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Quench-spallation Drilling: A Novel Drilling Head Design for Routine Heat Mining Above the Brittle-ductile Transition

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ABSTRACT

Reaching high temperatures in the crust (400-600 C) for heat mining is optimal for a number of reasons, but the primary one may be the extraction of fluids in a supercritical state. We present here a new patent for a drilling head (Holtzman, US 2022/0235612 A1, pending) that is designed to function at temperatures into and above the brittle-ductile transition, to take over where mechanical drilling is no longer practical. The process is similar in theory to standard hydrothermal spallation drilling in which flame or hot fluid jets applied to colder rock cause thermal expansion cracking and spallation. In our "quench-spallation" drilling (QSD) method, we flip the sign of the temperature difference to produce spallation by quenching. Cold fluids jetted onto hot rock will cause thermal contraction stresses and cracking, essentially converting the thermal energy of the rock to mechanical energy that drives cracking. In addition to this thermoelastic stress, decompression near the drilling face can drive cracking, as well as hydraulic stresses in cracks and hydrodynamic stresses from the fluid jetting. In its simplest form, the QSD head applies multiple jets to a rock face; in more complex designs, a spallation chamber is created to control fluid pressure at the rock face, such that local scale fluid pressure and solid stress gradients can be controlled to optimize spallation rates. Highly directional drilling should also be possible with our designs. Experiments and modeling of this spallation-by-quenching process are underway.

1. INTRODUCTION: TOWARDS DEEP GEOTHERMAL HEAT MINING

Interest in the geothermal industry is growing towards heat mining from "superhot" or "ultrahot" reservoirs in the crust for next-level generation efficiency and scale (referred to here as "deep geothermal"). The aim is to reach conditions that are hot enough that working or in situ fluids can be recovered in a supercritical state. If sufficient depths can be reached and heat extracted, this energy source could scale to levels needed to replace fossil fuels for electricity generation (e.g. Reinsch et al., 2017; Dobson et al., 2017; Watanabe et al., 2017; Okamoto et al., 2019; Garrison et al., 2020). As illustrated in Fig. 1, these conditions can be reached in most places on Earth, even with low (but not cratonic) geotherms. The main challenges lie in first accessing these depths and then extracting the heat. Conventional mechanical drilling (diamond bits) stops working as rocks warm up and get too soft to crack, within the difficult-to-define depths of the "brittle-to-ductile transition".

Thus, many efforts are underway to develop new high temperature, non-mechanical drilling methods, including focused electro-magnetic waves ("millimeter-waves"), (e.g. Houde et al., 2021), plasma drilling, using localized high voltage currents to disaggregate and/or melt rock, (e.g. Kocis et al., 2017), and "hot" hydrothermal spallation drilling using some combination of flames and hot fluids to drive thermal expansion, cracking and spallation, (e.g. Kant et al., 2017).

Here, we present a novel "quench-spallation" approach to high-temperature drilling. This method is based on the phenomenon that rocks contract and crack when cooled due to high tensile stresses. The larger and faster the temperature change, the more intense and penetrative the cracking front will be. Compared to hot hydrothermal spallation, our method flips the temperature difference, jetting cold water onto hot rock causing quenching. Conceptually, the process converts the rock's pre-existing local thermal energy to mechanical energy that drives cracking and disintegration to slurry. Thus, unlike a number of other approaches, our method requires little additional energy input. This aspect represents its fundamental advantage. Furthermore, the process could become more effective as the rock temperature and depth increase.

The aim of this paper is to articulate the scientific questions and engineering challenges in developing this drilling method into a fully operational technology. We first provide some background to understand the physical concepts associated with thermal cracking that are relevant to the drilling method. Then, we present the conceptual idea and a simple analysis to serve as a baseline model for approach's plausibility. Finally we discuss aspects of the drilling head design, with regards to assessing its potential for enabling deep geothermal heat mining.

