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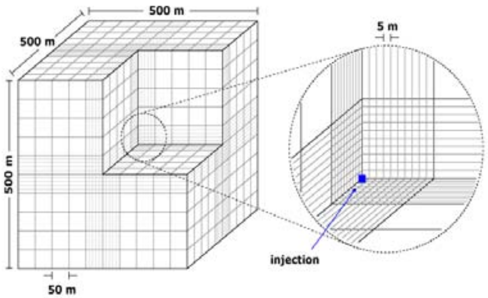

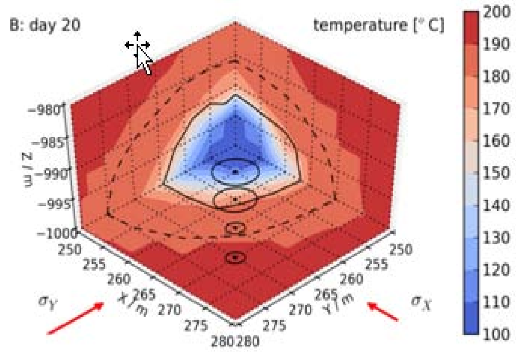

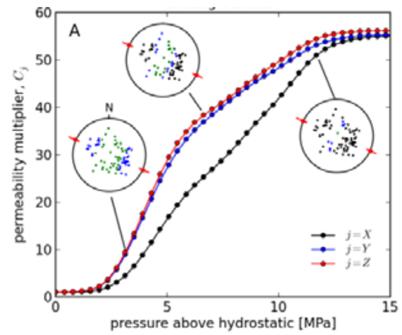

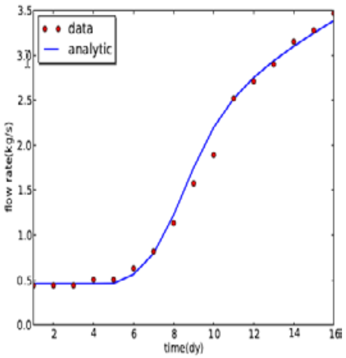

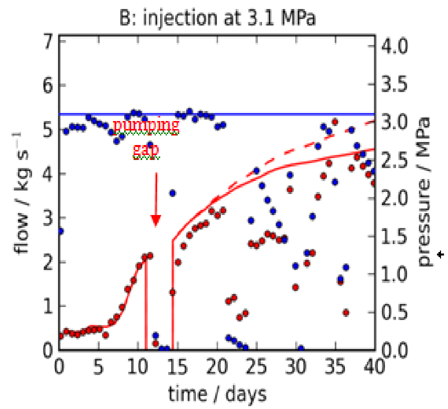

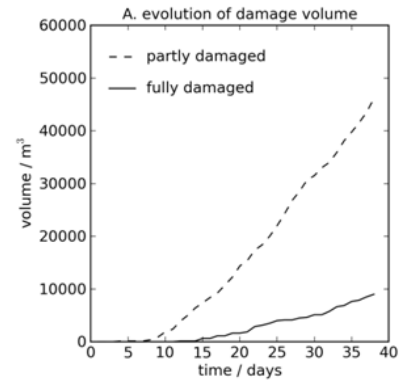

Project title: Stimulation at Desert Peak and Brady's reservoirs: modeling with the coupled THM code FEHM

Project Officer: Lauren Boyd

Total Project Funding: $200K

April 23 , 2013

Principal Investigator
Sharad Kelkar
Organization:
Los Alamos National Laboratory

Track Name: Modeling (3)

This presentation does not contain any proprietary confidential, or otherwise restricted information.

OBJECTIVES OF THE PROJECT

- Develop FEHM models of the Desert Peak system to match shear and tensile stimulation treatments, in combination with locations of microesismic events. Apply to various production scenarios.
- Develop FEHM models appropriate to the Brady's geothermal system; assist in development and interpretations of stimulation treatments. Apply to various field development and production scenarios.

BARRIERS ADDRESSED

F (MYRD&D): Modeling – Insufficient modeling and validation capabilities to effectively couple fluid flow, geochemistry, and thermal-mechanical phenomena for 1) stimulation prediction, and 2) reservoir simulation.

L(MYRD&D): Well Field Design – Inability to assess and select the most efficient well-field design.

