

Development of a Directional Cooling-Induced Fracturing (DCIF) Technology for near wellbore stress estimation in geothermal reservoirs

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Project Officer: Zachary Frone, Total Project Funding: \$1,422,214
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Section 1: Program Policy Factors

- *The [Multi-Year Program Plan](#) outlines the primary goals of GTO to support the growth and long-term contribution of geothermal energy. To what degree do the objectives of this effort align with the goals of GTO? How will the project strengthen the geothermal body of knowledge?*
- Understanding the subsurface stress state is critical for safe and effective hydraulic stimulation (both hydraulic fracturing and hydroshearing) of geothermal reservoirs. This has been demonstrated particularly by a recent DOE field laboratory project (Collab at SURF).
- However, conventional methods such as mini-frac (hydraulic fracturing) and overcoring are difficult to use in high temperature and pressure environment in a geothermal well.
- This research aims to develop a new technology suited for geothermal reservoir stress measurement, which does not rely on packers and potentially determines a full stress tensor.
- **The outcome of this project aligns and enhances all three goals within the GTO Multi-Year Program Plan. Specifically, the project outcome will provide critical subsurface characterization data to improve the viability, productivity, and overall deployment of enhanced geothermal systems.**

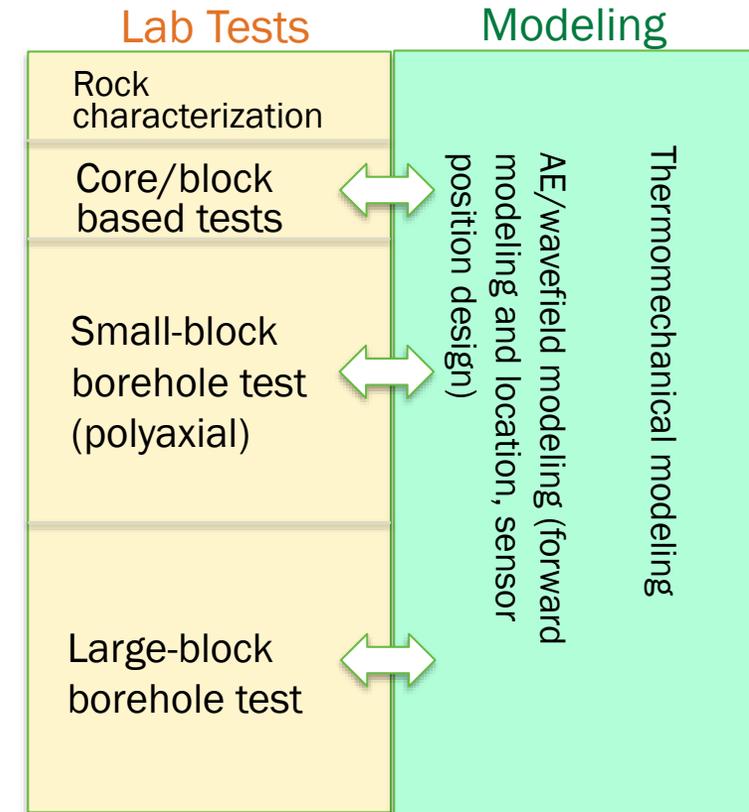
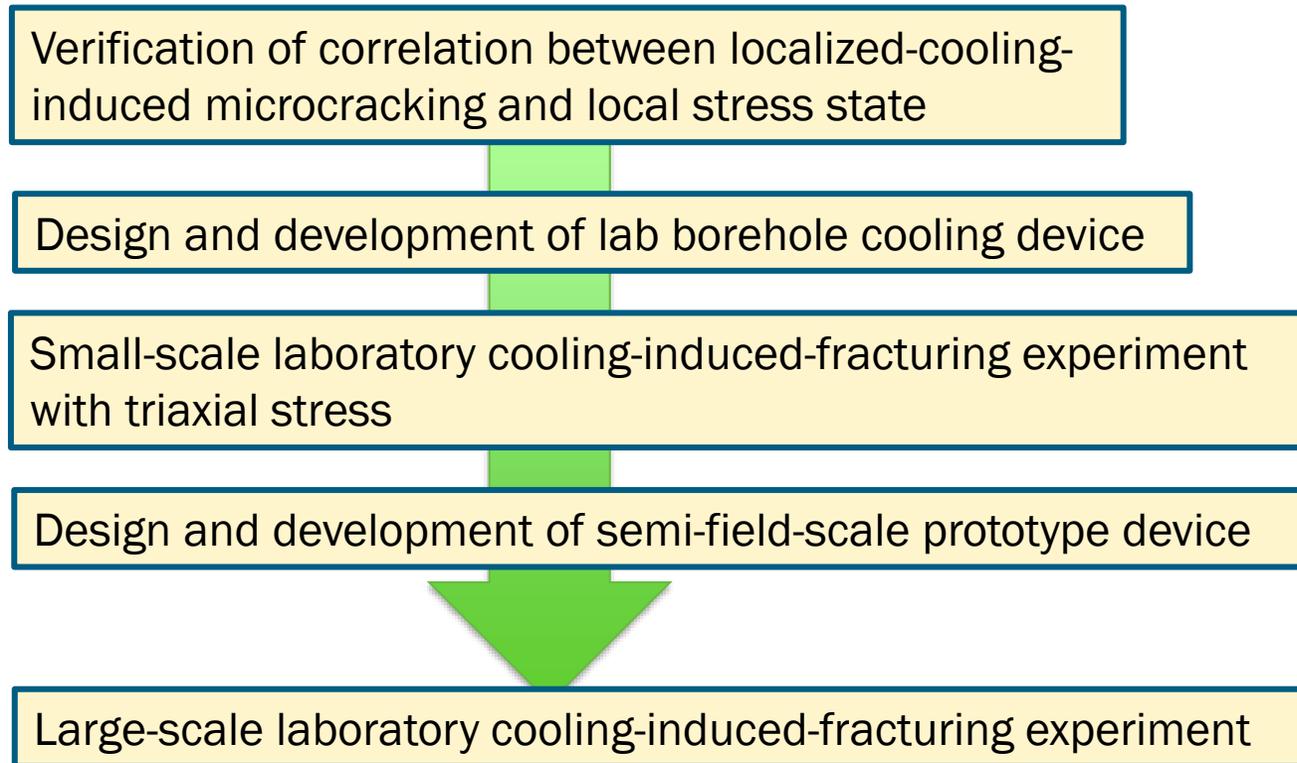
- *To what degree do the objectives address the needs of the geothermal industry at large? Will the project achieve additional goals that are not specifically outlined by the GTO objectives? How has the project improved the identification, access, and development of geothermal resources? How has the project overcome technical and non-technical barriers?*
- The project outcome will provide additional tools to the geothermal industry to improve the design and development of geothermal resources.
- We anticipate that the project outcome will also achieve similar goals in related industries, such as carbon sequestration, for cross-cutting benefits.
- At the completion of the project, the outcome is expected to increase the availability and deployment of geothermal resources by broadening the application and effectiveness of enhanced geothermal systems.

