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GRAIN-SCALE FAILURE IN THERMAL SPALLATION DRILLING

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ABSTRACT

Geothermal power promises clean, renewable, reliable and potentially widely-available energy, but is limited by high initial capital costs. New drilling technologies are required to make geothermal power financially competitive with other energy sources. One potential solution is offered by Thermal Spallation Drilling (TSD) - a novel drilling technique in which small particles (spalls) are released from the rock surface by rapid heating. While TSD has the potential to improve drilling rates of brittle granitic rocks, the coupled thermomechanical processes involved in TSD are poorly described, making system control and optimization difficult for this drilling technology.

In this paper, we discuss results from a new modeling effort investigating thermal spallation drilling. In particular, we describe an explicit model that simulates the grain-scale mechanics of thermal spallation and use this model to examine existing theories concerning spalling mechanisms. We will report how borehole conditions influence spall production, and discuss implications for macro-scale models of drilling systems.

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INTRODUCTION

Unlike many other renewable sources of power, such as wind and solar, geothermal resources provide a virtually constant supply of base-load energy without the need for additional power storage infrastructure, or modifications to the current power grid. A conservative estimate of resources in the United States suggests that there is sufficient recoverable geothermal energy to supply the country's needs for several thousand years (Tester et al. 2006). Nevertheless, to date, adoption of geothermal energy has been limited due to high capital costs. Chief among these are drilling expenses, which account for as much as 60% of the total capital investment in geothermal wells. Widespread geothermal energy production across the continental United States would require geothermal wells of 3km depth or greater (Tester et al. 2006). Moreover, geothermal wells are typically located in granitic rocks that present significant challenges to traditional drilling technologies, slowing drilling rates and increasing equipment wear - resulting in further delays due to replacement of worn and damaged drill bits. The impact on drilling rates from such delays is significant as the bulk of drilling costs at depth arise from time-related expenses (Dreesen and Bretz 2005).

These costs may be decreased in part by the adoption of novel working fluids, and heat exchange mechanisms that reduce the thermal differential needed for electricity production (Brown 2000, Pruess 2006, Randolph and Saar 2011). However, if successful, such technologies would still require geothermal wells at depths of several kilometers for large-scale electricity generation (Randolph and Saar 2011). New drilling technologies are required to reduce the capital investment needed to drill deep geothermal wells and to facilitate development of renewable geothermal energy production on a competitive basis with other energy resources.

One promising drilling technique is Thermal Spallation Drilling (TSD). Unlike conventional methods that employ mechanical means to penetrate rock, under thermal spallation drilling the host rock is fragmented into small pieces – "spalls" - through the application of heat. Laboratory studies demonstrate that TSD is capable of delivering penetration rates two or more times faster than conventional drilling methods in granite, quartzite, and dense sandstones (Potter et al. 2010). Moreover, as heat is delivered to the rock surface either through an intermediary fluid (e.g. a flame or super-heated water jet) or via radiative transfer (eg. from a laser or microwave source), there is less equipment wear and less time lost to equipment replacement as the drill-head does not make contact with the host rock.

The physical processes causing spall production were first outlined by Preston in the 1920's and 1930's (Preston 1926, Preston and White 1934). Under Preston's hypothesis, the imposed heat induces high compressive stresses adjacent to the rock surface. The high compressive stresses in turn cause fractures to grow parallel to the surface, triggered by inherent flaws and heterogeneities in the rock. Once these fractures have grown to a sufficient extent, the region near the surface buckles – breaking off as a spalled fragment (Figure 1).

Since it was first proposed, several authors have built on Preston's original description to model thermal spall of rock. In particular, several analytical models have been developed based on buckling theory (eg. Thirumalai 1970, Germanovich 1997). The advantage of these models is that they present an analytical closed-form solution, which can be rapidly evaluated under a variety of conditions. However, they must also employ simplifying assumptions that ignore the system heterogeneity – making it difficult, if not impossible, to predict the effect of different rock types on spallation rates and spall-size distributions.

