EARTH & ENVIRONMENTAL SCIENCES

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Intermediate-scale fracturing and induced seismicity in a deep mine

kISMET

Permeability (k) and Induced Seismicity Management for Energy Technologies

Stress measurement and fracture stimulation with borehole monitoring to characterize relations between stress, induced fractures, and rock fabric

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Participating Organizations

Sandia National Laboratories

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

BERKELEY LAB

Golder Associates

Pacific Northwest NATIONAL LABORATORY

INL Idaho National Laboratory

SOUTH DAKOTA SCHOOL OF MINES & TECHNOLOGY

Sanford Underground Research Facility

Los Alamos NATIONAL LABORATORY EST. 1943

Lawrence Livermore National Laboratory

Stanford University

FIRST Drilling

Participants in kISMET are from national labs, universities, and industry

Lawrence Berkeley National Laboratory:

Oldenburg, Dobson (PI's)
Wu, Daley, Ajo-Franklin, Guglielmi, Ulrich, Marchesini (monitoring)
Nakagawa, Kneafsey (laboratory measurements)
Cook, Siler (core logging and geology)
Rutqvist (modeling)

Partners:

Wang, Haimson, Sone, Vigilante, Lord (Univ. Wisc.)
Lee, Ingraham (SNL)
Doe (Golder)
Roggenthen (SDSMT)
T. Johnson (PNNL)
Huang, Zhou, Mattson (INL)
Heise, Vardiman, Pietzyk, et al. (SURF)
Zoback (Stanford)
P. Johnson, Coblentz (LANL)
Morris, White (LLNL)

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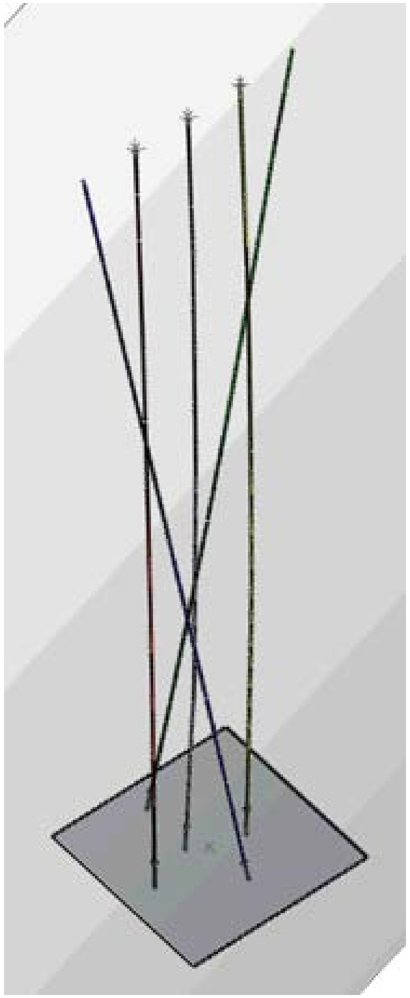
Outline

- **Benefits and Objectives**
- **Approach**
- **Accomplishments**
  - Site selection
  - Drilling and coring
  - Modeling and analysis
- **Next steps**
  - Stress testing
  - Stimulation
  - Borehole optical and acoustic logging
  - CASSM and ERT monitoring
- **Questions and discussion**



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kISMET Benefits

SubTER 2-yr goals:

- **Stress: Initial deployment of state-of-the-art stress measurement technologies at a dedicated field site**
- **Induced seismicity: Establish laboratory and meso-scale (1-10 m) experiments to investigate mechanics of fluid-induced fracture initiation and growth**

kISMET is located at a research facility in a deep former mine to:

- **Investigate relationship between induced fractures and stress, rock fabric, and stimulation approach to inform EGS stimulation**
- **Investigate microseismicity arising from fracturing as an analog for basement-rock induced seismicity underlying deep injection sites**
- **Establish kISMET experimental facility as a SubTER field test site**

Subsurface Control for a Safe and Effective Energy Future

Adaptive Control of Subsurface Fractures and Fluid Flow

Intelligent Wellbore Systems	Subsurface Stress & Induced Seismicity	Permeability Manipulation	New Subsurface Signals

Intermediate Scale Field Hydraulic Fracture Field Laboratory in a Deep Mine (LBNL)

Development of Novel 3D Acoustic Borehole Integrity Monitoring System (LANL)

Evaluating the State of Stress Away from the Borehole (LANL)

(In situ control of fracture toughness - submitted in FY14, SNL)

Borehole muon detector for 4D density tomography of subsurface reservoirs, geophysics, hydrology, geochemistry, and biochemistry (PNNL)

Ultrasonic Phased Arrays and Interactive Reflectivity Tomography for Nondestructive Inspection of Injection and Production Wells in Geothermal Energy Systems (ORNL, GTO)

Development of the microBayesloc Location Method (LLNL, GCS)

Imaging Fracture Networks Using Crosshole Seismic Logging and Advanced Change Detection Algorithms (SNL, GTO)

Big Data and Analytics for Induced Seismicity (NETL)

Photo-stimulated luminescence spectroscopy stress sensor for in-situ stress measurement (ORNL)

kISMET Approach

- Select a site at SURF to drill and core boreholes for fracture stimulation and monitoring
- Characterize the site
  - Lithology, rock fabric, structure, hydrology
- Instrument the boreholes and site surroundings to monitor fracturing and seismic response
- Carry out stress measurements and hydraulic fracturing in the center borehole while monitoring in the surrounding four boreholes
- Analyze seismic, ERT, and induced seismicity data to help characterize fracture(s)

Expected Outcomes

With characterized stress field, lithology, rock fabric, existing fractures, and a carefully controlled hydraulic fracture event with dense measurement and instrumentation, we can develop understanding of the factors that control fracture initiation and propagation, orientation, size, and aperture.

With careful monitoring of microseismicity, we can develop understanding of induced seismicity in rock very similar to deep basal units known to sustain induced seismic events.

With well-designed laboratory experiments on core from the sites, we can develop better understanding of how to do up-scaling from laboratory studies to the field.

kISMET Accomplishments

Site selection

Infrastructure development

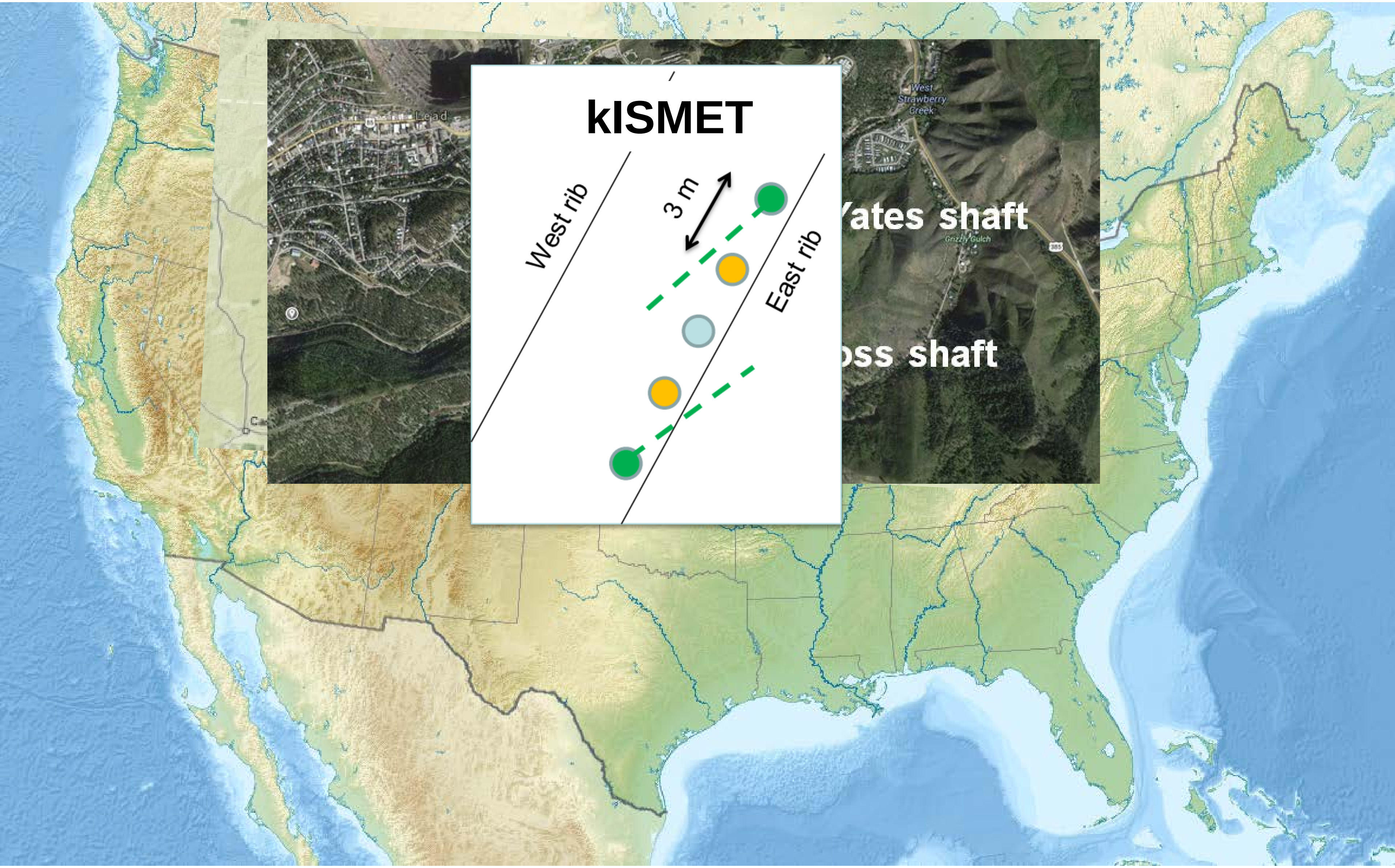
Subcontracts with UWisc, SDSMT, SURF, First Drilling, Professional Mapping and Surveying LLC

