Stimulation and Flow Tests in Deep Crystalline Rock – The EGS Collab Project

Tim Kneafsey and the EGS Collab team*

This project is supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office (GTO) under Contract No. DEAC02-05CH11231 with Lawrence Berkeley National Laboratory.

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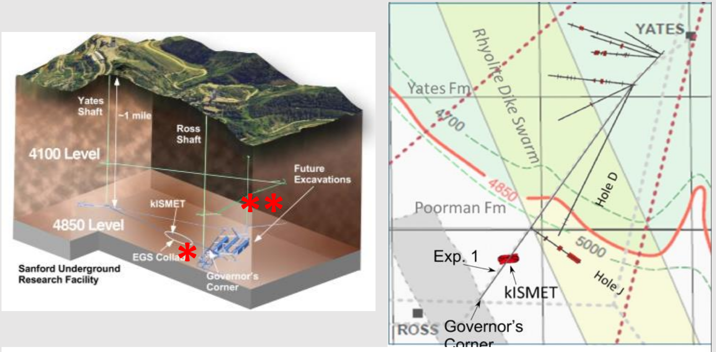
Motivations and philosophy

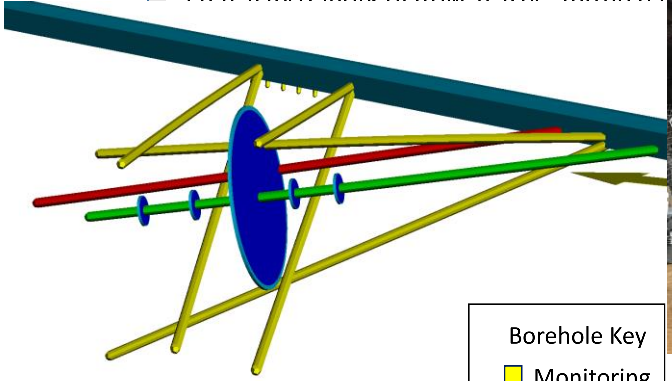
- Bridge the vast scale gap between lab experiments and field-scale application.
- **Validate EGS codes** in a relevant environment.
- Key strategic choices:
  - EGS-relevant stress state (~1500 m depth)
  - Temperature friendly to operation and measurement. (~35°C)
    - Compensated by circulating chilled water
  - Heavy investment in characterization and monitoring.
  - A collaborative research community.

EGS Collab Experiments: Three phases

- **Experiment 1**, intended to investigate **hydraulic fracturing***, at the Sanford Underground Research Facility (SURF) at 1.5 km. depth.
- **Experiment 2** is being designed to investigate **shear stimulation*** at 1.25 km depth.
- **Experiment 3** will investigate changes in fracturing strategies and will be further specified as the project proceeds.

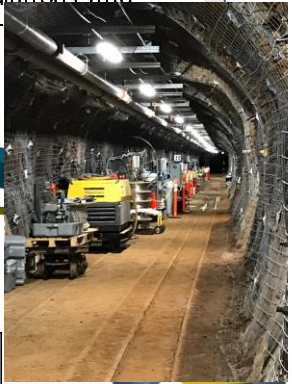


Each experiment consists of multiple stimulations and characterizations of flow, tracer, and heat t