The need to incorporate heterogeneity lead Dey and Kranz (1985,1987) to develop models of spall production based on Weibull statistical failure theory. These models were later adopted by Tester and co-workers (Rauenzahn and Tester 1989, 1991, Wilkinson and Tester 1993) in borehole scale simulations of flame-jet spallation. While successfully used to predict spall-size distributions and penetration rates, these models were largely empirical in form. In particular, the properties of the Weibull strength distribution required careful calibration by experimental results.

Although useful for predicting system response in a given context, Weibull-type models of spall production are less applicable outside their experimental scope. This becomes problematic, for example, if simulating spall production at depths relevant for geothermal energy production, or modeling TSD used in conjunction with other drilling techniques. A properly calibrated Weibull model would allow for industrial design optimization of thermal spallation drilling under field conditions. However, in the absence of experimental data, such a model would require calibration by explicit small scale simulations that fully resolve rock grains.

In the following sections, we outline an explicit model for simulating spall production at the grain scale**.** Results showing how microstructure, grain properties and borehole conditions influence spall production are also presented, and their implications for macro-scale models of drilling systems discussed.

MODEL DESCRIPTION

Spalls produced in TSD are typically disk shaped fragments less than a rock grain diameter thick, but , which may be several grains in width (Rauenzahn and Tester 1989). Thus, any model simulating thermal spallation at the grain-scale, must be able to represent both inter- and intra-granular fractures. To capture this behavior, we use GEODYN – a parallel Eulerian compressible solid and fluid dynamics code with adaptive mesh refinement (AMR) capabilities (Antoun et al 2001, Lomov and Rubin 2003). GEODYN contains a high-order material interface reconstruction algorithm (Hertel and Bell 1992) and advanced constitutive models that incorporate salient features of the dynamic response of geologic media (Rubin amd Lomov 2003). It is able to simulate materials under large deformations, resolve details of wave propagation within grains with high accuracy, and uses a continuum damage mechanics approach to represent fracture. Consequently, the simulations are able to represent grain-scale material and geometric heterogeneities, and can reproduce fracture both along grain boundaries and within grains themselves.

Granite microstructures comprising quartz, plagioclase, and potassium feldspar (K-spar) grains are considered in this paper – although more can be easily added to the model. The relative size distributions of the mineral grains are important in determining the strength of crystalline rocks (Fredrich 1990, Eberhardt et al 1999, Lan et al 2010). To reproduce the correct grain-size distribution, the simulated rock microstructure is created by generating Voronoi cells from an initially random set of points. These points are then each assigned a mineral type and target volume from the minerals' predetermined grain-size distribution. The volumes of the Voronoi-cells are then relaxed towards the target distribution over a series of iterations (Figure 2). The method can be used to generate microstructures in two and three dimensions, and grain-size distributions can be matched to arbitrary precision.

Separate mechanical properties are assigned to each grain according to mineral type. The individual minerals' constitutive behavior is modeled as elastic-perfectly plastic with Drucker-Prager yield criteria, and a grain fracture is simulated with a Johnson-Cook damage rule (Johnson and Cook 1985). The mechanical properties of the mineral are taken from Bass (1995) and Mavko et al. (2003). In addition, inter-granular contacts are represented by a separate, weaker material with compressive and tensile strengths fitted to granite properties described by Lockner (1998). A more detailed description of the mechanical models used for the minerals and their implementation in GEODYN is given in our earlier paper (Walsh et al. 2011).