Safety documentation and training

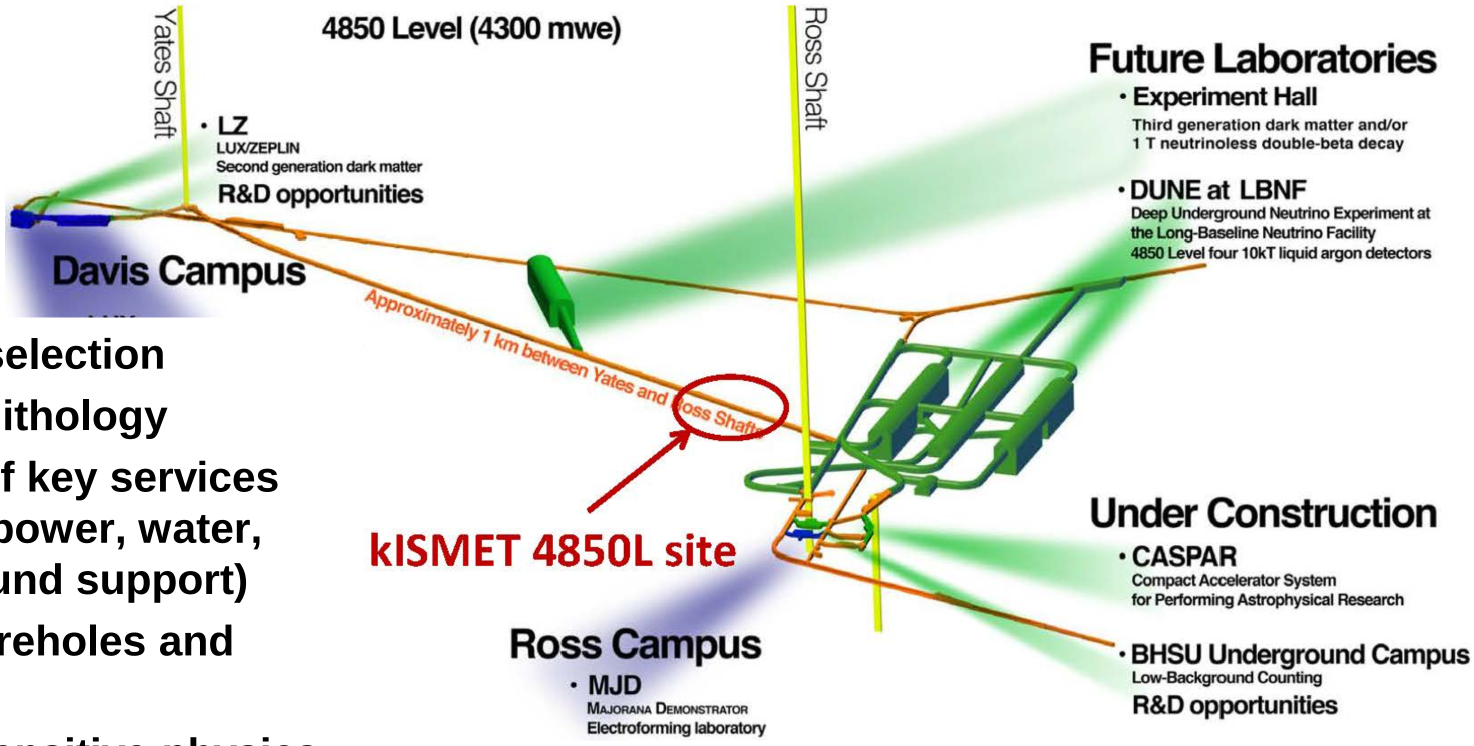
Drilling of five cored boreholes (four 50 m HQ holes, one 100 m NQ hole)

Gyro logging of boreholes and logging of core samples

Development of experimental plan for characterization, monitoring, stress measurements, and hydrofracture experiments


kISMET
West rib
East rib
3 m
Yates shaft
oss shaft
Lead
West Strawberry Creek

Selected kISMET site on 4850L



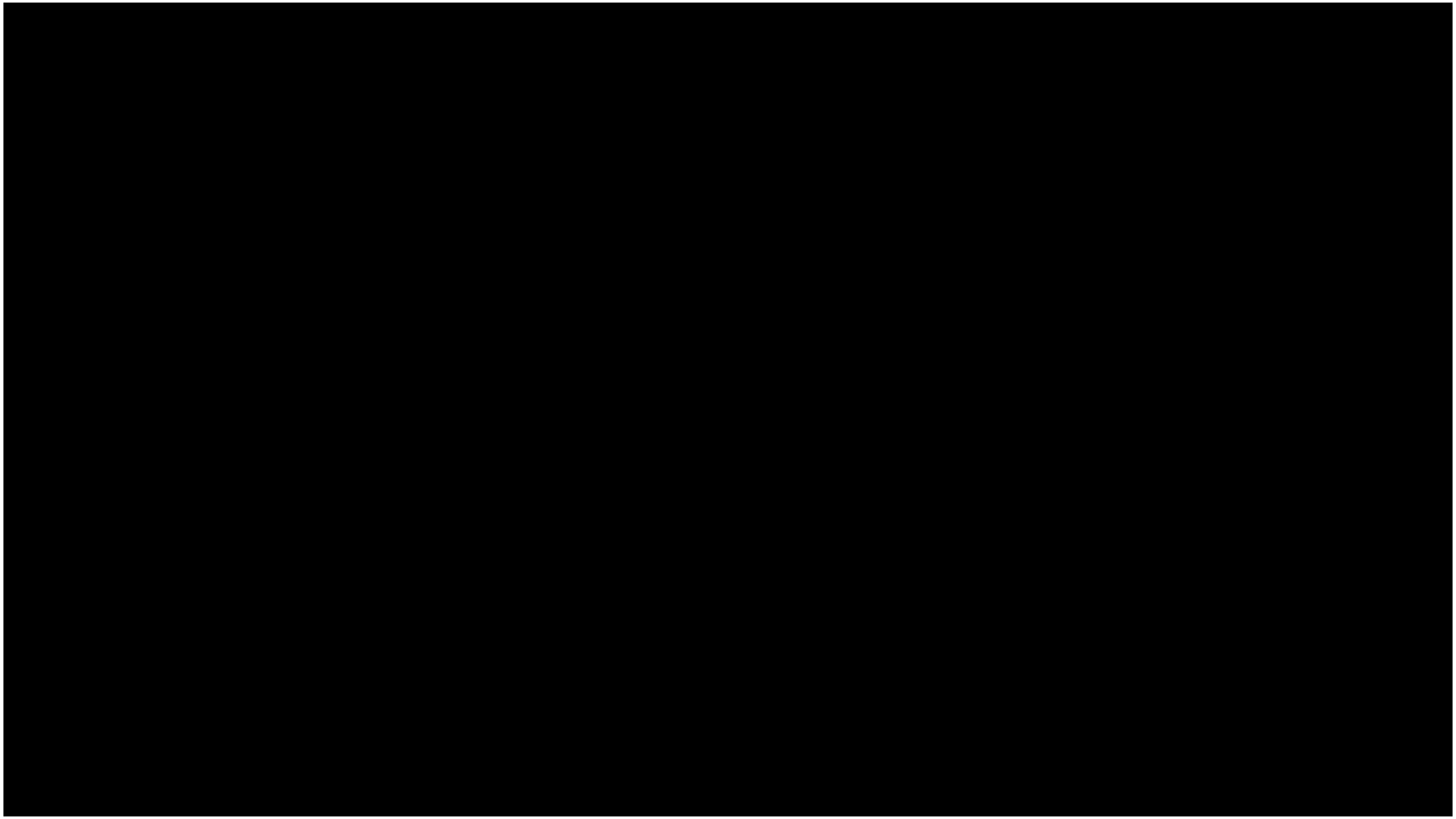
Oblique three-dimensional sketch of SURF showing the kISMET site with existing and proposed physics experiments.