- *The COVID-19 pandemic presented various operational and logistical challenges to many institutions that received federal funding. Were project modifications necessary to ensure the success of the project and were they a result of the COVID-19 pandemic? How did the project team adapt to the barriers that were caused by COVID-19?*
- Because the project does not involve field work, the impact from COVID-19 has been relatively minimal with limited modification required.
- The main impact from COVID-19 has been the inability for the project team to meet in person for research collaboration and project planning. However, the team has increased the frequency of virtual meetings to counteract this deficiency.

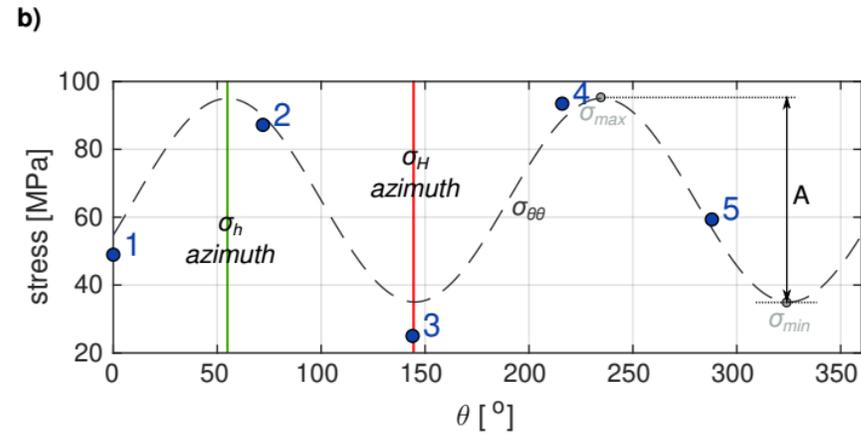
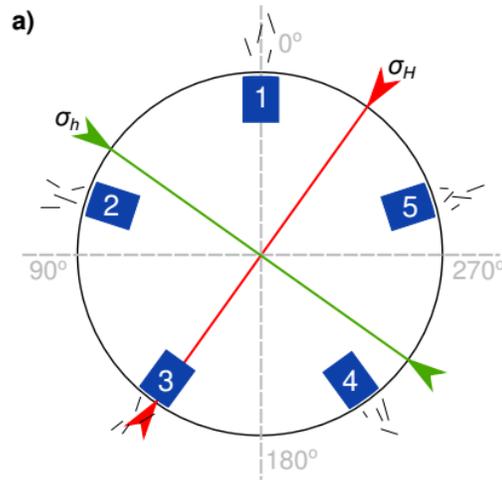
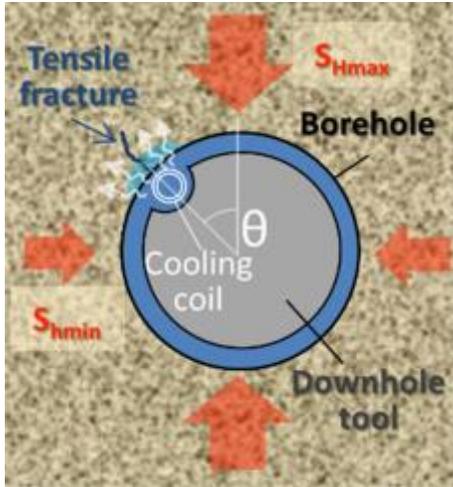
- *[Executive Order 13985](#) describes federal advancing of racial equity and support for underserved communities. To what degree has the project promoted Diversity, Equity, and Inclusion (DEI)? Has the project bolstered underserved communities? If the project does not explicitly include DEI initiatives, are there inherent attributes of the project that demonstrate inclusivity? If the DEI plans are limited in capacity, is there availability to promote inclusivity and diversity in the future?*
- At the time of the FOA application, the project did not explicitly include DEI initiatives.
- The prime recipient, RESPEC, is currently advancing several geothermal projects that are supported by indigenous communities. These projects include the [Clarke Lake Geothermal Project](#) and the [Nunavut Geothermal Study](#). We anticipate that the outcome from this GTO project will enhance the feasibility and accessibility of the geothermal resources within underserved communities, such as the indigenous communities that we are currently supporting.

Section 2: Technical Review

Overall Project Work Flow



DCIF in situ stress measurement: Basic principles



$$\begin{aligned} \sigma_{max} &= 3\sigma_H - \sigma_h & \sigma_H &= (3\sigma_{max} + \sigma_{min})/8 \\ \sigma_{min} &= 3\sigma_h - \sigma_H & \sigma_h &= (3\sigma_{min} + \sigma_{max})/8 \end{aligned}$$

For successful borehole application we need:

- a method to capture onset of fracturing (acoustic emission)
- relation between stress and onset of AEs: AE-criterion

LAB EXPERIMENTS

TEST A: Initial cooling test on unstressed samples (Lawrence-Berkeley National Laboratory)

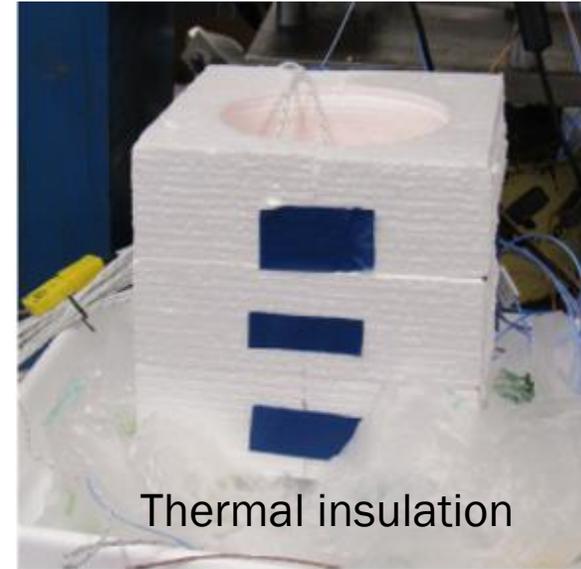
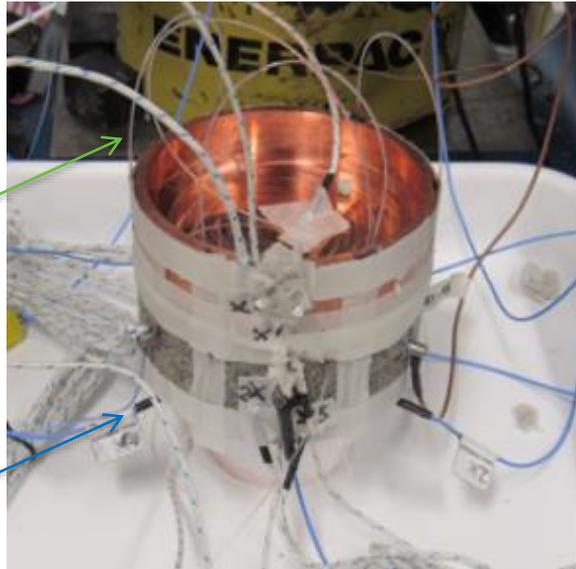
Objective:

- Correlate thermal diffusion and microcracking indicated by AE at unstressed conditions