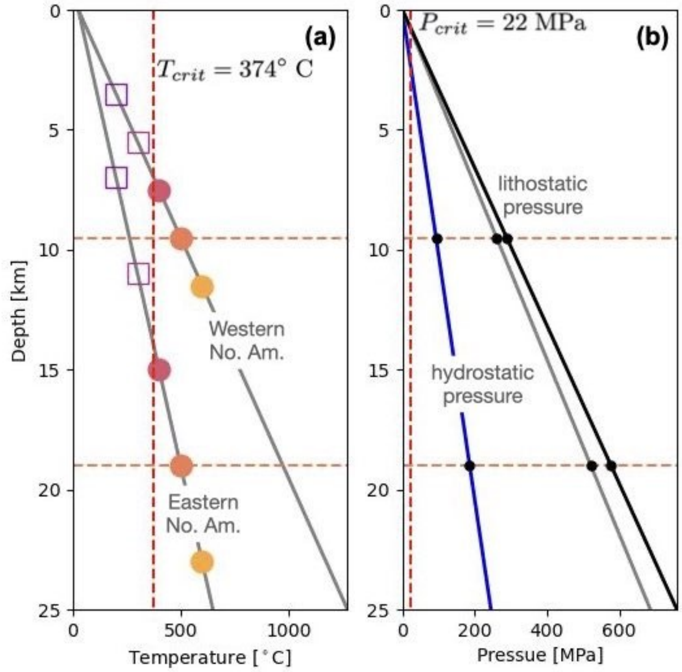

Figure 1: Temperature and pressure conditions in the crust for low and high geotherms. (a) Solid dots indicate conditions above 374 C (vertical red dashed line, at 400, 500 and 600 C respectively. 500 C lines are marked for reference, as they are used in the analytical model below. (b) Pressure-depth lines for lithostatic (granite-grey, basalt-black) and hydrostatic pressures. Horizontal dashed lines indicate the pressure differences at depths where 500 C is reached, used in Fig. 6. (Note these plots are first order approximations and do not include known dependences of physical properties on pressure or temperature)

2. BACKGROUND IN THERMAL CRACKING AND SPALLATION

Thermal cracking is a well studied, but incompletely understood physical process. Thermal crack- ing is understood to arise from (1) stresses that arise from local change in temperature, (2) stress gradients that arise from thermal gradients and (3) from internal, local stress concentrations at the grain scale due to thermal expansion anisotropy and mismatch in rocks (e.g. Fredrich and Wong, 1986). Although there is a large body of experimental data and empirical understanding, gaps still remain between experiment and theory.

2.1 Experimental studies

A broad range of experiments have been performed on thermal cracking in rocks and consequences for mechanical and transport properties. Among the earliest, to our knowledge, are Wong and Brace (1979); Yong and Wang (1980); Johnston and Toksöz (1980); Bauer and Handin (1983); Fredrich and Wong (1986). In experimental studies, acoustic emissions (AE), nano-seismic events recorded in samples, are taken to be a proxy for cracking events. Yong and Wang (1980) identified that the AE rate is dependent on the heating rate. They interpreted this result not as a direct re- flection of the rate. Instead, they posited that higher heating rate causes a steeper thermal gradient, higher thermal stresses, and thus higher AE rates. They also identified an example of a “Kaiser effect”: in thermal cycling, after the first cycle, cracking did not begin again until the temperature reached the peak value of the previous cycle. This phenomenon had been previously identified in cyclic mechanical stress loading in rocks (e.g. Kurita and Fujii, 1979).

Wang et al. (1989) found related behavior– episodic pulses of AEs during a monotonic temperature rise in granite of 1◦C per minute. They showed that the temperature associated with the onset of thermal cracking increases with increasing confining pressure. This critical temperature can be understood as the existence of a critical stress for thermal cracking (e.g. Meredith et al., 2001) that depends on the confining pressure, along with a reduction of elastic modulus with increasing crack density (e.g. Schubnel et al., 2006; Nasseri et al., 2009). These two factors can cause non-linearity in the relationship between thermal stress and AE rate through the governing equation for thermal stress, discussed in Section 5. When that stress is reached, thermal-elastic strain energy drives cracking until the stress drops below the threshold stress; as the temperature keeps rising, that critical stress will be reached again at a higher temperature. In other words, during the first cracking episode, the critical stress for the undamaged rock is reached at a critical temperature; with a lower elastic modulus, the damaged rock must reach a higher temperature to attain that critical stress.

Daoud et al. (2020) also observed a Kaiser effect in coarse grained granitic rocks with complex, interlocking grain boundaries. However, they also showed that fine grained (basaltic) rocks do not crack while temperature is rising, but only on the descending side of a cycle (as grain boundaries fail readily in tension), indicating that grain boundaries and their morphology play an important role in accommodation of thermally-driven local grain-scale stresses. We have not found a published constitutive model for thermal cracking that incorporates this grain size dependence or pressure dependence to the cracking rate. Such a model will be essential for extrapolating from laboratory to earth conditions.

As thermal cracking occurs, the crack density will affect most of the mechanical properties (e.g. Johnston and Toksöz, 1980; Fredrich and Wong, 1986; Faoro et al., 2013; Nasseri et al., 2007, 2009), heat transport properties (e.g. Wong and Brace, 1979), and fluid transport properties (e.g. Siddiqi and Evans, 2015; Liu et al., 2018; Jones et al., 1997; Watanabe et al., 2019), many of which are coupled. All of these properties will also vary significantly if the newly created crack porosity is filled with gas/vapor, fluid or supercritical fluid. Furthermore, beyond Daoud et al. (2020), we have found that most experimental studies address thermal cracking during heating, rather than during cooling, simply because significant cracking occurs during ramping up. However, the cooling path is essential for us to understand given our approach, and is likely to be different for the simple reason that rocks are weaker in tension (during cooling) than compression (during heating).