Criteria for site selection

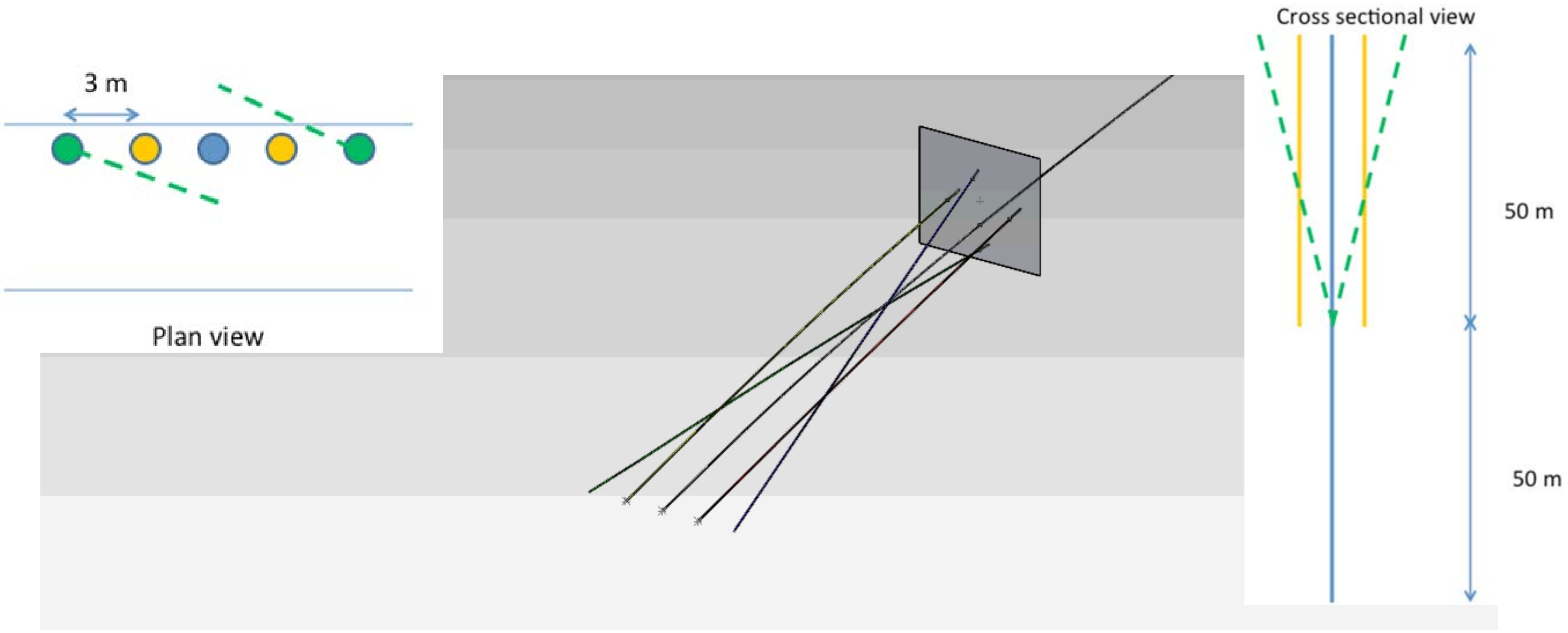
- **Appropriate lithology**
- **Availability of key services (ventilation, power, water, internet, ground support)**
- **Space for boreholes and equipment**
- **Away from sensitive physics experiments**
- **Minimum cost for site improvements**

Discussing drilling logistics at the kISMET site on 4/13/16

Video of Drilling and Coring



kISMET Borehole Layout



Key Activities – Drilling Phase

- Paul Cook, Bill Roggenthen & Drew Siler described and photographed core samples (100% recovery)
- Conducted gyro logs of boreholes for precise hole orientation
- Select core samples collected for CT scans

Paul Cook (LBNL) logging core at kISMET site on 6/21/16

KISMET Hydraulic Fracture Propagation and Induced Seismicity Modeling

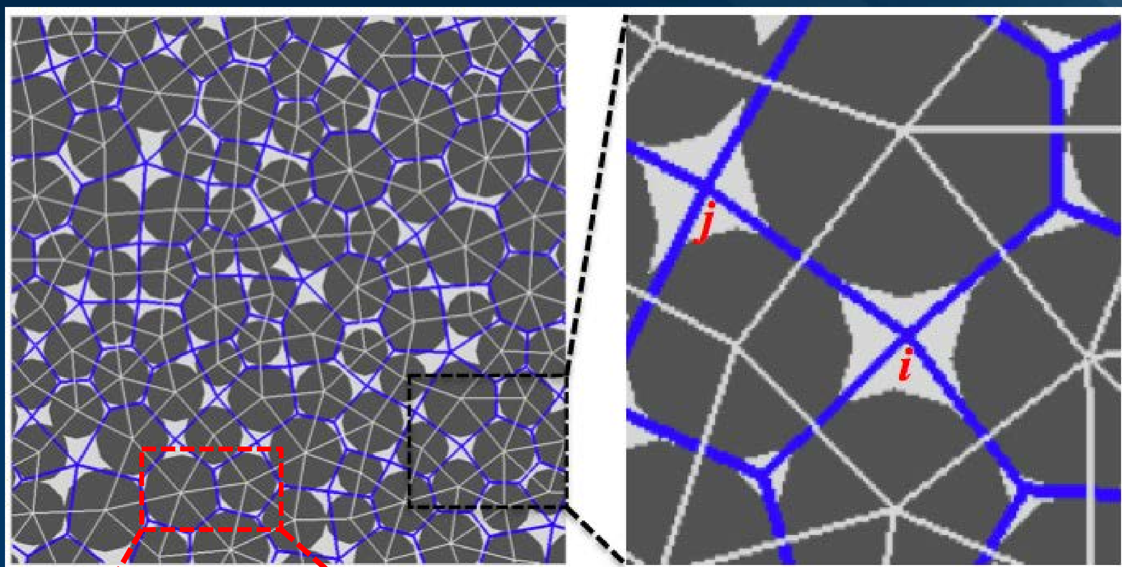
Team: Hai Huang, Jing Zhou and Earl Mattson

Objective: pre-test estimation of

- Breaking pressure;
- Fracture size;
- Induced seismicity magnitude

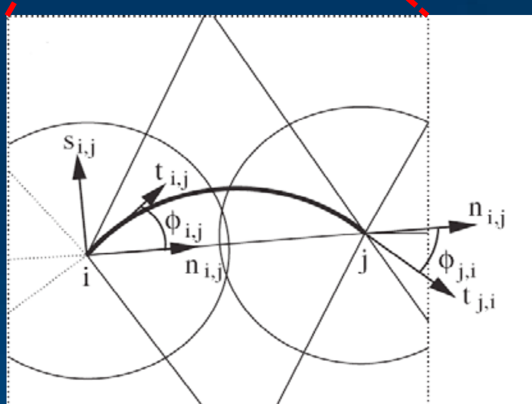
Dual Lattice Discrete Element Method

A Non-planar Fracture Simulator Fully Coupling Geomechanics and Flow



BLUE Lattice:
Flow network

WHITE lattice:
DEM network

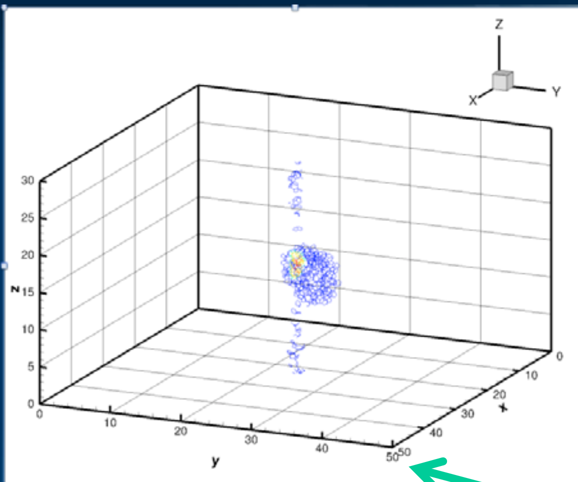


- **Rock is represented by network of mechanical elements**
  - *Connected via beams (elastic, viscoelastic etc.)*
  - *Local heterogeneity and anisotropy*
- **Beam breaking-relaxation:** force and moment balance
  - *fracture initiation & propagation*
  - *Elasticity, plasticity and visco-plastic-elasticity*