Liquid N₂ used to produce a large temperature drop at room temperature (~20 °C → ~-200 °C), simulating cooling of hot reservoir rock (~+200 °C → ? °C)

Optical fibers for
temperature
profiling

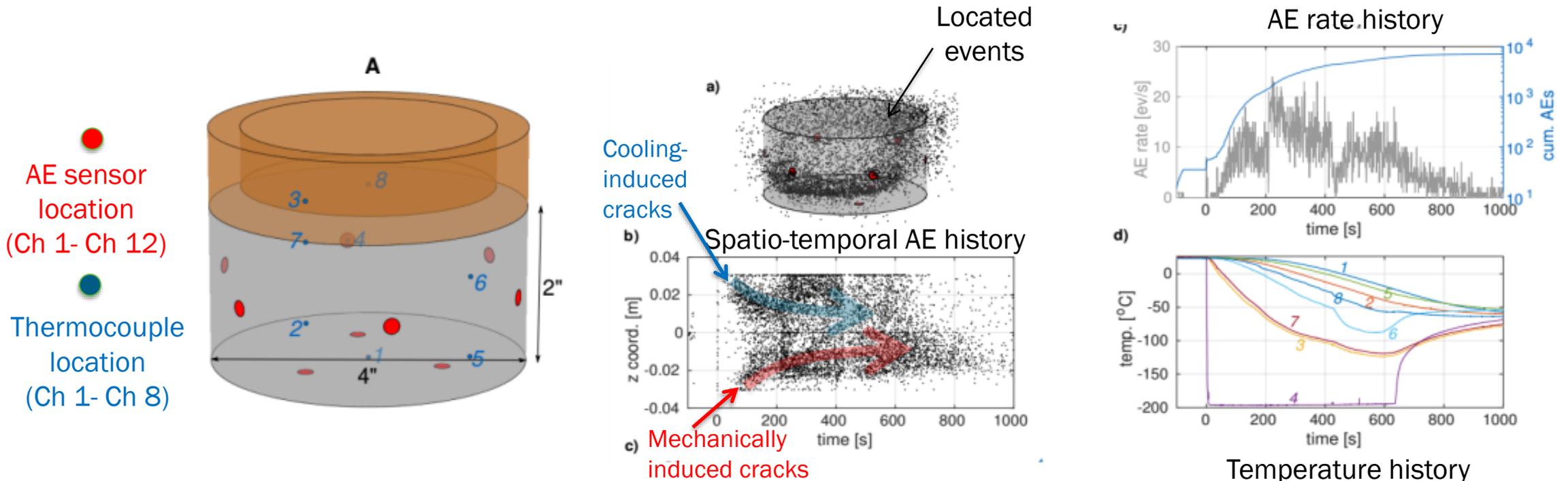
AE sensors



TEST A: Initial cooling test on unstressed samples (Lawrence-Berkeley National Laboratory)

Outcome:

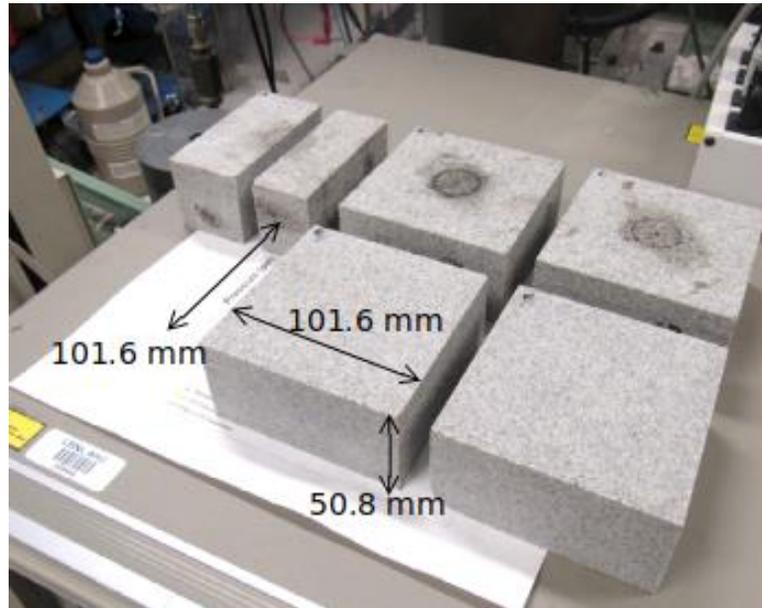
- A large number of AE events were recorded
- The onset of AEs was picked based on AE rate plot—Started immediately for the unstressed sample
- Thermal diffusion in the sample was observed and thermo-mechanical modeling was conducted



TEST B: Cooling tests on stressed samples (Lawrence-Berkeley National Laboratory)

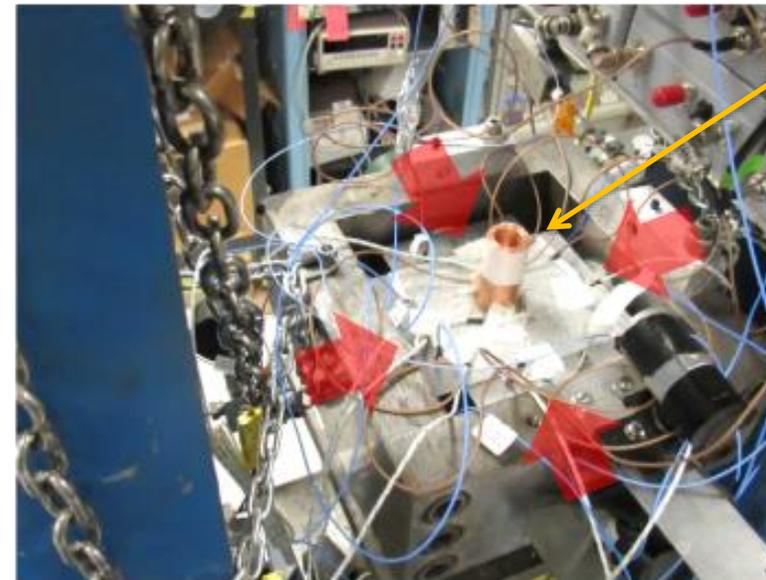
Objective:

- Examine and demonstrate correlation between applied stress and cooling-induced cracking