Heat capacities and relative thermal conductivities for each mineral are taken from Findikakis (2004) and Clauser and Huenges (1995). As the rate at which heat is transmitted into the rock ($O(m/h)$) is significantly slower than the speed of fracture propagation ($O(km/s)$), the simulated thermal conductivities are artificially increased by a factor of 10,000. This maintains a quasi-static temperature profile over fracture timescales while reducing simulation times to manageable levels. In this paper, we consider thermal spallation due to conduction from a high temperature fluid adjacent to the rock surface (e.g. flame-jet or hydrothermal spallation), rather than radiative transfer (e.g. laser spallation). To avoid thermal shock in the simulations, the fluid adjacent to the rock is gradually heated from the initial rock temperature to the target surface temperature, and held at a constant temperature thereafter.

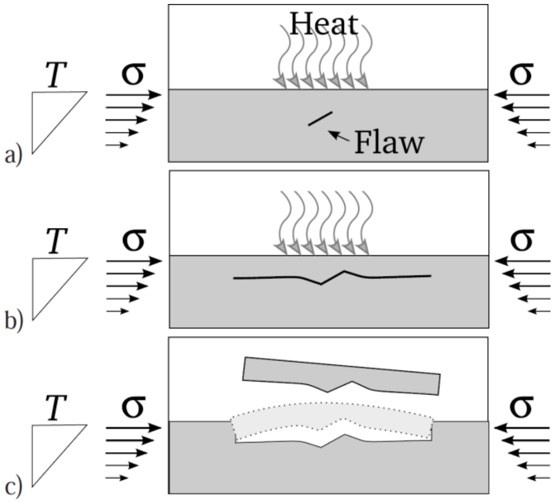

Figure 1: Preston's proposed method of spall production: a) Applied heat causes compressive stresses adjacent to the surface. b) Fractures grow parallel to the surface from incipient flaws in the rock. c) Once the extent of the fracture is great enough, the spalls buckle and are ejected from the surface.

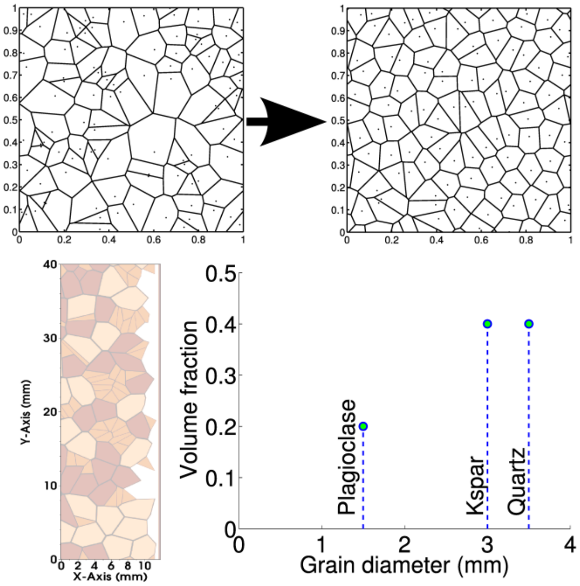

Figure 2: Granite microstructures employed in the simulations are generated via a novel Voronoi-cell based method. Cells are initially created from a random set of points, which are iteratively adjusted to fit the prescribed grain size distribution – illustrated in the upper row for a uniform size distribution. The lower row shows a grain geometry generated for a typical simulation containing quartz (off-white), plagioclase(orange), and K-spar(brown) grains.

Table 1: Mechanical and thermal properties by mineral type

	Quartz	Plagioclase	K-spar
Density (g/cm^3)	2.65	2.56	2.63
Bulk Modulus (GPa)	37.0	50.8	53.7
Poisson Ratio	0.08	0.26	0.28
Heat Capacity (J/g.K)	0.93	0.93	0.93
Thermal Conductivity (W/m.K)	7.7	1.5	1.5

RESULTS AND DISCUSSION

A typical spall-size distribution predicted by the model is given in Figure 3. The spall size distribution is generally log-normal in shape – qualitatively similar to what is observed experimentally. However, the model tends to predict larger spalls than would be expected from experimental results. This may be due to the fact that the present model does not account for intergranular flaws or it may be an artifact of the two-dimensional nature of the simulations. Alternatively, it may be a consequence of the spall collection method. Spalls are extremely friable and likely to suffer damage in the turbulent borehole fluid. Thus collected experimental spall-size distributions should be regarded as representing a lower bound on the actual spall size distribution.