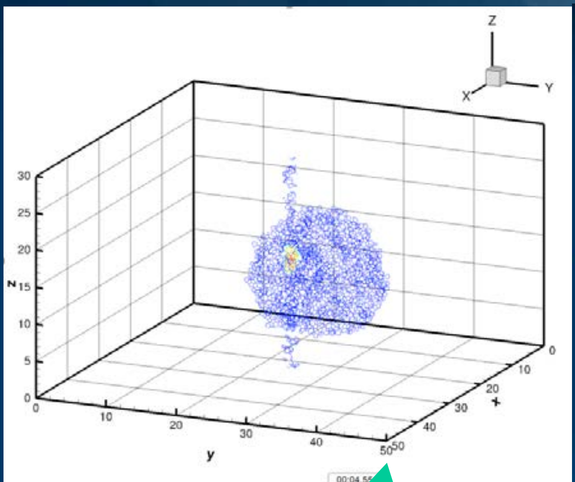
DEM is applicable at multiple scales: from grains to large geological faults

3 Dimensional Hydraulic Fracture Propagation

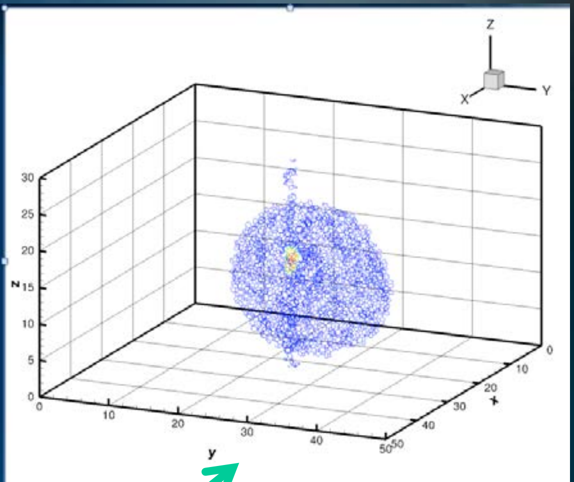
Fracture initiation



Early propagation



Propagation stage



In situ stress:

$\sigma_{vertica}$ =44MPa (6381.7psi)

σ_{Hmax} =30.35MPa (4401.9psi)

σ_{Hmin} =25MPa(3636.1psi)

Rock properties:

E = 41 GPa

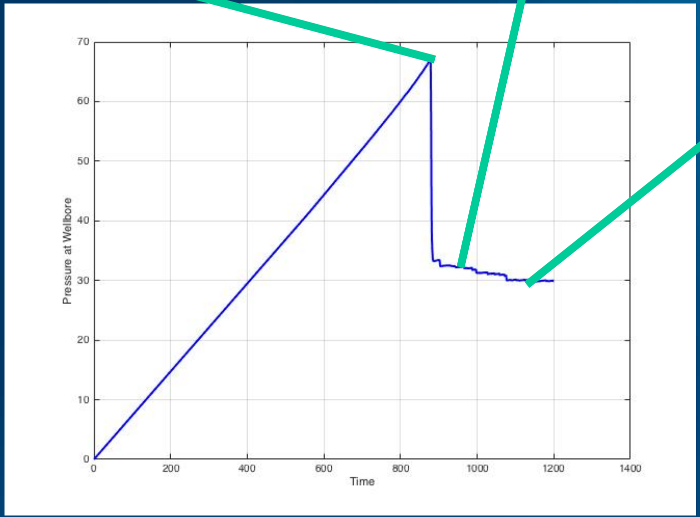
σ_T ***= 29.3 MPa***

Injection condition:

interval = *1m*

rate = 2 *L/min*

duration = 20 *min*

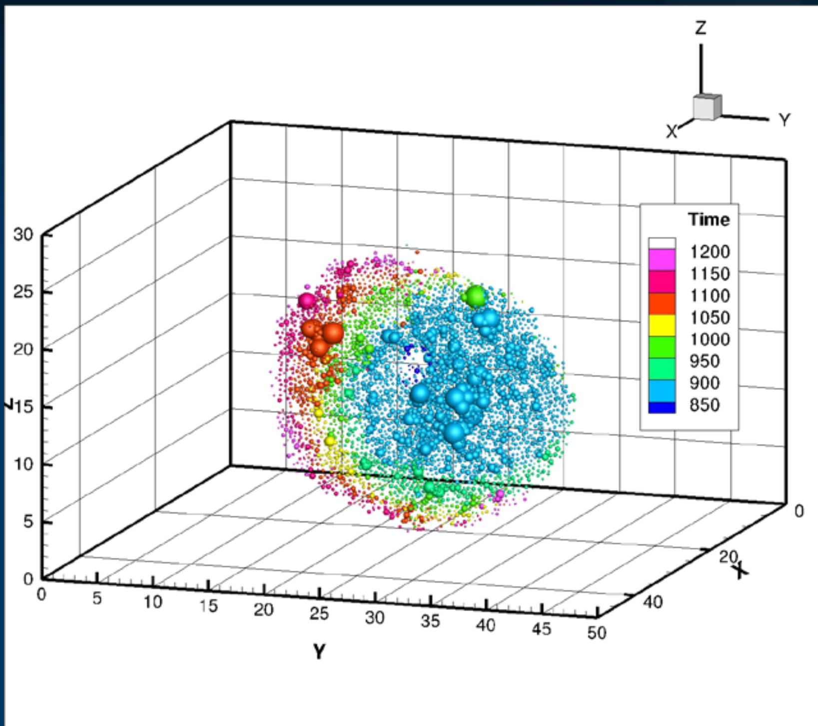


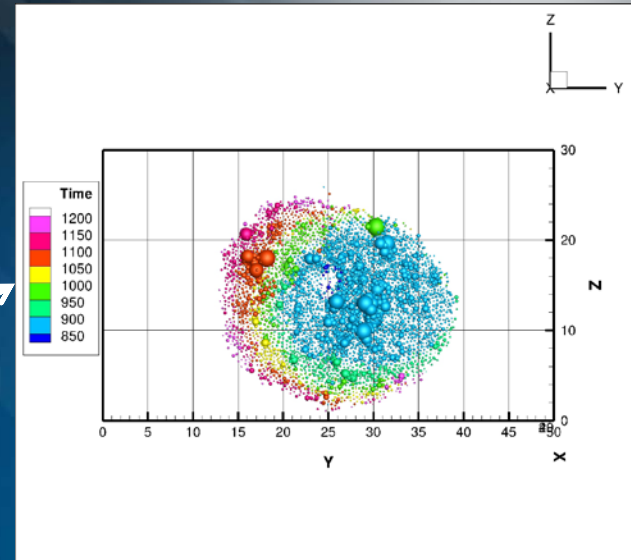
Wellbore pressure vs. time:

P_{break} = 66.78MPa (9685 psi)

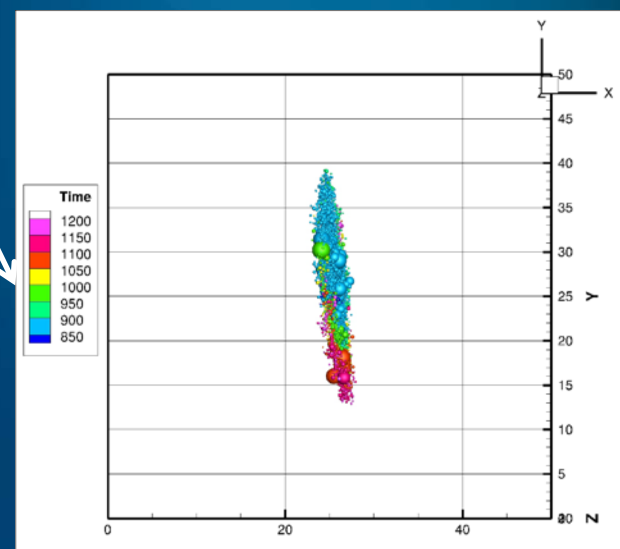
$P_{propagation}$ = 29.91MPa (4338 psi)