2.2 Theoretical and modeling studies

The effects of cracking on thermomechanical and transport properties enable a range of nonlinear couplings to occur. For example, in the case of strong thermal disequilibrium between the fluid and the rock, the heat transfer and mechanical processes will be closely coupled if cracking affects both the poroelastic stresses driving fluid flow and the transport properties, affecting the time scales of equilibration (e.g. Zimmerman, 2000; McTigue, 1986; Ghassemi et al., 2008). As they equilibrate, fluid and rock are both changing volume in opposite senses. As thermal cracking occurs, permeability increases, new surface area becomes available for heat exchange, and the effective elastic modulus and thermal expansion coefficient of the solid decrease. Effective heat transfer coefficients (at a range of length and time scales) may be changing locally in such situations, such that strong coupling and feedbacks may occur.

In the conditions of deep geothermal reservoirs, crustal rocks may be approaching, within or beyond the macroscopic brittle-ductile transition, depending on their bulk composition, microstructure, permeability structure, fluid composition and many other factors (Watanabe et al., 2019; Beeler et al., 2016). However, microscopic cracking will generally be an accessible process locally.

Thermal cracking in hot rock experiencing cold thermal shock may be particularly effective at creating permeability (e.g. Watanabe et al., 2019; Tarasovs and Ghassemi, 2014), but there are many open questions on roles of various thermally activated processes, such as viscous relaxation of crack tips and of grains in the rock matrix, that may work to both close and open porosity, locally. At higher temperatures, non-linear visco-elastic-plastic models may be needed to describe observed behavior. Thermal quenching, of most interest here, can be viewed as bring a rock rapidly through its brittle-ductile transition over short time- and length-scales, in non-equilibrium conditions. This scenario raises many interesting challenges for thermo-mechanical modeling.

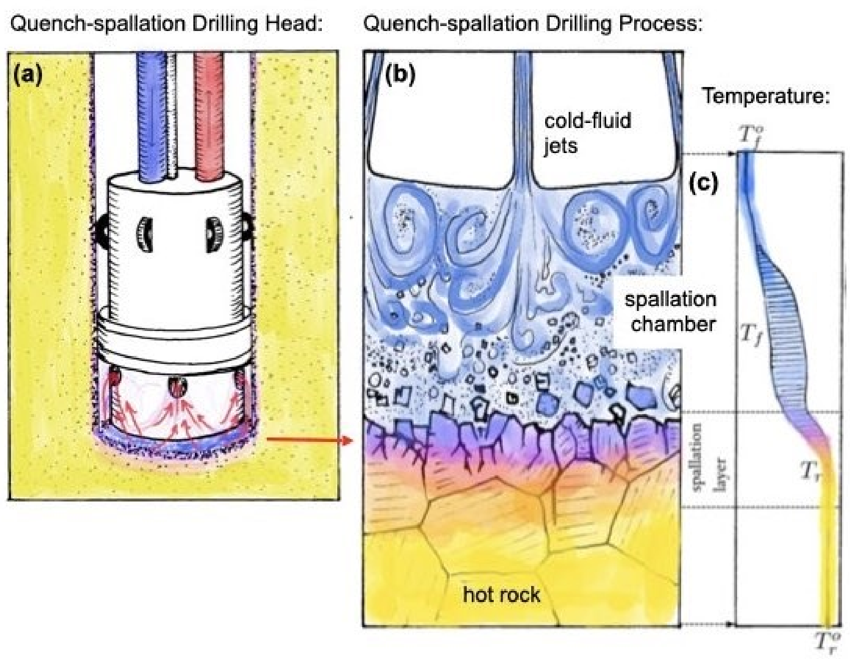

Figure 2: Quench-spallation drilling concept. (a) Schematic of the drilling head, showing a variation in which all fluids are routed through the drilling head from and to the surface, in order to control fluid pressure and temperature on the drilling face. The variations are discussed in Section 3.4. (b) Schematic view of the drilling process, in which cold fluid jets hit the rock surface, chilling it, causing thermal cracks in the "spallation layer". (c) Temperature gradient produces a thermoelastic stress gradient. The steepness of this gradient may be essential to the physics of the drilling method.

3 QUENCH SPALLATION DRILLING PROCESS AND HEAD DESIGN

Here, we describe the quench spallation concept. First, we describe the four sources of stress that we expect to combine and contribute to the disaggregation and spallation in the spallation layer, namely thermo-elastic stress gradient due to quenching, decompression due to the difference between the locked-in lithostatic stress and the borehole bottom pressure, local fluid pressure in the cracks, and hydrodynamic stress from the fluid jets. All of these may be at play to different degrees in the spallation layer (the region in between the drilling face and the cracking front). Then, we construct a simple linear model framework to analyze the thermoelastic stress gradient extending into the rock from the drilling face, and show that, at the two depths shown for a 500◦C in Fig. 6, the thermal stress alone could cause spallation. Finally, we end with a discussion of why a linear model is not likely to be sufficient in this non-equilibrium situation, and why we need laboratory testing to study this process.