The distribution of damage within a granite microstructure as a function of the applied surface temperature is shown in Figure 4. The simulations fail to produce significant spalling at fluid temperatures less than ~300C above the ambient rock temperature. As the temperature is increased the amount of damage also grows, however the sample will continue to fail at the same locations where failure has occurred at lower temperatures (Figure 4). This lends credence to the use of Weibull statistical failure models to represent spall production. Weibull models assume the existence of a distribution of critical flaws that fail upon exceeding a given stress state (eg. Rauenzahn and Tester 1989, 1991). By analyzing fracture nucleation sites it may be possible to obtain these critical flaw distributions directly from grain-scale simulations.

The model can also be made to mimic the assumptions adopted by analytical models of spall production by imposing a flat temperature profile on the granite body. In this case, the model predicts the nucleation of spall-fractures at the heat front due to buckling of the heated region. However, enforcing a flat temperature profile ignores the heterogeneity in the rock surface, as well as the mineral properties. Indeed over the sub grain-scale heat-front penetration distances typical of spall production, the temperature distribution deviates significantly from the flat profile assumed in analytical models, due to the higher thermal conductivity of quartz (Table 1).

Field studies of flame-jet spallation show increased rates of penetration with depth (Browning 1965). The increased drilling speeds were originally attributed to the fact that less oxidized and more competent rocks at depth spall more readily than damaged and weathered rock encountered near the surface (Browning 1965, Calaman and Rolseth 1961). However, this behavior might also be indicative of changes in the stress state at the borehole surface.

Figure 5 compares simulations with different internal friction coefficients representing borehole conditions at simulated depths of 1km and 4km. The simulations assume a hydrostatic pressure gradient of 10 MPa/Km and a lithostatic pressure gradient of 27 MPa/Km. To avoid damaging the rock and generate the correct stress concentration at the borehole surface, in these simulations the fluid and rock are initially held at the lithostatic pressure and then the fluid pressure is slowly reduced to the required hydrostatic pressure. At internal friction coefficients of 0.6 – typical of silicate rocks (Mogi, 1973), the rate of damage increases with depth.

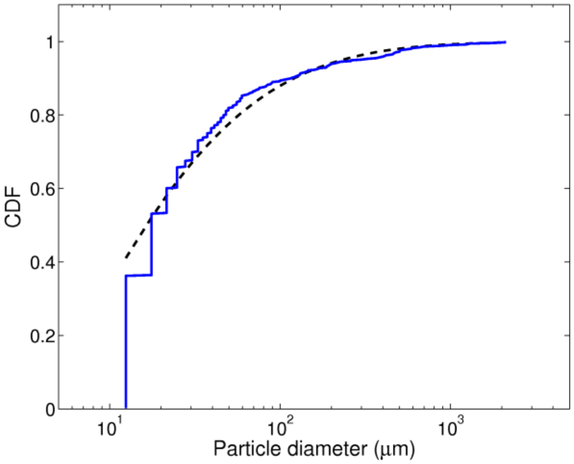

Figure 3: Spall size distributions (solid blue line) produced by the micromechanical model follow a log-normal distribution (dashed line). Note that the minimum resolvable spall diameter is ~12 microns in this simulation.

