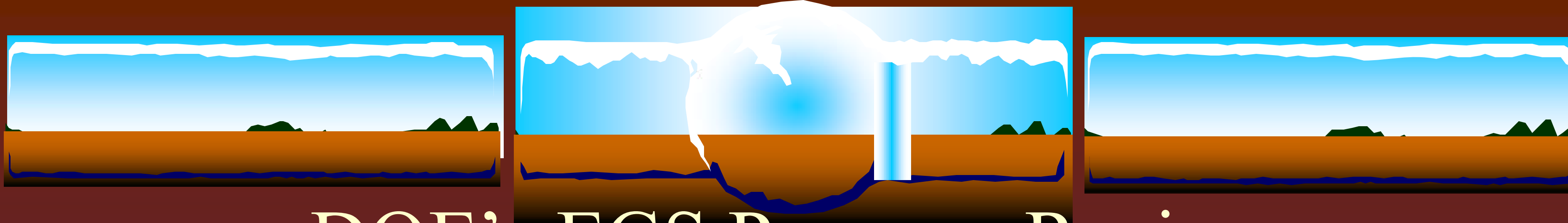

DOE's EGS Program Review

Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation

DE-FC07-01ID14186

Peter Rose, Principal Investigator

Jess McCullough and Steve Hickman, Co-PI's

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July 18, 2006

Marriott Hotel
Golden, CO

Project Objective

- To create an Enhanced Geothermal System on the margin of the Coso field through the hydraulic, thermal, and/or chemical stimulation of one or more tight injection wells.
- Hydraulically/chemically stimulate the deep open-hole section of Coso well 46A-19 to the point that it will accept 500 gpm at less than 100 psi wellhead pressure.
- To develop and calibrate geomechanical, geochemical, and fluid flow models in order to extend the Coso/EGS concepts to wherever appropriate tectonic and thermal conditions apply.

EGS Problem

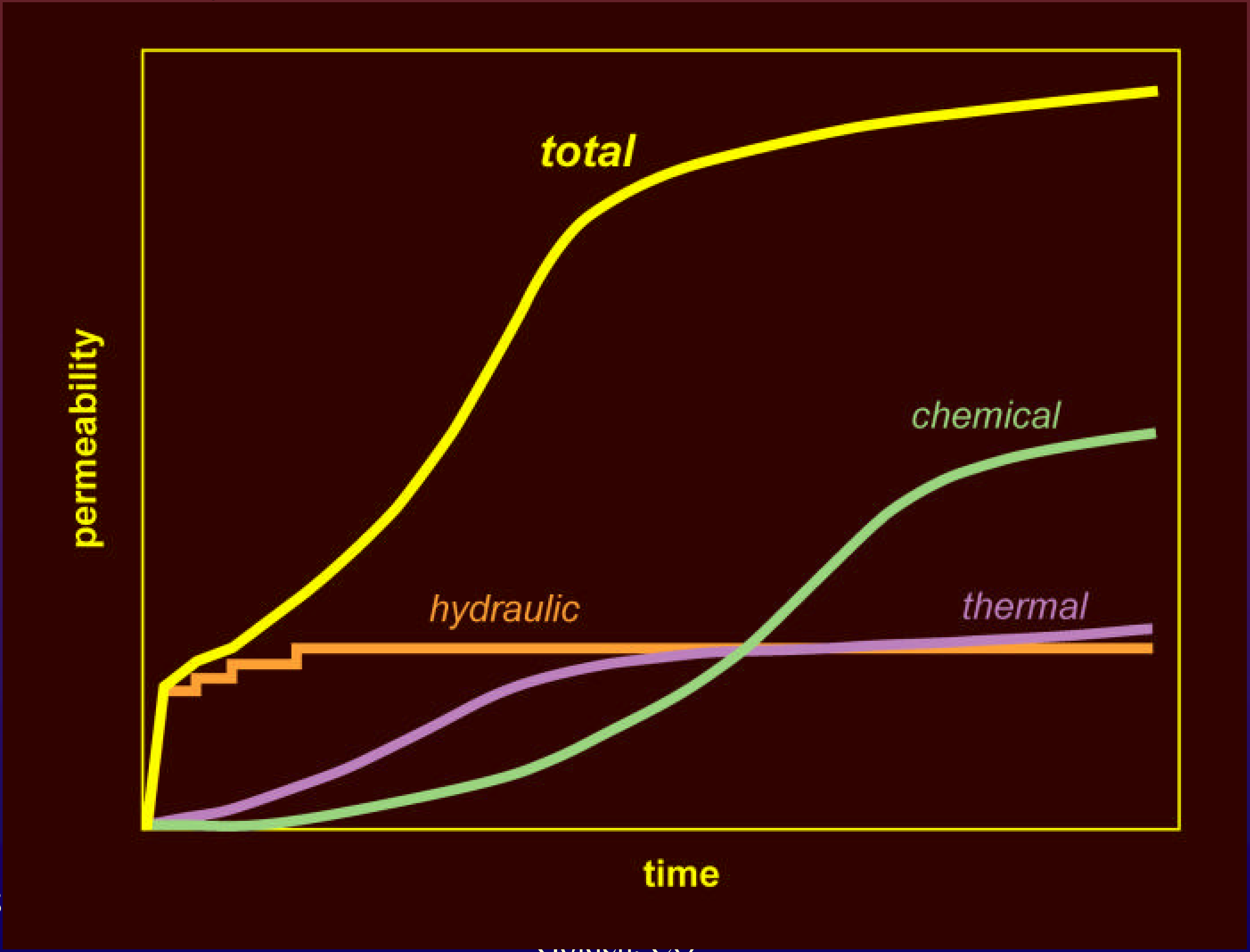
- Why is project important to EGS program?
  - Many of the technical challenges facing EGS are being directly addressed by this project: characterization of fracture networks and tectonic stresses; development and evaluation of techniques for the hydraulic and chemical stimulation of low-permeability formations; and the design and testing of methods for evaluating the success of those stimulation techniques
- What technical issue does the project address?
  - Hydraulic and chemical stimulation, fracture and stress characterization, microseismic monitoring, novel tracer technologies, fluid-flow and reactive transport modeling
- How will project help to achieve overall program goals?
  - Accomplishment of the objectives of this project will assist DOE in meeting its interim objective of demonstrating the feasibility of creating EGS circulation systems at commercial production rates by 2010.
    - Increase EGS net output power of one production well from 1.4 MWe to 2.5-9.8 MWe by 2010
    - Double the mass flow rate of one well from 15 kg/sec to 30 kg/sec
    - Increase the effective fracture contact area from 0.56 to 0.6 km^2
    - Increase the short-circuiting index from 0.000011 to 0.0033

Background/Approach

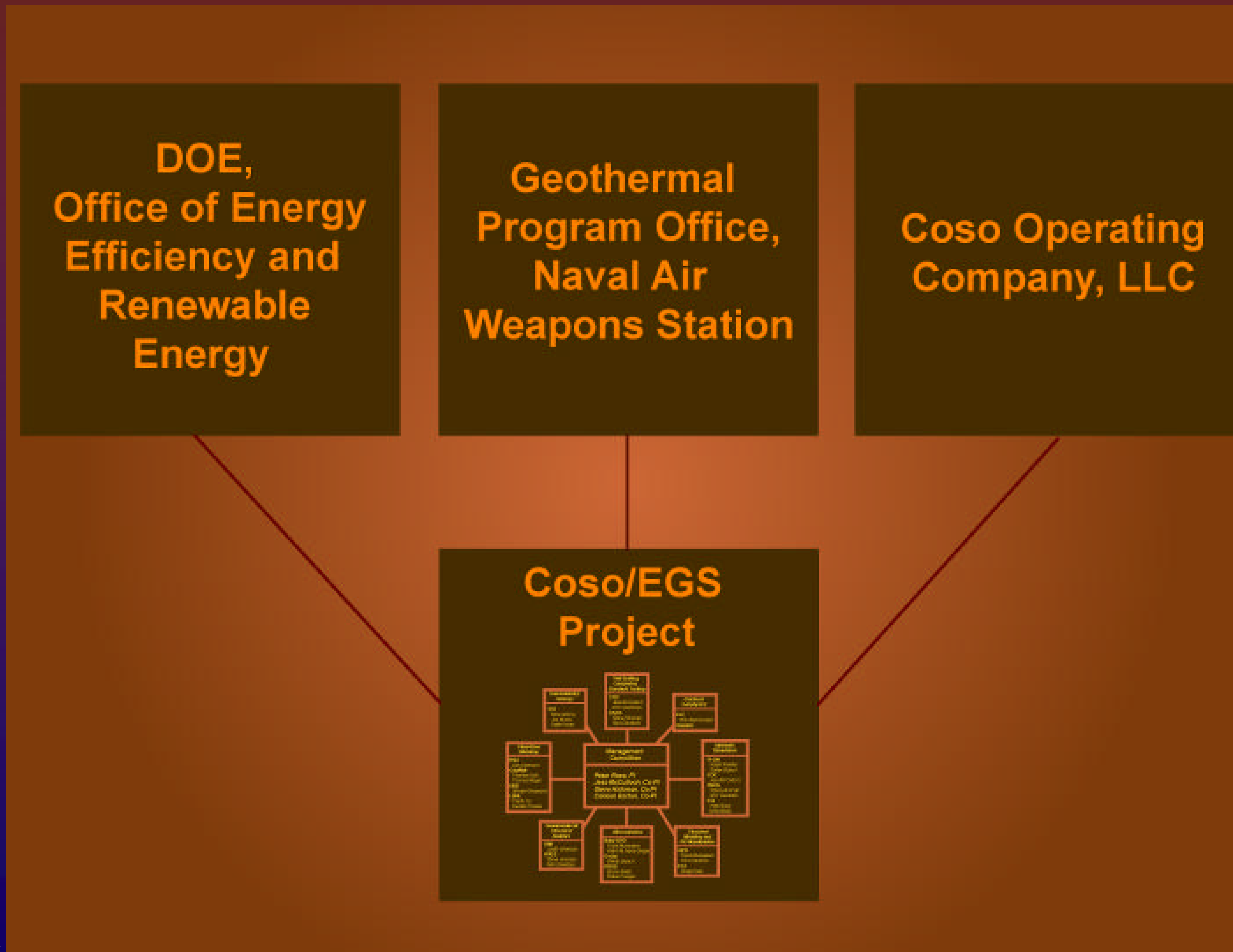
The Coso/EGS Concept

- Wellbore stimulation produces permeability enhancements due to a combination of hydraulic, thermal and chemical effects.
- Hydraulic effects are first order.
  - Fractures *re*-open through shear failure.
  - Fractures that fail in shear are self-propping.
- Thermal and chemical effects are second order.
  - Fracture apertures increase due to rock thermal contraction.
  - Fracture apertures change due to mineral dissolution and/or precipitation.
- These concepts can be extended to other geologic settings *where appropriate tectonic and thermal conditions exist.*