Induced Micro-Seismicity





YZ plane



XY plane

- Color – Time of microseismic events
- Size – Released Elastic Energy
- Average elastic energy release: 337 *J*
- Average moment magnitude : -4.315
- Fracture Radius = 3.81 *m* (12.5 *ft*)

kISMET Next Steps

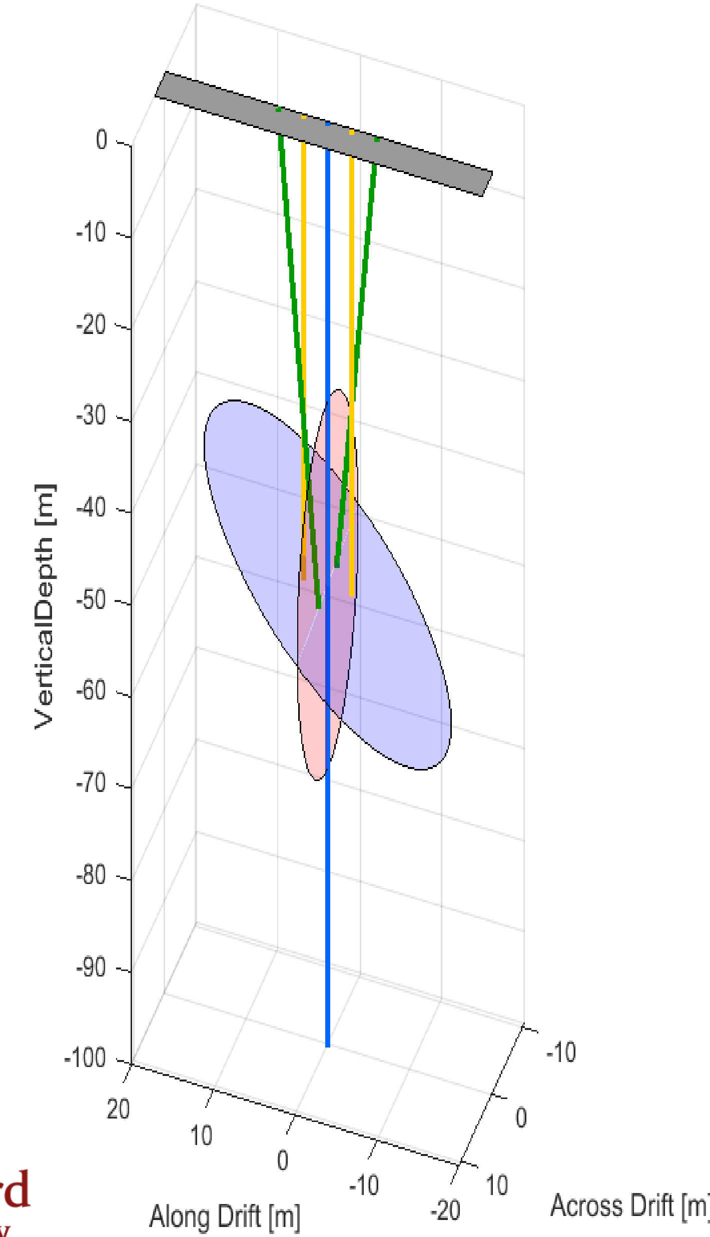
WGSS Hydraulic Fracturing for kISMET

Wisconsin: Herb Wang, Bezalel Haimson, Hiroki Sone, Peter Vigilante, Neal Lord

Golder: Tom Doe

Sandia: Moo Lee, Matt Ingraham

Stanford: Mark Zoback



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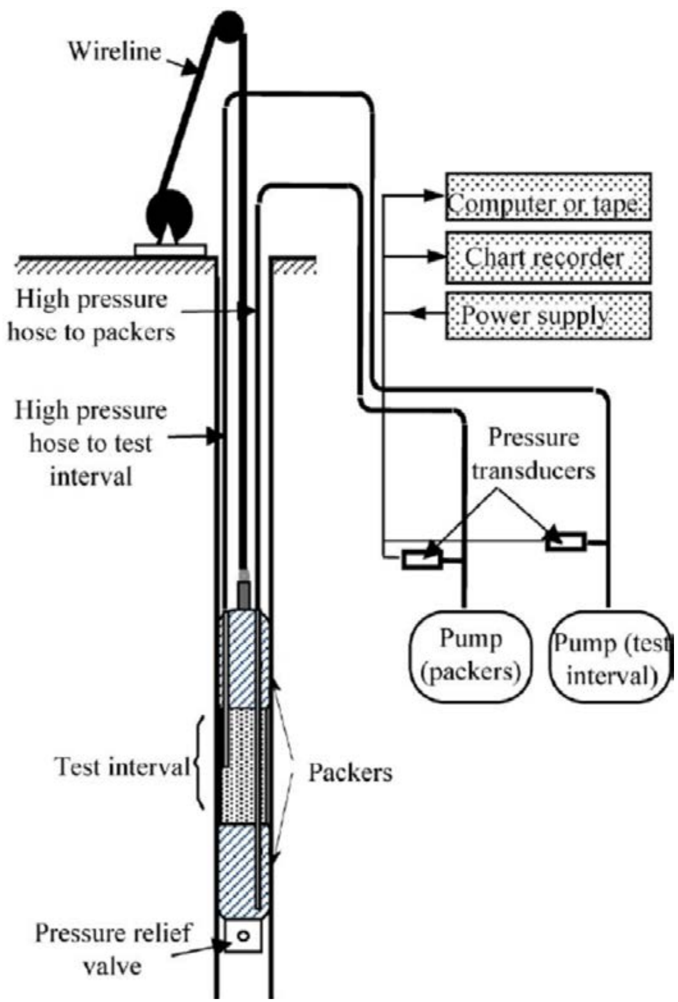
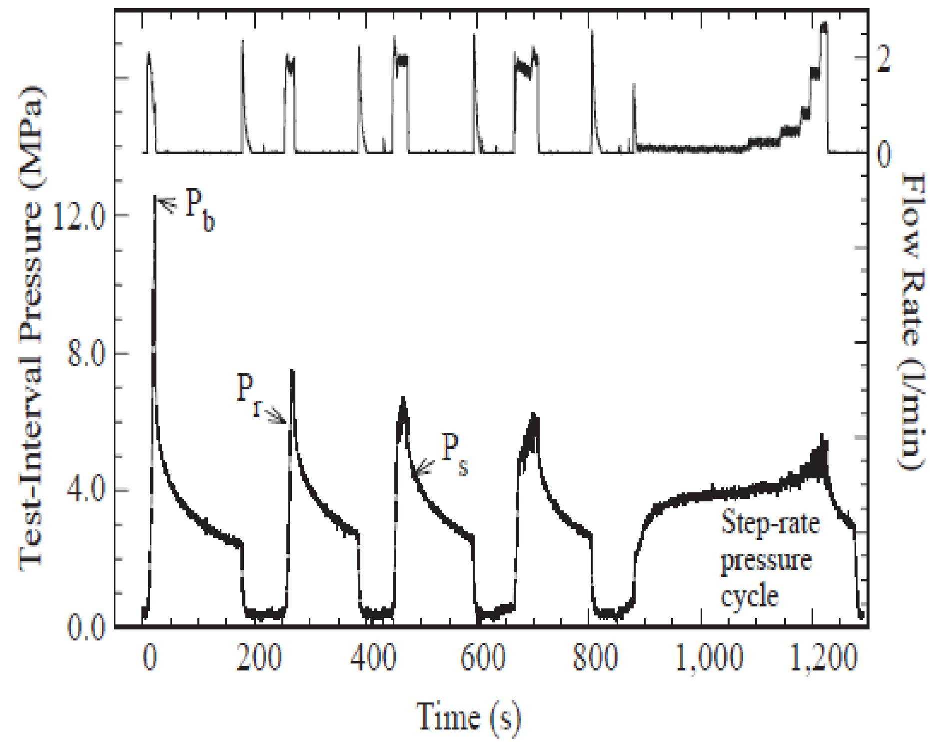
Sandia National Laboratories

Stanford University

In-Situ Stress by Hydraulic Fracturing (Haimson and Cornet, ISRM, 2003)





