Simulation Tools for Modeling Thermal Spallation Drilling on Multiple Scales.

Stuart D.C. Walsh, Ilya Lomov, Yuliya Kanarska and Jeffery J. Roberts
Lawrence Livermore National Laboratory, Livermore CA, USA

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Abstract

Widespread adoption of geothermal energy will require access to deeply buried resources in granitic basement rocks at high temperatures and pressures. Exploiting these resources necessitates novel methods for drilling, stimulation, and maintenance, under operating conditions that are often difficult or impossible to reproduce in laboratory settings. Physically rigorous numerical modeling tools are vital to highlight potential risks, guide process optimization and reduce the uncertainties involved in developing new technologies for these environments.

Lawrence Livermore National Laboratory has developed, and is constantly improving, several multi-physics solid/structural mechanics, fluid dynamics, chemistry, and discrete element codes. Integration of the LLNL simulation tools into a coherent simulation environment will provide a predictive capability for the thermomechanical response - in particular the spall and fracture - of basement rocks at high temperatures and pressures useful for drilling and other geothermal applications. The unified tool will be able to address problems that would be impossible to solve with any other existing technique.

This paper outlines a modeling effort investigating the processes involved in hydrothermal spallation drilling. These include interconnected phenomena on several length and time scales: from system-scale fluid dynamics and heat transfer of the high temperature jet to the rock face to the grain-scale thermomechanics of spallation. Three models are described to capture these different scale processes: a grain-scale model to investigate the onset of spallation; a particulate fluids model to simulate the transport of the produced spalls; and a borehole-scale model to represent the integrated system behavior.

1 Introduction

Geothermal resources hold great promise for clean, base-load energy, but their efficient exploitation will require development of new methods for drilling, stimulation, and resource management [1]. These new technologies will involve complex systems operating at depths and pressures that are difficult and costly to reproduce in the laboratory or test in the field. The use of computer aided design can reduce these expenses and accelerate the development of novel geothermal technologies [2]. However, to be successful these design strategies must be based on physically rigorous models, often integrating processes operating across a variety of time and length scales.

Thermal spallation drilling, and related thermal spallation excavation techniques, are examples of promising technologies with the potential to dramatically improve the geothermal industry by lowering drilling costs and improving well performance [3–5]. Unlike conventional drilling methods that rely on mechanical means to penetrate rock, under thermal spallation drilling rapid heating is used to break small disk-shaped spalls from the rock surface. A variety of heat sources are employed in thermal spallation drilling operations – examples include flame-jet, laser and microwave spallation. The examples in this paper concentrate on hydrothermal spallation drilling, in which heat is supplied by a high-temperature fluid jet. These drilling methods can deliver pentration rates two or more times greater than conventional drilling methods [3], and experience substantially reduced equipment wear (and hence time lost to drill-bit replacement). However, despite the fact that the underlying mechanisms behind thermal spallation drilling have been described for almost a century [6, 7], our understanding of these processes remain largely empirical. In part this is due

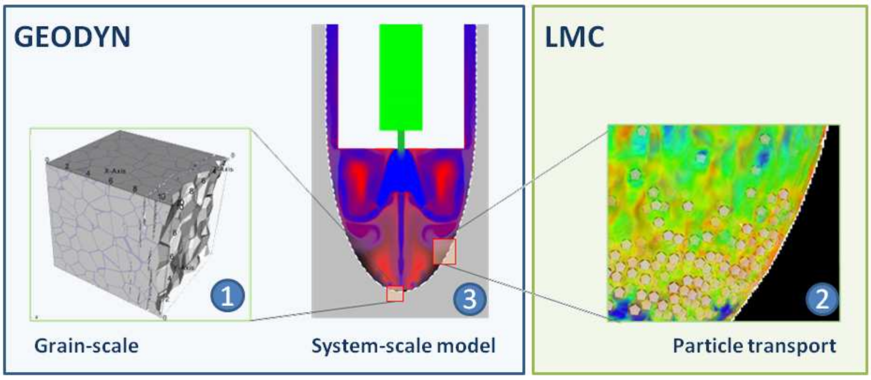

Figure 1: Illustration of the three models outlined in this paper: 1) a high-resolution model capturing the grain-scale failure of granitic materials; 2) a particulate-fluids model for spall transport simulations; and 3) a system-scale model to simulate the borehole behavior. The grain-scale and system-scale models are both simulated with the GEODYN modeling framework, while particle transport is simulated with the Low Mach Code (LMC).