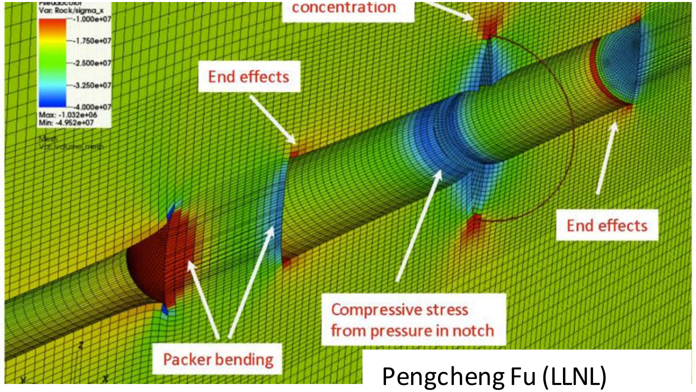


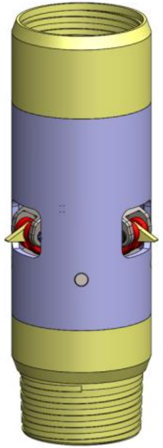
Conceptual design

Borehole Key
- Monitoring
- Stimulation
- Production



Modeling in support of experiment design





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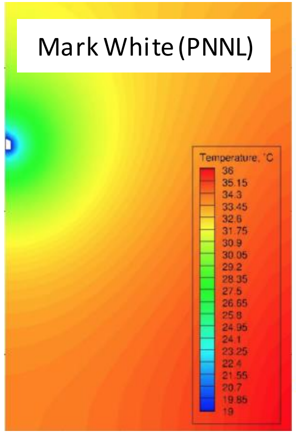
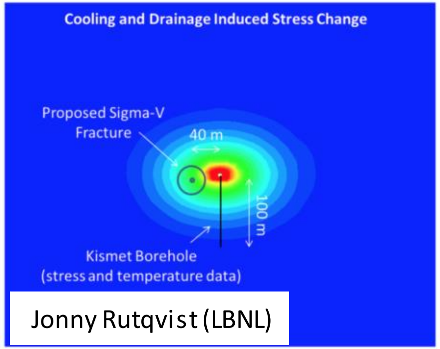
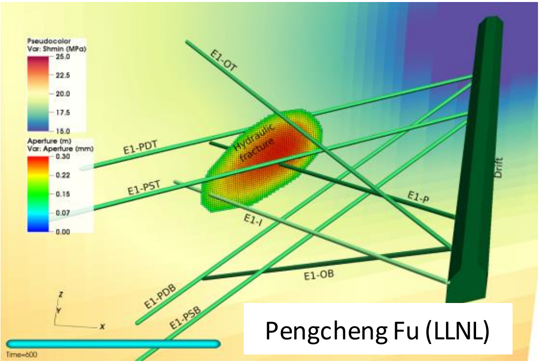






Testbed Characterization

Borehole

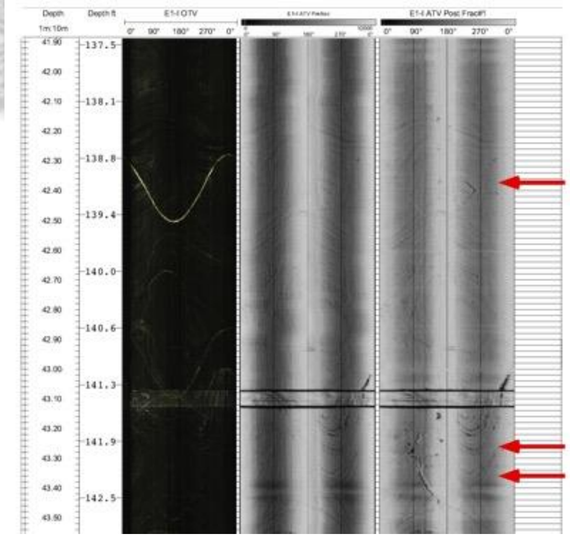
- Optical and acoustic televiewer
- Full waveform seismic
- Electromagnetic
- Gamma
- Temperature
- Fluid conductivity

Test “block”

- P- and S-wave characterization using mobile and grouted borehole sensors, grouted and mobile sources
- Extended hydrologic characterizations
- Electrical Resistance Tomography (ERT), baseline and flow

Core

- Lithologies, fractures, and veins
- X-ray CT, magnetic susceptibility, gamma density, p-wave velocity, Ca/Si, Ca/Al, Si/Al, and Fe/S ratios, light elements, Ca, and Si abundance



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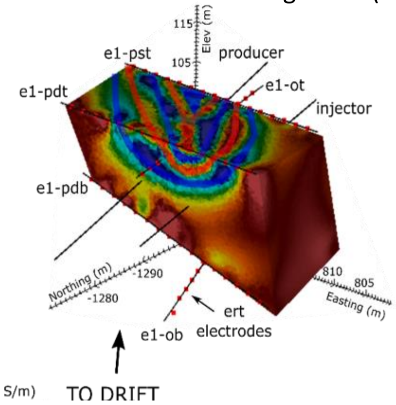