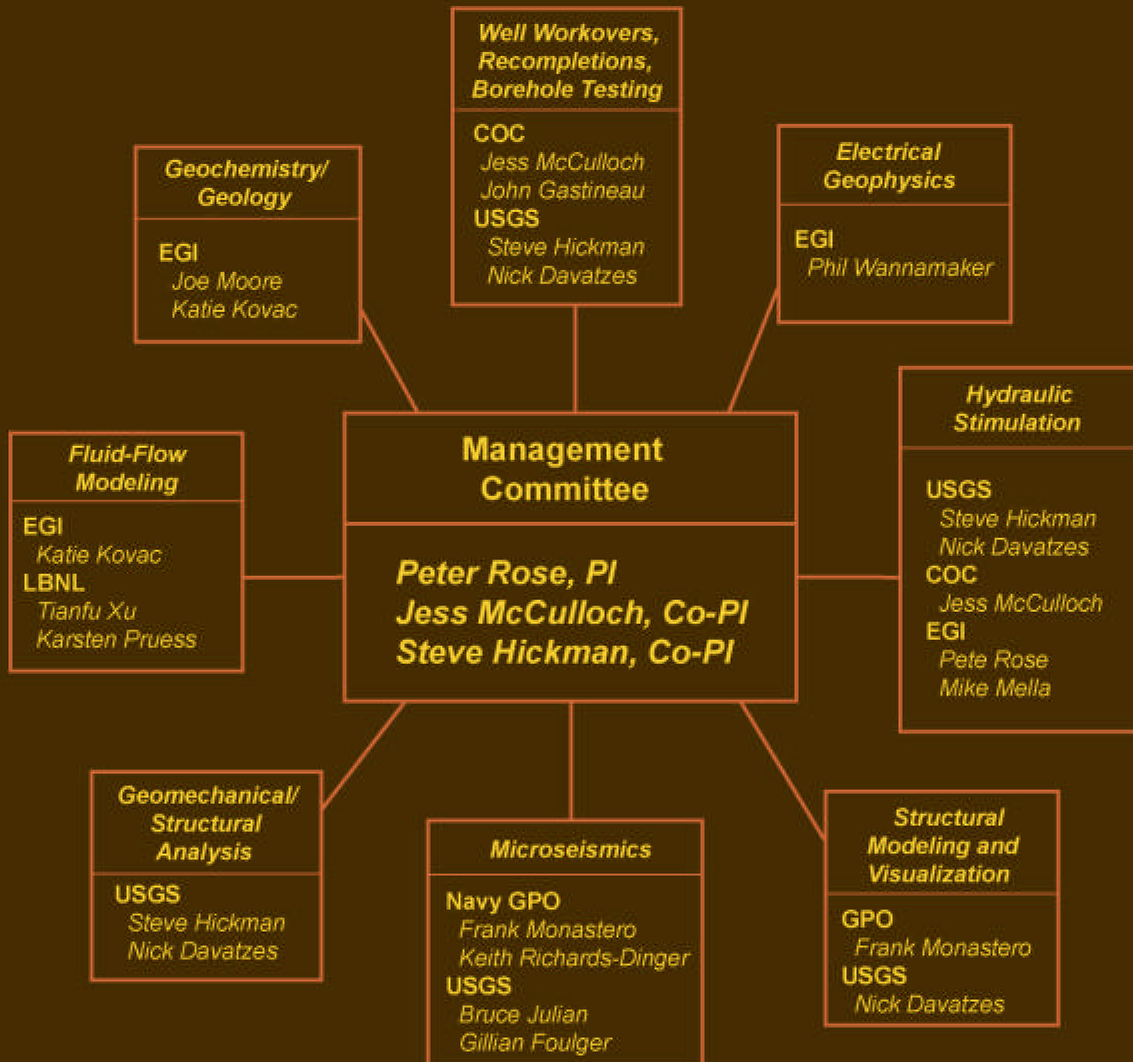
Reservoir Stimulation Is Achieved through a Combination of Hydraulic, Chemical and Thermal Effects