to uncertainties arising from interconnected phenomena acting across several length and time scales: from system-scale fluid dynamics and heat transfer of the high temperature jet to the rock face to the grain-scale thermomechanics of spallation.

The modeling effort presented in this paper seeks to understand thermal spallation drilling on three-levels: 1) a microscale-model investigating the onset of spallation at the grain scale, 2) a particle transport model examining removal of produced spalls from the borehole environment, and 3) a borehole-scale model examining the response of the system as a whole. A brief description of the simulators used to model these various components is given in 2. We then provide an overview of the grain-scale model and some of the key results in Section 3.1. The tools developed for simulating the explicit transport of spalls from the borehole, and the borehole system as a whole are presented in Sections 3.2 and 3.3 respectively. Conclusions and future directions are presented in Section 4.

2 Numerical tools

The models presented in this paper are conducted using two numerical simulators in development at Lawrence Livermore National Laboratory: GEODYN and LMC.

GEODYN is a parallel Eulerian compressible solid and fluid dynamics code with adaptive mesh refinement (AMR) capabilities [8, 9]. Among its many features are a high-order material interface reconstruction algorithm [10] and advanced constitutive models that incorporate salient features of the dynamic response of geologic media [11]. GEODYN is able to simulate materials under extremely large deformations, resolve details of wave propagation within grains with high accuracy, and uses a continuum damage mechanics approach to represent fracturing.

LMC (Low Mach Code) is a massively-parallel computer code that has been developed for direct numerical simulation (DNS) of particulate flows in fluid. The numerical method is based on a distributed Lagrange multiplier technique in which both fluid and particles are fully resolved and coupled [12, 13]. Particle-particle interaction is performed with frictional, inelastic contact forces similar to those used in discrete element models; moreover, the code is able to handle arbitrary particle shapes and size distributions. A parallel implementation is based on the LLNL SAMRAI (Structured Adaptive Mesh Refinement Application Infrastructure) framework which allows handling a large number of rigid particles [14, 15].

Both codes demonstrate excellent scalability to thousands of CPUs and have been optimized for LLNL supercomputer platforms.

3 Model descriptions

The multiple-scale modeling effort described in this paper consists of three parts: 1) an explicit model capturing the grain-scale failure of granitic materials; 2) a particulate fluid model to simulate the transport of the produced spalls from the borehole; and 3) a system model to represent the borehole-scale behavior. The relationship between the different classes of models and the two codes introduced in the previous section is illustrated in Figure 1.

3.1 Grain-scale model

The microstructure for the grain-scale model is created through an iterative approach that fits Voronoi-cell volumes to a target grain-size distribution [16]. Voronoi cells are generated from a set of random points, and each cell is assigned a target volume. The target volumes may be selected from separate grain-size distributions according to the grain's mineral type, or assigned on a grain-by-grain basis. The Voronoi-cell volumes are then relaxed towards the target distribution over a series of iterations. The iterative improvement is repeated until the average error in cell volumes is below a predetermined tolerance. The method is capable of reproducing two and three dimensional grain-size distributions to arbitrary accuracy, and is able to produce microstructures with periodic and radially symmetric boundary conditions. Non-ergodic microstructures, where the particle-size distributions vary as a function of space, are also possible – enabling, for example, consideration of stratified media (Figure 2).

Separate materials with distinct properties, and indeed separate constitutive models, are assigned to each grain in the assembly. Here microstructures consisting of quartz, plagioclase, and potassium feldspar (or K-spar) grains are presented, but more mineral types can easily be included. Mineral mechanical properties are taken from Bass [17] and Mavko et al. [18], while the heat capacities and relative thermal conductivities are based on values reported in Findikakis [19] and Clauser & Huenges [20]. Inter-grain contacts are represented by a separate, weaker material with compressive and tensile strengths fitted to granite properties described by Lockner [21].