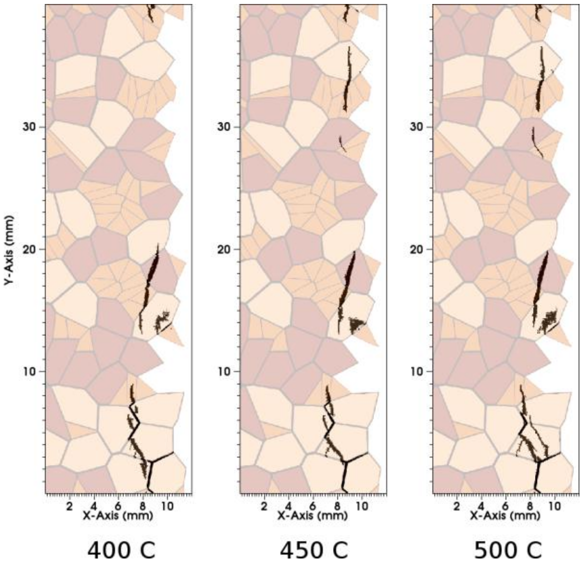

Figure 4: Damage distributions for different fluid temperatures. Light grains are quartz, orange grains are plagioclase, and brown grains are K-spar.

The difference in hydrostatic and lithostatic pressure and the stress concentration at the borehole surface were both found to influence the relative rates of spall production. Simulations that did not account for these factors predicted a decrease in spall rates in deeper boreholes (Walsh et al 2011). Indeed, by increasing the internal friction coefficient, or decreasing the difference in lithostatic and hydrostatic pressure gradients the rate of spall production can either remain static or decrease with depth (eg. Figures 5 and 6 in which an internal friction coefficient of the host rock minerals is set to 0.8). This suggests the rate of spall production is a function of both the pressure dependent behavior of the rock's yield surface, and the deviatoric stress-state at the borehole surface. This relationship would have implications for the drilling mud program, as it would be possible to influence the rate of spalling at depth by adjusting drilling mud weights. We are currently conducting preliminary three dimensional simulations to better investigate this relationship (Figure 7).

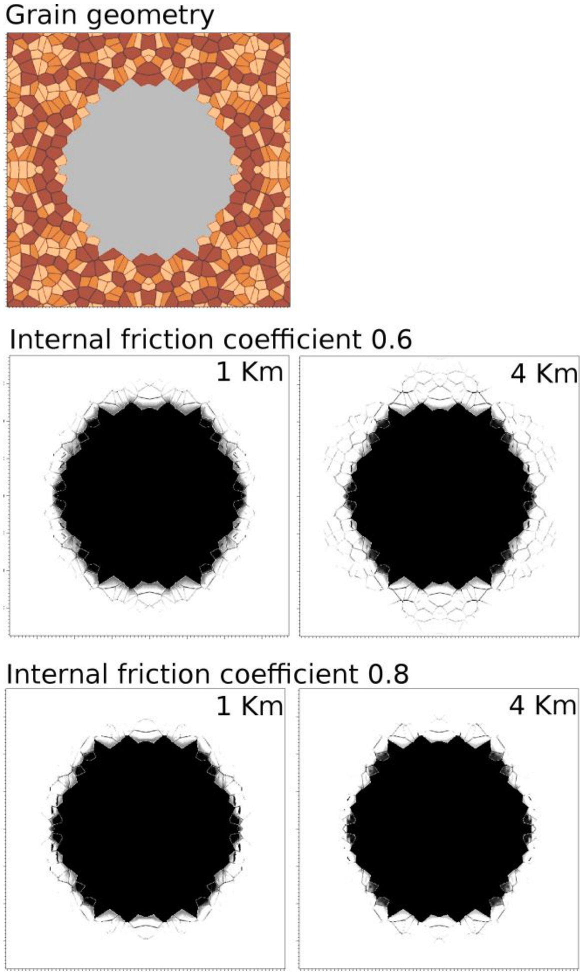

Figure 5: Damage as a function of borehole depth and internal friction angle. Top image shows distribution of mineral grains, the lower grid gives damage patterns for borehole depths of 1km and 4km, for rocks with internal friction coefficients of 0.6 and 0.8.