Relevance/Impact of Research

KNOWLEDGE GAPS ADDRESSED

Stimulation modeling techniques for geothermal systems are not a mature technology. Current models have not been effective in a geothermal environment (MYRD&D).

Existing reservoir simulation models are not fully coupled to enable planning of field expansion. Sufficient data to validate models is not available (MYRD&D).

IMPACT COSTS, PERFORMANCE

Estimating and minimizing the economic risks associated with an EGS project requires realistic estimates of reservoir productivity over the life of the system. Thus validated reservoir-scale models are necessary in order to make informed decisions regarding optimal EGS reservoir development (maximizing return on investment and minimizing levelized cost of electricity).

Relevance/Impact of Research

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INNOVATIVE ASPECTS OF THE PROJECT

The coupled THM(C) modeling code FEHM, developed at LANL, is perhaps the only fully integrated simulator available currently, with demonstrated capability of modeling reservoir scale systems over time span of interest (20-30 years) in fractured geothermal formations with material properties (e.g. permeability) that depend on pressure, temperature, and stresses in a highly nonlinear manner.

PROJECT INTEGRATION

This project is stand-alone, however, it is linked to the EGS projects at Desert Peak and Brady's (Nevada) geothermal fields. The modeling is informing the stimulation design planned for the Brady's field this year.

IMPACT ON THE GEOTHERMAL TECHNOLOGIES OFFICE'S GOALS

Goal 3 (MYRD&D): Develop improved tools for the characterization and modeling of the subsurface at EGS project sites.

Reservoir modeling techniques are being developed to match the pressure-flow rate data, in conjunction with microseismic event locations, during the stimulation treatments conducted in the Desert Peak Well #27-15. The experience thus gained is being applied to the Brady's geothermal system to aid in data interpretation and design of the future stimulation treatments. The expertise developed during these activities will be highly relevant to other field demonstration projects currently under way, and those being considered in the near future.

SCIENTIFIC/TECHNICAL APPROACH USED

- Develop Conceptual models for permeability-stress dependence, and implement them in FEHM
- Develop a numerical model based on the code FEHM incorporating nonlinear, coupled Hydrological-thermal-mechanical processes to simulate the shear stimulation of the Desert Peak well #27-15 (Nevada).
- Develop simplified theoretical models amenable to analytical solutions in order to gain insight into the reservoir processes of importance occurring during a shear stimulation treatment .
- Use the modeling tools and expertise developed to assist in the stimulation design for the Brady's field.

SCIENTIFIC/TECHNICAL APPROACH USED (cont.)

Modeling challenges and our approach

- Large changes in fluid pressure
- Large changes in temperature
- Large changes in stress
- Large problem size
- Highly nonlinear
- Many different space and time scales
- Matrix rock and fractures/faults are both important

•Continuum– dual porosity/permeability
•Full Jacobian – Newton-Raphson: choose levels of coupling
•Efficient evaluation of functions
•CV – FE
•Precompute geometric integrals
•Static force balance – elastic/plastic, small strain
•Code used and verified on a variety of projects including Geothermal, CO_2, Nuclear waste, Oil&Gas, ER, Arctic permafrost, Hydrates

SCIENTIFIC/TECHNICAL APPROACH USED (cont.)

Description of the numerical simulator FEHM

- **Subsurface physics**
  - Mass and Heat - Multi-phase, multi-fluid
  - Rock deformation-elastic/plastic
  - NAPL, Hydrates, Coal-Bed Methane
- **Multiple Scale**
  - Dual Porosity
  - Dual Permeability
  - Generalized Dual Porosity
  - Flux-continuous Anisotropy (CVFE based)
- **Fluid properties**
  - Rational polynomial fit to water/steam data
  - Functions of Temperature and Pressure

- **Solution of Equations**
  - Pre-conditioner accelerated for the linear equations.
  - DOF reduction techniques
  - Newton-Raphson for the nonlinear equations.
- **Advective Transport**
  - Multiple reacting species
  - Particle Tracking on non- orthogonal grids, including dispersion and diffusion
- **Choice of permeability/stress-deformation relationships**

HIGHLIGHTS

Demonstrate a well-designed project and project tasks relevant to the project's objectives

- In consultation with recognized experts (Dr. Hickman, Dr. Moos, and Dr. Davatzes); and using theoretical and numerical analysis, established physical processes of importance during shear stimulation
- In consultation with recognized experts and based on available data, indentified the range of values of important parameters
- Compared model results with available pumping data from Desert Peak
- Made progress in modifying the model to apply to the Brady's field.