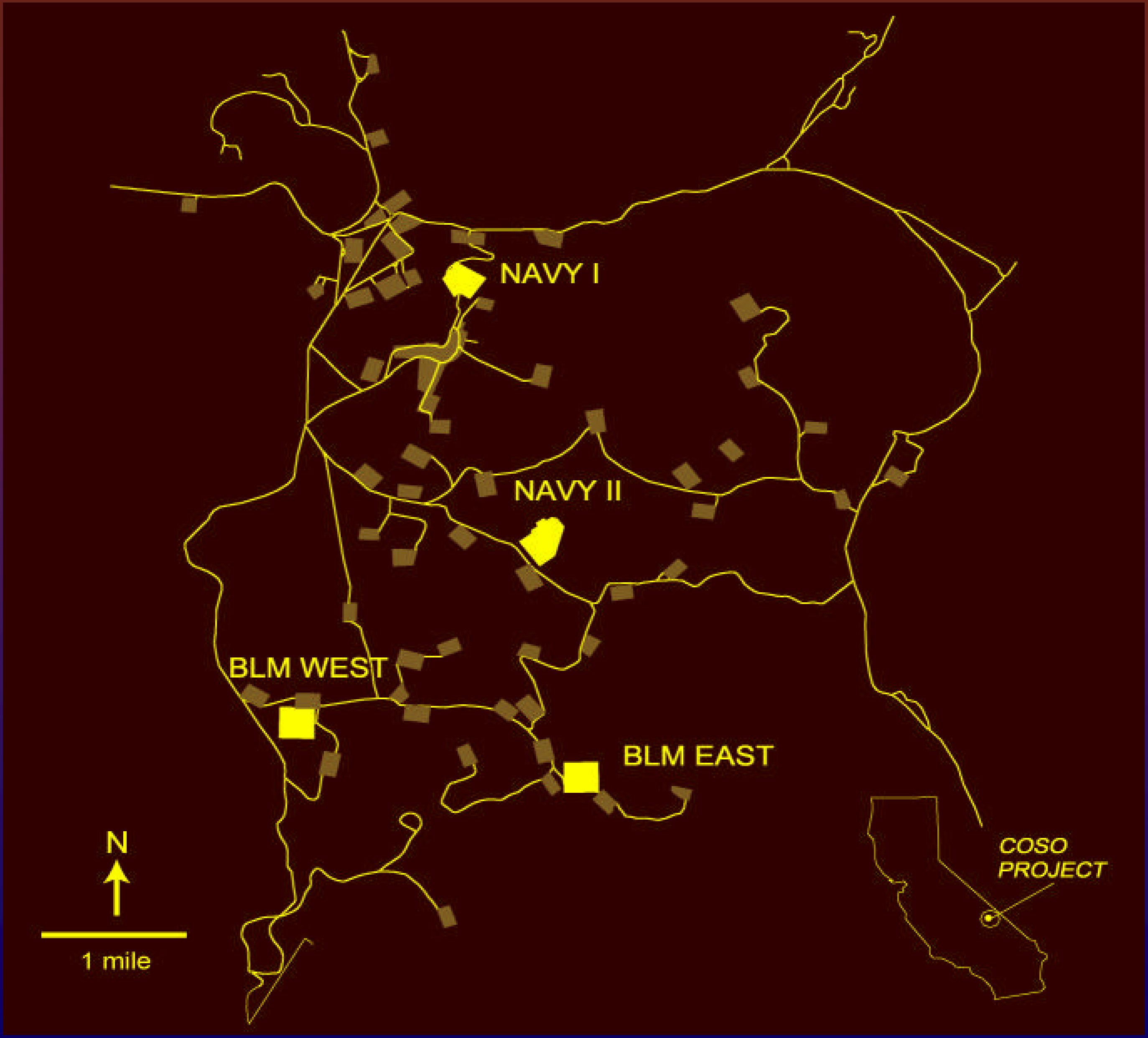
The Coso/EGS Project



The Coso/EGS Organizational Structure and Co-Investigators



The Coso Field



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Results/Accomplishments

Regional Stress/Structure and Fracture/Stress Analysis

Steve Hickman, Nick Davatzes and Frank Monastero

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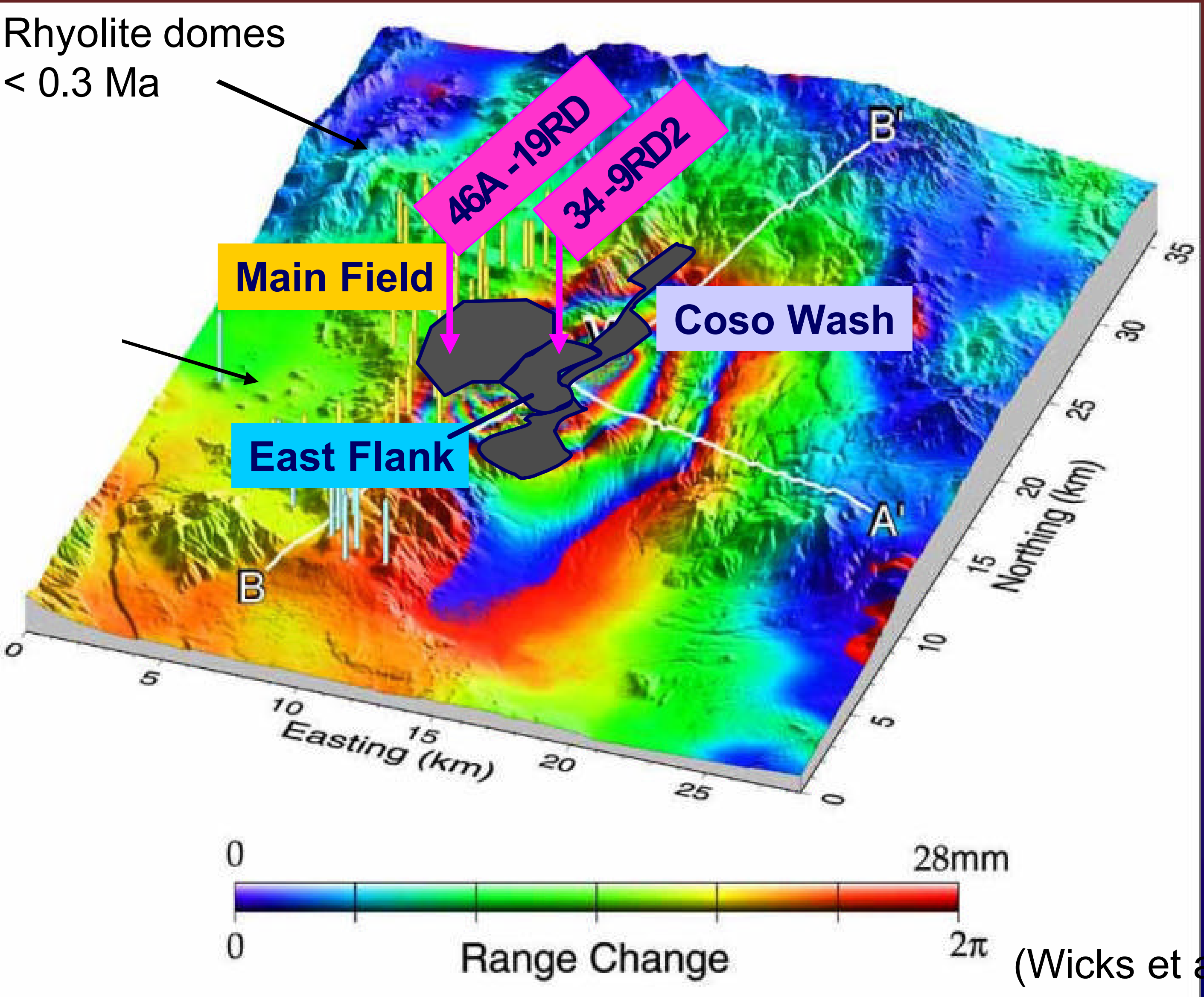
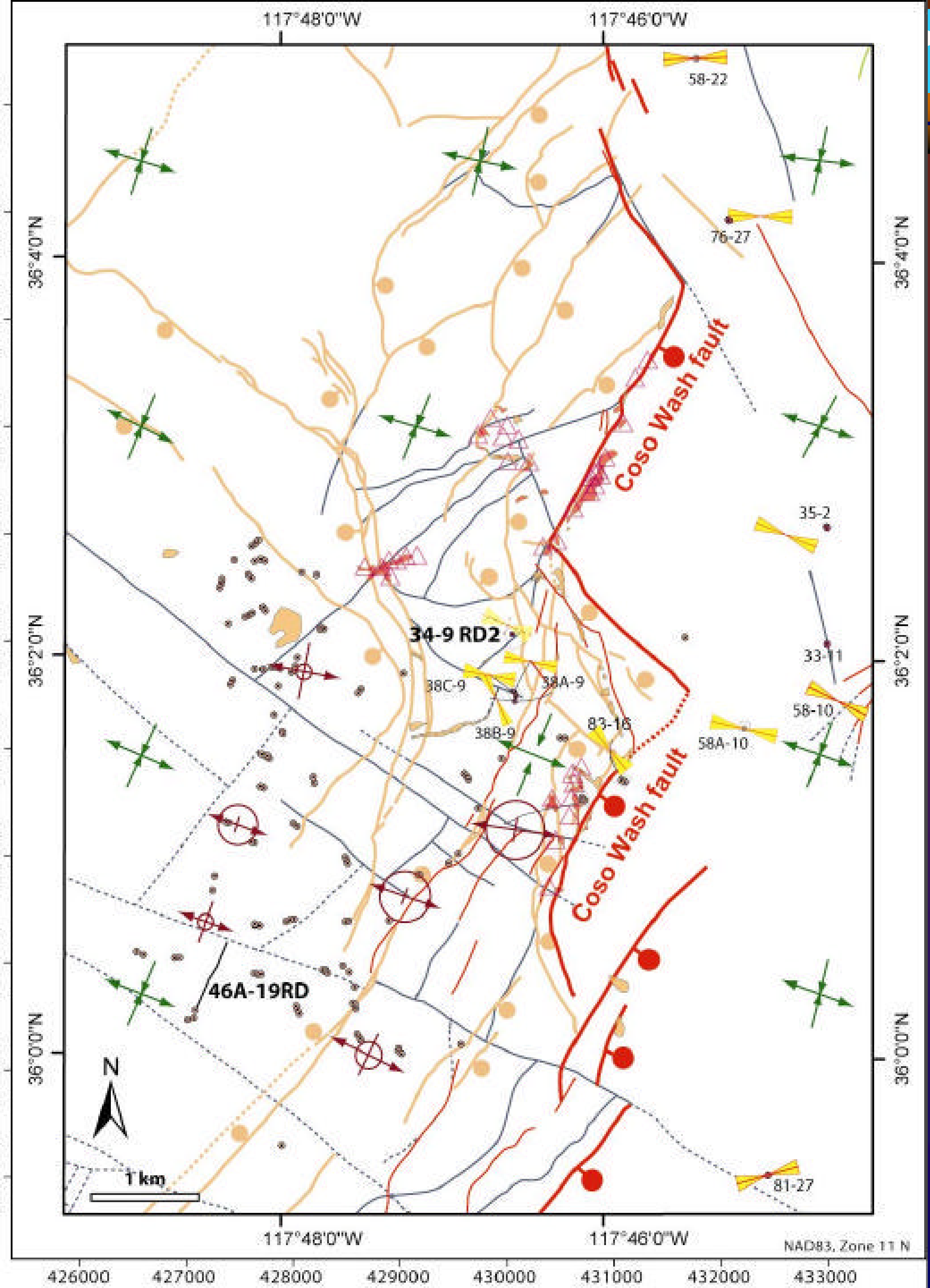
Deformation in the Geothermal Field



(Wicks et al., 2001)



Legend

Faults (ages from offset sediments)

Ancient and probably Inactive faults (?)

Faults active since 1.6 Ma

Modern fautls (offset Holocen sediments)

(Ball on down-thrown side)

Miscellaneous

Well head and trajectory of selected wells

Stress Direction

Least principal stress azimuth (mean orientation of induced structures in image logs of wells)
Davatzes & Hickman (2005a & b), Sheridan & Hickman, GMI (2003)

Least principal stress azimuth (inverted from seismicity; arrow: S_{hmin}, line: S_{Hmax}, circle: S_V)
Feng & Lees (1998)

Azimuth of principal strains (inverted from seismicity; outward arrow: extensional dir; inward arrow: contractional dir)
Unruh *et al.* (2002)