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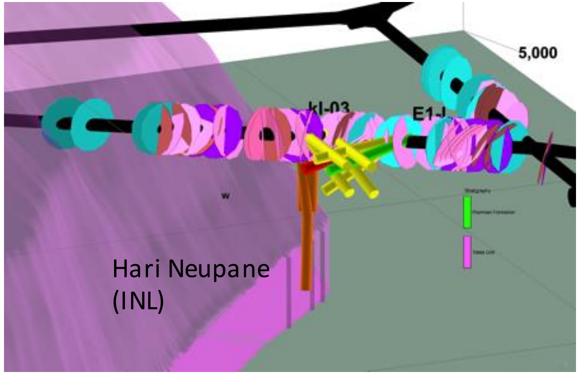
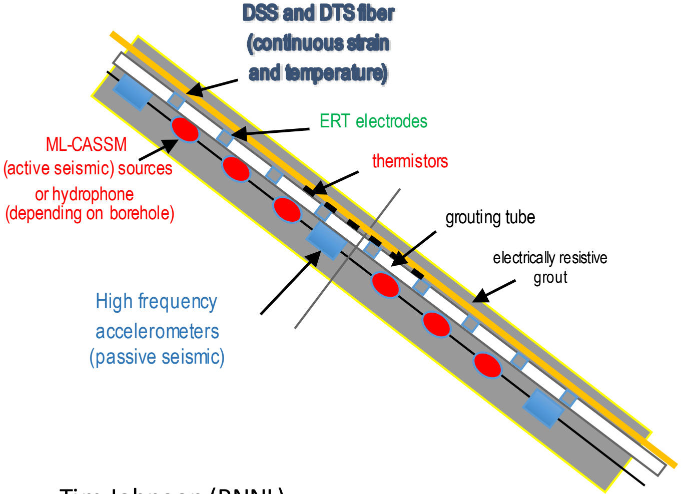


Hari Neupane (INL)

Monitoring systems for stimulation and flow

- Acoustic emissions (AE)
- Continuous Active-Source Seismic Monitoring (CASSM)*
- MicroEarthquake (MEQ)*
- Electrical Resistance Tomography (ERT)
- Temperature by distributed temperature sensing (DTS), thermistors
- Strain by distributed strain sensing (DSS)
- Direct 3-D fracture displacement using SIMFIP at injection and production boreholes

Fracture Perpendicular Configuration



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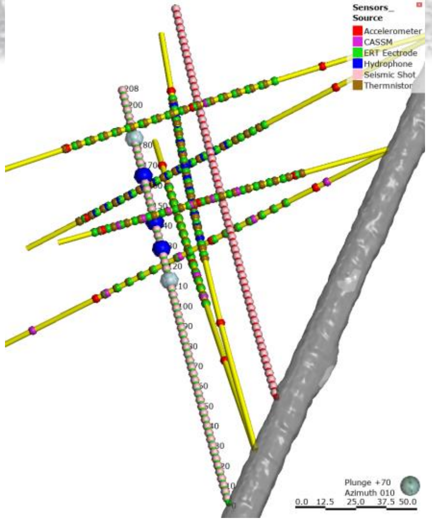
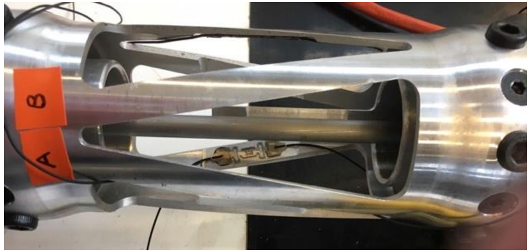


(Neupane et al., GRC, 2019)



Step-rate Injection Method for Fracture In-situ Properties

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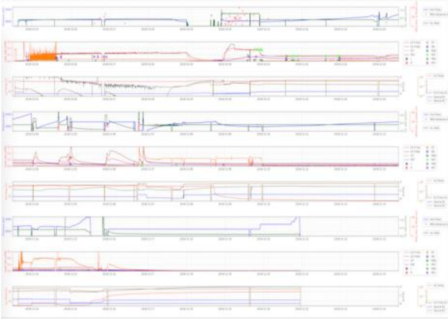
Major experiments/tests performed as part of Exp. 1

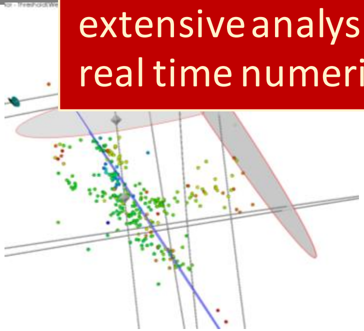
May to July, 2018: Stimulations of three intervals; established hydraulic connection between wells.