KEY ISSUES ADDRESSED AND THEIR SIGNIFICANCE

Models developed for petroleum and hydrothermal applications have been inadequate for making reliable prediction of stimulation results and identification of the best options for creating the EGS system (MYRD&D). We have been developing and verifying a capable, robust numerical simulator to couple rock- and fluid-mechanics theory with the measured properties and structure of the rocks.

THE APPROACH HAS BEEN EXECUTED IN PROJECT TASKS

We have demonstrated the validity of our approach and the numerical simulator by obtaining a good agreement with the pumping data from the stimulation treatment at the Desert Peak reservoir.

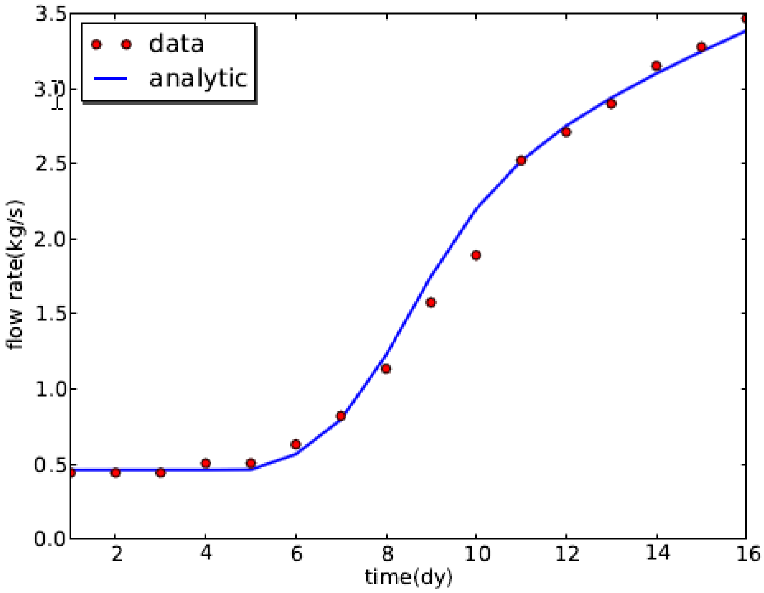
TECHNICAL ACCOMPLISHMENTS

Developed a simplified theoretical model that provides a good match to the Desert Peak data

(Submitted to *Flow in Porous Media*: “A model for tracking fronts of stress induced permeability enhancement” by K.C. Lewis, S. Karra and S. Kelkar)

Figure : comparison of the theoretical model solution the shear stimulation data from Desert Peak.

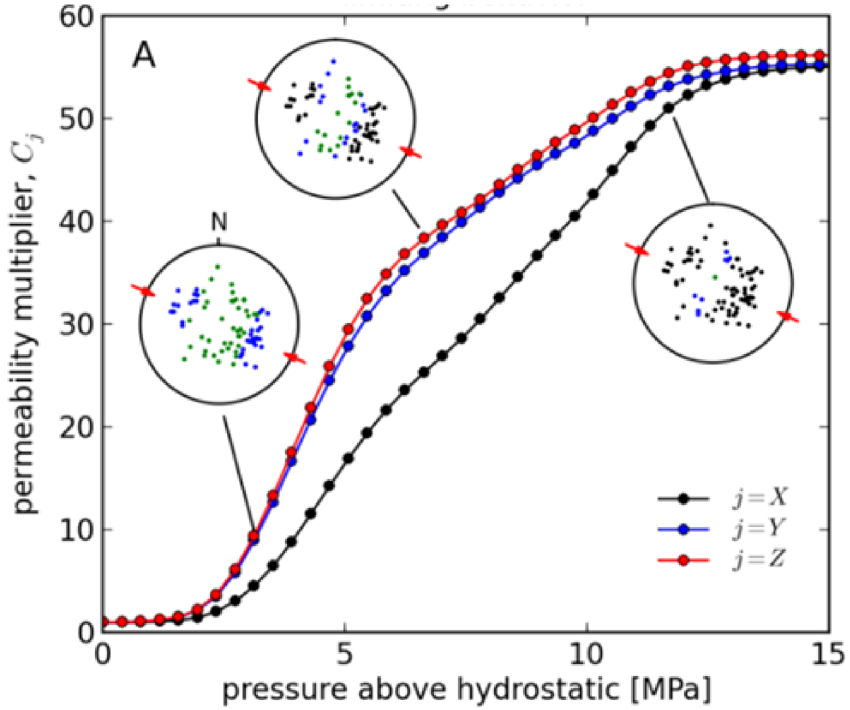
Derived the time dependence of injection rate using an analogy with the classical Stefan problem assuming an abrupt permeability (porosity) change at the damage front. Modeled spherical geometry in a thermally driven system.