Earthquake Magnitude

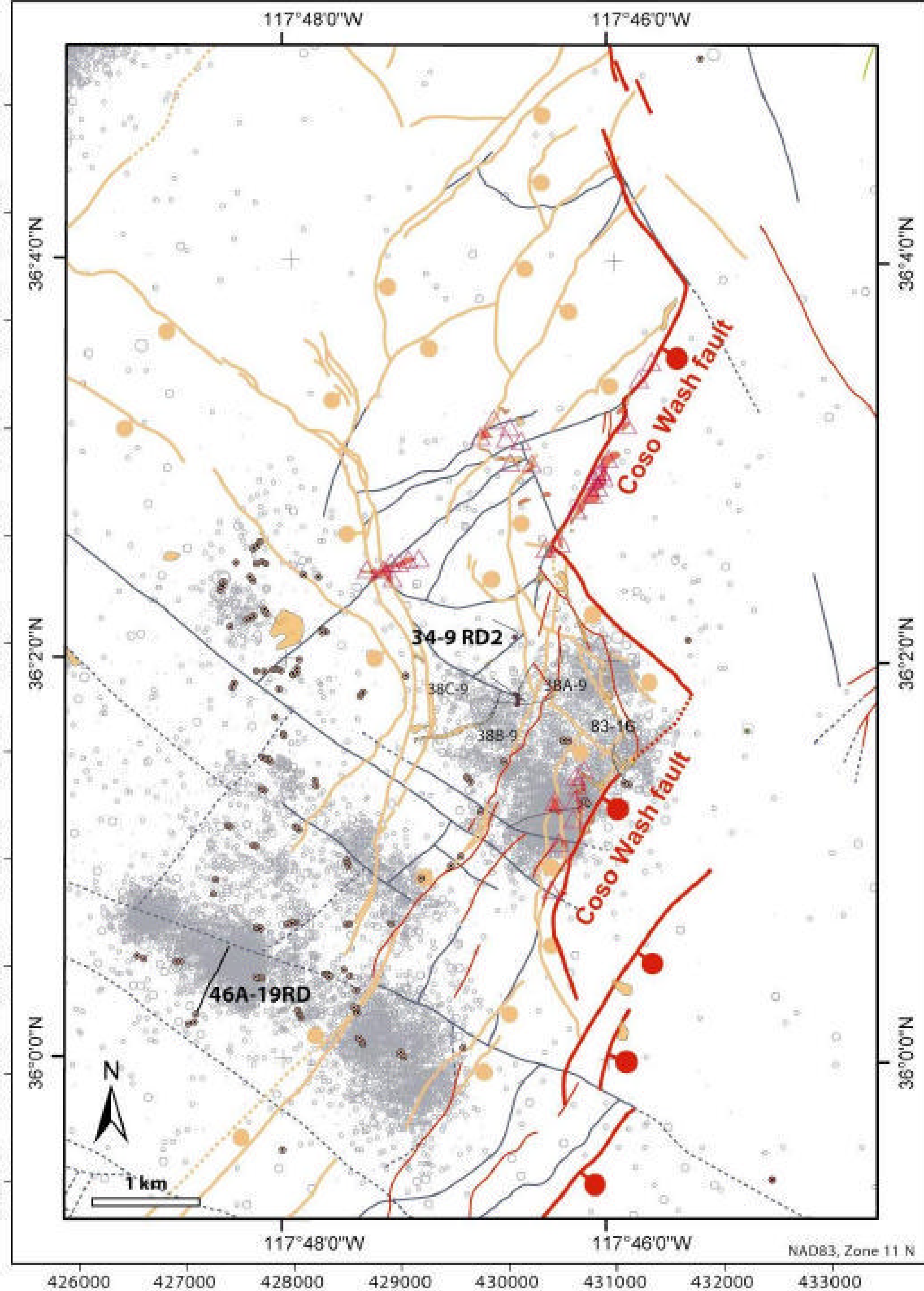
-2 to 0

0 to 1

1 to 2

2 to 3

3+



Legend

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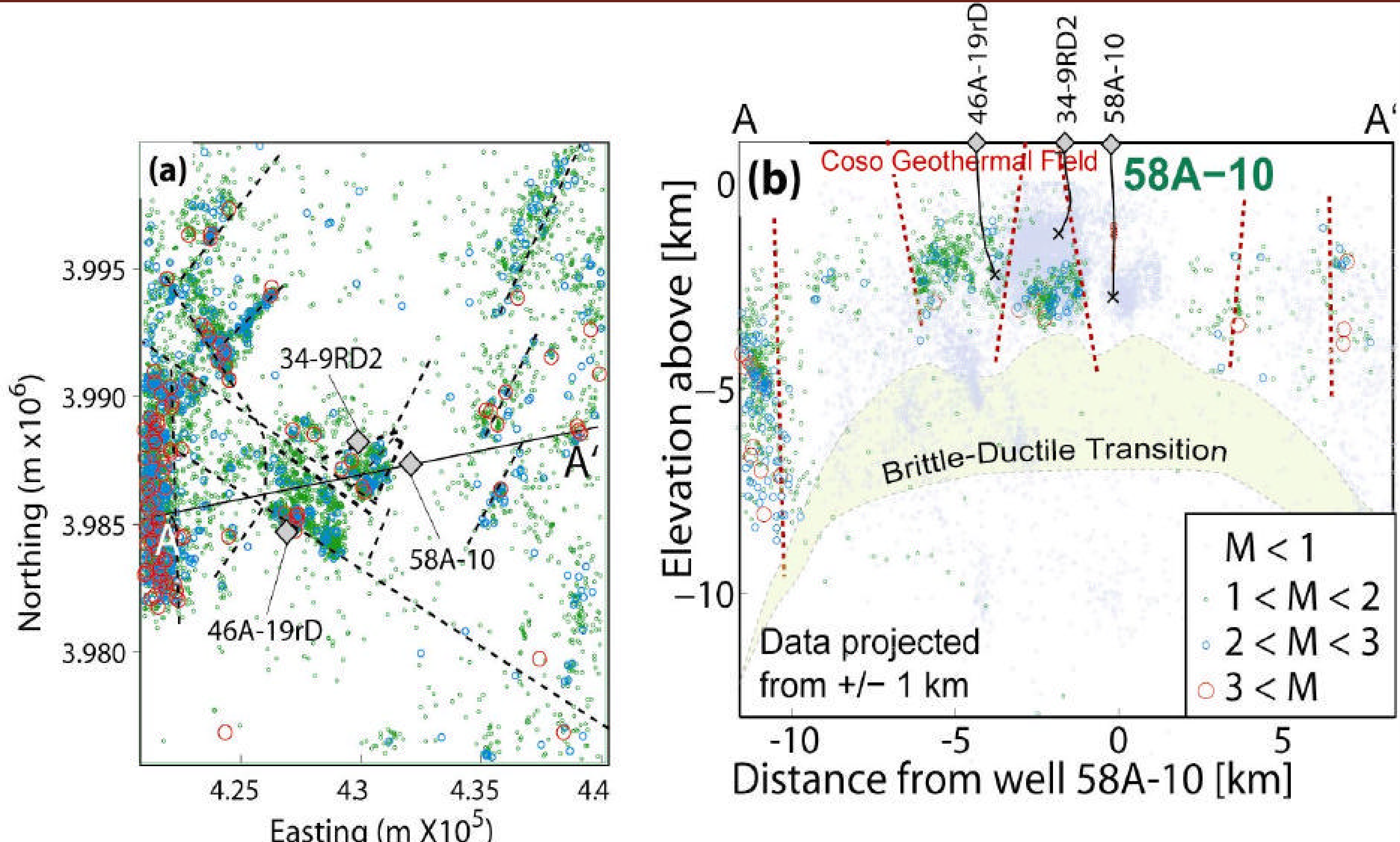
Earthquake Magnitude

- -2 to 0
- 0 to 1
- 1 to 2
- 2 to 3
- 3+

Earthquakes > 2 km



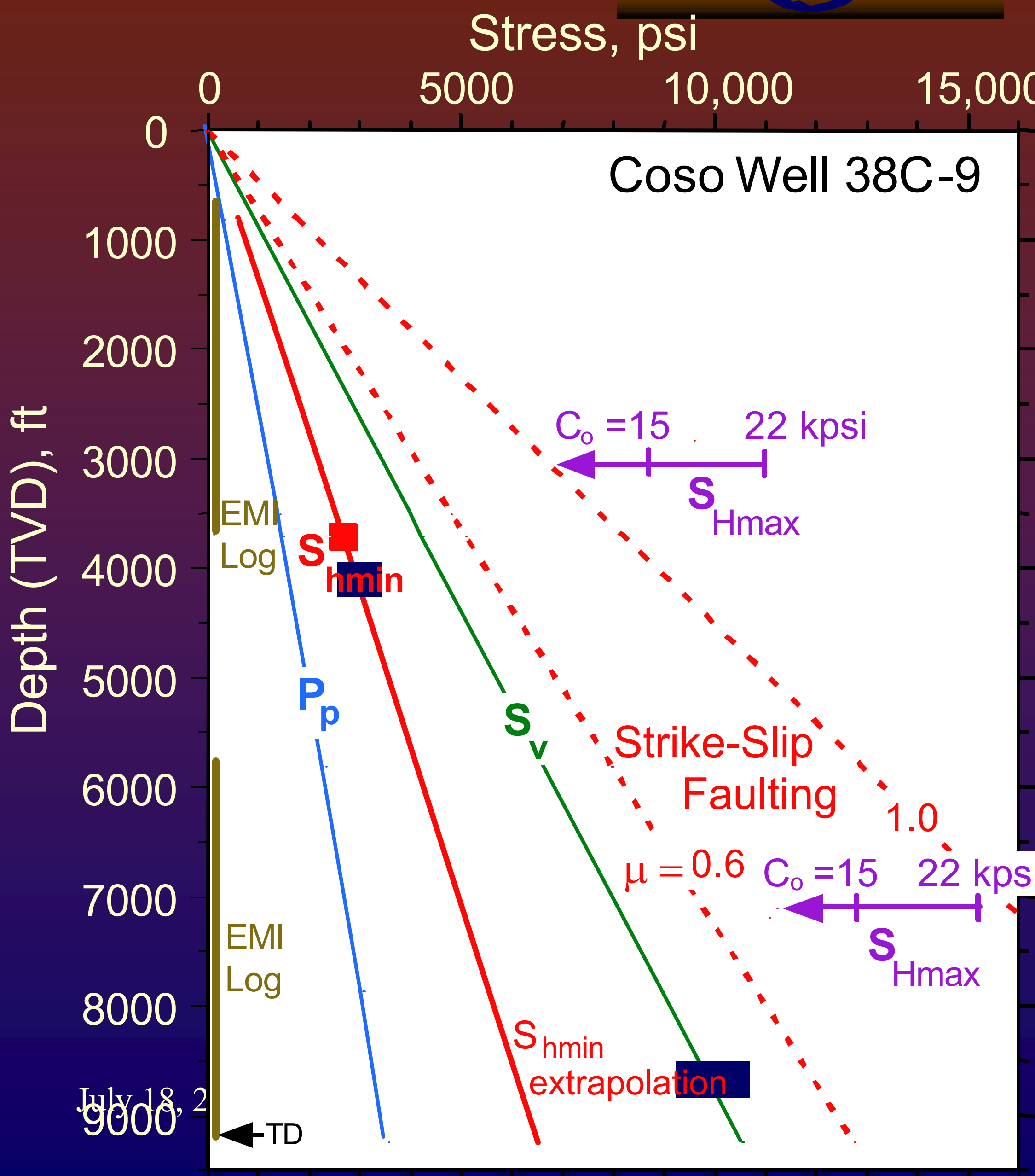
(a)
34-9RD2
58A-10
46A-19rD
A
A'
3.995
3.990
3.985
3.980
Northing (m x10^6)
4.25
43
4.35
4.4
Easting (m X10^5)
(b)
A
A'
46A-19rD
34-9RD2
58A-10
Coso Geothermal Field
58A−10
Brittle-Ductile Transition
Elevation above [km]
0
−5
−10
Data projected
from +/− 1 km
M < 1
1 < M < 2
2 < M < 3
3 < M
-10
-5
0
5
Distance from well 58A-10 [km]