Results from the model demonstrate the importance of heterogeneous material properties and geometry in determining brittle failure – factors that would be impossible to investigate with larger continuum-scale models [22, 23]. Surface roughness, grain size distribution, and thermal conductivities serve to generate local stress concentrations that trigger the onset of spallation. For this reason, inter-granular boundaries are frequently the sites of spall fracture initiation (Figure 3). The Eulerian modeling framework provided by GEODYN, also enables spall fractures to propagate within grains. The ability to capture this behavior is necessary, as spalls are often one or-more grain-diameters in extent with thicknesses less than a single grain diameter [24].

3.2 Particle-transport model

While the grain-scale model can supply information on the initial stages of spall formation, simultaneously simulating transport of the spalls from the rock face and along the borehole is impractical at such a high-resolution. Instead, this behavior is simulated with a separate model using the LMC simulator.

Understanding the behavior of ejected spalls is important as long residence times at the base of the borehole may interfere with conduction of heat from the fluid to the rock surface. Moreover, high spall densities can influence fluid dynamics and effect jet and outflow properties. The ability to simulate spall breakup is also valuable, as it impacts the spall-size distribution observed at the surface, complicating analysis of the downhole drilling conditions and how they may change at depth. Lastly, under some circumstances, suspended spalls may have a beneficial effect, as they serve as abrasive agents that can enhance borehole erosion.

The LMC simulator is particularly suited to this class of problems. It can account for particle-fluid and particle-particle interactions in suspensions of arbitrary shaped particles, allowing for consideration of interactions between the suspended spalls and the borehole wall.

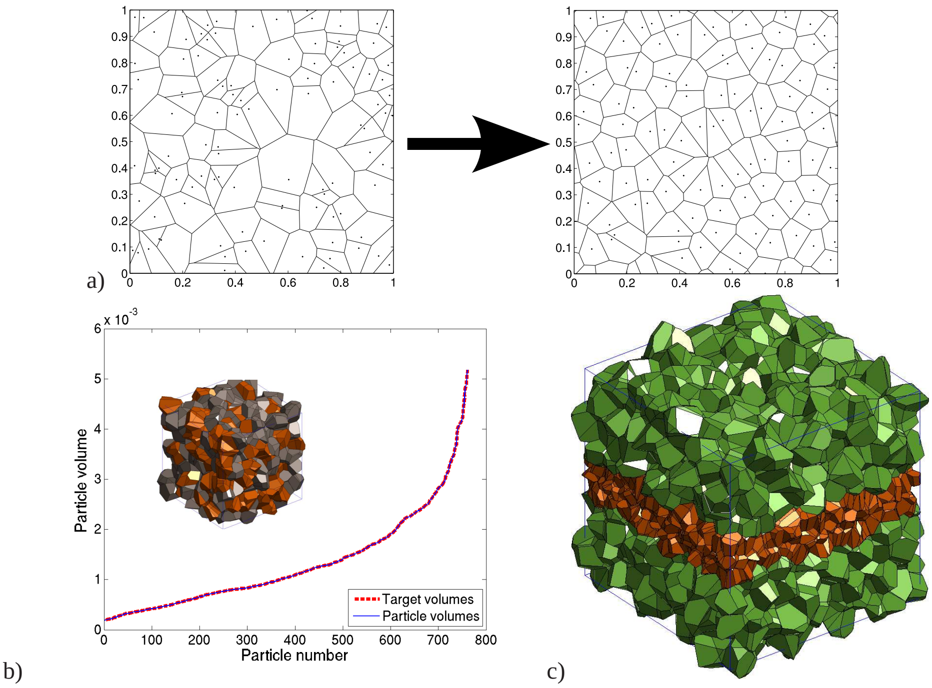

Figure 2: Examples of Voroni-cell based microstructures: a) Microstructures are generated from an random set of points, which are then perturbed over a series of iterations to fit a pre-determined particle size distribution, shown here for a two dimensional assembly; b) Target (dashed red line) and generated (solid blue line) particle-size volume for a three dimensional assembly (inset figure); and c) A layered three dimensional assembly.