TECHNICAL ACCOMPLISHMENTS (CONT)

Developed and implemented a permeability enhancement upon shear failure model incorporating a distribution of orientations of through-going fractures

Mohr-Coulomb criteria with effective stress is used for failure. Permeability multipliers as functions of pressure. Equal-area stereonet plots show unstimulated (green), partially (blue) and fully stimulated (black) Desert Peak fracture orientations. Orientation of the minimum horizontal stress is indicated by red arrows.



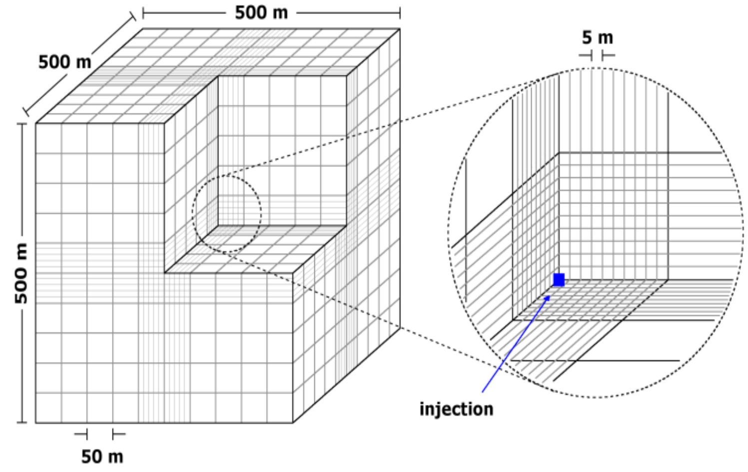
TECHNICAL ACCOMPLISHMENTS (CONT)

Developed a coupled Hydrological-Thermo-Mechnical model based on the code FEHM that provides a good match to the Desert Peak data

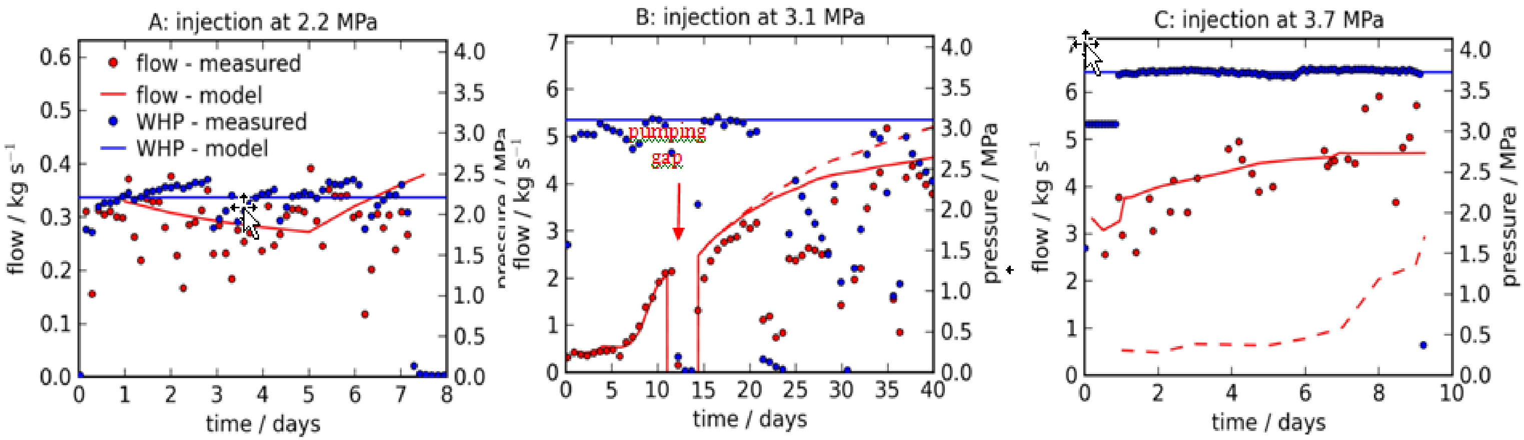
(1. Presented at the *2013 Stanford Geothermal Workshop*: “Modeling Shear Stimulation of the EGS Well Desert Peak 27-15 Using a Coupled Thermal-Hydrological-Mechanical Simulator” by Kelkar et al.