Fracture/Stress Analysis

Steve Hickman and Judith Sheridan

Objective:

To characterize reservoir fracturing and stresses in order to model and predict fracture shear failure and the subsequent increases in permeability that result from hydraulic stimulation



P_p and Failure Envelope drawn for surface hydrostat (pre-production)

S_{Hmax} bounds from general absence of breakouts, assuming *minimum* C_o shown (22 kpsi preliminary Coso strength tests, 15 kpsi typical granites [Lockner, 1998])

EGS Target Depth (Well 34-9RD2)

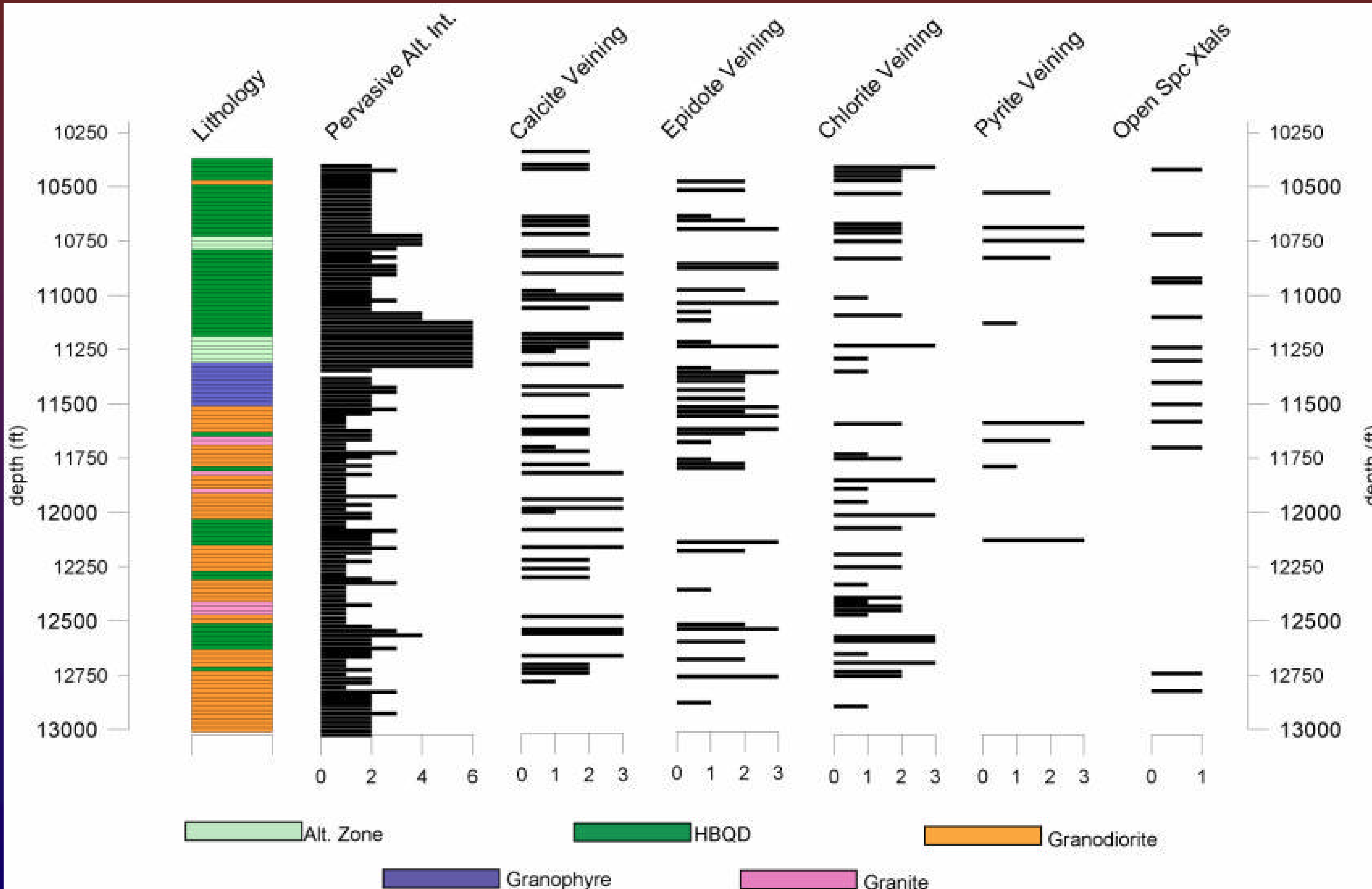
Geology and Geochemistry

Katie Kovac, Joe Moore, Tianfu Xu, and Karsten Pruess

Objectives:

- To correlate rock type and alteration mineralogy with permeability enhancements resulting from various stimulation approaches
- Conduct geochemical modeling studies to determine the effects of mineral dissolution and precipitation on reservoir permeability, given various injection fluid compositions, pH's, and temperatures

Petrography and Petrology of 46A-19RD from Drill Cuttings



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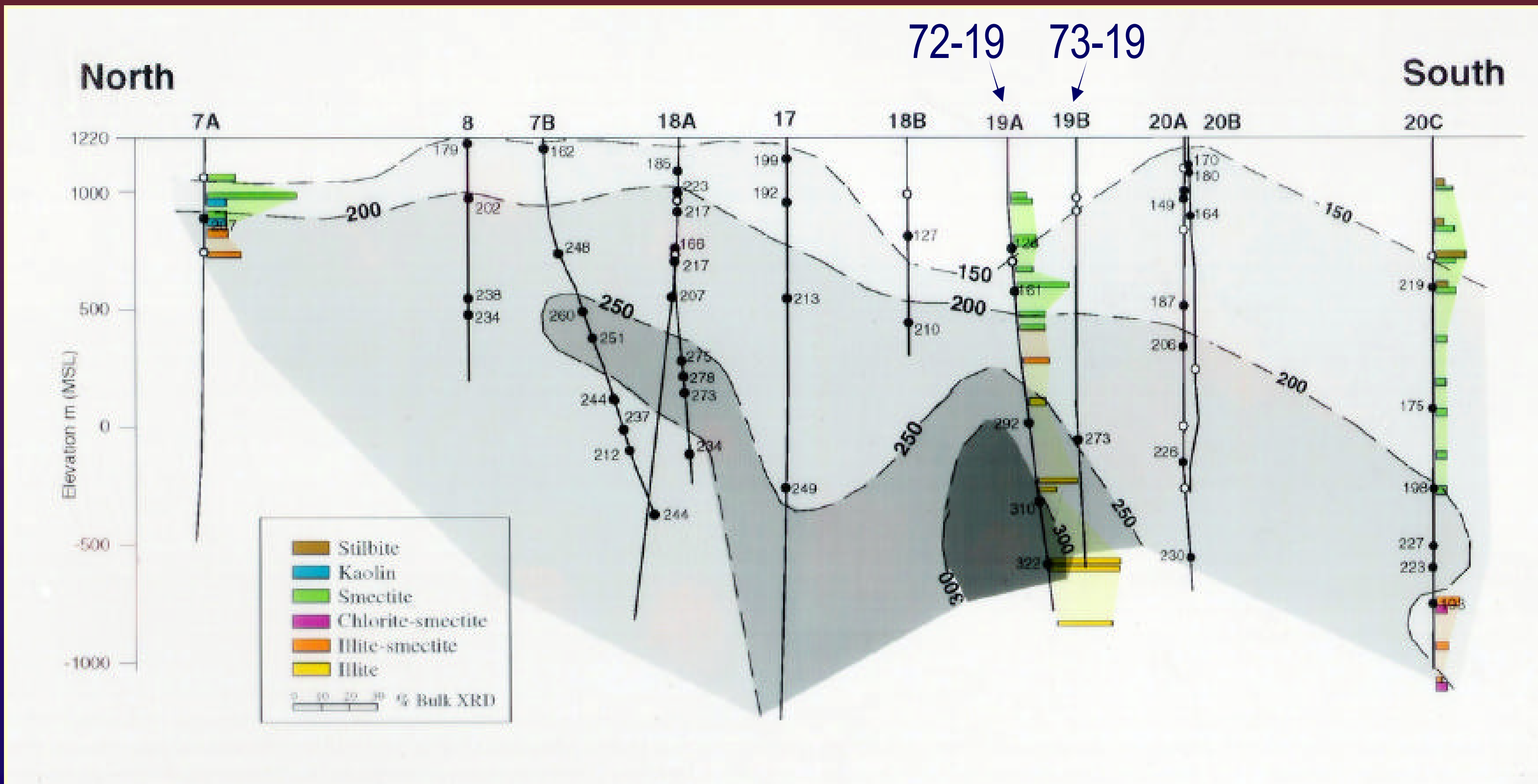
Fluid Inclusion Temperatures along a North/South Cross-Section