3.1 Conceptual model for the quench-spallation process

The four crack-driving processes are illustrated in Fig. 3, and described here.

- Thermoelastic stress: The primary source of stress in the QSD process is the sharp thermal gradient extending from the borehole surface into the rock. The relatively cold fluid temperature will establish a thermal gradient that drives heat flow from the rock into the fluid. Since the fluid is continually (but controllably) flushed across the drilling front, the temperature may be close to constant. Means of controlling this P-T relation in the fluid are discussed in Section 3.4. Below, we present an analytical solution for the thermoelastic stress gradient from Tarasovs and Ghassemi (2014).

- Decompression stress: The change in pressure in the rock from lithostatic to near hydro- static at the drilling face will create a stress gradient across the spallation layer. The length scale of this gradient will be on the order of the borehole width, from static elastic field around an inclusion Cheng (e.g. 2016). A more complete model will estimate the grain boundary tensile stresses due to this pressure gradient. We expect this gradient to help in the disaggregation and spallation by interacting with the thermal cracks.

- Pore fluid pressure: The effect of pore fluid pressure on the drilling process is complex. When the drilling face progresses into a volume of rock, if there are fluids present in that rock, their pressure will be close to lithostatic, while the pressure in the borehole will be closer to hydrostatic. So to the extent that the permeability allows, these fluids will flow into the borehole. However, at the local grain scale in the spallation layer, the tensile stresses that are pulling cracks open will have a pressure that is lower than hydrostatic, so would draw fluid in and equilibrate pressure over short length scales (i.e. over the thickness of the spallation layer). Fluid pressure increases or decreases in the spallation chamber would then affect the crack tip stress and propagation dynamics.

- Hydrodynamic jet forces: Waterjet cutting is an industrial process that utilizes a thin, extremely high pressure jet of water to cut through hard materials. At sufficiently high water speeds, material is damaged by the momentum of the jet hitting the surface. By creating sufficiently high-velocity jets of water, the quench-spallation drill head could cause further damage to the rock face to disaggregate the layer damaged by the previous three forces.

The drilling head must be capable, to some extent, of controlling the roles and ratios of these four forcings, to adapt to different geologic situations and optimize the drilling rate. In the following section, we provide an illustrative analytical model of the first. Quantitative models for the other three are left for future work.