Rectangular Westerly granite blocks used in the experiment

Biaxial stress test

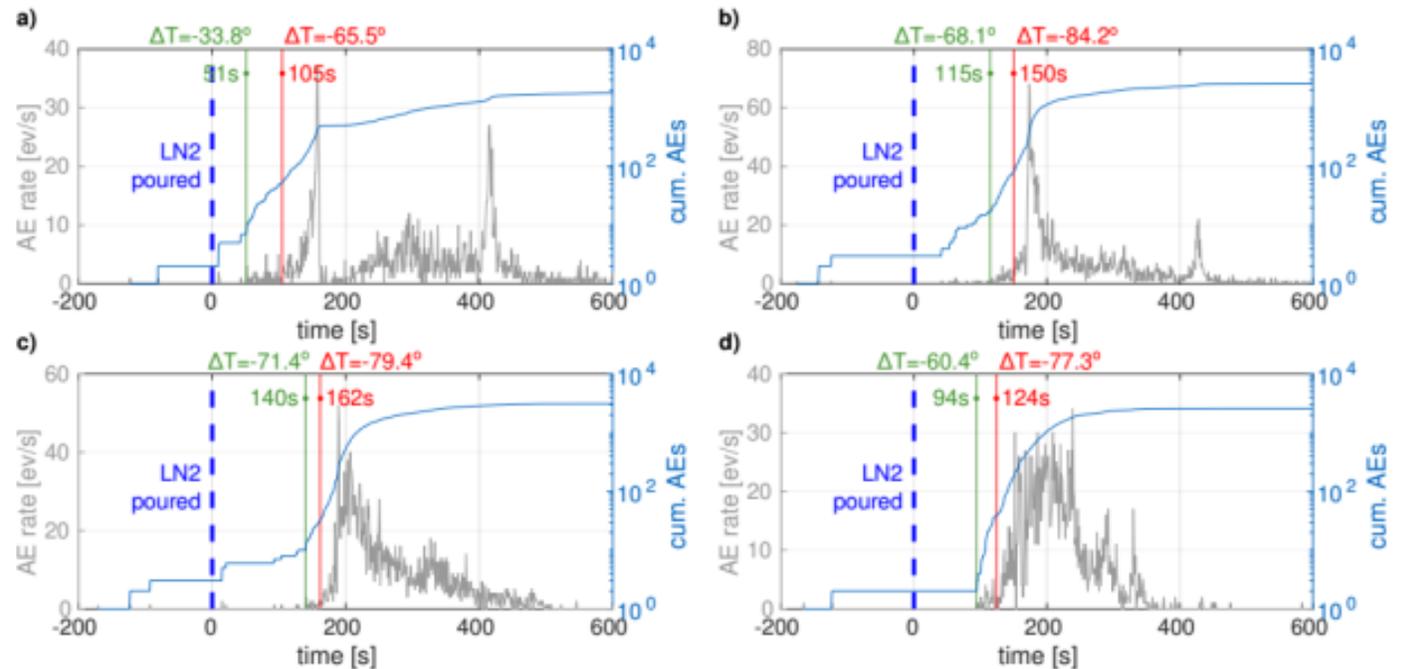
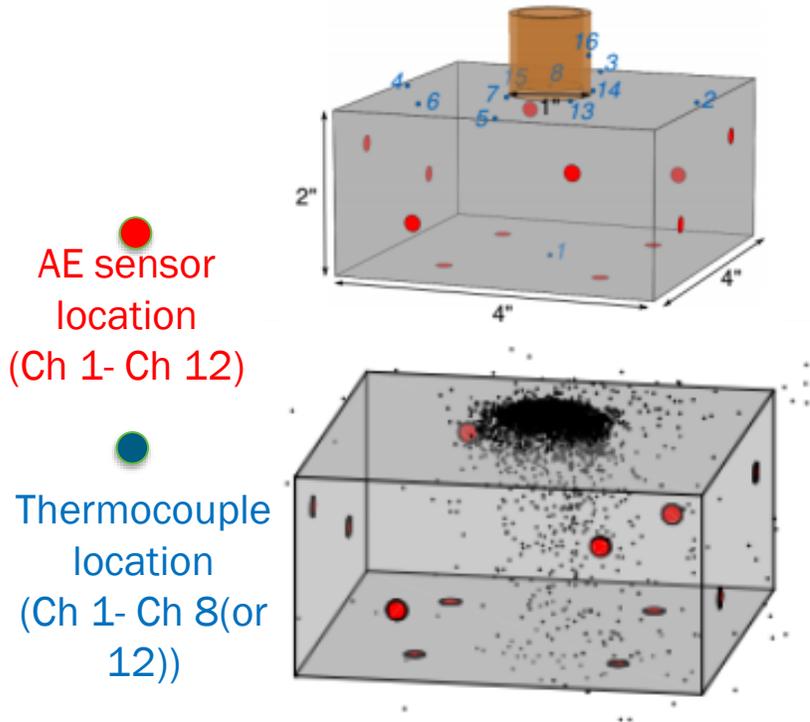


Small copper cup for localized cooling via LN

TEST B: Cooling tests on stressed samples (Lawrence-Berkeley National Laboratory)

Outcome:

- Best stress-cracking correlation indicator is the onset of AEs
- AEs onset is delayed with increasing compressive stress



Applied stress [MPa]:

- | | | | | | |
|----|-----------|-----------|----|------------|------------|
| a) | $S_x=2.8$ | $S_y=2.8$ | c) | $S_x=11.6$ | $S_y=11.6$ |
| b) | $S_x=5.6$ | $S_y=5.6$ | d) | $S_x=5.6$ | $S_y=11.6$ |

TEST C: Cooling tests on stressed samples with preexisting damage induced by heating (Lawrence-Berkeley National Laboratory)

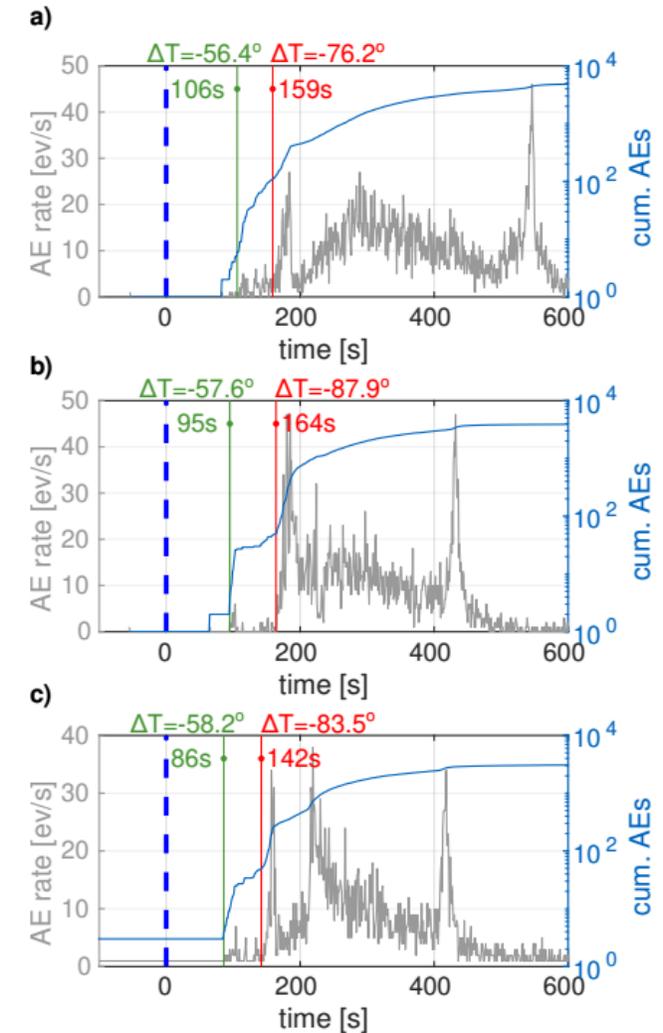
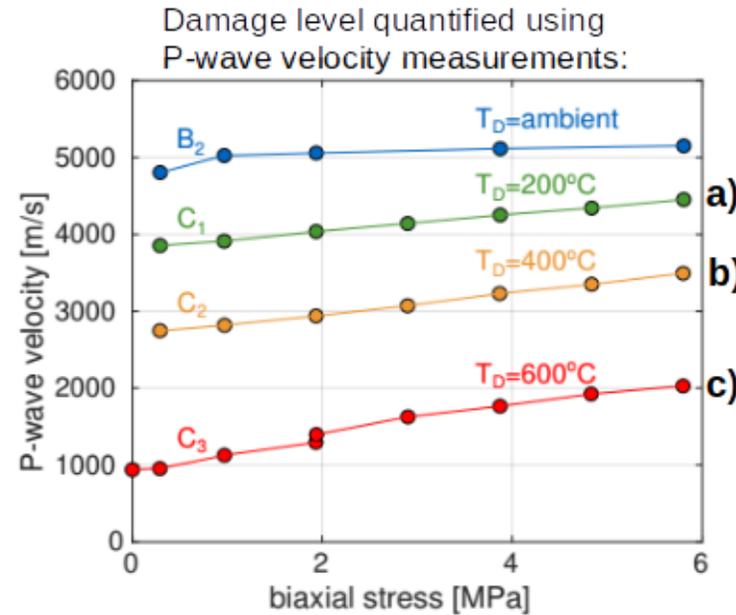
Objective:

- Examine the impact of preexisting microcrack damage in rock
- Analyze the influence of preexisting damage on observed AE signals

Outcome:

- Regardless of the damage level, the AE onset (green pick ==>) appears at similar temperatures

Heating-induced cracking was used to simulate different degrees of rock damage



TEST D: Unstressed cooling test in borehole (University of Wisconsin-Madison)

Objective:

- Examine the impact of realistic borehole geometry on cooling and AE generation
- Develop lab borehole cooling system

Outcome:

- Successfully produced A large number of events at the azimuth of the cooling pad

Liquid nitrogen cooling system



Cooling pad in the borehole:



Acoustic emission sensors to detect cooling induces failure:



Borehole cooling pad with thermocouples:



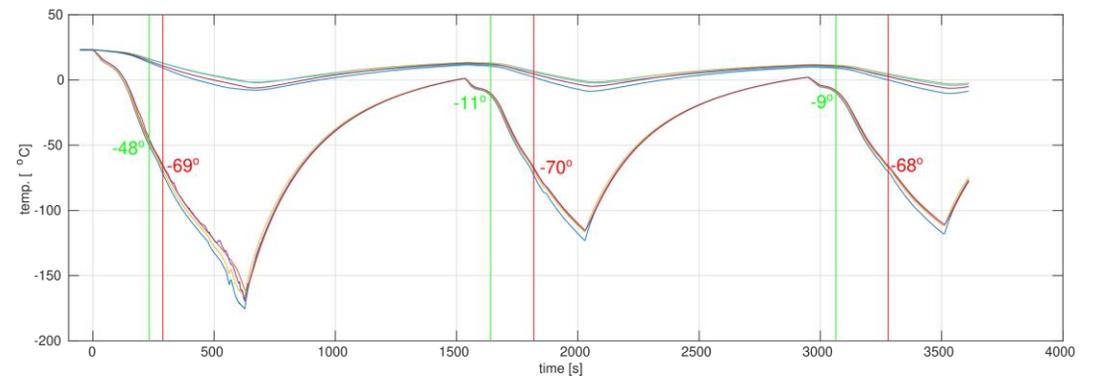
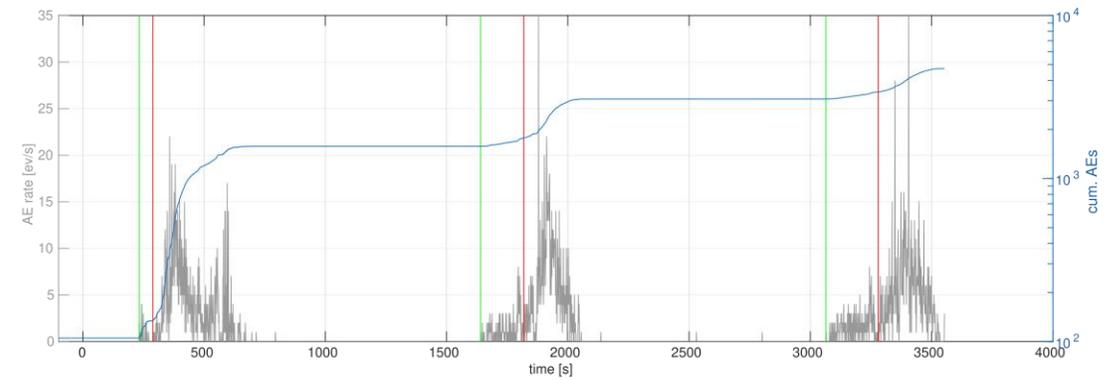
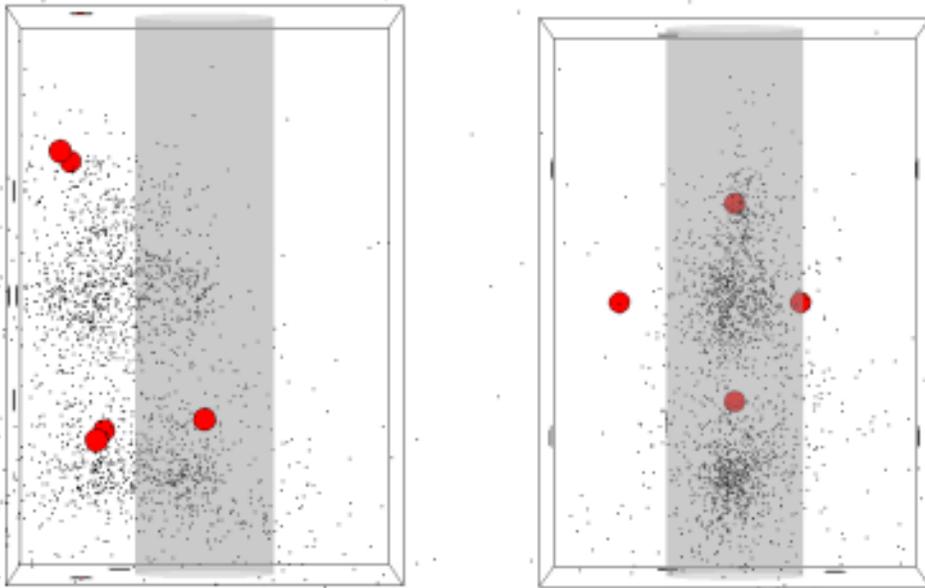
TEST D: Unstressed cooling test in borehole (University of Wisconsin-Madison)

Objective:

- Examine the impact of realistic borehole geometry on cooling and AE generation
- Develop lab borehole cooling system development

Outcome:

- Successfully produced a large number of events at the azimuth of the cooling pad



