emissions were also monitored, providing evidence for thermal-cracking-enhanced rock removal during flame-assisted rotary drilling. The latter removal approach was found to outperform standalone-mechanical drilling, both concerning the efficiency of removing the rock and regarding the transport of the produced cuttings. Finally, drilling performance parameters were evaluated for the CTMD technology and compared to conventional mechanical drilling. This comparison showed improved removal performance values of the hard granite rock, when the drilling process was assisted by a flame-jet.

This work concluded with investigating the potential of the CTMD technology in profiting from established knowhow in the drilling industry, towards its integration in conventional, state-of-the-art drilling methods, to facilitate accessing deep geo-resources in hard rocks.

5 Numerical modeling of thermal spallation drilling

(A complete description of this work can be found in the (link) attached journal paper (Vogler et al., 2020) in Appendix).

To further study the behavior of contact-less drilling, such as thermal spallation drilling, a numerical modeling framework was developed. This allowed to identify key parameters that resulted in drilling success, while also shedding light on the processes occurring during thermal spallation.

To this aim, the finite element framework MOOSE was used. MOOSE enables the coupling of different physical processes, such as heat transport and mechanical deformation. Specifically, a radially symmetric system domain at the bottom of a borehole was simulated. At the borehole bottom, a heat source was numerically applied, which was modeled after experimental investigations conducted on thermal spallation. This heat source led to heat transport in the rock, where different thermal and mechanical properties of the individual rock grains led to a heterogeneous strain field in the rock. These thermal strains have also been previously identified to be the primary source of crack initiation and subsequent damage during thermal spallation.

The numerical model showed that cracks primarily initiate along grain boundaries, with specific grain combinations being most favorable. Further factors, such as the heating on the borehole surface and the grain composition were also investigated, where we showed that especially the grain composition is important, with cracking almost vanishing if no material heterogeneities are present in the rock. As expected, higher maximum temperatures, observed on the borehole surface, increase thermal spallation of the rock. However, even when accounting for the energy required for a higher heating rate, applying higher heating rates most efficiently cause cracking and thereby thermal spallation drilling. This is caused by the increased thermal strains occurring at higher heat fluxes, which do not equilibrate as quickly.

The developed modeling framework can enable future investigations into additional factors, such as borehole depth and fluid saturation of the rock pores.

6 Conclusions and Outlook

(Conclusions and Outlook can be found in Chapter 5 in the attached Ph.D. thesis (link) in the Appendix and in the (link) attached journal paper (Vogler et al., 2020) on numerical modeling of thermal spallation).

7 National and international cooperation

National cooperation:

ETH D-MAVT: Institute of Process Engineering/LTR: Laboratory experiments, collaborators (students, assistants), workshop use.

ETH D-ERDW: Geological Institute: Laboratory analysis of rock samples, workshop, collaboration in work packages.

International cooperation:

GZB Bochum: Advanced Drilling group: Collaboration in the field activities. Scientific assistants and students in the project team. Drilling infrastructure. Drilling operations (rig operator).

Monash University: Civil Engineering: Stuart D.C. Walsh for collaboration on numerical simulator.

8 Publications

JOURNAL PUBLICATIONS

Rossi, E., Saar, M. O., & Rudolf von Rohr, P. (2020d). The influence of thermal treatment on rock-bit interaction: a study of a combined thermo-mechanical drilling (CTMD) concept. *Geothermal Energy*, 8(16), 1–22. https://doi.org/10.1186/s40517-020-00171-y

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Vogler, D., Walsh, S. D. C., von Rohr, P. R., & Saar, M. O. (2020). Simulation of rock failure modes in thermal spallation drilling. *Acta Geotechnica*, 15(8), 2327–2340. https://doi.org/10.1007/s11440-020-00927-7

Rossi, E., Jamali, S., Schwarz, D., Saar, M. O., & Rudolf von Rohr, P. (2020b). Field test of a Combined Thermo-Mechanical Drilling technology. Mode II: Flame-assisted rotary drilling. *Journal of Petroleum Science and Engineering*, 190(106880), 1–12. https://doi.org/10.1016/j.petrol.2019.106880

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9 References

(The references for this project can be found in the attached Ph.D. thesis (link) in the Appendix and in the attached (link) journal paper (Vogler et al., 2020) on the numerical modeling of thermal spallation).

10 Appendix

Below, please find the links to the Ph.D. thesis and the journal paper (Vogler et al., 2020) on numerical modeling of thermal spallation that resulted from the grant:

- Ph.D. thesis (Rossi, 2020): https://doi.org/10.3929/ethz-b-000405755
- Journal paper (Vogler et al., 2020): https://doi.org/10.1007/s11440-020-00927-7