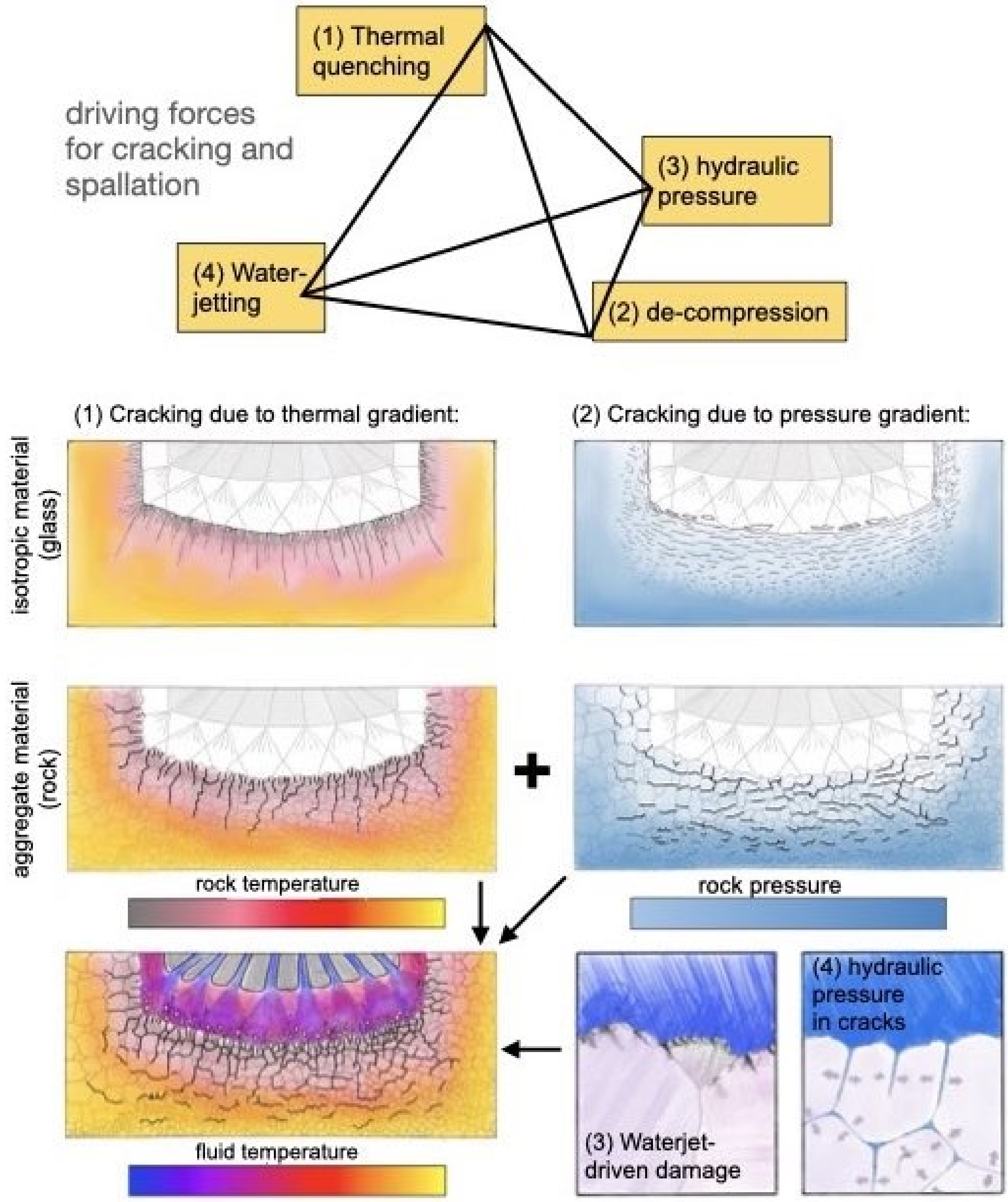

Figure 3: Sources of stress and damage operating in quench-spallation drilling, discussed in Section 3.

3.2 Analytical constraints on thermoelastic stress gradient

The transient thermoelastic stress gradient arises when a solid body experiences a change in temperature at its surface and the heat is conducted in or out as the body evolves towards thermal equilibrium. A simple model of this process combines the heat equation and a thermoelastic constitutive equation. In our case, when a cold fluid hits a hotter rock, the thermal stresses will be tensional as the solid contracts. These stresses will cause cracks to form in the solid if the fracture strength is exceeded, in any fracture mode. Here, we focus on tensional cracks, mode I.

Tarasovs and Ghassemi (2014) solve this system assuming constant values for all physical properties, in 1D, with a constant temperature boundary condition, assuming zero strain, using the erfc solution (Carslaw and Jaeger, 1986). We consider this condition to be relevant to our case, as the fluid in contact with the rock face will be constantly refreshed during the drilling process. The equations and values are shown in Fig. 4.

Solutions to these equations are shown in Fig. 5. For a 100 C fluid hitting a rock at 500 C, the thermal shock produces a sudden differential stress of about 550 MPa, for the granite parameters in Table 1. The assumption of zero strain is unrealistic on the free surface, but is quickly more reasonable deeper into the spallation layer. Thus, we do not take that peak stress to be realistic, but will use the stress at L and the dots in Fig. 5b and halfway between the maximum stress and the the dots as example values below, or 324 MPa. As the heat is progressively drained from the rock, the cooling zone progresses inward. We consider, conceptually, that the stress will drive cracking that accommodates strain and relaxes the stress, but also causes spallation, such that a more appropriate solution would be a moving boundary problem.

With that concept in mind, we can use this analytical solution to roughly estimate a drilling velocity. If the critical stress to drive spallation is reached at the squares in Fig. 5b, then the velocity is 1e-4 m/sec or about 9 m/day. We consider this to be a minimum estimate, because it includes the effects of only one of the four forces driving cracking discussed above.

In Fig. 6, we summarize our current simple estimates of the gradient in stress state across the spallation layer using a Mohr circle plot. Using the pressure differences between lithostatic (for granite) and hydrostatic, we assume that the decompression length scale will be on the order of the borehole diameter, based on static Eshelby-type solutions of the elastic field around an inclusion Cheng (2016). We also assume that the most compressive stress (σ_1) will be close to the lithostatic pressure, such that the differential stress will determine the least compressive stress. While we expect the orientations of these stress tensor components to rotate, the Mohr circle shows the invariants. If we thus estimate that thermal cracking will occur when the least compressive stress goes negative (absolute tensile) and hits the critical tensile yield stress, thermal cracking will occur. While we estimate this stress at 10 MPa for present purposes, we will obtain more precise estimates from measurements of the critical stress intensity factor KIc, from Ge et al. (e.g. 2021).

In Fig. 6, we plot the Mohr circles estimated from the differential stresses at the circles and squares (and one intermediate value) in Fig. 5b (95, 229, 324 MPa). It is clear, that at both depths, as the pressure decreases and the differential stress increases towards the spalling surface, it is highly plausible that the stress state reaches the critical tensile yield stress. Whether that yielding causes a crack density high enough to lead to disaggregation and spallation is unknown and needs to be explored in laboratory experiments. Here we demonstrate that reaching these stresses is highly plausible. We are also not including the local (grain scale) stress estimates modeled by Fredrich and Wong (1986), which will exist in almost all rocks.