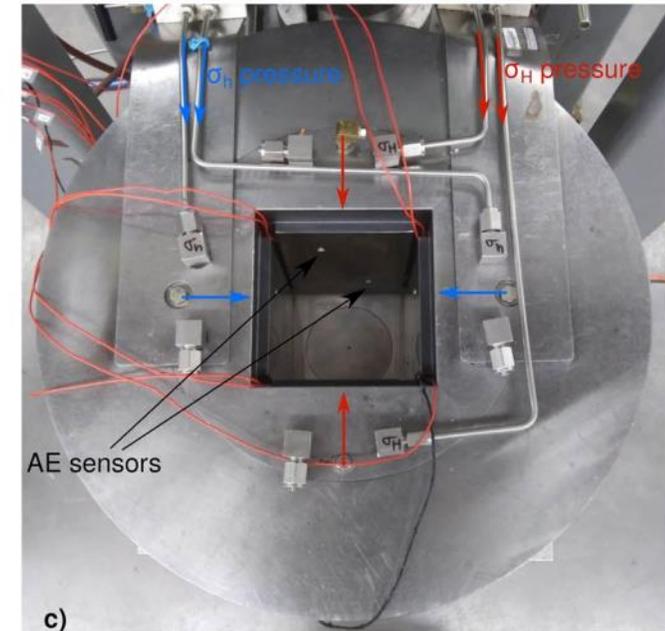
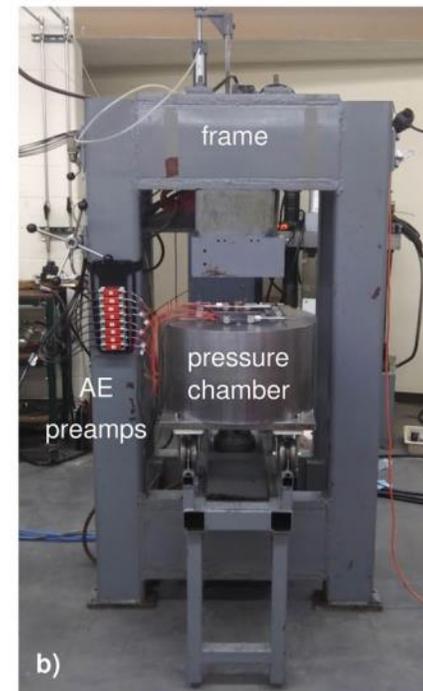
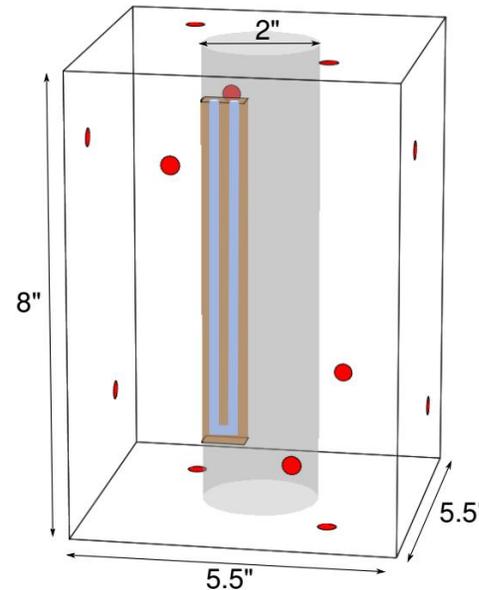
Planned cooling tests in true-triaxial apparatus in borehole geometry (University of Wisconsin-Madison)

Objective:

- Analyze hoop stress dependence of the onset of cooling induced fracturing

Outcome:

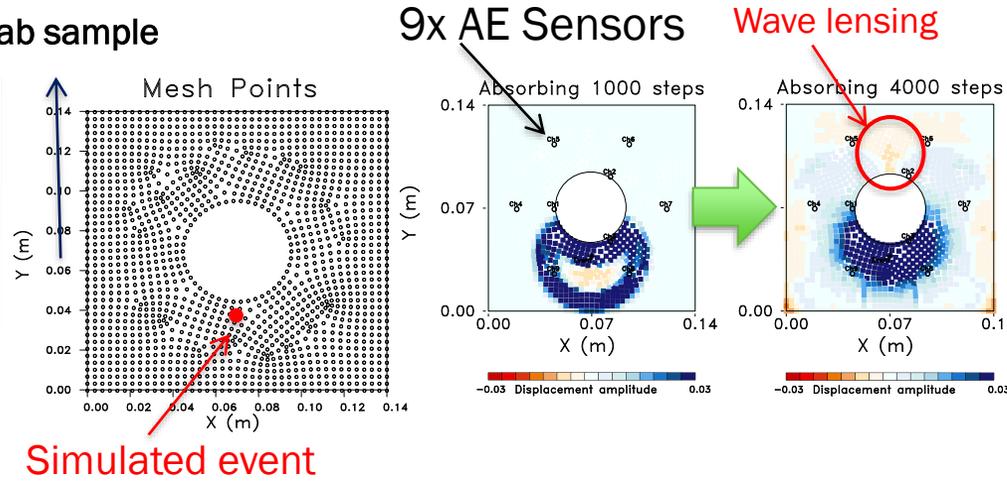
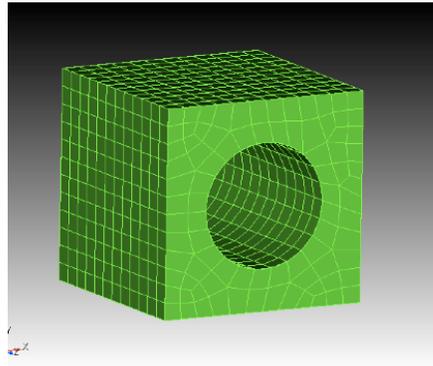
- Expected to observe azimuthal variation in temperature corresponding to onset of AEs