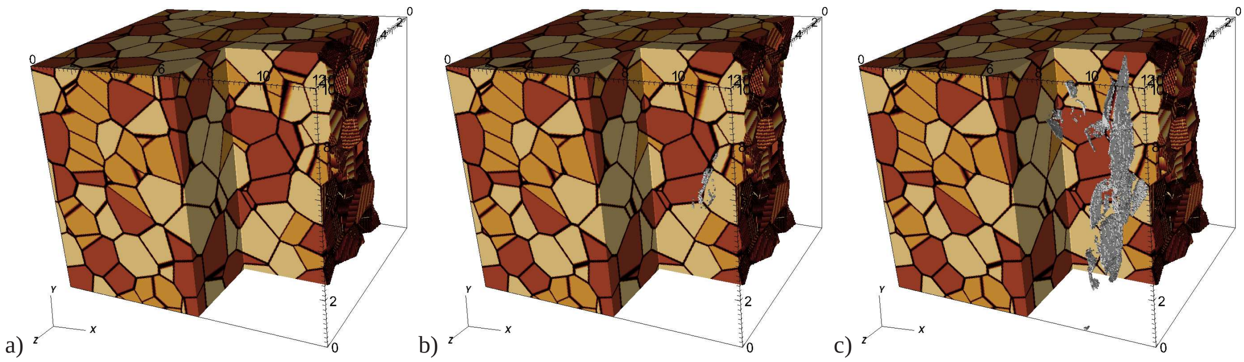

Figure 3: Fracture initiation and propagation in a three-dimensional grain-scale simulation. a) Cutaway of the grain microstructure: light colored grains are quartz; orange grains are k-spar; brown grains are plagioclase. The rock face is heated by fluid in the space on the right of the image. b) Fractures (gray planes in the cutaway section) tend to initiate at inter-grain boundaries, c) but propagate along the thermal front, following the principal compressive stresses.

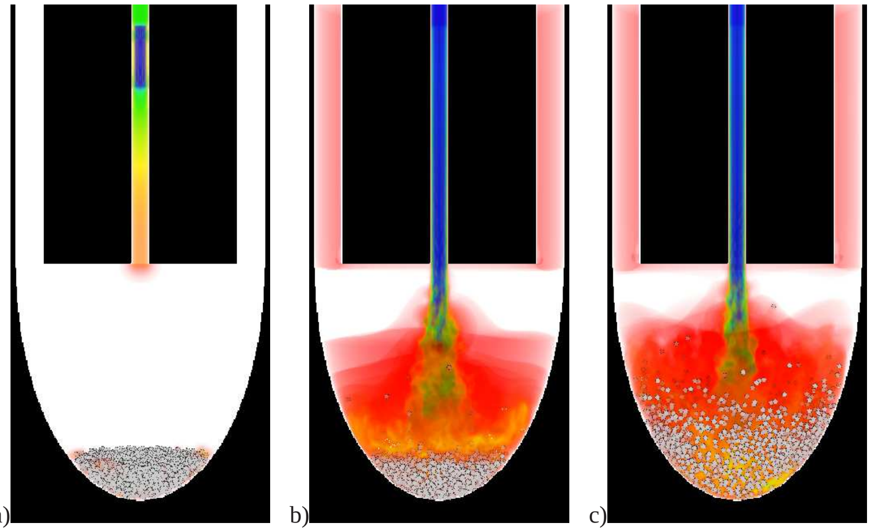

Figure 4: Three-dimensional LMC simulation of spall transport: a) Initial particle setup, b) vertical fluid velocities and particle locations at 0.01 seconds, and c) at 0.02 seconds, when all particles have been entrained in the flow. Two dimensional cross-sections of the borehole geometry and drill head are shown in black.