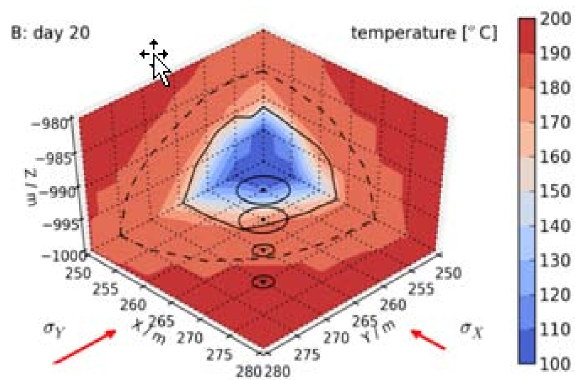
2. To be presented at the *2013 ARMA meeting*: “Modeling Shear Stimulation of the EGS Well Desert Peak 27-15 Using a Coupled Thermal-Hydrological-Mechanical Simulator” by Dempsey et al.
3. In preparation for submission to *Geothermics*: “Coupled Thermal-Hydrological-Mechanical Modeling of Shear Stimulation in EGS wells”, by Kelkar et al.)

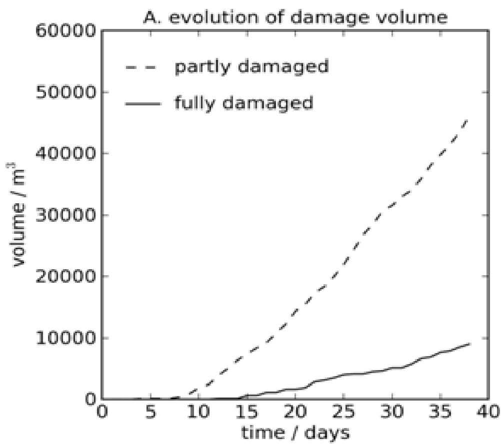
Model grid with a cut-away showing grid refinement and location of the injection point.
Parameter values are given in supplemental slides



Results using the coupled Hydrological-Thermal-Mechanical model with FEHM: comparison with the Desert Peak data







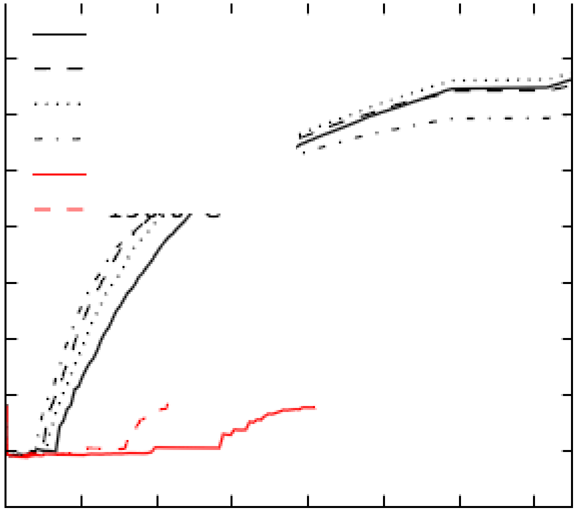
Work in progress on developing a coupled Hydrological-Thermal-Mechanical model with FEHM for stimulation treatments at the Brady's field