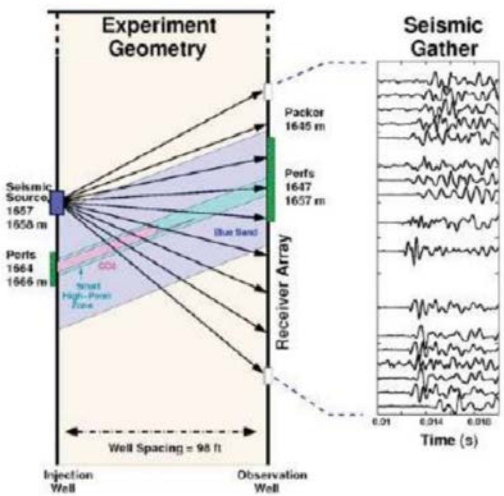
kISMET Monitoring

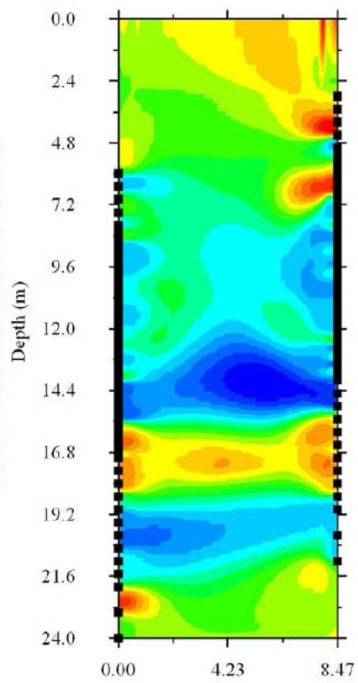
Team:

- LBNL: Tom Daley, Yuxin Wu, Craig Ulrich, Paul Cook, Jonathan Ajo-Franklin, Yves Guglielmi, Paolo Marchesini
- SDSMT: Bill Roggenthen
- PNNL: Tim Johnson

Approaches:

- Borehole coring and core logging
- Borehole televiewer and f.w. sonic logging
- Impression packer run after fracturing
- Active Source Seismic: CASSM
- Induced seismicity
- Electrical resistivity tomography (ERT)
- Borehole pressure monitoring





Objective:

Monitor hydraulic fracturing and induced seismicity and understand the effects of in-situ stress and rock fabric on fracture development

Summary

- **Objectives of kISMET project**
  - Investigate relationship between induced fractures and stress field, rock fabric, and stimulation approach to inform EGS stimulation
  - Investigate microseismicity arising from fracturing as analog for deep basement rock induced seismicity underlying deep injection sites
  - Establish kISMET experimental facility as a SubTER field test facility
- **Approach**
  - Locate kISMET in a deep mine with vertical principal stress σ_1
  - Conduct minifracs in vertical stimulation borehole to determine σ_2 and σ_3
  - Use packer assembly to create hydraulic fractures
  - Use proximal boreholes for active seismic and electrical monitoring during stimulation
- **Accomplishments**
  - Developed kISMET site on 4850L of SURF
  - Drilled and cored five vertical boreholes to create a five-spot pattern 50 m below invert
  - Carried out modeling and analysis of fracturing process and effects
- **Next steps**
  - Laboratory tests on core
  - Borehole optical and acoustic logging
  - Stress testing
  - Stimulation
  - CASSM and ERT monitoring

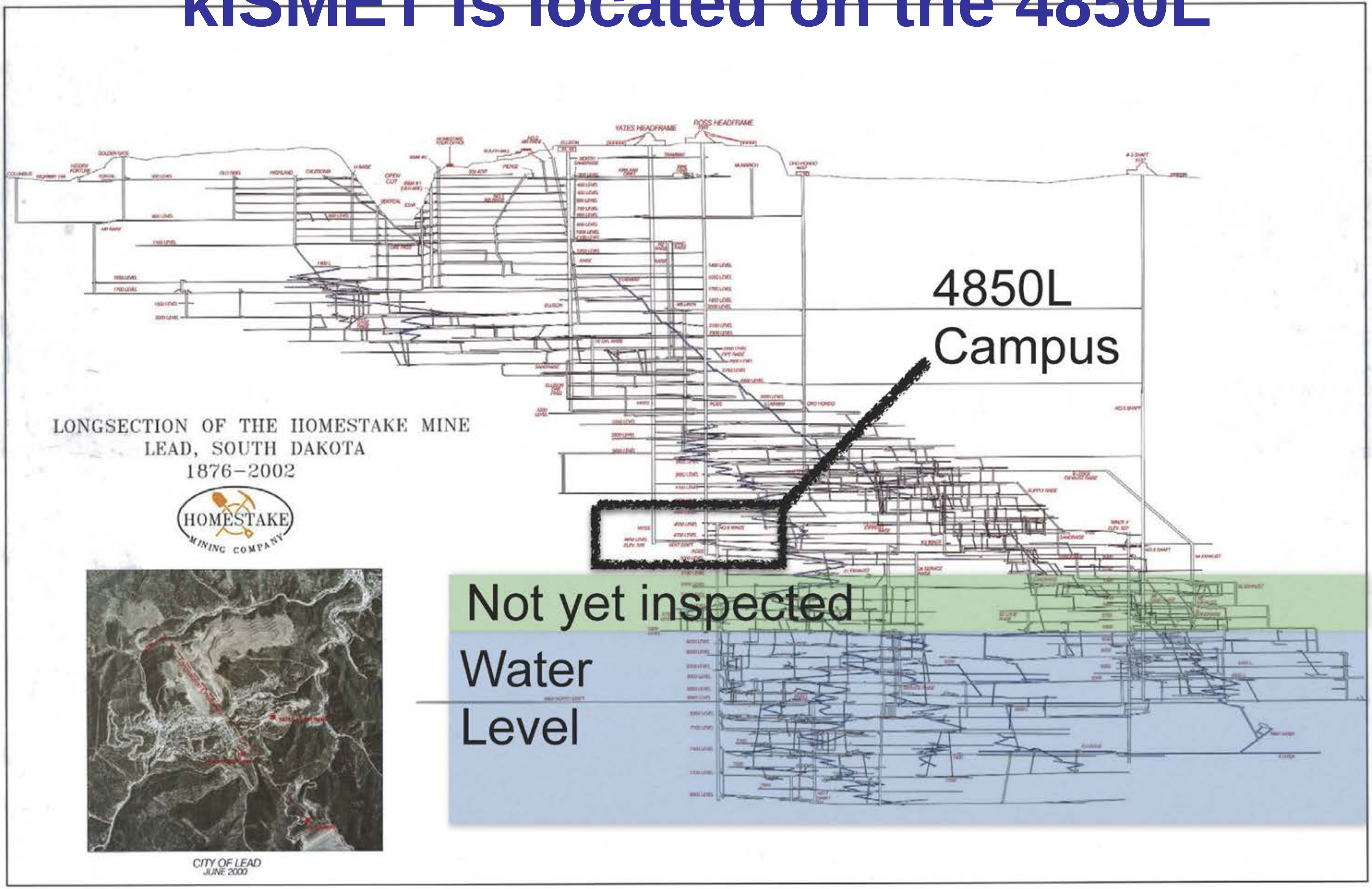
Acknowledgments

This work is under the auspices of SubTER with support by the Assistant Secretary for Energy Efficiency and Renewable Energy, Geothermal Technologies Program of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Questions, Comments, Discussion


LOADMATE

kISMET is located on the 4850L



Brief Site Description

- Deep (>8000 ft) gold mine operated for over 100 years
- Extensive workings, boreholes, core, geologic database (mine model)
- The rock is crystalline Precambrian phyllite, schist & amphibolite cut by Tertiary rhyolite dikes
- The rock is intensely folded, low- to moderately fractured, very hard, low-permeability
- The mine was allowed to flood starting in 2003
- Water reached the 5000 ft level before pumping was initiated
- Water level is now maintained at around 5700 ft
- There are two shafts (Yates and Ross) for access
- The maintained physics labs are at the 4850 ft level