Oct. to Nov., 2018: One month of cont. circulation; 90+% recovery for 4 days; revealed chemical/bio-

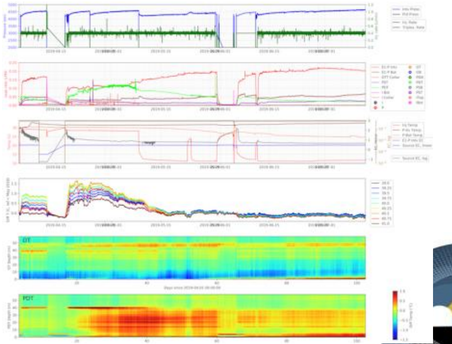


All subjected to continuous geophysical monitoring and extensive analysis aided by near-real time numerical modeling.

Dec. 2018: Further stimulation of the 142 ft interval. Stimulated a large natural fracture system and new hydraulic fractures



Feb. 2019 to present: Long-term circulation, tracer tests, thermal tests.



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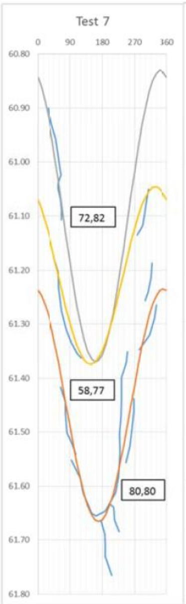
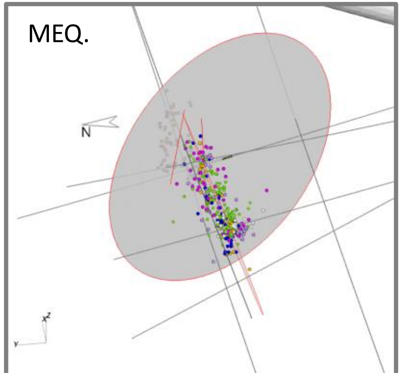
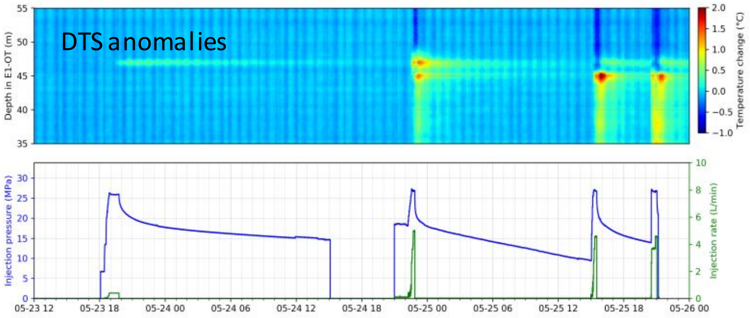
Multiple types of data corroborate each other

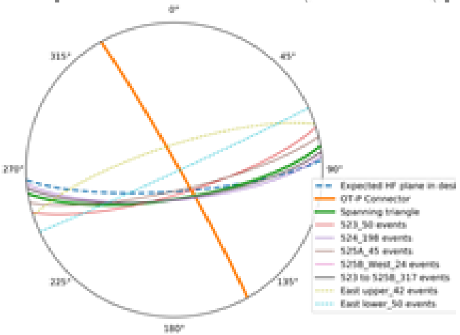
- e.g., to discern the nature of the fracture(s) stimulated in May 2018 and constrain the orientation, we had:

kISMET fracture orientation



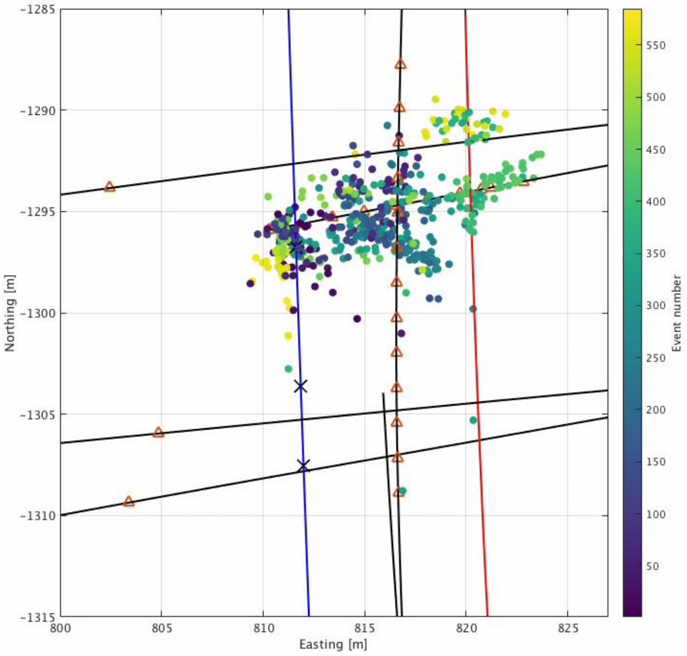




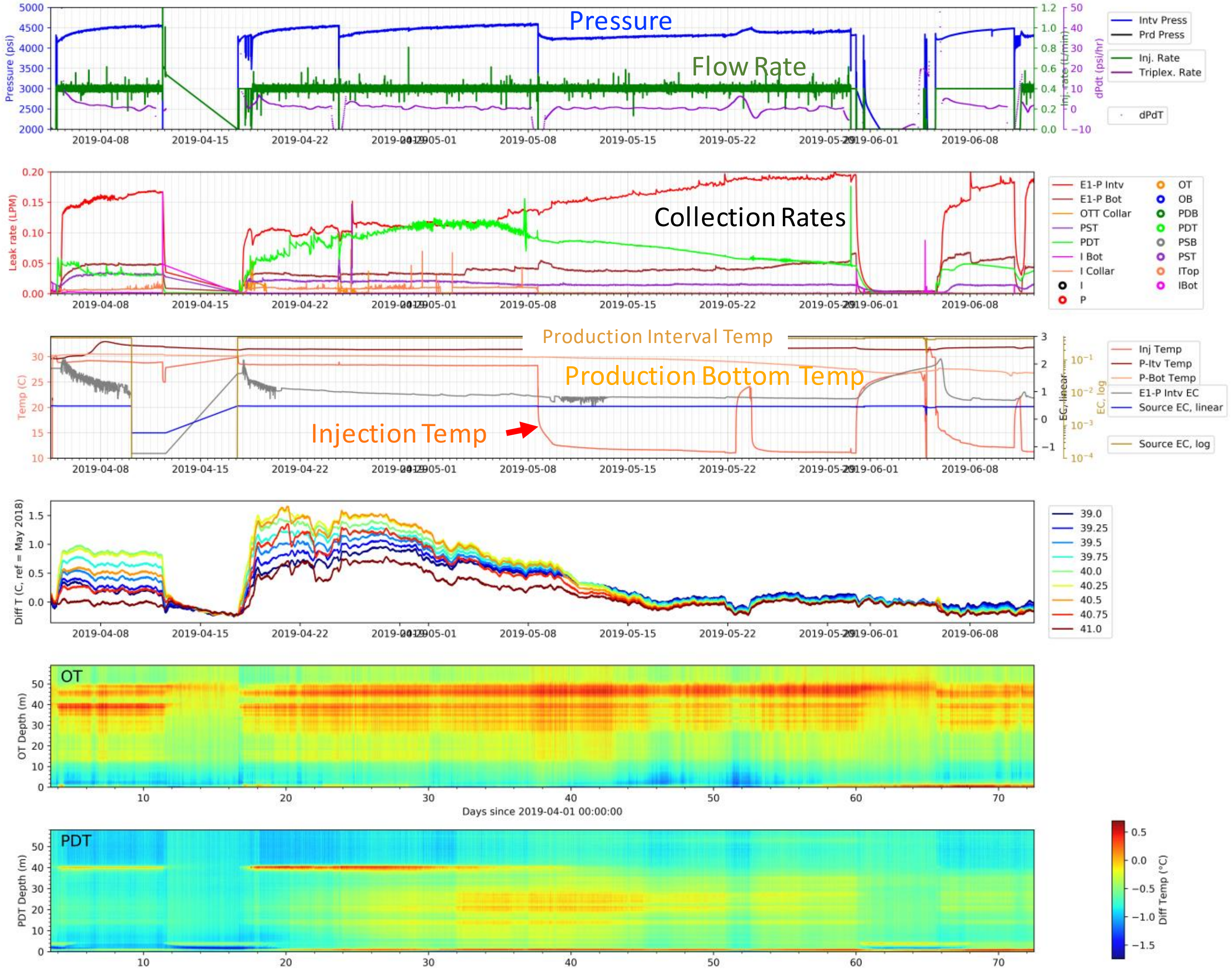


Stimulation and flow tests – Notch 2

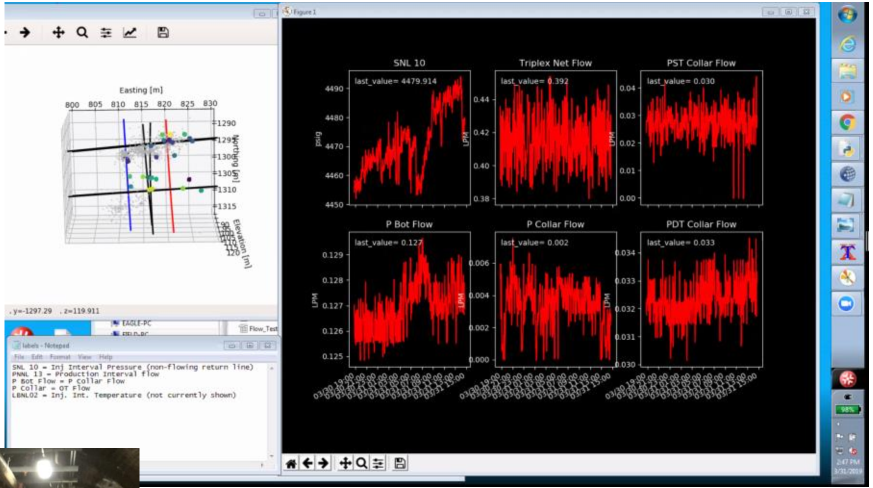
- One-sided fracture growing towards E1-P & E1-OT
- Main fracture orientation consistent with hydraulic fracture | | S_{HMax}
- Fracture growth direction changes from upward, to downward, to detached structures



Cold Water Injection April 2019 – June 2019