The LMC simulations have been used to examine spall-retention times at the base of the wellbore (Figure 3.2). An artificial borehole geometry was created approximating boreholes observed in experiments by Potter Drilling [3]. The base of the borehole was seeded with approximately 2000 particles, each with a radius of 0.45 mm. In under 0.02 seconds the particles had been entrained by the flow from the high-velocity jet from the drill-head. Thus under ideal operating conditions, particle residence times in the active part of the system are short relative to the rate of penetration – justifying the use of continuum models to represent low-concentration spall transport on the system scale. Future simulations will examine the effect of drill-bit standoff distance (and potential recirculation) on particle residence times; the role of particle size; and particle-wall collisions.

3.3 System-scale model

The three-dimensional models described in the previous sections may require several thousand CPU hours per simulation. Such models are impractical to run at full-scale for the purpose of industrial optimization. Instead we are developing separate system-scale simulations that incorporate the behavior observed in the explicit small-scale simulations in large-scale phenomenological constitutive models. Like the grain-scale simulations, the borehole scale simulations are implemented in GEODYN. In the borehole scale simulations, however, the individual grains are not represented explicitly, instead a homogenized granite model is used. The spalls in suspension are similarly represented by a continuum-based approach that tracks the particle concentration rather than individual particle locations.

Production of spalls at the rock surface is currently conducted via simple “reaction” type models that erode at a rate proportional to the amount of heat flux. Results from the grain-scale model suggest that spall fractures are consistently triggered at a select nucleation sites. This lends credence to the use of Weibull statistical-failure models to represent spall production on larger scales [25–28]. Such models are based on the assumption that spalled fragments are generated by the activation of critical flaws distributed through the rock body. We are in the process of testing this hypothesis using the grain-scale model, and ultimately, plan to develop a modified Weibull-type model informed by the results of these grain-scale simulations.

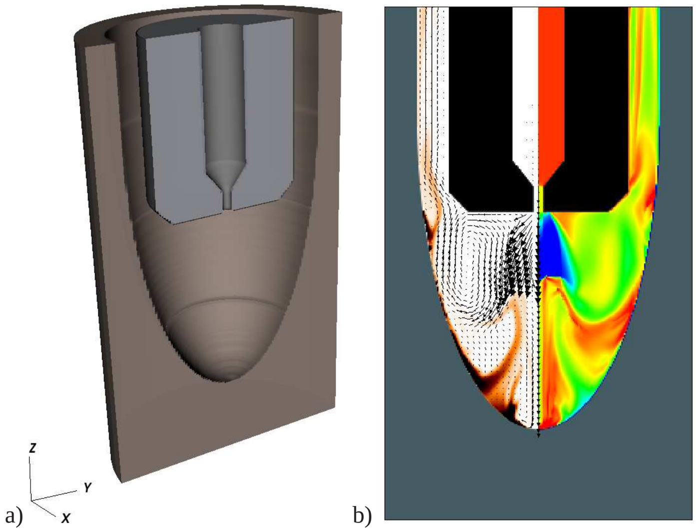

Figure 5: Axisymmetric GEODYN borehole-scale model: a) problem geometry showing a cross-sectional view of the borehole geometry (brown) and drill-bit head (grey); b) spall volume fraction and fluid velocities (left) and fluid temperature (right).

4 Conclusion

This paper describes the development of three new models capable of reproducing processes that influence thermal spallation on multiple-scales: an explicit small-scale model of grain failure; a particulate-fluid model of spall transport; and a system model at the borehole-scale. These simulations represent the initial stages in an effort to develop a simulation environment coupling thermal spall and particle-laden flows. The developed integrated simulation tool will provide a predictive capability of thermal spallation drilling useful for process optimization in practical applications.

New technologies are needed to make geothermal energy competitive with other energy sources, and high-fidelity simulations can aid in their development. The modeling tools described in this paper are also applicable to the analysis of thermal damage of brittle-rocks in other contexts. Examples include but are not limited to: thermal damage as a result of long-term thermal draw down over the lifetime of geothermal wells, or borehole damage due to heat exchange in hydraulic fracturing and EOR operations.

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