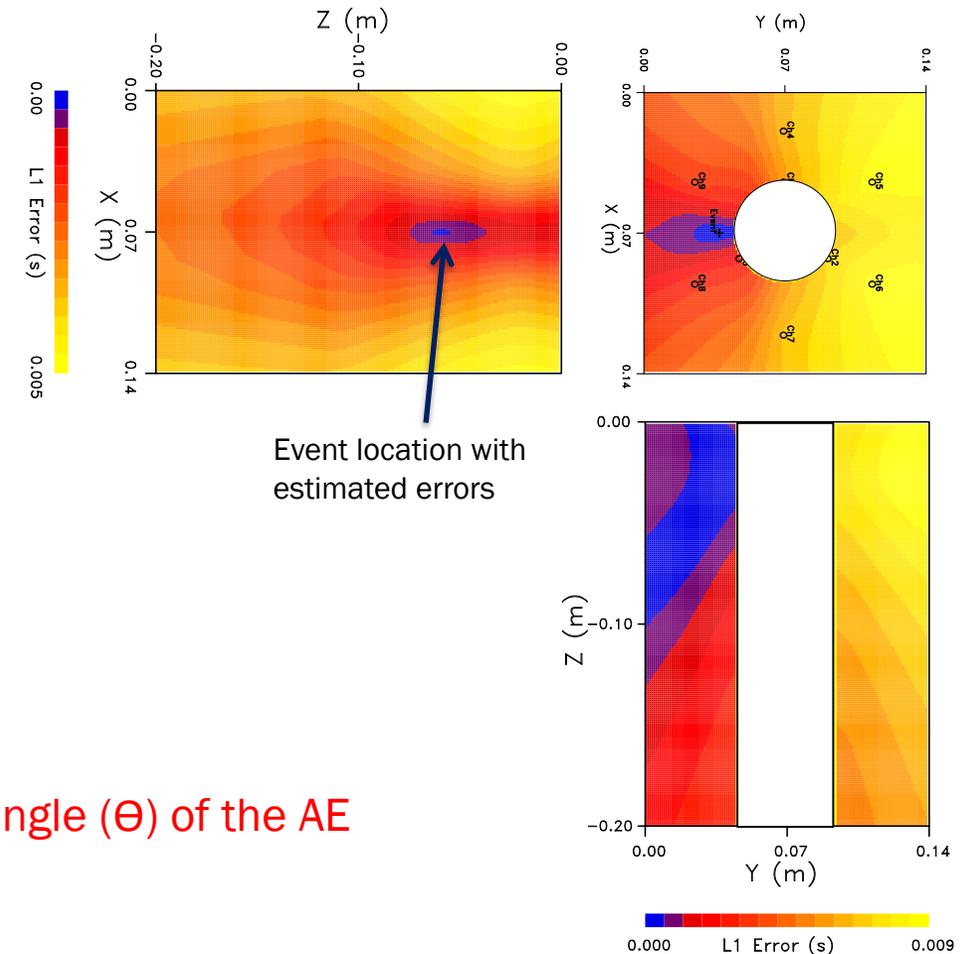
MODELING

AE/Wavefield Modeling: Unstressed cooling test in borehole (Lawrence Berkeley Laboratory)

FEM (SpecFEM) mesh of a lab sample



Location accuracy evaluation and sensor configuration optimization for laboratory samples



Objective:

- Examine the complex wavefield around a borehole
- Examine accuracy of AE event location
- Design sensor configuration for a field tool

Outcome:

- With a limited number of sensors (9), **the most important, azimuthal angle (θ) of the AE events can be determined with high accuracy**
- Radial (r) and axial direction (z) location accuracy is not very high

Prototype Field Tool Design: Downhole cooling tool (RESPEC)

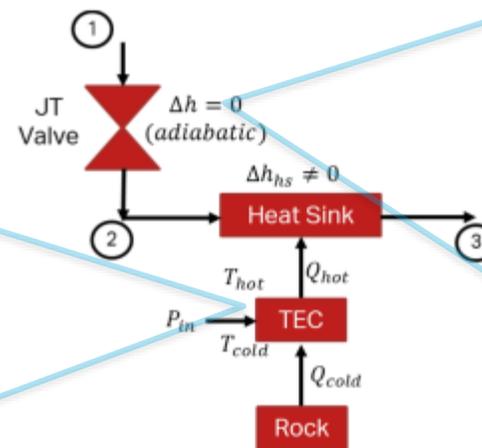
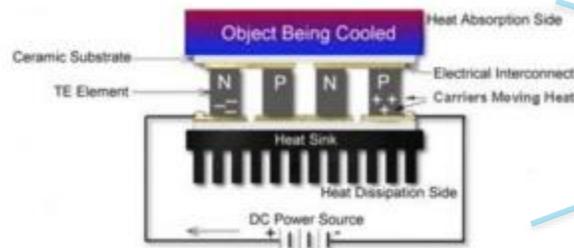
Objective:

- Examine feasibility of downhole cooling under geothermal reservoir environment
- Identify efficient cooling methods

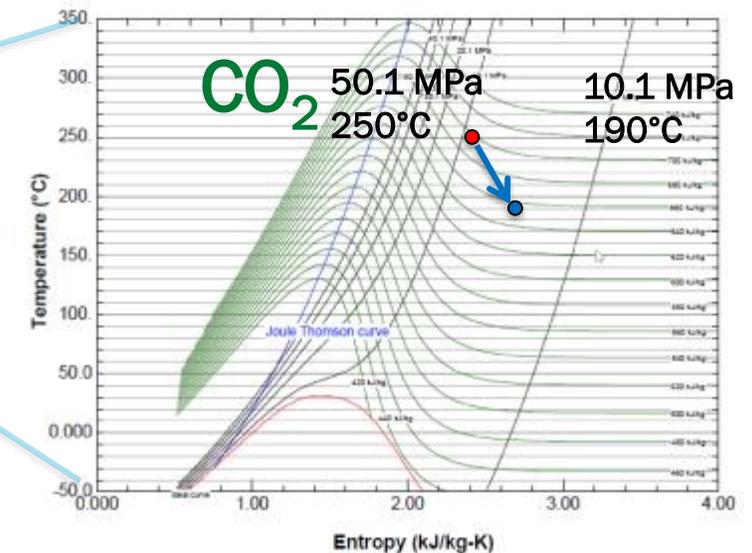
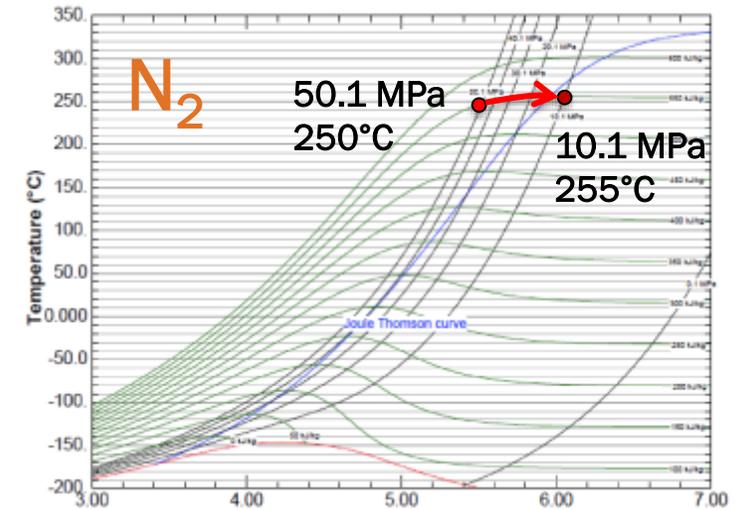
Outcome:

- N₂ Joule-Thompson effect not effective in the high P/T geothermal reservoir environment
- CO₂ however exhibits desirable cooling from its J-T behavior
- Thermoelectric (Peltier) cooling device can be used for rapid, and controlled cooling, in combination with J-T effect for removing waste heat