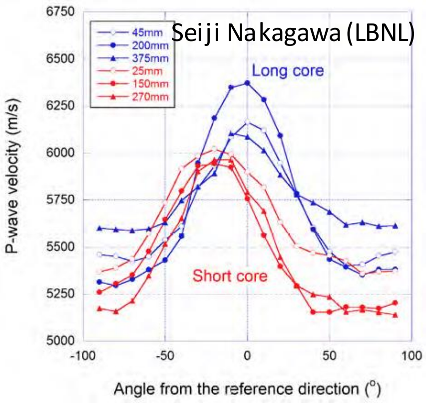


Engaging a large community of researchers in near-real time



Extensive laboratory testing

- Seismic anisotropy
- Anisotropic thermal conductivity
- Elastic constants
- Fracture toughness
- Microbiology
- High-Temperature flow/geochemistry
- Triaxial direct shear test
- True triaxial and triaxial injection
- …



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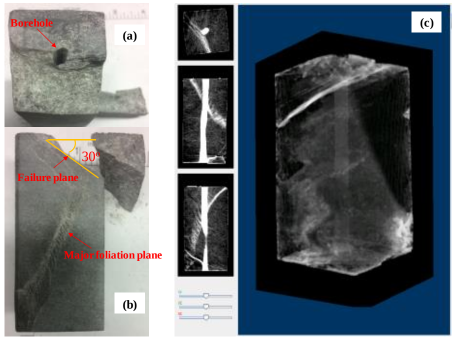