Microseismic Analysis

Bruce Julian and Gillian Foulger, USGS
Keith Richards-Dinger, GPO

Objectives:

- To measure the locations and magnitudes of earthquakes associated with the hydraulic stimulation of 46A-19RD in near-real time in order to characterize the effect of the stimulation process on regional shear failure

- To calculate moment tensors associated with the earthquakes associated with the hydraulic stimulation of 46A-19RD in order to characterize failure mechanisms

Development of Microseismic Methods for Characterizing EGS Processes

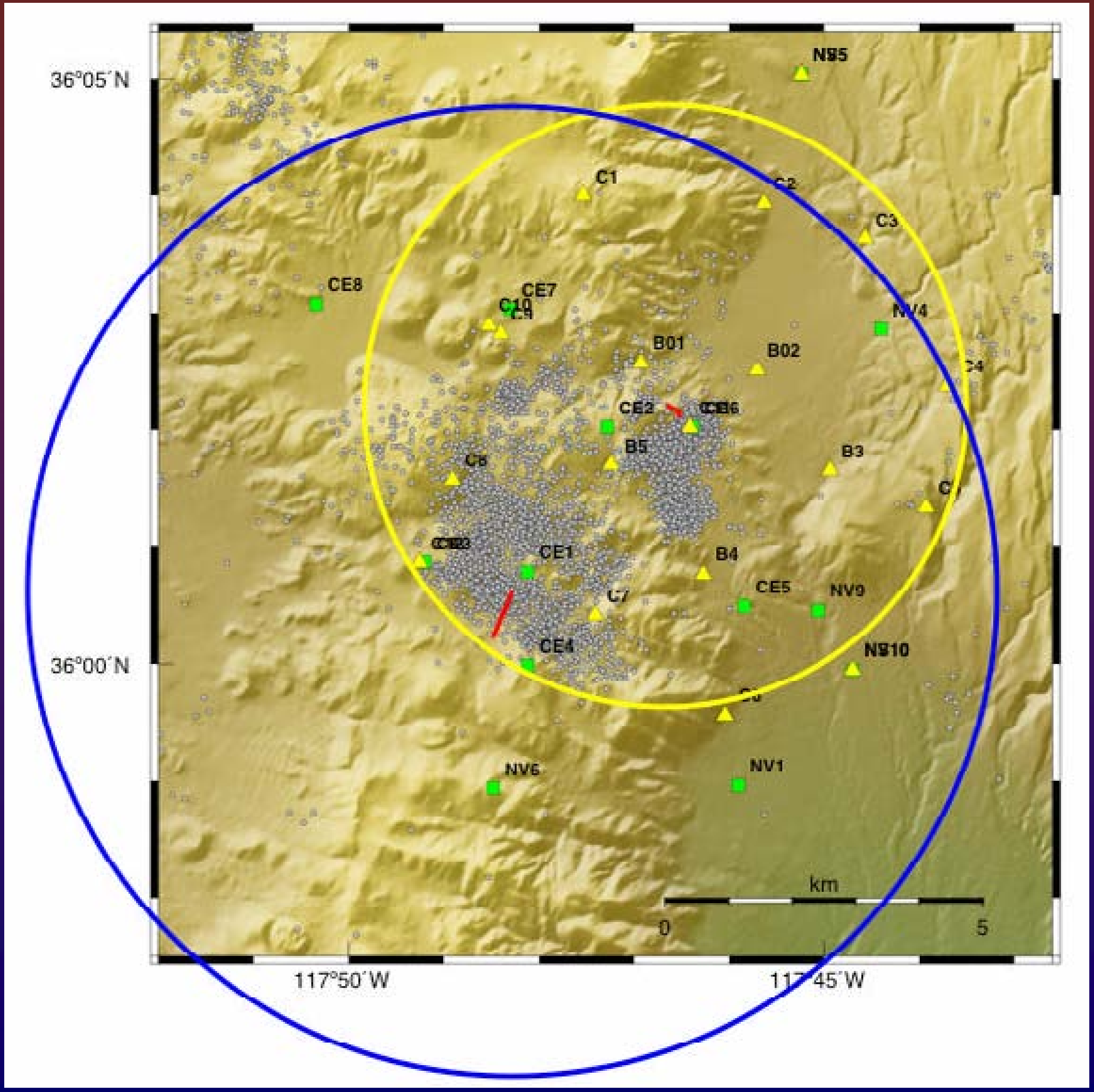
Bruce Julian, Gill Foulger, Keith Richards-Dinger, Frank Monastero

- Install and maintain a microseismic network to determine source mechanisms during stimulation experiments
  - Use the Navy's 18-station permanent sensor array combined with a USGS *EarthWorm/EarlyBird* system to generate real-time data
  - Use a 17-station temporary array to record additional data
- Develop and implement software (*hypocc*) for high resolution location of microearthquakes
- Monitor changes in fluid saturation between 1996 and 2003 using time-dependent seismic tomography

Real Time Monitoring

- A Sun Microsystems SPARC-10 computer running *EarthWorm/EarlyBird* was installed at China Lake for real-time automatic processing of telemetered data from 22 stations.
- It detects events in real time, saves digital waveforms, picks *P*-wave arrival times, and provides conventional hypocenter locations with time delays of ~ one minute.

Microseismicity



Conclusion

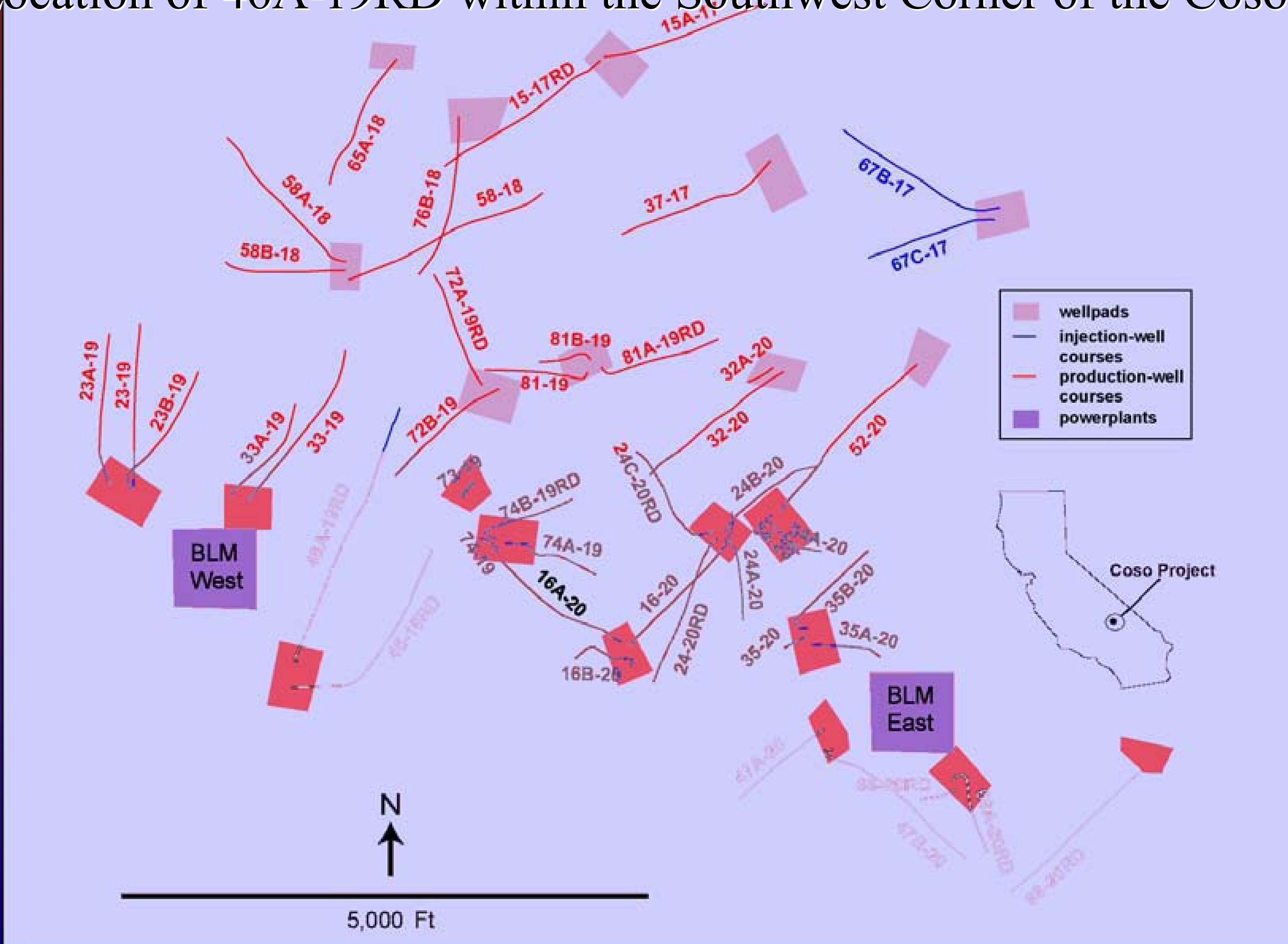
- Will the project objective (slide 2) be achieved by the project completion date? *No.*