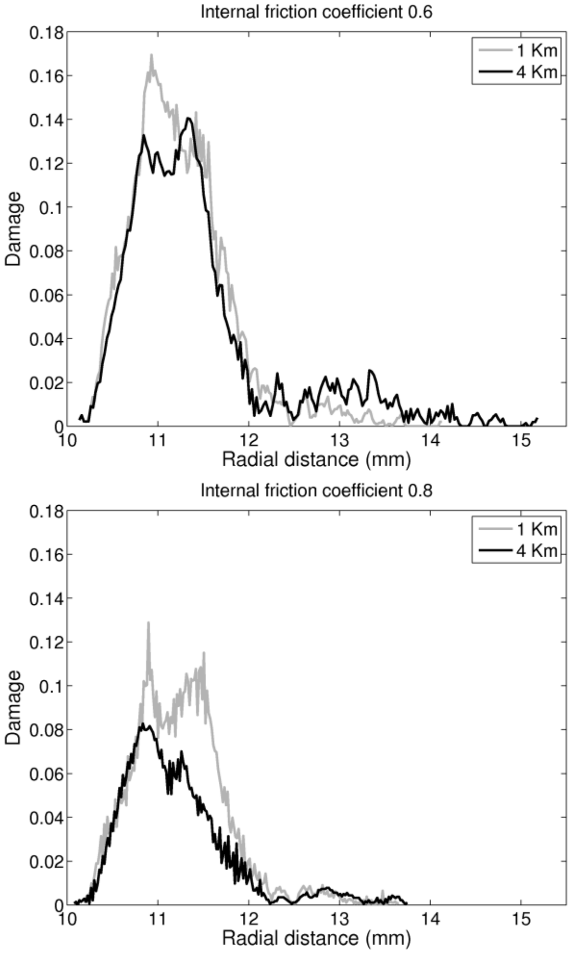

Figure 6: Plots of damage vs radial distance for the borehole images shown in Figure 5.

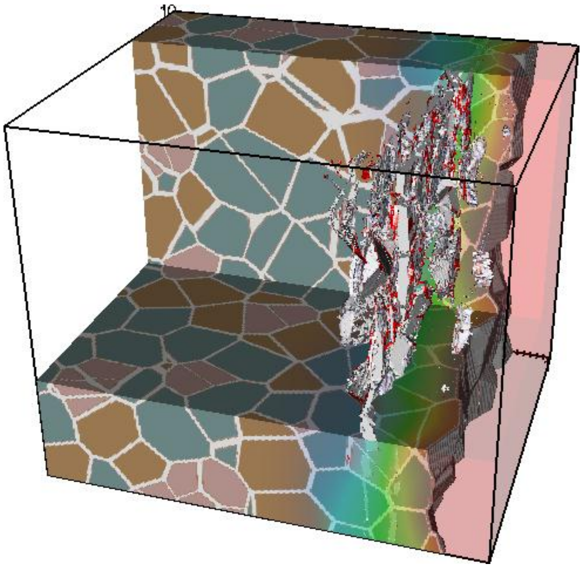

Figure 7: Microstructure, temperature distribution and spalling fracture planes from a three dimensional simulation.

CONCLUSION

New drilling technologies are needed to make geothermal energy competitive with other energy sources. One promising technique is thermal spallation drilling - a novel drilling method capable of faster penetration of hard brittle rocks compared to conventional mechanical methods. However, models of the processes driving thermal spallation remain largely empirical, making system optimization difficult under field conditions.

In this paper, we have presented results from a new modeling effort that reproduces the grain scale processes that influence thermal spallation. By adopting a Eulerian modeling framework the model is able to capture both inter granular fracture, and reproduced the geometric and material heterogeneity present in natural rock.

Results from the grain-scale model suggest that spall fractures are consistently triggered at a select nucleation sites. This lends credibility to the use of Weibull models to represent spall production on larger scales, as such models are based on the assumption that spalled fragments are generated by the activation of critical flaws distributed through the rock body. Future work will examine if such models could be calibrated by explicit small scale simulations of the type presented in this paper.

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