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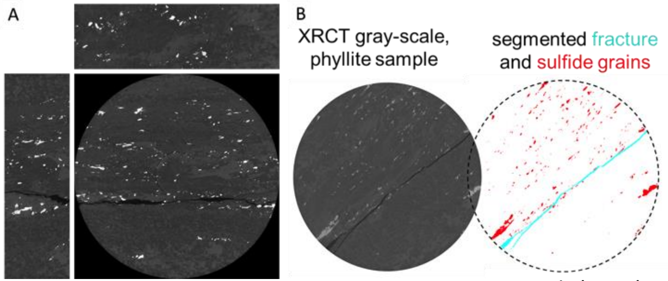

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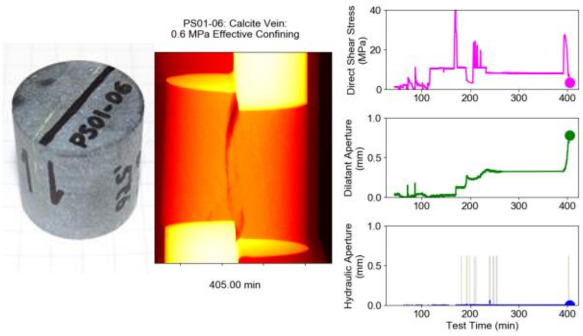

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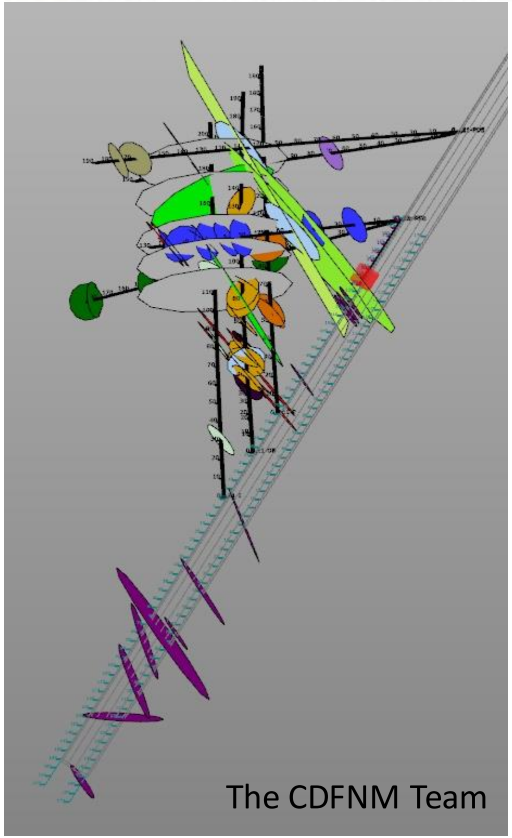
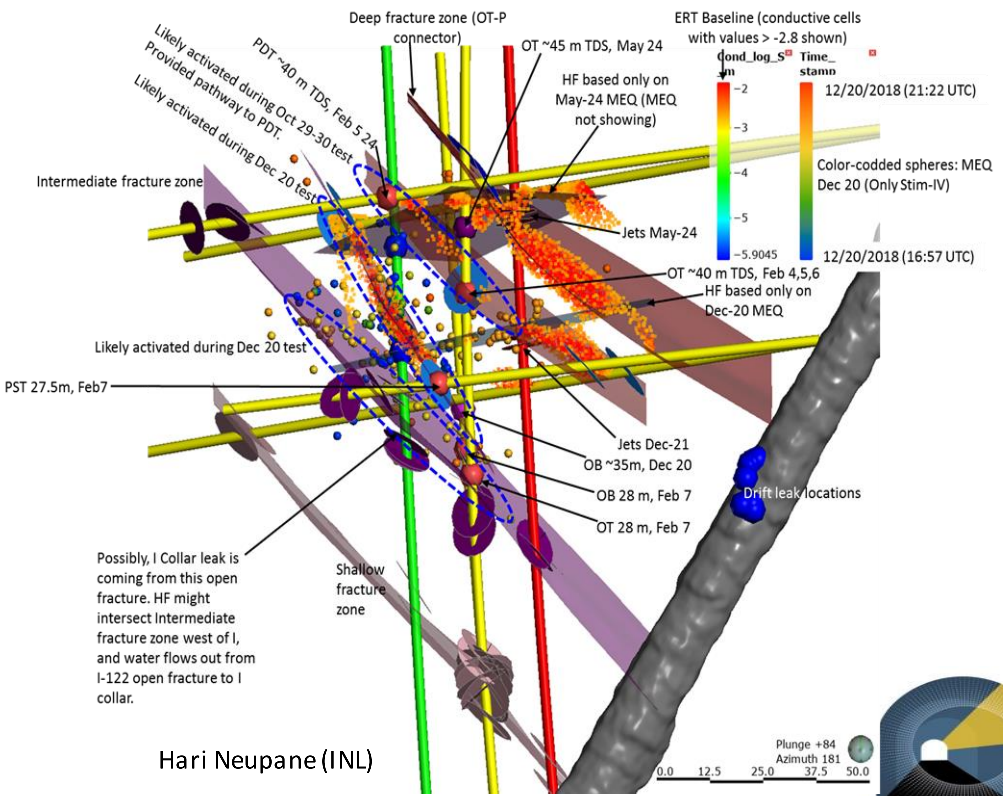
High-fidelity characteristics/behaviors of rock-fracture-fluid system