Plans for Project Completion

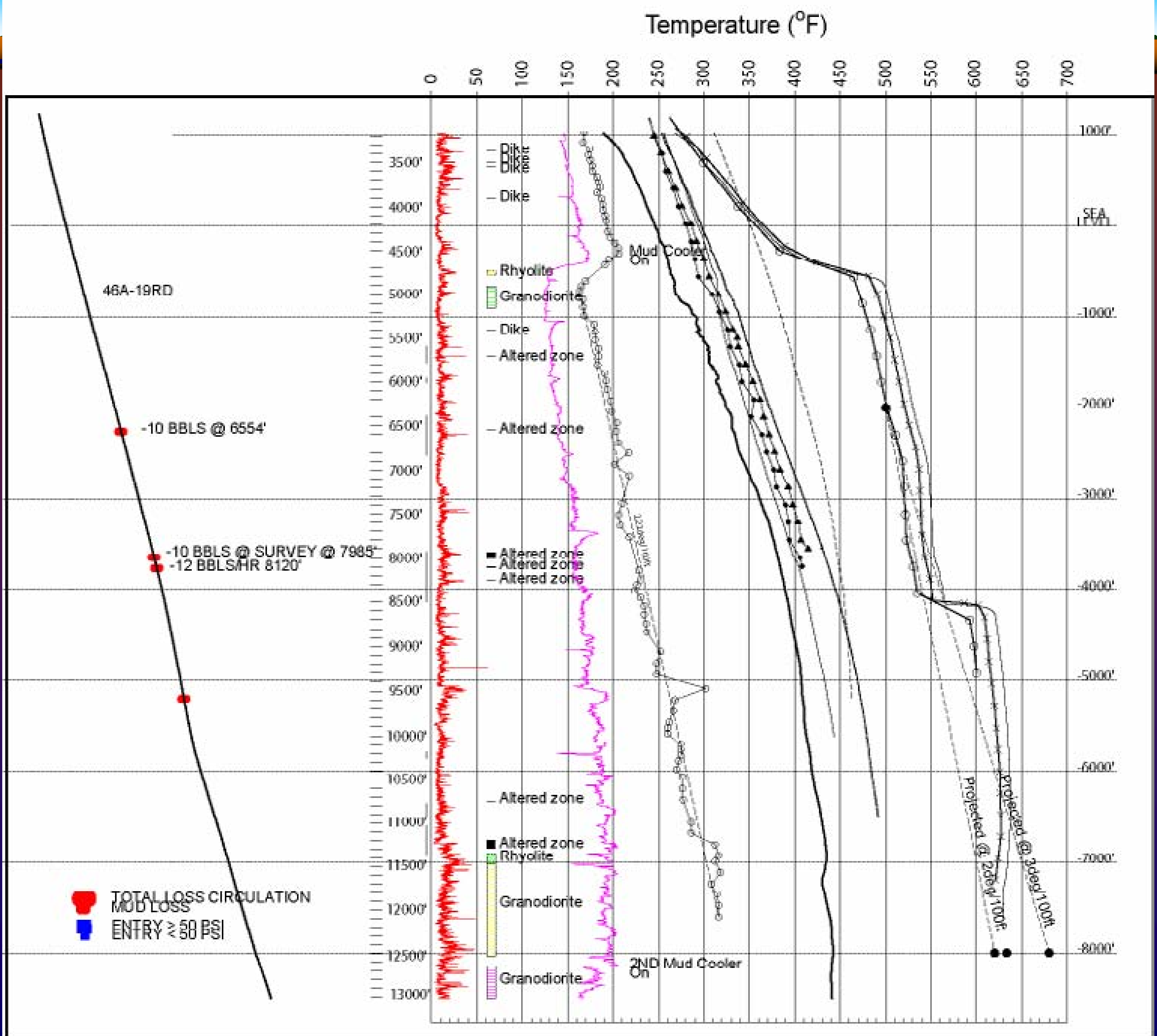
EGS Target Stimulation Well 46A-19RD

- Drilled in 1994 to a TVD of 12,678 ft
- Bottomhole temperatures estimated to exceed 350^{o}C
- Very low injectivity observed below ~10,000 ft

Location of 46A-19RD within the Southwest Corner of the Coso Field



46A-19RD



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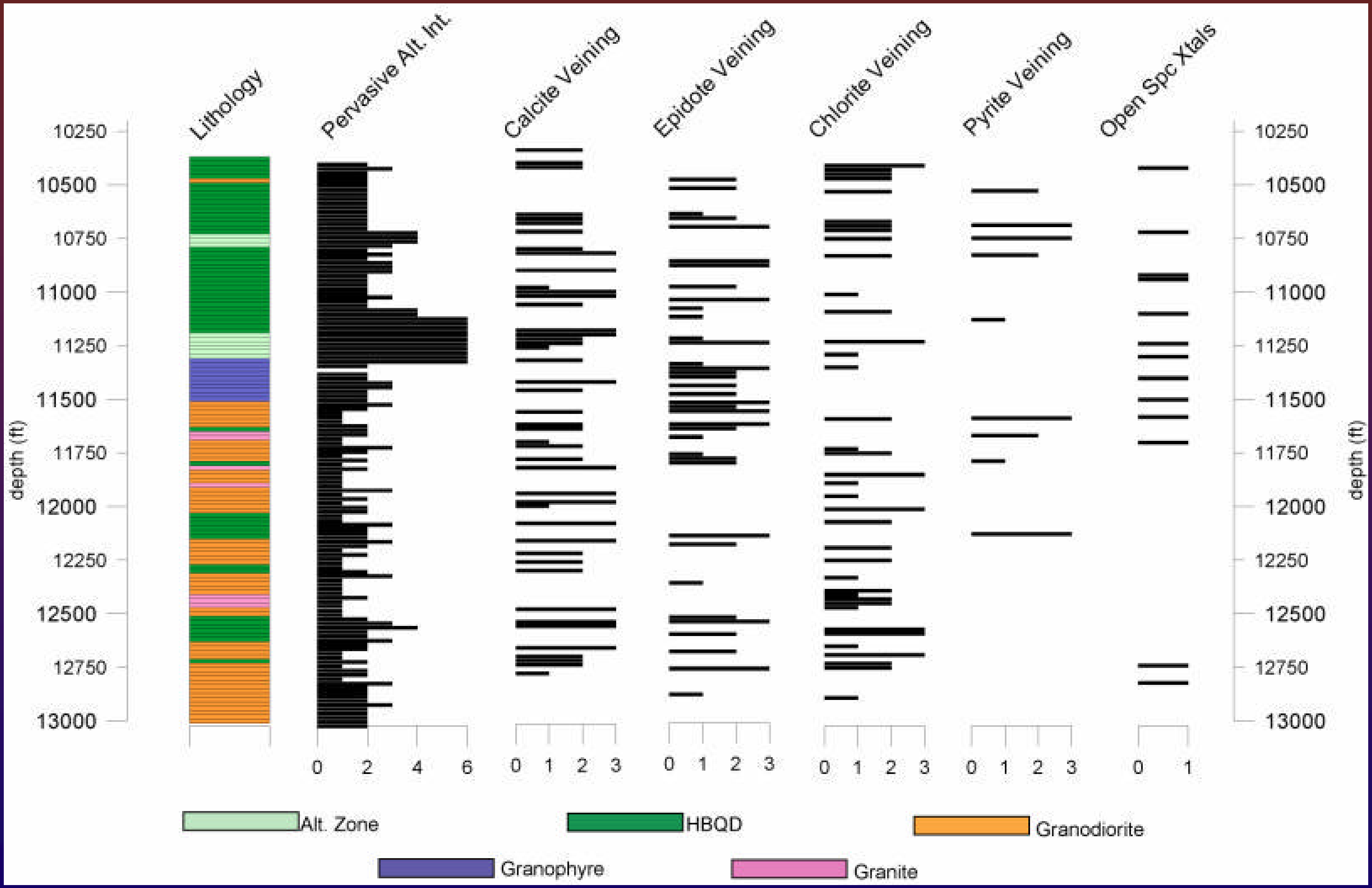
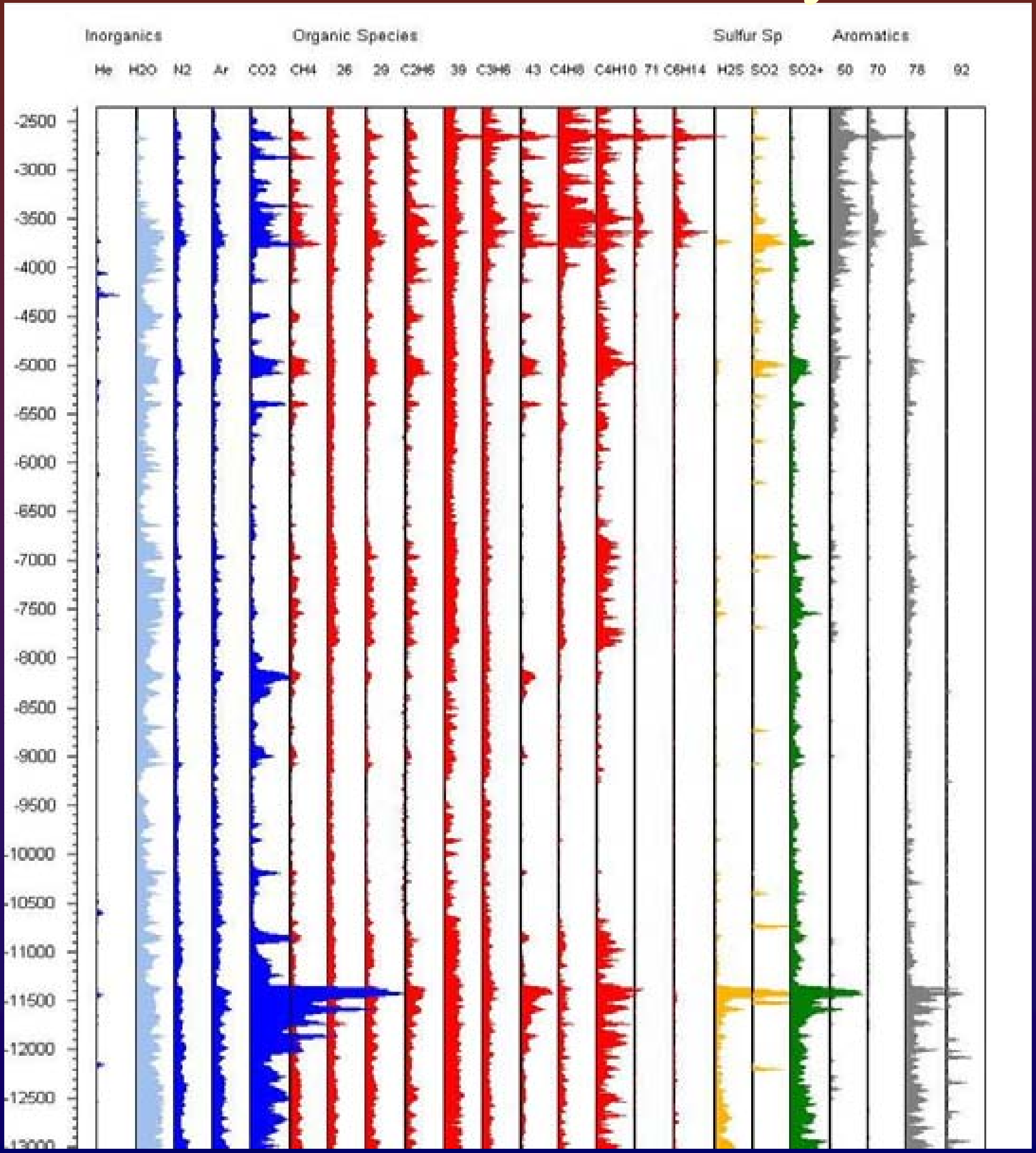
Petrography and Petrology of 46A-19RD from Drill Cuttings