Tarasovs and Ghassemi (2014) equation 1, 1D heat equation :

$$T(x,t) \quad = \quad T_0 - \Delta T \mathrm{erfc}\left(\frac{z}{L}\right) \tag{1}$$

where the intrinsic thermal length scale $L = \sqrt{(4tD_{th})}$, with thermal diffusivity $D_{th} = \kappa_{th}/\rho c_p$. Their equation 2 is:

$$\sigma_{th}(x,t) = \frac{E\Lambda_{th}(T_0 - T(x,t))}{1-\nu} \tag{2}$$

Parameter names and values given in Table 1.

symbol:	name:	units:	notes:
$\boldsymbol{\sigma}$	stress tensor	Pa	σ_s: scalar stress in solid
σ'	differential stress	Pa	$\sigma' = \sigma_1 - \sigma_3$
$P_{s,f}$	pressure	Pa	s,f = solid/fluid
$T_{s,f}$	temperature	C,K	
ρ	density	kg/m^3	granite: $\approx$ 2800
E	Young's modulus	Pa	granite: $E \approx 30$ GPa
ν	Poisson's ratio	–	granite: $\approx$ 0.25
Λ_{th}	thermal expansion coeff. tensor	K^{-1}	granite: $\Lambda_{th} \approx$ 35e-6 (1)
κ	thermal conductivity	W/m/K	granite: $\kappa \approx 3.2$
c_p	specific heat capacity	J/kg/K	granite: $\approx$ 800
$\boldsymbol{D}_{th}$	thermal diffusivity	m^2/s	$D = \frac{\kappa}{\rho C_p} \approx$ 1.4 e-6
K_{Ic}	critical stress intensity factor	[MPa m$^{1/2}$]	granite: $\approx$ 0.4 (1)
σ^*_{th}	yield stress for cracking	Pa	granite: of order 10 MPa
α_c	crack density	m^2/m^3	
α_g	grain size	m	

Table 1: Frequently used symbols. Sources: (1) Ge et al. (2021)

Figure 4: Equations and Table discussed in the text.

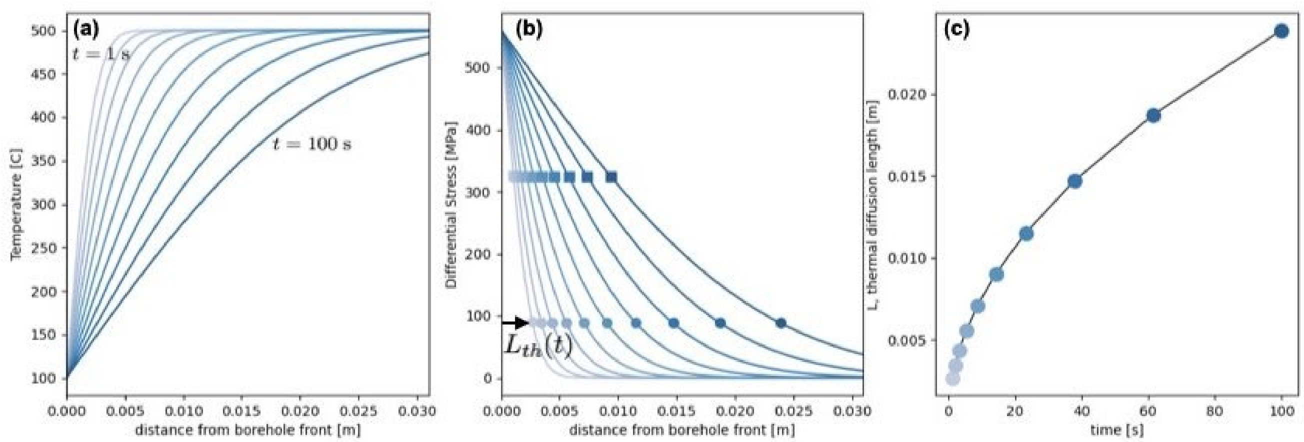

Figure 5: Thermal shock model solutions from Tarasovs and Ghassemi (2014) (a) Calculations of quenching front thermal profiles from 1 to 100 s, for a temperature difference of 400 C. (b) Stress gradient for each thermal gradient. Circles show where the characteristic thermal diffusion length scale is reached, as a reference. Squares are an arbitrarily chosen higher reference (324 MPa, the mean of the stress at L, 94 MPa, and the peak at 554 MPa). (c) Evolution of the diffusion length scale L with time.