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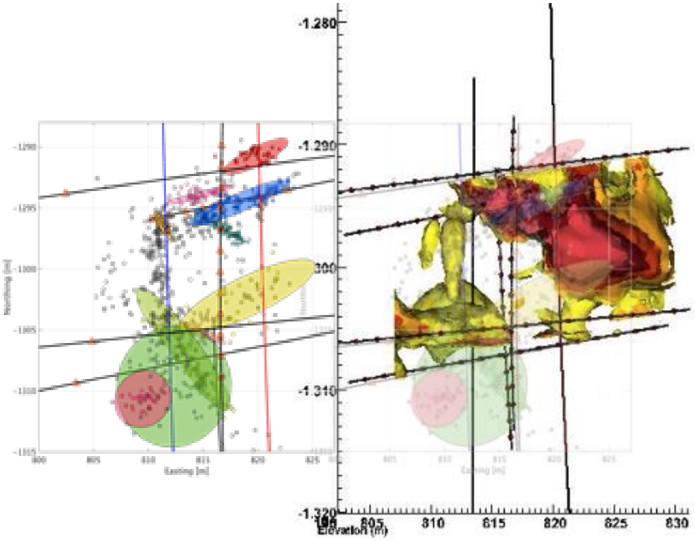
Partial list of successes

- Excellent characterization data
- Modeling studies to predict/analyze tests/occurrences
- MEQ/ERT; MEQ/CASSM/DTS; MEQ/DAS comparisons
- Predicted/actual fracture behavior/direction in thermally induced stress gradient
- Fracture opening and shear (SIMFIP)
- Analysis/stress testing of multiple test beds
- System evaluation by tracer/thermal tests
- Observation of fracture intersecting production well
- Data handling
- Team of scientists collaborating from many remote locations to modify experimental parameters in *real time* to stimulate rock 1.5 km below ground.
- Identification of negative Joule-Thomson coefficients as being a factor in assessing thermal breakthrough signatures.



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EGS Collab High-Level Lessons Learned

- Design-in flexibility to the extent possible. Seek open feedback.
- Shake down/test equipment, sensors, and methods under appropriate conditions prior to installation
  - Primary systems shaken down but some supporting infrastructure (e.g., grouting of instrument holes) would have benefitted from preliminary testing
- Openly analyze **all** characterization data, make available to all ASAP
  - Amount of data collected during experimental operations can be overwhelming – development of robust workflows to review all the data is vital
- Model responses of geophysical tools (microseismic, CASSM, and ERT) to optimize sensor placement locations prior to deployment.
  - Modeling was performed but in hindsight could have been used better to weigh optimization of sensor emplacement against impact on experimental operation
- Continuously challenge conceptual models and submodels. Recall previously ignored processes.
  - What you expect may well not be what you get.