Lithology and X-section from Caddey et al. 1991

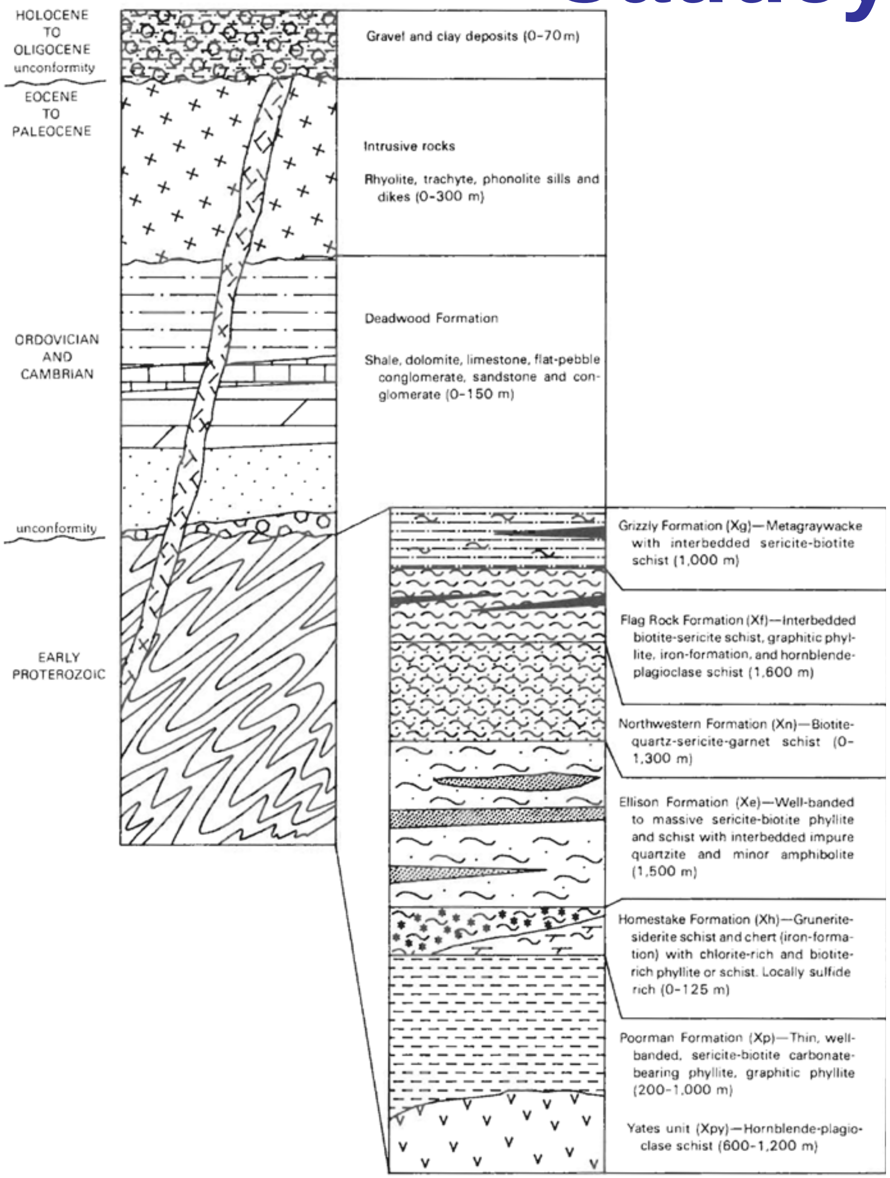


Figure J3. Schematic diagram illustrating stratigraphy (not to scale) of the Homestake area.

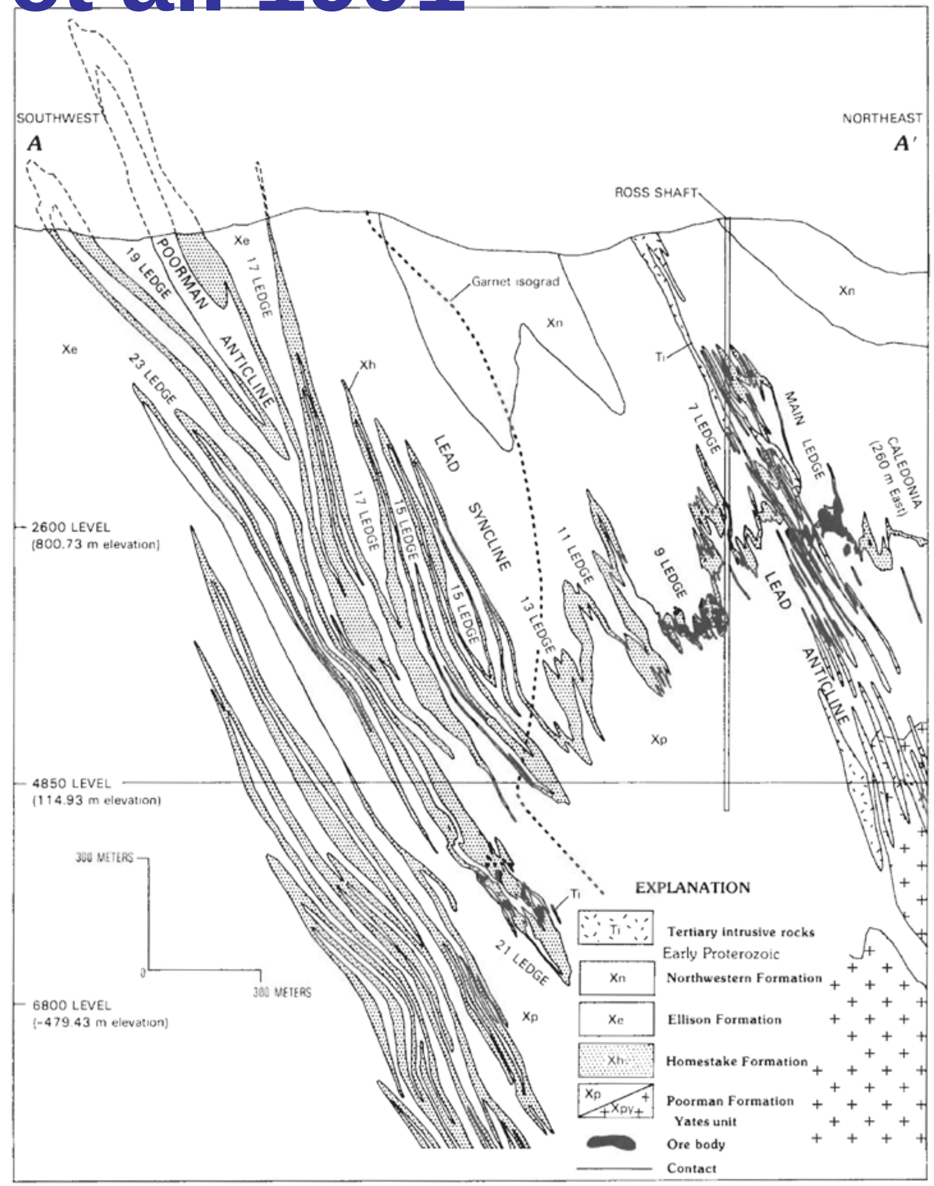


Figure J5. Generalized geologic cross section A–A′ through 33 Stope, Main Ledge Reference Line, Homestake mine. Position of section is shown in figure J4.

Four Sites Considered

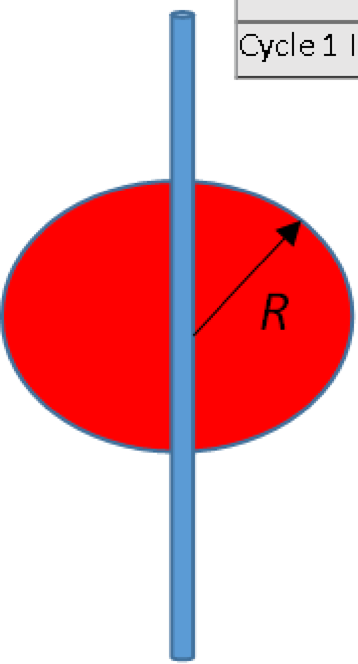
- 4850 level, near prior stress test sites by Yates shaft
- 4850 level, 17 Ledge area S of Ross shaft
- 4100 level, main drift near Yates shaft
- 4850 level, west drift near Governor’s Corner

Estimated fracture radius is 1.6 m for initial fracture assuming a Penny Crack

University of Wisconsin Team Analytical Calculations

Youngs Modulus	E	41.3	GPa
Fracture Toughness	K_{1C}	1.0	MPa $m^{1/2}$
Poissons Ratio	n	0.23	-
Fluid Density	r	1000	kg/m^3
Lumped Factor	D	8.0E+07	Pa kg^{-1} m3
Fluid Compressibility	C	5.00E-10	1/Pa

Cycle	Volume	Radius(1)	Area	$\Delta\sigma$	Aperture, e_{max}(2)
	liters	m	m^2	MPa	m
Cycle 1 Initiation	1	1.6	8.2	1.9E+00	1.8E-04