Fluid Inclusion Gas Geochemistry in 46A-19RD



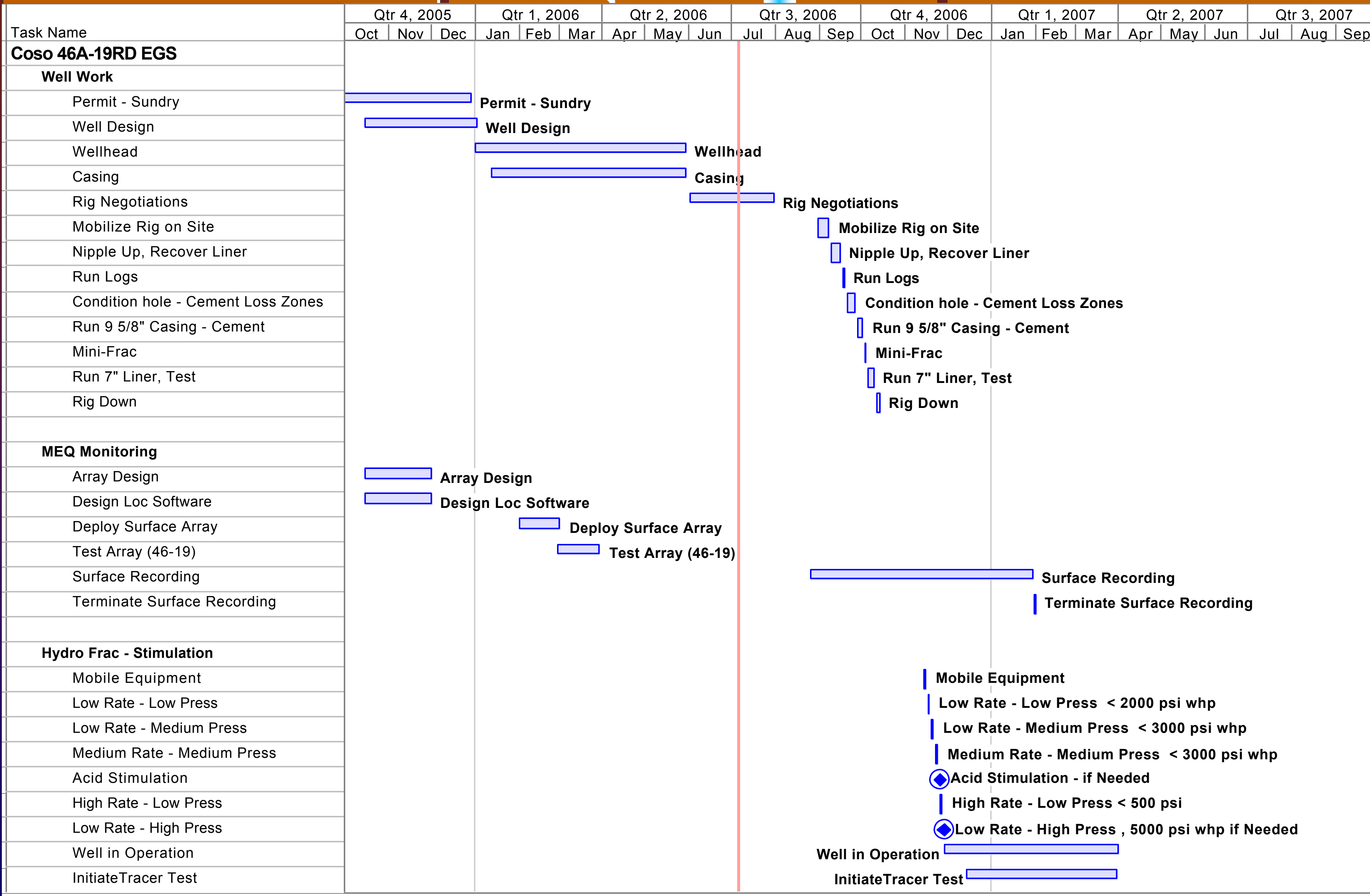
46A-19RD Preparation and Workover

- Install Navy's temporary seismic array, debug, test equipment, and collect background data in anticipation of workover and stimulation
- Move rig to 46-19 pad
- Remove liner from 2065' to TD
- Conduct borehole image log using the HT borehole televiewer
- Conduct suite of logs including PTS, natural gamma, velocity, and density
- Cement new 7" liner from surface to ~10,000 ft
- Conduct mini-hydrofrac in bottom, open-hole section
- Conduct rig-injection test in order to determine baseline injectivity and to help design the stimulation experiment

Summary of Preliminary 46A-19RD Stimulation Plan

Phase	Pmax (psi)	V (bbl)	Description
Fracture Initiation	1,500	2,000	Initiate fracture shearing at upper bound of target P
PTS log	200	--	Check flow profile
Fracture propagation--Phase I	1,500	30,000	Propagate fractures, monitoring with microseismics
PTS log	1,500	--	Check flow profile
Stepwise hydrofrac--if needed	3,000	2,000	Create hydraulic fractures
Fracture propagation--Phase II	1,500	50,000	Continue to propagate fractures, increasing connectivity

Schedule



Task Name
Qtr 4, 2005
Qtr 1, 2006
Qtr 2, 2006
Qtr 3, 2006
Qtr 4, 2006
Qtr 1, 2007
Qtr 2, 2007
Qtr 3, 2007
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
Coso 46A-19RD EGS
Well Work
Permit - Sundry
Well Design
Wellhead
Casing
Rig Negotiations
Mobilize Rig on Site
Nipple Up, Recover Liner
Run Logs
Condition hole - Cement Loss Zones
Run 9 5/8" Casing - Cement
Mini-Frac
Run 7" Liner, Test
Rig Down
MEQ Monitoring
Array Design
Design Loc Software
Deploy Surface Array
Test Array (46-19)
Surface Recording
Terminate Surface Recording
Hydro Frac - Stimulation
Mobile Equipment
Low Rate - Low Press
Low Rate - Medium Press
Medium Rate - Medium Press
Acid Stimulation
High Rate - Low Press
Low Rate - High Press
Well in Operation
InitiateTracer Test
Permit - Sundry
Well Design
Wellhead
Casing
Rig Negotiations
Mobilize Rig on Site
Nipple Up, Recover Liner
Run Logs
Condition hole - Cement Loss Zones
Run 9 5/8" Casing - Cement
Mini-Frac
Run 7" Liner, Test
Rig Down
Array Design
Design Loc Software
Deploy Surface Array
Test Array (46-19)
Surface Recording
Terminate Surface Recording
Mobile Equipment
Low Rate - Low Press < 2000 psi whp
Low Rate - Medium Press < 3000 psi whp
Medium Rate - Medium Press < 3000 psi whp
Acid Stimulation - if Needed
High Rate - Low Press < 500 psi
Low Rate - High Press , 5000 psi whp if Needed
Well in Operation
InitiateTracer Test

46A-19RD Post-Stimulation Analysis

- Conduct circulation test including tracer testing to confirm newly created fracture-flow pathways.
  - A liquid-phase-tracer test will use a combination of a thermally reactive tracer with a thermally conservative tracer.
  - A vapor-phase-tracer test will accompany the liquid-phase test.
- Continue to acquire and analyze microseismic data
- Evaluate and calibrate as necessary the fluid-flow models predicting effects of shear failure, temperature and chemical dissolution on reservoir permeability.