Conceptual downhole cooling device TEC + J-T



Isenthalpic (i.e., constant enthalpy) curves on a T-S diagram



- Most important technical accomplishments so far:
 - Confirmed that cooling will create acoustic emissions (AEs) that can be detected
 - Validated that the amount of cooling required to initiate AEs is qualitatively correlated to the stress state
 - Developed a feasible design for the cooling device based on off-the-shelf components
 - Verified that the directional cooling induced fracturing method can achieve reasonably accurate measurements of the stress state based on statistical modeling
- These accomplishments are aligned with the overall expected progress and outcome for the project
- The most important technical challenge so far is the development of an appropriate criterion to correlate the onset of acoustic emission to the far field stress state, which impacts our ability to measure the in situ stress. The project team plans to perform a combination of characterization laboratory tests and numerical modeling to define an acoustic emission criterion.
- **Although not complete yet, the accomplishments so far suggest a notable improvement to the current state of the art for geothermal in situ stress measurements, especially considering the potential to measure the full stress tensor with a single technology.**

Technical Accomplishments and Progress

Related Task(s)	Milestone Number	Milestone Title	Planned Completion Date	Revised Completion Date	Progress
1.1	1.1	Laboratory testing provides statistically viable rock properties that will improve our understanding of the planned DCIF development and experiments	04/30/2021	4/30/2022	Work in Progress
1.2	1.2	Complete at least three experiments to show a quantifiable correlation between the cooling front propagation and AE measurements of thermal fracturing.	10/31/2020	N/A	Complete
1.3	1.3	Complete biaxial stress experiments to confirm that directional-cooling-induced fractures can be created for a range of realistic stress states	04/30/2021	N/A	Complete
1.4	1.4	The small-scale cooling device is constructed and confirmed to meet the requirements of the polyaxial experiments	07/31/2021	11/30/2021	Complete
1.5	1.5	The statistical modeling suggests that the DCIF concept can measure the stress state to within an accuracy of approximately ± 25 percent based on reasonable geothermal reservoir input parameters	01/31/2021	N/A	Complete
2.0	2.0	Validate the conceptual tool design outcome to confirm the eventual DCIF tool construction can leverage existing technology or be adapted to the DCIF concept. A successful tool design will show no fatal flaws that would prohibit the construction of DCIF tool.	01/31/2021	N/A	Complete
2.1	2.1	Tool design is feasible, constructible, and has the greatest potential for successful deployment	07/31/2021	5/31/2022	Work in Progress
Budget Period 1 Go / No-Go		The initial analysis and laboratory testing successfully provide a proof-of-concept that local cooling can induce tensile fracturing on a borehole, which can be quantified and correlated to the local stress state	07/31/2021	N/A	Complete

Related Task(s)	Milestone Number	Milestone Title	Planned Completion Date	Revised Completion Date	Progress
3.0	3.0	Make a quantitative assessment of the impact of drilling-induced damage on the application of DCIF.	10/31/2021	12/31/2021	Complete
3.1	3.1	The cooling device, measurement sensors, and AE system function successfully in the polyaxial test machine.	10/31/2021	12/31/2021	Complete
3.2	3.2	The polyaxial testing provides conclusive evidence that cooling-induced fractures correlate to the stress state in a laboratory environment.	07/31/2022	N/A	Work in Progress
3.3	3.3	The thermal-mechanical modeling results accurately quantify the cooling-induced thermal stress as confirmed with the polyaxial testing measurements.	07/31/2022	N/A	Not Started
3.4	3.4	Forwarding modeling of the AE response confirms that the onset and location of cooling-induced fractures can be detected. An optimum AE sensor array is defined.	01/31/2022	N/A	Complete
3.5	3.5.1	The prototype tool is successfully constructed with off-the-shelf components and existing technology.	04/30/2022	N/A	Not Started
3.5	3.5.2	Initial benchtop testing of the prototype tool confirms appropriate functionality for the required DCIF testing.	07/31/2022	N/A	Not Started
Budget Period 2 Go / No-Go		Polyaxial testing, AE measurements, and thermo-mechanical modeling confirm the ability to create cooling-induced fractures that correlate to the stress state. A prototype tool is constructed that meets the functional requirements for the large-block-scale that is planned in later tasks	07/31/2022	N/A	Work in Progress

Technology Advancement

- So far, the project has advanced our understanding of cooling induced fractures and how they might correlate to the in situ stress state in geothermal reservoir.
 - Currently, the technology is approaching a TRL of 3
 - At the project conclusion, we fully expect to be at a TRL of 4

Data Dissemination

- The numerical modeling results were summarized and presented in a conference paper submitted to the 2021 US Rock Mechanics Symposium/ARMA meeting.
- The experimental results so far have been summarized in a conference paper submitted to 2022 US Rock Mechanics Symposium/ARMA meeting.
- Presented our research to the [Eavor](#) geothermal researchers and developers
- The team has presented and discussed multiple project updates with the GTO-funded EGS Collab team. The team members share lessons-learned with another DOE-funded project for in situ stress measurements (DE-FE0031688)
- The key laboratory experimental results have been uploaded to the GDR.

Research so far has identified needs for further research and development for

Robust AE/AE-onset based rock failure criteria

Actions Being Taken:

- (1) Detailed analysis of the experimental data obtained so far
- (2) Interpretation of the experimental AE location vs. prediction of the heterogeneous stress state predicted by the thermoelastic stress analysis
- (3) Use of NN (neural network)/ML (machine learning) to find quantitative correlations

Effective cooling and temperature measurement methods for a downhole prototype tool (Non-liquid-nitrogen cooling)

Actions Being Taken:

- (1) Hybrid design (gas throttling/Joule-Thompson effect based cooling + thermoelectric cooling mechanisms) is considered
- (2) Improvement of thermal coupling between a cooling pad and a borehole surface is being made during small, polyaxial block experiments

Milestones	Status and Expected Completion Date
FY2022 Milestones	
3.0 Study on the impact of drilling-induced damage	Completed. Has been reported.
3.1 Verification of thermal diffusion and calibration of lab AE system	Completed. Has been reported.
3.4 Forward modeling and AE analysis/ system proof of concept	Completed. The results will be included in FY2022 Q2 report
3.2 Polyaxial testing to determine DCIF correlation to stress state	In progress (July 2022 Completion)
3.3 Thermal-mech. modeling of experimental DCIF process	In progress. Close to completion (July 2022 Completion)
3.5.1 Prototype tool development and testing: Completion of tool fabrication	In progress. Completion may be delayed (May 2022 Completion)
3.5.2 Prototype tool development and testing: Initial benchtop testing	Has not started yet (July 2022 Completion)
FY2023 Milestones	
4.0 Large block scale load frame preparation	Has not started yet (October 2022 Completion)
4.1 Supplementary confirmatory modeling	Has not started yet (July 2023 Completion)
4.2 Interpretation of AE signals in large block scale experiments	Has not started yet (April 2023 Completion)
4.3 Large test block and AE system evaluation	Has not started yet (January 2023 Completion)
4.4 Large block scale test Phase 2, block test under uniaxial stress	Has not started yet (July 2023 Completion)

- Local cooling of a rock surface induced cracking which can be detected and quantified via AE
- The promising cracking indicator which can be related to the stress is the onset of AE (rather than catastrophic tensile fracturing)
- Microcrack damage existing in rock does not seem to impact AE onset, compared to the stress effect

- **No major red flags have been identified with the proposed technology and its potential application to measuring the in situ stress for geothermal reservoirs.**

Thank You