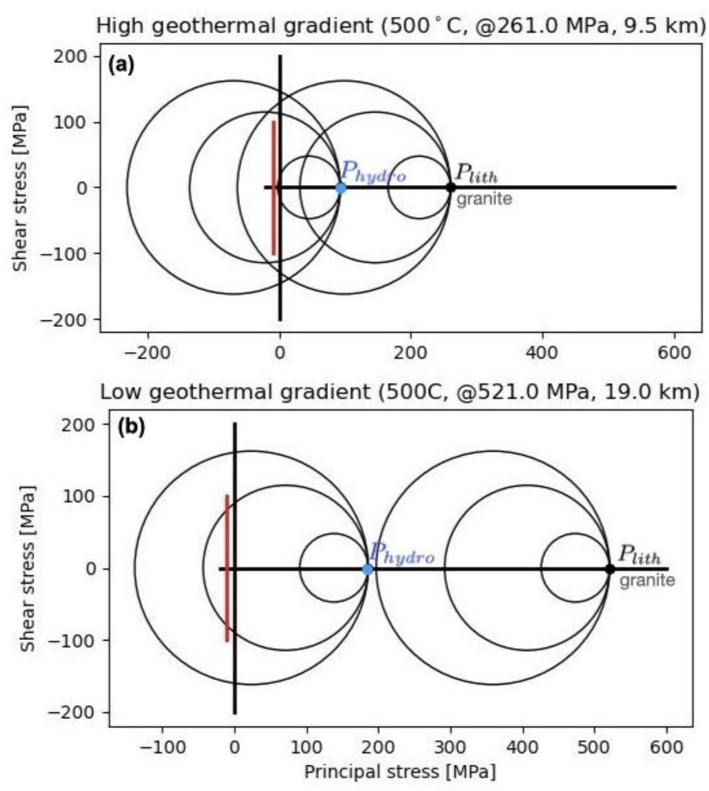

Figure 6: Mohr circle representation of constraints on stress gradient across spallation and decompression drilling face. The assumption here is that the principal compressive stress σ1 is equal to the confining pressure, which will grade from lithostatic towards hydrostatic at the spallation face. (a) Shallower 500 C reservoir (Low geothermal gradient) pressure difference estimates between granite lithostatic and hydrostatic pressure. Differential stress reference levels taken from the thermal shock solutions shown in Fig. 5. (b) Deeper 500 C reservoir (Low gradient). In both plots, the vertical red line is the estimate for the tensile yield strength of granite of 10 MPa. In both conditions, the tensile yield stress is easily reached as the pressure drops across the spallation layer.

3.3 The non-linear aspects

The above analysis is linear in the sense that all the physical properties are constant. In reality, cracks will affect all of them, as demonstrated in many laboratory studies. These nonlinearities may work in multiple directions, enhancing and dampening heat transport. For example, increasing fluid-filled crack density will increase the thermal conductivity, but will also enhance the permeability, allowing fluids to circulate at small scales, drawing heat from the crack surfaces and transporting it elsewhere. These effects need to be explored in the laboratory in the context of the QSD process, and incorporated into numerical models to estimate their extrapolations to earth conditions.

3.4 Drilling head designs and modes of operation

In the patent (Holtzman, 2022), we described several QSD head designs that are intended to enable different levels of control over the thermomechanical conditions at the drilling face. These are illustrated in Fig. 7. The simplest design contains a drilling face with multiple jet nozzles, and valves designed to operate at high ambient temperature to control the flow velocity of fluid through the jet nozzles at the drilling face. The slurry with spalled fragments then circulates around the drilling head and is not controlled by the drilling head. Its hydrostatic pressure is felt directly on the drilling surface. Slurry could be pumped to the surface through a tube not connected to the drilling head.

In a more complex design (Fig. 7b), the slurry can be drawn into conduits in the drilling head and evacuated to the surface through a tube. This design enables the pressure to be controlled to some extent such that the hydraulic pressure on the drilling face can be kept low to increase the fluid velocity through the jets and keep the fluid near the spallation front from heating up too much.

In a yet more complex design (Fig. 7c), the fluid pressure can be closely controlled in a spallation "chamber", created by extendable and retractable seals made of a heat-resistant but flexible material to reduce or eliminate flow past the drilling head. Instead, all slurry flow would be forced through the conduits in the drilling head, with controlled valves, and a pump if necessary. A pump at the surface keeping the fluid pressure low in the up-pipe could be used in combination with a valve in the head to control the flow velocity (mass rate) through the spallation chamber and thus the fluid temperature and pressure. The value of this level of control will depend on the necessity of controlling the thermomechanical conditions in the spallation chamber in varying these conditions as required by different rocks with variable structures and physical properties. The adaptability needed will be assessed in a laboratory testing facility that we intend to construct in the near future. Obviously, the drilling head could not move while the seals are in place, so it could have an extendable jetting face to keep a controlled distance between the nozzles and the rock surface as spallation progresses. When the extension limit is reached the face would retract and the head would be moved forward.

As discussed above, the drilling velocity will likely be faster than the model estimate because only one of the four forces is considered. The adaptability needed to optimize the velocity will estimated in laboratory tests.