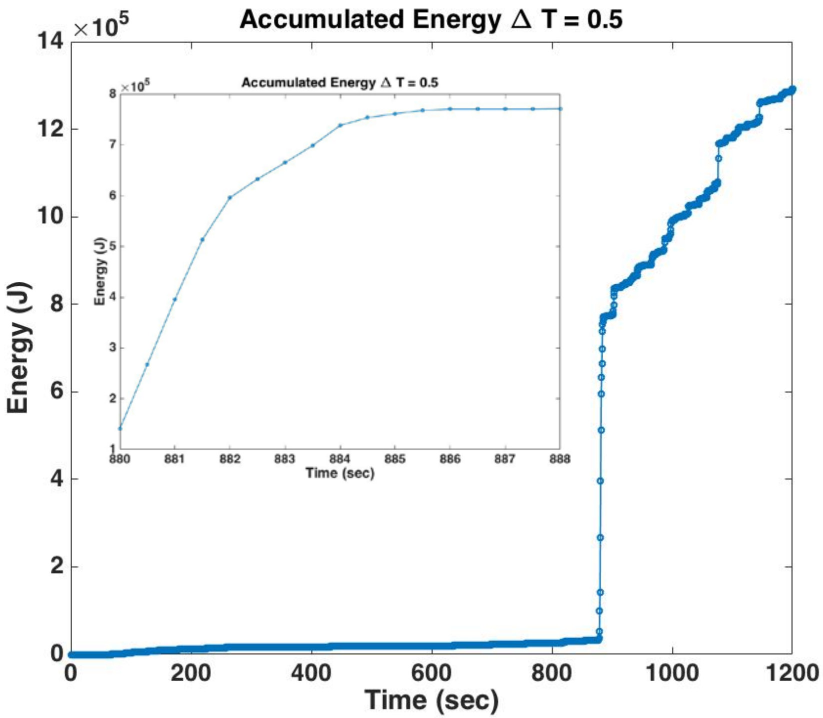
$$e_{\max} = \frac{8(1-\nu^2)}{\pi E}\Delta\sigma\, R$$

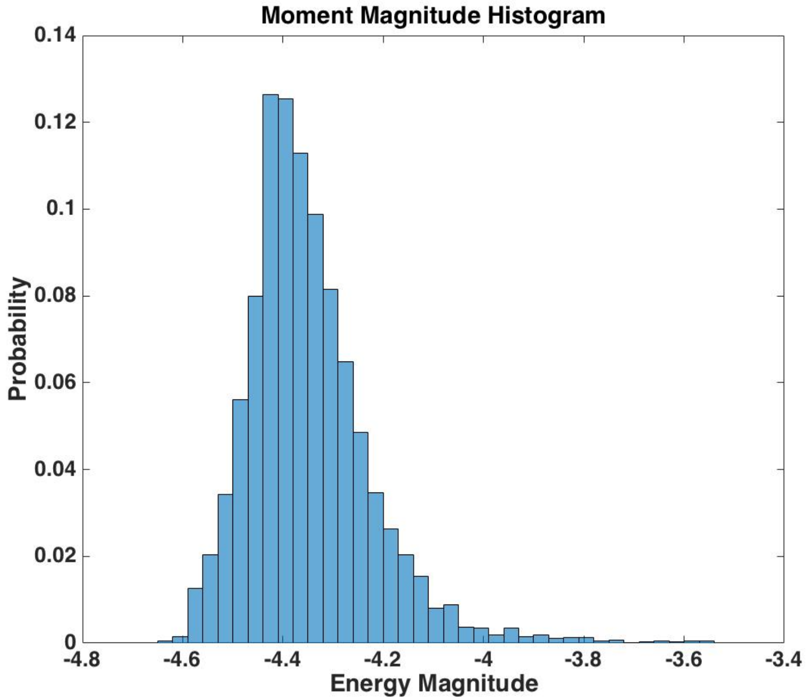
$$R = \sqrt[5]{\left(\frac{Q_e D}{\pi^{3/2} K_{1C}}\right)^2}$$

$$D = \frac{3\pi E}{8(1-\nu^2)\rho}$$

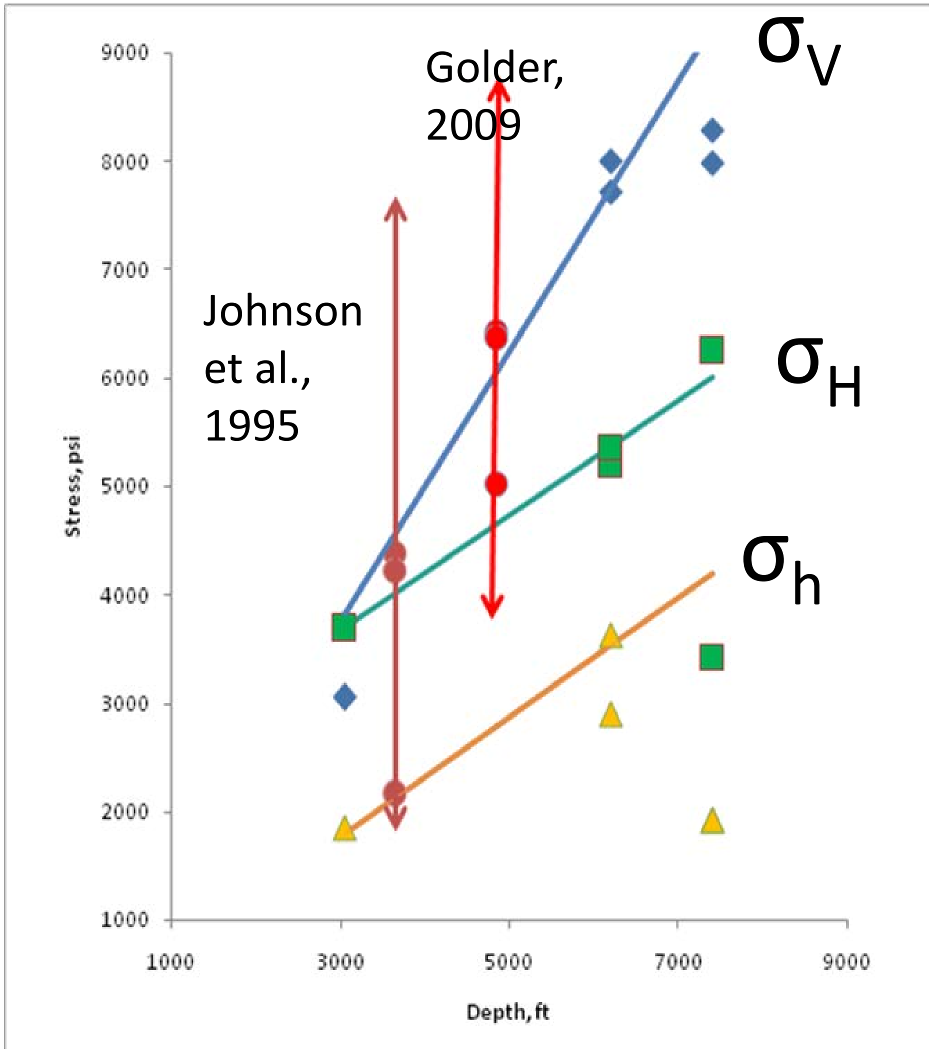
Abe, H., and H. Takahashi, 1987, Fracture Mechanics Applied to Hot, Dry Rock Geothermal Energy, in B. Atkinson (ed) Fracture Mechanics of Rock, Academic Press, p. 241-276

Moment Magnitude vs. Time

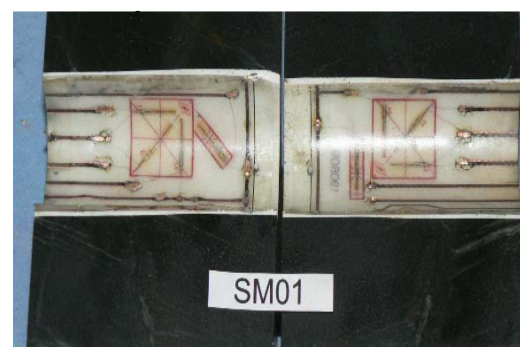




In-Situ Stress Measurements



- Wide range of stresses by Golder at 4850L from low of 3300 psi to high of 9000 psi
- Could be due to rock heterogeneity and anisotropy
- All measurements



Key Drilling Results

Drilled four HQ (~4" diameter) 50 m holes to form five-spot configuration around central 100 m borehole

- 6/13/16 – Drill equipment unloaded
- 6/21/16 – Spudded first borehole
- 7/20/16 – Final (fifth) borehole completed

Gyro tool used to orient drill string