Some preliminary results

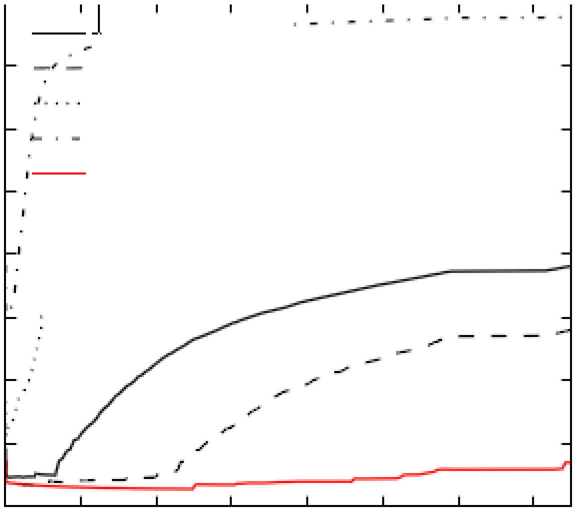
(scales not shown to preserve confidentiality)

Flow rate vs time at fixed injection pressure

Sensitivity to injection temperature



Sensitivity to cohesion



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DEPLOYMENT STRATEGY
expected outcome of the currently funded project (FY13)

Preliminary modeling of Desert Peak Hydrofrac treatment.

Preliminary shear stimulation model for Brady's field.

Milestone or Go/No-Go	Status & Expected Completion Date
Milestone: Desert Peak modeling report and data files	Sep 2013
Milestone: Brady’s modeling report and data files	Sep 2013

FUTURE RESEARCH, DEVELOPMENT OR DEPLOYMENT NEEDS
(FY14 and beyond, not funded under the current project)

- Extend the FEHM model of Desert Peak and Brady's fields to include systematic sensitivity analysis, stress partioning, anisotropic and inhomogeneous property distribution, anisotropic permeability, and post-failure softening
- Correlate microseismic and tracer data with the FEHM Desert Peak model including hydrofrac
- Develop a model of expected hydrofrac treatment for Brady's field
- Build models incorporating the coupled chemical simulation capabilities of FEHM to make forecasts for times up to 30 years.
- Modify FEHM to incorporate a dual-porosity stress formulation

Summarize the key points

- **Within budget and on time made significant technical achievements**
- **Progressed towards to addressing Barriers F and L**
- **Developed permeability enhancement upon shear failure model incorporating a distribution of orientations of through-going fractures.**
- **Developed a coupled Hydrological-Thermal-Mechanical model based on the code FEHM that provides a good match to the Desert Peak data.**
- **Developed a simplified theoretical model that provides a good match to the Desert Peak data and provides insight into the processes of importance**
- **Work in progress to apply the modeling tools and expertise developed to assist in the stimulation design for the Brady's field.**

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
July 2012	Sep 2013	July 2012	Sep 2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
$200K	-	$132.8K	$132.8K	$132.8K	$67.2K

- Summarize management activities or approaches:
  - In addition to PI, two post-docs working part time
  - Collaborating with Ormat Inc., USGS (Menlo Park), Baker-Hughes Inc., and Temple University (PA)

Parameter values used in modeling Desert Peak data

Parameter	Value
Operational	
Injection depth [1]	1000 m
Injection pressure [1]	2.2, 3.1, 3.7 MPa
Injection temperature[1]	100°C
Material	
Thermal conductivity	2.2 W m^{-1} K^{-1}
Density [7]	2480 kg m^{-3}
Specific heat capacity	1200 J m^{-3} K^{-1}
Porosity [7]	0.1
Coefficient of thermal expansion	3.510^{-5} K^{-1}
Young's modulus [7]	25 GPa
Poisson's ratio [7]	0.2
Reservoir	
Reservoir temperature	190°C
Initial permeability []	$1.28,1.54,1.0310^{-15}$ m^2
	Modified to account for stimulation during 3.1MPa pressure step.
Fracture	
Fractures per control volume,	100
[3]	1.5, 5 mm, 1.7 log(m^2)
	0, 3.5 mm, 0.75 log(m^2)
Cohesion,	2.7 MPa
	0 MPa
Friction coefficient, [7]	0.65
Fracture toughness, [20]	510^2 MPa m^{-1}

Additional Information