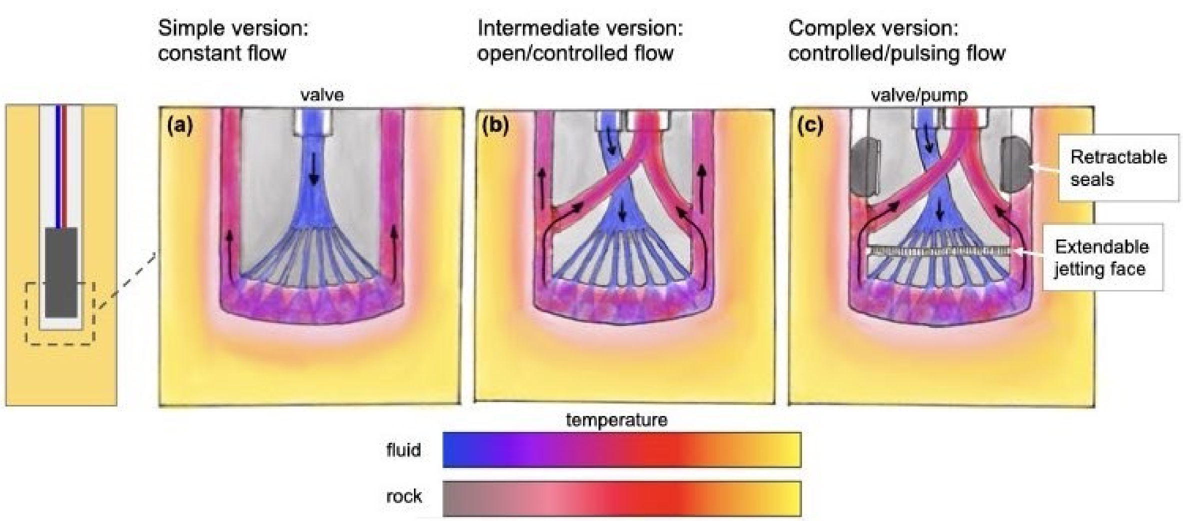

Figure 7: A range of designs of the drilling head

Finally, lateral drilling could be essential for creating fluid pathways at high pressure and temperature conditions. Creating and maintaining fracture networks at such conditions is likely to be more difficult than at lower pressures in the brittle crust, so other approaches for engineering reservoirs may be needed. Closed loop systems may be optimal, and if so, the need for lateral drilling is clear (Fig. 8a. Directional drilling could be achieved in the quench-spallation process by controlling the relative intensity of jetting in different sections on the drilling face, as illustrated in Fig. 8b,c,d.

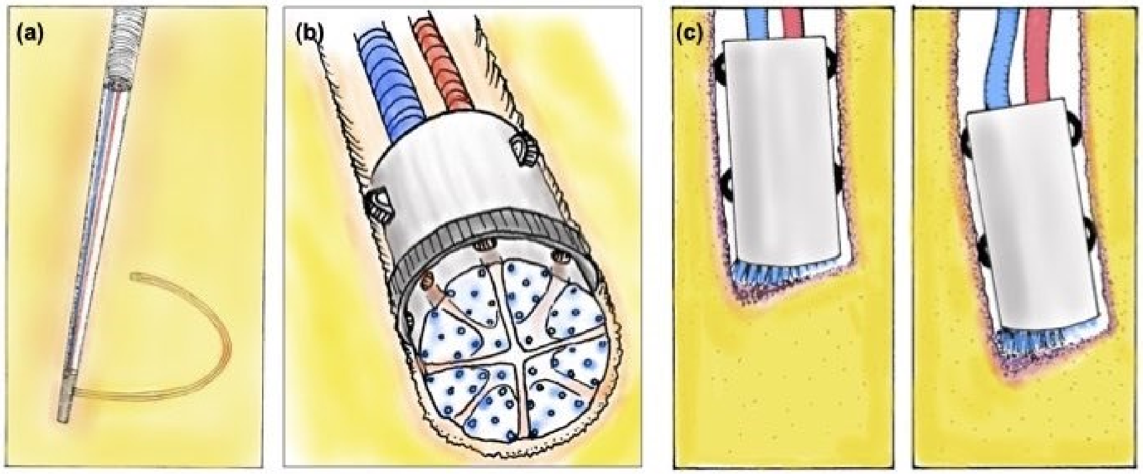

Figure 8: Directional drilling; modified illustrations from the Holtzman (2022) patent.

4 CONCLUSIONS & OPEN QUESTIONS

As discussed above, the main uncertainty is not whether thermal cracking can happen, but whether we can produce the crack density sufficient to cause disaggregation and spallation at the drilling face, and at a sufficiently rapid pace to make QSD an economically viable technology for accessing deep geothermal reservoirs. Therefore, we need to learn primarily through laboratory experimentation and testing, how the four driving forces for cracking articulated in Section 3.1 interact with each other and are controllable for different rock structures and thermomechanical conditions. We then need to understand how these various processes scale to conditions in the Earth, which will require sufficiently rich constitutive models for the various cracking processes. The effects of pressure and strong local pressure gradients are possibly the least well understood processes in terms of extrapolation. A better understanding of these interactions and their scaling behavior will inform our design of prototypes for field testing over the next several years.

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